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ABSTRACT

This report is one of a series produced by the National Center for Improving Science Education. The Center synthesizes and translates the findings, recommendations, and perspectives embodied in recent and forthcoming studies and reports in order to develop practical resources for policymakers and practitioners. Toward achieving the High School Panel's vision for a high school science education that provides all students with an opportunity for in-depth engagement with science, the Center presents a consistent and coherent blueprint addressing four aspects of science education: program; assessment; teaching; and teacher and organizational development. To meet the goals for program, assessment, teaching, and teachers, this report contains: (1) recommendations to guide program and policy development; (2) principles for course design, assessment reform, research-based teaching, teacher enhancement, and organizational restructuring; and (3) vignettes that illustrate how teachers and administrators can address practical and intellectual challenges they will face in implementing change. This document contains 75 references. (KR)

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of

The National Center
for Improving
Science Education

The High Stakes of High School Science

The National Center
for Improving
Science Education

The Center is a division of
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Foreword

This report is one of a series produced by the National Center for Improving Science Education. The Center's mission is to promote changes in state and local policies and practices in the science curriculum, science teaching, and the assessment of student learning in science. To do so, the Center synthesizes and translates the findings, recommendations, and perspectives embodied in recent and forthcoming studies and reports in order to develop practical resources for policymakers and practitioners. Bridging the gap between research, practice, and policy, the Center's work is intended to promote cooperation and collaboration among organizations, institutions, and individuals committed to the improvement of science education.

The synthesis and recommendations on assessment in this report were formulated with the help of the study panel whose members are listed in the front (page iv) of this report. Audrey B. Champagne and Senta A. Raizen had overall responsibility for the report plus Chapters II and III, respectively. Paul Kuerbis is the primary author of Chapter IV; Susan Loucks-Horsley, Chapter V. Each received major contributions from the other panelists: DeAnna Banks Beane, Gene Bottoms, Rodger Bybee, John Carpenter, Arthur Eisenkraft, Edward Haertel, David Heil, David Kennedy, Paul Kuerbis, Joseph McInerney, Ina V.S. Mullis, Jeannie Oaks, Harold Pratt, Cliff Schrader, and Ken Tobin.

We gratefully acknowledge the help given to us by many individuals who have supplied materials and made recommendations and suggestions for the text of the report. While the list would be too long to acknowledge individually, we wish to give special thanks to James Gallagher, Michigan State University, and Fred Newmann, University of Wisconsin, for their review of the report and their critical comments which helped to improve it. Thanks also are due to the support of the Center's monitor at the U.S. Department of Education, Wanda Chambers.

A summary of this report, designed for general audiences, also is available from the Center.

At the time this report was produced, the Center was a partnership between The NETWORK, Inc. of Andover, Massachusetts and the Biological Sciences Curriculum Study (BSCS) of Colorado Springs and was funded by the U.S. Department of Education's Office of Educational Research and Improvement. Members of the Center's advisory board are listed on page iii of this report. For further information on the Center's work, please contact Senta Raizen, Director, National Center for Improving Science Education, 2000 L Street, N.W., Suite 603, Washington, DC 20036. To order publications, call 1-800-877-5400.

CHAPTER I

Summary

High school science is high stakes for individuals and for the United States. Science education helps prepare individuals to be informed and active participants in civic life, productive workers, and life-long learners. Moreover, a good grounding in science contributes to understanding the natural environment and contemporary culture—particularly in an age when science and technology permeate U.S. life. Science education is of critical national importance. Maintaining a strong participatory democracy, strengthening a declining economy, and the advancement of science all demand a scientifically literate citizenry.

Science learning also is a lifetime pursuit. Ideally, the foundations laid through early experiences, in and out of school, lead to a perspective on the world and nature as rational. Citizens should view science not as evil or mysterious, but as reasonable and understandable. High school graduates should understand scientific research as a powerful and productive form of disciplined inquiry that has yielded rich dividends of knowledge and, through technology, has produced solutions to innumerable practical problems.

Science literally has enabled humans to reshape their environment and adapt it to their purposes. Students, however, should come to understand the provisional character of current knowledge of the world and should feel a healthy skepticism toward the pronouncements of scientists and nonscientists alike. High school graduates also should possess a common core of fundamental understanding in the traditional scientific disciplines—including biology, chemistry, physics, and earth sciences—as well as at least one social science and technology.

Yet just at the point that the need for a good grounding in science is increasing, the bulk of U.S. students do not have the opportunity to experience challenging high school science courses. Science education simply is *not* working for the majority of students. Especially poorly served are students who will enter the workforce immediately on graduation from high school and students from populations underrepresented in science. At least *two-thirds* of the nation's high school students typically do not elect science courses or achieve well in those courses they are required to complete. These students are disproportionally women, minorities—African Americans, native Americans, native Alaskan Americans Hispanic Americans—and low-income and non-college-bound Americans. Unless society prepares youth to understand science, the United States is in danger of becoming a nation of two cultures: one empowered with scientific knowledge; the other at its mercy.

Science education is of critical national importance. Maintaining a strong participatory democracy, strengthening a declining economy, and the advancement of science all demand a scientifically literate citizenry.

Even the student population best served by the current science education system—the college-bound—is getting short shrift. The high-school science education of the college bound student is dominated by the college science curriculum. Consequently the high school curriculum is characterized by strict disciplinary approaches to science that are limited to the body of knowledge with little attention to how that body of knowledge develops or how it makes an impact on culture and society.

This description of science education and the context in which it functions is consistent with the representation of the field in the over 300 reports about science education issued during the 1980's. Of these, a significant subset specifically addressed the status of science education. The science education reports are the basis of this National Center for Improving Science Education synthesis document. The science education reports were analyzed by a diverse group of science educators convened by the Center and charged with the creation of a synthesis document for use by educational practitioners and policy makers. The analysis that produced the vision of school science contained in this document reflects the Center's High School Panel's commitment to Democratic Common Schooling, a constructivist epistemology of science, and emerging intellectual and developmental theories of learning.[1]

An Alternative Vision

The Center's vision is for a high school science education that provides *all* students with an opportunity for in-depth engagement with science. Central to this vision are learning environments, created by teachers, in which students engage with the natural world and science-related issues. The product of this engagement is the development of scientific knowledge and habits of mind. The teaching strategies employed parallel closely the way that scientists and engineers build new knowledge through inquiry and design. Students develop understanding of the origins of scientific knowledge in scientific inquiry as they work to make scientific sense of the natural world. Students develop an appreciation of the power of scientific habits of mind as they address scientific questions and contemporary social issues.

Special Considerations

The rhetoric driving the science education reform reports primarily addresses the solution of national problems: a weak economy and the projected short-fall of scientifically trained people. The danger of this emphasis is the possibility of producing an imbalance in the school science curriculum that de-emphasizes the contributions of scientific literacy to personal empowerment. The Center's High School Panel believes that these contributions are significant and should not be lost as the nation addresses nationwide concerns.

The concept of personal empowerment is especially critical to students bound for the workplace, and students from populations underrepresented in science. Neither personal empowerment nor our nation's democratic ideals can be realized fully until all citizens are scientifically literate and trained in scientific habits of thought. Thus, this report emphasizes raising the participation in science of students from underrepresented groups, as well as those students who will enter the workplace upon graduation from high school. Students pursuing vocational studies need an opportunity to master core concepts from the natural sciences that will help them better understand broad vocational fields of study.

The High School Panel places a premium on the application of science to societal issues. Achieving this goal requires that some portion of each student's high school science program be in socially heterogeneous groups. Group composition should match as closely as possible the community where students will apply their knowledge of science and technology as citizens and adults.

Group experiences of this kind develop an understanding of the application of scientific knowledge to societal issues. In addition, group experiences contribute to improved conceptual understanding. Moreover, group learning mirrors scientific activities that occur *only* in groups. These include communicating effectively about research methods and theories, as well as integrating team members' contributions into a final product.

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[1] The philosophical and empirical bases for these foundations are discussed in Chapter II. In Chapter II, as well as those that follow, these foundations provide the rationale for the Panel's interpretations and evaluation of the many reports whose recommendations are reflected in this report.

Blueprint for Action

Toward achieving the High School Panel's vision, the National Center for Improving Science Education presents a consistent and coherent blueprint addressing four aspects of science education: program; assessment; teaching; and teacher and organizational development. Taken together, these aspects have the potential to forge a system that will meet, well into the twenty-first century, U.S. students' right to a first-rate science education.

Program

The science program the Panel envisions would require *all* students to take science courses during *all* four years of high school. The blueprint that follows provides practical suggestions to create high school programs that would:

- Meet national expectations for school science of high quality;
- Help *all* students attain the personal empowerment that derives from understanding the natural sciences and their applications;
- Better prepare students to succeed in a workplace that demands greater competence in science and technology;
- Better prepare students to use scientific and technological information when they make personal and social decisions;
- Increase the amount and quality of science instruction for students bound for the workplace; and
- Allow students to keep their options to study science open throughout the high school years.

The blueprint outlines programs that provide high school graduates with a common core of fundamental understanding in the traditional scientific disciplines—including biology, chemistry, physics, and earth science—as well as the competence to apply that understanding to personal decisions and societal issues. The blueprint also aims to make science learning a lifetime pursuit. High school graduates of programs that follow the blueprint proposed here will appreciate scientific research as a powerful and productive form of disciplined inquiry that has yielded rich dividends of knowledge and, through technology, has enhanced our quality of life. However, graduates also will be aware of the provisional character of scientific knowledge and exhibit a healthy skepticism toward the pronouncements of scientists and the promise of *the* technological fix.

Assessment

The blueprint contains strategies that will produce valid assessment results. Integrating these strategies into high school programs will mean that methods to assess achievement will be fundamentally altered. Assessments will directly address more complex types of learning than those measured by conventional tests. In addition, assessments will require applications of scientific knowledge and skills to "real world" situations faced by individuals at work, in their own lives, and as citizens of a community.

All types of science assessment—from the classroom to the national and international arenas—will emphasize more strongly:

- What students *do* know and *can* do, rather than what they do not know;
- Higher-order reasoning skills;
- Applications of learning to "real life" situations;
- Products of student work carried out over time; and
- More diversity in methods of assessment, including the use of computer technology, group activities, "hands-on" and perform-

ance tasks, projects, videotapes, and work samples drawn from students' classroom activities and homework.

The vision of good assessments incorporated in the blueprint differs greatly from today's typical assessments. A model of assessment that begins "Put your books under your chairs and take out a clean sheet of paper" implies that teachers splatter students with knowledge, then look to see how much of it has stuck. The alternative scenario, in which students are invited to take part in the assessment of their performance, makes them active collaborators responsible for their own progress. Ideally, assessments provide students with an ongoing way of learning. An overarching principle applies: assessment and teaching should reinforce one another—and be virtually indistinguishable, from the high school student's point of view.

Teaching

The Center's approach to teaching science is founded on the belief that effective teaching is linked directly to the growing understanding of human learning. A good teacher is one who can help his or her students construct new knowledge. The model for teaching and learning high school science has four stages:

Invitation. The invitation to learning originates with a question about the natural world (science) or a problem in human adaptation (technology).

Exploration, Discovery, and Creativity. In this stage, learners design and implement investigations.

Proposing Explanations and Solutions. Students need to learn to communicate their ideas, review them and take account of evaluation by others, propose alternatives, and come to closure.

Taking Action. To cement their emerging understanding of a scientific concept or the viability of a solution to a design task, students take action. Assessment is an integral part of taking action and provides students the opportunity of assessing their developing levels of understanding.

This model shares significant features with scientific inquiry and engineering design as practiced by scientists and engineers. Inquiry and design require investigators to actively join new information and concepts with their existing conceptual frameworks. Participants question, probe, follow "hunches," explore their own meaning, and communicate their new knowledge to colleagues.

Consistent with the practice of science and engineering, the teacher creates an environment where the students, acting as a community of learners, construct understanding. Students, like scientists, often learn best through interaction with one another and with their teachers. Hands-on science is vital to learning science.

This vision of science teaching creates classrooms that are learning communities where scholarship is valued and vigorously pursued. Teachers and students alike take responsibility for fostering learning. The science learning community as envisioned is characterized by:

- Written and spoken interaction;
- A common framework for inquiry;
- Design and laboratory investigations; and
- Mutual respect.

Teachers and Schools

In learning communities, teachers are also learners. These teachers have a personal vision of good science teaching, are committed to personal change, and reflect on their teaching practices and their impact.

The change required to construct the High School Panel's vision is a long-term process, at each phase using different combinations of strategies, resources, and individual and organizational roles and responsibilities. Learning of any type occurs slowly. Changing the *culture* of the school is an even slower process. Changing the culture means, among other things, thinking in new ways about what science is, what all students should know and be able to do, what role teachers and schools should play in science learning, and how individuals—including students, teachers, administrators, parents, and community members—and organizations need to act and interact to implement these fundamentally new ways of thinking.

Restructuring science education calls for a systemic approach. Many constituents need to work together to implement the Panel's vision. These include schools and districts (both regular and special educators); universities (in their work with undergraduates, inservice teachers, and administrators); state and federal agencies; communities; business and industry; and practicing scientists. Change will not occur without policies at all levels—federal, state, and local—to provide direction, expectations for change, decision-making prerogatives for teachers and school administrators, adequate resources, including financial, and other support for the necessary improvements.

The Center's strategy for strengthening science education starts with teachers because it is they who ultimately implement changes in the classroom. But the organizations in which teachers function also must change. The organizations in which teachers work, their departments, schools, and districts, must become "learning organizations" where teachers feel comfortable proposing and trying out new instructional strategies and materials and where they routinely share with one another at several levels. Relations among teachers and administrators must foster open communication, collegiality, support, trust, learning on the job, job satisfaction, and high morale.

To meet the goals for program, assessment, teaching, and teachers, this report contains:

- Recommendations to guide program and policy development;
- Principles for course design, assessment reform, research-based teaching, teacher enhancement, and organizational restructuring; and
- Vignettes that illustrate how teachers and administrators can address practical and intellectual challenges they will face in implementing change.

A key point recurs throughout the report. All four components—program, assessment, teaching, and change among teachers and in schools—must reinforce one another and proceed in tandem. For instance, changes in program require new means of assessment, new methods of teaching, and changes in teachers and schools. To foster one without the others is to invite disappointment and risk failure. Finally, while in the short term the educational cost of keeping options open throughout the school years seems high, data show the much higher social and economic costs society can incur by closing options prematurely.

Changes in program require new means of assessment, new methods of teaching, and changes in teachers and schools. To foster one without the others is to invite disappointment and risk failure.

CHAPTER II

Rethinking The High School Science Program

The over-arching purpose of the four-year high school science programs that the Center proposes is to empower students: to prepare them to be informed and active participants in civic life, productive workers, and life-long learners. Our conceptual framework incorporates recommendations contained in science education reform reports published during the 1980s and embodies the Center's social commitments, as well as contemporary philosophical perspectives and psychological theories.

The approach to science we propose 1) provides rich educational opportunities for all students, 2) reflects the nature of science as it is practiced, and 3) conforms to contemporary theories of how science is learned. The conceptual framework translates into science programs that aim at excellence, contain a common core of outcomes for all students, and occur in rich, adaptive learning environments.

Restructuring High School Science

The framework we propose radically restructures the high school program into **Core** and **Alternative Pathways** studies. The required **Core** meets the general education purposes of science education, preparing students for responsible civic and personal life. **Alternative Pathways** studies differentiate science education based on students' interests and career goals. The proposed framework shifts the traditional emphasis of high school science from college preparation for a select few to general education for all students. The framework strikes an optimal balance among the various purposes of high school science education, placing equal emphasis on two basic purposes of high school science: professional preparation for the workplace or further education; and personal empowerment. It takes into account the needs of gifted science students, as well as those underrepresented in science.

Adjusting the balance is necessitated by the overemphasis on preparation for college characteristic of most high school science programs. National tests and high school science textbooks align with this purpose. Despite persistent criticism about the limitations of this view, scores on scholastic achievement tests and advanced placement tests define public expectations for high school science. The content of these tests is determined by the universities and colleges that use test scores to make admissions decisions and to assign university credit for advanced placement courses. The use of these test scores is eroding as each year fewer colleges use SAT or ACT scores as admission criteria. In the absence of any alternative indicator of excellence, however, they remain influential.

The framework strikes an optimal balance, placing equal emphasis on two basic purposes of high school science: professional preparation for the workplace or further education; and personal empowerment.

Textbooks for high school science reflect the emphasis on college preparation. Texts for college preparatory students are only slightly diluted versions of the textbooks used in college survey courses, while texts for students in vocational and business courses are even more diluted versions of the same content. Consequently, high school textbooks are limited in scope. At best, they contain only brief mention of 1) the history or philosophy of science, 2) the interactions of science and society or technology, or 3) the applications of science to social, civic, or personal decision-making.

College texts are written by scientists and reflect the way that scientists think about their discipline. This structural organization assumes that students will apply their scientific knowledge to conducting scientific inquiries. Typically, the organization of content in high school textbooks mirrors college texts.

The emphasis in high school science on the preprofessional education of future scientists, engineers, and technicians was reinforced during the reform of school science in the 1960s. At that time, the nation's concern with the United States preeminence in science and technology created pressure on the schools to strengthen programs for students intending careers in science and engineering. However, the social and economic circumstances have changed. Today's reform is led by the private sector calling for intellectually demanding science courses for all students, particularly for students whose formal science education will end at high school graduation.

Only passing mention is made in the rhetoric of either reform movement to education for personal and civic empowerment. In this case, rhetoric follows practice because preparation for informed citizenship and personal empowerment places a poor third in the competition for time in the school science program. The framework we propose reconstitutes and restructures the high school science program to give serious attention to a broad range of purposes, not just preparation for college.

Achieving the Purposes of School Science

School science serves diverse purposes. Moreover, school science programs serve students with a wide variety of personal aspirations and cultural and intellectual characteristics—all of which influence the ways in which they learn science best. Programs for high school science must provide the variety of educational experiences that will enable all students to achieve the purposes of school science. A framework for such programs is described below. The high school science program we envision would:

- Accommodate cultural differences and intellectual preferences for approaching science learning;
- Accurately reflect the methods and intellectual products of science;
- Closely represent science as it is practiced;
- Provide students with opportunities for in-depth engagement with science; and
- Allow students to keep open options for continuing science studies.

Structure

The high school science program the Center proposes would require *all* students to take science courses during *all* four years of high school. The first two years would be devoted to **Core** courses. In years three and four all students would concentrate in one of three **Alternative Pathway** programs. These programs would meet individual students' science interests and career goals.[1]

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[1] Our recommended Alternative Pathways can be interpreted as a form of tracking, an educational practice under considerable fire. The Quality Education for Minorities Project, QEM (1990), for instance, calls for the total elimination of tracking because it reduces opportunity, especially for minority students. Our framework maintains opportunity by promoting a strong academic Core and Alternative Pathways that match the purpose of science education to student aspirations. In both the Core and Alternative Pathways, intellectual rigor is maintained.

The Core

Purpose. The primary purpose of the two-year Core is to meet the goals of general education for responsible citizenship, cultural literacy, and personal enhancement.

Structure. The Center's most radical proposal is to require the Core of *all* high school students and to keep students in *heterogeneous* groups for Core experiences. Groups of students should match as closely as possible the composition of the community that the high school serves. This proposal is consistent with the philosophy of democratic schooling that underlies the stated purposes of schooling.

The Center also proposes organizing subject matter of core courses around contemporary social, civic, and personal issues. These conditions —studying science in heterogeneous, representative groups, in the context of meaningful contemporary issues—would make the study of science authentic. That is, students' learning of science would occur in a context that mirrors the context in which what is learned would be practiced.

Outcomes. We envision that the core science experiences would:

- Develop integrated understanding of key concepts and challenging subject matter in biology, chemistry, physics, and earth science.
- Relate these understandings to historical and contemporary global, civic, and personal issues.
- Engender intellectual competency, including the capacity for self-directed learning; for gathering and evaluating information; for resolving issues and making decisions; and for communicating effectively by listening, speaking, and writing.
- Engender attitudes, appreciations and dispositions, including appreciation of the power of knowing; informed attitudes toward science and its applications; and the disposition to apply scientific knowledge and methods to resolve issues and seek solutions to problems.
- Develop understanding of the nature of science and its relationship to technology, the role of science and technology in society, and the contributions and limitations of science and technology to addressing societal and personal issues.

Some **key principles** that the core science experiences would develop:

- Science and technology are powerful forces for change in society.
- The scientific world view is a major influence in society. It directly affects the lives of individuals and organizations, as well as the operation of society at large.
- Science is a unique world view, but only one world view. A scientific world view assumes that the universe can be explained in terms of natural phenomena, without appeals to supernatural events.
- Similar assumptions and methods underlie scientific inquiry in all natural sciences.
- The boundaries between scientific disciplines are not distinct. Understanding the major concepts of many disciplines is necessary to understand any one discipline completely.
- Each scientific discipline provides different metaphors to explain the phenomena the practitioners in that discipline investigate.
- Scientific explanations apply across phenomena (horizontally) and through time (vertically).
- Science and technology, while closely interrelated in practice, have different purposes, and use different methods. For example:
    - Science's purpose is to construct rational explanations of the natural world.
    - Technology's purpose is to adapt the environment to human needs.
    - Scientific explanations are tentative. Technological adaptations involve trade-offs.

— Devices and strategies designed to achieve technological adaptations have side effects that often are unanticipated.

— Technological adaptations involve some risk. The degree to which society chooses to implement them is the degree to which society must bear the burden of risk.

Principles of science and technology can indicate what is and is not possible with respect to personal and societal needs—but not what individuals or society *should* or *should not* do.

Societal change induced by progress in science and technology has proceeded more quickly than society and individuals have accommodated to these changes with new ethical, legal, and public policy guidelines.

Alternative Pathways Program

The two years of required study in the Alternative Pathways program would mainly serve the vocational and professional purposes of school science. We propose an Alternative Pathways program as preparation for three further pursuits: college or junior college; technical or engineering schools; or the workplace, for those students who plan to enter the workforce upon graduation from high school.

■ *College- or junior college-bound students*

Purpose. This Alternative Pathway would meet entrance requirements for college or junior college and prepare students for introductory postsecondary courses in the natural sciences.

Program of study. The program of study would consist of half-year courses in four disciplines—biology, chemistry, physics, and earth and space sciences—as well as advanced placement courses in the natural sciences. While college-bound students would spend less time in studies oriented toward specific disciplines in the natural sciences, the Core would make up for this. Core experiences would impart sufficient science content and require sufficient intellectual rigor to engender considerable scientific understanding and qualify for credit for college admission.

Content. Content would emphasize the knowledge and methodologies of the natural sciences—their constructs, principles, and theories. Less emphasis would be given to the interactions of science with technology and society, although these would remain an integral part of content for those preparing for collegiate science. Like conventional science courses, course content would be organized according to the structure of the natural science disciplines.

Intellectual competency. The Pathway would emphasize scientific inquiry and academic problem-solving.

■ *Technical or engineering school-bound students*

Purpose. This Pathway would meet the requirements for admission to technical school and engineering colleges and prepare students for introductory postsecondary courses in the natural sciences, engineering, and technology.

Program of study. The program would consist of half-year courses that develop selected natural science concepts, principles, and theories in the context of agricultural, medical, or engineering applications.

Content. The content would emphasize the application of science to technical fields.

Intellectual competency. The Pathway would emphasize engineering design.

- ***Workplace-bound students***

Purpose. This Pathway would prepare students for competent performance in the workplace.

Program of study. The pathway would consist of formal academic coursework, as well as practical experiences in the workplace. Courses would be selected from those designed for students bound for college or technical schools. Students also would participate in supervised internships at local businesses and industries. Internships would provide the opportunity for students to experience first-hand the scientific knowledge and intellectual skills needed for success in the workplace. Students would reflect on their experiences in the workplace in seminars. These would enable upcoming students to identify formal academic courses that would prepare them for the workplace.

The science program for the workplace would be highly interactive, commencing with an experience in the workplace that (presumably) would motivate students to pursue further formal studies in the natural sciences.

Content. The content for students in this Pathway would vary greatly, depending on an individual student's interests and vocational aspirations. A clear principle should guide the individual's program planning: maintaining the student's involvement with science, while keeping options open for further study and career opportunities.

Intellectual competencies. The program would emphasize skills to engage in self-directed learning to solve problems of the kind that occur in the workplace.

To illustrate what the Center's vision of high school science might look like, the (fictional) Dunbeigh High School Science Program is described beginning on the next page.

Social, Philosophical, and Psychological Foundations

The Center's commitments to certain social values, philosophical perspectives, and psychological theories guided the analysis of our report's recommendations and subsequent conclusions regarding the goals and characteristics of ideal high school science programs. These are the intellectual foundations of the framework we advocate. Alternative views about the goals of school science and the nature of programs to achieve them are a natural consequence of commitments to alternative social values, different philosophies of science and education, and the application of other theories of learning.

We present the foundations of our programs in detail because of our conviction that debates about the goals of school science and the characteristics of science education to achieve them can be fruitful only when participants are clear about the intellectual foundations on which their views are based.

Social Commitments

The social foundation of the Center's high school science program framework is a commitment to make the most of the educational opportunity for all students, including gifted students, students from populations underrepresented in the sciences, students with physical and learning disabilities, and students who plan to enter the workforce immediately upon graduation from school.

This means that all students must have equal access to key components of successful science education: high quality science knowledge; qualified science teachers; tools to engage in science learning experiences (such as laboratories, computers, instructional materials, and library facilities); rich field experiences; interactions with scientists, engineers, and others performing work

Continued on page 17

Science At Dunbeigh High

A Handbook for Students and Parents

Students entering Dunbeigh High School design a science program to meet their science background, interests, and career aspirations. Individualized science programs are designed in cooperation with the school's guidance counselors, with the advice and consent of the students' parents or guardians. At the end of each school year, students meet with guidance counselors to review their science program and to modify it in accordance with changing career aspirations and interests.

Four years of science are required for all students at Dunbeigh High. The four-year plan consists of a two-year Science Core, and courses selected from three Alternative Pathways options that are designed to prepare students for collegiate study in the liberal arts, postsecondary study in technical subjects, or the workplace. Students move easily between the Alternative subprograms and, even while working to complete one, sometimes chose electives from another.

- The basic Science Core is outlined at right.
- Samples of Alternative Pathways options follow on pages 13-14.
- Transcript stories on pages 15-16 illustrate how three students might progress through the Dunbeigh High program.

Science Core

Course Offerings

Core Science 1

1A Contemporary Ecological Concerns
Solid Waste Management
Planning Our Petroleum Future
Benefits/Risk Analysis of Nuclear Power

1B Case Studies in the History and Philosophy of Science
Brewing: A Case Study in the Development of Science and Technology
Unfamiliar Women of Science:
Hypatia, Roselyn Frankel, Annie Cannon, Carolyn Herschel
The Lives and Times of Black, Hispanic, and Native American Scientists:
Charles Drew, Booker T. Washington
The Science, Technology, and Politics of the Cotton Gin
Conceptions of the Universe
The Development of Measurement

Core Science 2

2A Themes Across the Disciplines
The Construct of Energy in the Physical, Life, Earth and Space Sciences
The Construct of Systems in the Physical, Life, Earth and Space Sciences
Form and Function, Ratio and Proportion

2B Contemporary Ethical Dilemmas
Diagnosis of Genetic Defects
Commercial Applications of Genetically Engineered Microorganisms
Ethical Implications of Organ Transplant Technology
Preparation and Sale of Irradiated Foods

The Core

The Core Program at Dunbeigh High achieves the purposes of general education in the sciences through modules that organize the content in different ways. All core modules are interdisciplinary in approach. The interdisciplinary content is organized in different ways, however. Core Science 1A (CS1A) is a half-year program with a theme of contemporary ecological concerns. The content of the modules changes from year to year depending on the interests of the teacher. Modules for CS1A are supplied from many sources. Solid Waste Management, for instance, is taught using the module designed by the New York State Department of Education's Science, Technology, and Society Program. The Dunbeigh High CS1A chemistry module uses units from the American Chemical Society's *ChemCom* Program (1988).

Core Science 1B (CS1B) also is interdisciplinary in approach, structuring the science content around case studies from the history and philosophy of science. When CS1B is team-taught by a science and a social studies teacher, as it often is, the course serves as a core requirement for both science and social studies. Through the examination of historical events, the historical role of women in science, for instance, students gain insights into contemporary issues in the interaction of science, society, and technology.

Core Science 2A (CS2A) takes a thematic approach to science, examining similarities and differences in science constructs across the science disciplines. Concepts and themes for Dunbeigh High's CS2A are drawn from *Science for All Americans* (American Association for the Advancement of Science, 1989).

The theme of Core Science 2B (CS2B) is ethical dilemmas created by choices that scientific and technological advances provide humankind. It provides students from diverse cultural and religious backgrounds the opportunity to understand the scientific, technological, and ethical issues that surround the choice to utilize technological artifacts that prolong or enrich life.

College Preparation Alternative Pathway

Course Requirements

Freshman Year

Core Science 1A and 1B

Sophomore Year

Core Science 2A and 2B

Junior and Senior Years

Courses selected from:
Introductory Biology (1/2 year)
Introductory Chemistry (1/2 year)
Introductory Physics (1/2 year)
Introductory Earth/Space Science (1/2 year)

Advanced Placement Biology (1 year)
Advanced Placement Chemistry (1 year)
Advanced Placement Physics (1 year)

College Preparation Alternative. Courses unique to the college preparatory alternative are quite like conventional high school science courses. Content focuses on the natural science disciplines structured in traditional ways. A major difference is that these courses are only a half year long. This is possible because all students in the College Preparation Alternative are required to take the Science Core, which contributes significantly to the development of subject matter knowledge. Dunbeigh High continues to provide students planning on college the traditional advanced placement courses in the natural sciences.

Alternative Pathways continue on next page

Technical/Engineering Preparation Alternative

Course Requirements

Freshman Year

Core Science 1A and 1B

Sophomore Year

Core Science 2A and 2B

Junior Year and Senior Year

Courses selected from:
Principles of Technology/Chemistry-1
Principles of Technology/Physics-1
Principles of Technology/Biology-1
Principles of Technology/Chemistry-2
Principles of Technology/Biology-2
Principles of Technology/Physics-2

Technical/Engineering Preparation Alternative. Courses in Dunbeigh High's Technical/Engineering Alternative Pathways program are jointly sponsored by the science and technology departments. The courses are team taught by science and technology teachers. Science teachers take primary responsibility for the Technology 1 series focusing on science, but they use examples from technology and technology teachers. Technology teachers take primary responsibility for the Technology 2 series that focuses on applications. Any course in the Technology 1 series can be substituted for the conventional course in the College Preparation Program. Thus, a student interested in an approach to physics that is more applied than academic may elect to take Principles of Technology/Physics-1 in place of Introductory Physics.

Workplace Preparation Alternative

Course Requirements

Freshman Year

Core Science 1A and 1B

Sophomore Year

Core Science 2A and 2B

Junior Year and Senior Year

Courses selected from:
Principles of Technology and Introductory
College Preparatory Courses
Two years of Internship and Seminar

Workplace Preparation Alternative. Students in this Alternative Pathway generally take science courses designed for the Technical/Engineering Alternative. The unique Dunbeigh High School offering for students planning to enter the workforce upon high school graduation are the Internship and Seminars jointly sponsored by the Anycity Board of Education and the Anycity Chamber of Commerce. A committee composed of teachers from the program and cooperating business and industry representatives meets each month to assign students to internships, monitor student progress in the internships, and plan seminars that are jointly organized by teachers and industrial representatives. In addition to reinforcing the importance of competencies being developed in the school program, seminars help students learn about proper decorum in the world of work and how to take advantage of professional development opportunities provided by employers.

Students have been so well received by local businesses that this aspect of the Dunbeigh High School Program is quickly evolving into a cooperative work-study program. This program has social as well as academic benefits, keeping students in school who otherwise might drop out for full-time employment. Furthermore, because the school and the employers cooperate closely, they can monitor the time students spend in part-time jobs and help students avoid neglecting their school responsibilities.

Transcript Stories

The transcript stories that follow illustrate how three students might progress through the Dunbeigh High science program.

Student Transcript

Dunbeigh High School

Student	Kahena Washington
	Science
Freshman	Core Science 1A and 1B
Sophomore	Core Science 2A and 2B
Junior	Introductory College Preparatory Physics and Chemistry
Senior	Introductory College Preparatory Biology and Earth and Space Science

Kahena entered Dunbeigh High with a strong science background. Both the elementary and middle school she attended had implemented science programs that embody the recommendations of the Center's elementary and middle level reports. Kahena planned her science program in consultation with her mother and the high school guidance counselor. Kahena planned to enter college following graduation from high school. Consequently, her science program was planned to achieve general education goals, as well as to meet college entrance requirements.

The Core Sciences experiences at Dunbeigh High gave Kahena the opportunity to engage compelling topics in a safe but intellectually and culturally rich environment. She was able to work on issues that she may well face in her adult life, unencumbered by the emotional stress that accompanies making decisions in real life. Because she worked out intellectual and ethical issues with students from diverse cultural and religious backgrounds, Kahena came to understand why reaching consensus on issues often is so difficult politically.

Kahena's junior and senior science program engaged her in the study of the natural sciences structured in the conventional way. Because Kahena planned to major in economics in college, she did not take any advanced placement courses in her senior year. Even so, the cumulative effects of a strong elementary and middle level science programs and intellectually rigorous science in her Core courses enabled her to complete each of the half-year Core courses in the Academic Pathway with a well-structured base of knowledge equivalent to that which she would have achieved in full-year traditional courses.

Student Transcript

Dunbeigh High School

Student	Jose Sansone
	Science
Freshman	Core Science 1A and 1B
Sophomore	Core Science 2A and 2B
Junior	Principles of Technology/Physics-1 Internship and Seminar T/E
Senior	Introductory College Preparatory Physics Introductory College Preparatory Chemistry Internship and Seminar T/E

Jose entered Dunbeigh High hating science. His elementary and middle school science experience had convinced him that science was not in his future. He was distressed to learn from his guidance counselor that even as a student in the technical alternative he was required to take science for four full years at Dunbeigh. A program planning session with his counselor helped to relieve Jose's science anxiety. The Core science program the guidance counselor described certainly did not resemble any science course Jose had ever taken before.

"Maybe if I scrape through the core, I can negotiate my way out of science in my junior and senior years," he thought. However, after hearing about the Alternative Pathway for students interested in the workforce, Jose agreed to take Principles of Technology/Physics 1, the prerequisite for the study of the hydraulic, pneumatic, electrical, mechanical, and optical systems of household appliances and workplace equipment.

Jose did credibly well in his Core program. But he still did not believe he could "do" science. His experience in the Core program was so different from what he had previously experienced in science that he did not yet think of the Core as real science. Jose's two-year experience in the Core was adequate preparation for Principles of Technology/Physics 1. Because the science content studied in Principles of Technology/Physics 1 was presented in the context of devices and situations familiar to Jose, he learned it with surprising ease. In fact, he not only learned the content but also came to enjoy it. When Jose began Technology/Physics 2, he was bored. He already knew a lot about the appliances and equipment that exemplify the physical principles he had studied.

Besides, Jose had come to realize that he enjoyed science. Because his science background was strong, Jose was able to transfer without any problem from Technology/Physics 2 into Introductory College Preparatory Physics and Chemistry.

When Jose entered Dunbeigh, he was working at Monroe's Heating and Air Conditioning Shop. Through Sam Monroe's cooperation, this part-time job was converted to an internship for Jose. Monroe became involved in the T/E Seminar committee and now Monroe's provides equipment for the Principles of Technology/Physics 2 course.

Student Transcript

Dunbeigh High School

Student	Marjorie Long
	Science
Freshman	Core Science 1A and 1B
Sophomore	Core Science 2A and 2B
Junior	Principles of Technology/Physics-1 Principles of Technology/Chemistry-1 Internship and Seminar in T/E
Senior	Advanced Placement Physics Advanced Placement Chemistry Internship and Seminar in T/E

Marjorie Long entered Dunbeigh High planning to be an electrical engineer. Her engineering college preparation program is highly skewed toward physical science and engineering. Her part-time job at the local General Electric plant not only helped her save money for college expenses, but also gave her insights into the real-life activities of women in electrical engineering.

While the guidance counselor was concerned initially about the overemphasis in Marjorie's program on the physical sciences, she was reassured that the experiences of the science Core would balance out the life sciences portion of Marjorie's science knowledge and skills.

Continued from page 11

relating to science and technology; and information and guidance about the implications high school experiences hold for postsecondary schooling, occupations, and life opportunities. All students also should have access to women and minority scientists and science teachers who will act as role models. Moreover, direct experiences with these individuals will serve to broaden all students' images of who does science (Oakes, 1989, 1990; Oakes et al., 1990).

The access principle applies to mathematics, as well, because mathematics serves as a critical filter to opportunities in science. The Center's program maintains an appropriate balance between serving individual and societal interests and keeping program options open.

The Center's social values are reflected in strategies employed in the framework to broaden the opportunity to learn science. The school science program bears the primary responsibility for engendering scientific literacy. Thus our report gives special attention to curricular factors that facilitate science learning for all with careful attention to individuals from populations currently underrepresented in the natural sciences. This commitment is realized in our recommendation to keep options to study science open as long as possible. In practical terms, this means that the school science program is both diverse and rigorous. Diversity in the content as well as teaching method increases the probability of achievement and encourages students to persist in their study of science.

Intellectual rigor in all courses allows students to make adaptations in their science programs when necessary in their high school career. For instance, when entering high school, a young woman may chose to pursue a program of study that takes a technological or applications approach to the study of science. Later she may decide that her interests are more in the development of scientific theories than in applications of theory. The background she obtains in courses that emphasize applications should have sufficient intellectual quality that the student is adequately prepared to meet the demands of courses that take a more theoretical approach to science.

The high school programs the Center envisions would allow students to make choices compatible with their interests, while keeping open the possibility of making changes in their science programs that reflect their changing interests and aspirations. Not only is our recommendation to keep options open consistent with the nation's social values, it is also economically sound. While in the short term the educational cost of keeping options open throughout the school years seems high, closing options prematurely has much higher social and economic costs.

While in the short term the educational cost of keeping options open throughout the school years seems high, closing options prematurely has much higher social and economic costs.

We are committed also to school science programs that serve the interests of the society as well as the individual. These interests are complementary. Even so, social, political, and economic conditions often produce imbalance in the program favoring one or another purpose. Generally, the rhetoric driving the reform of school science addresses primarily the solution of national problems—for instance, insufficient human resources to maintain the U.S. preeminence in science and technology. This emphasis may well produce an imbalance in the school science program that deemphasizes the contributions of scientific literacy to personal empowerment in favor of its contributions to the nation's security and economic well-being.

In turn, an overemphasis on the utilitarian benefits of knowing science leaves little time in the program for students to learn about the contributions of science to a rich intellectual and aesthetically pleasing life. Because we consider all these purposes important, the framework for high school science programs that we propose maintains a careful balance between the contributions of science to individual and national interests as well as to science's utilitarian and aesthetic benefits.

Philosophical Perspectives

The Center's recommendations for science education favor a constructivist epistemology of science. In the constructivist epistemology, "*knowledge* refers to conceptual structures that epistemic agents, given the range of present experience within their tradition of thought and language, consider *viable*" (vonGlaserfeld, 1988). From a constructivist perspective, knowledge is a mental representation of the natural world. A critical question is whether representation is influenced by the knower's previous experiences and knowledge, culture, and language. The constructivist proposes that the knower's interactions with the environment are influenced by experience, knowledge, culture, and language; these along with the mental images of sensory input from the environment serve as the mental objects from which the knower constructs a representation of the interaction.

The constructivist perspective casts doubt on the possibility of objective knowing, and also asserts that the practice of science is value-laden. Values, experience, existing knowledge, culture, and language influence observation and also the issues scientists choose to investigate, as well as the hypotheses that guide their inquiries.

In the constructivist epistemology, proof is replaced by viability as the method for assessing the validity of knowledge. Viability is a measure of how well knowledge satisfies the goals of an individual, or an intellectual or social community, as well as its congruence with extant knowledge.

The distinction between personal knowledge and community knowledge is critical. Personal knowledge is knowledge that an individual has judged viable. Community knowledge is achieved when a collection of individuals assesses and reaches consensus on the viability of knowledge. Scientific knowledge in the constructivist perspective is knowledge that the scientific community has assessed and judged to be viable according to community standards of evidence and logical argumentation. The constructivist perspective acknowledges the tentative nature of scientific knowledge and rejects the conception of proof that an assertion, law or theory is *true* of the world. Rather, the constructivist recognizes the evolution of scientific knowledge, and acknowledges that scientific knowledge is knowledge which is deemed viable by the scientific community at a given time.

When the constructivist epistemology is applied to schooling, the purpose of schooling is to facilitate the evolution of personal knowledge into the knowledge of the learner's culture. Consequently, a goal of school science is to help the student shape his or her personal knowledge of the natural world into a form that agrees with the scientific view. The strategy we propose to facilitate the process engages the student in a process similar to the ways in which the personal knowledge of scientists is transformed into scientific knowledge. This strategy is consistent with cognitive psychological theory, as well as with the nature of science and scientific inquiry.

Psychological Perspectives

In many respects, contemporary theories of how science is learned are consistent with constructivist epistemology. Learning is conceived as a process of making sense of experience in terms of prior knowledge. The process of learning involves learners interpreting educational experiences and tasks in light of their existing knowledge and incorporating the experience as modified by the interpretative process into their knowledge structures. Learners' goals, previous experiences and understanding, culture, and language are called into play during the interpretive process.

Research and theory in the cognitive tradition provides empirical support for the constructivist view of learning. For instance, research on students learning physics demonstrates that students' observations even of "objective" events—a falling object, for instance—are influenced by their existing knowledge or by what they expect to observe (Champagne et al., 1985). Cognitive theory also is moving toward a view of formal learning that acknowledges and supports the contributions of social interactions to the development of conceptual understanding (Brown, Collins, and Duguid, 1989).

Purposes of School Science

The basic purpose of education is empowerment of the individual. Active participation in civic affairs, competent performance in the workplace, and ongoing personal enhancement are attributes of the empowered person. Empowerment is achieved through general and professional education. General education refers to those aspects of education intended to prepare for an ethical, reflective, and aesthetically rich life as distinguished from professional education, which prepares for the technical demands of the workplace.

In a society and economy where science and its applications are pervasive, competence in the natural sciences empowers. Philosopher Bertrand Russell comments eloquently on the need for all citizens to be scientifically literate. He observes that the knowledge developed by science has promulgated most of the changes in the modern world. He concludes that there is little hope of dealing with these changes unless the power that science confers "can be tamed and brought into the service not of this or that group...but of the whole human race" (Russell, 1962). Consistent with our social commitment, we envision a science program that conveys the power of science to all students.

General Education

In the reform reports of the 1980s, as well as in the history of education, theorists and philosophers have asserted the importance of the natural sciences in preparation for an examined life. Furthermore, in the recent history of science education, general education has been the primary *stated* purpose of school science. The Center's elementary and middle level reports reflect this emphasis. But at the high school level, where preparation for further education and the workplace are more immediate concerns, the importance of the natural sciences in general education all too often is neglected in the day-to-day activities of the science classroom in favor of academic preparation.

While the Center recognizes the need for greater competence in the workplace and the need for individuals trained in science and technology, we affirm the importance of general education and the contributions of the natural sciences toward this end.

Informed and responsible citizenship. Our report is based on the twin propositions that education should contribute to the development of effective citizens in a democratic system and that school science contributes to this goal by developing scientific literacy. While the goal of democratic common schooling is evident in the rhetoric of reform, the reality in the United States is quite different. Public schooling has for the most part maintained an elitist structure. (See *Elitism in U.S. Public Schools: A Brief History*, next page.) Consequently, the potential benefits of science to society have not been realized.

The world view characteristic of science has the potential to remove inequities and promote social progress. This power is embedded in the very nature of science. Instead of remaining with a mere statement of that which commends itself to personal or customary experience, science aims at a more universal statement to reveal the sources, grounds, and consequences of a belief.[2]

The function that science has to perform in the high school program is the one it has performed for humanity: emancipation from local and temporary incidents of experience, and opening intellectual vistas unobscured by personal habit and predilection. By emancipating an idea from the particular context in which it originated and giving it a wider reference, science puts the results of the experience of any individual at the disposal of all people. Thus, ultimately and philosophically, science is a major means of general social progress.[3]

Despite John Dewey, most U.S. public schools maintain a tracked system. Students are divided

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[2] When this achievement is ignored, science is treated as unelaborated information, which is uninteresting and remote from ordinary information because it is stated in unusual and abstract terms.

[3] John Dewey argued this point eloquently in his 1916 book, *Democracy and Education*.

Elitism in U.S. Public Schools: A Brief History

The elitist structure of U.S. public schooling was set early in the nation's history—even by a figure as dedicated to the democratic form of government and who contributed so much to Americans' understanding of the importance of an enlightened citizenry as Thomas Jefferson. In the early 1800s, Jefferson called upon the Virginia legislature to provide all children with three years of publicly supported education. But after three years, the children were divided into two classes: labor, or leisure and learning. Those destined to join the labor class became apprentices; those destined to lives of leisure and learning were sent to college.

In the mid-19th century, Horace Mann sought to increase the length of public education from three to six years. He did not, however, reject the separation of those destined to lives of labor or leisure. In the early 1900s, publicly supported education was extended to twelve years. But, to this day, the elitist structure remains.

John Dewey, in his 1916 book, *Democracy and Education*, was the first North American educator to reject Jefferson's proposition and to argue for a position of equality. Dewey asserted that all children in a democratic society have the same destiny—labor, leisure, and learning—and should have the same quality of education:

> *A democracy is more than a form of government; it is primarily a mode of associated living... The extension in space of the number of individuals who participate in an interest so that each has to refer his own action to that of others, and to consider the actions of others to give point and direction to his own [breaks down] those barriers of class, race, and national territory which kept men from perceiving the full import of their activity (Dewey, 1944).*

Dewey defined democracy as "associated living," made up of interactions among individuals and groups. Inherent in this notion is the idea of reciprocal obligation among individuals. Reciprocal obligation helps break the barriers that separate people through social inequities. Through diverse interactions, released from social restrictions, individuals are empowered.

In his chapter on "Interest and Discipline," Dewey anticipates aspects of science teaching recommended in this report:

> *The problem of instruction is [that] of finding material which will engage a person in specific activities having an aim or purpose of moment or interest to him, and dealing with things not as gymnastic appliances, but as conditions for the attainment of ends (Dewey, 1944).*

Dewey advanced this position as an antidote to conventional scholarship in the academic disciplines. Typically, these scholars conduct their inquiries in isolation, seldom looking outside the discipline for connections to other disciplines and bringing only their own disciplines to bear on the problems of human existence. By contrast, Dewey developed connections between experience and thinking that conform to constructivist epistemology and modern cognitive theory:

> *The general features of a reflective experience are (i) perplexity, confusion, [and] doubt... (ii) conjectural anticipation... (iii) a careful survey (examination, inspection, exploration, analysis) of all attainable consideration which will define and clarify the problem in hand; (iv) [an] elaboration of the tentative hypothesis to make it more precise and more consistent, because squaring with a wider range of facts; (v) taking one stand upon the projected hypothesis as a plan of action which is applied to the existing state of affairs [and] testing the hypothesis.*
>
> *It is the extent and accuracy of steps (iii) and (iv) which mark off a distinctive reflective experience from one on the trial-and-error plane. They make thinking itself into an experience (Dewey, 1944).*

The fruition of the reflective experience, as defined by Dewey, is science. And science, through its emphasis on the objective and universal, can break down the personal prejudices and narrowness of thought that lead to social inequities.

and pursue one of three loosely defined courses of study: college-bound, general, or vocational education. This elitist structure is still evident in today's schools and, rather than making the most of educational opportunity by adapting schooling to each individual student's aspirations, it has severely limited educational opportunities to learn science, especially for students in general and vocational educational programs.

Cultural literacy. In a nation and time where science pervades all aspects of culture, scientific literacy is an essential component of cultural literacy. Literature, the fine arts, and the place of humankind in the natural world, are just three aspects of culture that can be understood better with knowledge of scientific theories and the lives and times of the men and women who proposed them.

Scientific theories have revolutionized peoples' thinking about the place of humankind in the universe. Charles Darwin's *On the Origin of Species* placed in question the uniqueness of *Homo sapiens* among the earth's fauna. Copernicus's *On the Revolutions of Celestial Orbs* displaced humans and the planet we inhabit from the center of the universe. Lyell's *Geological Evidences of the Antiquity of Man with Remarks on Theories of the Origin of Species by Variation* diminished the temporal importance of humankind. The perspective that these theories provide for the place of humankind in the larger scheme of things is an essential component of Western culture.

In addition, reference to the foibles and triumphs of modern science is made routinely in casual conversation, the popular press, and cartoons. Scientific allusions and metaphors are ubiquitous in literature and the fine arts. Understanding these as well as other aspects of Western culture requires familiarity with Einstein and Newton, the Hubble telescope and AIDS, relativity and organic evolution.

Personal enhancement. The empowerment endowed by scientific literacy extends to the conduct of personal lives. Many personal and family decisions require a sound understanding of science and the capacity to gather valid information. The capacity to know where and how to seek scientific information and to evaluate its quality are critical components of scientific literacy and key ingredients of personal power.

Further Education and the Workplace

High school science traditionally has been a requirement for admission to higher education but not a requirement for entering the workplace. While over the past twenty years institutions of higher education have lowered their science requirements for admission (a trend that the current crisis is reversing), business and industry are calling for more science for those students who will enter the workplace upon completion of high school.

Leaders from the private sector observe that the workplace is increasingly based more on the manipulation of symbols than on physical objects and that scientific and technical principles provide much of the common language for communication. Consequently, the knowledge, thinking competence, and application skills that business and industrial leaders call for are similar to those for college preparation. Thus, it is important to make sure that the intellectual requirements of students preparing for the workplace are similar to those for academics.

A central purpose of science programs for high school students who plan to enter the workforce immediately upon graduation from high school is preparation to meet the demands of the workplace. There, as U.S. society and industry become more sophisticated technologically and the U.S. economy becomes centered on information, solving problems, communicating with fellow workers, and processing information are replacing physical labor as a new form of work. The information age has created an intellectual society.

The purposes of science education are varied and ambitious. The challenge to the nation's schools is formidable: achieving both the purposes of general and professional/vocational education for all students. Because the time allotted in the school curriculum to achieving the purposes is limited, difficult choices must be made. These choices must be reasoned and based on social and philosophical commitments, as well as the characteristics of the students for whom the programs are intended.

High School Students

Whatever society's needs and philosophical commitments, science education must reflect the characteristics of the population it serves. Social, demographic, and economic conditions influence the needs and characteristics of high school students served by the science program. Many high school students have adult responsibilities. Some are parents, hold jobs, have economic or care-taking responsibility for siblings or parents, and will take fiscal responsibility for postsecondary education.

Given that profile of students, the Center believes that schools should provide opportunities for students to take responsibility for their education in preparation for the greater responsibilities of adult life. One means to that end is to build curricular choice into the high school program. Choices, however, must be made with the advice of an adult who holds high expectations for all students. Students should not be afforded choices that limit their exposure to science. An overarching principle should apply: keeping open students' options for continuing study in science, while providing them with opportunities to make meaningful choices.

High school students are changing. The proportion of students from cultures and ethnic groups traditionally underrepresented in the natural sciences is rapidly increasing. The Center's recommendations are based on the premise that it is society's obligation to create science education programs that give *all* students the opportunity to achieve the purposes of education in the natural sciences. In practice this means that the programs serve students:

— Of high and low academic ability;
— Of varying academic preparation in the natural sciences;
— Whose motivation is high, or low;
— From diverse cultural and ethnic backgrounds;
— From limited as well as affluent economic circumstances;
— With learning and physical conditions that handicap learning;
— With limited English proficiency;
— Who are gifted in science.

Consistent with our social commitment to provide maximum opportunity and the nation's need for technical competence in the workplace, the Center advocates science programs that will meet the learning requirements of students from underrepresented populations and prepare for the demands of the workplace those students who choose to enter the workplace immediately on completion of high school.

Students from Underrepresented Populations

Of particular concern are students from populations underrepresented in careers in science and technology. Science knowledge must become an empowering tool for these students to help them establish priorities for their personal lives and communities in terms of health, safe environments, economic development, education, and providing other nurturance and support for themselves, their children, and their families. Consequently our report proposes a new vision and new strategies for high school science that would address social and educational inequities and allow all students to attain excellence.

At least two-thirds of the nation's high school students fall into categories that typically do not attain high levels of scientific competence: minorities (for instance, African Americans, Native Americans, Alaskan Natives, Hispanics); low-income and non-college-bound students; women; and individuals with learning and physical disabilities. Expectations for students in these populations are low.

These low expectations manifest themselves not only in the way school personnel think about students, but also in the opportunities that students are provided to learn science. Students from underrepresented groups routinely receive less access to knowledge, fewer resources, less interaction with teachers, and restricted learning activities (Oakes, 1990; Oakes et al. 1990). Moreover, counselors, teachers and other adults seldom encourage these students to demand more of themselves or encourage them to believe that they can succeed or benefit from more opportunities and resources.

Furthermore, the traditional, highly abstract, disconnected, individualistic learning activities that characterize much science instruction erect barriers and short-change even "successful" students by limiting their opportunities to integrate new science knowledge into their own ways of thinking about the world, and developing the facility to use science knowledge deftly to resolve issues and solve problems. As a result, these students are locked out of science careers and the knowledge that comprises science literacy (Quality Education for Minorities Project, 1990).

Expectations for students from underrepresented populations must be raised and programs designed that serve the learning requirements of students from diverse populations:

- The course content must be relevant to the students' world (Oakes et al., 1990; Beane, 1985);
- Teachers and the curriculum must value, respect, and adapt to diverse cultures, world views, and ways of approaching problems;
- The curriculum must provide opportunity for cooperative group learning (Slavin, 1987; Malcom et al., 1984; and Oakes et al. 1990); and
- The learning environment must enable students to learn science, to appreciate the benefits of knowing, and to experience the intellectual rewards of hard work and persistence.

Furthermore, to support and sustain science learning in the school, informal science programs must help those groups that have the least access to a variety of rich out-of-school science experiences, including television, museums, parks, science centers, and magazines. Informal approaches that reach underrepresented populations not only will help the current generation, but also can pass a positive disposition toward science from one generation to the next.

Workplace-Bound Students

Typically, students pursuing technical/vocational studies do not have access to and encouragement from counselors and science teachers in pursuing high school science programs. Fifty-one percent of vocational/technical students surveyed by the Southern Regional Education Board reported that *no one* advised them on science course choices. Twenty percent reported they received assistance from the school counselor. Ten percent received help from a nonvocational teacher. Only two percent received any help from a vocational/technical teacher (Bottoms and Korcheck, 1989).

Without encouragement from teachers and counselors, technical/vocational students will not have the opportunity to develop the skills and knowledge that will allow them to capitalize on the professional development opportunities available in the workplace. Unfortunately, most secondary schools operate on the assumption that technical/vocational students will not continue their learning after high school. This is no longer true, if it ever was. Vocational students who complete four or more credits in a technical/vocational major engage in a wide range of activities one year after leaving high school. Most continue their learning in either a work or an institutional setting. For example, 41 percent of those surveyed in a recent study were continuing their education in a variety of postsecondary institutions. Some 87 percent also were working either full-or part-time (Bottoms and Korcheck, 1989).

Low-level courses prepare students neither for jobs nor further education. Instead, technical students need courses that directly relate the principles of science to technical applications and provide students with a solid grounding in scientific concepts and thinking skills.

The science framework the Center proposes would result in science programs that prepare students to meet the demands of today's and tomorrow's workplaces. Students would be grounded in essential science principles and ways of thinking about science and technology. Science courses that are highly diluted versions of introductory college courses are not appropriate for the technical/vocational student. These low-level courses prepare students neither for jobs nor further education. Instead, technical students need courses that directly relate the principles of science to technical applications and provide students with a solid grounding in scientific concepts and thinking skills.

Science departments must place less emphasis on differentiating science content for these students and more emphasis on instructional methods that engage students and deepen knowledge. Students pursuing vocational studies need an opportunity to master *core* concepts from the natural sciences through a process that helps them better understand broad vocational fields of study.

Course Purposes and Structure

Central to the Center's vision of tomorrow's high school science program are courses designed to meet specific purposes of school science. The Center believes that no single organization of content or pedagogy will suffice. One practical task, then, is to organize science courses to meet the diverse purposes of high school science education. The organization depends on how the following questions are answered:

- Which science topics would the course address?
- How would topics be organized? In what sequence would material be presented within and among topics?
- What method of presentation would be used? What would teachers do and what would students do?

Answers to these questions depend, in turn, on assumptions about the knowledge, reasoning capacities, and dispositions that students must develop to meet the purposes of science education.

Most high school science courses, regardless of the goals they espouse or the learning characteristics of the students they serve, answer these questions in the same conventional way. They present each discipline in isolation. They structure content according to the framework of the discipline. And they overwhelmingly use lecturing, reading science text, and using the laboratory to verify scientific principles.

The rationale for organizing and teaching conventional courses this way derives from their primary purpose, preparing for college science study. Whether the conventional approach is appropriate preparation for collegiate study can be questioned. More fundamentally, increasing numbers of members of the scientific and educational communities assert that this approach does not meet the most important purposes of general education (American Association for the Advancement of Science, 1990).

Interdisciplinary Approaches to Science Courses

A number of national reports on the status and future of science education recommend interdisciplinary approaches to achieve the broader purposes of science education. These reports argue that fruitful approaches to contemporary issues are multidisciplinary. Furthermore, advocates of interdisciplinary approaches to science education assert that these approaches empower students with the knowledge and reasoning capacities they can use to educate themselves. This follows from the belief that transmitting ever-increasing volumes of information in the classroom will not close the gap between scientific knowledge and the public's comprehension of that knowledge. Thus, science educators and the public alike advocate building the knowledge and skills necessary for effective self-education.

However, knowledge and skills alone will not lead to self-education. Citizens and workers will apply their knowledge and skills only when they are motivated to do so. Motivation comes from recognizing the importance of actively making decisions about one's personal life, as well as about the wider world of civic affairs and the workplace. Thus, another important goal of interdisciplinary science education is to provide students with an appreciation of that wider world, including:

- The nature and behavior of natural systems;
- The interrelations of the human species with the natural world; and
- The relationships among science, the humanities, and the professions, especially engineering.

How specifically to combine disciplines in the high school curricula sparks many differences of opinion. The most spirited debate centers on the question of "knowing versus doing." Is it sufficient to know about the interactions among science and other fields of human endeavor? Or should students also be able to engage productively in cross-disciplinary inquiry? Is the goal for students to know the purposes of scientific disciplines and engineering and/or their major concepts and conceptual schemes? Or should students be able to apply the products of scientific inquiry and engineering design to make personal and societal decisions? Equally spirited debates surround the content and organization of content presented in interdisciplinary courses.

Expanding and reorganizing science content

Two approaches can be used to expand the content of science education to disciplines and professions beyond the natural sciences. *Non-disciplinary* approaches are structured around problems, issues, or topics. (Dunbeigh High's Core Courses on the theme of "Contemporary Ecological Concerns" and "Contemporary Ethical Dilemmas" are disciplinary in organization.) An assumption underlies such approaches: in the course of an investigation, students will learn subject matter drawn from a number of fields of study. Critics of non-disciplinary approaches claim that students cannot possibly learn any discipline in sufficient depth to appreciate its intellectual structure or modes of inquiry.

By contrast, *interdisciplinary* approaches seek to develop a deep understanding of more than one discipline and the interrelationships among them. (Dunbeigh High's Core courses, Themes Across the Disciplines, are an example of an interdisciplinary approach.)

The vignette that follows shows how a teacher, Mrs. Maria Brock, integrated topics from the natural sciences and the history and philosophy of science in a course that embodies constructivist principles of learning. Mrs. Brock's students examine the historical development of plate tectonics, using the example to illuminate features of the nature of scientific inquiry. (Mrs. Brock is hypothetical, but based on a "real life" teacher.)

Integrating the natural sciences. The most common approach to teaching interdisciplinary science is integrating the natural sciences. This approach achieves few of the possible goals for interdisciplinary science. Typically, little effort is taken to identify and clarify relationships among the natural sciences. For example, rare is the textbook that discusses how trans-disciplinary concepts such as "system" or "cause-and-effect" apply across the natural sciences. Also rare are discussions of the different forms of scientific inquiry that distinguish the natural sciences. Because courses that appear to integrate the natural sciences usually present topics selected

When Worlds and Worldviews Collide: Solving an Earth Science Puzzle

A radical new idea can revolutionize the way we look at the world. But such ideas do not always catch hold quickly or completely. Sometimes, scientists and others must overcome resistance to new ideas. New concepts must be supported by improvements in technology that make sense of previously unexplained data, observations, and relationships.

These were some of the key messages that Mrs. Brock wanted her core science students to take away from their study of plate tectonics, the theory of continental drift. She chose the topic, in part, because it integrated major themes in earth science.

The lessons, like the concept behind them, evolved slowly in her class. At the beginning of the school year, Mrs. Brock asked her students to begin to collect reports on earthquakes and volcanoes from news accounts and plot the events on a world map, using color-coded stick pins. Mrs. Brock did not explain why the events were occurring: she simply told the class that they were collecting data to understand concepts that they would study later that year.

When she was ready to begin the unit, Mrs. Brock asked her students whether they noticed any patterns in the data they had collected. Some classes observed that earthquakes and volcanoes occurred most often in certain geographic zones. For other classes, Mrs. Brock supplemented the data with data from the National Oceanic and Atmospheric Agency until a clear pattern emerged.

Before trying to make sense of these patterns, Mrs. Brock launched her class into another activity. She broke the class into small groups and handed each group some pieces of a jigsaw puzzle: the shapes corresponded to the lithospheric plates. Students were allowed to give pieces away that they did not need, but not take any from another group. Classmates also could not talk, point, beg, or indicate that they needed a particular piece. Classes were timed: the class that finished the puzzle first won. The exercise helped build group cooperation, develop nonverbal communication skills, and promote cooperation within each class and competition among classes.

After they had puzzled over the pieces, Mrs. Brock asked her students what observations they had and how they thought the exercise related to the maps they had made of earthquakes and volcanoes. She explained that the pieces corresponded to lithospheric plates; that scientists believed that these plates are moving relative to one another; that earthquakes and volcanoes occur most often along the boundaries of these plates; and that earthquakes and volcanoes are thought to erupt as the plates bump up against one another.

Mrs. Brock then noted that for more than 400 years, observers had collected data that pointed to clear patterns in the distribution of earthquakes and volcanoes. But not until 30 years ago could earth scientists clearly explain the patterns. Data had preceded theory. A mystery remained unsolved.

Along the way, a few brilliant theorists began piecing together the puzzle. One was Alfred Wegener, who in 1912 proposed the radical idea of "continental drift." Wegener pieced together scattered evidence, Mrs. Brock emphasized. This included the distribution of land fossils and rocks and data from ancient glaciers. He also went out on a limb: he did not know how the continents moved, but hypothesized that they moved through the earth's crust. That large land masses could from biology, chemistry, physics, and earth and space science serially, they fail to expose students to the intellectual relationships among the sciences.

Conventional science courses that integrate the natural sciences are good examples of all that critics claim is wrong with interdisciplinary courses. They lack rigor and do not help students understand the relationships among the natural sciences.

However, because these courses generally are not done well does not mean that they *could* not be done well. In fact, when science courses that integrate the natural sciences are organized around trans-disciplinary concepts and processes,

"drift" through seemingly brittle crust was a revolutionary idea.

Mrs. Brock then introduced another activity to her students to show them how earth scientists believe that the continents have moved over geologic time: "The Shifting, Drifting Continents." She related how Wegener's idea met with mixed reactions: scientists in the southern hemisphere generally were more accepting than those in the North. Mrs. Brock asked her students to ponder why that was; when a hypothesis can be tentatively accepted without a cause-and-effect relationship; and why it is that some scientists may not hazard hypotheses based upon data for which no explanation exists.

For 50 more years, the concept of continental drift was debated. Meanwhile, new data sets were developed for certain geophysical phenomena, such as gravity and heat flow. Mrs. Brock had her students explore these, without explaining how they relate to plate motions.

Then she explained how advances in technology led to a scientific breakthrough. During World War II, the Defense Department mapped the ocean floor to find ways to detect submarines more easily. This exercise dispelled the belief that the ocean floor was essentially flat. Great mountain chains and troughs were found, among other previously unknown features.

Armed with this knowledge, Mrs. Brock's students were ready for another exercise: to explore the physiography of the ocean floor. They began to see the relationship between paired features, such as trenches and volcanic island arcs.

Mrs. Brock also introduced her class to the fact that ocean strata vary in age. Through another exercise, students explored how radioactive decay can be used to date rocks. Students also learned about the magnetic characteristics frozen into rock as the earth's magnetic field changes over time. Along the way, Mrs. Brock related how investigators in the early 1960s pieced together patterns of magnetism and rock age and type in the oceans to devise a model of sea-floor spreading. At one swoop, this model explained the formation of mountain chains, the appearance of earthquakes and volcanic islands, and the movement of the continents. Great upwellings in the earth's crust were pushing the continents. When the land masses clashed, mountains were formed, earthquakes trembled, and volcanoes spouted.

This model is not perfect, Mrs. Brock stressed. But it explains many phenomena. To show her students how the model can be modified, she asked them to consider the Hawaiian islands. These do not occur along a plate boundary. The islands' oldest rocks lie farthest from the most active volcanic sites. Piecing together these and other phenomena, students were able to understand scientists' belief that the islands are drifting over a "hot spot" in the earth's mantle.

These last exercises helped students appreciate the changing nature of science: how scientific knowledge—and even the most compelling models—must be altered periodically as incontrovertible data emerge.

Mrs. Brock asked her students to consider whether the concept of plate tectonics was a hypothesis, a theory, or a law. The students concluded that it had progressed beyond the stage of hypothesis and was now a theory—one that explained the bulk of data now available.

Looking back over the year, students were pleased with the way they had learned by doing. They had manipulated data, materials, and ideas. They had learned firsthand about the tentative nature of science, and seen how a radical idea had evolved into almost universal acceptance. They had seen how scientists can overlook or ignore evidence, and how science builds on technology, and technology builds on science. All in all, they agreed, these were good points to drive home—especially from an exercise that began with some colored stick pins.

they encourage the development of a strong, well-structured scientific knowledge base. Examples of trans-disciplinary concepts include energy, scale and position, causality and consequence. Examples of trans-disciplinary processes include such scientific processes as collection, organization, and classification of information and the development of scientific explanations.

Integrating natural sciences and mathematics. For years, educators in the United States have debated the wisdom of integrating the natural and mathematical sciences. This approach has been implemented only minimally. The reason is familiar: educators in each discipline believe that integration will prevent students from developing deep understanding of either science or mathematics.

Two consequences stem from the failure to integrate these subjects. First, the curriculum becomes redundant. Second, despite this redundancy, high school graduates fail to apply the formal knowledge they have learned in mathematics either inside or outside school.

Ideally, students should learn science and mathematics while engaging in tasks that are both rich and demanding. The Omega River Dam exercise described in the Center's middle school assessment report (Raizen et al., 1990) and the soda pop investigation described in Chapter III below are examples. Engagement in tasks of this kind would encourage students to apply their mathematical and scientific knowledge to a broad range of situations.

Integrating natural sciences with the history and philosophy of science. This approach to teaching science was briefly tried at the school level in the mid-1960s, when the Harvard Case Studies in the History of Science (Conant, 1957) were adapted for high school use by Klopfer and Cooley (1963) and with the commercial publication of Harvard Project Physics (Rutherford et al., 1981).

Even with high-quality materials that made integration explicit, this approach never achieved popularity in the schools. Among the reasons for the failure of this initiative were lack of teacher preparation and incompatibility with existing science curricula.

Integrating natural sciences and technology. In the United States, concern about the nation's decline in the world economy has accelerated the trend to integrate technology and the natural sciences and has increased interest in adopting interdisciplinary approaches to teaching science. Several states have taken notice of the trend, as do the recommendations of the American Association for the Advancement of Science (1989) to integrate technology and the natural sciences. The state of New York, for instance, has mandated the teaching of technology in its middle schools. The trend to integrate science and technology is not confined to the United States. For example, the United Kingdom has made technology an integral part of the science program (Department of Education and Science and the Welsh Office, 1991), as have the Netherlands and several Scandinavian countries. A central factor in the integration of science and technology is experience in the process of design as practiced by engineers along with experiences in scientific inquiry as practiced by scientists.

The press to prepare youth better for the workplace has produced a change in focus for vocational education and a new name, "technical education." While, in the past, vocational education was concerned largely with developing craft skills, such as wood-working, metal-working, agriculture, and home-making, the current trend is to enhance craft skills with design capabilities. In effect, this means incorporating some engineering into vocational education and integrating the resulting technical education with the natural sciences.

The vignette that follows shows how a teacher introduced concepts of design to his students.

Courses that integrate technology with academic studies are being introduced. Courses last two years. In the first year, students learn basic science, including concepts, principles, and facts. During the second year, students study mechanical

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Building a Better Suntrap: A Core Design Project

As part of his Core science class, Mr. Gary Jackson wanted to expose his students to the process of design. He decided to have his students test the efficiency of an engineered artifact: a solar collector. Students were to test four collectors and identify the most efficient one. Students were to work in teams and use a systematic trial-and-error system to find the best design. "Everyone encourages others to participate, but no one gives orders," Mr. Jackson stressed. When the exercise ended, teams would evaluate their group skills.

Students gathered into their four-member teams and drew lots for roles of manager, timer, recorder, and communicator. Each team was to test two collectors and two designs. Team A was the control: it would record data for Collector 1: data from all other collectors would be compared to this. Team B would test only angles on its collector, using materials provided by Mr. Jackson. The other teams were free to bring in materials they thought would work best on the front or back panels of their collectors.

On Day 1, each team manager got the team's letter from Mr. Jackson. Students then read the chart in the hand-out to identify the two tests they were to conduct. The recorders prepared two data tables and a graph patterned after the samples in the investigation hand-out. All team members drew similar, but smaller, tables and graphs in their notebooks.

Next came the fun part! The teams (except for Team B) began to plan their designs. After 10 or 15 minutes of enthusiastic and imaginative discussion, teams so instructed debated which materials they would test. They weighed the costs, benefits, and availability of different materials: one student suggested using a very large, rectangular magnifying glass. They decided who would bring the materials they'd chosen to class the next day.

Day 2 was devoted to a dry run of the tests. The teams practiced setting up their equipment outside, but did not do a timed test. They'd need good teamwork the following day: they'd need a full 30 minutes to conduct their tests. Students roamed around, looking at the collectors that the other teams had designed. Mr. Jackson sat in the shade, observing the students. To his delight, not a single team communicator asked him for help setting up the equipment.

On Day 3, students were excited: time would soon tell if they had chosen the optimum design for their collectors. Most teams set up their equipment smoothly and were ready to begin timing within seven minutes. Each team's timer called time every two minutes: another team member read the temperature in the team's two collectors to the recorder; and the recorder recorded the two temperatures on two separate team data sheets. At the end of 30 minutes, all students copied their team's data into their notebooks.

Day 4 was for comparison and evaluation of results. As soon as they entered the classroom, the team recorders copied their team's data tables on the class data chart on the wall. The teams then met to evaluate their group process. Using a scale of one to five, with five the highest score, students rated their team as to whether everyone: brought materials; contributed ideas about designs; helped run the tests and record results; and encouraged others to participate, but did not give orders. Next, the teams answered the team questions in the hand-out.

After 30 minutes, the whole class met to answer the class questions from the hand-out. The team communicators presented their team's data and explained their team's best choice of the designs they had tested. The class discussed the efficiency of the angles tested, and the efficiency and costs of the front and back panel designs tested. Then they chose the optimum design for a solar collector. They discussed how a company might have limited time to develop and test a product and how costs could affect a business' choice of design.

Then students expanded their discussion to consider the advantages and disadvantages of solar heating. They discussed the impact of more widespread solar heating on environmental quality and energy resources. The class concluded by deciding which team had devised and tested the best design. Members of each team signed their team data tables and answer sheet and turned them in to Mr. Jackson. As they left school that sunny afternoon, some students saw the sun in a different light—as an energy resource.

and social systems that exemplify *basic* principles. Such courses have been developed in applied physics, applied mathematics, and applied communications. A similar course in biology/chemistry is under development (Hull and Parnell, 1991). For instance, in the course that integrates physics with technology, the second year is devoted to the study of hydraulic, pneumatic, electrical, mechanical, and optical systems. The chemistry/biology course will develop the scientific information base to deal with such problems and issues as air and water quality, natural resources, wellness, nutrition, and genetic engineering.

The applications portion of these courses emphasizes problem-solving in realistic settings. Students engage in the activity of engineers—design. By contrast, the most prominent interdisciplinary approach in the contemporary reform movement—which integrates science, technology, and society—is more intellectually inclined.

Integrating science, technology, and society (STS approach). This approach has vocal advocates in the science education community (Trowbridge and Bybee, 1990). Their perspective is echoed in a number of important reports that stress the need for scholars who can integrate perspectives from the humanities and social sciences to deal with the emerging problems of the global society. (See, for example, the Carnegie Foundation for the Advancement of Teaching, 1987). Advocates of the STS approach cite several advantages for it, compared to approaches that are narrowly focused on a single discipline:

- *The STS approach is more appropriate to resolving personal and social problems.*

Humankind faces problems of survival and evolution that are different in type and scale from those of the past. Solutions to these problems, from the alienation of individuals to the deterioration of large-scale ecosystems, demand new strategies of thought and action. Appreciation of both complexity and subtlety is required—as suggested by the increasing awareness of the interdependence of individual and collective problems. The survival of the global ecosystem increasingly requires the unification of inquiry and design strategies that have become separated, overspecialized, and relatively independent of one another. Strategies that addresses contemporary problems must be open-ended and encompass all modes of inquiry.

- *The STS approach more accurately represents the ethos of science.*

As Paul Hurd, the dean of U.S. science educators, observed in a 1989 speech:

> *Since 1900, there has been a continual fractioning of science disciplines, until today there are somewhere between 25,000 to 30,000 different scientific "disciplines," or, more correctly, research fields. The Library of Congress subscribes to 60,000 different scientific and technical journals, but knows there are over 10,000 they are not receiving. It has been estimated that there are at least 100,000 scientific journals published worldwide (Hurd, 1989a).*

These statistics suggest that the notion of four natural science disciplines—biology, chemistry, physics, and earth and space sciences—simply does not reflect the current structure of the natural sciences.

- *The STS approach integrates literacy in science and technology.*

The gap is widening between the production of scientific and technological knowledge and the transfer of that knowledge to society at large. The integrated approach advanced by STS studies can narrow this gap.

- *The STS approach reveals the social nature of science and technology.*

The STS perspective suggests that science education students—whatever their specific interests—focus on ways of living, social relationships, and values.

Advocates of the STS approach build a compelling case. In its ideal form, the approach develops knowledge, skills, and general problem-solving strategies that are well-matched to complex contemporary problems. These general strategies—the ability to frame a problem, break it into manageable parts, and identify and obtain information during the problem-solving process—can be applied to a wide variety of problems. Moreover, the cognitive strategies students develop in the ideal program are similar to those used by experts in engineering and the natural and social sciences.

Thus, the ideal graduate of the ideal program will have developed skills of inquiry characteristic of the natural and social sciences, as well as the design skills of engineers. Presumably, the STS approach also will engender a concern for the environment and the human condition that will motivate graduates to use their skills to solve civic and social problems. Typically, less attention is given by STS proponents to the knowledge base of the natural and social sciences and engineering.

Challenges in achieving interdisciplinary approaches

While interdisciplinary approaches may better meet the general education goals of school science, integrating science with other disciplines presents science educators with monumental challenges. Barriers to achieving interdisciplinary science include:

- A lack of consensus regarding appropriate goals, content, and pedagogy for interdisciplinary curricula;
- Teachers who are unprepared to develop or teach interdisciplinary curricula;
- Lack of interdisciplinary programs and materials;
- The perception among scientists and educators that interdisciplinary courses lack rigor;
- The concern that interdisciplinary approaches will contribute to the content overload of the science curriculum; and
- The cognitive demands that interdisciplinary approaches place on students, who must develop understanding of scientific and technological concepts and principles, as well as the capacity to inquire and design and the inclination to apply their understanding and skills in a specific context.

Recommendations

1. All components of the educational system should seize the opportunity afforded by the national concern for the quality of school science to embark on a coordinated system-wide effort to restructure the high school science program to reflect the nation's social commitment to empower all youths.

The Center's proposed radical restructuring of the high school science program requires the coordination of the educational system's diverse organizations. School districts do not function in isolation; they are constrained by policies and regulations mandated at the local, state, and federal levels. Public expectations, legislative policies, and bureaucratic regulations often are at odds with one another and with the changes required to improve the science achievement of all young people.

For local efforts to succeed, the larger world must be prepared. Parents must come to understand when heterogenous grouping is appropriate to achieve the purposes of school science. State departments of education and institutions of higher education must accept the intellectual validity of multidisciplinary science courses structured in unconventional ways. This understanding must be embodied in state graduation requirements and college entrance requirements.

Institutions responsible for monitoring the progress of school science at the district, state, national, and international levels must not be satisfied to assess only those purposes of school science that are easy and inexpensive to measure. Instruments must be designed and implemented to asses the broad range of valued purposes of school science.

Professional societies, both educational and scientific, must become conversant with the changing nature of school science to act as effective advocates for radical reform.

Teachers and curriculum specialists who recognize science's contribution to general education and personal empowerment are critical to successful restructuring. This view will be pervasive only when all graduates of colleges and universities have experienced science as a liberal art (American Association for the Advancement of Science, 1990).

2. Organizations responsible for the nature and quality of high school science programs should evaluate existing programs against the standards set forth in this chapter to determine where change is required.

Program evaluation should be a cooperative effort, involving individuals from all segments of the educational system. Teachers from various fields, administrators, curriculum specialists, parents, legislators, bureaucrats, and graduates of existing programs should be involved.

Evaluations, using the Center's standards as criteria, should address the following questions:

- Does the program provide all students adequate opportunity to become scientifically literate, to meet their personal and civic responsibilities, and to meet the demands of the workplace and postsecondary education?
- Does the program have intellectual integrity? Do the science courses agree with the practice of science and fulfill the requirements for entrance to postsecondary institutions?
- Are the content and organization of science topics appropriate to achieving the various purposes of school science by students with diverse learning preferences?
- Are the science content and contexts in which it is learned and applied appropriate to the needs of students from culturally diverse populations?

3. Federal, state, and private agencies must provide resources to develop and test programs and courses that meet both general education and professional preparation goals of school science.

Schools have responsibility for critically analyzing the purposes of school science and deciding about allocating resources among the various purposes. But, resources for the development of materials, courses, and programs to achieve these purposes is generally beyond the capacity of local districts. Consequently, other agencies must become involved, coalescing resources to complete this difficult task.

CHAPTER III

Engineering The Assessment Revolution

Fueled by more than 300 reports emphasizing the inadequacies of students' science learning and highlighting the country's educational crisis, the President and state governors met in the fall of 1989 at a historic summit in Charlottesville, Virginia. The meeting led to the adoption of a set of national education goals; several directly address improvements in science education (National Governors Association, 1990).

- By the year 2000, Americans will leave Grades Four, Eight, and Twelve having demonstrated competency over challenging subject matter including...science...and every school in America will ensure that all students learn to use their minds well...The academic performance of elementary and secondary students will increase significantly in every quartile, and the distribution of minority students in each level will more closely reflect the student population as a whole.
- By the year 2000, U.S. students will be first in the world in mathematics and science achievement.
- By the year 2000, every adult American will be literate and will possess the knowledge and skills necessary to compete in a global economy and exercise the rights and responsibilities of citizenship.

Articulating such goals is valuable. But what does it actually mean to say, for example, that U.S. students should lead the world in science and mathematics by the year 2000? We at the Center suspect it means that students should perform well on international science assessments and on standardized tests that allow comparisons over time. By this standard, the assessment measures used to compare students' achievement among countries (or among states or school districts, or over time) become the operational definition of national (or state or district) success in achieving goals for science learning.

It is crucial that goals in science assessment, curriculum, and instruction are aligned with one another. As schools and school policy-makers consider ways to reshape science education, they also must consider ways to reshape methods of assessment. This is true for assessments and tests given by teachers for their own purposes, as well as for large-scale assessments given to monitor students' progress, evaluate the quality of the education they are receiving, and track progress toward national education goals.

To provide valid assessment results, both the types of learning assessed and the methods to measure such learning need to be fundamentally altered.

To provide valid assessment results, both the types of learning assessed and the methods to measure such learning need to be fundamentally altered. Assessments must address the more complex types of learning described in this report, including the application of scientific knowledge and skills to "real-world" situations faced by individuals at work, in their personal lives, and as citizens of a community.

Purposes of Assessment

Assessment purposes vary. One type of assessment is conducted by teachers to meet their own purposes. For teachers, assessments can:

- Guide instruction and make it more effective by establishing what students bring to the classroom and what they learn as science instruction and activities proceed;
- Impress upon students, school staff, and parents the expectations for science learning; and
- Document each student's progress throughout the year, or as a student moves to the next level of education or into the workplace.

This last function becomes especially critical in high school as students and their advisors, including parents, counselors, and teachers, plan for further education or prospective jobs.

Another type of assessment provides information about large groups of students. Generally referred to as external assessments, these can be useful for changing policies that affect science education. For policy-makers, assessments can:

- Monitor the outcomes of science instruction, particularly students' achievement and competencies in science;
- Provide the basis for planning and implementing improvements in science education (together with information about schooling context and program variables); and
- Provide guidance on how resources could be allocated most effectively to advance science education.

Why an Assessment Revolution?

Assessments in science are important at the high school level because people care what they show. Interest is keen in improving high school science. Better assessments could help for the following reasons:

1. Testing affects what students choose to learn and teachers choose to teach.

The age-old student query—"Will it be on the test?"—demonstrates the power of assessment to convey teacher expectations of what students are to learn. Teachers, schools, and school systems also respond to the form and content of tests administered by outside groups, including assessments of large groups; such external assessments can influence curriculum and instruction. They should do so in a manner consistent with good science and good science education.

2. New assessments can answer important questions that current assessments cannot.

Even if existing and redesigned assessments could correlate perfectly, redesigned assessments would document levels of science knowledge and competencies not now measured at all.

3. If curriculum and instruction change in the direction the Center advocates, information from current assessments will become increasingly useless as indicators of school success.

Assessments will have to change to accommodate the Alternative Pathways we have suggested.

4. Most important, current tests contribute to a misleading picture of students' science understanding.

Grades achieved in science courses become an important factor in shaping perceptions of an individual's ability and prospects for further education in science or technical fields. Yet, all too often, grades are based on narrowly framed tests that reward quickness of recall of factual information and mental agility in solving problems by rote. These tests do not probe students' depth of understanding or their ability to think through unfamiliar situations that require them to apply their science knowledge and skills. A high score on such a test leads students, teachers, and parents to believe that students have gained scientific understanding, when they have not.

The kind of quickness and agility rewarded by current tests is associated with students who possess a particular learning style. By emphasizing these tests, high schools, unintentionally, discourage many other students from engaging further with science—particularly individuals from populations underrepresented in scientific and technical fields. Science is seen as elitist (Welsh, 1990), suitable only for the largely white male whizzes: the 15 percent or so of the student body who take physics. More diverse, open-ended assessments could counteract these divisive tendencies.

Moreover, teachers are most apt to use assessment for the purpose of grading students. They tend to ignore assessment as a tool to improve their own instruction, thereby shortchanging their own development as teachers. Teachers rarely use the full range of assessment strategies that would provide deeper insight into what students understand and can do in science.

The following section translates the curricular goals described in the preceding chapter into operating statements aimed at designing appropriate assessments at the classroom level and beyond.

Ideal Outcomes of Science Teaching

The Center is convinced that valid assessments in science education should focus on the following rich and varied goals.

Intellectual Goals

- Students should understand the power of knowing. They should understand that science embraces methods and processes of inquiry, as well as a substantial body of findings, principles, and provisional "truths," that can help to understand and resolve human problems in virtually every sphere of life.
- Students should know how to learn. Scientific and technical knowledge is growing and changing far too quickly for high schools to pretend to attain the goal of teaching students everything they will need to know for the rest of their lives. Students must acquire both the skills and disposition to locate and master the information they need to address new questions and unanticipated problems that arise.
- Students should be able to monitor their own growth and understanding in science and technology. "Self-assessment" is one of the most important skills students should acquire. They should be able to take satisfaction in the growth of their own understanding, recognize where their knowledge is insufficient to address some question or problem, and be resourceful in obtaining the additional knowledge and skills they require. Students should develop a habit of reviewing their own solutions to problems and offering critiques of their own work. All the while, they should build generalized problem-solving skills by tackling specific problems.

- Students should become adept at gathering and evaluating information. They should be able to obtain the cumulative results of past scientific inquiry and technological invention. In addition, students should learn to develop new knowledge to cope with practical quandaries and scientific questions. Students should be able to evaluate the intrinsic worth and relevance of information.
- Students should be able to resolve community and personal issues and make decisions using their science knowledge. Students also must be able to frame their concerns clearly, formulate alternative courses of action, and choose among these alternatives.
- Students should be able to communicate by listening, reading, speaking, and writing, as appropriate. Learning how to learn and gathering information require students to master reading and listening skills; sharing the results of their own scientific reasoning and deliberation requires mastery of writing and speaking. With these skills, students should be able to participate in a community of scientific discourse.

Affective Goals

A comprehensive science assessment system also will address students' attitudes, interests, and values. For all students, but especially for those from underrepresented groups, science learning must become a tool for personal empowerment: to establish priorities in their personal lives and communities in terms of such basic issues as health, safety, economic development, education, and other provisions to nurture and support themselves, their families, and their children.

Underrepresented groups need to see science as part of a culture they have helped to create. The scientific knowledge and experience that individuals ought to acquire in high school could help them address successfully the wide range of issues and decisions faced by all young adults, as well as the special challenges—in the workplace, in academic settings, in the military, and in community life—that confront groups traditionally underrepresented in science and technical fields.

A Vision for Assessment

Teaching and assessment are more effective if they derive from and reinforce each other. Thus, as the curricular and innovative instructional approaches outlined in this report are implemented, it is important that both classroom and large-scale assessments keep pace with the desired changes in student learning. All types of science assessment must more strongly emphasize:

- What students know and can do, rather than what they do not know;
- Higher-order reasoning;
- Applications of learning to "real life" situations;
- Actual products of student achievement; and
- More diversity in assessment methods, including the use of computer technology, group activities, hands-on and performance tasks, projects, videotapes, and work samples drawn from students' classroom activities and homework.

Emphasizing what students know and can do. As teaching and learning become more problem- and student-centered, students will need to assume greater responsibility for monitoring their own learning. Classroom assessment should come to show what students know and can do, rather than documenting what they do not know and cannot do. Opportunities for performance testing should become common as students carry out science investigations and increase and demonstrate their understanding.

At the high school level, however, far more than at the elementary or middle school levels, external assessments will pose qualitatively greater challenges because they need to probe a far more complex body of knowledge and sophisticated range of competencies.[1]

Higher-order reasoning. Inductive and deductive reasoning—verbal, analogical, and spatial reasoning—and creative and critical thinking are among the primary elements of scientific thinking. Yet current forms of assessment do not stress these activities. Instead, current methods tend to ask students to memorize scientific facts or explain known principles.

Assessing students' ability to interpret and make inferences using scientific information involves asking students to make predictions and apply their scientific knowledge to new situations. For example, to assess their understanding of ecosystems, ask students to go beyond reciting the names and roles of the different organisms in an ecosystem—producers, consumers, and decomposers—and ask them to apply what they know to various new situations. Thus, students could study an unfamiliar ecosystem and predict how the extinction, or removal, of a particular organism would affect the rest of the ecosystem. Or, using an unfamiliar ecosystem, students might be asked to predict how such an environmental disturbance as acid rain or pesticide poisonings might affect the ecosystem.

Assessment that emphasizes higher-order thinking is well suited to focus on the methods, as well as the content, of science. Students can demonstrate their understanding of scientific concepts, principles, and theories, or their strategies for thinking, or both, as they solve problems and conduct inquiries. For example, one rather well-known "hands-on" task developed by the United Kingdom's Assessment Performance Unit (1984-85) measures students' ability to conduct a complete investigation. Students are asked to determine which of two fabrics would keep them warmer on a mountainside on a cold, dry, windy day. They are given a broad array of equipment that may or may not be useful in making their determination, such as an electric fan, an electric kettle, graduated cylinders, measuring cans, paper towels, pins, rubber bands, a ruler, scissors, a stopwatch, tape, a thermometer, and a thermos. Students must identify the variables to be manipulated, controlled, and measured. Then they must make accurate and reliable measurements, record their findings, and draw reasonable conclusions.

Inductive and deductive reasoning—verbal, analogical, and spatial reasoning—and creative and critical thinking are among the primary elements of scientific thinking. Yet current forms of assessment do not stress these activities. Instead, current methods tend to ask students to memorize scientific facts or explain known principles.

Assessment designed to measure students' ability to integrate both principles and methods may be more efficient as well as more comprehensive than traditional assessment methods. The assessment's findings, however, may not be clear in all cases. For instance, if students cannot perform a specific task of inquiry, it may be unclear whether their lack of understanding lies with the principles of science involved, or with the methods required to solve the problem, or both.

Several approaches can clarify this confusion: including several tasks that require students to apply scientific principles to new situations; including other tasks that require students to design and implement experiments; or dividing assessment tasks into stages. For example:

- The first step could require students to use their science knowledge to develop a hypothesis or explanation of what should happen in the new situation and why.

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[1] See two reports by the National Center for discussions of new directions in classroom testing in elementary school and the middle school grades (Raizen et al., 1989, 1990). These general recommendations hold for the high school level, as well.

- The second step could require them to design and perhaps conduct an experiment to implement the hypothesis.
- A third step might require them to revise their initial understanding.

Application to "real life" situations. A primary purpose of school science is to cultivate scientific literacy. As we have noted in Chapter II, instruction should help students acquire the knowledge, skills, and understanding necessary to fulfill their individual, social, and economic responsibilities. Yet school science often fails to make connections with students' daily lives. As a result, many students do not understand the relationships that exist among scientific principles and current issues and events. For example, students may memorize information about new work in genetics but never understand that this work has many direct applications to their lives, from curing human diseases to improving agricultural output.

Yet high school students routinely engage in activities related to science—from regulating their daily diets, to monitoring their muscular system while playing sports, to applying electrical principles while working on cars. Some students design new features for their rooms, breed pets, raise plants, or concoct recipes.

To encourage students to see the connections between science learning and real-life experiences, assessment should be placed in everyday contexts, whenever possible. For example, after studying the effects of nutrition on the functions of cells and human organ systems, students could be provided with nutritional information about a variety of "typical" American diets: one low in protein; one deficient in minerals, such as calcium and iron; and one high in calories, fat, and cholesterol. Students then could evaluate the potential metabolic and physiological effects of each diet. Alternatively, students could design the appropriate diet for someone training to be a long-distance runner.

Products of student achievement. Just as curriculum and instruction should stress students' ability "to do," so should more formal assessments. Students should conduct experiments, research issues, and engage in creative problem-solving. To reflect and assess their efforts, students should produce a variety of products, including laboratory work, models, research reports, and videotapes.

Diversity in assessment methods. Broadening the *products* to be assessed means that the *methods* for conducting assessments must be extended, as well. Educators must expand their vision of assessment beyond group-administered, paper-and-pencil tests. The new methods need not create warehouses full of science projects, however. For example, students could design a new household "gadget," or utensil, and build it. They could present a picture of their invention and explain how it works. Or, students could conduct independent experiments and present a carefully prepared research paper describing their step-by-step procedures, rationales for these procedures, and results.

Computer technology may create new avenues for large-scale assessments. Students could work through simulations; the record of their progress would represent the product to be evaluated. Similarly, video-disk technology may present new opportunities to conduct assessments. Students could be shown complex experiments via video, then asked to evaluate the methods used and interpret the results. If teachers keep portfolios, these could be submitted for evaluation at central locations, along with videotapes.

No single assessment exercise encompasses all the learning goals of sound high school science courses. The vignette that follows, however, shows how to evaluate many goals.[2]

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[2] This vignette was adapted from the description by Baron et al., 1990.

A New Type of Pop Quiz

Popping open a can of soda, Alan Rodas told his senior high school science class that they were about to learn more about one of their favorite beverages—soda pop. They would be given two unmarked samples of soda. Without tasting the pop, students were to decide which was the diet variety and which was the regular kind—based solely on the samples' physical and chemical properties.

Their task was to identify and evaluate promising laboratory techniques for distinguishing the regular soda from the same brand's diet variety. They were to devise a research plan, test the techniques that they had proposed to see which was most reliable scientifically, and apply the technique they had identified on unknown samples of soda. Their work would be done in small groups.

The "pop quiz" was designed to help Mr. Rodas and his class gauge students' progress along several important dimensions, including their capacity to:

- Understand scientific concepts and principles and apply them to real-world situations;
- Design an empirical test;
- Apply scientific modes of thought;
- Apply and perform scientific laboratory procedures; and
- Work effectively with peers.

Mr. Rodas asked students to get started by themselves. They wrote down at least three ways to distinguish between the two sodas, and explained why they chose those methods.

Then they joined small groups and brainstormed. Each group chose two tests to carry out and designed an experimental plan for these tests. Students chose a variety of techniques, including testing the samples' boiling point, freezing point, density, conductivity, and solubility. Some students suggested using the "sticky test" or urine glucose test sticks to gauge sugar content. Some wanted to add yeast and Benedict's solution to the samples to test chemical reactions. Others suggested adding sulfuric acid to identify caramel. Students also proposed testing the samples' aroma, color, and amount of fizz.

To challenge his students, Mr. Rodas put out various pieces of equipment and materials that were not necessarily needed. He encouraged the class to use these materials in ways that were not thought of previously.

Once Mr. Rodas approved their plans, the groups carried out their experiments. Then groups prepared a report of their results and presented their findings orally to the class.

Mr. Rodas filled out a form for each group gauging how well they met the objectives. Performance was rated as "excellent," "good," or "needing improvement." If a student's work was exceptional, he noted that.

Each group also rated each member's performance on the following measures: group participation; staying on the topic; offering useful ideas; showing consideration to other group members; judging the extent to which each involved others; and ability to communicate. If the group could not agree on a rating, they could comment on the process.

When the ratings were complete, Mr. Rodas asked the students to finish the exercise by themselves. He told them to imagine that they were given two samples of liquids, one containing a mixture of two sugars (fructose and sucrose), the other containing only one of the sugars.

> ***Their task was to identify and evaluate promising laboratory techniques for distinguishing the regular soda from the same brand's diet variety.***
>
> ***They were to devise a research plan, test the techniques that they had proposed to see which was most reliable scientifically, and apply the technique they had identified on unknown samples of soda.***

Students were asked to list all of the tests that had been tried on the soda samples which would be useful in testing the two new samples. Then Mr. Rodas asked students to propose other tests.

Finally, students were asked to react to the experiment, stating what they liked and didn't like; how they felt about working in the group; why, or why not, they would like more group problem-solving activities; how they felt about using tasks to evaluate knowledge and skills; and what, if anything, they had learned.

Then Mr. Rodas opened up a case of soda and the class happily consumed its evidence.

Turning Vision into Reality

Some inherent difficulties arise in introducing new assessments and instructional methods. People are likely to say: "That all sounds good. Proceed. But don't stop doing anything you're doing now."

It is necessary to state explicitly *what can or should be given up* to make room for the new. This may involve some controversy, especially if recommendations are quite specific. For example: Everyone may agree that meaningless, rote memorization is bad, but most will assert that their own particular type of rote memorization is meaningful and important. They may insist that there is an aesthetic beauty to the names of the orders of insects or that important knowledge lies in the arrangement of elements in the periodic table.

Nevertheless, if science learning is to encompass some of the higher-order goals spelled out above, some traditional content must yield. The Center is not suggesting that reasoning, problem-solving, and other higher-order thinking can be learned in the absence of rigorous content. Rather, we argue that broad coverage must be given up in favor of learning in depth. Giving up some traditional content coverage may be painful, but ultimately it will be healthy.

Students and teachers alike should experience school science as engaging and exciting, whether in the form of instruction or assessment. Students should have multiple opportunities, alone and with others, to do sustained work on interesting, non-trivial scientific problems. The Center cannot emphasize too strongly that the term "non-trivial," and even the term "problem," take on meaning only when applied to a particular learner or group of learners. Problems trivial for an expert may be far from trivial for the novice. Problems interesting to an adult or of obvious social importance may seem remote and contrived to a high school junior.

We recognize that the notion of a "non-trivial problem" is far from an exact concept. It has some connection to the idea of "authentic" problems (Wiggins, 1989; Archbald and Newmann, 1988). Non-trivial problems may be specific to one discipline or interdisciplinary. Often, they will have some direct connection to the student's life—but they need not. They may be suggested by students themselves, but the skillful teacher at times may be able to suggest just the right problem to get a particular student or group of students excited and engaged. Students are much more likely to find problems interesting and exciting if they have a sense of ownership. For that reason, it can be pedagogically sound to give students some choice in the problems they address.

Our curriculum recommendations are based on conceiving of science as containing core ideas, part of the common cultural heritage, as well as conventions for organizing, understanding, and naming things in the world. We also recognize that schools have a responsibility to teach this common core, and that such lessons at times may be didactic, involving lectures and textbooks and reference to canonical knowledge, as well as "hands-on" activities. Science teaching, however, should never lapse into the mere imparting of information that has no connection to deeper knowledge structures, concepts, or important questions. The emphasis must remain on learning major, generalizable principles, skills, and dispositions by studying a few problems deeply and well.

Classroom and School-Level Assessments

As students progress through high school, their growing maturity should enable teachers to make expectations clear and increasingly pass on to students responsibility for their own science achievement and performance. Expectations and standards of performance should become internalized; the teacher's role should become one of facilitating learning, rather than inculcating knowledge. As a consequence, the purposes of classroom-level assessment—guiding instruction, communicating expectations for science learning, and documenting student progress—should meld together. Instruction and assessment should become indistinguishable from students' point of view.

Students as Independent Learners

The Center views learning as a process of making sense of experience in terms of prior knowledge, where experience can range from reading of text and formal lectures to hands-on investigations carried out by groups of students. How can assessment establish what sense students have made from their instructions based on what they brought to the classroom?

The most important aspect of thinking about assessment as an opportunity for students to demonstrate their knowledge is the potential for transferring responsibility for their learning to the students. As their stake in their own education increases, so can students' motivation and excitement. Moreover, giving students control in some circumstances mirrors something quite important in science—making choices about one's investigations and problem-solving strategies.

How can students gain some autonomy in selecting what they will be assessed on and when they will be assessed? Obviously, some negotiation about assessment should occur, just as negotiation occurs about learning. The Center argues that, for at least a significant proportion of the grade in a subject, students should identify tasks that would be appropriate measures of what they have learned. At the same time, high standards must be ensured. Teachers should examine students' proposals and make suggestions to ensure that assessment is consistent with instructional goals.

Teachers and other assessors should realize that students will make their *own* sense of what the task requires of them. When students respond, they will do so by attempting a solution in terms of what they understood of the task, not necessarily what the assessor intended when structuring it. Even though an important component of an assessment is students' ability to interpret with accuracy what was intended, this ought not be the sole criterion for assigning or denying credit. If students assign a meaning to a task that is different from that intended by an assessor, the students' responses might veer widely from the assessor's preferred response. If the responses are rational, given the constructed meaning of the task, is it reasonable to deny all credit for the solution? Or can the teacher assign partial or nearly total credit? The answer to such questions will depend on the goals of the course or the component of the science curriculum being addressed and how clearly these goals are articulated to students.

To make students independent learners, teachers must switch from being authorities responsible for conveying science knowledge to being mediators who facilitate students' science learning. Such changes require teachers to reflect on their teaching practices, many of which have become routine during years of teaching. Such routines must be carefully reconsidered; appropriate changes must be designed and subsequently implemented. When teachers are satisfied that the change has produced greater effectiveness, they can make the new strategies routine.

Teachers should be as concerned with their methods of assessment as with their instruction. Many teachers conceptualize assessment in terms of the technology developed to make fine distinctions among individuals on the basis of curriculum-neutral general aptitude tests, such as the Scholastic Aptitude Tests (SATs). Accordingly, when teachers utilize traditional assessment practices, including short quizzes and multiple-choice tests, they feel professional because they are doing what other professionals do. Even instructors who are changing their teaching to reflect constructivist perspectives about the learner often continue to use assessment practices that are inconsistent with these perspectives. Because their traditional assessment practices make sense to them, they feel little impetus to change. When this situation arises, the issue must be raised with teachers so they can reflect on assessment in relation to their overall teaching philosophy and strategies.

The vignette on the following page illustrates how improvements in assessment can be initiated if the teacher reconceptualizes assessment on the basis of changed teaching practices.

Blending Assessment and Instruction

Ms. Lopez's science instruction (see below) involves different kinds of processes and activities. The forms of assessments she chose needed to be correspondingly diverse. As the emphasis in classrooms around the nation likewise shifts from competition to collaboration, assessments must provide information on how well students are actively engaging with non-trivial problems.

In the classrooms the Center envisions, teachers will understand that assessment to support instruction need not compare one student to another directly and quantitatively. If students have some choice in the problems they tackle, then different students' products or performances may look quite different superficially.

Students at the high school level should be treated as important, perhaps *the* single most important, users of assessment information about their own learning. An integral part of their active problem-solving should be to document, both for themselves and the teacher, how they are progressing. Tasks to be measured include students' ability

Assessment in the Classroom

It was time for change, thought Marcia Lopez. For 10 years, she had been teaching her chemistry and marine biology classes in traditional fashion. She had emphasized the teaching of basic facts of the science; she often had her chemistry classes practice appropriate algorithms to obtain answers to exercises from the textbook. Ms. Lopez had believed such an approach was needed to prepare students for college science courses. She had resisted change, believing that she was an effective teacher. After all, that's what she had been told by colleagues, school administrators, and students—students who subsequently had done well in college.

Then Ms. Lopez read about the constructivist approach and saw it demonstrated. She was impressed. She decided to switch her approach from teaching facts to teaching science. She oriented her marine science class toward work on projects. Instead of attending lectures, students focused on doing investigations. Soon, they were conducting field investigations with local relevance. Students constructed mini-ecosystems, similar to such natural ecosystems as salt marshes, oceanic zones, and estuaries, and completed long-term projects involving aquaculture and hydroponics.

Because grades were required, Ms. Lopez needed to conduct formal assessments. She believed that traditional tests would be inappropriate for her marine science class. She preferred oral assessments, noting that these gave her "the freedom to probe kids, yet still figure out who doesn't know" concepts and material.

Ms. Lopez adamantly insisted that she had not changed her approach to teaching. She claimed that she had always believed that the investigation-driven approach was appropriate in science courses for non-science majors. These students did not require the same foundation of systematically organized science knowledge as did prospective science majors preparing for university science. However, because of her positive experiences with the marine science class, Ms. Lopez also decided to change her approach to chemistry teaching to emphasize investigations and project work. After briefly introducing her classes to some basic facts about chemistry, students tackled investigations. Groups of students undertook projects, after negotiating about the focus with one another and her. Each group undertook its own investigations and tended to work independently of other groups.

Ms. Lopez was comfortable with her new approach. She fit smoothly into a new set of roles, including assessing student learning. Because students were learning science in different contexts, she faced the challenge of finding out what they were learning. Her first idea was to assess learning through personal interviews. This ushered in a student-centered approach to learning. Students had control of their own learning, and Ms. Lopez had time to to formulate alternative approaches to a given problem; to apply their basic communicative competencies to chronicle and report their work; and to use such information resources as texts and other print media, information storage and retrieval systems, libraries and other archives, and the teacher's lectures.

In addition, assessment should gauge students' ability to work with others to arrive at a plan for investigation. Students must agree on separate responsibilities, maintain a climate of mutual support and respect for their peers, and carry out their plan. Students might even be asked, at the end of the assignment, to critique their own choice of an issue to investigate.

This scenario matches much of what Ms. Lopez introduced into her changed classroom; it differs greatly from typical assessments today. A model of assessment that begins "Put your books under your chairs and take out a clean sheet of paper" implies that the teacher splatters students with knowledge, then looks to see how much of it has stuck. The alternative scenario, in which students are invited to take part in the assessment of their performance, makes them active collaborators responsible for their own progress.

interact with students in a leisurely manner.

Ms. Lopez decided to assess five students per class period. She gave the students an oral examination in which she questioned individuals on any aspect of their project. She recorded whether each student's responses to questions were adequate. She considered this process fair because she asked each student a similar number of questions. Furthermore, she believed that each student should know about all aspects of the group's project. Ms. Lopez also required students to construct a concept map as part of their project. She asked them to discuss the map with her and answer any questions she might have.

Ms. Lopez's students expressed a preference for oral examinations. Because some had communication problems when required to write answers, they enjoyed the opportunity to be graded on oral responses.

She used other forms of assessment, too. Initially, she required students to make daily entries in a data book. Before long, however, many students found daily record-keeping burdensome. Ms. Lopez gave them the option of preparing weekly summaries. Some students did so, while others continued with daily summaries. She collected the data books each week and assigned 25 points to those that were complete. Students also were required to submit research papers. After Ms. Lopez had commented on the papers, students submitted two revised versions. Each revision was worth 50 points; the final report was assigned 250 points. Ms. Lopez set high standards for the final report: it was to be "like other scientific papers, with procedures written clearly so they could be repeated" and, if possible, achieve publication quality.

Ms. Lopez graded class participation randomly. When she had a spare five or ten minutes, she surveyed the class and entered a 5 or 0 for each student. She used participation assessment to motivate students when she felt they were not working hard enough. If students' progress appeared to be slow, she would grade the class for participation every day for a week to "get them motivated to engage in the project."

When Ms. Lopez discussed her teaching methods with colleagues, they suggested that she reconsider her method of grading students for class participation. Ms. Lopez defended her approach, however, believing it was necessary to get the best out of her students in a project-oriented learning situation. Her colleagues suggested that this be the next aspect of her teaching that she change. They also mentioned that she might have to reconsider her emphasis on interviews and oral responses, if presented with a different cultural mix of students. They suggested that she might start keeping records of her systematic observations of students as they proceeded through their investigations and incorporate her observational judgements into the students' grades, as well.

Another important contrast emerges when one compares these two models. Conventional assessments currently used by teachers yield quantitative scores (often of highly questionable reliability, let alone validity) and little else. A teacher's comments on a student's approach to inquiry or investigation tends to be incidental to the seemingly important matter of arriving at some numerical score.

In assessments that support good instruction, the first and primary presentation of information would *not* be quantitative. Comparisons among students within a classroom would still be an important part of the assessment, but would take the form of students learning from one another: reflecting together on their joint or respective problem-solving endeavors; and profiting from one another's experiences so that they could make better future choices about which problems to find, what approaches to take, and how to communicate their solutions. Of course, the limits of the teacher's own information-processing regarding students' performance will still require some more efficient summary. For that purpose, numbers still probably will provide the best vehicle, as they do in Ms. Lopez's classes.

Scoring schemes should accommodate not only test scores and grades given on homework assignments, but also the teacher's observations of student performance in class, both in individual work and as a team member. Moreover, students should participate in the appraisal. Teachers could rate students' self-analysis on simple scales measuring such dimensions as their use of resources, effectiveness of presentation, and appropriateness of problem choice. In this rating, "progress" could be differentiated from an absolute level of attainment.

This new form of assessment poses new challenges for managing information, although technology is providing some resources to deal with this problem. All assessments need not be reduced to columns of ciphers in a teacher's grade book. For example, as students or teachers create portfolios of student work or as students keep journals, computers could be used to summarize quantitative information, as well as maintain information in the form of text created by students related to their science work and possibly by the teacher *about* each student.

Even this may be unwieldy, however. A high school teacher who sees 180 or more students per week may be unable to manage weighty collections of documents or large amounts of information stored in a computer for each student. Current approaches used by the National Assessment of Educational Progress and by several states (California, Illinois, Michigan) to assess writing and the development of mathematics portfolios (in California) could provide guidance on what is feasible in assessing student achievement and performance in science. The experiments with alternative forms of assessment currently occurring in Vermont and Pittsburgh also deserve scrutiny for possible wider-scale application in the classroom.

Summary

Several features should characterize assessments controlled by classroom teachers:

- Assessments should be multidimensional, drawing information from a variety of sources. Traditional tests retain a role, but should not be the sole determinant of grades.
- Assessments carried out through the year should probe all major course goals.
- From the student's point of view, instruction and assessment should be indistinguishable —work to be accomplished, perhaps in cooperation with others, under the tutelage of a respected individual more experienced in the field.
- Instruction and assessment alike should allow students to make some choices about their work.
- Self-evaluation should be built into most assessments, whether they are short- or

long-range. This is true both for students and teachers. Good teachers re-evaluate the effectiveness of their instruction as they gather information on students' progress and change their teaching approaches to increase students' learning and competencies. In this way, assessment information can enhance science instruction, while providing a rich portrait of the science achievement of individual students and the class as a whole.

Information Needs at the School Level

In the schools the Center envisions, both students and teachers participate in constructing a learning community. Thus, students, as well as teachers, will have a voice in designing curriculum. This process represents a natural extension of current reform efforts aimed at passing more decision-making, particularly about curriculum and instruction, to schools and teachers.

A comprehensive system of science assessment could help students express their own interests and preferences, yielding information that in turn could help schools and districts improve educational planning and make it more responsive. Under the current system, courses are specified, with more or less fixed numbers of slots set aside for students. Somehow, students must be found to fill these slots. By collecting information before course registration begins about students' perceptions of their own interests and needs, schools could become more responsive.

In today's educational system, critical curriculum decisions are made for individuals by a process that is poorly understood, sometimes haphazard, and all too often prejudicial (Oakes et al. 1990). Students are tracked into vocational, general, or academic programs as they pass from middle to secondary schools. If assessments of student interest and needs were designed explicitly to meet school- and district-level information needs, the sometimes too-rigid boundaries among these tracks within the comprehensive high school could begin to soften. For example, as we intimate in Chapter II, science and vocational teachers might cooperate in designing rigorous applied science and technology courses, on the model of the promising experiment to reform vocational education by the Southern Regional Education Board (Bottoms and Presson, 1989).

External Assessments

External assessments, unlike classroom assessments, are not under the control of classroom teachers. Such assessments include high-stakes individual-level examinations generally taken at the student's own initiative, including college placement examinations, Advanced Placement tests, and such state-level examinations as the New York Regents examinations and California's Golden State examinations. They also include large-scale assessments designed to document levels and trends in the achievement of groups or populations, rather than individuals. Examples include the National Assessment of Educational Progress (NAEP), state-mandated and designed assessments such as the California Assessment Program (CAP) and the Connecticut Assessment of Educational Progress (CAEP), and international assessments.

High stakes assessment. Tests to establish eligibility for college admission or enrollment in advanced placement courses, or to receive such credentials as a "Regent's Diploma" in New York, generally are most relevant to students in the academic track. These are "high stakes" tests. Good performance produces rewards desired by students and their parents. Moreover, these students and their parents are likely to be among the most articulate groups in expressing their educational needs and concerns. Hence, such exams often exert a powerful, if localized, influence on the school curriculum. Advanced placement courses in a particular subject are highly similar throughout the nation. Similarly, state-level exam programs tied to more distinguished high school credentials may influence instruction throughout a state.

Such exams tend to be relatively rigorous. They can employ free-response problem-solving exercises and sometimes even laboratory work, in addition to multiple-choice items. For the most part, these tests are the "success stories" of measurement-driven instruction. On balance, they have had a salutary influence on the more elite high school science courses. But high test scores should not become an end in themselves. Instructors must ensure that their courses are genuinely interesting and must not lean too heavily on the final exam as a convenient motivator.

Measurement-driven instruction also runs the risk of foreclosing spontaneous opportunities to learn. Courses planned to prepare students for a test are unlikely to encourage divergent inquiries into topics of interest to individual students. The teacher hardly will be able to afford the luxury of spending a few days on some topic that arises fortuitously (such as cold fusion or the optics of the Hubble Telescope) that might otherwise become the most memorable part of a science course for some students.

Finally, the risk with measurement-driven instruction is that the validity of test questions will be diminished if teachers teach to the test. For example, if it was known that a mathematics test required a formal proof of any one of a dozen propositions, some students simply might memorize the 12 proofs, rather than master the fundamental principles that would let them prove any proposition.

Often, exam questions are repeated from year to year to save money and to maintain stable scoring criteria. This allows students to "cram" for the test by studying the answers to past exams. This problem may be lessened by avoiding or minimizing the repetition of questions and by carefully specifying areas to assess. For example, if a test would draw not from 12, but from 500, propositions, students almost certainly will try to master the principles, rather than a handful of examples.

Large-group external assessment. In the past, individual-level assessments have wielded far more influence on curricula and instruction than assessments to establish the level of achievement of groups of students. This is likely to change as the United States strives toward the national education goals proclaimed by the President and the governors. Pilot experiments are being conducted in mathematics and reading to establish the feasibility of using National Assessment of Educational Progress (NAEP) assessments to compare student achievement among U.S. states. Adaptations of NAEP tests (International Assessment of Educational Progress, IAEP, Lapointe et al., 1989) and new tests constructed by the International Association for the Evaluation of Educational Achievement (IEA, 1988) are being used to compare the science achievement of students in more than a dozen countries, including the United States.

International comparisons will take on a special role as a way to gauge progress toward the nation's educational goals. But international comparisons pose special hazards, as a recent British critique of the IAEP science assessment points out (Association for Science Education, 1990). The critique argues that:

1. The IAEP test had restricted content validity because items emphasized recall of facts and did not represent the practical laboratory work stressed in English classrooms. Moreover, the test's contents did not match the English school curriculum. In fact, English students (who scored in the middle) performed better than Korean students (who scored in the top) on topics—such as physics and the "nature of science"—that *are* part of the English curriculum at the grade level assessed.

2. The test had doubtful face validity because English pupils were unfamiliar with the question format—multiple choice—and sometimes with the structure and language used in the items.

3. Concept validity also was questionable because the items did not necessarily test the concepts

they purported to test. according to experienced teachers and examiners who reviewed them.

Even giving due allowance to the vagaries of sampling and differential selectivity in various nations' educational systems. the consistent pattern of findings for the United States is grim. U.S. students perform poorly in mathematics and science, compared to students in many other nations. Ample room for improvement exists even in the limited range of knowledge and skills addressed by current assessments. Moreover. if performance comparisons on more complex and comprehensive assessment exercises could be conducted today. it is likely that the United States would fare at least as poorly. relative to other nations.

If the United States is to move toward meeting its national goals regarding achievements in science in the international arena, then new educational processes *as well as* new assessments must be implemented without delay. Over the longer term, both types of assessments, short answer and more complex measures, must evolve to provide better information about the complex and comprehensive learning outcomes that are the goals of science education. The United States must work closely and cooperatively with other nations on current and future cross-national assessments. In particular, the cooperation of other nations will be needed to implement the more complex and more costly (open-ended, hands-on) assessments that the Center and other advocates of testing reform envision.

Designing External Assessment

Instruction at the secondary school level is highly differentiated. In contrast to the "common school" curriculum at the elementary and middle school levels, high school students often are loosely tracked into academic, general, and vocational programs that generally offer quite different curricula. Within each program, students often enjoy substantial flexibility in electing specific courses. Even within courses, as high school students assume increasing responsibility for their own learning and pursue their studies more independently, considerable diversity may occur in the particular areas of knowledge they develop. The restructuring of secondary school science envisioned in this report would bring even greater heterogeneity to students' learning.

Accompanying the current tracking of students are inequalities in access to high-quality science instruction (Oakes et al. 1990). These occurrences, however, do not negate the desirability of allowing students to follow their own interests and build on their competencies, once they have mastered the core science knowledge and understanding the Center advocates. The Center's ideal is diversity based on informed choice and equitable access to science learning resources.

That diversity raises serious challenges for external assessment. Complex reasoning processes and practical problem-solving in any particular area depend on substantial knowledge of that area. They cannot be treated as abstract, disembodied processes for assessment purposes. Even if all students have an opportunity to engage in serious scientific problem-solving, it may not be possible to find any single assessment task for which all, or even a substantial fraction of, students possess the prerequisite knowledge.

If the United States is to move toward meeting its national goals regarding achievements in science in the international arena, then new educational processes as well as new assessments must be implemented without delay.

If an assessment is to serve policy purposes, it will need to address learning outcomes, students' backgrounds, and "context" variables. At a minimum, the background questions for a large-scale science assessment should document the amount and kinds of science instruction to which students have been exposed: courses they have taken: their relevant science experiences, both in science and other courses; and their "informal," out-of-school science experiences.

Questions should be designed to indicate the overall success of the school or education system in meeting students' diverse needs. Special attention should be paid to the different experiences of groups traditionally underrepresented. Such information as course offerings, science experiences, and the quality of teaching staff should be reported by gender, race, and ethnicity, as well as by indicators of poverty or socioeconomic status. Opportunities provided to the scientifically most capable and most interested students also should be documented. In short, background and contextual information should indicate the extent to which science education is enabling *all* students to develop their interests and talents to the fullest extent possible.

Test content. A critical difference exists between assessments used by teachers to document students' progress and large-scale assessments intended to report on the science achievement of groups or populations. It would be patently unfair to test and grade individual students on science knowledge and skills not included in the curriculum and which they had no opportunity to learn. This does not imply, however, that students should be given only those exercises, tasks, or questions that they can address with success—particularly if the teacher wants to find out where further instruction is needed.

In a well-designed assessment, examinees are exposed to challenging items they cannot answer. In a teacher-controlled assessment, these should be firmly anchored in the curriculum. By contrast, in an external assessment designed to document the level of science knowledge and skills of groups of students, it is not reasonable even as a goal to avoid testing students on topics and skills they have not studied. Significant learning outcomes should be assessed *whether or not* they are among the learning outcomes intended for a given curriculum. It is important, however, to know what, if any, discrepancies may exist between curriculum content and test content. This helps determine whether the intended curriculum was inadequate or whether the delivery and implementation of an otherwise adequate curriculum were ineffective for a particular student population.

Matrix sampling. The number of items required to sample a content area as broad as "science" is far too large to administer to any one individual. Thus, modern educational assessments of large groups do not test all examinees on all items. Typically, assessments employ some form of matrix sampling: different examinees take different exercises. Care is taken to ensure that examinees exposed to any particular item or task form a random sample from a defined population. If this condition is met, results can be pooled to estimate knowledge and skill levels for the entire population across the entire area.

One response to assessing curricular diversity is to address it through matrix sampling. A large pool of exercises could be developed to cover different topics various students *might* have studied. These would be matrix-sampled, without regard to the particular topics students *actually* had studied. Valid estimates of the population proportions that responded to each exercise could be obtained.

The Center believes, however, that it is preferable to take some account of the various problems students have studied in depth, and to probe their understandings of those topics in greater depth. Psychometrically, this has the advantage of efficiency. Substantively, it answers the important question of how well students have mastered specific topics they have studied at greater length. In terms of assessment policy, it avoids the problem—inherent in a straight "matrix-sampling" approach—of sending a message to the schools that the best way to improve performance is to try to cover *everything*.

The overall plan for the assessment the Center envisions would include several components, two of which are essential to probing students' core knowledge and skills in science:

- A broad, matrix-sampled coverage of the knowledge, skills, and dispositions identified as important learning outcomes at the given grade level; and
- A set of exercises, selected on the basis of prior information about the specific topics students had studied.

A Multi-Stranded Assessment Approach

To match the core-plus-diversity curriculum the Center advocates, assessment strategies must address common learning as well as the learning goals embodied in electives. To assess the core, some tasks would be given to every student, but matrix-sampled. Other tasks could be chosen by the student, teacher, or test designer/administrator to respond to the curriculum. Portfolios of students' work could represent students' performance without the time limits posed by formal assessments. In addition, group tasks and hands-on performance could be used. These different techniques are not mutually exclusive, but can be combined in various ways.

An overview of the approach the Center envisions for large-scale assessments is presented below with some examples. The examples are illustrative, not exhaustive.

We invite readers to draw on their knowledge and experience to improve our examples and create new ones suitable for their students and schools. We also ask readers to check the accompanying boxes for more examples.

■ *Assessing core learning*

1. **Assessment tasks given to everybody, but matrix-sampled.** A variety of tasks and modes of presentation can be used, including classroom demonstrations, computer simulations, paper-and-pencil, and videotape.

a. *Solve mini-problems that tap fundamental science knowledge.*

These mini-problems lie between the tidy, artificial, decontextualized problems too often found in textbooks and the diverse, messy, interesting problems that best meet some pedagogical purposes. They raise questions about the real world students live in: about how things work, why things happen, and how things could be changed or improved.

Mini-problems are open-ended, but prompt answers that are clearly correct or incorrect. Deriving a correct answer requires students to correctly apply specific scientific principles or problem-solving procedures. However, students are not told which principle or process to apply. Where appropriate, problems require students to present a brief narrative explanation of the phenomenon described, along with a quantitative description or solution that employs appropriate mathematical symbolism. Problems also could require students to construct diagrams, sketch graphs, organize tables of information, or use other means of scientific communication.

For example, explain that bicycle riders soon discover that it is more difficult to maintain their balance on a bicycle moving very slowly than on one moving quickly. Ask students why and ask them to redesign a bicycle to make it easier to stay balanced when moving slowly. Assume that the two wheels are still the only parts to touch the ground. (See the box below for further examples.)

More Mini-Problems

Section 1.a.

- When you open the refrigerator door on a hot day, you feel cool air come out. Can you cool off the kitchen by leaving the refrigerator door open for an hour? Explain why or why not, describing the different kinds of energy and energy flows involved.
- Describe the sequence of physical, biological, and chemical processes involved in making a loaf of yeast-raised bread.
- Explain why a can, or bottle, of a carbonated beverage foams or fizzes more upon opening if it is shaken first, or if it is warmer.
- When water is brought to a boil, what's inside the bubbles that rise to the surface?
- Explain why a soap bubble floating into air is spherical.

Continued on next page

b. *Communicate using scientific concepts and terms, through such tasks as reading scientific material, arguing points of view supported by facts, and making reasonable judgments.*

For example: Give students two editorials; one arguing the importance of nuclear power plants as a source of energy, the other stressing the potential dangers posed by nuclear plants. Ask students to use the information from the editorials, as well as their own knowledge and experience, to articulate and support a point of view either in favor of, or opposed to, the widespread use of this source of energy.

c. *Synthesize data from given information and interpret the results.*

Ask students to make sense of data. For example, give students the results from an experiment

More Mini-Problems

- A gravid female of a non-native species of insect is accidentally introduced into a new habitat. Describe at least five factors that may determine whether the insect becomes established in the new habitat and whether it becomes a threat to native species.
- Design a cup or mug to keep coffee hot longer. Beginning with a typical ceramic mug, describe three changes you would make and explain how each change keeps the coffee hot longer. (Answers could include using a different material or shape, a smaller aperture, a lid, double walls, or a different color.)
- When a car is parked in the sun for awhile, the temperature of the air inside the car rises above the ambient temperature outside. Why?
- Why does a fireplace "draw" better with a taller chimney?

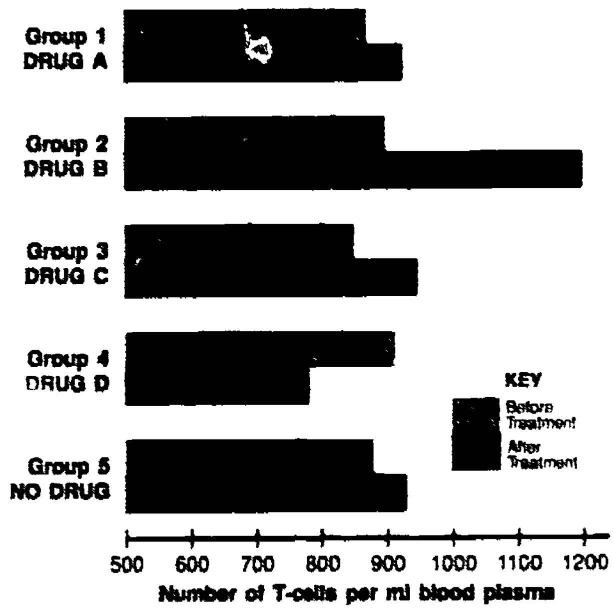
Data Interpretation

Data and details, using mice to test drugs
Section 1.c.

Mean Number of T-cells per ml of Blood Plasma

	Group 1 Drug A	Group 2 Drug B	Group 3 Drug C	Group 4 Drug D	Group 5 Control
Before Treatment	870	900	850	910	880
After Treatment	920	1,150	940	780	930

N = 6 laboratory mice for each group



Students should recognize that the number of T-cells increased in Groups 1, 2, 3, and 5, but decreased in Group 4. Students also should understand that the increase in Group 1 is not substantially different from the increase in the control group. This may mean that Drug A has little or no effect. Students also could be asked to suggest ways to improve the experiment: for instance, by increasing the number of mice used in each group; repeating trials with different groups of mice; or using mice with identical T-cell counts at the beginning of the experiment.

designed to test the effects of several different drugs on the production of immune system cells in laboratory mice. (See box at left for details.)

d. *Describe and explain physical phenomena.* For example, ask students to explain the slow motion flight of a baseball, demonstrated or presented on videotape.

e. *Discuss changes in the view of Western science.* For instance, ask students to explain why views have changed regarding particular phenomena, such as the conscious control of some autonomic human body functions, like blood pressure.

f. *Give students evidence of the success or failure of a technological application in a particular setting, such as Western-style agriculture or medicine in a less developed country, and ask the class to explain the reported results.*

g. *Evaluate or design an experiment or design an object to perform some specified function.* To test students' understanding of the "scientific method," present students with a description of an experimental procedure and ask them a series of questions about the procedure, its purpose, and interpretations of possible outcomes. (See box at right for further explanation).

2. Tasks based on in-depth studies. Students or teachers can choose these tasks, or they can be designed by assessment developers.

a. *A student chooses one of 25 current events involving technical issues and discusses potential problems in reaching a solution, specifying scientific details.*

b. *From the same list, students choose an issue with which they are not totally familiar and describe how they would research it further: where they would obtain more information; what additional scientific research should be*

Evaluate or design an experiment

Section 1.g.

One simple example is an experiment involving treatment and control groups. The experiment could be flawed by confounding two or more causal factors that would be varied simultaneously among groups. Alternatively, ask students to sample data over time. Students could fill a jar with hot water and let it stand at room temperature. Periodically, students could insert a thermometer and record the time and temperature. Or students could measure the heights of corn plants grown with different amounts of fertilizer.

Students might be told the purpose of the experiment or they simply might be given a description of the experimental procedure and asked what the investigator was trying to find out. Have students offer ways to improve the experiment. (For example, the hot water and fertilizer experiments could be flawed by irregularly spacing measurements through time or across levels of fertilizer, or by failing to cover a sufficient range of times or levels.)

A second type of exercise, more challenging, more open-ended, and more difficult to score, presents a hypothesis and asks students to describe an experiment to address it. Students can be told what apparatus is available and could be primed by being given descriptions of related experiments.

Another type of exercise describes some problem or phenomenon, asks students to generate plausible hypotheses about it and then to devise an experiment to test one, or more, hypothesis. Examples could include: a farmer's observation that crops grow taller in one part of a field than another; the appearance of excessive cracking in the foundations

Continued next page

done; and which parties might have an interest and should be involved in resolving the issue.

c. *Selected on the basis of information provided by the school or students themselves, essay questions about topics or issues they had studied could be presented to students to allow them to explain their knowledge in detail.*

3. **Portfolios.** Students and teachers can select appropriate materials to represent work that occurs in the daily classroom environment. Portfolios can record daily or weekly progress. progress in more extensive projects, or performance in group work.

Clear guidelines are needed about the criteria used to include material: whether it is to be representative of a student's work—a pilot's log: whether it demonstrates a student's best work—an artist's portfolio; or whether it shows a student's growth in knowledge and competence during some time period.

Portfolios and their uses can take almost as many forms as there are teachers using them:

- **To record progress in students' daily work.** Students routinely use a folder, box, or drawer to keep a log of their activities and ideas, lab notes and reports, and other daily or weekly assignments. By having students build on their work from day to day, educators and students can easily track students' short-term progress. In addition, by assessing the growing sophistication of materials over time, students can appreciate how much they are learning, and teachers can gain a concrete basis to evaluate student performance.
- **To record progress in more extensive projects**. Students' work on more extensive, long-term projects also can be kept as part of a running record or portfolio. Taken together with students' daily work, such longer-term efforts can be used to highlight students' capabilities.

Evaluate or design an experiment

Continued from previous page

of buildings in one area of the city; or a finding that in an apartment building, television reception is poor on a certain channel during one part of the day.[3]

Alternatively, students could be presented with a pair of tables, one presenting the active ingredients of four different laundry detergents and the other rating each detergent's ability to remove each of a dozen kinds of stains. (A sound hypothesis might be: enzyme cleaners work especially well against protein stains.)

Another type of exercise presents students with some hypotheses to critique. For example, in the case of poor television reception, one hypothesis might be a power "brown-out" during the period when many people arrive home from work and turn on air conditioners, stoves, and other appliances. That hypothesis would not fit the fact that the problem is reported on only one channel. A "brown-out" at the station would be ruled out by the fact that the reception problem was confined to one apartment building.

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[3] One provocative problem would involve "ghosts" that appear on the television screen when a nearby drawbridge is raised. Some students may not know what "ghosts" are, having never known the joy of tinkering with rabbit-ear antennas because cable is becoming so widespread. The potential obsolescence is interesting in itself: it shows how, as technology improves, items based on imperfect technology may become dated.

- **To record progress in group work.** Projects become more meaningful to students if the results of collaborative efforts are shared among students, kept as part of the record of class progress, and considered as central in evaluating individual performance.

The application of portfolio procedures to large-scale assessment is somewhat problematic because uniform evaluation of complete portfolios for a large number of students is difficult to implement. However, selections can be taken from portfolios for large-scale evaluations. Alternatively, particular sets of tasks can be assigned by states or districts to create portfolios. For example, a state or district can ask each student to prepare one research project report and one report of a laboratory experiment. Staff can evaluate these at a central location.

4. **Group tasks and assessment of cooperative group work.** This is a distinctive feature of the external assessment the Center envisions and is important for two reasons. First, inclusion of group work in the assessment will reinforce its importance, sending a message to educational practitioners and policy-makers. Second, and more critically, certain significant science learning outcomes can be assessed *only* in a group context. Notable among these skills are identifying subproblems within a complex problem, assigning work on subproblems to different team members, working cooperatively, communicating effectively about tasks, and integrating team members' contributions into a final product. For small groups of students drawn from classes or schools, assessments could include:

a. *A task and relevant resource material presented on a diskette, which would also become an unobtrusive record of students' work. (See box at right for details.)*

To collect information about collaborative work as part of external assessments, personal computers can be used to collect background information on group members, to probe the problem-solving methods used by group members, and to document their final product.

The assessment task can be sent to participating schools in the form of user-friendly floppy diskettes, one for each cooperative group. Instructions discuss the problem-solving process and present the problem, along with such "tool" programs as spreadsheets and simple statistical, graphic and word processing software. "Monitor-

Group Tasks and Assessment of Cooperative Work

Group task presented on diskette
Section 4.a.

The problem can be a simulation of a complex system, such as an ecological setting with various populations to be kept in dynamic equilibrium. Students have to figure out how to tune the system to maintain it. Some information can come from outside resource materials; some can require "hands-on" experimentation, such as a vial of pond water which students test for key pollutants.

Following instructions on the screen, students start by jointly discussing what to do and how to do it. Then they complete a brief, interactive questionnaire identifying and describing themselves (presenting their names, gender, age, and relevant courses taken, and answering background questions). They describe how they plan to divide the problem's work, and who will do what. They indicate what information they need to obtain and answer questions about their cooperative work. This indicates whether they have learned any special vocabulary to discuss group work (for example, by self-assigning different roles or following rules for helping or respecting one another).

ing" software can maintain an unobtrusive record of all keystrokes and mouse movements to record the group's problem-solving process and solution.

As the assessment unfolds over, say, two hours, students also document their false starts and partial solutions, along with their final solution. Finally, they are asked to critique their own work, both the process and product.

Completed diskettes are returned to a central site outside the school for analysis. Detailed scoring for various aspects, such as the processes used, can be done initially for a random subsample. The products of different groups can be rated for evidence of effective collaboration, use of information resources, innovation and creativity in the solutions developed, quality of final solution, and quality of students' reflection on the process.

Group Tasks and Assessment of Cooperative Work

Collecting and analyzing data in a survey
Section 4.b.

First, students are asked to design their study, taking into account where to post students to collect information, how to collect information, and what times of day should be monitored and for how long. Students also determine what constitutes a reasonable sample size and identify any features of their study that might introduce bias. For example, many cars might frequent the local fast-food restaurant. Do these represent a cross-section of the cars and drivers in their community? Many students might ride bicycles to school. Do they present a good cross-section of bicycle-riders in general?

In the exercise's second and third stages, students collect data and analyze results. Such studies can become quite sophisticated. In the foreign versus domestic car count, students might discover that ratios differ, depending on the locations surveyed and time of day data were collected. In the bicycle helmet study, students might find that more people wear helmets on weekends than on weekdays. Students have to think of reasonable explanations to interpret the various patterns they found in their data.

Such an assessment can be more or less "high-tech." At one extreme, the entire exercise *could* be done using "low-tech" paper and pencil, although it would be very cumbersome and costly. It would be nice, using current technology, to have students input, for example, diagrams using a Koala pad. A "high-tech" method could employ interactive video disk and digitized voice to present the problem and record students' work.

b. *Tasks involving collecting and analyzing data.*

To assess students' cooperative skills, as well as their ability to conduct scientific studies, students can design surveys and then collect and analyze survey results. For example, students can be given several tasks related to their community life, such as determining the ratio of foreign to domestic cars or the patterns of use for bicycle helmets or car seatbelts. (See box at left.)

c. *Tasks like the soda pop exercise and other sustained investigations currently being developed by a group of states under the leadership of Connecticut (Baron et al. 1990).*

Groups could work together through electronic links. Each group would be responsible for collecting its own data, such as acidity of rain, patterns of soil erosion, or temperature, but analyzing data and formulating and reporting conclusions would involve several or all the groups.

5. **Hands-on tasks.** Students can be given a situation and asked to develop a hypothesis or theory to explain it.

Then they could design and conduct an experiment to test the viability of their hypothesis or theory, using scientific procedures and equipment effectively. Tasks could include:

a. *Creating, observing, and explaining a chemical reaction.*

b. *Using a microscope to analyze and interpret information on slides.*

c. *Using a computer to generate information, for example, using microcomputer-based laboratories (MBLs) to collect data or using a computer to convert music or motion patterns to patterns on a computer screen for purposes of analysis.*

d. *Building a structure to accomplish a particular purpose or fixing a mechanism so it would work.*

■ Assessing electives

At these more advanced levels of study, examinations should more nearly resemble college-level or professional school examinations. The kinds of examinations used by other industrialized nations to assess whether students are ready for further study also provide interesting models (Madaus and Kellaghan, 1991). The examinations need to be based on the individual student's course of study. They can by tailored to one of the natural science disciplines, or to engineering, technology, and design. Even within these constraints, they also can be branched according to ability level, permitting top students to show what they know and can do.

Some Problems and Caveats

The pervasiveness and persistence of multiple-choice standardized tests is not difficult to understand, as Linn (1986) observes. The format provides reliable and efficient measurements, and scores on multiple-choice achievement tests correlate moderately well with subsequent academic performance as measured by grades and similar indicators. It will be a significant challenge to develop new forms of assessment that are simultaneously reliable, valid, and efficient.

Performance exercises. Most of the performance tests now being investigated for use in state testing and assessment programs (for example, in Connecticut and California) are modeled after instructional tasks. Although these tasks might be used quite successfully as performance tests in the classroom, the modifications required to create low-cost, standardized, objectively scorable assessment items requiring only a few minutes to administer may significantly diminish their validity and pedagogical utility.

California recently piloted five science performance exercises at the sixth-grade level, dealing with such topics as a simple electrical circuit (conductors and insulators), acids and bases (with indicator paper), and the classification of objects according to similarities and differences. The reaction to the pilot assessment was for the most part quite enthusiastic: teachers never before had been asked, "Can we take that test again tomorrow?" State administrators were excited and pleased that the difficult logistical problems of distributing materials, training people to administer the tasks, rotating students through stations to perform different tasks, and holistic scoring of performance could be successfully negotiated.

The success of the performance assessment as a reliable and valid measurement device was less clear, however. Of course, the pilot assessment was not intended to produce usable data. The participating schools were small and were not selected at random. Volunteer samples of students and administration procedures were varied systematically from site to site to learn more about the assessment process itself. The reliability and validity of an operational performance assessment would certainly be higher.

Initially, it may be that the sole use of performance assessments of this kind will be to document the generally poor quality of science learning outcomes and students' limited exposure to *any* "hands-on" science; for these purposes, such assessments should suffice. Moreover, including these exercises in a state assessment will send a powerful message to local curriculum planners, textbook publishers, districts, schools, teachers, and the public at large about the commitment of the state to new forms of science instruction.

If these performance exercises are to be of significant value over the long term, however, it is important that they test significant science content and processes. They also must be better integrated with the curriculum (or a state's science framework) and with a coherent domain description indicating the class of potential performance tasks that those chosen for the assessment are meant to represent.

New forms of assessment will influence instruction only if educators modify their teaching to improve test performance. Teaching the particular items that appear on a test is of little value; for that reason, educators typically are not informed of the precise content of future tests. Educators must have some information, however, about the kinds of items likely to be used and the approximate nature of the test if they are to formulate appropriate instructional approaches. The five science exercises piloted with California sixth graders were chosen to represent different science disciplines and to focus on different skills. But beyond these rudimentary concerns with content coverage, it was not clear what portions of the state science framework the exercises were intended to cover or what "parallel forms" might be administered in future assessments.

Scoring problems. Two potential difficulties in scoring new forms of science exercises exist: recording relevant behavior; and deriving reliable and valid scores from those records. If the behavior to be scored is limited to the written records produced by a student (such as answers to test questions or a laboratory notebook), then recording relevant behavior is not a problem. If, however, laboratory technique, interaction with a cooperative learning group, or problem-solving approaches are to be observed and rated, then data acquisition might be costly and potentially filled with errors. Whether written records or some other form of data are collected, scoring will be complicated by the large number of potential responses to open-ended tasks.

Interesting science activities at the high school level often yield more than one correct solution and procedure. It may be possible to prepare nearly exhaustive keys listing all correct responses, but preparation and use of such keys is laborious. The alternative of relying on the scorer's judgment and understanding may require the use of more qualified (and/or more extensively trained) judges and may prove less reliable.

Costs. The costs of new forms of science assessment will be higher, not only because assessment materials will be more expensive, but also because more time will be required of students and test administrators. The time to train test administrators will be greater. Moreover, scoring will be a more complex process and may be difficult to automate, though relevant experiments are currently proceeding using compact disk technologies.

Implications for comparisons over time. Comparisons over time are of considerable interest for many external assessment purposes. These comparisons usually involve administering somewhat different test batteries in successive rounds of data collection.

Test items, of necessity, must change over time. Items may become dated as the school curriculum and scientific knowledge evolve. Even if items remain serviceable, the content validity of the test as a whole may decline as the curriculum changes. Some items may be released to the public to aid in interpreting test performance. Some items may be found to be technically flawed. In addition, if serious reform efforts are successful, it may be appropriate after some time to include more difficult items in the test. For all these reasons, longitudinal comparisons of large-scale assessment performance have come to rely on sophisticated psychometric methods to link or equate successive test batteries. These methods generally require large pools of items.

As assessments move toward the use of fewer, more complex items, new psychometric methods may be required to establish that successive assessments are in fact tapping the same underlying dimensions of science proficiency, and to relate these successive assessments to one another with sufficient accuracy that progress or lack of progress can be judged reliably.

At present, changes in the direction of more complex learning outcomes and more authentic applications of science knowledge and skills to "real world" problems are likely to result in tests that will yield an even more dismal picture of students' capabilities. Nevertheless, the country will not achieve its goals in reforming science education unless assessments of student learning faithfully mirror these goals.

International Assessment Tools

Incorporating the techniques the Center recommends into classroom and larger-scale assessments also will help provide data that permits fair and valid cross-national comparisons according to U.S. criteria.

Multiple forums for international comparisons should exist. Programs such as the International Academic Olympiad, the cross national studies conducted the by the International Association for the Evaluation of Educational Achievement, and the newly established International Assessment of Educational Progress should be encouraged and continued. Any assessment data become more valuable when they can be incorporated into longitudinal trends. Americans need to know where U.S. students fall short if the nation is ever to be able to look back and see how far it has come.

The Center also envisions cross-national comparisons measuring very different science outcomes. For instance, the United States might be interested in learning whether this country's students lead the world in old-fashioned Yankee ingenuity. Assessments must pose practical, common-sense problems whose solutions hinge on science knowledge and scientific problem-solving approaches, but that do not look like textbook science problems.

The "high-tech" assessment scenario presented above for external assessment is even more unrealistic in a cross-national context (unless the United States wants to compare itself to a very short list of countries that are capable of such assessments). It should be possible, however, to present intellectually honest and valid problems simply using print materials.

In general, the exercises presented should *not* require students to remember many detailed scientific facts. A situation should be described in some detail, and students should spend a substantial amount of time—at least a half hour or so at the secondary school level—solving a single exercise. The emphasis should be on approaches taken and the quality of reasoning evidenced, *not* on getting the "one right answer." Exercises should have face validity. People seeing them should agree that this is what the outcomes of science learning should be.

Recommendations

1. States should undertake vigorous efforts to improve the assessment skills of teachers, science supervisors, and educational administrators.

As part of their training, science teachers, supervisors, and educational administrators should be exposed to and practice with a variety of assessment modes. This will help educators understand the purposes and uses of assessment modes within the classroom and in external assessments.

To refresh and update educators' knowledge of and expertise with assessments, staff development programs should be conducted for practicing teachers and administrators.

2. **Researchers and analysts should report and responsibly interpret the results of national and international science assessments.**

This step includes giving due consideration to the inevitable biases and limited precision of assessment data. Every effort should be made to ensure that policy-makers understand the limitations, as well as the strengths, of research findings. This holds true especially for international assessments, which are often less precise than smaller assessments because of looser controls on sampling, administration conditions, student motivation, and amounts and kinds of specific student preparation for assessments.

3. **Testing centers should conduct additional research on task formats and ways of presentation to help choose the most feasible assessment form that yields the most information.**

For example, compare the costs, feasibility, and information produced by paper-and-pencil exercises, hands-on tasks, and computer simulations (see Shavelson et al., 1990).

4. **Researchers should conduct pilot studies to determine ways to measure students' internalization of self-assessment techniques.**

For example, students could be asked how confident they are about their solutions to some mini-problems. This would provide a basis to probe students' self-assessment in more challenging and complex areas, such as decision-making.

5. **Public and privage agencies should support a significant program of research and development to improve large-scale science assessment.**

The research program should include: Study of new item formats suitable for external assessments, especially hands-on exercises; investigations of the validity, reliability, and efficiency of alternative exercise formats and scoring schemes; and development of pools of exercises.

6. **Responsible agencies should seek support to improve data collection, analysis, and reporting of large-scale science assessments.**

The National Research Council, the National Center for Education Statistics, and the National Science Foundation should maximize the deployment of resources invested in national and international science assessments, with a view toward increasing investments to improve assessment tasks, as well as the reporting of results.

Rather than focusing exclusively on larger samples, finite resources should be allocated to ensure adequate scoring, analysis, and reporting of science assessments. Sufficient investments also should be made to prepare and document public-use files to ensure ready access and sufficient technical support for secondary analysis.

CHAPTER IV

The Learner And Teaching

The teaching approaches the Center recommends are grounded in research on learning, because we believe that effective pedagogy must be directly linked to our growing understanding of human learning. That research supports a constructivist view that learners generate a personal understanding of a concept by actively linking new information with their prior knowledge to form a new view. Thus, a good pedagogue is one who can effectively help his or her students construct new knowledge.

In the Center's view, teaching is more than telling. Students can gather information—by reading texts, interviewing experts, and attending timely lectures. In addition, students must bring their own meaning to the questions, puzzles, and materials selected by the teacher. Thus, teachers must consider the processes of learning, as well as the content of science and technology, as they structure the classroom learning environment. Teachers must be flexible in their choice of exercises, their approach to teaching, and their methods of assessment. An important task for teachers is the long-term engagement of students on topics so that the learners continually have opportunities to make sense of new information in light of their current conceptual understandings.

What might a "constructivist" classroom look like? What would the teacher do? The students? To answer these questions, we turn to a vignette about a hypothetical biology teacher, Mrs. Maureen Spenser. Her story on the next page is based on real classroom experience.

Interpreting Mrs. Spenser's Classroom

That vignette exemplifies current knowledge of and research on human learning. Mrs. Spenser used her understanding of that knowledge as she planned the unit of study on photosynthesis. Moreover, she implemented what the Center believes is a successful model for teaching and learning high school science and technology.

That model begins with a teacher inviting students to ponder a problem or concept—one of their own choice or one the teacher provides. The teacher poses questions designed to elicit responses from students that reflect their current knowledge. This unique beginning differs substantially from the more typical teacher monologue in which a teacher expounds on a subject, but learns little about students' level of understanding about that topic.

Effective pedagogy must be directly linked to our growing understanding of human learning. Learners generate a personal understanding of a concept by actively linking new information with their prior knowledge to form a new view. Thus, a good pedagogue is one who can effectively help his or her students construct new knowledge.

Mrs. Spenser did not lecture to her students at first; she purposely engaged them in the learning process by giving them a chance to explore their understanding about plants, "food," and photosynthesis. She kept them engaged by challenging them to design experiments that could provide data to help them answer their many questions. Only after her students had a chance to explore answers concretely through active investigative science did Mrs. Spenser introduce standard terms and accepted definitions to her students. Then she had them read additional information in their texts and other sources. Soon they would be back in the lab, exploring their new ideas in a slightly different context. In this way, her students generate new knowledge about plants and photosynthesis and actively link that knowledge to their personal networks of already familiar ideas.

Changing Techniques to Meet New Needs

Mrs. Spenser's teaching differs substantially from the traditional approaches she utilized when she was first hired. Fortunately, several years ago, her department chair and principal encouraged her to examine her teaching approaches. One close, nonscience colleague provided moral support. The support of colleagues, coupled with her own frustration at having students claim they understood something, but failing to perform well on her tests, drove Mrs. Spenser to enroll in a series of inservice classes on curriculum design and student learning. During these classes, she embarked on a renewal of her ideas and practices about teaching. This led

A "Constructivist" Biology Classroom

Holding up a potted green plant, Mrs. Spenser asked her students, "How do plants get their food?" Initially, only a few students did not respond that "plants make their own food." Instead of remaining content with that answer, Mrs. Spenser pursued her students' understanding. Rather than lecture her class on the principles of photosynthesis, she asked questions to engage them in thinking about photosynthesis.

Yet as Mrs. Spenser asked additional, related questions, she learned that many more students had a vague understanding of the concept "food" and seemed less than certain that plants made their own food.

For example, while many students claimed that plants made food via "photosynthesis," they claimed that minerals and water were food, too, and that plants got that food from soil. One student even mentioned that he had heard his parents say just a week earlier they were going to "feed" their lawn with some fertilizer they had purchased. Many students seemed confused about what plant food was. Finally, a student volunteered that minerals and water just helped plants make food.

The session ended with Mrs. Spenser inviting her students to help her design an experiment to determine whether plants made their own food, and whether water, minerals, and fertilizer were food for plants or simply helped plants make food. As the students left the class, they were abuzz with ideas.

For several days, the students explored a series of experiments that they hoped would yield data to determine whether plants made their own food, with the help of water and nutrients in soil. Students worked in small, cooperative learning groups; there, they encouraged one another to carry out investigations to produce information that might tell them whether they were right or wrong.

One group set up two plants on a countertop near a window, one potted in soil with nutrients and one without soil, but with water. The group set two similarly arranged plants in a darkened cupboard below the countertop. Other groups arranged similar sets of plants.

Meanwhile, Mrs. Spenser prepared a data table from experiments conducted by other young investigators. She was getting ready to have a large group discussion in which students would report and discuss their interpretations of the data they had gathered. Only after that session would she provide students with some new vocabulary and information on plants—their nutrients, the role of sunlight, and an acceptable definition of the word "food." Then students would read some information in their texts and again perform some experiments in which they could apply their new knowledge.

That sequence of lessons, she had to admit, was a far cry from the traditional instruction she had practiced as a novice teacher. In those days, she generally began with a lecture, provided students with laboratory data that substantiated the concept under study, and gave the students a chance to confirm this new knowledge through a straightforward lab from a text series adopted by her school district. With the new method, she was learning alongside her students—gaining a clearer, more scientific view of photosynthesis herself, and gaining further insights into the teaching-learning process.

to her viewing curricula and pedagogy as closely linked and seeing that "instruction" was an important, yet small, component of pedagogy. She, as a teacher, needed to learn, alongside her students, in at least two areas.

1. She actively sought greater understanding of photosynthesis by reading the textbook and studying notes and books from her college days. Her teaching had, in fact, helped her realize that there were areas of this topic she did not understand.

2. Her interactive teaching approaches allowed her to gain a better understanding of how photosynhesis can be taught—what Lee Shulman (1987) has referred to as content pedagogical knowledge.

The Center's Teaching Model

The Center's teaching model for high school science mirrors the model the Center recommended in earlier reports for elementary (Bybee et al., 1989) and middle-level (Bybee et al., 1990) science. It is a model that the Center believes *all* secondary teachers can follow.

A Mirror of Science

The Center suggests that a teaching model should parallel the methods scientists and engineers use to uncover new knowledge and solve problems. In an active, constructivist classroom such as Mrs. Spenser's, the content of science and technology are taught side by side with the methods and attitudes associated with these endeavors, including questioning, skepticism, and wonder.

Science as a way of knowing and understanding (Moore, 1984) and technology as a way of adapting and solving problems (Harlen, 1985), as depicted in Figure 1 on the next page, are important themes for learning in the successful classroom, the Center maintains. By pursuing those themes, students can grow to appreciate that, while science and engineering are separate fields of endeavor with distinctly different approaches, the two are inextricably bound.[1]

At the high school level, adolescents can use their developing intellectual powers to begin to understand the rich relationships between science and technology, while simultaneously seeing how the two endeavors remain distinct. Students can see science and engineering as ways of asking questions, tinkering, searching for answers, confronting problems, evaluating possible explanations and solutions, weighing risks and benefits, and sharing discoveries—all the while refining their understanding of scientific and technologic concepts.

That learning and teaching should parallel the methods of science and technology is not a novel idea. Welch (1984) suggested that "the methods for learning science should be the same as the methods for doing science." He argued that the approach was a valid way of teaching not only conceptual knowledge, but also the skills and attitudes associated with science.

Gil-Perez and Carrascosa (1990), in answering the question of what to do about science misconceptions, point out the parallel "between the construction of meaning by learners and the work carried out by scientists." They also suggest that science learning must reflect the methodology of scientists. The approaches used by scientists and engineers in their work are consistent with the emerging constructivist view of learning; these approaches also help learners develop skills and habits of mind associated with science and technology.

Using the Model

Teachers can use the model the Center proposes, as depicted in Figure 2, to design daily lesson plans and weekly (or longer) unit plans. The model aims

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[1] For example, only about 30 percent of current scientific research can be labeled "pure" science, while more than two-thirds of recent Nobel Prizes in science and related fields have been given for technological, rather than purely scientific, advances (Hurd, 1989).

to ensure that science teaching and learning embody multiple approaches to learning, tantamount to the experiences of active scientists and engineers. Learners should ask questions, experiment, and communicate their new knowledge to colleagues. Students also should have the opportunity and responsibility to act on newly reformulated knowledge and to ask new questions. The model should suggest to teachers and students that science and technology are dynamic fields of study and human endeavor. Questions and problems lead to tentative explanations and solutions that, in turn, generate new questions and problems, as indicated by the varied paths depicted in Figure 2.

A Dynamic Model

The proposed teaching model is based on four phases, characteristic of the approach taken by practicing professionals in science and technology when they learn and apply new skills and information within their fields. The model is dynamic—like the processes of science and engineering. While single lessons or units of study may have a beginning (invitation) and an end (taking action), new skills or knowledge will inevitably lead to new invitations, thereby continuing the cycle. Thus, while the model appears to be sequential, it actually can be non-linear. The phases of this model can be considered in parallel or in series.

At each phase of the model, parallel activities in science and technology are suggested, as indicated in Figure 2. For example, at the invitation stage, when considering an example from science, students would observe and ask questions about the natural world and form hypotheses about why natural phenomena occur the way they do. When considering an example from technology, they would observe the human-made world, recognize a human-made problem, and identify possible solutions.

FIGURE 1

The Relationships between Science and Technology, and their Connection to Educational Goals

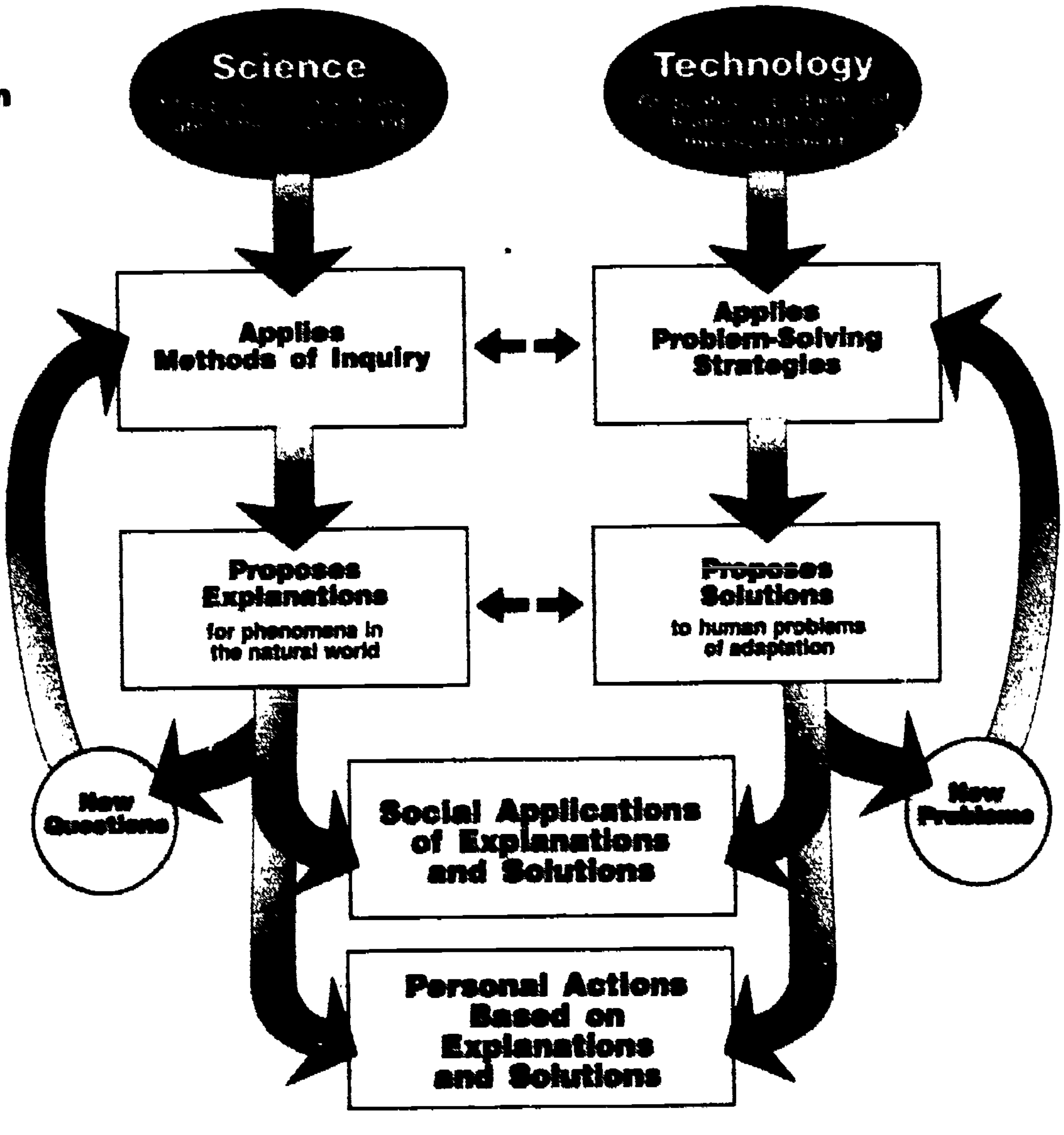

FIGURE 2

The Teaching Model

Examples for Science	Stages	Examples for Technology
Observe the natural world Ask questions about the natural world State possible hypothesis	***Invitation***	Observe the world made by humans Recognize a human problem Identify possible solutions
Engage in focused play Look for information Observe specific phenomena Collect and organize data Select appropriate resources Design and conduct experiments Engage in debate Define parameters of an investigation	***Exploration, Discovery, Creativity***	Brainstorm possible alternatives Experiment with materials Design a model Employ problem-solving strategies Discuss solutions with others Evaluate choices Identify risks and consequences Analyze data
Communicate information and ideas Construct a new explanation Evaluation by peers Determine appropriate closure	***Proposing Explanations and Solutions***	Construct and explain a model Constructively review a solution Express multiple answers/solutions Integrate a solution with existing knowledge and experiences
Apply knowledge and skills Share information and ideas Ask new questions	***Taking Action***	Make decisions Transfer knowledge and skills Develop products and promote ideas

Under the model, the instructor becomes an active participant in the learning process. The model provides a guideline for the teacher's learning, as well as the students' learning, because many high school teachers have received little formal training in the processes of science and technology.

In fact, the Center considers the model to be universal in describing any learning in science and technology, including learning by professional scientists and engineers, teachers, and students. The model can be applied in classrooms and laboratories alike, as well as in less formal settings, such as the home, parks, museums, nature centers—literally any place where an invitation to learning may be recognized and accepted.

Teaching Model Phase 1: Invitation

The beginning of any learning process in science and technology is characterized by an invitation. The invitation originates with a question about the natural world (science) or a problem in human adaptation (technology). An invitation may be quite spontaneous, such as a student discovering an empty eggshell in the park. Or the invitation may come from a teacher's demonstration of an event that fails to conform to students' familiar views, and so provokes questions. In both cases, questions emerge immediately. The students and the teachers observe events together; the stage is set for investigation.

It is important to remember that invitations must engage the learner. Thus, the learner must understand the event, question, or problem well enough to begin thinking actively about it. If the question or problem is not one that students are curious about, one they initiated, or one they want to address or solve, then it will be difficult to engage students further. Little more than rote learning is likely (Hawkins, 1983).

In the case of Mrs. Spenser, the class was challenged with the question, "How do plants get their food?" As her class demonstrated, such a seemingly simple invitation can lead students to search for additional information as they struggle to find answers to questions and issues that seem to be simple, but that actually are complex.

With an invitation grounded in technology (such as "How can we conserve water?"), students begin by putting the question into a context, clarifying the question (What are the goals and constraints?), and considering knowledge that they currently possess.

Figure 2 lists suggested activities that characterize this beginning stage of the model. At the elementary school level, teachers and students frequently focus on this stage. However, with high school students, who are developing abilities to think formally, it is important to spend ample time on the next three stages of the model.

Teaching Model Phase 2: Exploration, discovery, and creativity

This stage of the model builds upon and expands the learning initiated by an invitation. At this point, it is critical that adolescents have access to materials to further their engagement and spur their inquiry. They also need ample opportunities to observe, collect data, begin organizing information, and think of experiments to test their possible explanations and solutions.

This phase is characterized by a strong element of informal investigation. Students try one approach with various materials, share their findings with one another, and then try other approaches. If they are tackling a technological problem, students might explore the suitability of various materials and tools and seek additional resources. They employ verbal, as well as graphic, designs and begin to weigh alternatives as they construct a variety of prototypical solutions. If they are focusing on scientific concepts, they may use analogies or visual imagery to help them think about the new concepts that they are encountering. They begin to explore how new information gained from their investigations relates to their previous experiences and their current level of understanding.

In this process, teachers are co-learners and facilitators who use their pedagogical content knowledge to choose materials and activities that are likely to lead students to new discoveries and information. Teachers observe along with students and ask questions with them. Teachers can encourage many of the responses—such as enthusiasm, curiosity, skepticism, and the temporary suspension of judgement—that characterize scientists and engineers during active investigations. Teachers also can informally assess adolescents' developing understanding of a concept or formulation of a solution and pose questions that motivate them to continue their investigations and to link new findings to their current understandings.

Figure 2 lists possible activities for this phase. At this stage, students' active reconstruction of knowledge frameworks should be well underway. Teachers continue to monitor this reconstruction, eventually making a judgement that the students can embark on the next phase of the instructional model.

Teaching Model Phase 3: Proposing explanations and solutions

In this phase, learners continue to refine their developing understanding of a concept and/or of a solution to a problem. They integrate their current conception with new information, which they have gained through their explorations and discoveries and through the appropriate use of textbooks, other materials, and information provided by the teacher. Then they analyze data that they had begun to organize during the preceding stage and consider alternative interpretations prepared by classmates and the teacher. Ultimately, students develop a new understanding of a concept.

If students are engaged in problem-solving, they implement a possible solution—the design that emerged as most workable among several that they explored during the earlier phases. Students test whether the original design answers the initial invitation. They check whether the test of the design is fair and whether the results are reasonable. The students may consult additional sources of information—such as teachers, engineers, and texts—to determine whether they can improve their design.

Cooperative learning can be an important part of the teaching approach we describe. By sharing information and actively listening to one another's proposed explanations and solutions, teachers and students can jointly develop new explanations or solutions. Cooperative learning or some similar small-group interactive learning activity keeps the students engaged in developing new understandings while allowing for individual, idiosyncratic understandings to emerge. Students, guided by the teacher, may decide to perform additional investigations or investigate modifications of an early prototype. The results of these experiments help resolve conflicts that students are experiencing between their previous understanding of a concept or solution and their newly emerging view.

Each learner, with the teacher's assistance, brings new meaning to a concept or solution. Such cooperation between students and the teacher is an opportunity for the teacher to foster qualities that characterize scientists and engineers: proposing and accepting alternative points of view; listening and questioning; persistently seeking solutions; weighing alternatives; and working together cooperatively. Figure 2 lists activities that characterize this stage of the model.

Cooperative learning can be an important part of the teaching approach. By sharing information and actively listening to one another's proposed explanations and solutions, teachers and students can jointly develop new explanations or solutions.

Teaching Model Phase 4: Taking action

To cement their emerging understanding of a scientific concept or the viability of a solution to a problem, students take action. Figure 2 lists possible ways they can take action and demonstrate that they have truly integrated their newly discovered information and proposed solutions into their existing framework of understanding. Students might defend a point of view before the class or write a letter to a local authority, thus learning what it means to conceptualize a point of view. Their new level of understanding may, and frequently does, lead to new questions that provide the foundation for new explorations and refinements of conceptual understandings or solutions. The teacher's role is to encourage students to take action and to help students transfer their new knowledge to other fields of study.

Evaluation is an integral part of taking action. Students themselves can assess their developing levels of understanding. For example, they can reflect on solutions they have designed. Their review and critique of both the process used and the product produced may lead students to continue their investigations. Teachers also can assess—informally and formally—each student's new level of understanding and gauge the effectiveness of the science program. This helps teachers plan future activities appropriate for students.

The teaching model the Center proposes is intended to serve as a framework for teachers and curriculum developers to use as they plan instruction and organize the curriculum. We believe the model can be used to teach science and technology together or separately. In addition, the model encourages students to seek a deeper understanding of scientific concepts in a technological context. Figure 3 on pages 68-69 is designed to help teachers and other educators better see how phases of the model appear in practice and how constructivist teaching differs from traditional teaching.

A Compatible Teaching Model

The Center's teaching model guides teachers as they construct their instructional programs; it parallels the model of science and technology provided in Figure 1. The teaching model's phases are presented sequentially to ease interpretation of the model. However, practicing scientist and engineers rarely, if ever, follow a step-by-step learning model, given the complex nature of scientific investigations and technologic problem-solving.

The Center's teaching model is compatible with several other models of learning and teaching briefly described below.

The Generative Learning model (GLM). The GLM model proposed by Osbourne and Wittrock (1983) and summarized by Kyle and colleagues (1989) has four steps that closely parallel the Center's proposed model of learning and teaching:

- In the preliminary step, before beginning any formalized instruction, teachers assess students' ideas and conceptual explanations;
- In the focus step, the instructor provides experiences related to the particular concept that motivate the students to explore their level of conceptual understanding;
- Next, the teacher helps students exchange points of view and challenges students to compare and contrast their ideas and support their viewpoints with evidence (the challenge stage); and
- In the application stage, students use their newly refined conceptual understandings in familiar contexts.

The Riverina-Murray model. The Riverina-Murray Institute of Higher Education (Boylan, 1988) presents a five-stage model of learning and teaching that learners must pass through as they develop a new level of conceptual understanding. The stages are:

1. The teacher identifies and establishes the learner's naive ideas about a selected concept;
2. Based on that information, the teacher selects events, situations and activities for the learner to explore;
3. The exploratory phase provides a practical base upon which the learner begins to develop a new understanding. The learner is encouraged to make the concept explicit and also is introduced to new language and symbols;
4. The learner organizes the new idea and establishes links with relevant prior knowledge; a new mental scheme emerges; and
5. The learner practices and applies the new idea in novel situations to consolidate the newly developed understanding.

The Hewson-Hewson model. The Hewsons, after reviewing studies on science learning, summarize "key points in instructional strategies which help students overcome their naive, inappropriate conceptions" (Hewson and Hewson, 1988:607). Teachers must:

- Diagnose students' thoughts on the topic at hand;
- Provide an opportunity for students to clarify their own thoughts;
- Directly contrast students' views and the desired view through teacher presentation or class discussion;
- Immediately provide an opportunity for students to use the desired view to explain a phenomenon; and
- Provide an immediate opportunity for students to apply their newly acquired understanding in novel situations.

The Lawson-Abraham model. Anton Lawson (1988), Michael Abraham (1989), and colleagues (Lawson, Abraham, and Renner, 1989; Renner, 1986) long have advocated a three-step learning cycle. This is based on a three-step cycle first proposed by Atkin and Karplus (1962), who later used it in the innovative elementary science program, the Science Curriculum Improvement Study (SCIS). Derived from Jean Piaget's developmental theory, the learning cycle approach first uses a laboratory experiment to expose students to the concept to be developed. Abraham calls this the exploration or gathering data phase. Next, the students and/or teacher derive the concept from the data, usually a classroom discussion (the conceptual invention phase). The final phase, expansion, gives the student the opportunity to explore the usefulness and application of the developing concept. Lawson (1988) and others prefer to call the second phase "term or concept introduction" because they recognize that, while teachers can give students new terminology, ultimately the student must actively invent or generate the concept.[2]

Driver-Oldham model. Driver and Oldham (1986) describe a constructivist teaching sequence used in the Children's Learning-in-Science Project. They suggest that it be viewed as a flexible outline because the demands of different conceptual areas and the time available for learning and teaching will vary.

- In the orientation phase, students are motivated to learn the topic.
- In the elicitation phase, students make their ideas explicit through discussions, creation of posters, or writing.
- In the restructuring phase, teacher and students clarify and exchange views through discussion; promote conceptual conflict through demonstrations; exchange ideas; and evaluate alternative ideas.
- In the application phase, students use their new ideas in familiar and novel settings.
- The review phase allows students to reflect on how their ideas have changed.

The model incorporates several aspects of technological problem-solving and decision-making, notably evaluation of alternative ideas and reflection at the end of the learning sequence.

Stages in Understanding Science and Technology

Students—and teachers—build a lasting understanding of science and technology through several interrelated steps, educators and researchers increasingly agree.

Starting Point. A good starting point is a problem (for example, how to lower auto emissions) posed by the teacher or generated by students, Dunn and Larsen (1990) propose. Students must initially clarify the problem, ask additional questions, begin to gather information, and brainstorm about possible solutions.

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[2] Lawson has recently proposed that there are three kinds of learning cycles: descriptive, empirical-deductive, and hypothetical deductive. The sequence of learning-teaching events is essentially the same in each.

FIGURE 3

What The Teacher Does

Stage	**Consistent with the Model**	**Inconsistent with the Model**
Invitation	■ Creates interest ■ Generages curiosity ■ Raises questions ■ Elicits responses that uncover what the students know or think about the concept/topic	■ Explains concepts ■ Provides definitions and answers ■ States conclusions ■ Provides closure ■ Lectures
Exploration, Discovery, Creativity	■ Encourages the students to work together without direct instruction from the teacher ■ Observes and listens to the students as they interact ■ Asks probing questions to redirect students' investigations, when necessary ■ Provides time for students to puzzle through problems ■ Acts as a consultant to students	■ Provides answers ■ Tells or explains how to work through the problem ■ Provides closure ■ Tells the students that they are wrong ■ Gives information or facts that solve the problem ■ Leads students step-by-step to a solution
Proposing Explanations and Solutions	■ Encourages students to explain concepts and definitions in their their own words ■ Asks for justification (evidence) and clarification from students ■ Formally provides definitions, explanations, and new labels ■ Uses students' previous experience as the basis for explaining concepts	■ Accepts explanations that have no justification ■ Neglects to solicit students' explanations ■ Introduces unrelated concepts or skills
Taking Action	■ Expects students to use formal labels definitions, and explanations provided previously ■ Encourages students to apply or extend concepts and skills in new situations ■ Reminds students of alternative explanations ■ Refers students to existing data and evidence and asks: "What do you already know? Why do you think...?" (Strategies from the previous stage apply here also.) ■ Looks for evidence that the students have changed their thinking or behavior ■ Asks open-minded questions, such as "Why do you think...? What evidence do you have? What do you think about x? How would you explain x?"	■ Provides definitive answers ■ Tells students that they are wrong ■ Lectures ■ Leads students step-by-step to a solution ■ Explains how to work through the problem

FIGURE 3

What The Student Does

Stage	**Consistent with the Model**	**Inconsistent with the Model**
Invitation	■ Asks questions such as "Why did this happen? What do I already know about this? ■ Shows interest in the topic	■ Asks for the "right" answer ■ Offers the "right" answer ■ Insists on answers or explanations ■ Seeks one solution
Explanation Discovery Creativity	■ Thinks freely, but within the limits of the activity ■ Tests new predictions and hypotheses ■ Forms new predictions and hypotheses ■ Tries alternatives and discusses them with others ■ Records observations and ideas ■ Suspends judgement	■ Lets others do the thinking and exploring ■ Works quietly with little or no interaction with others (only appropriate when exploring ideas or feelings) ■ "Plays around" indiscriminately with no goal in mind ■ Stops with one solution
Proposing Explanations and Solutions	■ Explains possible solutions or answers to others ■ Listens critically to others' explanations ■ Questions others' explanations ■ Listens to and tries to comprehend explanations offered by the teacher ■ Refers to previous activities ■ Uses recorded observations in explanations	■ Proposes explanations from "thin air" with no relationship to previous experiences ■ Brings up irrelevant experiences and examples ■ Accepts explanations without justification ■ Does not attend to other plausible explanations
Taking Action	■ Applies new labels, definitions, explanations, skills in new, but similar, situations ■ Uses previous information to ask questions, propose solutions, make decisions, design experiments ■ Draws resonable conclusions from evidence ■ Records observations and explanations ■ Checks for understanding among peers ■ Demonstrates an understanding or knowledge of the concept or skill ■ Asks related questions that encourage future investigations	■ "Plays around" with no goal in mind ■ Ignores previous information or evidence ■ Draws conclusions from "thin air" ■ Uses in discussions only those labels provided by the teacher

Step Two. The learning process continues as students construct prototypical solutions (such as a product or service). Eventually, students select one and implement it.

Step Three. Then students reflect on the viability of the product or service they created. Such reflection may well lead them to further question and refine their initial prototype; then the cycle begins anew.

A similar problem-solving model was employed in an interdisciplinary course within a university engineering department (Rubenstein, 1975). It has four stages:

- **Preparation.** Students go over elements of the problem, looking for relationships;
- **Incubation.** Students think about and sleep on the problem;
- **Inspiration.** The solution appears; and
- **Verification.** Students check the solution against the desired goal.

The four stages could take place in parallel, rather than in serial, stages, Rubenstein observed. The model reflects the experience of scientists who have solved difficult problems by inspiration, such as Descartes' discovery of Cartesian coordinates as the link between algebra and geometry, Rubenstein argued.

Bransford and Stein (1984) cited such diverse problems as resolving the Cuban missile crisis and finding a cure for polio as examples of how our lives are affected by our predecessors' problem-solving abilities. They have proposed a five-step problem-solving model that they have given the acronym "IDEAL:"

- **I**dentify potential problems;
- **D**efine and represent the problem;
- **E**xplore possible strategies to yield solutions;
- **A**ct on those strategies;
- **L**ook back and evaluate the results.

The Biological Sciences Curriculum Study (1985) (see also Bybee and Landes, 1988) employs a similar decision-making model in its elementary and middle-level science, health, and technology curricula. The model serves as the basis for teaching students how to make sound decisions. It has five steps:

- Identify the problem;
- Describe what is known;
- Explore alternatives;
- Arrive at a decision; and
- Solve the problem.

Striking parallels exist between the constructivist models of learning and the models of design, problem-solving, and decision-making used in engineering and technology. Science and engineering alike require students to actively join new information and concepts with their existing conceptual frameworks. Moreover, both scientific and engineering models recognize that teaching is more than telling and that learning is more than listening. Students, as well as scientific investigators and technologists, question, probe, follow "hunches," explore their own understanding, and communicate their new knowledge to colleagues.

Although the models just reviewed appear highly sequential, in practice they have both linear and non-linear dimensions. Above all, the models are composed of phases or stages, not simple steps. Conversely, traditional "problem doing" and "exercises" are more linear in structure; learners follow an algorithm in finding a solution to a problem for which a solution already exists (e.g., balance the following chemical equation...).

Conceptual Change, Skills, and Habits of Mind

The Center's proposed teaching model draws on and is consistent with the models just reviewed. These models focus on conceptual change: bringing about a new understanding of science and technological concepts in students. But educators might question whether the Center's model can help students to learn the thinking and performance skills of science and technology and the habits of mind generally associated with science and engineering. In the Center's view, this is not only possible but the model also provides an important way for students to see that concepts, skills, and habits of mind naturally intertwine.

When Welch (1984) proposed that the activities of the classroom should be patterned after the endeavors of scientists, he argued persuasively that such an approach would enable students to practice and learn all aspects of science: conceptual knowledge; skills, such as observing, experimenting, analyzing and synthesizing; beliefs about nature, methods, and knowledge; and personality traits, such as curiosity, creativity and commitment. Welch believed that by taking a scientifically-based approach, teachers could help students become effective pursuers of knowledge.

Recently, Black (1987) presented a rationale for basing the school science curriculum on frameworks for science and technology. The two frameworks are instructive, because each asserts that content can not be separated from process. In the science education framework, Black proposes that investigators and students cannot learn about processes *or* concepts in isolation because "it is the dialogue between concepts and processes that is fruitful—in learning and in being a scientist" (p. 15). Through science investigations, by finding out why, and proposing and testing models, students attain full scientific capability. Similarly, in the technology framework, Black argues for the inseparability of content and processes—in this case, technological concepts and skills for construction and design. Through technological tasks—identifying a need and constructing an optimum solution —students attain full technological capability.

The Center is convinced that its model of learning and teaching accommodates the ideas presented by science educators and cognitive scientists during the last two decades. The Center's model proposes that students must be active learners; can engage in scientific and technological inquiry and problem-solving; and must learn science and technological concepts, processes, and habits of mind together, rather than separately.

Implications for the Classroom

What changes does the teaching model imply for teachers and students? In large measure, teachers of science and technology must acquire confidence in their skills of facilitation. Too often, instructors see their role as lecturers, as one-way communicators of ideas. Within the Center's teaching model, teachers function more as facilitators in which they ask provocative questions, provide open-ended experiences, monitor student progress, challenge assumptions, encourage alternative solutions and explanations, and provide a psychologically safe classroom environment for sharing of viewpoints without fear of ridicule. Nonetheless, the Center believes that there is a time and place for teachers to share with students new information and knowledge.

In this section, we explore what changes the model implies in the current use of textbooks and lectures and ways that teaching and learning styles can be incorporated into classrooms using the Center's model as a framework.

Use of Textbooks and Lectures

It is not an overstatement to say that the science textbook is *the* organizing framework for the vast majority of high school science courses. Moreover, reading the textbook is the dominant method of instruction in secondary schools. More than 90 percent of science teachers use published textbooks (Weiss, 1978, 1987). Science instruction tends to be dominated by students listening to teacher lectures and reading the textbook (Weiss, 1987; Mullis and Jenkins, 1988).

Thus, any consideration of reforming science education at the secondary level must examine the role of the textbook and lectures in instruction. As Bransford and Vye (1989) point out, relevant declarative knowledge—information communicated through texts, lectures, and similar sources —frequently remains unused by students. How, then, can teachers help students come to new understandings? That task requires resolving a dilemma.

A majority (76 percent) of science teachers *do not* consider textbook quality to be a significant problem, according to a recent study (Weiss, 1987). Many science educators, however, *do* view textbook quality and usability as problems (American Association for the Advancement of Science, 1985; Carter, 1987; McInerney, 1986; Moyer and Mayer, 1985; Rosenthal, 1984).

In a national survey of science education, Weiss (1987) asked science teachers several specific questions about the quality of science textbooks. A majority of science teachers rated the following items favorably:

- Appropriate reading level (87 percent);
- Interesting to students (52 percent);
- Well organized (85 percent);
- Develop problem-solving skills (61 percent);
- Explain concepts clearly (74 percent); and
- Suggest good activities and assignments (74 percent).

The problem is clear. Science teachers use textbooks extensively; they perceive the quality of their textbooks as adequate. Yet scientists and science educators evaluate textbooks as inadequate.

Unfortunately, the solution is not clear. Many states develop textbook adoption lists and provide guidelines for acceptable materials. California and several other states have provided leadership by revising their guidelines. However, the issues of teacher selection of and satisfaction with textbooks remains. At the secondary level, these issues are complex because most textbooks used for secondary science programs follow on a discipline-based approach.

The Center's recommended policies are intended to remedy the current situation. The textbook problem is quite complex and requires a systemic solution. The Center suggests that educators start the process by considering how textbooks and lectures can be used in the constructivist classroom.

Problems with textbooks. Textbooks have produced mediocre learning from students, even though publishers have attempted to present scientific information in innovative ways. In an attempt to increase students' comprehension of textbook information, publishers have improved the sequential nature of the text material; provided vocabulary lists at the beginning of each section emphasized new vocabulary through the use of bold type; and provided study questions at the end of sections. Unfortunately, students have responded by learning the new information by rote. When answering a question, for example, many students focus only on the appropriate key word in the question, search for that word in the text, and then copy the sentences that contain the word. Moreover, textbooks currently in use rarely encourage students to interpret new information in light of their prior knowledge.

Students, therefore, do not improve their conceptual understandings: "Merely reading new information in textbooks does not necessarily lead to effective learning because the new information does not replace previous misconceptions" (Bransford and Vye, 1989:193-194). When students encounter a novel situation, their problem-solving is more often driven by their misconceptions than by new information or by newly generated understanding.

Roth's (1985) research found that the weakness in the traditional textbook approach may lie in how students read textbooks. She found that students employed one of five strategies:

- Avoiding thinking about the text, while reading and relying on previous knowledge to answer problems related to the text;
- Relying on key words in the text to answer questions;

- Memorizing facts, but not relating this new information to real-life experiences and knowledge;
- Relying strongly on prior knowledge to make sense of the text reading and ignoring text information that does not match prior knowledge; and/or
- Changing one's prior knowledge to match the text's information.

Roth found that students using the last strategy frequently felt confused and recognized the conflict between knowledge presented in the text and prior knowledge. These students, however, made the greatest conceptual change, compared to those using the first four strategies.

The design of textbooks is also part of the problem. The table of contents of most precollege texts reads like a four-year college course catalogue. Texts try to cover too many topics, instead of integrating fewer topics. New vocabulary often exceeds that in a foreign language course (Eylon and Linn, 1988).

Improving textbooks. Recently, a national conference on improving textbooks (Education Development Center, 1987) recommended that textbooks:

- Get students ready to learn new information;
- Actively engage students in integrating and organizing new information and old information; and
- Accommodate students' diversity and tap their strengths and interests when helping them extend new knowledge.

These recommendations are consistent with the constructivist view of learning and with the Center's teaching model.

The Center also is convinced that teachers need to use textbooks differently than they do now. Students need time and frequent opportunities to read, discuss new words and ideas with peers, and relate that information to what they currently know. Students can profit from readings after they have first explored a topic. Teachers also can use texts to help students link new information to students' existing knowledge. Teachers and textbooks will have to "abandon their common practice of 'covering' a great deal of material by treating it briefly with few connections among the information" (Resnick and Klopfer, 1989:207).

Using, Preparing, and Delivering Information

How teachers perform tasks also must change. An important component of constructivism is the active involvement of learners as they construct their own interpretations of knowledge. Tobin (1988:12) and Von Glaserfeld hold that, for the constructivist "language is not a means of transporting conceptual structures from teacher to student, but rather a means of interacting that allows the teacher...to constrain and thus guide the cognitive construction of students."

Resnick points out that "comprehension takes place when the speaker and the listener construct a common space of representation." A teacher can be sure that no student will receive the information presented in a lecture precisely as it was transmitted. Most students will get some portion of the information; a few will receive a garbled message; a few will go beyond the information the teacher delivered. As Resnick concludes, "It is not enough just to focus on making an excellent presentation" (cited in Brandt, 1988:15). Rather, it is important to find ways to instruct that do not merely impart knowledge, but help students construct new interpretations. A clear lecture can be the basis for learning—provided that students have time to reflect on the new information and link it to their existing knowledge and to problems they are solving (Driver and Oldham, 1986).

Teachers can use silence effectively to increase student reflection. Rowe's (1983) research on waiting time substantiates the importance of pausing about three to five seconds after asking questions and after student responses. This permits students to begin integrating new information into their existing knowledge. Tobin (1988) found that teachers using longer periods of silence effectively improved elementary and middle-school students' achievement when compared to teachers who used half-second waiting times. Rowe (1983) also found that learning increased when high school teachers provided about two minutes per each ten minute-block of class time for reflection and discussion. Clearly, providing students with ample time to think about and interpret new information improves the effectiveness of lectures.

Including ample wait-time in one's teaching begins to encourage students to link new information with their existing knowledge. Giving students ample opportunities to discuss and to write about their new understanding engages them further and enables them to make sense of the new information and enhances their developing understanding of major scientific and technologic ideas. The Center agrees with Hawkins, who summarizes the case for instruction through lectures and textbooks:

> *Past experience must indeed be somehow summarized. [It] cannot be relived in its totality. [To] relive all past errors and discoveries...would be a commitment to absurdity. A part—indeed a major part—of the structuring of our minds must come from instruction. But...instruction by a teacher fails without a matching construction by the learner, induction without spontaneity, words without things. The lecture or the textbook passage that succeeds is one that meets an apperception well prepared. When we merely surrender to the textbooks, we surrender to defeat (Hawkins, 1983:73).*

Learning Styles and Teaching Styles

Some students blurt out responses to questions before teachers finish asking them. Others reflect on possible answers for several seconds or more. Some students learn effectively from lectures and readings, while others benefit from concrete and visual approaches. All these behaviors reflect what researchers call *learning styles:* the ways individuals perceive, interact with, and respond to the learning environment.

The concept of learning styles dates at least to Hippocrates, who identified four personality types. During the past decade or so, educational researchers have refined knowledge about learning styles, but these concepts are still evolving. Some researchers suggest that educators must become more knowledgeable of their personal styles in order to understand how they teach and how their students may learn. Some suggest that the concept of learning styles should be applied to curriculum design and instructional approaches. Others urge educators to take a prescriptive approach where teachers are called upon to match teaching approaches to individual style differences.

Adolescent learning styles. Adolescents exhibit a wide variety of learning styles. Entwhistle (1981) has provided an extensive review of student learning as it is influenced by style and describes learners who are "deep processors," "surface processors," or a combination. Another model describes learners as either field-independent or field-dependent—whether they concentrate on the details or see the big picture. Research suggests that there is a strong correlation between a student's degree of field independence and performance on Piagetian formal thinking tasks. Helgeson (1989) suggests, therefore, that inquiry and discovery methods that encourage initiative and autonomy may foster field independence and subsequently intellectual development.

All students display another aspect of learning style—**learning modes.** These can be tactile, visual, or auditory. Teachers can present new science information through several modes; most use a verbal mode through lectures and text readings. Research suggests, however, that "whenever students were taught through resources or approaches that complemented their modalities, they achieved significantly higher test scores" (Dunn and Dunn, 1987:59).

Implications for Teaching a Diverse Student Body

The findings have important implications for a student population that is becoming increasingly diverse. Evidence is growing to support Anderson's (1988) conclusion that different cultures produce different learning styles. Evidence exists to suggest that at-risk students learn better through direct experiences, cooperative activities, and high levels of interaction (Slavin, 1987). Yet, as Anderson points out, the curricula and instruction in most schools reflects the Euro-American analytical, detached, non-affective, field- independent style of teaching and learning.

Such approaches do not work well for many students, particularly minority students, who are more likely to exhibit a field-dependent style of learning. Recently, Bell and McGraw-Burrell (1988) reported that low-achieving black children have culturally specific learning styles that make it difficult for them to succeed in schools dominated by monotonous and repetitive tasks, as opposed to varied ones. Cole and Griffin (1987) reported several studies involving native Americans, native Hawaiians, blacks in the Southeast, and Hispanic children in the Southwest. These studies all lend credence to Anderson's conclusion. More importantly, these studies suggest ways in which "reorganization of lesson formats to make them sensitive to linguistic and cultural variations can promote educational excellence" (Cole and Griffin, 1987:35).

Research on learning styles begins to "point the way to making instruction more responsive to youngsters who do not learn and retain information in ways that conventional education provides" (Dunn and Dunn, 1987:55). Our increasing knowledge of student learning styles suggests that teachers must adopt a variety of parallel teaching styles. Research clearly suggests that multi-modal approaches—through which learners engage in auditory, visual, and kinesthetic activities—help learners gain greater understanding of concepts. The constructivist learning model can be used to suggest different modes of active teaching (and learning) that might be effective.

The Integrated Curriculum

The Center recommends using a core, or integrated, curriculum in the first two years of high school, rather than one based on separate disciplines. The need to integrate the curriculum hinges on at least four factors, Jacobs (1989) argues:

1. Knowledge is growing exponentially, while the length of the school day has remained largely unchanged since the turn of the century;
2. Subjects suffer when they are crammed into a series of 45-minute blocks;
3. Twenty-five to forty percent of U.S students drop out of school each year, prompting questions about the current organization of the curriculum; and
4. An integrated curriculum more closely resembles the workplace where youngsters will soon find themselves. There, workers will confront problems best solved by using knowledge gained from several disciplines and problem-solving strategies that cross traditional discipline boundaries.

Teaching Methods

High school educators have a range of options as they consider the issue of integrated curricula. Curriculum developers can select planning models that range from orientation along strict departmental lines to a fully integrated approach that treats disciplines in parallel or clusters them. Alternatively, interdisciplinary units or programs can be used.

Parallel method. In the parallel teaching approach, two or more instructors examine the scope and sequences of their courses to see when subtopics could overlap or interrelate. By carefully sequencing instruction in each subject, the content that students learn in each class becomes mutually reinforcing. For example, a physical education teacher might plan to focus on respiratory (fitness) activities at the same time that the classroom biology teacher would focus on the cardiovascular system. The only change in teaching that is required is timing what is already taught.

Clustered method. Alternatively, similar disciplines can be clustered so that teachers can work together from time to time on specific projects. For example, when each teacher at the same grade level has expertise in a certain topic, such as ecosystems, the teachers could work together to explore the mathematical, social, and scientific aspects of that topic.

Unit method. A third approach is to design a complete curriculum unit, such as one on "evidence and argument," that includes contributions from several disciplines. Frequently, this approach stimulates new ways of looking at knowledge.

Interdisciplinary method. Finally, a full-scale interdisciplinary program can be developed. For example, at a given grade level, several disciplines could be integrated. Students could spend one or more hours each day for an entire year focusing on a central theme, such as the Arctic (Holmes, 1988).

The Center urges secondary level educators to consider which scenario seems best suited for their school, their students, and their instructional program. Many secondary schools can manage interdisciplinary units. But *how* does a team of teachers drawn from several disciplines, including science, design an interdisciplinary unit? Jacobs (1989) suggests a four-step process. First, the design team selects a topical theme around which they can design the unit. A conceptually rich topic should be chosen, such as light, world hunger, pioneers, or change. Next, the team brainstorms to find associations of disciplines that illustrate the chosen theme. Third, the team establishes questions that will serve as a framework to guide the scope and sequence of lessons. As Jacobs notes, the questions can cross disciplinary boundaries; they can serve as organizers, like chapter headings in a textbook. Fourth, the team generates teaching-learning activities.

Criteria for units. The Center suggests using the following criteria to select appropriate themes or topics for units of study:

- They build upon students' prior experiences and knowledge;
- They capture students' interest;
- They lend themselves to interdisciplinary study so that students can see that reading, writing, mathematics, and non-science disciplines are part of science and technology;
- They are vehicles for teaching major conceptual themes in science and technology, as well as scientific and technological attitudes and skills; and
- They allow a balance of scientific and technological activities.

The Center also suggests that science educators examine the criteria set forth by Jacobs (1989). A theme deserves selection when:

- It has validity within each discipline under consideration because it applies broadly and pervasively within each discipline;
- It has validity across the disciplines because it points out similarities and contrasts across the disciplines so that a concept, such as "evidence," is better understood than if approached through one discipline only; and/or
- It has validity beyond the disciplines, so that the whole is greater than the sum of its parts. A theme, such as pollution, gains validity because the design team has reason to believe that the science content will be better

understood when the students see it interrelated to technical, moral, and political issues.

Learning from the past. The Center is convinced that secondary level educators should learn from past efforts to integrate curricula. Many efforts failed, or encountered resistance. According to Jacobs (1989), two problems characterized these efforts. Many units merely sampled content from different disciplines, did not follow a carefully constructed scope and sequence, and did not aim for depth of understanding. In other instances, design teams failed to recognize that both discipline-based and interdisciplinary experiences are required. The two are not mutually exclusive.

Cognitive Development and Concept Learning

The Center's teaching model focuses on helping *all* learners improve their ability to grasp concepts and conceptualize. Many researchers have investigated how students learn various concepts. Their findings emphasize the value of covering topics in depth because it helps students to understand science coherently (Eylon and Linn, 1988).

Do students' levels of intellectual development affect their ability to develop in-depth understanding of science concepts? Lawson's (1985) review of research on formal reasoning and science learning strongly suggests that variations in cognitive development relate significantly to variations in science achievement. Much of the work on how learners develop concepts has been inspired by Piagetian theory. Research based on this theory used age to explain similarities in student performance. Neo-Piagetian research, however, cautions that some learners retain a concrete perspective on scientific phenomena throughout their lives; on the other hand, some quite young students reason abstractly. Much research has indicated that scientific reasoning is domain-specific and closely related to working memory. Recently, research has confirmed Piaget's important realization that students must reflect on their ideas to improve their scientific understanding.

Driver and Easley (1978) suggest that developmental studies are valuable because they can raise awareness of the possible perspectives pupils may bring to class and the difficulties they may have in learning science concepts. Researchers also have investigated whether curricula engage students at the higher intellectual levels (Mitman et al., 1984; Tobin and Gallagher, 1987a). In order to do so, the classroom must be managed effectively to ensure ample on-task behavior (Gallagher and Tobin, 1987). One way of effectively managing activities that demand higher-level thinking is to plan more small group activities and to structure the inquiry so it is more directed (Tobin et al., 1988; Germann, 1989). These steps are helpful in mentally engaging the students so that conceptual change is more likely.

The Classroom as a Science Learning Community

The Center's teaching model is best accomplished in classrooms that are learning communities. There, teachers can create a social environment in which sense-making is highly valued (Anderson, 1987).

For learning to occur, it is imperative that teachers establish a classroom climate where science becomes coherent and sensible. When it is not, students have the right, and responsibility, to ask questions and argue points of view. Even giving correct answers is insufficient; the reasoning behind the answer must be uncovered.

Elements of a Well-Functioning Community

Taking another look at Mrs. Spenser's classroom is a way to identify the elements of a well-functioning community of science learners. These include:

1. Dialogue and writing. These provide critical means of uncovering misunderstandings, reflecting upon new knowledge, and integrating new concepts. Mrs. Spenser used dialogue and writing in various ways. Students employed journal writing and dialogue as they studied photosynthesis. Early on, Mrs. Spenser employed Socratic dialogue to bring into focus various correct and incorrect views. This phase set the stage for students to make sense of data from a variety of sources, including their experiments, information gleaned from their text, a video on photosynthesis, and a software package describing the basics of photosynthesis.

The students wrote almost nightly, sometimes responding to specific study guide questions in their text. Mrs. Spenser knew from experience that this text would trigger students to begin to integrate new information with their older viewpoints.

Writing experiences are important during the "taking action" part of the teaching model (Kenyon, 1989). In Mrs. Spenser's classroom, students had opportunities to challenge points of view expressed earlier, using their new information. Mrs. Spenser interjected questions to encourage students to resolve conflicting data and points of view. Additional experiments and hands-on activities moved students to reflect on, and accommodate, new perspectives. It also encouraged students to ask questions and eagerly explore new avenues of experimentation and information.

2. Cooperative learning. Such activities increase student achievement (Jones, 1985). Mrs. Spenser frequently employed cooperative groups in her classroom. She developed management techniques to ensure that all members of each group interacted in a positive, interdependent manner and that group and individual accountability occurred. In the beginning, she assigned roles to students in a group.

Mrs. Spenser found that her new cooperative approach was much more effective than the techniques she had used as a beginning teacher. For example, Mrs. Spenser used a large-group brainstorming approach to get the class to explore possible experiments they might conduct to determine the variables governing the production of sugars and starches in plants.

Then, the class formed eight smaller groups and followed specific experimental approaches. After some time, Mrs. Spenser brought the class back together as a whole to present data and to discuss the meaning of results. This class meeting set the stage for Mrs. Spenser to introduce the class to the chemistry of photosynthesis. Integrating chemistry and biology allowed students to see the importance of chemistry. For example, they could begin to understand "light reaction" because it is part of the context in understanding plant life (Anderson, 1989).

3. Laboratory activities. These also improve conceptual development. They became an important part of Mrs. Spenser's curriculum, occupying at least 40 percent of her contact time with her students. This was a switch from her early years of teaching, when she emphasized the written curriculum, mainly the textbook her district had adopted. Over time, however, she learned that appropriately designed laboratory activities motivate students to explore otherwise difficult concepts (such as light reaction) and provide a concrete context that enables most students to grasp such abstractions as photochemistry. Although she was no longer able to cover the entire text in a year, what she covered was understood better by students, as evidenced by their test performance.

Many laboratory exercises were modified by the class in large-group brainstorming sessions. Mrs. Spenser's students were actively involved in designing and carrying out laboratory experiments to fit the information they sought in attempting to make sense of varied viewpoints.

Some laboratory exercises differed from the open-ended inquiries Mrs. Spenser had used almost exclusively in her early years of teaching. Mrs. Spenser learned that some of her students needed more structured approaches. Accordingly, some laboratory activities took on a more directed inquiry approach. By combining large-group and small-group instruction, Mrs. Spenser found it easy to ensure that students received sufficient guidance. No longer were there "lab days" when students engaged in process skills and "content days" when Mrs. Spenser lectured. Rather, in the science learning community that she had established, she and her students together engaged in an evolving dialogue and in timely experiments as they made sense of scientific concepts.

4. Educational technology. Use of technology can enhance learning, particularly of curricula that blend understanding of science concepts and learning about technology. Making use of a network of teachers can help to ensure more effective use of technologies (Ellis and Kuerbis, 1988).

With the help of her teacher network, Mrs. Spenser located software to provide visually-oriented activities to support her unit on photosynthesis. She also used a videodisc to share with students film clips demonstrating the diversity of green plants. Mrs. Spenser was pleased with her progress in learning how to incorporate technology in her teaching. She found that girls as well as boys used the computers and videodisc to seek more information and improve their understanding of photosynthesis. Some students became familiar with computer word-processing capabilities and routinely turned in laboratory reports that they had processed on the computer.

Classroom use of technology: An example

Technology has many classroom uses. The Technical Education Resource Centers' (TERC) global ecology project is a science project in which teachers in this country and abroad engage students. For example, one teacher and his students decided to begin a study of the pH of a major river, a study that might carry on for a number of years. Successive classes can use the data to begin to uncover important information about environmental pollution from industrial plants, the formation and distribution of acid rain, and the subsequent impact on the river and the communities that depend on the river.

The use of a computer allows teacher and students to establish an important database. Through a modem and satellite communication, they can communicate with other groups interested in being part of the global ecology project.

The teachers in the project literally create their own curricula, curricula that are more project-driven than textbook-bound.

Curriculum: A Different Definition

For many educators, the word "curriculum" has a static meaning. It is simply the adopted textbook, the outline, or the guide of content to be covered in a course. This is unfortunate, because the meaning can be much richer.

The curriculum is a dynamic enterprise, perhaps best defined as a program of activities undertaken by students and teachers, alike. Lessons evolve as they are taught and learned. So do textbooks and outlines of content—the products traditionally thought of as curricula. Curriculum, therefore, is both product and process, and the two interact. As Murnane and Raizen (1988) have argued, curriculum has at least three phases: the intended curriculum; the taught curriculum; and the learned curriculum.

What a teacher or school district decides as constituting the curriculum is not likely to be solely what gets implemented in the classroom and acted upon by students and teachers. And what is ultimately learned by students may vary considerably from the intended and implemented versions of the curriculum.

The curriculum is a dynamic enterprise, perhaps best defined as a program of activities undertaken by students and teachers, alike. Lessons evolve as they are taught and learned. So do textbooks and outlines of content—the products traditionally thought of as curricula. Curriculum, therefore, is both product and process, and the two interact.

To reflect the Center's new view of instruction, perhaps a new term is needed: **curriculum and co-instruction**, or more simply, **construction**.

The term construction implies that teachers and students engage in the kind of activity together that ultimately results in the generation of new understanding. At the very least, the Center insists on viewing curriculum and instruction as different sides of the same coin.

In restructuring a high school science program, it is imperative that all those concerned with educating our youth consider curriculum and instruction together. The dynamic nature of curriculum and its inseparability from learning and instruction have important implications for the development and use of curricula, particularly the textbook component. Curricula and textbooks must change (Hart and Robottom, 1990). They must help students link, interpret, and explain new information in light of students' existing knowledge (Resnick and Klopfer, 1989).

More importantly, textbooks are just one piece of curriculum. Knowledge comes from information in those sources that students act upon. This suggests that curriculum developers and textbook writers should recognize that the structure of thought of the learner is at least as important as the structure of the discipline, a point made compellingly by Driver (1981).

As we note in Chapters III and V, the dynamic definition of curriculum also has important implications for the assessment of students and programs and for the preparation of teachers.

Recommendations

1. **The educational community, including teachers, administrators, and curriculum developers, should implement an appropriate and effective teaching model that is grounded in learning in the sciences.**

2. **Science teachers should attend to the learning needs of *all* students, including those in groups that historically have been underrepresented and underserved, by utilizing a range of teaching techniques and strategies consistent with an appropriate and effective teaching model.**

3. **Science teachers should have a support system that enables them to manage the learning environment so that *all* students achieve a level of scientific understanding, appreciation, and skill in thinking and performance that serves them as citizens, workers, and learners well into the next century.**

4. **Schools must restructure the science curriculum to include an emphasis on major scientific and technological conceptual ideas, use of educational technologies, teaching approaches that are varied and constructivist in nature, with assessments that are compatible with the design of the curriculum.**

CHAPTER V

Promoting Change In Teachers And Schools

Teachers are key to science learning; they create the context within which the curiosity, enthusiasm, and intellectual capabilities of students either flourish or wither. It therefore stands to reason that teachers will be most affected by the profound changes in thinking and behavior called for by the Center's recommendations on curriculum, instruction, and assessment.

How teachers approach and engage in these changes will be highly influenced by their current situation—by the way they interact with their students and the schools in which they teach. Before discussing how to promote needed changes in science education, it makes sense to portray the scene teachers face today. On the following pages is a physics teacher's account of a typical day spent teaching in his school: one that many people would consider "as good as it gets." The account is from the journal he keeps as he carries out his assignments in a professional, suburban community that offers a wide range of opportunities for students to learn science.

Looking at a Teacher's Typical Day

This brief picture reveals a lot about the teacher and the school. Clearly, the teacher's life is full and busy; his only breathing room is brief and tightly scheduled. He spends the bulk of his "on" time with students. He spends his "off" time planning, preparing, and following up on class assignments, laboratory experiments, and other activities.

The account provides some evidence that the teacher's behavior mirrors the recommendations of this report. Certain arrangements, such as double class periods that accommodate the need for extra time for labs, respond to the need for more flexible high school scheduling. The teacher's focus on instruction reveals a genuine commitment to helping students learn, with an effort to spark student interest (by discussing images of life in Galileo's time) and depart from cookbook labs (by requiring students to improvise with lab equipment). Student study groups provide opportunities for enhanced learning.

The teacher's focus on learning is complicated by a concern about student self-management and deportment (such as scheduling make-up tests and monitoring conduct in the halls). Yet the picture reveals a relatively orderly learning environment where competing demands, while a nuisance, do not throw learning into disarray. Accounts of other settings—such as those in the inner city—would likely reveal that this suburban scenario is as good an environment for learning physics as students are apt to experience in today's education systems.

Teachers are key to science learning; they create the context within which the curiosity, enthusiasm, and intellectual capabilities of students either flourish or wither. Therefore teachers will be most affected by the profound changes in thinking and behavior called for by our recommendations on curriculum, instruction, and assessment.

Nonetheless, the account provides food for thought. This report suggests many approaches to

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A Day in a High School Science Teacher's Life

6:50

Leave for school. Sip coffee from my travel cup.

7:20

Arrive at school. Get a few minutes to say hello to colleagues before I sit down to grade papers.

7:30

A student shows up and wants to know what he missed while he was away for three days visiting colleges. I tell him to get notes from a friend; I remind him that he has homework due and has a test in two days. He wants to know if he can skip the test and take a make-up exam because he missed so much work. I tell him that he should see me for extra help today and tomorrow and should plan on taking the test with the rest of the class.

7:40

Homeroom. I wish my students good morning. We recite the pledge of allegiance, I take attendance, and a student reads the daily announcements. Most students would rather talk to one another, but they give the announcements half their attention.

7:45

The bell rings. My advanced placement (AP) physics class starts in three minutes. Today, we have a double period. We'll devote the first 42 minutes to reviewing homework problems, conducting a demonstration, and discussing an upcoming science competition. In the second period, we'll do a laboratory activity. Although the AP class has the best students in the school who will be going to the most competitive colleges in the United States, they are still high school students: they constantly must be reminded to do their homework; their parents must be notified if they cut class (a rare event) or if their work is not up to par (a frequent occurrence). Even though all are excellent students, the range of abilities is quite wide. Some students live and breathe calculus, while others (also concurrently enrolled in calculus) make trivial algebra mistakes as they strive to understand physics.

As we review the homework, I find that six of 20 students did not attempt the assignment. They quickly give me a host of reasons. I respond that they can not learn physics by watching me solve problems on the board, nor can they help other students in their study groups. The class continues.

8:30

After a three-minute break, the students return for their lab activity. They are continuing their investigation of simple harmonic motion by comparing the motion of masses on a spring with the values they had found previously for the spring constant. I remind the students that an error analysis will be required in their lab report, which will be due one week from today.

9:15

A few students stay for two minutes to ask me brief questions about the lab. This is my prep period; I soon head to the teacher's cafeteria for a cup of coffee. On the way, I must watch for students breaking disciplinary rules. If I see an infraction, I must decide whether to address it. If a student is spitting in the hall, I will confront him. This will usually take five minutes. I will have to ask the student for his name, ask why he broke the rules, and make sure he goes to the Dean to sign up for detention. The situation can take longer to resolve if the student decides to make an issue of it. Usually students are not spitting, but eating, running, or punching a friend in the hall. Each situation requires a decision about what to say and how hard to press.

I reach the cafeteria and must wait five minutes in the student line to get my coffee. I chat with some students about their after school jobs, concerts, and school work. I drink my coffee in the science room upstairs and find a student waiting to take a make-up test. I tell her that she should come after school for the test. (This is my policy.) She explains that she has to go to work; I try to explain that school is her "primary" job.

I try to xerox some lab assignment sheets for next week. The machine jams.

10:00

My double period of first-year physics begins. The entire double period will be devoted to a lengthy lab investigation. Students will measure the acceleration of balls moving down ramps, using equipment that was available to Galileo, such as water clocks and rulers. We discuss our images of life in the early 1600s. I describe what Galileo intended to study, and we try to decide on a suitable investigation. I like this lab because I no longer provide ramps and students must improvise. The students like the lab because they get a little wet from the water clocks and enjoy timing the ball. During the lab, I walk around observing the students, making sure that *all* students are actively engaged and that they are sharing responsibility for the lab. I raise questions to promote each group's understanding. For instance, I ask one group how they can be sure that they are starting the ball from the same height. I ask a second group how they can be sure that the water clock maintains a constant flow of water.

11:00

The lab continues. Students who need a quick break can go to the bathroom, but one period flows into the next. The last 12 minutes of the class are devoted to cleaning up and summarizing what was found.

11:30

Lunch. A chance to relax and to talk to teachers in other departments. The conversation usually includes some jokes, some quick solutions to world political crises, and an interesting anecdote or two about what happened when a student did something outrageous and how the teacher handled it.

12:15

My second physics class begins. This class will be performing a lab experiment tomorrow. Today, we'll continue to explore what it means for objects to have constant acceleration. Research has shown that students have a difficult time understanding the differences among position, velocity, and acceleration. Students will analyze and discuss scenarios and tackle qualitative and quantitative problems.

Then, 10 minutes into class, the fire bell rings. Students parade out of school and march back in. The whole process takes only five minutes, but it certainly disrupts instruction.

Although only 10 fire drills are required by law, other interruptions—such as announcements, assemblies, and student government meetings—make this class typical.

1:00

My hall duty commences. I go to a corridor and sit down, hoping to get a little work done while I remind students that they cannot go to their lockers or that they should not be in the hall. One incursion into a student's freedom will undoubtedly become a minor confrontation (requiring two minutes and presenting no real hassle). A student in one of my classes comes by to show me an article that he read in a science magazine. He offers to loan it to me and I tell him that I hope to read it.

1:45

Last class of the day—general science. These students are the least motivated. Having them at the end of the day makes the class a real challenge. The class is more structured because these students seem to require it. They also need more feedback. I have found over the years that these are the students who build strong emotional bonds with their teachers. I don't know what these students see as their futures. I worry about them more than I do about my AP physics students.

2:30

This last 45 minutes is devoted to providing students with extra help. They show up to study or take a test that they missed. (If there is a test tomorrow, the number of students that show up increases markedly.) Why is it that the students who really need extra help (even those who promise to come) often don't make it?

On Wednesday, in lieu of the extra help period, we have a meeting of the full faculty, the department, or the union.

3:30

I often use this time to set up labs for the next few days or dismantle and return used equipment. I also work on committees concerning scholarship, technology, ninth-grade planning, drug and alcohol abuse, or assemblies, student absence, and lateness. I also may get a chance to return or make a phone call to a parent about his or her child's performance.

I make a list of tasks that I must complete:

> ***The confrontations in the hallway, filling out the lateness questionnaire, and seeing students not accepting responsibility for tests, make-up tests, or homework were low points for me. However, once we were inside the classroom, we were learning...we were all working toward the same goal—getting our minds to understand something that is difficult, in hopes that we can better appreciate the world around us.***
>
> ***We were also building relationships..***

- Write mid-quarter notices, due next week. (Will I be able to give one more test before I write these evaluations?)
- Write eight more college recommendations. (I sure hope that colleges read these. Each one requires at least one to two hours to write.)
- Start writing the test for the day after tomorrow.
- Grade lab reports for AP physics.
- Grade lab reports for first-year physics.
- Compose homework sheet for general science.
- Fill out school questionnaire about student lateness.
- Read science article that student gave me.
- Choose which conference to attend. Fill out district paperwork and find out if the district can find $50 to pay the registration fee.
- Check mail. Anything interesting in the new science supply catalog?

4:30

Head home.

5:00

Arrive home. Read the paper. Help prepare dinner. Visit with my kids. Ask them how much homework they have and when they will do it.

6:00

Eat dinner. Then help my kids with their homework. If possible, I will complete some lesson plans or grade lab papers while the kids are engaged in their homework.

8:30

Spend some time with the kids before they go to bed. Write one college recommendation before I get too tired to do much of anything. Plan to work on college recommendations during the weekend. I guess that's when I'll do the mid-quarter notices, too.

10:30

Bedtime! Looking back on the day, it was hectic, but typical. The confrontations in the hallway, filling out the lateness questionnaire, and seeing students not accepting responsibility for tests, make-up tests, or homework were low points for me. However, once we were inside the classroom, we were learning. I was challenged, the students were challenged, and we were all working toward the same goal—getting our minds to understand something that is difficult, in hopes that we can better appreciate the world around us. We were also building relationships. I really enjoy teaching and I really enjoy the students. I get older and more experienced each year. The students in my class remain the same age. What an interesting interaction!

Continued from page 81

curriculum, instruction, and assessment that are not demonstrated in this vignette. There are no indications that the curriculum is integrated with other science disciplines or other high school subjects. There is no explicit connection made to students' worlds or to their prior knowledge. Assessment amounts to testing students' understanding of certain science principles and associated factual information; this allows the teacher to grade students and proceed to the next topic.

Further, in this teacher's busy day, there is no evidence of teachers connecting with one another around issues of teaching and learning: no talk about integrating content; the learning occurring among particular students; or about new ideas, strategies, or knowledge. In fact, there is no explicit opportunity for teachers to learn, either formally or informally. Thus, even in what many would call a "best case scenario," changes are called for—in what *teachers* do and in how the *system* supports them.

Teacher change results from learning, and the Center draws from a constructivist view of learning to understand and support the profound changes teachers will need to consider. Like their students, science teachers need opportunities to challenge and extend their current knowledge and to reflect on and experiment with new ideas if they are to change their practices.

However, science teachers cannot, and will not, take advantage of such opportunities unless they are in an environment that supports their growth and the risk-taking that necessarily accompanies it. The organizations in which they work—their departments, schools, and districts—must become "learning organizations" where "people continually expand their capacity to create the results they truly desire, where new and expansive patterns of thinking are nurtured, where collective aspiration is set free, and where people are continually learning how to learn together" (Senge, 1990:3).

To achieve the changes in science education that the Center envisions, two main actions are key: 1) promoting teachers as active learners, and 2) advancing schools as communities that help teachers learn. First, however, it is important to understand how teachers learn.

Teachers As Active Learners

For many years, approaches to developing science teachers (and teachers in general) have been influenced by the view that knowledge is "out there" in the world. Learners merely need to access this knowledge through the senses. According to this philosophy, learners' objectivity lets them match their observations with an external and accessible reality, and so take in the new information.

These assumptions about knowledge have shaped traditional strategies for preservice and inservice science teacher education, which often incorporate a conduit metaphor: knowledge is piped from an expert to a learner. The priority is on learning truths that have been "validated" by research and/or that represent the conventional wisdom of science educators.

The constructivist perspective challenges this approach (Tobin, 1990; von Glaserfeld, 1988). In this view, knowledge is a construction of reality. When new experiences introduce knowledge that disagrees with existing knowledge, learners can adapt their existing knowledge. They can clarify, elaborate, describe, compare, negotiate, and reach consensus on what specific experiences mean to them.

Thus, an individual constructs knowledge through successive experiences and reflections. This implies that, in a learning environment (whether it be a classroom or a staff development session), individuals need time to experience, to reflect on their experiences in relation to what they know already, and to resolve discrepancies between what they know and experience.

Ultimately, each individual conducts this learning process within him- or herself. Individuals, however, can supplement their inner voice and understanding with discussions with others. Learning has an important social dimension. The main value of speaking with others is that it can help learners clarify their understandings, and justify and re-explain their points of view. They articulate their experience, listen to others' points of view—and the process by which others arrive at those views—and decide whether they agree with them. Often, in the course of discussion, learners can resolve discrepancies.

This view of learning summons up a much different picture than that of learners passively receiving expert knowledge—whether from a person (an instructor, trainer, or teacher) or the printed word. It underlines the point that learners must be active intellectually if they are to construct their own knowledge from what they see, hear, and otherwise experience.

How does this more active view of learning affect thinking about teacher change? In their research on science teacher learning, Tobin and Jakubowski (1990) found that, for active learning and subsequent change to happen, three cognitive requisites must be present:

1. Science teachers must devise a vision of what science classes could be like and personalize that vision.
2. Teachers must forge a personal commitment to change.
3. They must also reflect on their actions and allow their reflections to influence subsequent actions.

The implication of this observation is that teachers must develop a coherent sense of personal meaning regarding a change in their science teaching: they must understand what it is, what it is for, and what it involves (Fullan, 1990b).

Facilitating Change in High School Science

Educational systems approach large-scale changes in three general ways. In the staff development approach, the focus is on individual teachers who upgrade their knowledge, skills, and teaching behavior. They master new, required science content, understand and experience the ways scientists work, and learn to design and implement appropriate science learning opportunities for students. Typically, this approach uses inservice workshops, summer institutes, sabbaticals, conferences, teacher academies, and internships with local science firms (Loucks-Horsley et al., 1987).

A second approach to large-scale change focuses on such organizational aspects as philosophy, goals, structures, and climate. Districts, or high schools, engage teachers, administrators, and community to establish a new philosophy or goals, sometimes for science only, or, more recently, for science in concert with other areas (e.g., mathematics and technology, or technology and society). For example, several districts are currently using the framework provided by a 1989 report by the American Association for the Advancement of Science, *Science for All Americans*, to redesign science, mathematics, and technology education in large, multi-constituent development teams whose work spans several years. The focus is on organization-wide pursuit of and engagement with new goals for science, with a special effort to change the structures and processes through which students learn science.

A third approach to large-scale change focuses on replacing the curriculum. A new curriculum is developed or selected to be used school-wide or district-wide. Appropriate staff development activities—including workshops, follow-up, and coaching—are planned and a support system to organize and deploy materials is established. The focus is on the program and its implementation in the system.

Needed: A More Synthetic Approach

Most high school science improvement efforts combine elements of the three approaches, but they typically emphasize *one* aspect: the individual teacher, the organization, or the curriculum. Each approach has its advocates and is backed by evidence that it works, at least to some extent.

Yet over time, even staunch advocates of each have come to believe that a more synthetic approach is needed to produce the changes required to make today's schools work for tomorrow's students and society's needs.

First, teachers need more than an opportunity to learn to use a curriculum or program formulated or selected by others. High school science teachers must actively engage in exploring new options, accepting or rejecting them, and collaborating in designing and implementing changes. Only then can teachers develop the personal vision and commitment that makes change meaningful to them.

Second, changes will not occur throughout a department, school, or district when individual teachers are the focus. One of the lessons of the National Science Foundation teacher institutes of the 1960s and 1970s was that, while individual teachers could gain the knowledge, skills, and enthusiasm needed to implement new curricula by attending intensive summer sessions, they rarely could implement and sustain their new program back home, where the support systems and expectations of administrators, colleagues, and parents had not changed at all. A critical mass of teachers is needed for meaningful change to occur. So are appropriate changes in the system to support the new directions.

Finally, as the fundamental premises underlying learning, teaching, and schooling increasingly are questioned and become the focus of experiments nation-wide, it appears that the real agenda must be changing the culture of the school, rather than implementing isolated innovations (Fullan, 1990b). Changing the culture means, among other things, thinking in new ways about what science is, what all students should know and be able to do, what role teachers and schools should play in science learning, and how individuals—including students, teachers, administrators, parents, and community members—and organizations need to act and interact to implement these fundamentally new ways of thinking.

Science is taking its place alongside other disciplines whose professionals and their associations are actively advocating new ways of thinking (as the new standards for mathematics developed by the National Council of Teachers of Mathematics and the whole language movement aptly illustrate). These new ways have much in common across disciplines and could usher in a fundamental change in culture, rather than implementing numerous new, but disconnected innovations.

Reconstructing high school science education in the ways the Center recommends in this report requires a systemic approach to teacher and school change that attends to all of its parts—individuals, organizations, and programs—through coordinated changes in school organization, staff development, preservice teacher education, and local and state policy-making. Yet, every school, district, and state begins with a different set of conditions and will choose a different way to achieve the desired student outcomes.

For this reason, there are no pat formulas for how change should proceed. Rather, a number of factors must be considered and activated to make change succeed. The particular context dictates which combination of factors will ultimately work.

Factors Critical to Successful Change

The Center realizes that many barriers stand in the way of change. These include declining financial resources, poorly trained teachers, controls and constraints placed on teachers, schools, and districts by states, unions, and the federal government. In addition, change is a process that takes time and often yields few immediate effects (except feelings of overload by those most closely involved). Further, there are few exemplars of large-scale change in high school science, especially along the lines of the Center's recommendations. This makes it difficult to give people confidence that change can occur, or that suggested strategies can make it happen.

Yet, there also are countervailing forces, especially the continued public demand for improvement and the increase in available funds, especially at the federal level (but also in many states), to pursue changes. In addition, state agencies are becoming more amenable to waiving requirements and rules in support of experiments to enhance student learning.

Creativity in reallocation of funds, different use of staff resources, scheduling of school calendars and classes, and collaboration with businesses, universities, and service agencies has allowed schools and districts to pursue new directions.

What is most important at this juncture is that new initiatives do not suffer from amnesia about what is necessary for change to succeed. Decades of innovation—both successful and unsuccessful—have led to a wealth of understandings and strategies that can guide these new efforts. The critical factors that contribute to successful change are:

- Understanding and managing the change process;
- The school work environment and culture;
- Approach to and opportunities for staff development;
- Leadership;
- Resources; and
- Policies.

The conscious and careful combination of these factors will appropriately support teachers' active learning.

Understanding and Managing Change

Understanding the change process, its phases, and the different emphases required during each phase are important factors in successfully reconstructing science education. Although some debate occurs about the extent to which change is a manageable process, only with an understanding of the process can those responsible for overseeing change anticipate and plan for the actions that must be taken, the structures that must be established, and the support that must be garnered—to create a context for successful change.

The change process has been the subject of intensive and extensive study and research, especially in the past two decades. In education, the process has been examined from all angles—that of the individual, the organization, and the innovation. Just as many practitioners have come to realize that successful change requires attention to all three perspectives, so have researchers. This is due, in part, to the early, ground-breaking work on understanding change, including the RAND change agent studies (Berman and McLaughlin, 1975); the Study of Dissemination Efforts Supporting School Improvement (Crandall et al., 1982; Huberman and Miles, 1984); research on the Concerns-Based Adoption Model (Hall and Hord, 1987); and analysis and synthesis of research through the early 1980s (Fullan, 1982). At this time, however, an increasing number of policymakers, practitioners, and members of the public have set their sights on large-scale, transformational changes as the direction for the 1990s. Newer understandings of the change process, such as those of Fullan (1990a) and Louis and Miles (1990), can contribute to the success of these efforts.

Agreement with the idea of planned, system-wide change is not yet unanimous, as indicated by the nature of some current mandates that require change in single components of the system, such as graduation requirements, the length of the school day, or certification requirements for teachers. Yet few would disagree that change is a process, not an event. This process occurs over time and requires different kinds of attention along the way. General agreement exists that any planned change effort—in classrooms, schools, or larger systems—involves three major phases: initiation, implementation, and continuation. The three phases are not distinct; each is connected to and affected by the others. Some tasks in adjacent phases occur simultaneously.

Moreover, in large-scale change, the three phases are not merely linear, but cyclical. Evaluation of implementation efforts often leads to continuing some practices and programs that prove to be worthwhile and to initiating new efforts to replace other components of reform that did not live up to expectations.

Initiation. *Sometimes labeled adoption or mobilization*. Initiation begins with the awareness of the potential for change and leads to the decision to adopt a new practice or proceed with a plan. This phase may start in a variety of ways. A school board may mandate change to improve science education. A group of teachers may compare teaching approaches and decide that their students would benefit from multiple approaches in the same classroom. Or the science department may conclude that the current curriculum is hopelessly outdated.

Initiation is a period of inquiry, reflection, and planning. Decision-makers and program developers weigh preliminary decisions about the need for change, gauge interest for a particular direction, determine what kind of priority the change deserves, and consider some of the administrative requirements, such as costs, materials, personnel, and space, needed to bring about change.

Fullan (1990a) notes that the best beginnings combine the three "R's" of relevance, readiness, and resources. "Relevance" refers to the interaction of three issues: need, clarity, and understanding the innovation and its value to teachers and students. Relevance relates to the process of "meaning making." It includes a measure of teacher advocacy: teachers must move in the direction of the change. At an organizational level, it requires the recognition of the need to improve science learning.

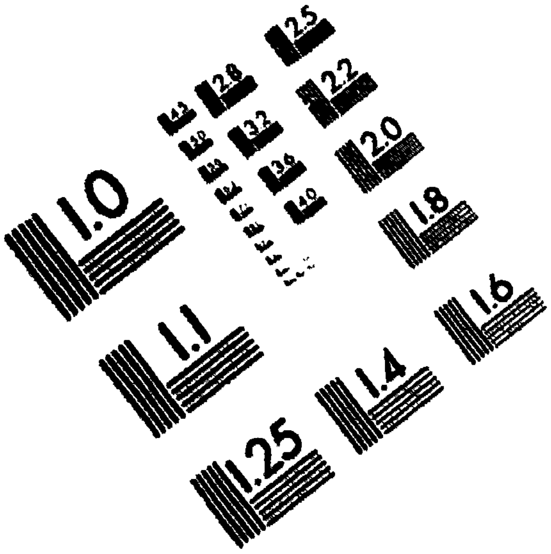
"Readiness" refers to a system's capacity, practical and conceptual, to select a new direction and develop and implement programs to accomplish it. This includes acknowledging that science education is an important priority and the willingness to pursue its reconstruction; access by the department, school, or district to new ideas and programs; the commitment and support of those in positions of authority at each level (such as the superintendent, principal, or department chair); and community support or apathy. (Obviously, community opposition blocks change.)

"Resources" refers to the availability of such factors as money, time, and materials to support the change immediately and over time. Access to external assistance and resources is often critical to the success of the change (Odden and Marsh, 1988).

Implementation. Implementation spans the first two to three years when change is put into practice. Unfortunately, most of the attention and resources for implementation are usually concentrated on the first few months. In the typical "front-loaded implementation plan," a decision to adopt a new practice triggers an awareness session for teachers. An inservice training program quickly follows. Teachers receive a clearly-tabbed teacher's guide that will answer all the questions they didn't quite understand during their inservice training.

Implementation spans the first two to three years when change is put into practice. Unfortunately, most of the attention and resources for implementation are usually concentrated on the first few months.

This approach perceives change as an event. Yet the success of the implementation phase depends on a far more complex process. Meaningful teacher change occurs only over time, with many opportunities for teachers to practice, master, and reflect on their new knowledge, skills, and behaviors. The clarity, complexity, quality, and, especially, practicality of the new curriculum, program, and ideas that are being implemented all play a role.



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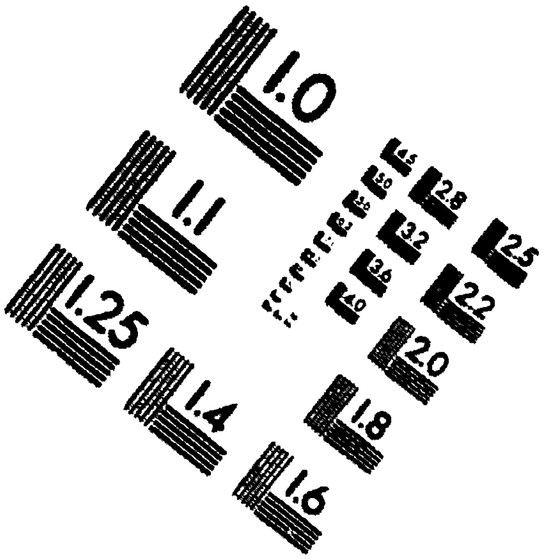

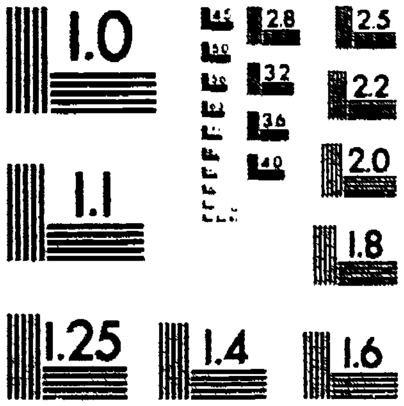

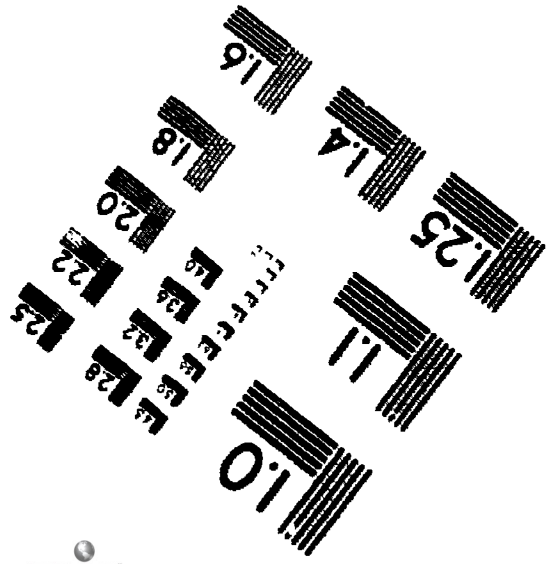

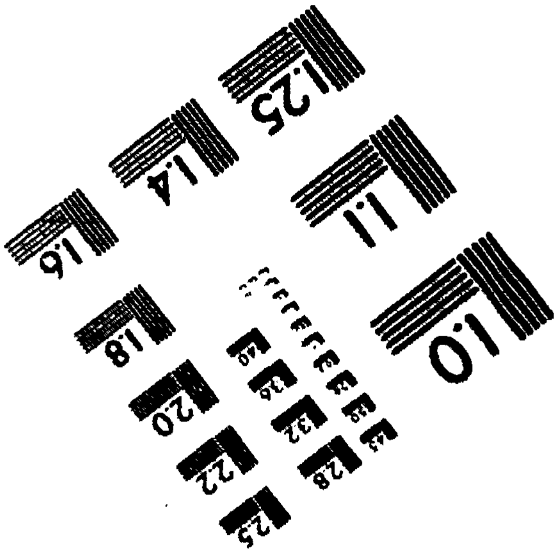

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Finally, the organizational units, the department, school, district, and state, play important roles in creating and sustaining the direction and press for change: empowering and supporting individual agents of change; providing learning opportunities and resources; and creating the settings in which individuals are motivated and rewarded for change. These elements will be revisited in more detail later in this chpater.

Continuation. The third phase most often has been called "institutionalization" to indicate whether changes have been incorporated into such school routines and regular products as budgets, policies, and curriculum guidelines.

In the context of the reconstruction of science education, the term seems inappropriate and bureaucratic. Instead, large-scale change must be viewed as an on-going process that is intended to promote constant growth and renewal of the system: to change how people think about science and science education and the culture of the school that supports new directions—rather than a fixed stopping point for change.

At the same time, institutionalization remains an important concept when applied to the specific programs and practices that make up fundamental reform. Most people working with a new practice are pleased with themselves and others if they get through the first year or two successfully. Usually, this is too soon to celebrate. There is an element of excitement to implementation, but when it fades, people can lose interest in sustaining the new program, especially if special funding for it begins to dry up, or if the person who championed the cause moves on to another priority. Managing this phase of change requires attention to stable and sustained leadership and continued clarity of purpose; incorporating the changes into "standard operating procedures" and curriculum guidelines; and continuing staff development opportunities that encourage teachers to expand upon and enhance their new ways of thinking and acting.

A School's Work Environment and Culture

This factor is particularly important in achieving the Center's ultimate goal in reconstructing science education: changing the culture of the school as it relates to science—the way science is thought about, its place in the life of the student, and whether learning is viewed as everyone's primary task.

Change often is difficult. Many factors constrain teachers to do what they do in schools, sometimes in contradiction to their firmly held beliefs. For example, most teachers assert that district and state level assessments force them to cover textbook content and to emphasize rote learning to solve such problems as those found at the ends of textbook chapters. The existing assessment system may lead to a form of teaching that consists mainly of lecturing and seatwork activities involving the textbook (Stake and Easley, 1978; Tobin and Gallagher, 1987b).

When laboratory activities are undertaken, they usually are of a cookbook type, in which students manipulate materials in specified ways to obtain pre-determined results (Tobin, 1990). It is unlikely that teachers will be able to make significant changes in their practices unless attention is given to the reasons they give for doing what they currently do.

Most science teachers are isolated from each others. They have barely enough time to prepare for their classes, much less reflect thoughtfully on their work. They are pressured to cover content rather than experiment with new ideas. Yet, teachers, like students, need to be learners, and they need similar conditions to support their learning. The same conditions that make classrooms good places to learn science make schools good places for science teachers to continue to grow professionally and feel good about their work.

Schools where teachers feel comfortable proposing and trying out new instructional strategies and materials, and where they routinely share with each other at several levels—from talking about teaching to co-developing units of instruction—are more effective in increasing teachers' learning, as well as that of students. Research indicates that the quality of working relationships among teachers is strongly related to successful change.

In her study of schools as workplaces for teachers, Rosenholtz (1989) found a vast difference between "learning impoverished" and "learning enriched" schools. The main difference was in the degree to which enriched schools fostered collegiality, open communication, trust, support, help, learning on the job, getting results, job satisfaction, and high morale. These were places where teachers challenged each other's ideas and helped each other resolve problems—not places that were merely friendly and socially supportive. These were the work environments that stimulated continuous improvement.

Creating Environments for Change

A study of six urban schools (Little, 1982:12-13) characterized the kinds of teacher-to-teacher interactions through which improvements were most readily and thoroughly achieved:

> *Teachers engage in frequent, continuous, and increasingly concrete and precise talk about teaching practice (as distinct from teacher characteristics and failings of teachers, their social lives, the foibles and failures of students and their families, and the unfortunate demands society places on the school). By such talk, teachers build a shared language adequate to the complexity of teaching that is capable of distinguishing one practice and its virtues from another....*
>
> *Teachers and administrators frequently observe one another teaching and provide one another with useful (if potentially frightening) evaluations of their teaching. Only through such observation and feedback can teachers develop shared referents for the language of teaching, and both demand and provide the precision and concreteness that makes the talk about teaching useful.*
>
> *Teachers and administrators plan, design, research, evaluate and prepare teaching materials together. The most prescient observations remain academic ("just theory") without the machinery to act upon them. By joint work on materials, teachers and administrators share the considerable burden of development required for long-term improvement, confirm their emerging understanding of their approach, and make rising standards for their work attainable by them and their students.*
>
> *Teachers and administrators teach one another the practice of teaching.*

Teachers working together clearly improve the *act* of teaching, as well as the content of teaching. This point has special relevance for implementing the curriculum the Center advocates. That curriculum requires that the disciplines of science be taught in an integrated way; that scientific knowledge be related directly to the society in which students live and make decisions that will influence their futures and others' futures; and that links to science be made with students' other subjects, such as mathematics and vocational coursework.

To plan and implement such a curriculum, teachers must collaborate with colleagues from other subjects. They must invest time and energy in discussions of their different disciplines and how the disciplines can be combined without sacrificing their fundamental principles Through such dialogue, teachers push themselves and their colleagues to deeper understandings.

Supportive ways. Examining the curriculum and the schedule can reveal ways for teachers to collaborate in planning their courses. This would provide students with a wide variety of faculty to assist them in interpreting problems. For example, a vocational education teacher and a science teacher could highlight the employment potential of certain areas of science by examining how science principles apply to technology. Similarly, a science teacher could collaborate with a social studies teacher to identify social and political aspects of a problem under investigation: this would assist the problem-oriented approach to learning that the Center advocates.

Work environments that support new directions in science teaching and learning also are influenced by the degree to which teachers have a say in important decisions that affect their students. The literature on teacher professionalism asserts a clear connection between teachers' commitment and effort and the extent to which they are involved in decisions about instruction (Lightfoot, 1983).

Darling-Hammond (1986) notes that, when teachers are involved in making decisions about such matters as instructional materials and methods, structures and programs, and directions for improvement and staff development, absenteeism and turnover decrease. Greater consensus about school priorities and practices occurs. This more tightly couples educational goals, content, activities, and assessment—and thus improves the learning that occurs in classrooms. Combining school-wide influence with a degree of autonomy over classroom curriculum and instruction "helps shift teaching away from technical work and toward professional practice" (Darling-Hammond, 1986: 62).

Changing secondary school culture. Major changes in the culture of secondary schools are required if greater teacher collaboration and involvement in decision-making are to occur. Constraints include time, scheduling, organizational structures, policies, and procedures. Attention must be directed to the people in the culture who influence these constraints. Often, control belongs to the teachers themselves. However, sometimes constraints take the form of policies, customs, or norms that are controlled by the science department, school, district, or state. To overcome these constraints and facilitate the process of change, negotiations are needed. These negotiations often need to involve teachers as well as others from the community including administrators, parents, business leaders, school district personnel, and state level science educators.

Student roles in change. What happens in schools depends upon student perspectives as well. Students come to school with a set of expectations about what will happen. They have goals and behave in ways that allow them to achieve their goals. The Center advocates a change in the goals of science education. For this strategy to succeed, it is important that students understand these goals and reconceptualize their own roles within the school's culture. Teachers cannot assume complete responsibility for the science learning of students. Students must acknowledge responsibility for their own learning and should understand and reflect on their roles as learners. If the changes the Center envisions are to occur, students must construct perspectives that will enable them to learn with understanding and empower themselves through science education.

Staff Development

Effective staff development incorporates individual, system-wide, and curricular changes. Although the most important focus is on the individual's knowledge, skills, and behaviors, the organizational dimensions of any innovation need attention, too.

The goal of staff development is reflected in the Center's advocacy of teachers as active learners. Good staff development aims to help teachers construct new ways of thinking about their teaching. It gives teachers opportunities to articulate their current ideas, introducing them to discrepancies with good teaching practices. It provides access to alternative strategies and models of good teaching. Such access might be through training (as in cooperative learning), through visits to other teachers and schools, or through conferences.

But effective staff development does not stop there. It also provides teachers with time to practice, letting them try out new strategies and receive coaching and feedback from qualified individuals. It provides opportunities for teachers to reflect together on their new practices and act on their reflections (Joyce and Showers, 1988; Sparks, 1983).

Staff development activities should go on within a school. The school should be seen as a learning community for teachers, as well as students. Accordingly, most of the teachers' learning should occur at the school site, and it should be ongoing. This will help form a critical mass of teachers moving in the same direction. In turn, this will facilitate school-wide, or at least department-wide, change and have more potential to influence student learning over time. Moreover, organizational structures and norms are more likely to become part of the process of staff development.

On-campus development. On-campus staff development activities have another advantage. Often, teachers can more readily apply what they have learned when the context in which they learned new approaches is similar to the context in which they will apply their new knowledge. On-campus staff development activities also are convenient: they eliminate the need for travel. Moreover, the presence of outsiders coming to the school campus to help teachers learn sends powerful signals to encourage and validate change.

Off-campus development. Learning experiences outside the school also are valuable. Teachers gain important perspectives and awareness of a wide variety of approaches, materials, and directions from attending conferences. University-sponsored courses and institutes expose teachers to expertise that may not be available in their school. Both introduce teachers to different ways of thinking, contexts, and challenges—again, with the potential of creating a disequilibrium that can lead to new and important learning.

Change Is a Slow Process

It is important to realize that learning of any type often is a slow process. This is even more true when veteran teachers are asked to learn new approaches to the teaching and learning of science. Teachers are likely to cling to strategies that have worked for them for many years. Thus, change is likely to occur slowly.

One approach to staff development is to help teachers learn about their own personal theories of knowing (epistemologies) and beliefs about student learning. Tobin (1990) notes from his work with science teachers that, when teachers learned about constructivism, most opted to become constructivists. As they began the journey to constructivism, they made sense of teaching and learning differently. They used a different set of theories to build models for what the classroom might be like; they personalized their vision of what science could be like in terms of constructivism. Initially, this process took the form of internal, cognitive shifts. However, changes in the classroom often were observed within a few weeks after teachers had learned about constructivism. More significant changes usually could be observed in classrooms after several months. Major changes, which require a major reconstruction of science learning opportunities, might take as long as one to two years to accomplish in the classrooms of veteran teachers.

Good staff development provides teachers not only with access to knowledge about learning, but it also updates their knowledge of science content. An additional, and critically important, kind of knowledge is knowledge about the teaching and learning of science: pedagogical content knowledge (Shulman, 1987). This knowledge extends to such activities as:

- Knowing the most appropriate laboratory activities and demonstrations to use to teach different science concepts;
- Knowing what explanations to give, what questions to ask, how to react to specific misunderstandings students might have;
- Knowing how to clarify and elaborate explanations for students when they have alternative frameworks for given phenomena;
- Maintaining knowledge of resources (such as videotaped programs, videodisc and computer software, and books); and
- Being able to construct evaluative tasks to assess what students have learned.

A focus on pedagogical content knowledge requires teachers to be active learners because it is knowledge that helps them make decisions minute-by-minute as students learn.

Learning from One Another

Teaching knowledge can be learned best from colleagues. Teachers should have opportunities to share, discuss, and critique the activities they have taught, the resources they have used, and the handout materials they have produced.

Reviewing videotapes. A valuable way of obtaining such knowledge is to review a videotaped lesson of a colleague. This exposes people to the content of what is being taught, but also to the questions, explanations, reactions, demonstrations, and experiments used in a specific lesson.

Using case histories. Case histories of teaching also can help (Shulman, 1987). Teachers might videotape key lessons in their courses and make these videotapes available to their colleagues in future years. In this way, a library of lessons becomes available to teachers for each part of the science curriculum. Professional review of the teachers within each school or school district can maintain the quality of the library.

The organizational dimension of staff development is particularly important. It helps provide a consistent direction for improving science and a structure that ensures that all individuals and parts of the school are involved. A collaborative, comprehensive staff development system works at either the department, school, or district level. It involves teachers in setting directions and making decisions about their own professional growth. It promotes collegiality, collaboration, experimentation, and other norms that foster successful change. It provides a common mission, set of goals, and framework to reconstruct science education. It orients curriculum development, staff development, and organizational development activities, so that they are coordinated and heading in the same general direction (Arbuckle and Murray, 1990; Loucks-Horsley et al., 1987).

Leadership

The nature of leadership required for change of the kind and scale recommended in this report is highly complex. It will take a combination of leaders with formal authority in the school and district and informal leadership provided by a wide variety of teachers, administrators, support staff, and community members to stimulate, guide, and coordinate the kind of energy and resources needed.

Such designated science leaders as department heads and science coordinators play critical change agent roles. With leadership authority vested in them, they have the important role of orchestrating change in many areas (curriculum, instruction, assessment, staff development, school structures, etc.) in a way that is coordinated and eventually integrated.

It may be more useful to think in terms of the functions leadership must fulfill, rather than what a particular leader must do. For example, examination of science programs recognized in the National Science Teachers Association's *Focus on Excellence* indicated that, in each case, someone took responsibility for designing the program (Yager, 1984). Sometimes, this was a central office administrator; other times, it was a master science teacher. In different situations, different configurations of leaders from the school and district, and even from outside the district, may be needed to help teachers initiate, implement, and sustain changes in their science programs (Cox et al., 1987).

When teachers take leadership roles, they can build the foundation for a shared vision of science education. Administrators and other leaders from the school and district can help develop structures that support constructive change and eliminate structures that inhibit it. Such sharing of leadership functions is becoming the mode of operation in many schools, as well as in other kinds of organizations.

The reconstruction of science education, like other major change, needs leadership that can develop and maintain a vision. Bennis and Nanus (1985:101) note in their study of exceptional leaders:

> *If there is a spark of genius in the leadership function at all, it must lie in [leaders'] transcending ability, a kind of magic, to assemble—out of all the variety of images, signals, forecasts, and alternatives—a clearly articulated vision of the future that is at once single, easily understood, clearly desirable, and energizing.*

In discussing the image of teachers as active learners, the Center has argued that teachers should be committed to a vision of science teaching and learning that guides their learning and actions. In this light, it makes sense for vision building to be a shared activity—one in which teachers, administrators, and others interested in and/or responsible for science education participate. When this occurs, the result is mutual understanding of what science learning consists of, what environments for effective science learning look like, and what can be expected as outcomes.

School administrators as leaders. School administrators need to be involved as teachers begin to reconceptualize their roles and construct a vision of what the science curriculum might be like. Administrators should not only know *what* is to be done, but they should understand *why* it is desirable to restructure learning and teaching in the way that is advocated. For example, principals should understand why classrooms become noisy when teachers work to create learning environments where students discuss and negotiate their ideas with others.

The reconstruction of science education, like other major change, needs leadership that can develop and maintain a vision.

Teachers as leaders. Teachers have important leadership roles to play for one another. In their work with science teachers, Tobin and Jakubowski (1990) designate at least two teachers per school as coordinators of the change process. These teachers assume responsibility for initiating the types of interactions that must occur to produce active learning. Moreover, the coordinators help communicate and construct the collective vision of what science can be like school-wide.

As their colleagues communicate their understandings of that vision and demonstrate a commitment to personal change, the teacher-leaders challenge new understandings. Tobin and Jakubowski found that teacher-leaders are necessary to ensure that a vision of science is dynamic, that teachers strive to attain a curriculum that is compatible with that vision, and that, ultimately, all science teachers become community members who participate in the reconstruction process.

Resources Within the School

If teachers are to learn in the manner envisioned by the Center, it is essential that budgets for science education provide resources to back a comprehensive approach to teacher development and support. If the goal is to enhance students' learning, fostering teachers' learning must be a major priority. Staff development for science teachers should be guided by a curriculum that is carefully planned and funded to ensure that all teachers are prepared to undertake their professional responsibilities.

Budgetary needs. Science teacher development and support require budgets. Money is needed to buy equipment and supplies. Funds also are required to hire substitutes or make other accommodations to release teachers from some of their classroom responsibilities. In addition. money is needed to support mentor teachers who can guide new teachers and those changing teaching assignments.

Time needs. Similarly, time is a critically important resource that influences the quality of the changes made in classrooms and schools. Teachers simply cannot make the profound changes called for in this report while they meet all their classes and conduct business as usual. Nor can they do so with occasional, short periods of released time. They need time to attend learning sessions, conferences, and meetings on and off campus; visit the classes of colleagues in the same and different schools; and reflect by themselves and with colleagues. They need time to reconstruct their programs and make the changes needed to implement the new programs in their classrooms.

How much time is enough time? There is no pat answer, but there are examples to point to. How much time has to be allocated depends on the situation, the goals and the available resources. Some program planners build in a half day of released time each week or every other week, dismissing school at noon every Wednesday, for example. Others rely on two- or three-week summer institutes or work sessions, followed by full-day released time at regular intervals throughout the year. At the extreme, design work for districts participating in the American Association for the Advancement of Science Project 2061 supports participating teachers and administrators (25 for each district) to the equivalent of one day per week released time during the school year, plus one month during the summer. Once time is allocated, it is critically important that it be spent well, with clear milestones and carefully documented outcomes.

External supports

Organizations external to schools are another resource for developing and supporting teachers. They can aid teacher development by providing knowledge, programs, and support for new directions. At the state, regional, or large school district level, an array of external support structures can be developed for these purposes (Louis and Loucks-Horsley, 1990). They include a resource center that maintains a bank and/or list of exemplary practices, materials, and programs that teachers and schools can refer to in their search for new programs. Such a center can arrange visits to exemplary sites, and connect schools so they can exchange resources, network, and receive on-site training.

School networks. Also useful is a network of schools that have implemented steps such as those recommended in this report to reconstruct their science programs and that can help others learn about, adapt, or adopt them for use in their own schools. Schools in the network should receive assistance to prepare materials promoting awareness and training, visitation schedules, and other resources. Schools also should receive funds to disseminate such resources to others. (For example, they could have a faculty team that is released from part of its work load so it can work with other schools.)

Ongoing education. The reconstruction of science education also can be helped by academies that provide in-depth institutes and regular meetings for participants. There, school or district-wide teams of teachers, administrators, and others—including support personnel, community members, and representatives from business and industry—can receive help in designing, planning, and supporting the implementation of changes in their science program. Such institutes might be cross-disciplinary, for example, working with social studies and science teachers, or they could even focus on change throughout the entire school.

Professional development schools. Another external support structure is a professional development school, a working school whose faculty (called the clinical faculty) has implemented changes. This school can act as a model or exemplary setting where visitors can come and prepare themselves to implement their own changes. Such a school can function much as does Pittsburgh's Shenley Teacher Center, which focuses on the development of generic teaching strategies in its district's teachers (Bickel et al., 1987).

Using a professional development school created to foster new directions in science education, groups of teachers and administrators from other schools could be released from their responsibilities for an extended period of time (six to ten weeks) to observe new methods, attend seminars and workshops, practice new strategies with the clinical faculty, develop curricula, and perfect classroom, curriculum development, leadership, and management skills. Working and learning as a team, they can design an action plan and strategies to implement it when they return to their own school.

Policies

Policies undergird and reinforce systemic changes. The key to systemic change is coordination at the system level—whether it is the department, school, district, state, or nation. For systemic change to occur, the many players involved must be considered and included in discussions and activities. For example, if institutions of higher education are not part of the change, teachers will not be prepared appropriately. The institution's resources will be neither available nor appropriate to contribute to in service teacher development and support.

Policies can contribute to systemic change two ways:

- First, they can set parameters and direction and provide pressure and incentives for change;
- Second, they can provide resources, including the support structures, needed to bring about change.

Both elements, pressure and assistance, have been found to be necessary for successful change to occur (Crandall et al., 1982; Huberman and Miles, 1984).

The first element is regulatory; it is often viewed by practitioners as heavy-handed and insensitive to the realities of schools because it mandates actions that people in schools have not themselves deemed to be necessary. However, strong external stimulus may be needed to overcome inertia and resistance to change, because individuals and organizations often seek to maintain the status quo. Moreover, teachers and administrators rarely have time or the inclination to seek out and synthesize the current research upon which to base general directions for change. Such immediate demands as student learning activities, schedules, student deportment, and fire drills command their attention. External stimulus may be needed to direct their attention and energies to broader change.

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Developing policies. Policies that set parameters and directions for change are best developed in collaboration with those in schools, especially teachers and administrators. At minimum, avenues for input should be open to influence the nature of the policies being developed. These policies must provide frameworks based on research and exemplary practice and consider and actively articulate all parts of the system. Finally, they should contain areas in which people at all levels can exercise options. For example, they should be neither so tight nor so prescriptive that teachers lack room to create and commit to a personalized vision of change.

Change also requires support and resources. Without them, mandated change fosters no more than "lip service" compliance. Once individuals and organizations set off on the path to change, they need to feel that they have the wherewithal to proceed. They need sources of knowledge (such as reference materials, programs and practices, and expert advice), systems through which they can attain that knowledge (such as staff development opportunities, networks, and professional associations), and environments that support change.

In addition, people whose job it is to foster and support change need to be actively involved. These can include mentors for beginning and reassigned teachers, trainers and consultants with particular expertise to share (who may also be teachers or administrators), and facilitators whose expertise in the change process helps cross-role groups at all levels create visions and move towards achieving those visions.

Policies that contain the two elements of pressure and assistance can take many forms. At the state level, three approaches have been followed.

California's approach. The California approach relies on developing a framework for science teaching and learning that stipulates what students need to be taught and how. That framework drives other parts of the system. Staff development offerings help teachers acquire the knowledge, skills, and attitudes required. Teacher preparation programs and certification requirements include elements of the framework. Assessment systems test what the framework suggests students should be taught. And textbook specifications parallel the contents of the framework.

Michigan's approach. The approach followed by Michigan makes staff development the core. The emphasis is on developing teachers who have adequate science content knowledge, pedagogical content knowledge in science, and generic teaching skills. Staff development programs are developed and sponsored at the state, regional, district, and school level. Networks are formed and professional associations are encouraged. Exemplary materials, programs, and practices are identified and made accessible to improve the quality of teaching.

Connecticut's approach. The approach followed by Connecticut involves developing a new assessment program. The state is building on its Common Core of Learning (Connecticut State Department of Education, 1988), a statement of preferred outcomes for students developed by consensus of educators and communities throughout the state. Connecticut is designing a system to assess these outcomes. Innovative assessment processes cover the full range of learning about science content and process. Teachers participate in developing and administering the procedures to students. This approach is based on the truism that what is tested is most often what is taught. Thus, it assumes that teachers and schools will work to change in ways that will help their students achieve the learning outcomes.

These policy approaches also are possible at the local level, depending in large part on existing state policies, traditions of local control, school and teacher autonomy, available resources, and leaders' vision.

Other Elements Influencing Change

Two elements often are overlooked in a discussion of teacher and school change. One—the preparation and certification of teachers—is largely conducted in institutions remote from schools; schools seem to exercise little control or influence over them. Accordingly, a discussion about teacher and school change mistakenly can ignore the contribution teachers' preparation can make to how they act on the job.

The second commonly overlooked element is the participation of minorities in science careers, which at the current time is severely limited. This is due, in part, to the dearth of females and students from minority groups who participate fully in high school science courses. The limited number of teachers who come from minority groups aggravates the problem. Concern for increasing the participation of *all* students should permeate the transformation of high school science.

Teacher Preparation and Certification

The new vision of science in high schools requires an adequate preparation in science, teaching science, and education. Requirements for teacher preparation should not only be thought of in terms of numbers and types of courses required, but also in terms of what is learned in these courses. Specifically, students not only need to learn science when they participate in science courses, but they also must learn how to *teach* science. Accordingly, it is essential that college science courses be taught in a manner that is consistent with the Center's recommendations. The best university-level science courses (which are rare):

- Teach science in the way that it is practiced, pursuing real questions about the natural world and incorporating investigative methods with knowledge of the important facts and concepts of the discipline;
- Relate their particular field to related fields. For example, a chemistry course would refer to physics, mathematics, and biology;
- Ground the discipline in its philosophical assumptions and historical context; and
- Help students relate the content to societal issues (American Association for the Advancement of Science, 1990).

Good courses in science emphasize depth over breadth, as do programs of study for science teachers. This raises an issue often debated about course requirements. The issue is to what extent teachers of one science discipline, such as biology, should be grounded in other disciplines, such as chemistry or earth science. Current National Council for Accreditation of Teacher Education requirements call for students to study 32 hours in their major and at least 18 in two other areas. The purpose is to give both depth in one area and some grounding in others.

Some argue that these requirements are too stringent. Majors in one discipline have little opportunity to study another. Similarly, students have few opportunities to study the history and philosophy of science.

Proponents of a broader-based course of preparation argue that all prospective teachers be required to study physics, chemistry, biology, and earth science, as well as the history and philosophy of science. This exposure, they argue, would ensure that prospective teachers have opportunities to learn science content and develop pedagogical content knowledge in areas they are likely to teach in schools.

The Core studies recommended by this report require teachers who are literate in science and can teach across the traditional disciplines. Furthermore, the Center recommends that all prospecti _ teachers study social science. The social implications of science should be examined and understood by all prospective teachers.

Underrepresented Groups in Science

Two forces acting against equal opportunities in science relate directly to teachers. First, low-income and minority students have less contact with well-qualified science and mathematics teachers (Oakes et al. 1990). Principals and teachers in racially mixed and high-minority schools complain more often than those in other schools that science and mathematics instruction suffer because of lack of teacher interest and/or inadequate preparation. Fewer teachers in these schools are certified to teach science and mathematics, hold bachelors or masters degrees in these subjects, and meet the standards set by professional associations.

The qualifications of teachers within schools also differ. In secondary schools, students identified as low-ability generally are taught by less qualified teachers. Often, these "low-ability students" are low-income and minority youngsters. As the Oakes study points out, lower-track students in higher socio-economic-status, white, suburban or rural schools frequently are taught by teachers more qualified than those who teach the higher tracks in low-income, racially mixed, or predominantly minority schools.

A dearth of teachers from underrepresented groups also exists. Just as students from these groups do not choose science careers, they do not choose to teach science. Of course, this is a vicious circle, because one reason they do not choose to teach science is that few, if any, of their science teachers have come from underrepresented groups. Students from these groups need role models to emulate. They need to see that it is possible for them to succeed in science.

Another benefit would flow from having more teachers from underrepresented groups: they understand students from these groups. To understand minority students is to know their culture and speak their language (both literally, for those who do not speak English, and figuratively, for those whose first language is English, but who use a special lingo and nonverbal cues to express themselves). Teachers' understanding extends to ways of thinking about the natural world and the place of humans in it—both integral to learning science. Teachers from underrepresented groups are more likely to use the language of students from that group, understand their learning styles, and make sense of the nonverbal cues associated with learning.

The problems of underrepresented groups require careful attention. In particular, better qualified teachers are needed to teach these students. The highest priority should be given to teachers from minority groups. Special recruitment is needed. This might begin in high school. Future teacher clubs and opportunities to tutor younger students would help. In colleges, special recruitment programs and incentives could be established. Similar programs also are needed in schools and districts. Preservice and inservice teacher development programs should include special attention to the needs of students from underrepresented groups. Such programs should stress cross-cultural sensitivity and introduce strategies for teaching to different learning styles.

Sound science curriculum and instruction should work for *all* students. Similarly, the kinds of teacher development opportunities and leadership and support structures discussed earlier in this chapter encourage teachers to improve continuously and maintain their commitment to the learning of all students. In particular, restructured school settings in which teachers work with parents and the community to make important decisions affecting student learning can increase greatly the attention paid to needs of different students, thus equalizing opportunities for all.

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Recommendations

1. The science education community should engage in a dialogue that allows its members to consider incorporating the following beliefs into their vision:

The primary goal of the reconstruction of high school science should be the creation of schools as learning communities where teachers as well as students are active learners. Active learners have a personal vision of good science teaching (in keeping with the Center's recommendations); are committed to personal change; and reflect continuously on their teaching practices and their impact.

These beliefs assume a new view of learners as individuals who construct their own knowledge, based on previous experiences. Learners are not viewed as empty vessels to be filled. Efforts to help teachers change should always acknowledge that the ultimate aim of teacher and school change is to promote student learning.

2. Change in science education should be systemic.

Many constituents need to work together to implement the Center's vision. These include schools and districts (both regular and special educators); universities (in their work with undergraduates, inservice teachers, and administrators); state and federal agencies; communities; business and industry; and practicing scientists.

3. Change should be viewed as a long-term process, at each phase using different combinations of strategies, resources, and individual and organizational roles and responsibilities.

4. Policies must be formulated at each level (federal, state, and local) that provide direction, expectations for change, decision-making prerogatives for teachers and school administrators, and adequate resources and other support for the necessary changes.

5. States and school districts must make resources available to support necessary changes.

These include adequate release time for teachers to learn, plan, collaborate, design and try out curriculum; reflect upon and practice new behaviors; help others change; and assume leadership roles in their schools and districts. One possibility is to place all or some teachers on a full-year contract.

6. School districts should vest leadership in a number of individuals beyond, but including, those in official authority positions, including teachers and members of the school and scientific community.

Leadership roles include building collaborative visions and commitment; communicating expectations and exerting pressure for change; providing resources; and furnishing continuous support for learning and change.

7. Schools and districts must support staff development that is (a) geared to individual visions and needs, (b) collaborative and collegial (including opportunities to work and reflect together and to coach peers), (c) long-term, and (d) school-based.

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In addition, it must offer teachers opportunities to learn from research, development, and the practices of others.

8. The science education community must create incentives for minorities to enter and remain in science teaching.

Special efforts should be made to recruit students from these groups. This might begin in high school. Future teacher clubs and opportunities to tutor younger students would help. In colleges, special recruitment programs and incentives could be established. Similar programs also are needed in schools and districts. Preservice and inservice teacher development programs should include special attention to the needs of underrepresented students. Such programs should stress cross-cultural sensitivity and introduce strategies for teaching to different learning styles.

9. Institutions of higher education, in collaboration with state agencies and local school districts, must prepare teachers for the new vision of high school science.

Course content must be adequate (for example, by including the study of social issues and the history and nature of science). Courses must be taught with the same learning model as that proposed for high school students. Adequate and appropriate clinical experiences, including a first-year program where each teacher is supported by a mentor, should be supplied.

10. States, regions, and large school districts should help develop an infrastructure to support teacher and school change.

This should allow and promote access to innovation by identifying and disseminating exemplary materials, programs, and practices: providing opportunities for cross-role teams to learn skills to plan, design, and implement new visions for science education: and giving opportunities for teachers to learn new instructional practices.

11. Schools and districts should develop and implement strategies to ensure collaboration within schools among science teachers and teachers of other subject areas, including vocational education.

This collaboration should aim to connect learning experiences for students, thus making science more meaningful in their academic and out-of-school life, alike.

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