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ABSTRACT

The urgency to enhance the quality of science education for all of the nation's children and youth increases as we approach the next century. To address some of the issues and to obtain insight from a variety of sources regarding the problems facing educators in science, mathematics, engineering, and technology education, a Summer Symposium was held with a small group of respected international scholars attending. The Summer Symposium concluded with an all-day invitational meeting that involved the symposium team of international scholars, a select group of U.S. science and mathematics educators invited to critique the scholars' draft report, and invited guests from professional associations and Government agencies responsible for science, mathematics, engineering, and technology education. This report contains several recommendation in order to meet the needs of a technology-oriented, information-driven society. (ZWH)

DIVISION OF **RESEARCH, EVALUATION AND DISSEMINATION • REPORT**

Science, Mathematics, Engineering, and Technology Education for the 21st Century

Summer Symposium on
Educating for Citizenship in the 21st Century
July 1992

Final Report

National Science Foundation
Directorate for Education and Human Resources
Division of Research, Evaluation and Dissemination

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Science, Mathematics, Engineering, and Technology Education for the 21st Century

Summer Symposium on
Educating for Citizenship in the 21st Century
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Ubiratan D'Ambrosio
Paul Black
Mohamed El-Tom
Michael Matthews
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1993

1992 NSF Summer Symposium

In 1992, the Directorate for Education and Human Resources (EHR) of the National Science Foundation (NSF) organized a 4-week Summer Symposium on International Perspectives on Science, Mathematics, Engineering, and Technology Education. The project was designed by Dr. Kenneth J. Travers, Director of the Division of Research, Evaluation and Dissemination, with the endorsement of Dr. Luther Williams, Assistant Director, Directorate for Education and Human Resources.

The Summer Symposium concluded with an all-day invitational meeting that involved the symposium team of international scholars, a select group of U.S. science and mathematics educators invited to critique the scholars' draft report, and invited guests from professional associations and Government agencies responsible for science, mathematics, engineering, and technology education. The opinions expressed herein are the authors' and do not necessarily reflect those of the National Science Foundation.

The Participants

Symposium Members

Ubiratan D'Ambrosio, Brazil
Paul Black, United Kingdom
Mohamed El-Tom, Sudan
Michael Matthews, New Zealand
Bienvenido Nebres, Philippines
Tibor Nemetz, Hungary

U.S. Discussants

Alphonse Buccino, Office of Science and Technology Policy (OSTP), the White House
Robert B. Davis, Rutgers University
Michael Feuer, Office of Technology Assessment (OTA)
Jeremy Kilpatrick, University of Georgia
Senta Raizen, The Network Inc.
Leo Sayavedra, Laredo State University
Robert Tinker, Technical Education Research Center (TERC)
Sylvia Ware, American Chemical Society (ACS)

International educational exchange is the most significant current project designed to continue the process of humanizing mankind to the point, we would hope, that men can learn to live in peace—eventually even to cooperate in constructive activities rather than compete in a mindless contest of mutual destruction. . . . We must try to expand the boundaries of human wisdom, empathy and perception, and there is no way of doing that except through education.

J. William Fulbright

For the remainder of the decade and into the next century, our nation faces both challenge and opportunity in science and mathematics education. A national consensus has emerged that the United States must renew and improve its science and mathematics education enterprise.

Luther S. Williams
Assistant Director
Directorate for EHR
NSF, 1992

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Foreword

The urgency to enhance the quality of science education for all of the nation's children and youth increases as we approach the next century. The Directorate for Education and Human Resources of the National Science Foundation is fully committed to finding ways to address this need. To do so requires the best intellectual resources that can be found within the United States and around the world.

This report evolved from a Summer Symposium organized in 1992 by Dr. Kenneth Travers while he was the Director of the Division of Research, Evaluation, and Dissemination. This symposium provided the Foundation with a unique opportunity to interact with a small group of highly respected international scholars and to gain from them their perspectives of the needs for science education and how those needs can be best addressed. As this report indicates, the problems facing educators in science, mathematics, engineering and technology are ubiquitous and daunting, for, as the panel reluctantly observes, "Science, one of humankind's most creative, productive and liberating achievements is not engaging the interest and minds of students." Their report contains several important recommendations as to how curriculum and instruction must be reconstructed in order to meet the needs of a technology-oriented, information-driven society. For example, education must be firmly grounded in the experience of the learner. As Professor D'Ambrosio notes, effective instruction must, "...build on children's dreams, on their fantasies and imaginations, giving them room to experiment and create without fear of punishment."

It was a distinct privilege for the Directorate for Education and Human Resources to host this symposium and I commend this report to your reading, contemplation and action.

Luther S. Williams
Assistant Director
Directorate for Education and Human Resources

There are many reasons for seeking to provide a world class education. One reason is that education is important for its own sake. But education for its own sake is not as compelling an argument for government support as is the fact that a world-class education system is essential if we are to improve our standard of living and the quality of life on our planet.

Walter E. Massey
Director, NSF, 1991-1993

Setting the Stage: Personal Remarks From the Symposium Chairman

Ubiratan D'Ambrosio

Preface

This report represents the work of a team of six scho. rs from different parts of the world - all with expertise in science and mathematics education - who were invited by the National Science Foundation to participate in a Summer Symposium on International Perspectives on Science, Mathematics, Engineering and Technology Education. I was priviledged to chair the group during the 4 week project, which took place in 1992. Our task was to investigate current programs these four fields of study at all levels of schooling in the United States. We also reviewed ongoing reform initiatives in science and mathematics education and their global implications for the 21st century.

The symposium was unique in several ways. Probably the most innovative feature was its interdisciplinary nature. NSF decided to bring together scholars from different countries, the diverse backgrounds and different areas of expertise science and mathematics education. The team included Paul Black from England, Mohamed El-Tom from Sudan, Bienvenido Nebres from the Philippines , Tibor Nemetz from Hungary, and Michael Matthews from New Zealand. Margarita Pena from Colombia was invited but unable to participate. It may be surprising to some that despite our diversity the group saw clear indications that in the curricular designs of the future, science, mathematics, engineering, and technology education will probably appear as a unified field of study.

Much of our work in the symposium dealt with the future. We tried to probe well into the 21st century - as far as the year 2061 when Halley's Comet will reappear[1] - into a future when todays children will be in charge and coping with the effects of our decisions. By the year 2061, very few of us will be around to justify or explain our visions and intentions. Yet, given the accelerated pace of change and the increased interdependence of nations the decisions we make today seem somehow more critical than do those made by our predecessors generations ago.

Another important NSF innovation was to invite to the symposium only foreign scholars, all with considerable knowledge of the educational scene in the United States but without any commitment to institutions, projects, or programs in this country the makeup of this group allowed for an open, objective, and critical assessment of science and mathematics education in the United States.

During the summer we had the oppotunity to meet with representatives of major proffessional societies in the Washington area, including the American Association for the Advancement of Science, the National Science Teachers Association, the Mathematical Association of America, and the National Council of Teachers of Mathematics. We also had opportunities to interact with staff from the

[1] In 1910, when Halley's Comet flew past the earth, few people could have predicted the extraordinary scientific and technological changes that would occur on the planet during the 75 years before the comet's next appearance. Concurrent with that visit in 1985, the American Association for the Advancement of Science (AAAS) launched Project 2061 to promote reform of science, mathematics, and techhnology education. Their efforts are funded by a number of foundations, private companies, and federal agencies, including the National Science Foundation. Undoubtedly, science and technology will shape the future, but it is hard to predict just how different life will be by 2061, the next scheduled flypast of Halley's Comet.

White House Office for Science and Technology Policy and from NSF—not only from within EHR, but also from other NSF Directorates.

To cap our month-long deliberations, a 1-day invitational conference was organized to present a draft report to personnel from the many Federal agencies (in addition to NSF) concerned with science, mathematics, engineering, and technology education. In the morning, eight recognized American experts in these fields were invited to react to our paper and serve as a sounding board for our ideas. At each table during the working lunch, one international scholar, one American expert, and invited guests continued the debate. An NSF staff member from each table summarized the discussions after lunch. The main report incorporates critical commentary and suggested additions that surfaced during the conference.

I would like to express my appreciation to Ken Travers, who designed the NSF/EHR Summer Symposium, and to Luther Williams, who lent his enthusiastic support to the project.

Dr. Williams met with the team several times throughout the summer to provide probing commentary and to challenge us to push our thinking beyond existing parameters. Our work was made easier, thanks to the facilities of Georgetown University, the expert writing of Elaine Orr, the logistical support of George Mattamal (NSF), and support from Walcoff & Associates, Inc.

The difficulty of our task—to attain consensus on a final report—was evident from the earliest meetings. Because each scholar interpreted the reading material and the presentations in distinctly different ways, discussions were animated. Our recommendations were not always unanimous. As an introduction to the final Symposium report, I would like to offer some personal reflections on several key issues affecting the decisions that today's educators must make about the science, mathematics, engineering, and technology education of tomorrow.

The World Scene

The Summer Symposium was designed to study and assess science, mathematics, engineering, and technology education in a broad context, taking into account the enormous changes that are occurring in the economic and social life of the United States and the entire world. We also recognized and built into our work "the most horrifying fact in all our lives: civilization is now capable of destroying itself." (Gore 1992)

Five hundred years after Christopher Columbus and other explorers began making global contacts, industrial development has imposed on the entire planet new ways of thinking and new scientific paradigms. Modern life depends on exploiting the world's resources and inventing new ones. The industrial revolution, for all its material benefits and scientific discoveries, has left us with a dichotomy: about 20 percent of the world population lives in prosperity while the other 80 percent lives in physical and psychological misery. That is to say, only one in every five human beings can be said to live in dignity—free of hunger, disease, humiliation, fear, and despair. Clearly, the starting point for educators must be to agree on a set of basic values—ones that exclude hunger, disease, humiliation, fear, and despair.

Goals of Science, Mathematics, Engineering, and Technology Education

Education may be conceptualized, in broad terms, as the strategy of social action that leads individuals to—

- Become cognizant of the values that constitute the basic texture of their culture.
- Act in accord with individual and societal interests.
- Behave according to agreed patterns of that culture.
- Be active, creative participants in their society.

As educators, and particularly as science and mathematics educators, we recognize that scientific and technological advances have to some degree caused the distortions and imbalances that pervade our society. **At the same time, we are convinced that science and mathematics provide the tools to redress these imbalances.** To bring about such dramatic changes, I believe we need a change in attitude toward science, mathematics, engineering, and technology. Many people see these fields as merely instrumental in providing sources of employment. We need to recognize that science, mathematics, engineering, and technology stimulate

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human thought processes. These disciplines encourage creativity and liberate the mind, thus allowing us as individuals to satisfy our human need to explain and understand the world around us.

This change in attitude toward science, mathematics, engineering, and technology must accompany a different definition of citizenship—one that allows greater participation in the decision-making process. Is this not the ultimate goal of a democratic society? The challenges facing our rapidly evolving society call for greater participation in decisionmaking, not less involvement. A citizen, by my definition, does not relinquish that power and responsibility to others. The educational systems of the future must prepare citizens to be active, creative participants in the world. Education should prepare students for life by being creative and participative itself. Science, mathematics, engineering, and technology should play crucial roles in redefining "citizenship."

Creativity

A basic assumption of the 1992 Summer Symposium was that our species, unlike any other animal species, goes beyond trying to satisfy pure survival needs. We have developed a need to transcend our own existence. We have acquired a sense of time, therefore a sense of history and progression. We search for ways to explain and understand our natural, social, and cultural surroundings.

The sequence of steps from the generation of knowledge through the progress of knowledge is the result of a complex conjunction of factors. For example, mathematical knowledge and practices develop because of immediate needs for a solution, relationships with other knowledge or practices, critical reflection and theorization, curiosity, and intrinsic cultural interest. These factors produce ad hoc knowledge, but the key questions are the following: When does ad hoc knowledge become methods and theories? How do theories translate into inventions? Both questions are germane to any investigation into the nature of knowledge. Where do new ideas come from? How are they organized? How does knowledge advance? Do these ideas have any connection with the broad environment, be it sociocultural or natural?

Generating new ideas or paradigms has always been a challenge to philosophers. What brings about a rupture with the status quo or a move away from tradition? Throughout history, scientists and mathematicians have sparked "revolutions" while mulling over ideas. The modern computer, in fact, is the result of previous generations of scientists who dared to think in creative, unusual ways. We recognize—

- Archimedes' fascination with large numbers in the second century B.C.
- The true sense of computing depicted in the *Liber Abaci* of Leonardo di Pisa in the 8th century and then improved on by John Napier in the 16th century.
- Attempts by Pascal and Leibniz in the 17th and 18th centuries to create a calculating machine.
- The more successful efforts of Charles Babbage in the early 19th century.

The work of late 19th century thinkers contributed to Herman Hollerith's design for the modern computer. Although early computers represented a "revolution," they really did no more than perform large calculations. They served as an extension of human capability to collect data and calculate—only a small fraction of the power of the human mind. Microelectronics, however, brought onto the scene powers of memory and speed only dreamed of hitherto. Scientists boldly imagined more: a machine that makes decisions. Thus, in the mid-1940s, cybernetics was born. Suddenly, the progress in solid-state physics and the emergence of microelectronics allowed humankind to see as future reality what had once been marginalized as pure science fiction.

In recent times, some of the most striking, creative revolutions have occurred in telecommunications and information processing. This technology has the potential to transform education as we know it today.

Our Global, Technological World

Distance and physical borders do not separate peoples as they once did. The way we do business has dramatically changed as a result of advanced transportation and communication technologies and worldwide access to peoples and markets. For education to meet the demands of our global, technological world, it is imperative that corresponding changes as dramatic as those in business take place in education. Globalization is an essential part of our lives; therefore, it must be a part of our education systems. Advanced telecommunications and information technologies provide the means to think, create, participate, and act globally.

The technology that will revolutionize education is teleinformatics, that is, computers linked by communication networks. The worldwide use of telephone systems and the availability—at decreasing costs—of computers, will allow networks to be part of educational systems around the world. This is already happening in limited ways. For example, the community of networks called "Internet" allows a variety of information providers to communicate with each other. Internet consists of approximately 1.5 million host machines worldwide that each, in turn, serves a local area network. Started over 25 years ago, Internet currently links some 15 million people in government agencies, research facilities, universities, and commercial firms. Local communities and school systems are only just beginning to take advantage of Internet.

I see computer networks serving as an antidote to intolerance and bigotry by fostering better understanding among peoples and nations. Better understanding could counteract the spread of fundamentalisms, nationalisms, dogmatisms, and other threats to global peace. Collaborative, network-based projects involving global contacts can facilitate global understanding; such projects are already being undertaken at the elementary, secondary, and college levels. They range from comparative environmental monitoring to more elaborate projects dealing with economics and trade to interdisciplinary research projects. Contacts between cultures and countries may encourage more foreign travel and student exchange programs. Global projects dealing with comparative analyses of data will enhance the quality of science and mathematics education for all who are involved. Moreover, they encourage students to grapple with complex problems and their complex outcomes—the essence of scientific work and the source of scientific discoveries.

It was surprising to learn that, even in a technologically oriented country like the United States, so few projects of this kind exist today.

Equity in the U.S. Classroom

Education today appears to place too much emphasis on creating and using standardized curricula with the hope that students will score higher on standardized tests. Many persons do not seem to realize that "standardized tests remain[ed, as before,] a highly accurate method for measuring little more than the ability of children to take standardized tests." (Reich 1991)

I personally believe a social distortion exists in the United States that is incompatible with the democratic ideals of this country. That is, while the vast majority of American children receive an education focused on standardized tests for a standardized (but now outmoded) economy, too few American children have access to a high-quality education. Too few students learn how to face new situations, how to think systemically, or how to experiment and probe into the unknown. Too few learn how to work in teams on joint projects, how to share knowledge and abilities to reach a common goal, or how to benefit from modern communication and information technologies to access useful data. Why is a high-quality education not available to every child in this country? How can this inequitable situation be justified?

Technology in the U.S. Classroom

The dramatic changes of the last two decades in telecommunications and information processing technologies—with their tremendous economic, political, and social consequences—appear to have had hardly any impact on the U.S. educational system.

Surprisingly, many science and mathematics educators in the United States seem hesitant to try something new, to make use of the amazing technology that is available for education at all levels. For example, at the graduate level, it seems that virtually the same syllabus is repeated in dozens of institutions. It is, in most cases, designed for a small number of students and often taught by

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young faculty who do not go much beyond the information found in textbooks.

I believe that graduate faculties should pool their resources and offer telecourses taught by teams of senior professors, with local junior faculty acting as monitors. The broad expertise of the senior professors would facilitate dynamic question-and-answer sessions. Online computer networks would allow participants to access and exchange information until the next telecourse. Would not a greater number of students be able to participate in higher quality courses? This example focuses on higher education, partly because universities generally have more computer and communications equipment available. I believe the same sort of video and computer hook-up should be used at every other level of education as well: elementary, secondary, technical, undergraduate, professional.

The classroom of the future will be linked to geographically and culturally remote environments and will benefit from all the contacts made possible by advanced communications. Crossing cultural and natural barriers without leaving the classroom is a potentially revolutionary development with enormous implications for enhancing the quality of education. There is absolutely no reason to delay moving into this new form of education. The United States can do it right now—the technology exists, as does the equipment to support these global projects. If every school system could purchase some material, economies of scale would apply and prices would drop accordingly. The overall cost of education would decrease, and the quality of education offered would escalate dramatically.

The Classroom of the Future

It is imperative that we move beyond the idea that education occurs only within the physical confines of school buildings. Many children around the world are "at home" in the streets. That is their natural environment, where they develop their basic capabilities in the context of ample space, mobility, and freedom. An appropriate learning environment offers the learner a high degree of space, freedom, and play. It includes the unexpected and the games that young people encounter in familiar environments. Children live in a world of fantasy, which is their familiar emotional environment; games play a major role in fantasy. And computer games are amazingly attractive to children. Why not incorporate some of these games into learning activities, as constructive instruments to stimulate children's imaginations and encourage creativity? As an added benefit, many computer games include a significant mathematical component.

Effective pedagogical approaches rely on two basic principles. One is to allow children to learn and perform in environments similar to those that are part of their life histories, where they acquired their first explanations of the world. The other is to build on children's dreams, on their fantasies and imaginations, giving them room to experiment and create without fear of punishment. These principles are not commonly applied in today's traditional educational systems. The environments created in some schools are contrary to the environments in which children find joy and security.

But where does the computer fit in all of this? Computers are, after all, part of our world. As Norbert Wiener says, "We do not even have the choice of suppressing these new technical developments. They belong to the age." (Wiener 1948) Children readily learn, "I can activate the machine. I can master this." This is the powerful message children get during their early experiences with computers. Informatics holds the potential to liberate the human spirit and, consequently, liberate human beings. And the first step toward progress is freedom.

The Teacher of the Future

I see the role of the teacher changing considerably in the future. The teacher as mere "transmitter" of information will disappear. After all, the amount of knowledge that a teacher is capable of storing and transmitting is extremely limited compared with what is available via computers and communication systems. For the pure transmission of facts, computers outperform teachers because computers can repeat themselves endlessly. Computers are also patient, tolerant of error, and nonaggressive. Furthermore, research has shown that an individual's creative potential flourishes in an environment that is patient, respectful, and nonpunitive.

Using computers in the classroom does not, however, decrease the need for good teachers. On the contrary, the need for well-prepared teachers increases as learning becomes more creative, hands-on, team-oriented, and linked via technology to global resources. The well-prepared teacher is indispensable as a transmitter of attitudes and values and as a participant in the creative experience. Computers do not develop attitudes and values, do not show emotional reactions, do not share abilities and know-how, and do not create.

Technology can help reduce the isolation experienced by many teachers today. Communicating via networks with a wider group of fellow teachers and students who are studying similar subjects and working on related projects can stimulate lifelong, inservice learning.

The Workforce of the Future

While the value of education goes much beyond its relation to production and the economy, the fact that education has a connection to future employment should not be overlooked. Students expect their education to have some influence on their ability to get good jobs as well as to satisfy their intellectual curiosity. The workforce of the 21st century, however, will have to be prepared differently from the workforce of the 20th century.

We are entering what has been called the era of human capital, when industry and the job market in general will depend less and less on individuals trained to be physical "hardware." Robots and other cybernetic devices can perform these functions much more efficiently and at lower social and economic costs. The job market will depend instead on "human software." Thus, preparing for the labor market in school takes on another dimension. As companies replace equipment (hardware) at a faster and faster pace, the ability of the workforce to adapt to new instruments becomes the key qualification. In the new productive system, flexibility of the worker in changing roles and dealing with more sophisticated hardware will be vital.

In the context of a global economy, flexibility of the worker is particularly crucial because it affects the quality of production. If individuals work without a sense of pleasure and pride in their performance, if they feel they are just cogs in a machine, they will not do a high-quality job. Science, mathematics, engineering, and technology education should not be producing persons who are merely observers of gauges and manipulators of levers. Regrettably, it appears that the U.S. school system is inadequately preparing graduates for fast-paced, rapidly changing, innovative, skill-intensive production. Upgrading the skills of the workforce is not considered a major goal of the education system; thus, individuals are not prepared to adapt to future changes in the needs of the workplace.

Our increasingly specialized society relies greatly on education provided by science, mathematics, engineering, and technology. Educators and curriculum designers have been concerned that the ability to read and understand instructions is not achieved in U.S. school systems; projects geared to correcting this are already under way. But there is much more to education than that. New situations are faced and problems are solved not only by learning facts, formulas, and routines but also by learning to be creative when faced with something new. Creativity must be a component in the education system of this country. We should expect school systems to develop students' capacity to analyze, speculate, innovate, create, evaluate, communicate, and participate—all tempered by a critical awareness of the cultural and social implications of their actions. No educational system can fulfill its goals without instilling these critical capabilities in its students. As we enter the era of human capital, a revamped educational system is needed for the workforce of the future.

The Team's Final Report

Any inquiry into the generation, transmission, institutionalization, and diffusion of knowledge requires a multidimensional—indeed, holistic—review of the education system. Thus, our examination of science, mathematics, engineering, and technology education covered many dimensions

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cultural, psychoemotional, cognitive, epistemological, sociopolitical, historical, and environmental. By not limiting our debate, we were able to draw up broad, general proposals for science, mathematics, engineering, and technology education for the 21st century. Our work acknowledges the growth of telecommunications and the increasing use of very powerful information processing technologies—both characteristic of contemporary society and certain to take on increasingly dominant roles in future society.

We must return to basics, but the "basics" of the 21st century are not only reading, writing and arithmetic. They include communication and higher problem-solving skills, and scientific and technological literacy—the **thinking** *tools that allow us to understand the technological world around us.*

Educating Americans for the 21st Century
National Science Board, 1983

Executive Summary

We face a major educational and cultural paradox: science, one of humankind's most creative, productive, and liberating achievements, is not engaging the interest and minds of students. This paradox occurs at a time when the effects of science, mathematics, engineering and technology (SMET) on personal life, culture, and society have never been greater.

Many extra-educational factors contribute to this unfortunate circumstance; however educational factors also contribute and include the way the subjects are supported, scheduled, taught and assessed; the textbooks used; and the pre- and in-service preparation teachers receive.

Revised goals for science, mathematics, engineering, and technology education must be formulated so that these subjects make their best possible contributions to the broad goals of education and social improvement. These goals include the development of moral understanding, the capacity to reason and to communicate, knowledge and understanding of the natural and human-made world, and practical skills for solve problems.

Science, mathematics, engineering, and technology education must produce not only knowledge and competence in these areas but also knowledge *about* these areas, including their histories; their philosophies; the personalities and circumstances that contributed to their development; and their effects on culture, belief, philosophy and the material circumstances of life. A good SMET education should produce some degree of contextual knowledge. It should also encourage adequate numbers of career specialists in scientific fields by providing students opportunities to appreciate the creative and challenging aspects of science, mathematics, engineering, and technology

Technology Education

The needs of those who are to live in a world dominated by rapid technological change can only be met by the establishment of a new school subject. This new subject should be based on a view of technology as a disciplined process using resources of materials, energy, and natural phenomena to achieve human purposes.

Pupils in school technology courses should engage in realistic tasks to meet human needs, supplemented by broader studies of technology from contemporary society, other times, and other cultures. As students consider personal and social needs that technology can meet they can discuss the issues of morality and value entailed in technological change.

Good technology education will stimulate students' practical capabilities. It will increase their capacities to plan action, make decisions, get things done, and evaluate results. Such capability is a seriously neglected part of present school curricula.

Mathematics Education

Mathematics continues to be difficult and inaccessible for many students. Too often, the subject is seen as abstract and inhuman. Everyone should learn more and better mathematics for daily living. The challenge for educators is to introduce mathematics as a human activity, in part by showing how people apply mathematics today

It is possible today to make a broader range of concepts, processes, and skills accessible to students. Several contemporary curricula around the world accomplish this goal by defining different levels of attainment-basic levels for all and more challenging levels for others. The possibility of this richer range of mathematics for all students takes advantage of using the calculator and the computer in the classroom.

The desire to develop mathematics education along the lines described above has led to several continuing efforts. Ethnomathematics, which begins with mathematics in a people's history and culture and in the daily lives of students has now become a special field of mathematics education. Technology, especially computers allows new approaches to understanding and carrying out mathematical proofs.

Science Education

Science can become more relevant to pupils if it begins by allowing them to think through and express their explanations of natural phenomena. Teaching science throughout elementary school can enhance student progress in science and enrich other aspects of the curriculum.

Secondary school science should be taught according to a coherent, unified plan that spans work in all of the sciences and covers all the years of formal study. Teaching separate sciences in separate year blocks cannot produce satisfactory leaning of the subject.

Science education should deal with fewer issues; furthermore, issues that are dealt with should be addressed in greater depth and from a practical perspective. At some stages, students should design and execute their own investigations, through which they can develop a range of skills and learn how scientists work. Work in concepts, skills, and explorations should be complemented by studies of the types of reasoning used both by the pupils themselves and by other scientists.

Science teaching should stress the technological and social effects of scientific advance; however, a full consideration of the role of science technology may require the broader approaches recommended for school technology.

Assessment and Learning

Society needs judgments about student performance for a variety of purposes. Summative assessment, designed to give an overall grade to each pupil is widely used and is based largely on standardized tests. Summative assessment is an imprecise (and sometimes counterproductive) way of assessing learning in which the outcome of several years of learning is decided in 1 to 2 hours of selecting from among the right and wrong answers of other people.

Formative assessment uses a variety of oral and written methods to judge student performance, and entails more student-teacher interaction to guide future learning. The results of teachers' formative assessments, suitably monitored, should contribute to the overall summative assessments of pupils. A judicious choice among testing options can mean that this assessment tool is more valid; "training for the test" is much closer to authentic learning.

The Teaching Profession

Improperly trained teachers cannot provide effective instruction. Initial teacher education progress should focus on three areas: preparation in subject matter, learning about educational principles, and development of classroom techniques.

Ensuring an adequate supply of well-prepared and enthusiastic teachers goes beyond pre- or in-service education. Teachers are underappreciated, are underpaid, and lack sufficient classroom materials to do effective work.

Implicit in suggestions for improving science, mathematics, engineering, and technology education is the belief that teachers need to expand their professional development if they are to stay abreast of new teaching practices and evolving technologies. Ongoing teacher interaction with peers is essential to developing cross-disciplinary work; some aspects of teachers' roles vis-a-vis students may also change, with teachers likely to spend more time as guides and sources of information as students work independently or in team. Programs to enhance professional development require a radical change in teachers' career expectations and in education funding.

Concluding Thoughts

This report reflects on the following key changes needed to reform science, mathematics, engineering, and technology education.

- Educators should recognize that "less is more" (cover fewer topics but in greater depth); they should also focus science, mathematics, engineering, and technology education on key concepts and learning modules. New instructional approaches should encourage students to identify and tackle real problems. Subjects should be taught across disciplines so that students understand the relationship of what they learn to other knowledge, their lives, their communities, and the global environment.

- Routines or procedures not regarded as sacrosanct such as the schoolday schedule or the grouping of grade levels, must be reevaluated.

- External testing must be made more reliable, valid, and supportive of student learning and must be effectively linked with classroom instruction. The success of any educational reform requires active involvement of teachers and administrators at all levels, strong management commitment to implementation, and recognition that effective change may require larger budgets.

A number of experiences in designing science, mathematics, engineering, and technology education in an integrative way have shown the obstacles to be overcome. However when attempted, the integrative approach has unleashed student energies because it gives meaning and relevance to the content and process of learning.

...before we can compete in a global economy, our people must learn to think for a living.

Unfortunately, an outdated assumption that rudimentaey skills are sufficient for a lifetime of work still haunts the Nation's education, industry and labor systems. At an earlier time in our lives, basic skills were sufficient because the United States ahd no serious international competition and production had a larger natural resource content.

But today, when the latest technology is readily available to every country in the world, and where almost everything of value has a larger knowledge content, high incomes depend heavily on higher-ordered thinking skills

Ray Marshall
Professor of Economics and Public Affairs
University of Texas at Austin
NSF, 1993

One: World Futures

The 20th century has been characterized by an exponential growth in knowledge and information. This growth often makes prediction more precise, as with forecasting weather and making medical diagnoses. At other times, the vast amounts of information combine with continually new technologies and other factors to make us realize that the task of predicting the future—even for the medium term—is more complex than was envisaged. Studies will thus disagree on a number of relevant issues, including the nature of future societies and the trends that shape them.

Consider, for example, growth (of population, human use of resources, or pollution). In *Beyond the Limits*, the authors assume certain limits to growth and claim that, in certain cases, we have gone beyond these limits. Yet in *Megatrends 2000*, the authors state that, "There will be virtually no limits to growth" and that everything "that comes out of the ground will be in oversupply for the balance of this century and probably much longer."

Futurists agree that th world is going through a major process of transformation and that the rate of change is rapid. They disagree on the extent, duration, and repercussions. One group sees this process leading only to further advancement in industrial society. However, a second group, as expressed in *The Knowledge-Value Revolution*, believes that the society we have experienced thus far will give way to a social structure quite unlike the one we now take for granted.

This chapter outlines major events and trends shaping the future. Those discussed here should have a strong impact on education (broadly understood) and particularly on science, mathematics, engineering, and technology education.

Scientific and Technological Advances

The next 50 years will witness great advances in our understanding of biological processes and innovations and developments in biotechnology, informatics, and information technology. Understanding the human brain will probably be a very important scientific problem of the next century. The pace of development in genetic engineering is so rapid that it is almost impossible to predict all of its outcomes. This field's well-publicized developments probably constitute the tip of the iceberg.

Dramatic innovations and developments in computers (size, power, and cost), automation, robotics, and telecommunications are certain to evolve well into the next century.

Social Structure and Value Systems

The developments outlined here have affected and will continue to greatly affect the social fabric of societies and their value systems. The population will probably grow healthier and older in industrialized countries, younger and more needy in many developing countries. Millions of factory and business jobs will likely be eliminated; new job opportunities (many related to the computer industry) will be created.

The nature of many occupations, from menial to professional, will most likely change. The family and schools will be faced with greater degrees of stress. Lifestyles will keep changing. All this will undoubtedly lead to new moral dilemmas and evolving value systems.

Globalization

The trend toward globalization is well under way. The next decade will bring about an increasingly integrated world economy. Another relevant trend is the awareness of the importance of a global approach to environmental problems.

Polarization

By the turn of the century, the world population will be about 6.4 billion, three-fourths of whom will be living in developing countries. Even sharper divisions may mark the "haves" and the "have-nots" with vastly different aspirations and concerns. These trends, combined with globalization, may lead to a resurgence of the desire for identity assertion and cultural conflicts.

Conclusion

The future is shaped by physical, economic, and social realities, human action, and chance. The future is pregnant with opportunities and dangers. If we are wise enough to make the right choices, we can bring about a future that is worthy of our humanity.

Education faces a major challenge. In addition to the challenge of purposes, education needs to face major problems related to its practice. We end by asking, What role may science, mathematics, engineering, and technology education play to meet these challenges?

Two: Future Issues in Education

Science, mathematics, engineering, and technology education are affected by broad economic and political trends as well as changes in the field of education itself. For the latter, there are divergent opinions on which paths to take, as reflected in the many reports and books on education reform that have been published in recent years.

Just as classroom education reflects the values of society, so education's role in society is related to broader societal issues, such as how public resources are allocated and how much worth the general public attaches to top-quality education.

Making Education Accessible to All

To create excellence in education and to offer equal access for all, particularly for disadvantaged children, youth, and adults are two of the challenges facing educators. Assuming that awareness and skills in science, mathematics, engineering, and technology can play increasingly greater roles at home and in the workplace, then depriving some individuals of full opportunities to learn is to deny them full citizenship.

There are at least three major concerns of access in schooling: access through secondary school (eliminate dropouts); access to all subjects and programs (language, mathematics, and science) that are central for full participation in the workforce; and access to significant positions and professions.

These concerns are interrelated. If education programs are stimulating and open to all, students are more likely to believe that they can enter and succeed in any trade or profession. They should better understand the value of education, study a wider range of subjects, and remain in school

Today, various mechanisms limit access:

- **Unequal distribution of resources.** Material (money, facilities) and human (quality teachers, administrators).
- **Culture and values.** Despair, which leads to self-fulfilling low expectations by students and parents; apathy from the community; and a need for instant success, which makes it difficult to understand the importance of persisting in schooling to attain long-range goals.

Experience has shown that the most important ingredient in encouraging students with low self-esteem or from disadvantaged families to stay in school is to create an environment that makes students, teachers, and parents believe in the abilities of these students to achieve.

Broad Curriculum for Full Citizenship

Education is not designed primarily to prepare people for jobs. Although specialists should still be prepared for different fields (as discussed in Section Eight), the broader mission for education systems is to offer people the opportunity to enhance their creativity and fulfill their personal goals.

While elements of a broader curriculum may take time otherwise allotted to professional subjects, the fuller human development of citizens must not be sacrificed to a narrower professional development.

The media and social pressures emphasize producing and consuming goods and services. Education needs to broaden, if not in some ways counter, this emphasis and prepare individuals for full citizenship. Education should help each person exercise, in a critical and conscious way, all rights and perform all duties associated with citizenship.

Impact of Information and Information Technology

The information revolution, as it is often dubbed, will affect education much as broad-scale literacy forever changed the nature and teaching of literature and creative writing. Computers are only one tool that influences education. Hand-held calculators with powerful microchips enable students to solve complex problems almost instantly. Electronic networking permits students in one country to compare science experiment results with their peers halfway around the world.

Even before children reach the classroom, they have honed fine motor skills on video games and have practiced the alphabet by using educational software designed for preschoolers. Once in the classroom, pupils can work at their own pace with interactive software. This not only changes learning methods but also alters the role of the teacher, who would serve more as resource person than instructor when such software is in use.

Once limited to learning through teacher instruction and texts, students now have access to online databases and university resources. Commercial interactive education software permits them to participate in scholarly contests or meet students with interests like their own.

The issues discussed here address the present. It is difficult to speculate on the impact that information technology and related studies may have on education of the future. These ever-evolving fields will present continuing opportunities to enhance learning as well as challenges to effectively incorporate those opportunities into the learning process.

Relating to the Broader Environment

Technologies are part of students' daily lives, as are students' family structures, economic backgrounds, exposure to television, and familiarity with violence through media and sometimes direct experience. The school must build upon and challenge the out-of-school environment so that students can relate what they do in the classroom to the world they live in and so that education expands their horizons and possibilities beyond their immediate communities.

Education also fosters international collaboration and understanding, preparing citizens for responsible participation in the global community. Some of the most needed and attractive fields of study of the future—particularly those related to the environment—cannot advance without a planetary outlook. This is possible today because of the revolution in computers and communications.

Three: Educating Children To Be Valuable Members of Society

Science, mathematics, engineering, and technology education have key roles to play in educating children to be valuable members of society. Before these four areas are discussed, a comprehensive view of the goals of school education should be developed. In light of these, the goals that are specific to science, mathematics, engineering, and technology can be judged within the broader context of children's education.

The goals of an education system that is designed to serve all children must be realized within the context of the development of the powers of the young child. In particular, through the critical period of adolescence, children struggle to establish their autonomy and develop a readiness to give of themselves to others in society.

Although education is only one factor in the personal development of a child, it is nevertheless important. This means that it must build upon a child's existing attitudes and knowledge to develop a child's self-esteem, creativity, and power to cope with and control the environment.

Developing a Child's Moral Framework

Education must develop each child's care and respect for fellow beings and nature, and it must help the child to respect the pursuit of knowledge and the need to engage in productive work. In addition, tolerance, open-mindedness, curiosity, and critical discrimination are necessary if education is to contribute to self-fulfillment and social responsibility.

Children must develop their learning in a moral framework that helps them to consider the purpose and use of their learning. This implies that children should explore and understand their own values, beliefs, and commitments, linking such exploration to understanding the values of moral issues and of the various ways in which issues of belief and value are handled by different groups. Such learning should help children link these understandings to their personal commitments and to the policies and practices of their societies.

Learning To Reason and Communicate

Children need a variety of communication skills. They should learn to express themselves orally, in writing, and in graphic form. Children also need a critical understanding of oral, written, graphic, and visual communications so that they can analyze the messages the media convey. Children should also develop some understanding of the role and working of the media in society.

The development of communication skills should be taken further and enriched as children become acquainted with and develop some aesthetic appreciation of the arts, including literature, music, drama, painting, and sculpture.

Similarly, children need to develop their capacities to think quantitatively. This means that they should understand and use numerical, algebraic, and spatial methods and develop an ability to apply quantitative methods to appropriate problems. Children should also come to understand ways of analyzing and presenting data, including appreciation of chance, probability, and risk.

Education should also help children cultivate reasoning skills. This should develop understanding about argument, assumptions, evidence, and logic.

Children should know about different sources of information and evidence and be able to use these to extend their own knowledge. They should begin to appreciate that there are different ways of arriving at knowledge, understanding, and beliefs and that the different ways may give different perspectives on any issue or problem.

Consider the variations that exist in the Traditional (Western) and Confucian (Eastern) approaches to learning. The variations reflect each culture and lead to major differences in emphasis on how education is organized.

Traditional (Western)	Confucian (Eastern)
Individual work	Group work
Emphasis on concepts and insight leading to skills	Emphasis on graded skills exercises facilitating understanding of concepts and insight
Understanding leads to doing	Doing leads to understanding
Children grouped by their abilities within their age groups	Children of all abilities are merged by age group, but slower students are given more time and extra help

Understanding the Natural and Human-Made World

Children should learn about some of the main ideas that physics, chemistry, and biology have produced and understand how these ideas help to interpret, predict, and control phenomena in nature. This learning should include the main ideas of earth science. Using these and ideas from the other natural sciences, children will be able to understand our own planet—how it provides the conditions for human life, globally and locally, and what developments threaten these conditions.

Study of nature leads to learning about the world humans have made. Children need to know how human technology has developed and what effects it has had in shaping and transforming society. This includes knowing how goods and services are produced, financed, distributed, and marketed.

The other development from natural science is more personal. Children have to know about the working of their own bodies and understand the conditions for ensuring good health. This should include knowing how to exercise their bodies and develop physical skills, including the ability to express themselves through movement and drama. Learning should help children know about their own physical, emotional, and social development and understand their emotional and social needs and those of others.

Developing Practical Skills

The preceding sections offer an incomplete view of education because they appear to emphasize only academic and theoretical learning. These aims must be closely coordinated with the development of practical skills in observing, measuring, making hypotheses, and interpreting empirical data. Children should be able to apply these skills in practical investigations. Although such skills may be applied in finding out, there is a matching need to develop practical skills in using and transforming food, fabrics, and common construction materials to construct artifacts and systems that meet human needs.

More generally, pupils should have opportunity and stimulus to develop practical capability in tackling problems, including identifying needs (whether personal, community, national, or global), taking initiatives, making decisions, evaluating progress and outcomes, and working collaboratively with others. This generative capacity can only become effective if children can organize and effectively orchestrate the various cognitive, social, and behavioral skills they are learning; without this capacity, much of their learning may have little relevance to their futures.

Beyond the Immediate Place and Time

Just as they need to understand the natural world, children also need to understand society—locally,

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regionally, nationally, and globally. Children need to appreciate how human groups—including personal and family clusters and wider social and political groupings—function. This implies knowing about the rights and duties of citizens in different societies, particularly their own. Such knowledge should be linked to some study of other cultures, and thus children should acquire some knowledge of at least one language other than their own.

Finally, children should learn about some features of the history of human societies. In so doing, they need to understand the nature of historical evidence and how significant features of their own societies have arisen from their particular histories.

Putting It All Together

The above considerations might appear to prescribe an impossible exercise if the various phrases were interpreted at a sophisticated level. The program implied will only be feasible if these issues are made accessible to all children in a worthwhile way. This can and must be done.

To be made effective, these aims need to be implemented within and across school curricula. Science, mathematics, engineering, and technology have key contributions to make to these aims and so have key roles to play in educating children to be valuable members of society. These roles are discussed in the ensuing chapters.

Learning is the indispensable investment required for success in the "information age" we are entering. . . . The people of the United States need to know that individuals in our society who do not possess the levels of skill, literacy and training essential to this new era will be effectively disenfranchised, not simply from the material rewards that accompany competent performance, but also from the chance to participate fully in our national life.

A Nation at Risk
National Commission on Excellence in Education, 1983

Four: Redefining Science, Mathematics, Engineering, and Technology Education

There is a major educational and cultural paradox: science, one of humankind's most creative, productive, and liberating achievements, is not engaging the interest and minds of students. Unfortunately, a well-documented flight from the science classroom and from scientific understanding has occurred.

Similarly, mathematics, engineering, and technology are not engaging the majority of contemporary students. This phenomenon is even more serious because it occurs when the effects of science, mathematics, engineering, and technology on personal life, culture, and society have never been greater.

Why Study Science, Mathematics, Engineering, and Technology?

Science and mathematics have been intimately connected since Galileo and Newton in the 17th century adopted Euclid's geometry to analyze and reason about the physical world. In those days, artisans perfected the clocks, telescopes, barometers, and pumps so essential to the new science.

Today, global environmental and ecological crises are increasingly evident. Their monitoring and solution will depend on scientific and technological competence. Science and mathematics do more than simply provide students with academic competence; they have historically promoted and encouraged rational thinking. All of these capabilities must be brought to bear to address and resolve contemporary problems.

Good science, mathematics, engineering, and technology education, in its broadest sense, offers an entitlement to all citizens—that of living in the modern world and appreciating the historical processes that have produced the society as we know it. A democratic and critical nation requires the bulk of its citizens to possess some minimal scientific competence and habits of mind.

Creation of the Paradox

Science and mathematics have had exciting and enormously influential histories. Interesting, creative, intelligent, and morally sensitive individuals have contributed to these areas of knowledge. Yet, these subjects are often taught in schools in such a way that most students have little interest in the subjects, know little of their histories, and understand even less of their contents or procedures.

In the United States, elementary school teachers are required to study very little science. It is thus not surprising that elementary school students study on average only about a half hour of science per week. Three-fourths of U.S. students do no more school science than the minimum required for high school graduation. Where they can choose to continue with science-related studies, they overwhelmingly choose not to do so. In the aftermath of the report titled *A Nation at Risk: The Imperative for Education Reform* (National Commission on Excellence in Education, 1983), all states are increasing their science and mathematics requirements for high school graduation. Nevertheless, these requirements are still minimal.

A variety of factors accounts for little attention to science in school. There is a lack of laboratory assistants and equipment. The failure of schools to schedule double-period science lessons militates against the possibility of rich practical work and investigations in science. The importance given by university admission offices to content-free tests such as the Scholastic Aptitude Test and a failure to reward students doing difficult courses also contribute to the flight from the science classroom.

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Other factors that contribute to the flight from science, mathematics, engineering, and technology education are the way the subjects are supported, scheduled, taught, and assessed in schools; the curricula adopted; the textbooks used; and the pre- and inservice preparation given to teachers. These systemic educational factors need to be addressed in any reform proposal.

Problems Beyond the Classroom

Many extra-educational factors contribute to these troublesome circumstances. Scientific and technical careers are ill-rewarded in comparison with other professional careers, and the public image of science and scientists is often unappealing—particularly to women and members of minority groups, who seldom see their peers in positions of influence or esteem in the science, mathematics, engineering, and technology communities. Science is often portrayed as the servant of war and destruction, and the exploiter of the environment.

Science and mathematics can be fun. They require creativity and intuition. However, science and mathematics also entail a commitment to the rational appraisal of evidence; the partial mastery of a corpus of agreed results, concepts, and procedures; the acceptance of reason above emotion; and self- or group interest in the evaluation of truth claims. Much of contemporary culture does not value or encourage such commitments.

Rising to the Challenge

Over the past decade, the crisis in science, mathematics, engineering, and technology education has occupied the attention of governments, foundations, business and professional associations, educational administrators, curriculum developers, and teacher organizations. Across the world there have been new curricula planned and adopted. Not since the 1960s has such concerted effort gone into the reform of Western scientific and technical education. The fast-approaching 21st century has given added impetus to the reform process.

As John Dewey remarked in 1934, ". . . the responsibility of science cannot be fulfilled by [educational] methods that are chiefly concerned with self-perpetuation of specialized science to the neglect of influencing the much larger number. . . ." There needs to be a "Science for All" emphasis in our educational planning.

Suitable, informative, and challenging science, mathematics, engineering, and technology education is essential for all students—the high achievers, the low achievers, those pursuing scientific education, and those entering other professional and semi-professional fields. Students entering the unskilled workforce and those joining the ranks of the unemployed could also benefit from science, mathematics, engineering, and technology education.

Thinking about educational reform has raised fundamental questions about the purposes and goals of science, mathematics, engineering, and technology education. These queries encompass the most appropriate interconnections of SMET education and how education in these subjects can relate to and inform education in other subjects, including history, social studies, religion, and literature.

The growth of technical understanding and competence has not proceeded in an ethical, psychological, or political vacuum; some sense of this should be conveyed in the classroom. In appreciation of this, Alfred North Whitehead, said in 1929—

> The antithesis between a technical and a liberal education is fallacious. There can be no adequate technical education which is not liberal, and no liberal education which is not technical: that is, no education which does not impart both technique and intellectual vision.

The Contextual Teaching of Science, Mathematics, Engineering, and Technology

Whitehead's position has been expressed in a number of contemporary science curriculum projects. The British National Curriculum has stated that—

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Pupils should be given opportunity to develop their knowledge and understanding of how scientific ideas change through time and how their nature and the uses to which they are put are affected by the social, moral, spiritual and cultural contexts in which they are developed.

Project 2061 of the American Association for the Advancement of Science takes a similar view. Concerning the place of history in the science curriculum, it says that "generalizations about how the scientific enterprise operates would be empty without concrete examples." Furthermore, "some episodes in the history of science are of surpassing significance for our cultural heritage." The Project then mentions the epochal work of Galileo, Newton, Darwin, Pasteur, Lyell, and other contributors to the scientific tradition.

The Biological Sciences Curriculum Study framework for science and technology education also says that there is a "need for historical and philosophical perspectives in science and technology education, as well as scientific and technological perspectives in social studies education." The Canadian government's "Science for All Canadians" recommends a similar contextual approach to the teaching of science. The Danish national technology curriculum is developed on historical grounds.

Much work is being done on the history of mathematics and its contribution to mathematics pedagogy. Work is also being done on the philosophy of mathematics and its ability to enrich the classroom.

Context in Action

The teaching of pendulum motion well illustrates the difference between routine and contextual approaches to science. The standard treatment is to state the law of isochrony, the law of independence of mass, and the law of independence of amplitude; derive each law from Newton's laws; and then illustrate the pendulum laws with a demonstration. In more progressive approaches, students are encouraged to discover the pendulum laws for themselves; the derivation from Newton's laws is then shown.

What both approaches leave out is the rich intellectual, cultural, and commercial context in which Galileo first formulated the laws of pendulum motion. The magnitude of this achievement is apparent when we remember that people had been looking at pendulums for thousands of years without seeing what we now expect junior high school students to see. Leonardo da Vinci described pendulums but never saw any of the laws operative. Indeed, great technicians and mathematicians at the time of Galileo disputed his findings.

It was mathematics, specifically Euclidean geometry, that enabled Galileo to prove his laws. Once the laws of pendulum motion were proven, it was the task of artisans and technicians to develop timepieces based upon the pendulum. These were the first accurate and convenient measures of time that the human race had constructed, and they helped solve the longstanding problem of determining longitude at sea. Thus, the development of timepieces led to increased exploration and navigation, subsequently boosting international commerce and bringing all its attendant cultural implications. The standard science program leaves out all of this rich history and intellectual struggle as it rushes students through the pendulum and on to the next topic.

Reductionism and Synthesis in Science

The successes of modern science have emphasized analysis and the reductionist breaking down of science into more and more subparts, as opposed to a synthesis that integrates and connects parts. This reductionist approach has also entered engineering and technology education, inasmuch as the dominant point of view is to see technology as applications of science. Today, however, there are cogent reasons to see technology as a completely different activity. Technology is not about analyzing reality into little bits but is about making things and integrating parts into wholes. The following table helps to compare and contrast technology and science:

Technology	Science
Integration/connecting parts	Reduction
Synthesis	Analysis
Design/process/construct	Research
Teamwork/multidisciplinary	Independence/single discipline

Shifting the balance and giving a stronger place to the integrative in education requires, among other things, giving primacy to making something (design, implementation, evaluation) instead of learning specific concepts or skills. This entails the following:

- Bringing together a multidisciplinary group of teachers who can help students and be resources for them in their project work.
- Developing project-based learning packages that require different scheduling and resource allocation and different forms of evaluation.

There exists today a number of examples of designing technology education in an integrative way. They show that there are many obstacles to be overcome; but where the integrated approaches have been attempted, they have unleashed student energies as they give meaning and relevance to the content and process of learning.

Pondering the Fundamental Questions

Questions about the purposes, limits, and goals of technical understanding have been raised in this pedagogical rethinking. What is the nature of the science, mathematics, engineering, and technology that all students should be exposed to? This is a reasonable question, especially given the multicultural nature of our world and our classrooms.

Is the long-accepted assumption of a universal science, mathematics, engineering, and technology education warranted? Even if it is, what do we make of ethnosciences, ethnomathematics, and ethnotechnologies? Ethnostudies emphasize knowledge and practices that developed in distinct cultural environments throughout generations. What can be learned from them and how might educational systems respond to them?

Science, mathematics, engineering, and technology education needs to produce not only knowledge and competence in science, mathematics, engineering, and technology but also knowledge about the endeavors: their histories; their philosophies; the personalities and circumstances that contributed to their development; and their effects on culture, belief, philosophy, and the material circumstances of life. In the last decade there has been a significant rapprochement among these fields. These integrative and contextual approaches to technical education have led the American Association for the Advancement of Science to speak of *The Liberal Art of Science.*

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Five: Technology Education

Our lives are dominated by the artifacts, systems, and environments created with human technology. The dynamic of technology continues to change our world with a power that seems difficult to comprehend, let alone predict or control. It is essential that education prepare students to understand this power and to learn about the opportunities and threats that it poses for their future. The fact that education has yet to formulate an effective and agreed-upon way to meet this need should be regarded as one of its most alarming deficiencies. To remedy this situation, a new school subject needs to be constructed.

A broad definition of technology includes its products and processes. For the purpose of this report, a suitable definition of technology is as follows:

> Technology is a disciplined process using resources of materials, energy, and natural phenomena to achieve human purposes.

This definition has several important implications for education. First, the scope is broad. Second, it clearly distinguishes technology from other subjects, notably science, in emphasizi: the meeting of human purposes. This latter aspect implies that issues of judgment and value are involved in considering these purposes.

Third, technology is a field about which students learn by critical study and by hands-on involvement. This involvement will help them develop practical capability. Fourth, students need to acquire, learn to select, and use a wide range of intellectual and physical skills if their hands-on work is to be authentic as technology and valuable for personal development.

Obstacles to Technology Education

There is widespread disagreement about the definition and role of technology as a subject of study, particularly at school level. Technology is variously regarded as craft, as craft and design, as linked to art in art and design, as the applied extension of science, or as the school preparation for professional engineering courses or vocationally oriented training. Less common is the inclusion of the technologies of food, fibers, textiles, and the home (often treated separately as home economics) and of studies of the constructed environment, mass production, and business. Inclusion of these subjects is linked to a corresponding diversity in the areas of competence of teachers. The status of technology as a school discipline is generally low, and it is not regarded as an essential field of study for all.

Whatever might be the best definition of technology as a school subject, technology is clearly a field of practical action. Education generally gives high status to learning **about** things—to critical, academic study—and low status to **doing** things, to creative construction. In consequence, practical capability is not encouraged or developed; many (including some of the most talented) students are not motivated and the development of all students is distorted. This bias against doing things is linked to the neglect and low status of technology studies.

Essential Components of a Learning Program

A Common Framework

The first essential component is that there be a single coherent program embracing the breadth of interests encompassed by the definition of technology stated at the beginning of this section. This implies, for example, that teachers of craft and design, home economics, and business studies—together with those concerned with the technological implications of such subjects as science and mathematics—must work together within a common framework.

Student Accountability

Secondly, students should be engaged in carrying out technological projects or tasks in which they have responsibility for what is accomplished. In general, tasks should involve identifying a human need or opportunity, selecting and designing an optimum solution, implementing that solution by making an artifact or system, and then evaluating the product in practical use. Some tasks might not include all of these aspects, and the steps will not necessarily be explored in the sequence specified here, but the overall experience should pay attention to all and to their interconnections. A progression in the tasks should involve, for example, moving from local to national and then to international problems, or from activities requiring common-sense knowledge and a few elementary skills to those calling for a range of sophisticated knowledge and skills.

Varied Settings, Multiple Skills

Next, the "menu" of tasks should ensure that, over time, students work in a variety of contexts, such as the home, the local environment, industry, and business. Students should also be challenged to develop and use a range of knowledge and skills, including skills of craft and design, the knowledge and understanding of science and mathematics, powers of communication, and the ability to weigh conflicting issues of value and judgment. This development should be linked, where relevant, to the learning of the other school subjects involved.

Personal Development

Such tasks should include development of personal capabilities, such as—

- Personal qualities of enterprise, resourcefulness, and determination.
- Innovative powers of imagination, invention, and intuition.
- Willingness to make and carry through on decisions.
- Sensitivity to the needs being served, to the possible consequences of alternative solutions, and to the values involved in judging any one problem and its solution.
- Ability to work in cooperation with others in a group.

Critical Assessment

Finally, students should be able to reflect on their experience with a variety of technological tasks to develop an overview of the issues and methods involved. Such critical reflection should be enriched by study of the technology of others, which should encompass historical and contemporary examples in order to illuminate the numerous influences—historical, cultural, economic, and political—that have influenced and have been influenced by the development of human technology. Among the range should be examples from different cultures, which can often be used to show how routines and artifacts that seem strange—or perhaps primitive—are actually effective and very efficient in the contexts of their use.

Implementation: Some Points To Keep in Mind

In principle, this discussion of technology education can apply to elementary as well as to secondary schools. Indeed, given the absence of the boundaries created by having subject experts and subject departments, primary schools may be better placed to include technology and to draw into it work from other areas. Experience in England, where students must learn technology from age 5, has shown that young pupils can be every bit as enthusiastic and imaginative as their

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older peers. The problem is to support such creativity to promote achievement of higher standards of thoughtfulness and skill in turning ideas into practical solutions.

It is commonly assumed that technology follows from science and is no more than the applied results of science. This view is dangerously narrow in that it can lead to neglect of the complex set of human factors involved in technological development. It is also misleading; although new scientific results have often been the seeds for technological change, the history of technology shows numerous examples of important technological changes that did not emerge from science and of many technological changes that actually influenced scientific development. It may be useful to teach about some technological effects as part of a science course, but this cannot substitute for full treatment of technology as a subject in its own right.

The two implications—of an interdisciplinary approach and of commitment to practical capability—imply radical changes in many aspects of school practice. Such changes cannot be implemented unless there is understanding and commitment of the school as a whole, led by its administration, to make the changes effective. In addition, teachers will require a great deal of outside support involving curriculum materials and equipment, re-education, publicity to help parents and employers understand changes, and development of professional associations to provide peer interaction. These initiatives should include ways to enhance the status of the subject of technology in the opinions of students, parents, teachers, and society.

Working Across Curricula and Schedules

The best way to meet the new aims may not be to define technology as a school subject of the conventional kind—with several dedicated staff, space, and regular schedules; instead, technology could be regarded as an interdisciplinary activity to be implemented by new forms of organization. For example, in one school in England, teachers of four subjects agreed on an interdisciplinary task. They pooled their schedules for a few weeks so that pupils worked about 40 percent of the time on a single task for which they had to call on specialists from all four subjects.

In another school, a period close to the beginning of the summer break—when serious work has usually finished—was revamped by suspending class schedules for 4 days. Pupils from several classes in the same grade were put together to work on a shared task. Groups were to design a new water supply system for a remote (real) village in Peru, involving building a dam and pumping and piping systems.

Activities included a debate—among planners, engineers, farmers of the land to be flooded, and the villagers—about the need for the new water system. In the debate, student groups planned and acted out the roles of the various Peruvians involved. Different groups then planned and carried out, on a model scale, building the dam from local materials, building cheap pumping and piping systems, choosing a site, designing the layout, and planning the amount of water needed.

During this period of intensive work, teachers set themselves up as resource experts: the geography teacher, for example, was available in one room to provide maps and information about terrain and geology. Teachers aimed to be responsive but to leave the initiative in the hands of students until it was time to evaluate the final presentations. This project was noteworthy for the ingenuity and hard work that it generated at a time when students were usually filling time aimlessly.

A Sample Technology Unit

The possibilities for implementation may be illustrated by a project that was undertaken with a class of 12-year-olds who were asked to investigate the problem of deaths from hypothermia among elderly people who lived alone and were unable to protect themselves. The class divided into groups to explore the different problems of hypothermia, calling on different subject teachers as indicated. Some groups constructed devices to set off warning lights and alarm bells at low room temperatures (physics). Other groups explored nutrition to

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propose and test inexpensive and nutritious meals for the aged (biology, home economics).

Still other groups explored insulating materials to see whether cheap supplementary "blankets" could be provided (physics, home economics). Finally, one group interviewed elderly people with a survey they devised (English) and collated, analyzed, and displayed their results (English, mathematics); others interviewed the local social services department (English, civics). The various efforts were put together in a closing symposium. The symposium included a demonstration of the warning signal devices. Symposium participants also weighed the warning signal against the survey report that the elderly would never accept devices that signaled to their neighbors that they were poor or unable to fully care for themselves.

Learning From the Examples

These examples illustrate that no one method can meet the aims outlined in this report. The pace at which teachers and schools can make the changes and the methods in the organization of curricula and class schedules to be adopted are matters for experiment and, perhaps, for local determination. However they are effected, the changes include fundamental shifts in how teachers relate to one another and to their students and, perhaps, shifts in the structure and organization of schools.

Attempts to draw on present practice should be made. For example, in Junior Achievement, pupils implement tasks that closely aim to meet the needs of technology education. Some examples of school–industry links might also serve the subject, particularly in recruiting local help in formulating, equipping, and evaluating some student tasks.

Experience with such work has shown that it excites new talents among pupils and that giving students responsibility for a practical, real task usually evokes great commitment. With groups of mixed ability, some surprises emerge—certain students regarded as less able in academic work suddenly show unexpected talent (and vice versa). Furthermore, with students working in teams, leaders and followers emerge so that all contribute—even though the quality of their contributions varies from one student to another. It is also possible to fine-tune many tasks, broadening or narrowing their scope and varying the amount of help given according to the potential that different groups display as they approach the tasks.

Links Within, Across, and Outside the School Curriculum

Human problems rarely evoke or need the insights of only one of the academic disciplines. Using the approach of one discipline is often inadequate and sometimes disastrous, partly because the problem itself is misconstrued by the bias involved in defining it in terms of one discipline. A school thus cannot educate students in a humane response to technological problems unless it can organize cooperation across its own subject boundaries to provide a context in which students can tackle problems with a multidisciplinary approach.

The needs of technology directly challenge one of the fundamental weaknesses of the present structure and staffing of schools. Meeting this challenge does not imply that traditional school subjects should lose their identities. Traditional subjects could instead be strengthened by motivating pupils to develop and apply, in realistic and meaningful contexts, the knowledge and skills that they have to offer.

The view of technology presented here offers a second very important enhancement to school learning. Technology as a school subject can provide a context in which practical capability can awaken and develop, supplying an outlet for many pupils who are not motivated by the more passive roles required in almost all academic study. All students could receive important stimuli for aspects of personal development that schoolwork often tends to ignore or even suppress.

Six: Mathematics Education

Mathematics has been and continues to be affected in important ways by the processes of change at the end of the 20th century. On the one hand, mathematics has attained dizzying heights of abstraction; yet the incorporation of new and powerful tools into its repertoire of concepts and methods has greatly broadened the landscape of mathematical applications.

The computer has invigorated research in some areas of mathematics, helped create new areas of research, and forced rethinking of fundamental notions. As the 21st century approaches, mathematicians will strive for higher levels of abstraction, the computer will be a familiar tool of research, and the interaction between mathematics and the sciences (including engineering) will be strengthened.

Athough basic theorems or applications of algorithms may remain unchanged, the methods used in discovering, proving, and applying them have been profoundly changed by modern technology. Calculators reduce to seconds the time needed to make complex calculations, and the computer can determine the probability of a random occurrence almost as soon as the operator's fingers leave the keyboard. One challenge to educators is to help students take advantage of this technological progress without losing the solid grounding in problem solving that traditional teaching methods sought to achieve.

The Importance of Learning Mathematics

It is important not only to learn mathematics but also to learn *about* mathematics. The history of human thought and culture is incomplete without learning about Pythagoras and why Plato wrote above his study, "Let No One Ignorant of Geometry Enter." Also notable are the great Arab mathematicians who introduced algebra to the West, or the Chinese collection of problems that has led to the Chinese Remainder Theorem (and its applications to modern coding theory).

For more than 2,000 years, school children have learned deduction and reasoning from Euclid's Elements; for the last two centuries, scientists and engineers have had calculus at the foundation of their studies. The nature and the power of mathematics is at the center of much of Western philosophy, particularly the understanding of what and how we know.

The rapid scientific and technological developments in East Asia are better understood if we recall that a highly developed Chinese and Japanese mathematics discipline served as intellectual preparation for the rapid absorption of Western mathematics and science by Asians.

Those who would see mathematics as only a lofty analytic discipline or a research tool for other complex subjects would miss its role in everyday life. One cannot balance a checkbook, comprehend the rapidly announced statistics during a baseball game, or calculate the mortgage amortization schedule on a house without being competent in mathematics.

Whether for higher education, trade work, or domestic life, all students need to learn more and better mathematics. Learning more and better mathematics presents a great challenge because the standard mathematics curriculum was designed for a small elite, and the transition from mathematics-for-the-elite to mathematics-for-all demands greater flexibility in the curriculum to meet the needs of different groups. On the other hand, the revolution in educational technology now allows for coverage of a broader range of topics in mathematics and for the greater variation and flexibility needed for learners of different abilities.

Obstacles To Learning Mathematics

A major obstacle to learning mathematics is the sense that mathematics is "inhuman" or "ahistorical," that there is a magic grab bag of mathematical formulas and tricks that remains unreachable except to the initiates. Many view mathematics as a collection of unrelated finished products, having little use in daily life. This image of mathematics is far removed from reality and obstructs effective learning; it is, however, understandable. Do children see many "math heroes" on television or hear their parents discussing such figures? While children may idolize astronauts, they have little awareness of the solid grounding these space pioneers have in mathematics.

Children who are taught mathematics in a language other than their mother tongue often face a major obstacle in learning mathematics. In a way, these children are required to learn two languages at the same time.

As a hierarchical discipline, mathematics requires learners to build on previous knowledge as they learn new skills. In the classroom this can be frustrating because children who do not grasp the fundamentals find themselves falling further and further behind. Recognizing this problem and providing the means to identify and help the frustrated child is one key to having that youngster achieve some success and start to make progress.

One challenge is to help parents—many of whom find current mathematics texts challenging (if not threatening)—understand the role of mathematics in modern society. Children take many cues from their parents; a parent who is intimidated by modern mathematics or its applications may not be able to transmit a full appreciation of the discipline or its value in many other subjects.

Our ability to equip individuals with the mathematical competencies required by future society and to attract able students to mathematics depends on our ability to overcome these obstacles. Curricula reform must take into account the various obstacles and constraints that may hinder change. The conditions essential for success in this and other areas of education compel us to rethink teacher education and training programs and to seriously ponder the role of the computer in the enhancement of mathematics instruction and learning.

Essential Components of a Mathematics Learning Program

The Human Connection

Mathematics should be introduced as a human activity. This can be done by teaching a thorough history of the people who built mathematics. Archimedes, Newton, Leibniz, and Gauss were immensely rich and interesting personalities. It is also important to connect with real people doing mathematics today, such as teams in mathematics olympiads and mathematical innovators whose work relates to things students can see and touch (such as telecommunications). An example might be the one-page profiles of current applied mathematicians that have recently appeared in *Scientific American*. Such profiles can introduce people with whom students can identify, thus providing the sense that mathematics is something students can own and share.

A Comprehensive Approach

Students should be introduced to mathematical concepts, processes, and skills over as wide a range of mathematical areas as possible. These should include the traditional areas of numbers, calculation, algebra, geometry, and measurement as well as statistics, discrete mathematics, and using computers. Students should also be given adequate experience in the processes and skills imbedded in these mathematics areas.

Problem Solving

Students should learn to develop approaches to problems and problem-solving skills. They should be guided through the experience of formulating problems, making conjectures about possible solutions, checking the validity of each conjecture, and learning to move to a solution step by step. These experiences can give students the confidence that comes from small successes. Over time, students can develop the complex thinking processes and skills referred to as mathematical power.

Achievement for All

The essentials of a broad range in mathematical content, processes, and skills cannot be achieved if we think of mathematics as a stepladder on which students must first climb to arithmetic, then algebra, and then statistics (for the few who get there). Today we have standards and curricula, developed in various parts of the world, that show it is possible to provide this broad range for all students—at a basic level for some and at a more challenging level for others.

The British National Curriculum in Mathematics provides such a range by setting five attainment targets: using and applying mathematics, number, algebra, shape and space, and handling data. The attainment targets are subdivided into three strands each, and achievement levels are divided into tenths. The strand on reasoning, logic, and proof, for example, aims at level 1 to train students "to make predictions based on experience" and at level 10 "to handle abstract concepts of proof and definition." The strand on patterns and relationships aims at level 1 to train students "to devise repeating patterns" and at level 10 "to use a calculator or a computer to investigate sequences." *Curriculum and Evaluations Standards*, a publication of the National Council of Teachers of Mathematics, gives examples of similar levels for the different curricular standards.

Appropriate Equipment

A condition for achieving the above goals is that people take full advantage of the range of technology available for learning mathematics. It is assumed that appropriate calculators are available to students at all times and that a computer will be available in every classroom for demonstration purposes. Students should have access to a computer for individual and group work, and they should then learn to use the computer as a tool for processing information and performing calculations to investigate and solve problems.

Nonmathematical Applications, Nonlinear Learning

Students should have opportunities to experience the role of mathematics in broad, problem-solving situations, some of which may not require mathematics as the decisive component. Activities and projects such as those envisioned in the standards of the National Council of Teachers of Mathematics and the British National Curriculum (particularly broader ones in conjunction with science and technology courses) should provide opportunities to develop analytic and problem-solving skills in broader and more integrated situations. Formulating a problem in a wide setting, devising a strategy for solution, suitably modeling the mathematical component of the solution, and providing a mathematical solution in closed form or approximation under constraints exemplify such skills.

Students should experience the interactive relationship among the concepts, processes, skills, and activities involved in mathematics learning. The traditional organization of mathematics textbooks usually presents the relationship as strictly linear: from concepts to skills to applications in activities. Discovery in mathematics is often nonlinear: a back-and-forth relationship actually exists among components. It may be useful to approach topics in different ways and show this oscillatory interaction among the components.

Concepts/Structures ⟷ Processes/Skills
↖↘ Activities/Projects ↙↗

As noted above, students should be provided opportunities to participate in projects in a wider setting. Mathematical modeling offers such opportunities. Examples include the projects on hypothermia and on the water system for the Peruvian village described in section Five. The hypothermia project provided the experience of obtaining several sets of numbers (temperatures of rooms and of the older people, number of calories, costs of different solutions), finding appropriate relationships among these numbers, and understanding the interdependence among these sets of numbers. The Peruvian village water project provided similar opportunities. Clearly, these projects bring in variables and expertise beyond science, mathematics, engineering, and technology and include social science, management, and the politics of consensus and decisionmaking.

Some Recent Trends

Efforts to begin implementing changes in mathematics teaching have led to a trend to enhance learning—especially among children whose cultural or home environments differ from those of the majority in their classrooms—by introducing mathematics in the context of a child's familiar community. Termed "ethnomathematics," this emphasizes knowledge derived from practices and reflections of quantitative and qualitative natures, accumulated through generations in distinct cultural environments. Ethnomathematics in school thus builds on children's experiences and abilities to deal with situations in their daily out-of-school environment. For example, in some areas of Peru, children are taught mathematical history through descriptions of the contributions the Aztecs made to mathematics. Students may also be taught how street vendors use addition and subtraction to service their customers. This gives students a sense that mathematics is part of daily life and offers the opportunity to build skills using familiar examples. One challenge is how to make the transition from the informal algorithms in these historical or everyday examples to the formal ones in our present mathematics.

Another trend is to use computers to enhance learning and widen the range of approaches to mathematical concepts, processes, and skills. Computers now run through many examples of a mathematical theorem in a relatively brief time. Computers offer an approach of "plausibility" as opposed to "rigorous proof." A balance between the two approaches is needed. Students should be introduced to enough experience of mathematical proof to understand its process and importance. On the other hand, the presentation of a wide range of results through "plausibility arguments" would allow students to experience a broader range of mathematics.

A third trend is to change the organization and dynamics of the mathematics classroom. New approaches to teaching and learning mathematics present aspects of mathematics as a laboratory subject, requiring the continuous laboratory hours long used in science. They also present mathematics as a "project-based" subject, such as technology, requiring a multidisciplinary approach over a longer period of time. As with science and technology, new approaches to mathematics change the teacher's role from that of a simple dispenser of knowledge to a guide, a facilitator, and a discussion leader. The demands and challenges thus presented to the teacher are taken up in Section Ten of this report.

Seven: Science Education

Science today is changing more rapidly than ever. In one direction, the investigations of cosmology and of fundamental particles are leading to exciting developments in understanding the origins of the universe and the basic forces and fields that control the rearrangements and transformations of matter. Yet this excitement comes with a high price, given the costs of increasingly powerful accelerators and more elaborate space platforms.

In a different direction, the interplay of the biological and health sciences is opening up new possibilities that could lead to new choices, with concomitant moral dilemmas for everyone's lives. At the same time, new substances, new materials, and new sources and ways of using energy are being developed so quickly that it is hard to predict whether the human race will soon face critical shortages in resources or is on the brink of a new richness of material possibilities.

There are also changes of a different sort. Concern that we have held out false hope for applications of science that can actually lead to unexpected disasters has called into question the wisdom of conventional support for science. In the past, such support has sprung from a belief that each country's progress depends on the quality of its pure science research. That belief is now being challenged. In the future, science may have to make the case for its support to a far more critical public and political audience.

The sharp contrast between the excitement and the cultural, social, and personal importance of science on the one hand and the evident weaknesses of science education on the other is cause for grave concern.

Obstacles To Learning Science

Many pupils find science, particularly the physical sciences, extremely difficult. Scientific material is often too abstract; there is so much of it to be learned that there is no time to reflect on it, let alone read and discuss it. The image of science projected by schools is that of an impersonal activity in which issues of human, historical, and social concern appear to have no place. For many students—and particularly for females—this aspect of science is unattractive.

Another misleading impression is that science consists of fixed rules and formulae to apply. Science appears to be a chiefly passive or routine activity, with experiments set up simply to "prove" theories; imagination and creativity appear to have no role in scientific activity.

To cap all of this, the information presented in science classes can seem to most students to have no relevance to the main concerns of their lives. For far too many, science is simply boring.

Essential Components of a Learning Program

Science as a Human Activity

The first component of an effective science learning program was explained in full in section Four. Students should learn about science as a human activity. They should appreciate that scientific achievements have emerged in particular historical contexts, depending on the beliefs, technology, social systems and, above all, human personalities of those contexts. Students should also realize how evidence, experimentation, hypotheses, models, and mathematics are combined in the development of science.

Understanding Science and Its Methods

Students should understand the origins of science by participating in it. This involves a three-part approach. Students should first learn about the ideas of science. These ideas form a structure of concepts, many of them quite abstract, that can be a powerful means for predicting and controlling natural phenomena.

Students educated in science should then acquire some appreciation of scientific methods and their diversity. They should learn to use practical skills, such as observing, measuring, analyzing data, and interpreting results. The methodological skills are not, however, merely practical but extend to intuition, creativity, and imagination in hypothesis development and experimental design. Methodological skills also extend to procedural matters about how evidence relates to hypothesis and belief as well as the complex but interesting issues of when to maintain, modify, or reject beliefs in the light of aberrant evidence.

Thus, creative and analytic skills play roles in science and critical thinking. The analytic skills are often overlooked; however, their cultivation contributes to the development and habituation of logical reasoning and critical thinking.

Neither concepts nor skills can be properly understood in isolation, however. It is not possible, for example, to make observations or to propose hypotheses except in the light of some preconceived model of the system under consideration and in relation to concepts and rules for their formulation. Conversely, understanding how concepts have developed can only be reached by using these skills in attempts to make sense of the natural world.

The interaction between concepts and skills constitutes the activity of experimental science, which leads to a third way in which students can learn science by doing it: pupils should have personal experience of experimental science by being given responsibility to plan, design, carry out, and interpret their own experiments. Only through this experience can students develop a full and authentic understanding of what science involves.

For example, in exploring plant growth, pupils could be asked to ponder the factors that affect plant growth and then to investigate the effects of light and water on the growth rates of some plants. To do this, students could set up a design in which the two variables are varied one at a time, with the other controlled, and with attention being paid to controlling additional variables such as the initial height of the plants and the soil characteristics. Care should be taken in measuring; choosing amounts of water and light to use offers an opportunity for sophistication by looking, for example, for effects of interaction among the variables.

As a whole, such an investigation would be carried out as one stage in a sequence of activities designed to explore plant growth and would not be seen as a "process" exercise divorced from the business of learning concepts. Students might also go on to look into the work of von Helmont in the 17th century, who was the first to show experimentally that the mass added to a tree in its growth could not have come from soil and water alone. In this way, students can appreciate being part of a tradition of investigation.

While it is argued that concepts, methods, and explorations should all be included in a learning program, it is not implied that every new idea must be developed through students' personal investigations. However, having personal experience of investigating some ideas and phenomena should help pupils understand how others have arrived at new ideas through scientific investigation.

Knowing About the Results of Science

The third component needed for an effective science learning program is that students should know about a large number of results of scientific work that are important to their lives. A full list is not given here but it should include such facts as

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limitations on efficient uses of energy, alternative sources of energy and prospects of future supply, composition of the atmosphere and how atmospheric changes can threaten humanity's future, opportunities and dangers presented by genetic engineering, and how the AIDS virus can infect and kill.

It seems neither possible nor necessary that all of the topics in a comprehensive list could be studied as deeply as suggested in the tripartite interaction of concepts, skills, and processes discussed above. A few topics could be studied in this way to develop a full appreciation of the workings of science; but others may be studied less deeply, emphasizing those features that individuals need to know and understand to lead healthy and responsible adult lives.

Implementation: Some Points To Keep in Mind

Work in one of the three essential components can often lead to one or both of the other two components. A variety of sequences is possible.

Science teaching often attempts to cover too much in the time available. A few topics studied more thoroughly, leaving time for reflection and discussion, will give students a far more authentic and interesting view of the subject. As Ernst Mach said a century ago (and as many have repeated subsequently), covering less material results in learning and understanding more.

Learning science can be relevant to most students if the starting points are everyday issues or problems. The science curriculum cannot be planned as a sequence of conceptual areas set out in time according to the logic of the conceptual structure. Instead, a sequence of a series of relevant issues could help students increase their conceptual understanding and competence in the skills.

No one recipe can secure relevance, however. Students can be interested in systems of ideas and marvelous exploits that are quite remote from their daily lives, provided that the presentation is imaginative and conveys real enthusiasm.

Studies of how students learn have shown that much teaching is ineffective. The key to improvement appears to be changing the approach to teaching new topics. There must be a radically new emphasis on starting from students' own ideas, helping them express and explore these ideas with each other, and then challenging them to see the point of changing old ideas and adopting the (frequently unusual and even unnatural) ideas of science.

Facilitating Learning

In some countries, pupils are taught science throughout school in mixed ability groups, whereas other countries use some form of streaming or tracking. There is clearly a case to be made for some differentiation at the higher levels if the more talented students (particularly those more talented in the mathematical and the abstract parts of the subject) are not to be frustrated. However, there are alternatives to separate tracking that are preferred by many teachers who want to avoid the need to label children. Negative labels applied at an early age can become self-fulfilling prophecies, with damaging effects to a child's self-esteem.

When work is organized in topic modules, formative assessment after students complete a basic core of the material can help determine which students can go further—perhaps working on their own or in small groups. Other students can do work that rehearses or repeats the basic ideas they found difficult. At the end of the topic, all the students may have reached a basic level of understanding, while others can have completed advanced work.

Where work on students' own investigations plays a part, differentiation can be achieved by varying the scope of the task and advice according to the needs of each student group. Individualized learning programs in science have been found unsuitable because of the difficulty of incorporating laboratory work—providing equipment and supervising labs to meet safety requirements turn out to be very difficult obstacles to overcome.

Even when pupils work on the same prescribed experiments, it is very difficult to imagine how a science teacher can prepare and implement the experiments as well as demonstrate in other parts of teaching without having some technical assistance in preparing, running, and clearing up laboratory sessions. If open-ended investigations are to be encouraged and more experimental activities are to be supported to accommodate a range of abilities, then technical assistance in school science departments is absolutely essential. Many countries regard such provision as a normal requirement. Any educational system that does not provide such help either does not understand what science teaching requires or is not serious in trying to provide high quality science education.

Placing an emphasis on a multicultural approach to science is likely to be advantageous. Most contemporary science is the product of the Western tradition, and there are few opportunities to emphasize contributions from different cultural traditions—except perhaps in the pre-Renaissance history of science. However, non-Western understandings of health, navigation, medicine, the environment, and animal husbandry can all be used to challenge accepted views. A varied approach building on student perceptions of their own social, cultural, and natural environments is the essence of the ethnoscience.

Most of these considerations apply as much to university courses as to high school work. Indeed, unless such changes are implemented at the university level, it is hard to see how future generations of teachers can be prepared to deal with a new style of curriculum. For current teachers, continuing education should focus on two radical changes. One is the need to include discussion of historical and philosophical aspects of science. The other is the need to include pupils' own investigations—a need that can only be met through major changes in classroom practice. Careful trial and guidance will be essential.

Beginning Science Early

There are important reasons why the science program envisaged here should start in primary school. Young children's interest in the natural world is easily stimulated: they are capable of developing some of the skills, such as measurement or testing ideas, and can show initiative in carrying through tests of their ideas.

The foundations of conceptual learning can be related to discussion of children's ideas, but it would be a mistake to go beyond the first steps. For example, children can play with batteries, bulbs, and wires and learn that a complete circuit is needed for anything to work, that a bulb needs two connections to work, that bulbs can be arranged in series or parallel, and that the bulbs will be brighter as more batteries are used. At this first stage, children do not need—and can neither understand nor use—the formal concepts of current and voltage.

Such activities can develop a child's enthusiasm for science. These activities can also provide a good starting point for descriptive and imaginative writing and for developing skills of oral description and discussion—to enable science to fit comfortably into the natural interdisciplinary approach of primary schools. It is also evident that children need to start learning and acting upon many scientific facts at an early age, especially those scientific facts concerned with personal health and safety. Finally, building on the basis of several years of primary science work and sufficiently uniform practice across the schools in a region, any middle or secondary school can progress further than schools that must start teaching science from the beginning.

There seems every reason, therefore, to develop the role of science in the primary school. The main obstacle is that most primary teachers have not been trained to teach science, probably participate in little science at school themselves, and are frightened of the subject. Strong and ambitious training programs are needed to overcome this obstacle. Primary science is beginning to flourish in several countries around the world that have given priority to primary science and in whose schools inservice programs have been held over several years.

Links Within, Across, and Outside the School Curriculum

Applications of science in daily life should be a part of any school program. Scientific applications would have more prominence as starting contexts

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for topics of study than as thoughts inserted after an abstract treatment. However, it may be more realistic to consider scientific application in everyday life and in society from the broader perspective of technology, in which context scientific contributions should be seen as one of several influences on development.

This leads to discussions of the effects of scientific work in society, as often covered in science/technology/society programs. These discussions have been a valuable enrichment to the science curriculum. However, the approach to technology recommended in section Five of this report provides a better context in which to consider such problems. If developments of the type proposed can be achieved, then the introduction of science/technology/society topics into the science curriculum might be restricted, concentrating on those in which the direct relevance of the scientific influence is clear.

Much of what is recommended applies across the spectrum of the separate sciences. There is a strong case for treating at least some concepts in a unified way because they apply in many different areas of science. For example, a study of energy would draw from physics, biology, and newer fields such as ecology. The plan for studying the sciences should span all the years of compulsory schooling. Such a plan would incorporate work on the sciences into a coherent, linked sequence and would not present these subjects in isolated blocks—let alone in separate years.

In general terms, the conceptual basis of science has a definite structure represented under the divisions of biology, chemistry, earth science and physics. Such a structure should be reflected in planning a curriculum but should not lead to teaching four disconnected subjects with no coherent overall plan.

Finally, more serious attention should be given to establishing links between science and other school subjects. For example, the history of science can foster interdisciplinary cooperation with history, literature, and religious studies staff. Reenactments of historical episodes and debates can bring drama and expression into the science classroom. Many scientists wrote splendid literature; these writings, with their uses of metaphor, analogy, and argument, can be considered in literature classes and can provide excellent models of lucid expression. Scientists were often engaged in moral, religious, and political argument; some sense of these disputes can be conveyed and related to contemporary tensions in science.

Innovations

Of the points raised in this chapter, three in particular present a considerable challenge to teachers and schools. First, teachers will need to extend their knowledge and adopt new teaching styles to introduce historical issues and philosophical reflections into their science teaching.

Second, teachers will have to overcome many logistical problems to cope with introducing pupils' own investigations, changes in planning to integrate such work into their teaching schemes, and changes in their roles with pupils because teachers should guide pupils' initiatives rather than tell them what to do.

Third, all secondary school science teachers should learn to work together in new ways to provide a coherent program of science for all, while those in primary schools should be prepared to implement primary science as a normal and significant part of their programs. Taken together, these changes constitute a fundamental and formidable challenge to the teaching profession.

Science is rarely the hypothesis-experiment-analysis-conclusion paradigm so often taught in school as "the scientific method." Scientists do not follow a prescription; why should students? "Real science" involves messing around, often with new instruments, and looking for something "interesting."

Robert Tinker, 1993

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Eight: Educating Specialists

Educators face the challenge of how to provide students with a sound general education as well as the opportunity to spend more time on particular subjects for which they exhibit a keen interest or talent. Among the issues considered when discussing specialized education are the needs to—

- Ensure students are exposed to a wide range of subjects and options from which to select particular pursuits.
- Consider the age at which children are able to decide on a special interest to pursue without unknowingly limiting their options.
- Ensure students who specialize in one field possess sufficiently broad experience with other disciplines to be good critical thinkers and be comfortable in the modern technological world.
- Identify students with high potential and provide them with enrichment opportunities or special classes, doing so in an equitable way.
- Have sufficient numbers of individuals in given programs so that society has, for example, requisite numbers of physicians, ecologists, physicists, mathematicians, or computer programmers.
- Provide adults with options to specialize in subjects or career fields at later points in life if, after completing their secondary or university educatio they decide to pursue another career path.

While none of these goals conflict, each requires different strategies to ensure that the needs of learners (students or adults) and society are met.

When To Specialize

There has been a range of approaches to student specialization, including some highly tailored to the capabilities of exceptionally bright children and others that designate a given age or grade level after which children follow selected paths of study. Some of these choices are as broad as college preparatory versus vocational education, while others identify a specific discipline and channel a large proportion of a student's time to related coursework.

Part of the debate over an appropriate age at which children should pick a field of specialization focuses on when children can make the most informed decisions. For example, in the United Kingdom, where students traditionally had to choose one or two subjects from biology, chemistry, and physics at age 13, females were likely to choose differently at age 13 than at age 16. At the earlier age, still influenced by stereotypes of traditional careers for women, females generally picked the humanities and biology as specialty areas; few opted for the physical sciences. When choice was left until age 16 and females were less encumbered by old conventions and more confident of their skills, far more of them selected the physical sciences for advanced study.

Also at issue are the "nontextbook" aspects of education, such as emotional development and learning to interact among peers. Although subject specialization at an early age does not necessarily inhibit student growth in such areas, students should continue to associate with peers in other-than-academic settings.

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Different Issues for Different Educational Goals

While students may choose to specialize in a given subject area, their goals for doing so can be quite broad. Some students envision scholarly or research pursuits and plan to take advanced degrees. Others need a broad background in a given field but will probably spend their careers applying the specialty rather than leading the discipline. Still others may take a range of specialized secondary courses so that they can pursue careers as technicians.

Although the numbers of students involved in the various areas of specialized study are quite large, there is a special subgroup of students who are highly talented in particular subjects. These are particularly valuable students who need special attention if their gifts are to be fully developed. Their needs will be given separate attention later in this section.

While "educating for citizenship" means primarily education for all, it is in the interest of any nation to ensure that the future specialists, including the exceptionally talented, are encouraged and provided with a deeper education. Actions to achieve this objective involve three tasks:

- Encouraging, attracting, and enriching.
- Selecting.
- Providing special types of education.

The second and third tasks will be discussed later in separate sections on the broad group of specialists and on the highly talented group, respectively. The first task will now be considered in a discussion covering both groups.

Encouraging, Attracting, and Enriching

Countries employ a number of known avenues to help interest young people in given subjects and to enrich their learning opportunities. Many of these approaches are geared toward gifted students, but the activities permit all interested students to learn beyond the classroom.

Even in countries with histories of student self-selection into special programs or university degree areas, there are at times special programs to encourage students to choose specific areas. Often, these special programs are geared to encourage students to enter career fields in which the nation believes it has a skills shortage.

Examples include—

- Local and regional competitions in science, mathematics, engineering, or technology, some pitting individual students against each other and others in which teams from various schools compete. Outstanding among these are the national and international Olympiads.
- Subject-specific clubs that provide added challenges as well as the opportunity to spend time with students having similar interests. Most clubs provide hands-on experiences.
- More passive provisions, such as public television programs that highlight outstanding people in a field or special periodicals that cover science, mathematics, engineering, and technology.
- Use of telephone, radio, electronic mail, scanners, or personal computers through which especially interested students can share interests or consult in science, mathematics, engineering, and technology activities.

These largely extracurricular endeavors are supported by dedicated faculty members. The faculty help to run activities after school hours, which most often attract the bright or highly motivated students. However, if brought into the schoolday, these activities may also appeal to the average or poorly motivated student.

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Education and Selection for Future Specialists

In some countries, there is no provision in schools for work specifically designed for future specialists, so that a student's first experience of such study comes after entry into tertiary education. In other countries, notably Great Britain, most students take very specialized courses in the last 2 years of secondary school so that they are as well equipped on entry to tertiary courses as are students at the end of their first college year in some other countries.

Both of these extremes have serious disadvantages. A better policy for the last years of compulsory schooling might be to have a substantial and broad common core taken by all and then, for a minor portion of the time, to provide specialist courses. Students should be able to choose a few of these without such choice being a final commitment.

The problems of selection for entry to tertiary courses are difficult to resolve in ways that are fair to all and yet do not harm the learning or motivation of students. Such selection should be based on assessment of performance, both across a core and in relevant specialist studies. To be valid, selection to tertiary programs should draw on a range of evidence collected in a variety of contexts and should include a substantial component contributed by each student's teachers on the basis of work performed over extended periods of time

Evaluation and Selection for the Highly Talented

In addition to the programs for specialists at all levels of ability, the highly talented need extra stimulus and encouragement. Some countries have gone to the lengths of separating such students and teaching them in special institutions, often as a preparation for representing their countries in international competition. Such procedures seem to endanger the broader education of the students as well as their personal and social development.

Less radical provision has also been found to be successful. One example is provision of "master classes" run by high-level subject experts with a talent for teaching. Students may attend these classes simply on the nomination of their schools, spending half a day each weekend in a local center performing advanced work in one subject—each center serving a large urban area.

Another example is to run highly specialized classes in a few schools, within the normal school-day schedule. These schools select students on the basis of each school's own entry tests. In both examples, students maintain a high level of commitment and enthusiasm. In general, education of these highly talented students should be linked to university centers rather than to selected schools.

Selection of these pupils should be informal and allow them to leave the programs at any time, for whatever reason. Usually, the students envisaged here are outstanding; what is needed is to publicize the opportunities and encourage potential users rather than conduct examination boards.

Learning New Specialties in Mid-Career

With the massive changes technology brings to local and world economic structures, it has become more common for people to be faced with the choice of remaining in stagnant careers, joining the unemployment lines, or going back to school. Thus, planning for this area of specialist education should not be confined to traditional school education.

Many potential specialists can be trained at later ages. They may find some aspects of learning more difficult than younger students, but they may also be more highly motivated.

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What distinguishes the present reform movement from all precedents is its truly revolutionary premise that all students can and must learn. Assessments should be used to determine what students have learned and what they still need to learn. They should never be used to filter students out of educational opportunity.

Hyman Bass, 1993

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Nine: Assessment of Students

Assessment is needed and used for a variety of purposes. The aim must be to match methods and procedures to the various purposes in the best possible way. In doing this, it is important to note that what suits one purpose may not suit another and that conflicts of purpose frequently arise.

The terms *assessment*, *testing*, and *evaluation* are used with overlapping meanings. The focus in this section is on collecting and using information about the performance of individual pupils to guide their learning or determine future possibilities. The word assessment will be used to cover all these procedures.

It is important to note that this section does not discuss evaluation of teachers or of school performance.

Summative Assessment

Summative assessment is designed to give an overall grade to each student, usually because society—and perhaps the student—requires a judgment about performance. Such assessment usually implies high stakes. For these purposes, summative assessment is usually conducted from outside the school. Where it is well constructed, such external assessment can provide clear targets for pupils; if authentic methods are used, it can also provide good models for teachers and so be a useful guide to teaching.

However, there are two serious difficulties. The first is that external summative assessments are of necessity limited in the time expended and in the range of instruments to be used. For example, it is hardly possible to assess a pupil's ability to design and carry out a pr actical investigation within the limitations of external assessment.

Such shortcomings can seriously limit the reliability and validity of any results. For example, where a particular aspect of performance is to be assessed over a wide range of contexts and using a variety of ways to present an assessment item, it is often found that a pupil's performance shows very big differences between one item and another—even though they are all designed to assess the same element of the subject. The solution of asking many such questions and taking the average—or best—performance usually takes longer than can be allowed. The alternative of cutting out "aberrant" items can narrow the range of items used and so reduce the validity of the assessment. It is also inadequate because different items may be "aberrant" for different students.

The second difficulty is that the importance of such assessment means that it can come to dominate schoolwork and, insofar as the assessment is limited in range and style, can seriously distort teaching and learning. This effect is well known. A typical instance is that learning experimental science is reduced to drilling in multiple choice questions to prepare for a session in which the outcome of several years of learning will be decided in 1 to 2 hours of selecting from other people's right and wrong answers.

One essential for reducing the undesirable effects is to use a variety of tests, including essays, short problems, library projects, comprehension tests on passages of science writing, multiple choice questions, short skill tests with equipment, and longer pupil investigations. A judicious choice from such a range can bring an assessment system, taken as a whole, much closer to a valid assessment, so that "training for the test" is as close as possible to authentic learning.

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A second essential for improvement is to put at least some of the assessment in the hands of the student's own teacher so that extended pieces of work—projects, investigations, or essays—can be assessed under natural working conditions. Teachers can thus vary the amounts of help they give according to each student's needs and allow for such help in their assessment. The challenge is to set up calibration systems so that users of the results, including pupils themselves, can be assured of the comparability among different teachers. This is further discussed later in the report.

Formative Assessment

Formative assessment is the day-to-day appraisal that gives learner and teacher the feedback they need to evaluate progress and so appraise learning needs. It is an essential part of good learning and can use a variety of formal and informal methods. This states an ideal; however, while most teachers test their pupils in several ways, practice often falls far short of this ideal. Few teachers have developed methods that reflect the broader aims of their teaching. Marks may be assigned at the end of a block of work, but all students proceed with the next block, with no action being taken on the basis of these marks.

Whereas summative assessment may be criterion referenced or norm referenced, formative assessment should be criterion referenced to meet the aim of making clear how far the student has succeeded. Ideally, students are able to check the extent of what they can do and so be clear about what needs to be done next. Thus, formative assessment becomes more effective when it is set in a framework guiding the overall progress that is needed.

The information gained in formative assessment is for the learner as much as for the teacher. The assessment is far more likely to be understood, accepted, and taken seriously by students when they are involved in their own assessments. This implies that the aims of any piece of work are clearly thought out, understood, and shared by the student, so that assessment becomes the student's day-to-day guide to success. Rather than a threat and stigma of failure, the assessment is a positive incentive and guide to learning.

Reconciling Summative and Formative Assessment

Good formative assessment is essential to enrich learning, but it has been inadequately developed in school practice. Bad summative assessment has done great damage in the past and given assessment a bad reputation. However, some form of summative assessment is an inevitable and legitimate requirement that society makes of educational institutions.

Institutions that have to select from among many eager applicants need indicators of student performance on a single scale. External summative tests meet this need in an apparently fair way. However, their limitations in respect to reliability and validity and their bad effects on teaching indicate that better ways should be sought. An additional factor here is that there can be serious bias effects in such tests. Because the tests can only take a short time and because they have to present items in the same way to all candidates, the tests may create unfair burdens for students from minority cultures and/or impoverished backgrounds, not least because of difficulties with the formal language used.

A start can be made by ensuring that all assessments, whether summative or formative, are designed and marked in relation to whether certain criteria of performance have been met. Thus, a criterion-referenced approach should be universal. To simply report a student's achievement as related to the performances of others is of little value either in guiding learning or in providing information to ensure fair selection.

An attractive solution could be to strengthen formative assessment and to try to arrange that—in addition to serving its primary purpose as an intrinsic element in learning—formative assessment could also, without distortion, provide the information needed for summative assessment. The first problem here is to put the assessments from a variety of teachers and schools onto a common scale. One way could be to combine external tests and internal assessments, using the external test results to scale the internal assessments. The drawback here is that it is, in principle, wrong to use a

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measurement of one set of aims to calibrate measures of a different set of aims.

Another way could be to provide some form of school inspection so that an external expert can calibrate by inspecting samples of the evidence on which internal assessments are based. A third way could be to set up meetings of groups of teachers from different schools so they can inspect samples and results from the work in each other's classrooms and arrive—through a formal procedure—at agreed adjustments. This is the most expensive of the three procedures, but experience using it has shown that the exchanges are of great professional value to the teachers who take part.

Whatever procedures are involved must be sufficiently rigorous that all people involved, particularly the pupils and those making difficult selections, can have confidence in the fairness of any scaling. The problems involved here will be more complex if there are wide variations among schools in the curricula followed and the aims pursued. The problems of comparability may then become almost insuperable. One escape from these is to use so-called tests of aptitude, but the relationship of these tests to the achievement or aptitude of the student is problematic. The use of subject tests set by a national agency simply means that an agency is given power to specify a common curriculum.

A second prob'‹ ·n that arises in such use of formative assessment is that it can put pressure on the process of learning, in stressing important outcomes. By so doing, formative assessment might inhibit free exchange between teachers and students. Teachers might be less willing to be critical of faults and students less able to listen to and profit from such criticism. The final outcome might be experienced as "progressive harassment." This raises the further choice between frequent assessment (where one is never free of the assessment effect of what one does) and terminal assessment (which takes away the day-to-day pressure but makes one's fate depend on the vagaries of one specific, brief, and highly charged occasion).

The tension between summative assessment for external use and formative assessment to guide learning is also bound with tensions between internal and external assessments and between continuous and terminal assessments. Such tensions are inevitable. The ideal might be attained it, through involvement in their self-assessments, students could come to see assessment as an essential and positive guide—even when its outcome meant that an ambition was going to be frustrated by the results.

An optimum solution might involve combining frequent and terminal assessments with teachers' internal and external assessment methods. Considerations between primary and secondary schools here might be different, with primary schools relying more on internal and informal methods and avoiding terminal—and stressful—assessment occasions.

The overall aims being pursued in developing such combinations should, however, be kept in clear view. These are to—

- Strengthen the practice and the status of formative assessment as intrinsic to teaching and learning.
- Involve pupils in sharing and taking some informed responsibility for their own assessments.
- Use a broad range of assessment methods so that results are as valid and reliable as possible and the feedback effects on learning are positive.
- Eliminate, as much as possible, bias in respect to gender and culture.
- Ensure that teachers' own assessments make a substantial contribution to the summative assessments of their students.
- Provide results that can command confidence among all those who have to make use of summative assessments.

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In this new pursuit of excellence . . .
Americans have not yet fully recognized two essential truths:
first, that success depends on achieving far more demanding
educational standards than we have ever attempted to reach before, and second,
that the key to success lies in creating a profession
equal to the task—a profession of well-educated teachers prepared
to assume new powers and responsibilities to redesign schools for
the future.

A Nation Prepared: Teachers for the 21st Century
Carnegie Forum on Education and the Economy, 1986

Ten: The Teaching Profession

This section of the report considers issues that bear upon the central role of the teaching profession in any program to improve schools. First, the education of teachers is discussed, with considerations of pre- and inservice aspects. This is followed by consideration of the role of teachers in reform and the related issues of their status and level of responsibility.

Future society and the workplace within it depend upon the energies of teachers. Teachers cannot fulfill their duty on the basis of initial training alone. They need regular retraining, essential to keep up with the changing needs of students, changes in aims and methods of learning, and changes in educational technology. Acceptance of this point requires a radical change in the career expectations of teachers and in funding of education.

Many issues are entailed here: What should initial training encompass? In what sequence should the various components of initial training be arranged? At what sites and under whose aegis should retraining courses be held? How should such courses be related to the classroom? Who should bear responsibility for the funding? These are all difficult matters to resolve.

Meeting the Needs of Students

It is important to keep in mind that the objects of the instructional process are not abstract entities; rather, they are children of different ages, environments, cultures, and mental capacities. Through the training process, teachers must learn how to respond to the varying needs these differences imply.

One important difference is age. It is common to group students according to three age-groups.

- Ages 5–10, including kindergarten and lower primary (elementary) education.
- Ages 10–14, also called middle or lower secondary school.
- Ages 14–18, known as secondary (high school) or preuniversity education.

Children in these three age-groups have different needs that must be reflected in the preparation of their teachers. An elementary educator probably does not need to know very much about solving differential equations; however, secondary mathematics teachers should be well versed in deeper mathematics. A similar set of distinctions could be made for science, engineering, and technology education.

Many believe that the middle school years are neglected. Indeed, there are only a few countries in which teachers are licensed or certified for these middle grades. In systems with two major tiers of teacher training (elementary and secondary), it might not entail much additional effort to add a middle school specialty or at least to give this area special attention in the two existing tiers.

Three aspects of teacher education programs will be considered—preparation in the subject matter, learning about educational principles, and development of classroom techniques.

Training in the Subject Matter

There is a natural tendency for academic specialists in the curriculum subjects to exert a strong influence on the high school curriculum. Their

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interest is essential, but it can be dangerous. Work on specifying such a curriculum and on the subject training required for it should involve collaboration among subject experts, science educators, and those with expertise in children's learning. A particular reason for this is the need for continuity among the three stages of school education. University-imposed curricula are notoriously unsatisfactory.

The influence of expertise in children's learning will be particularly salient in the elementary phase; the balance between subject matter training and learning about pedagogy should reflect this. A thorough understanding of basic concepts and skills and of the (well-documented) difficulties that children encounter with them requires particular attention because this area spans the boundary of responsibility between training in the subject and training in the pedagogy of the subject. It would also be valuable if the training in science, mathematics, engineering, and technology that elementary teachers receive could form a coherent, single course to be taken by all.

For the older age-groups, the curriculum organization in schools needs to be reflected in the structure of subject training. For example, teachers specializing in one of the sciences should also have some continuing study of the others. To the extent that, as recommended in this report, stronger links are developed in schools across education as a whole, teachers trained for any one of the four areas should also have some substantial experience of learning about the other three and of interdisciplinary work involving all four.

Lee Shulman, director of the Carnegie National Teacher Assessment Project, has drawn attention to teacher competence and command of subject matter in relation to how they can make it intelligible to students. In one of his influential publications, Shulman has said—

> To think properly about content knowledge requires going beyond knowledge of the facts or concepts of a domain. It requires understanding the structures of the subject matter. . . . Teachers must not only be capable of defining for students the accepted truths in a domain. They must also be able to explain why a particular proposition is deemed warranted, why it is worth knowing, and how it relates to other propositions, both within the discipline and without, both in theory and in practice.

This type of teacher competence will be enhanced if science, mathematics, engineering, and technology teachers have some interest in and familiarity with the history and philosophy of their discipline and are capable of imparting such knowledge and interests to students. At least one such course should be part of teacher training programs; provision for further investigation could be made in teacher-enhancement programs.

Future teachers should also have opportunities to relate their subject work to the work of peers in other subjects (such as history, language, or drama) so that they can learn about the serious attention to subject interactions that they should pursue later in their own teaching.

Learning About Pedagogy

While teacher education courses generally focus on how children develop and how their personal, social, and learning needs may best be met, the study of adolescence seems to be a neglected area. This may be related to the neglect of specific preparation for the middle school level.

Future teachers of science, mathematics, engineering, and technology should have more than standard courses in psychology taught by psychology specialists. Such courses must address the growing body of knowledge about how children learn the particular topic areas of science, mathematics, engineering, and technology.

Such preparation should also reflect the changes that are taking place in the role of the classroom teacher. Greater emphasis should now be put on the teacher as a manager of learning, assembling material for children and guiding them to take initiatives in learning. A particularly important consideration here is the need to develop the skills of handling discussions with pupils. Another consideration is the need to develop the management techniques required for classrooms in which different groups of children will work simultaneously on different projects.

Central to most of a teacher's interactions with students and their professional lives in schools is an implicit or explicit philosophy of education—a view of the aims of education and of the rights and responsibilities of students, teachers, administrators, and governments in schooling, etc. Developing such a philosophy of education should occur as a part of teacher education programs. Some of the training in pedagogy designed for K–12 teachers could be used for future college teachers.

Classroom Techniques

Teachers exercise a very complex set of skills in managing the busy reality of classrooms. This complexity is enhanced whenever interactive styles of teaching and work with practical equipment are involved. Thus, the areas of science, mathematics, engineering, and technology include very demanding requirements. Training in these areas should be grounded in experience and should deal with the many practical details so that overall aims are not lost. This should be done by practicing teachers or by practicing teachers working in collaboration with teacher trainers who maintain their contacts with and experience of the realities of classrooms. In many countries, decades separate teacher trainers from their own classroom experience.

Inservice Education

The education system must be responsive to changes in society's expectations, changes in society, and changes in education itself. Many changes in education arise from changes in the subjects being taught, changing practi es in schools, insights provided by the research and development projects funded by governments and others, and changes in educational technology.

Teachers cannot possibly respond to such needs in their spare time. At a minimum, teachers should have the time and facilities for regular retraining that any other high-quality profession provides for its members. To achieve such training at the requisite level requires a significant shift in perceptions from governments about funding needs; from inservice providers about the quality of their contributions; and from teachers and schools about their expectations and career plans for regular, full-time retraining.

Institutions that provide training should be concerned with the capacity of their staffs and the appropriateness of their course designs to stimulate and support changes in classroom practices. Courses that leave the teacher to put new ideas into practice without followup support are usually of very little value. Likewise, courses that do not incorporate contributions from teachers who have actually put the new ideas into practice may lack credibility or be ill advised.

There is some virtue in schools conducting inservice training on their own premises among their own staff, perhaps with one teacher delivering materials with which he or she has become familiar through an external course. The possibility of developing inservice materials designed for use in courses of this type should be explored. Likewise, countries that have developed large organizations devoted to distance-learning, such as the Open University in the United Kingdom, are using this vehicle to conduct inservice courses for teachers in a wide range of topics and over a wide range of levels. Thus, there are opportunities to explore diverse strategies to serve teachers and schools working with many different needs and constraints.

The Future of the Profession

The analysis and recommendations presented in this report add up to a formidable agenda for an overlapping set of fundamental changes. Most of the burden of such changes will fall on teachers and schools, while the impetus for them may be coming mainly from society as a whole. It seems possible that society will expect extraordinary efforts from the profession without, at least in some quarters, understanding the magnitude of the burdens.

Yet it is also evident that the teaching profession is underappreciated, underpaid, undereducated, and lacks sufficient resources. There is therefore a serious question as to whether the changes should even be attempted unless all levels of society are prepared to change their attitudes toward the profession. Society in general and its politicians in particular cannot be passionate about the need for better education and lukewarm about the status and support of teachers. Without changes of this type, the passion for reform will probably be frustrated. The daily practice of a profession cannot be improved by law and statute alone—although it can be all too easy to demoralize such practice by these means.

Where Does Change Happen?

In addition to the arguments presented so far, there is another issue: the extent to which teachers should have a say in determining the substance of any reforms. Moves for reform cannot achieve anything unless they are turned into practice by teachers in their classrooms and schools. Yet this obvious feature seems to be neglected time and again when administrators make policies and turn them into plans and prescriptions without considering the experiences and opinions of those who will have to implement them.

Plans for educational change should undergo radical reappraisal if this sort of error is not to be repeated. If new ways of securing the intelligent commitment of large numbers of teachers cannot be found, then the next rounds of initiatives will probably have as little effect as their predecessors have had.

Eleven: Examples of Systemic Change

The process of educational change includes at least three levels of participation. These are political leaders at the national or state level; professional educators, usually at the university level; and teachers and administrators at the elementary and secondary school levels. The following examples seek to illustrate the interplay among these levels of participation.

United Kingdom

The recent reform of the curriculum in England was established by the Education Reform Act of 1988, which established new powers for the government to prescribe curriculum and procedures for national assessment at several ages, including the certification examinations at the end of compulsory schooling. All children between the ages of 5 and 16 have to study science, mathematics, engineering, and technology.

Detailed specifications for each subject were developed on the basis of proposals put forward by groups of professional experts. However, these proposals were subject to extensive consultation and to amendment by the government. The new curricula for science and mathematics had to be implemented for some grades in all schools by autumn 1989. However, the curricula have since been revised with little professional input. The changes have upset many of the teachers who supported the original reforms.

Three issues should be noted here. First, when politicians gain control, the principle of paying respect to professional opinion—to which some political officials may subscribe in the initial stages—may not be sustained when politicians are lobbied by special-interest groups. Second, politicians and ministry officials—and, indeed, the public—seem to have little real understanding of the scope and amount of the work required to implement a completely new curriculum.

There is a third, much larger, issue about educational innovations. Many well-documented examples show that innovations intended to improve teaching and learning have not achieved their aims, even in the hands of those who have adopted them willingly. There is a chasm between laying down new programs and having them realized in the hands of teachers.

The difficult choice for those attempting to make very large changes is to judge the scale and the pace at which these can proceed as well as the processes of consultation—perhaps of trial and evaluation—that will best secure the desired effects.

Japanese Curriculum Change in the 1980s

Japanese curriculum changes came from an initiative of the Ministry of Education in 1973. The changes illustrate initiative coming from the top in response to growing dissatisfaction from students, parents, and teachers. The Ministry of Education convened a Committee for Deliberation of Curriculum. It had many subcommittees, and the process took more than 7 years to implement.

After the long process, which involved intensive consultation among all sectors, implementation was total and rapid; consensus was achieved. There is agreement on what the problem was: too many students falling behind in school mathematics. There is agreement on the lines of a solution: not to develop a multitrack system but to change standards to sufficiently remedy the situation. The reason for the choice of approach is understood: the value given to uniform development in Japanese society.

Mathematics Reform in Hungary

It should be noted that even in Japan, a very homogeneous country, it takes a couple of decades to work out and implement reform. Some remarks of the late Professor Tamas Varga about the process of the mathematics reform he led in Hungary illustrate the importance of time frame and the role of political leaders. Varga remarked that the new curriculum he initiated went very well in the beginning. He compared it with infecting the system with a "good virus" and noted that the spread of change in the beginning followed the usual rates of "spread of infection." The problem came when political leaders decided that the curriculum change was so good that everybody must have it immediately. The organic process of change was disrupted, and the final results were not as desired.

Secondary Education Development Project in the Philippines

The Philippines is in the final year of implementing a major reform of the secondary school curriculum, including science and mathematics. The time frame of the reform is extremely constricted, in part because it is funded through a World Bank loan with a 5-year period. There is deep concern that this reform may come like a flash flood: sweeping by, leaving the earth unfertilized, and possibly causing numerous problems.

This is partly the reason for an intermediate effort that began in 1992. The project is to improve science and mathematics programs in 110 leader high schools throughout the country. These high schools are clustered geographically around teacher-training colleges, and these colleges are given responsibility for helping upgrade the high school programs. Part of the goal is to have these leader schools be the "good viruses" to support the overall reform in the Secondary Education Development Project.

Latin America

In the 1970s, a number of Latin American countries instigated significant educational reforms. Many of these were aimed at recognizing cultural differences, thus moving from a centralized curriculum to local curricula. Many countries introduced bilingual education.

As an example, Brazil had a single national curriculum. Reform made the curriculum the responsibility of each teacher—although in practice, coordination needs to be achieved at the school and state levels. Other countries reformulated their curricula nationally, taking into account regional and cultural differences.

A new effort toward curriculum development was necessary to implement the reforms. Implementing these changes relies on leadership that normally comes from the faculty of teacher-training institutions. The cultural and environmental differences of the children are considered in the redefinition of curricula in science, mathematics, engineering, and technology.

Different cognitive styles of learning and understanding resulting from these differences are of major importance. As an example, consider the implications of structuring a curriculum for children who live in an overpopulated urban region and experience deficiencies at home (lack of adequate lighting or even lack of adequate space in which to do homework), as opposed to rural children for whom the day normally begins at dawn and ends at sunset or suburban children who live in comfortable homes. These different situations all call for special approaches to curriculum.

These considerations led the Organization of American States to generate a special program on "Leadership Development for Curriculum Innovation in Science and Mathematics," based since 1975 at the State University of Campinas. An interdisciplinary approach to science and mathematics education was proposed. Many of the resulting innovations can be seen in ethnomathematics and ethnoscience programs where motivation for study came from environmental circumstances, not from artificial arrangements.

West Africa

The same ideas were also the basis of a program sponsored by the United Nations Educational, Scientific and Cultural Organization and the United Nations Development Program in the early 1970s to prepare graduate faculty to implement science and mathematics educational reform in West Africa. The project, labeled "Centre Pedagogique Superieur," was located at the Ecole Normale Superieure de Bamako, Mali. Through an interdisciplinary approach, the program had significant impact on teacher training in the region.

These experiences, focusing on the importance of the sociocultural and environmental determinants of a curriculum, place emphasis on the "training of trainers." Without special attention paid to the leadership, the preparation of teachers capable of carrying on reforms cannot be achieved.

The Sudanese Educational System

In the Sudan, curriculum reform may be initiated by the Minister of Education or the Department of Curriculum, which is part of the National Institute for Curriculum and Teacher Education.

New curricula are developed, tested, and evaluated at the National Institute. After they are adopted by the ministry, teacher inservice training courses are conducted, new national textbooks are prepared, national examinations must be reviewed, and the new curriculum is then implemented nationwide.

An advantage of this system is that the several bureaucratic agencies responsible for school curriculum can work together in a coherent way. A drawback is that the teacher has no role at all, either in initiating or developing reform.

New Zealand Science Education Reforms

The central government of New Zealand contracted a university department to create, in consultation with teachers and other groups, a new high school science curriculum. Work, discussions, and drafts proceeded for about 4 years. When the curriculum was finally presented to the government, the responsible minister said that it was not what was required. After thousands of hours of work, this decision was not universally lauded. The process suggests that closer consultation between curriculum framers and final decisionmakers should occur at all stages of curriculum revision.

Conclusion

There can be no single recommendation for the best way to make changes in all educational systems. The best method for any particular nation can be formulated only by those with an intimate knowledge of its schooling and politics. However, several points that emerge from the above accounts follow.

- Society's legitimate role in influencing education should not be left entirely in the hands of either national interests or local pressures. The best balance between these two areas may be very different in separate circumstances.
- Too rapid or radical a change can be counterproductive. Preparation and trial that do not work according to a schedule and with a firm intention for decisions can lead to frustration.
- Teachers cannot be expected to put reforms into practice unless their expertise is respected in formulating them.
- Top-down reforms can achieve the appearance of effective and rapid action but risk being ineffectual and demoralizing for teachers—those on whom the health of education mainly depends.
- A delicate balance should be struck between decentralization that allows education to work from a diverse local culture and central targets that enable children to transcend deprived local environments. A centralized system also helps internal mobility.

Today we maintain ourselves.
Tomorrow science will have moved forward
yet one more step,
and there will be no appeal from
the judgment which will then be pronounced on the uneducated.

A. N. Whitehead, 1929

Biographical Sketches of International Scholars

Ubiratan D'Ambrosio is a professor of mathematics (emeritus) of the Universidade Estadual de Campinas, Sao Paulo, Brazil. He was chief of the Unit of Improvement of Educational Systems of the Organization of American States (1980–82) and director of the Universidade Estadual de Campinas' Institute of Mathematics, Statistics, and Computer Science (1972–80). Dr. D'Ambrosio has served on the faculties of the State University of New York at Buffalo (1968–72), the University of Rhode Island (1966–68), and Brown University (1963–65). He has also been visiting professor at the University of Illinois at Chicago, Ida Beam Distinguished Visiting Professor at the Science Education Center of the University of Iowa, and a visiting lecturer at the Biozentrum of Basel Universitaet, Switzerland. He was vice-president of the International Commission of Mathematics Education (1982–86) and president of the Interamerican Committee of Mathematics Education (1979–87). Dr. D'Ambrosio gave the Opening Plenary Address to the International Congress of Mathematics Education in Adelaide, Australia, in 1984 and has been distinguished as a Fellow by the American Association for the Advancement of Sciences. Dr. D'Ambrosio's Ph.D. in mathematics is from the Universidad de Sao Paulo, Brazil.

Paul Black is a professor at the Centre for Educational Studies at King's College, London. After 20 years as a researcher and teacher in physics, Dr. Black moved from professor of physics at the University of Birmingham to the chair of Science Education at Chelsea College, which subsequently merged with King's College, London. Here he served for several years as dean of education and director of the Centre for Educational Studies; Dr. Black also served on many national bodies in the United Kingdom, notably as chair of the group that advised the Minister of Education on assessment and testing in the new National Curriculum. Dr. Black served for several years as deputy chair of the National Curriculum Council for England and Wales. He is a member of the International Commission on Physics Education and consultant to the OECD Project on Innovations in Science, Mathematics, and Technology Education. Dr. Black has worked in several curriculum projects and has directed research projects concerned with the national monitoring of British science education, the development of technology and of other cross-curricular work in schools, and student understanding of science concepts. He obtained his Ph.D. in physics at Cambridge, England.

Mohamed El-Tom is a professor of mathematics at the University of Khartoum, Sudan. He has held various academic and research positions at the University of Khartoum; the new University of Ulster, United Kingdom; and CERN (Geneva), Switzerland. In 1978, Dr. El-Tom was a visiting associate professor at Arizona State University, Tempe, Ariz. His main areas of research interest are numerical analysis and the role of education in building mathematics in Third World countries. Dr. El-Tom has edited two books and published several papers in mathematics and mathematics education. His Ph.D. and B.S. in mathematics are from Oxford University, England.

Michael R. Matthews is professor of science education at the University of Auckland, New Zealand. Initially trained in geology, Dr. Matthews taught high school science for a number of years, during which time he completed advanced degrees in psychology, philosophy and education. He has been involved in teacher education for 20 years. Dr. Matthews' research interests and publications have covered the philosophy of education, the philosophy of science, and the history of science. Some recent edited publications include *The Scientific Background to Modern Philosophy* (Hackett Publishing Company, 1989) and *History, Philosophy and Science Teaching: Selected Readings* (Teachers College Press, 1990). Dr. Matthews is founding editor of the international quarterly *Science & Education: Contributions from History, Philosophy, and Sociology of Science.* His Ph.D. is from the University of New South Wales, Australia; and his M.A., B.S., and B.A. are from Sydney University.

Bienvenido Nebres is president of Xavier University in Northern Mindanao, Philippines, and chairman of the Project Advisory Group for the Philippine government's Engineering and Science Education Project, which includes development of science and mathematics programs in public high schools throughout the country. Dr. Nebres has served on the Executive Committee of the International Commission on Mathematics Instruction and has participated in the ICMI study titled *School Mathematics in the 1990s.* Because of the wide variety of situations in East and Southeast Asia and their clear impact on science and mathematics education, Dr. Nebres has been particularly interested in the social and cultural variables that affect mathematics education. He focused on these issues in his plenary address at the International Congress on Mathematics Education in Budapest in 1988. He did his earlier work in mathematical logic. Since 1970, Dr. Nebres' main science work in the Philippines has involved building graduate programs in science and mathematics and training high school mathematics teachers. Among his degrees are an M.S. and Ph.D. in mathematics from Stanford University and an M.A. in philosophy from Berchmans College in the Philippines.

Tibor Nemetz is a senior research fellow at the Mathematical Institute of the Hungarian Academy of Sciences and professor at the Department of Probability and Statistics, Eotvos University of Science, Budapest. Dr. Nemetz has participated in and conducted a number of preuniversity educational projects, his primary interest being in teaching statistics, application, and mathematical modeling. He is one of the conveners of the ICMI Study Group on Mathematics as a Service Subject, was chief organizer of the Sixth International Congress on Mathematical Education (ICME-6), and was a member of the program committee for ICME-7. Between 1990 and 1991, Dr. Nemetz served as chair of the Committee for Mathematical Education of the European Mathematical Society. His mathematical interests cover information theory, probability, statistics, and discrete mathematics. Dr. Nemetz is author or co-author of 90 publications, including secondary school texts, college texts, and lecture notes. Dr. Nemetz' doctoral degree and diploma in mathematics are from Eotvos University of Science, and he has served as a postdoctoral fellow at Carleton University, Ottawa, Ontario, Canada.

Biographical Sketches of U.S. Discussants

Alphonse Buccino was a staff member at the White House Office of Science and Technology Policy during 1992. Dr. Buccino is Dean of the College of Education at the University of Georgia, a position he has held since 1984. From 1970 to 1984, Dr. Buccino served in various capacities in science and engineering education at the National Science Foundation.

Robert B. Davis has taught mathematics at MIT, at Syracuse University, and elsewhere He served as the Director of the Madison Project, a nationwide effort to improve school mathematics, and was leader of the team that created mathematics courseware for the University of Illinois PLATO computer project. He is presently New Jersey Professor of Mathematics Education at Rutgers University, and Editor of the *Journal of Mathematical Behavior.*

Michael J. Feuer was a senior analyst and project director at the Office of Technology Assessment (OTA), U.S. Congress, where he specialized in education and human resources from 1986 to 1992. He is currently Director of the Board on Testing and Assessment at the National Academy of Sciences. Prior to 1986, Dr. Feuer was assistant professor in the Department of Management and Organizational Sciences at Drexel University.

Jeremy Kilpatrick is a professor of mathematics education at the University of Georgia. He currently serves as vice president of the International Commission on Mathematical Instruction. Before joining the faculty in Georgia in 1975, Dr. Kilpatrick taught at Teachers College, Columbia University.

Senta A. Raizen serves as the director of the National Center for Improving Science Education. Ms. Raizen began her career in science education and evaluation with Sun Oil Company in 1945. Since then she has worked for the National Academy of Sciences, the National Science Foundation, the National Institute of Education, and The Rand Corporation.

Leo Sayavedra is president of Laredo State University, where he began as an assistant professor of education in 1975. From 1960 to 1972, Dr. Sayavedra was involved in education from the elementary years through graduate work, teaching chemistry, physics, and mathematics; he also coached football, basketball, and the University Interscholastic League. From 1972 to 1977, Dr. Sayavedra taught education as an instructor, a teaching assistant, and an assistant professor.

Robert F. Tinker is the principal investigator for the Global Laboratory Project at Technical Education Research Centers (TERC). Dr. Tinker is also the director of the Cambridge Development Laboratory, which he founded in 1979. From 1977 through 1989, Dr. Tinker directed the Technology Center for TERC. Beginning as an instructor at Stillman College in 1964, Dr. Tinker later taught at Amherst College, Springfield Technical Community College, and Hampshire College.

Kenneth J. Travers was a staff member at the National Science Foundation from 1990 to 1993 and Director of the newly established Division of Research, Evaluation and Dissemination from 1992 to 1993. He is a professor of mathematics education at the University of Illinois at Urbana-Champaign. Prior to joining the faculty in Illinois in 1963, Dr. Travers taught mathematics at the school and college levels in British Columbia, Canada.

Sylvia Ware is the director of the Education Division of the American Chemical Society (ACS). Joining ACS in 1979 as the first manager of the Office of High School Chemistry, Ms. Ware later became head of the Educational Services Department in the Education Division. She is currently the editor of the news magazine *Chemunity News* for ACS. Ms. Ware has worked for Imperial Chemical Industries in her native England. She has also taught chemistry for the British University entrance examination; physics and biology for the West African Examinations Council school-leaving examination; and chemistry and physical science in schools in Atlanta, Ga., and Washington, D.C.

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