What Works: Building Natural Science Communities

A Plan For Strengthening Undergraduate Science and Mathematics

Volume One
Kaleidoscope is an instrument that reveals “what works” in undergraduate science and mathematics education. By documenting success and identifying effective strategies, we offer tested models of action and suggestions for future change for those who wish to join in the national effort to reform science and mathematics education at the undergraduate level.

The title of this effort, Project Kaleidoscope, serves as a metaphor on three levels:
• To display the pieces that must come together;
• To exhibit how these pieces connect;
• To show that patterns will differ in different settings.

As a kaleidoscope creates a multitude of patterns in response to change, so our agenda encompasses a multiplicity of approaches that can be adapted to specific circumstances and institutional environments.

Our work convinced us of several things:
• The diagnoses of weaknesses in America’s education programs for science and mathematics are on the mark.
• The search for solutions would proceed more effectively if we could come to understand better the guiding principles that drive strong programs in science and mathematics in diverse institutional settings.
• Now is the time for action. There is a national consensus about the nature of the problem and the need to address it. All the partners — schools, colleges and universities, federal and state governments, professional associations, and private foundations — are moving from analysis to action.

Unless everyone with a stake in undergraduate science and mathematics education makes tough decisions now about strategic priorities — about dollars, people, space, and time — effective reform will not happen. Unless all partners work together, this nation’s educational shortcomings will not be addressed adequately. Effective reforms take money, to be sure. But more important is an environment for reform that encourages planning, fosters creativity, and rewards useful innovation. The environment for reform must be based on a driving vision of what works.

Our approach has been simple. We looked carefully at successful undergraduate programs in mathematics and science across the country. We reflected upon our own experiences in classrooms, laboratories, and administrative offices. We identified central principles that guide strong programs in science and mathematics in the nation’s liberal arts colleges. What we offer are plans and programs based on the wisdom of experience and the evidence of what works.

**Goals and Objectives**

**GOAL I.** Increase the number, quality, and persistence of individuals in careers relating to science and mathematics, and educate citizens to understand the role of science and technology in their world.

---

I am tired of hearing about studies and analyses of the current problems this nation faces in science and technology. We know what works. Let’s stop studying the problem; let’s move from analyses to action!

A. To kindle the interest of all students in science and mathematics.
B. To focus faculty and institutional energy on student learning.
C. To increase the total number of students, especially women and minorities, completing the baccalaureate degree in science and mathematics.
D. To promote the professional development of those who teach science and mathematics at all educational levels.

GOAL II. Promote understanding of “what works” in teaching and learning undergraduate science and mathematics.
A. To foster the development of learning communities for the study of the natural sciences and mathematics.
B. To promote an investigative, hands-on curriculum.
C. To document and strengthen the critical link between faculty scholarship and teaching.
D. To advocate the teaching of science, mathematics, and technology in context, emphasizing connections across the curriculum and impacts on contemporary life.

GOAL III. Increase recognition of and support for the essential role of the liberal arts colleges in meeting the challenges faced by our nation in science and technology.
A. To ensure that the contributions of liberal arts institutions are taken into account in the development of national policy on education and research in science and technology.
B. To develop coherent, long-range plans at the institutional, regional, and national levels to sustain the contributions of liberal arts colleges.

C. To build partnerships among all those committed to strengthening undergraduate science and mathematics.
D. To develop strategies for dissemination and evaluation of “what works.”

Where To Start
There is much to do, but these initiatives must receive the highest priority over the next five years:
• Revitalize introductory undergraduate courses in science and mathematics. No reform in undergraduate science and mathematics education is more urgently needed.

We recommend substantial expansion of support for faculty development, curriculum innovation, instructional equipment, and science facilities that focus on building communities of learners for first-year undergraduate science and mathematics students, both prospective majors and general students.
• Support an integrated role for faculty as teachers and scholars within the community of learners.

We recommend a wider range of research and enhancement opportunities for undergraduate faculty at all career stages, to be awarded based on determination of the impact that such support would have on strengthening undergraduate science and mathematics.
• Incorporate guiding principles of “what works” into existing programs for teacher preparation and enhancement.

We recommend that national efforts to reform pre-collegiate science and mathematics education recognize liberal arts colleges as an essential resource that can make a unique contribution to the national reform effort.
• Forge partnerships to support creative and effective reforms.

We recommend the development of mechanisms, including computer networks and regular regional meetings, to link individuals and institutions — including federal and state agencies, private foundations, business, industry, and schools — in new clusters to focus on the process of strengthening undergraduate science and mathematics.

Support capital needs for science facilities and equipment appropriate to an active community of learners.

We recommend expansion of programs that support facilities, laboratories, computers, and scientific equipment that are of vital importance to effective science and mathematics education at the undergraduate level.

These suggestions represent a modest but essential beginning of a ten to twenty-year effort to transform undergraduate science and mathematics education in America. They tell us where to start — with a focus on introductory courses, on the role of faculty, on teacher preparation and enhancement, on partnerships, and on facilities. The following letter from the Executive and Advisory Committees to Dr. Walter Massey presents recommendations for the leadership role of the NSF in addressing these initiatives.
Teaching Nature’s Curriculum

The science curriculum, someone has said, is set by the world. If there is only one reality, only one truth, how can there be a question about what to teach?

During the generations since the natural sciences became commonplace in the curriculum, there has been a sameness of approach found virtually everywhere, a unanimity that suggested that nature herself was the source. In fact, the source was material set forth in major texts and graduate schools. But the old approach — what has seemed so natural — has failed us. As the quantity of knowledge has grown,

Teaching science is, at its best, a modeling of behavior, a demonstration of the true nature of investigation.

the curriculum has become overstuffed with facts, with terms, with content that must be “covered.” Pedagogy, too, has become stuffy and lifeless, a matter of endless telling and explaining by masters to initiates.

The thought that the collection of people assembled by the Kaleidoscope project might together have an influence on the undergraduate science curriculum of the future has filled us with both

humbility and zeal. But the fact that our visions converge gives us hope that the view expressed in this report is itself in a way natural, an idea whose time has come.

The redesign of science curricula, for us, starts with some questions:

♦ Scientists love doing science. How can the curriculum be organized so as to induce science students to enjoy science from the first day?

♦ Real science is carried out by teams in settings where face-to-face communication and shared values create a common culture. How can students begin to develop a sense of membership in a science community from the first day?

♦ Science is a human enterprise, internally connected, and linked also with the world, with other disciplines, with social and political forces. Beliefs and actions regarding science have important consequences. How can we teach science so that those connections and consequences are visible and appreciated from the first day?

Our discourse about these questions has made it clear to us that curriculum and pedagogy are inseparable. In science perhaps more than in any other field, the true subject matter is methodology. Teaching science is, at its best, a modeling of behavior, a demonstration of the true nature of investigation.

A key goal is to improve national literacy in science and mathematics and meet future requirements for trained people in science and engineering. This is essential for our future economic prosperity in an increasingly technological and competitive world.

A Learning Model

Student learning is the central activity of science education and must be the first concern of those wishing to improve it. If students learn well, other responsibilities such as the good of the nation, the scientific pipeline, the mission of the institution, and the quality of teaching will be faithfully discharged.

A good model for learning science has great potential for improving science education. Science faculty constantly choose what to teach and how to teach it, frequently in the face of evidence of their students' learning difficulties. An apt learning model would provide faculty with ideas for immediate action and for proposals to improve programs. It would also provide useful perspectives for academic

We reject models that conceive of learning as a constant test put to isolated and beleaguered individuals who are thereby winnowed so that only the strongest and brightest remain.

Another prominent theme that can be observed in the experience of science education at liberal arts colleges is the personal character of learning. Recent reports have emphasized that learning in science and mathematics is idiosyncratic: each learner must absorb ideas and learn to apply them in his or her own way. The underlying philosophical principle is exposed by Michael Polanyi's argument that all knowledge is personal. An adequate model for learning science and mathematics must recognize that learning is a personal endeavor.

The theme of connectedness of knowledge weaves through our entire discussion, in confirmation of Whitehead's position cited earlier. In the practice of science, the fundamental connection is between

Competence in modes of inquiry and in writing does not develop in a vacuum. Thinking is always about something, and therefore it is inextricably grounded in content.

To believe, in this era, that a person possesses a liberal education who is ignorant of analytic skills and technological skills is to make a mockery of the central concept of liberal education and to ignore the nature of the world in which the graduate will live.


theory and experiment, between mathematical model and empirical data. Connections among the natural sciences, as well as those between mathematics and science, serve to reinforce motivation and enhance student learning. Connections imply a frame of reference in which ideas can be examined, tested, and put to work.

We are led, therefore, to postulate that the ideal model for learning science and mathematics in college has three irreducible qualities:
- The learner is enmeshed in a community of learners;
- The learning experience is personal;
- The learning establishes connections that place science in context.

These qualities will meet the test of diffusibility. They can be created anywhere, not just at liberal arts colleges. Our mutual agenda for the 1990s, the agenda for all of the partners in undergraduate science education — colleges, parents, students, foundations, other private philanthropists, and federal and state governments — should be to bring this vision more fully to realization. That is our message.

Two Populations, One Need

Both the curriculum and the rhetoric of science education divide our students into "tracks." When speaking about science education we carefully explain which courses are for the specialist — the potential major — and which are for the non-specialist, the so-called "liberal arts" student. This way of talking wrongly evicts the sciences from the liberal arts. In fact, at most liberal arts colleges a strong core curriculum often results in science students receiving the most diversified liberal education. Although as members of the community of higher education we too find ourselves talking about two tracks (and may sometimes do so in this report), we are determined to resist the naive notion that our students fall nicely into two distinct camps. The evidence of experience shows that this is clearly not a useful model of real students in real courses.

A great parade of students who initially think of themselves as potential science majors abandon their plans after the first or second course in the "majors" track. These science dropouts graduate with other majors, and eventually enter non-science careers. For these students, the so-called "introductory" course is often the last course in which a student is provided with an opportunity to study science. Has their brief encounter with introductory science courses equipped them well to be science-literate citizens? Few would argue that a frustrating and ultimately unsuccessful experience with science is the best approach to scientific literacy.

Conversely, as teachers we often see the frustration of a student whose first introduction to science is a course for "non-majors," who discovers too late that he or she has the appetite and aptitude to do further work in science. But the non-major course, designed to be "terminal," doesn't carry students forward towards the specialists'
sequence. Traveling along two diverging paths, each of these students is deprived of the introduction the other received but found inadequate to his or her need.

The irony in this all-too-common picture is that many excellent courses for non-majors offer useful material about the context and consequences of science, material that the science major may need yet miss. Moreover, the non-major course often skims in its presentation of the activities and results of science, material needed both by the student who might want to be a scientist and by the student who—as a citizen—needs to know more about what science is and how it operates.

To meet the science needs that all students have in common, we must blur the distinctions between the introductory courses for majors and non-majors. Historical, philosophical, sociological, and political insights should be part of all science courses, offering all students the deep perspective on science which comes from understanding in context. Likewise all students should be introduced to the content and method of science, including laboratory work involving the design of experiments and the analysis of data.

Multiple tracks are best justified, we believe, not by a desire to segregate the science major from the non-major, but as a means of providing differential entry points into science for the prepared and the less-prepared. Often these different needs reflect differences among entering students in their ability to employ the language of science—mathematics—as an effective aid in their work. The objective of such separation at the introductory level should always be to enable students who embark from different places to converge to a single curriculum.

Good teaching depends on a sense of intellectual community, a common commitment of scholars to approach learning as an integrative rather than a disaggregative enterprise. Just as good teaching stimulates students to learn from one another, so must it grow out of a collective commitment on the part of the faculty to be teachers and students to one another...


What Works: Natural Science Communities

When we speak of the classroom as a science community, we picture an organization based on dialogue and activity. Knowledge is not transmitted so much as it is constructed, cooperatively, by students working together under the guidance of faculty and—at more advanced levels—by students and faculty working as teammates. The capacity of students to teach one another has been well demonstrated in countless settings, from one-room schools to graduate seminars. The effectiveness of such teaching as a spur to learning is remembered by every faculty member who began to fully understand his or her own discipline only after teaching the introductory course.

To create community, we advocate further blurring of distinctions—here the distinction between pedagogy and content and the
distinction between classroom and laboratory. In an effective laboratory where knowledge is being constructed, students do not merely replicate idealized experiments presented without historical context. The construction of personal knowledge involves a good deal of

The construction of knowledge is also the construction of motivation.

play and many false starts. Nature does not always live up to her reputation for predictability; students must measure things that wiggle and recognize things that are misshapen. They may use their textbook to clarify and organize ideas, but not as a source of answers to which they must struggle to match their data.

The construction of knowledge is also the construction of motivation. Many scientists testify that science began to feel like fun only when the text and lecture were left behind and the problems took center stage. Every student can know the success of solving problems at some level. And not all problems involve quantitative analysis. The skilled teacher sets good problems, maintaining balance in their level of difficulty. Success in problem solving is motivating; when solutions are out of reach, students experience frustration and self-doubt which drives them away from science.

To achieve the goal of making a classroom into a science community, it is not enough to organize people into groups. A community shares values and fosters mutual respect. Students differ in their skills and successes, but in a supportive community they will not be made to feel like failures when their achievements fall short of the hopes of their teachers. A person who has not yet learned to play the piano is not a failure; he or she is only a beginner. A student who is beginning to learn science — even a slow student — can be helped to feel that with hard work future success is still possible.

Because science and mathematics classes have been used by many colleges and universities as sorting devices for predicting who will make the grade as a “real” scientist or a physician, the idea of using those classes to attract and keep students rather than to frighten them away may seem foreign, perhaps impossible. Nevertheless,

Many students value learning through collaboration and discussion. And they find these missing in the culture of competition which they associate with undergraduate science study. They reject the anonymity of large classes and the isolation of solo work. Instead, they seek very deliberately to be part of a “culture of commitment and competence.”


Good teaching can transform introductory science courses from a filter to a pump in the nation’s pipeline of science education.

good teaching can transform introductory science courses from a filter to a pump in the nation’s pipeline of science education.

Think of our writing classes: Do we say to our students, “Sorry, you can never learn to write”? Of course not. We expect and demand that every student will learn to write to a reasonable degree. But in science and mathematics our expectations are different. Too many faculty expect that many students will
... I asked myself what it was that had so fascinated me. The answer is simple. The results were not presented as ready-made, but scientific curiosity was first aroused by presenting contrasting possibilities of conceiving the matter. Only then the attempt was made to clarify the issue by thorough argument. The intellectual honesty of the author makes us share the inner struggle in his mind. It is this that is the mark of the born teacher.

- Albert Einstein.

fail — will never learn to solve quantitative problems, for example. In many institutions, calculus and chemistry are the great rivers which only some may cross.

The success of women's colleges in educating women and of historically Black colleges in educating minority students has been well documented. The high retention rates in science programs at such colleges result from the fact that communities are fostered within which students feel supported and respected. Respect for each student is not a technique or a deliberate retention program, but a background fact that faculty assume and that students understand.

Science educators have traditionally assumed students to be isolated individuals. This assumption is most clear in the design of the introductory science courses that many undergraduates experience — a large lecture two or three times per week given to an audience of a hundred or more students. No one pretends that this instructional method promotes a sense of membership in a learning community.

The implications of "community" for institutional and departmental policies are profound; they reach to architecture, study arrangements, access to facilities, grading standards and policies, campus life, opportunities and arrangements for research, visiting speakers, seminar programs, displays in the department, internal communications, involvement of students in educational policies, teaching loads, and sectioning of courses and laboratories. For individual faculty, implications include new attention to grading assumptions, homework assignments and laboratory exercises, course emphasis on the social context for science and scientists, and arrangements for office hours, help sessions, tutoring by upper-class students, and testing.

The lack of community is vividly demonstrated by the in-depth observations of sophisticated learners who took such courses in a study undertaken by Sheila Tobias. Grading, for example, was a central complaint. These learners did not object to having their competence evaluated, but "grading on the curve" was deeply disturbing, for two reasons. One student commented that you could get a B+ and know that you had mastered nothing; you could be "totally
fogged” on what it meant or how it applied or why it worked, yet have gotten by quite well by memorizing the tidy manipulations needed to solve problems. Furthermore, grading on the curve was seen as the enforcer of the banal and degrading “culture of competition.” It made learning into a zero sum game. It stifled the impulse to get together with one or more classmates to discuss and work over the course content, labs, and problems, because curved grading has a quota of high grades. If your neighbor does better, you do worse.

The alternative, which demands more thought by faculty, is to assign grades on the basis of an absolute assessment of competence. But all are in the game together; it is the whole class — including the instructor — as a community trying to understand nature.

The Personal Character of Learning
One of the major realizations of philosophers of science in the 20th century is that science is much less objective and impersonal than it is widely thought to be. Polanyi and Kuhn have led this re-evaluation, and they argue persuasively that misunderstanding is rife concerning this aspect of science. It contributes to the ugly caricature of the scientist as a rationally rigorous automaton who sees other humans as mere items for manipulation.

Polanyi demolishes the myth of total objectivity by demonstrating how the scientific process is a perpetual feedback between the individual scientist and a disciplinary community that is connected to the larger community that we call a culture. New knowledge may be won by the mind and hands of one person, but this is trial knowledge until the knowing community of the discipline has “stood in the place” of that investigator and eventually agrees that the new version of reality is true.

Science relies heavily on scientists’ sense of what is an interesting result, an apt or conclusive experiment, and significant work. These judgments comprise the key characteristics of a scientist, and the attributes of judgement, incisiveness, and “feel” for reality are decidedly personal. Even the process of interaction by which scientists form the community of knowers is personal, because it involves transfer of knowledge by standing in another’s place or seeing through another’s eyes.

This conception of science supports “hands-on” learning, one of our most-repeated admonitions about what makes good science instruction. “Hands-on” means doing science in person rather than receiving science vicariously. Personal interaction with a well-selected scrap of reality means that you see it in your own way, that you know how it looks, feels, and smells, that you could do it again, and that you can take the image of it with you to use and ponder about forever.

The idea that learners should be active constructors of their own knowledge is a theme that runs through many studies in science education and cognitive psychology. The new principles of active learning are being adapted and applied in hundreds of new educational environments. Curricular materials, computer software, and a wealth of new experiences are rapidly becoming available to others who want to join the enterprise of discovery-based science teaching. The time has come! We should help undergraduates move from being passive receivers of truths revealed in the canonical introductory science texts, to being disciplined solvers of problems, and finally to becoming constructors of their own knowledge. For those few who study science at the advanced level, they should aspire to create new knowledge that is worthy of being reconstructed by future students. We should help our students ask and answer the questions posed by Arnold Arons. “How do we know? What is the evidence for...?”

— Priscilla Lauts
Project Kaleidoscope
National Colloquium,
Several other shibboleths of healthy science instruction also have their roots in personal knowing. It is the basis of the widely recognized superiority of small classes where learners get to stand in other knowers' shoes to learn personally the content of the course. It also explains the characteristics of great teachers as persons who can engage students by showing without tedium or posturing how other minds have struggled and prevailed and who can shake students loose from self-consciousness by disarming revelation or a spontaneous joke that is apt. These are profoundly personal attributes of healthy teaching and learning.

Connections and Investigations
The property of connectedness in science is crucial because it gives the learner something to think about. Lessons lacking connections are meaningless, rote, and authoritarian. Since there is little logic in such lessons, the learner has no means other than the authority of the textbook or the instructor to tell when the material has been learned, what it might be good for, or how to keep it straight in memory. Only a tiny fraction of such learning accumulates, and the main message of the accumulation is that it was not any fun. The world is almost full of science avoiders who have learned these kinds of lessons.

Connections can be of many different kinds. The historical context in which scientific or mathematical concepts emerged, and what ideas they competed with, replaced, or joined with to shape a new reality is often interesting and helpful to learners. Similarly, a social context in which a scientific concept is important is a wonderful way to give the idea place and connection. Acid rain can interest students in the subject of pH, and much else. The blue sky-red sunset and the greenhouse effect are magnificent contexts for talking about almost anything connected with electromagnetic radiation. The microbiological flora of the human species are prompt and useful spurs to learning about microbes.

Investigation should be invoked throughout a science curriculum. Each science laboratory should include open-ended experiments in which the objective is generally specified but the means of achieving that objective is not. Students should be given a substantial introduction to the disciplinary content and tools in the library, and then given an investigational assignment that opens them to the power of the library and the amazing truth that they can already read some of the original research reports of practicing scientists. Each department should also have a well-organized program of research opportunities and seminars in which all majors are invited to participate. Upper-class students will socialize lower-level students to expect that research is simply part of learning science, which indeed it is.
It is a truism among people who study such things that ten minutes is about the upper limit of comfortable attention to lecture material. The attention span of a student in an investigative laboratory is far longer. This argument alone should persuade us as faculty to change the means by which we present material to our students.

But the advantages of the lecture method have always been attractive to faculty. Chief among these is the feeling of reassurance that it gives to the lecturer, that he or she is working hard, covering the material,

***

Ownership of scientific knowledge belongs to the practitioner.

and giving students their money’s worth. Lecturing makes the faculty member feel good by giving the appearance of transmission of knowledge being passed down from teacher to student. Nevertheless, there is deception in this notion that ideas are transmitted intact by means of a lecture. In fact, mastery of material is rare in students, and it almost never occurs in a setting where the learner is passive. The essence of science is process, method, and practice. Ownership of scientific knowledge belongs to the practitioner.

These notions of connection and investigation apply with equal force to teaching science to general students. Non-majors must be shown the context of science as well. If their courses really take pains to demonstrate big ideas thoroughly, even hard-core science avoiders can be educated in science.

Welcoming Students

If a science major is to be attractive to beginning students, introductory courses must be accessible and engaging. Such courses are characteristically overstuffed with pre-formed packets of information that represent a survey of what one needs to know to enter the discipline. These courses are typically obtuse about the history of the discipline, its methods of investigation, its distinctive ways of knowing, and the relationship of science to society. These connections would be of great value and interest to the introductory science student.

In fact, introductory courses typically skip over the meaning and implications of big ideas, preferring to concentrate instead on how one applies these concepts to “solve problems.” Much of this “problem solving” in introductory physics, chemistry, and mathematics is little more than repeated testing over not-very-sophisticated — but always tedious — algebraic calculation. In biology and geology, the point of the packets is to expose the student to important concepts and facts, the “lesson” usually consisting of memorizing the material for an examination.

The work of these courses — what students do with their time — is considerable and poses a daunting test of perseverance. Nonetheless, much of this effort is fundamentally misguided. It draws on a narrow range of human abilities and requires inordinate tolerance for blandness and lack of connection. Proponents of these kinds of courses should ask themselves

— ACS Priestley Medalist
whether they tend to draw into science those persons with the qualities a scientist should have.

Several eminent scientists have argued that leading students to investigate well-selected phenomena should be the primary aim of introductory science courses. Connecting concepts to observable phenomena — regardless of which comes first — is healthy. The phenomenon is reality.

Beyond the introduction, there must be sufficient flexibility in ways of progressing through the major. Science and mathematics do need substantial course sequences. Nevertheless, it must be made clear to prospective majors that the

Leading students to investigate well-selected phenomena should be the primary aim of introductory science courses.

pursuit of science has many attractive outcomes. If the curriculum looks like you must start it in the first year, that you have to do everything right for seven straight semesters, and that you will be qualified for a narrow range of career options if you do, there are not going to be many takers. Many science curricula are set up this way in the mistaken belief that rigor requires it. Rigor results when an intelligent person realizes that it is necessary in order to be effective. When rigor is built rigidly into the sequence of a curriculum, it is often destructive of good education.

Building attractive curricula for science majors can begin with some simple actions such as offering introductory courses as often as possible, publicizing several options for completing the major, and designing and scheduling courses so that one can complete the major by starting in the sophomore year. This publicity should also show how different major paths could lead to various career outcomes.

Science departments should also have a steady and visible seminar program or club that all junior and senior majors are encouraged to attend and participate in. We emphasize this because the community of science needs to meet together, to see each other, and to learn what the others are doing. Any research going on in the department should be presented at seminars, and the faculty needs to take a strong role in creating a healthy atmosphere for it. Students who have done good research should also be encouraged to prepare presentations for local academies of science, Sigma Xi, or regional science meetings. There should also be a sprinkling of scientists from outside the institution who give presentations at least once a month. These visitors should have substantial time to interact directly with students, the benefits being that students will sense their membership in the larger community of science and be drawn into participation.

Science Literacy

Whereas the fruits of applied science and technology are substances, processes, and devices that are useful, the fruit of pure science or mathematics is

To be scientifically literate, it is necessary to have a minimal understanding of the processes of science, of scientific terms and concepts, and of the impact of science on society. [By this standard,] six percent of American adults would be classified as scientifically literate in 1988.

more subtle. It is understanding. It takes insight and conviction to argue that understanding is worth substantial effort and expense.

The reason to be literate in science and mathematics is the same as to be literate in history, literature, philosophy, or art. Ignorance causes lives to be lived superficially. People who don’t know that matter and energy are discontinuous, or that energy is conserved, or that life forms cannot be genetically “trained” by environmental stress are in a real sense less alive. Innumerate workers cannot do “back-of-the-envelope” calculations that yield odds on events, economic preferences, and basic insight about the plausibility of claims. They are more fearful, more subject to the predations of charlatans and the whims of fortune. Adults who are ignorant of science are less effective citizens.

The value of scientific literacy to liberal education far transcends the practical benefits conferred on citizens who live and work in a technological society. The proper study of science — of its methods, its history, its accomplishments, and its failures — serves well all educated persons. Of the many lessons that science teaches, some are especially apt for those who will become leaders of tomorrow’s society:

- Learn from mistakes. Science teaches better than most subjects what few political or industrial leaders appear willing to admit — that one learns more from what goes wrong than from predictable successes. Scientists seek insight from experiments that fail. Society would be well served if all leaders expressed authentic respect for honest error and openly admitted to changing their views.

- Share ideas freely. Science thrives on the exchange of ideas and data, since only through such free flow can understanding be achieved and validated. The benefits that accrue from widespread availability of information apply as well to other spheres of human endeavor: insight, understanding, and wisdom emerge better from fully informed intellectual communities. There is no surer defense against persistent folly than the bright light of complete information.

- Trust information. Although data can surely mislead or be misinterpreted, they are less subject to anomalous perturbations than are strongly held convictions or ingrained prejudice. To be effective in any field, one must constantly test ideas against the hard truth of reality. This lesson, which scientists learn from years of laboratory experience, would be of immense value to our nation’s political, social, and educational leaders.

Although no one would claim that science is the paradigm for knowledge — since other perspectives also make distinctive and valuable contributions to our understanding of ourselves and our world — science does provide important lessons that should inform all aspects of culture and society.

The design of courses intended to improve science literacy has long been suspect. Many institutions have weak science requirements, and some have none at all. Faculty
increasingly find themselves unable to reach agreement on a well-integrated core curriculum. The alternative is usually a set of distribution requirements that often lack coherence.

The courses that are commonly offered for this purpose have tended to miss the mark for a variety of reasons. A typical example is the "Physics for Poets" course which is not really for poets but for anyone who plans to take only the minimal requirements in science. Unfortunately, such courses do not introduce interesting issues of science or art. They are, too often, watered-down courses whose content is similar to a course for science majors but where assignments are less rigorous, more descriptive, and less mathematical. These courses introduce lots of terms — "basic concepts," properties, and definitions. They often are neither intellectually challenging nor aesthetically satisfying; only the dullest, most dutiful, or most optimistic students emerge from them with the passion for science still burning.

Students seeking general education in science may of course take an introductory course intended for science majors, but such courses are too often not appropriate even for prospective science majors. They are particularly inappropriate for non-science majors. Liberal arts students would like to learn the major understandings of science and how they were won. Instead, students are taught an endless stream of technical detail. This type of course provides poor education to both majors and non-majors alike.

The key missing properties of general education courses in science are connections and investigation. Students need to see a few big ideas of science that are thoroughly treated. They need to perform hands-on experiments that reveal phenomena relevant to those ideas.

Students need to see a few big ideas of science that are thoroughly treated.

explore current situations and historical contexts, and solve real problems using the concepts. We think of these courses as sitting down with a subject for a couple of weeks, looking at it in detail, and then moving on to the next one — without any worry that not all big ideas can be covered in this way.

In recent years various educators and critics have chosen undergraduate education — especially the core curriculum — as the site for rhetorically heated battles over societal values. Science is notable for its absence from most of this verbal sparring — except for occasional lip service paid to environmental issues, often in a rather non-scientific context. Often it appears as if the public aversion to science extends to the college campus, making science taboo outside science departments themselves.

How often are the contributions of science and mathematics treated seriously in mainstream courses in history? Do the curricula of women's studies and ethnic studies include science as an equal partner in culture? Do core curricula require participation in modern science and mathematics on a par

During our planning year we discovered a landmark book entitled Experiential Learning by Cognitive Psychologist David Kolb, who felt that optimal learning in any field requires the use of a learning sequence not unlike those recommended by several science education researchers. Most of the learning sequences we considered mimic the time-honored scientific method, typically involving several steps: (1) making predictions, (2) testing the predictions with casual observations, (3) reflecting on the observations and making correlations, (4) developing formal models and theories, and finally, (5) testing of these theories quantitatively and applying them to new phenomena. It came to our attention that observational learning might be greatly enhanced by kinesthetic experiences in which students use proprioceptive senses to feel forces, remember distances, cause motion or experience the tingle of electric current.

— Priscilla Laws
Project Kaleidoscope
National Colloquium,
with the requirements in humanities and arts? Have scientists chosen to become involved in such issues? On most campuses, the answers to these questions are negative. For the most part, science is marginalized by the curriculum to a separate turf, disconnected from other courses and from the daily lives of students.

If undergraduate education in science is to be effective, the natural science communities must be broadened to include, in appropriate ways, the entire campus. Students need to hear from faculty.

---

If undergraduate education in science is to be effective, the natural science communities must be broadened to include, in appropriate ways, the entire campus.

---

in all fields about the connections of their discipline to science, and about the impact that the scientific and information revolutions have on all parts of human culture.

---

The Lean, Lab-rich Curriculum

Science has expanded at such a furious rate that no individual can hope to learn but a fraction of even one specialty. Fortunately, this expansion ceaselessly gives rise to better and more general methods of investigation. The healthiest science curricula, therefore, constantly review and turn over their content because parts of the huge “canon” of the discipline — the established knowledge and methods — must be displaced by more important or coherent material.

Unfortunately, stagnation is a common failing of science and mathematics curricula. Its prevalent manifestation is a curriculum that has too much in it. Its signs are too much detail, incoherence in the lessons or their progression, and declining success in getting students to undertake the curriculum or to persist in it. Stagnation also shows itself in outdated and inadequate facilities. First-rate libraries, instrumentation, and laboratories are expensive, but they are especially hard to finance when they are not being used effectively in instruction and research.

The benefit of investigation for teachers is the insight that one doesn't need to know or be exposed to everything in order to be equipped to work in the discipline. This criterion works like fresh air to ventilate a stuffy curriculum. Some phenomena are simply more instructive than others. Only certain laboratory techniques need to be taught. They need to be taught carefully and deeply — so that students see what is really at issue.

---

One doesn't need to know or be exposed to everything in order to be equipped to work in the discipline.

---

in using the techniques effectively — but not every technique needs to be taught. Shrewdly selected experiments will stand for lots of others that use similar principles, as will well-chosen themes for
Undergraduate Research

Many anecdotes and some studies suggest that the greatest single influence that transforms a science student into a young scientist is an undergraduate research experience. Although student-faculty research partnerships are costly in college resources and faculty time, they represent for many faculty the most rewarding aspect of teaching and for many students the most effective approach to learning. A college that emphasizes genuine research for its students is simultaneously supporting professional development for its faculty. And here another familiar distinction is blurred: that between teaching and research.

Students often report that undergraduate research experiences are of immense value, generating insight from such simple problems as

The creation of knowledge that is truly new is exhilarating for both faculty and students.

figuring out what type and size flask to use for a chemical reaction, how to use or fix an instrument, and how to find what you need to know in the library. They also report that these research experiences were valuable for all manner of subsequent settings such as medical school, graduate school, law school, and business management.
The creation of knowledge that is truly new is exhilarating for both faculty and students. When that research is publishable, as so often it is, the reputation of the college is enhanced, the scientific work of the faculty member is affirmed, and the career of a student scientist is launched. Many liberal arts colleges make student research a primary instructional mode for advanced students. The pleasures and rewards of student-faculty research partnerships should be extended to more students — in more institutions, in all science disciplines, and earlier in students’ college careers. Students can be prepared to take maximum advantage of such opportunities if their introductory and intermediate classes offer a prototype of the research environment.

Scholarship helps faculty “discipline” both their own professional work and the college’s curriculum. Faculty-initiated research places the faculty member doing it — and therefore his or her academic pro-

gram — into the larger community of scientists. The research effort causes the faculty member to read current journals, maintain contacts with other scientists, write proposals and papers, serve as reviewer of the work of others, participate in scientific meetings, visit other laboratories, maintain decent instrumentation, and keep the library holdings current. There are multiple benefits here for students, the faculty member, and the school.

Research and scholarship are a matter of vision, persistent and able faculty, a little money, and an administration that value them. Science is dead in the classroom without the quickening spirit of investigation.
To understand nature, one must learn to speak nature's language. Number, shape, dimension, chance, change, symmetry offer vocabulary appropriate to both observation and theory. Mathematics is the apt language to express human understanding of nature, yielding returns on insight that, in Eugene Wigner's memorable phrase, are "unreasonably effective." Mathematics is "a wonderful gift that we neither understand nor deserve."

Historically, mathematics has been set apart from the natural sciences as a discipline rooted more in a priori epistemology than in empirical investigation. Mathematical truths are absolute; mathematical proofs are exemplars of convincing argument. In learning mathematics, one learns not only the language of nature, but the archetype of reasoning on which our scientific and technological society is based.

Today, however, as computer methods intrude empirical methods into mathematical investigations, the repertoire of those who practice mathematics often includes activities similar to those of the laboratory scientist. Exploration, conjecture, hypothesis, and investigation are as much part of

Mathematics can be said to be the science of patterns.

the modern mathematical method as they are of scientific practice. Indeed, mathematics is itself becoming a type of science: as biology is the science of life, and physics is the science of matter and energy, so mathematics can be said to be the science of patterns.

Mathematics is the foundation of science; without strong mathematics, there cannot be strong science. Because it is a foundation subject, mathematics — like English, but unlike physics — incorporates a full K-12 school curriculum preceding college. For this reason mathematics has been unjustly accused of being the "critical filter" that impedes free flow in our nation's scientific and technological pipeline.

One consequence of being both the foundation and filter for science is that mathematics has been thrust into the foreground of national efforts to revitalize science and engineering education: unless mathematics becomes a pump instead of a filter — to use a mechanical metaphor — the flow of students into scientific careers will remain inadequate to America's needs. Indeed, the mathematical community has responded with energy and vision: the nation's mathematics teachers have responded to the challenge with new standards for school mathematics; the National Academy of Sciences has issued a series of reports on mathematics education; and the National Science Foundation selected calculus as one of two target areas for the initial phase of its recent undergraduate curriculum initiative.

One paramount lesson has emerged from the many recent national initiatives concerning undergraduate mathematics: for most students, the traditional way mathematics has been taught in universities does not work. What gives this message meaning, however, is the recognition that other styles of learning do work, and that they work even for

Undergraduate mathematics is the linchpin for revitalization of mathematics education. Not only do all the sciences depend on strong undergraduate mathematics, but also all students who prepare to teach mathematics acquire attitudes about mathematics, styles of teaching, and knowledge of content from their undergraduate experience. No reform of mathematics education is possible unless it begins with revitalization of undergraduate mathematics in both curriculum and teaching style.

Exploration, experimentation, and innovation — along with occasional failures — are the hallmarks of a department that is committed to effective education. Mathematics programs that work can be found in all strata of higher education, from small private colleges to large state universities, from average to highly selective campuses. The variety of mathematics programs that work reveal what can be achieved when circumstance and commitment permit it.


students whose backgrounds suggest little prospect of success. Across the landscape of U.S. colleges and universities, mathematics departments of every size and type are beginning to adapt their traditional styles of instruction to new approaches that are more effective.

What Works
Although details and emphases differ greatly from one institution to another, the general features of programs that work in undergraduate mathematics reflect principles that are widely practiced in the nation’s liberal arts colleges:
• Community. Students learn best when they work with each other and with their instructors to explore ideas, articulate possibilities, and critique analyses. They need to speak and argue, to listen and learn in a supportive environment that sets high expectations even while encouraging risks and supporting failures.
• Investigation. One of the insights revealed by contemporary research into learning is that mathematical concepts are distinctly personal.

Mathematical concepts are distinctly personal — that these concepts are constructed anew by each student in terms of his or her unique background, rather than transferred as a finished body of knowledge from instructor (or textbook) to student. To learn mathematics, students must be provided ample opportunities to

Good mathematics teaching constantly reveals connections.

investigate and explore in realistic contexts that encourage the development of important mathematical constructs.
• Experience. Although mathematics is a deductive, cerebral discipline, the learning of mathematics (whether by a student or a researcher) requires considerable experience with the raw material from which patterns emerge: real data, computer simulations, observations, and visualization. Today computer labs establish powerful environments that permit students to experience mathematical patterns, thus enhancing motivation and understanding of more theoretical approaches.
• Connections. Mathematics provides a window through which students can perceive scientific connections: by abstracting a pattern from a particular context (e.g., bacterial growth), the same pattern can be seen in unrelated contexts (e.g., compound interest). Good mathematics teaching constantly reveals connections, both within mathematics (e.g., number theory applied to computer codes) and with other disciplines (e.g., geometry applied to cosmology).
Several recent studies stress the need to focus mathematics teaching on ways to develop each student's mathematical power — a mixture of self-confidence, specific skills, and actual experience that enables the graduate to use and teach mathematics with flexibility, authority.

Empowerment flows from motivation for learning.

and wisdom. Such learning occurs most readily in a supportive environment built on a lean, active, experience-centered curriculum that stresses insight and principles over techniques of computation. The focus of such a program is as much on the personal development of students as it is on their mathematical maturity: empowerment flows from motivation for learning.

Breaking Barriers

As the critical filter for students preparing for careers in science and technology, mathematics bears much of the burden of failure in the U.S. system of science and mathematics education. On the one hand, the filtering action of mathematics is performed at the behest of science and society; school policy at all levels uses performance in mathematics as a key indicator of future success. On the other hand, the practical effect of the mathematics filter is to impose selective pressure on different societal groups, inhibiting especially the scientific career aspirations of women, Blacks, and Hispanics.

In recent years the demographic reality of the emerging U.S. workforce has awakened policy leaders to an impending crisis of scientific leadership. In the first decade of the next century, four out of every five new workers who enter the workforce will be drawn from those in our population who are most heavily filtered out of the scientific pipeline by their experiences with school and college mathematics. To ensure an adequate supply of scientific and technical talent, the U.S. must adopt different strategies that will help convert mathematics from a filter to a pump.

Too often students are victims of a conspiracy of low expectations created by parents and teachers who think that only those with some special gift are capable of learning mathematics. In order for students to gain self-confidence in their mathematical abilities, teachers above all must demonstrate confidence in their students' ability to learn. Teachers of students who succeed with mathematics do not accept the notion that certain students are destined to fail.

Tragically, schools have reinforced expectations of underachievement by a tradition of tracking that denies

Precalculus courses all too often do little more than remind students of their past failures in mathematics.

Undergraduate students should not only learn the subject of mathematics, but they also must learn how to learn mathematics.

The fact that the number of young people selecting science and engineering careers has not increased during a generation in which [science and technology] pervades every aspect of our lives is nothing less than a scandal.

— AAAS President Richard C. Atkinson, 1990.

remind students of their past failures in mathematics. Fortunately, there are many colleges — especially smaller institutions and the historically Black institutions — where beginning courses do draw students forward into advanced study of science and mathematics. But on many other campuses, especially in larger institutions with more impersonal settings, the precalculus course completely fails to achieve its purpose of enabling students to succeed with calculus and to enter calculus-based careers. It is not uncommon to find on these campuses that only a tiny fraction of students who begin in these courses actually reach their objective of a career in science or mathematics. This failure is largely predictable: the instruction in these courses merely repeats in content and approach the corresponding high school course, thus signaling clearly the remedial nature of the work.

First-year students should instead plunge directly into a supportive community of learners where each student is expected to learn and is openly respected for what he or she already knows. Teaching methods that work in mathematics resemble those that work in science: exploration, discussion, group work, reading, writing, and reporting. Active learning will engage the student’s mind to construct meaningful knowledge of lasting benefit. By moving ahead to new ideas — with support to fill in missing pieces as needed — each student will grow in expertise and confidence. Instead of repetitive remedial work, the student will be challenged to explore exciting areas of mathematics that are recognized steps along the pathway to professional stature.

Many students enter college having been sold short by schools that condone (and sometimes even encourage) minimal preparation in mathematics. Many such students are quite capable of advanced work in science and mathematics, but need to have their interest rekindled. To attract these students to the collegiate study of mathematics, many institutions have introduced innovative courses in quantitative reasoning, workshops in elementary mathematics, and first-year mathematics seminars as alternatives to the traditional precalculus course. Much of this exploration takes place naturally in liberal arts colleges where the environment encourages curricular innovation.

Reinforcement and broad support are crucial to students’ success in mathematics, as well as in science. Too often mathematics is ignored or deprecated in other science courses; too often mathematics is more suppressed than enhanced across the curriculum. Students need to know that mathematics is of value — not only to their mathematics professors, but to many others as well; they need to be assured that the hard work required to learn mathematics will be respected and rewarded in other disciplines. Enhancing self-esteem, especially in those who may have not had a strong school mathematics background, requires effort from the whole campus community.
Few students learn a mathematical idea well the first time they encounter it. Far more commonly, students need to see an idea (for example, integration) from several different points of view — geometric, analytical, applied, computational — before they are able to construct for themselves, in their own mind, a model that both works and lasts. Science faculty need to recognize this need for multiple exposures as a natural part of all learning processes, and not as a failure of the student to learn or of the mathematics instructor to teach. Students’ mathematical self-esteem can be destroyed as easily in a science class where ridicule rains on those who have forgotten a key formula as in a mathematics class where the lecturer takes far too much for granted.

A better model, which thrives in a climate of dialogue and good will among scientists and mathematicians, is for science instructors to willingly reconstruct the relevant mathematics in the context of their own applications, showing equal respect for those students who have forgotten what they learned in their mathematics class as for those who remember. Such differences do not distinguish smart from dumb students, nor do they reveal incompetent mathematics instruction. What they do reveal, and what every instructor needs to be sensitive to, are students at different stages of their mathematical development. To help all learn mathematics, each professor — in natural and social sciences as well as in mathematics — must accept the responsibility of adding one more perspective to the student’s emerging view of mathematics.

Mathematics is a difficult subject which takes a long time to learn. Virtually all students, properly motivated, can learn it, although different students will learn at different rates and with different styles. The personal, active, exploratory context for learning that is characteristic of liberal arts colleges provides an ideal framework in which students of varied styles and approaches can succeed. Many universities have recently begun to develop programs of similar focus and intensity, and have reported significantly improved results. What all these programs have in common is respect for the student, belief in the student’s ability to learn mathematics, and numerous layers of support that provide a personal, multi-dimensional character to the context for learning.

**Instilling Motivation**

The paradox of mathematics is how such a powerful subject has been so easily trivialized when packaged in standard introductory courses for undergraduates. Instead of re-creating the wonder of Descartes’ discovery of how algebra can reflect geometry, students in precalculus courses spend hours memorizing formulas that they will rarely ever use again. Calculus students
wrestle with rules for differentiation and integration without understanding the historical significance of calculus as the engine of the scientific revolution. In statistics, students memorize summation formulas for correlation and standard deviation instead of exploring the profound yet controversial logic of scientific inference based on statistical reasoning.

There are many good examples of meaning-filled introductory courses in the mathematical sciences, but unfortunately these are not the norm. Contemporary experiments cover the spectrum of first-year courses, including calculus, statistics, quantitative literacy, discrete mathematics, and precalculus. Virtually all have in common decreased emphasis on acquisition of algorithmic skills (for processes that are now almost always done by computer) together with increased emphasis on fundamental concepts of deep significance.

As learning shifts from technique to concept, courses become less mechanical and more reflective. Teaching styles that were developed for delivery of mechanical courses — large lectures with routine homework — are no longer adequate to the mental and verbal intensity of a meaning-filled, concept-intensive course. So the shift to a more effective model of instruction is intimately related to the improvement of introductory courses: only with an active, supportive, experience-rich model of learning can one hope to engage students effectively in the big issues of mathematics — in change and chance, in dynamics and inference, in form and quantity. Whereas sterile techniques can be taught and learned without special instructional effort, deep ideas require a rich context for learning.

One of the many impediments that make such meaning-filled courses difficult to implement is the tradition of expectations that have grown up around calculus, and, to a lesser extent, around statistics. Students come to expect a techniques course, so anything else is viewed with suspicion and hostility. Some mathematicians and statisticians are urging radical reform ("by-pass surgery") to avoid entirely the restraint of conventional wisdom imposed by the calculus and statistics markets — each representing well over half-a-million students a year.

As mathematics has come to be used in a wide variety of disciplines and vocations, as the spectrum of commonly used mathematical methods has expanded to include

\[ \text{Whereas sterile techniques can be taught and learned without special instructional effort, deep ideas require a rich context for learning.} \]


As teachers of collegiate mathematics, each of us has always thought deeply about what we teach. Our call for change requires us to think equally deeply about how we teach.
We discovered at Berkeley that we could serve 100 to 200 students very well in a faculty-managed intervention program. I was amazed to learn that at an elite private liberal arts college with which I am working, Freshman Calculus is done the same as at Berkeley. The course has the same textbooks, the largest enrollment, and gets the least faculty energy. When we looked at ten years of mathematics majors, we discovered that only four majors in ten years had actually taken first-semester calculus. So we had a freshman program that was not an effective route into the major.

— Uri Treisman.
Project Kaleidoscope
National Colloquium

... calculus or to statistics? Of course, a new first-year course would entail, eventually, a complete reconstruction of the mathematics major. Such a challenge, though immense, might emerge as an outgrowth of some of the many experiments now underway. Liberal arts colleges offer an ideal venue for such curriculum construction, both because of size — small enough to make change possible — and institutional commitment — strong enough to make change likely.

Preparing Teachers

Undergraduate mathematics is unique among the sciences in its extensive responsibility for preparing teachers, both of school mathematics and, indirectly, of college mathematics. Approximately one in five students who major in mathematics also receive licensure to teach secondary school mathematics; approximately one in ten will eventually teach mathematics in institutions of higher education, whether that be at a two-year college (where one in three first-year mathematics students are enrolled) or in a college or university.

It is widely recognized that the typical U.S. high school graduate is ill-equipped to function in a world that depends increasingly on mathematics. It is less widely recognized, but nonetheless true, that the typical undergraduate mathematics major program is ill-suited to preparing high school teachers who will teach a curriculum that meets the new NCTM Standards for school mathematics. The misfit is only partly one of curriculum, and this inconsistency is relatively easy to correct (require more statistics, geometry, and applications, and somewhat less advanced analysis). More difficult to fix is the lack of synchronization in philosophy and style of teaching. Contemporary standards for the mathematical education of teachers of mathematics call for an approach to pedagogy at the college level that reflects the varieties of styles of instruction that will be expected of teachers in school. These styles incorporate features we have already identified as especially effective for science courses: active, student-centered, exploratory courses emphasizing group work, oral and written activities, and realistic data. The introduction of computer labs into many college mathematics courses will be of great benefit to those who would teach in school, since the lab environment mirrors many aspects of instruction that future teachers will be expected to employ.

The confluence of pedagogical needs of secondary school teacher preparation with intrinsic requirements of undergraduate learning is a fortunate but not entirely accidental occurrence: both stem from the same fundamental recognition of how students learn mathematics. Much the same applies as well to elementary school children, yet virtually all elementary school teachers take the preponderance of their undergraduate work in departments or schools of education. Typically, prospective elementary school teachers take only one or two mathematics courses, including a very tradition-laden mathematics methods course.
Many educational reformers have called recently for new models of (elementary) teacher preparation that would replace the education major with a regular major in the traditional arts or sciences. Even the National Academy of Sciences has recommended the development of a cadre of mathematics-science specialists to work in elementary schools, perhaps paired with language arts specialists at each grade level.

This suggests another challenge for colleges that are willing to invest time and energy in curricular reform: to develop an honest major combining mathematics and science that would be suitable to replace the education major for prospective elementary school teachers. Such a major might begin with the same new first-year course in college mathematics that could serve well a large number of liberal arts students. The major itself would examine in depth many phenomena and patterns of science and mathematics that are within the scope of school children, seeking connections and basic principles that explain elementary concepts from an advanced viewpoint. In contrast, traditional majors push on to the study of advanced concepts, many of which are largely beyond the experience or imagination of elementary school children. A legitimate new major in elementary school mathematics and science would have to focus on deep ideas that have the power to develop childhood intuitions and curiosity along pathways that can blossom later in more formal science and mathematics courses.

**Encouraging Research**

Science education in liberal arts colleges thrives best in an atmosphere that is saturated with opportunities for undergraduate research. Students in such programs engage science through apprenticeship education; faculty maintain active professional lives that support both research and teaching; and the department develops a vigorous mission shared by faculty and students that serves goals of both science and education. Other sections of this report recount the numerous benefits of undergraduate research to undergraduate science education, benefits which have been documented in numerous studies.

In mathematics, however, the relation of research to education at the undergraduate level is far more problematic. Neither mathematics faculty nor mathematics students produce as many research papers as do their colleagues in the natural sciences; relatively few departments of mathematics set undergraduate research as a goal for majors; and the participation by mathematics departments in NSF-funded opportunities for undergraduate research has always been small in comparison with the participation rates of the natural sciences.

There are many reasons for this anomaly. Foremost is the theoretical nature of mathematics, which has meant that most frontiers of mathematics cannot be reached by undergraduates. The vast gulf between the research frontier and the undergraduate curriculum also means that most mathematicians who are active in research will be

The range of opportunities for independent investigation is so broad and the evidence of benefit so persuasive as to make unmistakably clear that research-like experiences should be part of every mathematics student’s program. Undergraduate research and senior projects should be encouraged wherever there is sufficient faculty to provide appropriate supervision. Effective programs must be tailored to the needs and interests of individual students; no single mode of independent investigation can lay claim to absolute priority over others. Flexibility of implementation is crucial to ensure that all experience the exhilaration of discovery which accompanies involvement with mathematical research.

—“Challenges for College Mathematics,” 1990.
Technology also seems to work, although not necessarily for the reasons one might expect. It certainly can change the content of a calculus course, but its influence on pedagogy is perhaps more important. Classroom demonstrations are not the point. The real impact of technology is the opportunity it provides for students to explore, to work in groups, to write laboratory reports and projects.


unable, despite good intentions, to find any significant part of their research that could be carried on with an undergraduate partner.

Other reasons are more mundane, but nonetheless real. Mathematics as a discipline has received much less federal funding than have the natural sciences, so many fewer faculty receive research support. A much larger fraction of the teaching in departments of mathematics is devoted to service courses, so a larger fraction of the faculty do not view research as a primary feature of their professional lives. And many mathematicians believe that learning fundamentals is a prerequisite for independent investigation, so they give priority in the undergraduate years (and indeed, in the first two years of graduate school) to offering basic courses.

Nonetheless, a growing minority of mathematics faculty have established effective undergraduate research programs in the mathematical sciences. These programs produce results — some of which get published — and they attract bright students to careers in mathematics. The rapid increase in affordable computer power is one factor that has made such work possible: in those parts of mathematics that closely mimic the laboratory sciences, the proven methods of apprenticeship education work just as well. Other factors that have led to an increase in popularity of undergraduate research programs include the widening recognition of the benefits of styles of instruction that involve students in shaping their own learning (including such opportunities as internships, industrial projects, independent study, and teaching — as well as research); the sustained concern that U.S. research mathematics is failing to renew itself; and the example set by other disciplines that use undergraduate research as an effective means of education.

There is now widespread recognition of the benefits of student-led educational experiences such as major modeling projects or undergraduate research opportunities.

Employing Computers

It is hard to over-estimate the impact that computers have had on the practice of mathematics. First numerical methods, then computer graphics, and now symbolic systems have gradually inserted computers into the formerly equipment-free world of mathematics. Ordinary
affordable computers are now powerful enough to be of immense aid in mathematical research and applications.

It is equally hard to overstate the sluggish response of college mathematics departments to this significant change in the nature of mathematical practice. But when change occurred, it often took place first in small colleges, where the climate is receptive to such experiments.

Computing can and will affect virtually every course in the mathematics curriculum, but it is not without considerable risk. Its use in mathematics research and college instruction is now so common that the Notices of the American Mathematical Society devotes a regular column to innovative uses of computers at the college and graduate levels.

Computing changes what is taught as much as how we teach. Some topics diminish in importance, others become more significant. Visualization and patterns become more powerful as a carrier of intuition, while calculation becomes more routine. Computers stimulate faculty to rethink courses and majors, thereby benefiting undergraduate mathematics even if the computer itself is rarely used in the course. It is in this capacity — as a stimulus to curricular change — that computers play their most significant role in undergraduate mathematics.

Computing also influences how we shape the spaces in which mathematics and the sciences are taught. Until recently the centuries-old model of chalkboard lectures recorded by student scribes dictated that the typical environment for mathematics instruction would be a rectangular room equipped with rows of student desks. But today the need for computer laboratories networked to other computers in offices and dormitories provide unprecedented pressure for flexible space in departments of mathematics.

It should come as no surprise that much of the leadership for infusing computers into college mathematics should reside in the same institutions that have historically been at the forefront of curricular reform. What may be surprising, however, is the evolution of concern of many of these early pioneers: in virtually all cases, what began with computers led first to curriculum change, but then quickly to issues of teaching and learning. Teaching with computers has revealed as nothing else had the numerous false pedagogical premises of most mathematics instruction.

When instructors work with students who are using computers either to learn or to do mathematics, they observe through a new window the obscure and idiosyncratic process of constructing mathematical mental images. Reflection upon these observations leads in turn to renewed concern about the context for learning. What instructors often rediscover are learning models that have proven so effective in other liberal arts and sciences: the value of investigation, experience, community, and connections — all of which emerge and thrive in an active computer lab.
Science and mathematics are created, transmitted, and applied by people. They are fundamentally human activities. If we are to continue having good science and mathematics, then human resources — the education and continued engagement of scientists, mathematicians, and scientifically literate citizens — is almost the only important question. Indeed this entire report, focused on undergraduate science and mathematics education, returns over and over to the question of how we are to realize Franklin Roosevelt’s dream of “... the continuing future of scientific research ... and a fuller and more fruitful life ...”

We — and the entire nation — know several distressing things about the national human resource situation in science and mathematics:

♦ A national crisis is looming concerning an excess of demand over supply of scientists, mathematicians, engineers, and science and mathematics teachers.

♦ Women and minorities are severely under-represented in science and mathematics careers.

♦ The level of literacy in science and mathematics is unacceptably low in the general population.

♦ Our students have shockingly low scores on standard science and mathematics exams compared to students from other countries.

We also know that there is no quick fix. It takes a great deal of lead-time to educate persons for scientific literacy, and for careers in science and mathematics. It takes even longer to readjust entrenched policies, procedures, and programs to new approaches that work.

Studies have shown repeatedly that a significant number of predominantly undergraduate colleges, including some Historically Black Colleges and Universities and some women’s colleges, have had extraordinary success in producing graduates able to move easily into scientific and technological careers. Their success applies as well to minority students and women — two groups that have historically been denied equal access to science and mathematics careers, but whose future success in science and mathematics is critical to meeting the nation’s needs. The success of predominantly undergraduate colleges in attracting, retaining, and graduating persons who go on to science and mathematics careers and who become scientifically literate citizens can be traced directly to the manner in which science and mathematics education takes place in these colleges.

Science and mathematics education succeeds whenever it takes place within an active community of learners, where students work in groups of manageable size to enhance collaborative learning and where faculty are deeply committed to teaching, devoted to student success, and confident that students can learn. Effective science learning is never passive. It is active, hands-on, experiential, and research-based — from the very first introductory courses to the completion of students’ science and mathematics education. Effective education engages students in activity that is meaningful in a highly personal way; it is connected to historical context, to other fields of inquiry, and to practical applications of interest to students — in other words, to the reality students experience.

To be effective for all students, the science and mathematics curriculum must support multiple entry points and multiple pathways through the curriculum. Faculty in programs that work meet students where they are and support them as they work to learn. In such settings, science and mathematics education focuses on “cultivating” rather than on “weeding.”

This kind of education both motivates and empowers students to learn science and mathematics. Predominantly undergraduate colleges achieve positive outcomes because the education they seek to provide to their students comes close to matching this ideal community-based model of learning science and mathematics. Although short-term incentives to induce students to make different choices at points along the career pipeline can temporarily affect the supply of scientists and engineers, any long-term response must entail systemic changes to bring the kind of learning environment that works to all levels of education — from kindergarten through the undergraduate experience.

Increasing Participation

Membership in a community of learners is a salient characteristic of the lives of science students in most successful liberal arts colleges. Because community improves the persistence of individuals and the continuity of instructional programs, it should be sought as a deliberate goal of policy and design in all baccalaureate learning environments.
We need new thinking about “who will do science” and “why,” thinking that may challenge college science teachers to grapple with issues they have not focused on before … how to recruit, teach, reward, and cultivate different kinds of students to science, students who are not younger versions of themselves … But scientists are not likely to do such rethinking so long as they continue to expect the next generations of science workers to rise, as they did, like cream to the top. This is why introductory college courses remain unapologetically competitive … designed to winnow out all but the “top tier” and why … there is little attempt to create a sense of “community” among average students of science.


The role of community in the learning environment for science parallels a crucial aspect of science itself. Knowing ultimately depends on a community in which the methods and standards of a discipline are embedded, and reality for that field is agreed upon.

To be effective for all students, the science and mathematics curriculum must support multiple entry points and multiple pathways through the curriculum.

The ideals on which the scientific community rests are honesty, impartiality, and openness. No individual can perfectly manifest these virtues; the test of a scientist lies in his or her aspiration to them. A scientist is assumed to report the truth conscientiously; scientists do not knowingly deceive and remain scientists. The truth is accessible to any person: one’s capacity to know and to participate in the knowing community is not restricted by race, gender, physical handicap, or social standing. Finally, the scientific community can thrive only when results and findings are openly communicated and evaluated: secrecy and political favoritism are anathema to science.

The science learning community therefore parallels the science community in the same way that science learning parallels science. Our country is currently rediscovering that science cannot exist for long without science learning. The lesson of this rediscovery is that we are really talking about one integrated community. Yet women, several racial minorities, and physically disabled persons represent smaller proportions of scientists and mathematicians than they do of the population as a whole. Government agencies and private organizations, acting on a great variety of theories about the problems and their solutions, have mounted vigorous efforts to increase their representation in science.

We acknowledge many unsettled questions of social, educational, and science policy in regard to these matters. We are particularly concerned here with learning at the undergraduate level. We believe that emphasis on community as a means of learning science furnishes a singularly auspicious focus for increasing the participation in science of women, minorities, and the handicapped. The model transcends institutional differences.

Emphasis on community as a means of learning science furnishes a singularly auspicious focus for increasing the participation in science of women, minorities, and the handicapped.

and it furnishes plenty of room for serious effort for each and every person in science.

As evidence that the learning community is an active force for broader participation, we note that the schools with the highest percentages of women and minority science and mathematics majors
Between 1960 and 1980, the fraction of 22-year-olds receiving baccalaureate degrees in the natural sciences and engineering hovered between 4 and 5 percent. Recent data indicate that the conferral rate this year (1989) will be 4.5 percent, at best. That rate would have to increase to over 6 percent by the turn of the century to maintain the current supply of scientists and engineers.

— AAAS President Richard Atkinson, 1990.

include many predominantly liberal arts colleges — women's colleges, historically Black institutions, and selective coeducational colleges. What these schools have in common is a strong tradition of community. This is the crucial enabling factor in the success of historically Black colleges and of other colleges that succeed with minority students. Community is also what propels many graduates of women's colleges to successful careers. Ernest Boyer has noted the damaging effects of the decay of community in higher education generally; his studies show by many measures that liberal arts colleges have retained community more than other kinds of collegiate institutions.

The single most enabling lesson for the science or mathematics learner is the central cognitive feature that knowledge is accessible, that it coheres, makes sense, and is a pleasure to apprehend. This lesson is much more likely to be learned by a student if he or she has regular personal contact with an experienced and dedicated teacher than if this contact is absent. The teacher can best communicate that the student's gender, race, or handicap are irrelevant to success in learning by teaching based on context, connections, and investigation. Such lessons will allow the student to see that the intellectual standard in science is inclusive and impersonal. For one and all, it concerns how well learning equips one to understand nature. Recognition of this standard puts the student, the teacher, and the other members of the class in the same boat. Cooperation helps everyone in such a classroom or laboratory.

Since the objective is to increase everyone's understanding and investigative power rather than to sort the students by their current level of scholastic achievement, students are encouraged to work together, to help each other, to form a community.

Learning communities are awesome teachers, especially of those who need larger than usual amounts of socialization in order to become scientists. Students need strong interactions with cooperative, mutually engaged classmates, as well as instructors, to acquire a sense of identity, to gain perspective on the field, to learn strategies for solving problems when they are stuck, and even to provide tomorrow's assignment when the syllabus gets mislaid.

Faculty must use every ounce of their energy to foster community, because otherwise students, whatever their personal characteristics, may not have the resources or fortitude to meet the standards of science.

Learning communities are awesome teachers, especially of those who need larger than usual amounts of socialization in order to become scientists.

That means that faculty must treat students evenhandedly, expect that they will work hard, show interest in their personal progress, struggle constantly to expose the logic and meaning of science through its connections and contexts, and prod students to ask why, to seek causes, and to ask questions. Faculty can
foster community by grading on an absolute basis rather than “on the curve.” The former unites the faculty and students in a common quest whereas the latter puts the teacher in the role of the sorter and the student in the role of competitor.

The ideal of the learning community is diminished when the phrase “role model” is used to imply that only minorities can inspire minorities, or that only women can inspire women. While we acknowledge the importance of role models to many students, White males, who are currently the large majority of scientists and science teachers, should be encouraged to think of themselves as credible mentors for all students. Such a commitment should not excuse backsliding in the effort to appoint more persons from under-represented groups to college and university faculties. It is, rather, a call for unity and action in the struggle for social justice.

Encouraging Women in Science

There is now an enormous literature on the causes of the under-representation of women in science and mathematics careers. Yet the last two decades have produced significant growth in the numbers and proportion of women receiving bachelor’s degrees in science or mathematics. Sadly, in most areas, the increased percentage of women is due more to declines in the number of men majoring in science and mathematics than to increased participation by women, but the trend is nonetheless important.

Private Liberal Arts I colleges — both coeducational and women’s colleges — have been especially productive of women science and mathematics graduates and of women graduates who subsequently earn a doctorate in science or

It is now clear that women can succeed in great numbers in science and mathematics.

mathematics. Indeed, these colleges produce a higher percentage of women science graduates than any other non-specialized category of institution. Nonetheless, women are still under-represented among their science graduates.

It is now clear that women can succeed in great numbers in science and mathematics. The success of women in science and mathematics is greatest in settings — both single-sex and coeducational — characterized by the kinds of learning communities described in this report. These settings warm the chilly climate for women so often noted at all levels of education in this country.

Where Minorities Succeed

All analyses of the rates of participation of Blacks and Hispanics confirm a picture of severe under-representation in science and mathematics at all levels of our system of education. Nevertheless, there are
Getting and keeping good minority students on track is not as difficult as it might seem, because it has been done before. But we keep throwing away things that work. Good programs that were funded by various federal agencies in the 1960s and 1970s were abandoned before they had time to flourish. It takes a sustained commitment to change things. You can't correct a hundred years of discrimination in ten.

— Clark Atlanta University President Thomas W. Cole, Jr., 1988.

Where are these minority graduates in science and mathematics receiving their undergraduate educations? Black science and mathematics graduates are trained extensively in the Historically Black Colleges and Universities (HBCUs). For example, in the mathematical and physical sciences, 45% of the 1986-87 bachelor's degrees that were awarded to Blacks were earned by graduates of the HBCUs, even though only one-third of Black undergraduates are enrolled in the HBCUs. A number of HBCUs are among the most productive of all institutions in the percentage of their graduates with degrees in science or mathematics. Indeed, three of the top five in chemistry are HBCUs (Xavier University of Louisiana, Talladega College, and Tougaloo College), and three of the top ten in physics are HBCUs (Lincoln University, Talladega College, and Fisk University). This record provides a startling and powerful refutation of the myth that Black students cannot succeed in the physical sciences.

This high concentration of Black science and mathematics graduates in the HBCUs stands in sharp contrast to the almost complete absence of Black graduates in science and mathematics at the vast majority of the nation's colleges and universities — this despite the fact that nearly all colleges and universities have Black students. Fewer than 100 colleges and universities had more than two Black mathematics baccalaureate graduates in 1986-87; fewer than 90 had more than two Black physical science graduates. Even in the life sciences, only 200 institutions had more than two Black graduates.

Similarly, Hispanic graduates are prepared in greatly disproportionate numbers in Puerto Rican colleges and universities. In physical science 30% of Hispanic graduates were prepared in Puerto Rican institutions; in life science the percentage was 43%, and in mathematics 18%. In contrast, only 33 institutions had more than two Hispanic mathematics baccalaureates, only 49 had more than two Hispanic physical science graduates, and only 133 institutions had more than two Hispanic life sciences graduates.

These data documenting the non-participation of the vast majority of America's colleges and universities in the preparation of Black and Hispanic science and mathematics majors is nothing short of a national disgrace.

The outstanding success of Black students in HBCUs is due in large part to the presence on these campuses of the type of natural science communities advocated in this report. The factors necessary

The non-participation of the vast majority of America's colleges and universities in the preparation of Black and Hispanic science and mathematics majors is nothing short of a national disgrace.
for collegiate success — a supportive community and "social connectedness" — are the same for all students. A great number of predominantly White colleges also

The factors necessary for collegiate success — a supportive community and "social connectedness" — are the same for all students.

provide these kinds of communities, but Black students who attend such colleges seem to gain access to these majority-dominated communities less reliably and less often. Studies show that Blacks are more likely to persist at HBCUs due to a greater degree of involvement in campus life and a greater growth in self-confidence in their academic ability. Academic integration based on relationships with faculty and satisfaction with the academic environment leads to higher grade-point averages. Blacks tend not to have this academic integration on predominantly White campuses, so they tend to be less successful. The lack of strong student-faculty relationships seems to be a very important impediment for Blacks on predominantly White campuses.

Someone who has few role models is not likely to get a confident vision of the possibility of a career in science or mathematics from his or her background. Rarely will such an individual obtain sufficient clues or inspiration from family associations. For most such children, incentives for science must be provided by the educational process
The trend is unmistakable: our children are losing ground...
Of the more than 73,000 baccalaureates awarded in engineering in 1986, just 6 percent went to non-Asian minority students; of the more than 16,000 mathematics degrees, just 7 percent went to minorities; in the physical sciences, we received just over 7 percent. If we were receiving these degrees in proportion to our share of college enrollment, these figures would be twice as high.


if they are to be provided at all. Many students enter HBCUs inadequately prepared for science courses in terms of content and study skills. Yet these institutions have been able to prepare their students for the successful pursuit of graduate study in major Ph.D.-granting universities. This has been accomplished despite severe financial constraints, reflected in inadequate scientific instrumentation and other resources, and heavy faculty teaching responsibilities.

The existence of effective learning communities in HBCUs is an important factor in the success of students in science, but it is not the only factor. In HBCUs professors expect that the students can and should achieve. They demand serious study and hard work, and they believe that deficiencies in background can be overcome. Faculty provide close contact and mentoring, and take pride in their students. Each student is recognized to be important as an individual. Promising students are encouraged to engage in research projects. As a result of high expectations held by the faculty, students see success in science and mathematics as attainable, and therefore they achieve.

Prescription for Change

All colleges and universities can learn much from HBCUs that can help minority students succeed in science and mathematics. Their experiences provide solid evidence for ways to work with all students, no matter what their backgrounds. Because there are so many more data and studies available on the situation in HBCUs, we have concentrated heavily on them here. Although we have far less information on which to base an analysis, we believe the general picture to be much the same for Hispanic and American Indian students, even though the particulars of their experience are different. What HBCUs do to “cultivate” and “pump” can be done as well wherever Hispanics and American Indians attend college.

The disgraceful situation of minority students who are attempting to pursue science and mathematics degrees at majority institutions can be corrected. Although offices of Minority Affairs help students with

◆

All colleges and universities can learn much from HBCUs that can help minority students succeed in science and mathematics.

certain problems, primarily with adjustment to the total college environment, such offices serve more to keep the students at the institutions than to keep them in science. Science and mathematics departments themselves must implement constructive plans to alleviate the multitude of problems that limit the academic performance of minority students.

The success of Uri Treisman’s program at the University of California at Berkeley has clearly demonstrated the effectiveness of a community of learners in any
institution. This program enables students to study and learn together, eliminating much of the isolation they feel, at the same time as it addresses the problem of poor study skills and inadequate high school preparation. In effect, it re-creates in the midst of a large and impersonal university environment the type of supportive community characteristic of HBCUs. Such programs cannot eliminate alienation, and may not work in an institution with only a handful of minority students taking science and mathematics courses, but they do provide a proven model that works.

Another important aid is to sensitize an entire science faculty to be aware of the role they play in the success of minority students. Indeed, this should happen across campuses. Majority faculty automatically play this role in the success of majority students, but they must learn to do so consistently and effectively with minority students. They must learn to look at minority students when they give lectures, to expect them to answer questions, and to let them know of such expectations. Confidence and high expectations must be transmitted to all students. Faculty must work to discard beliefs that minority students cannot do science, because this attitude cannot be hidden from the students and will therefore be fulfilled.

Majority faculty should be willing to serve as mentors, and should not expect the few minority faculty at an institution to take care of all minority students. Majority faculty too can be effective role models. If White faculty at HBCUs can serve as role models for Afro-American students, White faculty at majority institutions can do the same.

Science departments must become the same kind of natural science communities for minority students as they are for majority students. Only in this way will we increase the number of minority students who gravitate toward and remain in science.

Science Teachers: Partners in Community

A student who has been lucky enough to have been a member of a science learning community or a partner in a research collaboration is learning more than science. Such a student is learning how to teach. It is possible, perhaps even likely, that such a student will consider teaching as a profession.

Never has our country been more in need of dedicated, well-trained, and imaginative science and mathematics teachers. Students who understand both the pleasure and the importance of teaching are a national resource. Yet too often prejudices and lack of imagination keep many such students from becoming teachers, especially at the pre-college level. Education is cyclic; those who study become teachers of others who study, who in turn grow to love knowledge, and may become teachers themselves.

It is, however, a sad truth that the faculties of colleges and high schools rarely encounter one another. People who are equally
dedicated, equally passionate about knowledge and about students, and sometimes equally beleaguered, are isolated despite their common enterprise. Between school and college there is little sense of community.

College faculty should recognize that their students are bridges that link their world to the high schools: high school teachers pass students on to college, and many of those same students prepare in college for careers as teachers. The natural science community bridges the gap between levels of schooling. No longer should science education be artificially divided between school (K-12) and college (13-16); far better that it be viewed as a continuum that spans the total breadth of student experience. Indeed, curricular and enrollment realities suggest that schools, colleges, and the nation would be better served by thinking and planning in terms of K-14. Every institution of higher education should feel obligated to ally itself in multiple partnerships with pre-college educational institutions and teachers.

Broad-based science communities can be fostered through creative partnerships between pre-college teachers and college faculty members who together design a curriculum that introduces high school students to real college science (which may well receive college credit) and introduces college students to the same course. High school seniors and first-year college students are not very different after all, and the curriculum which motivates one can excite the other as well. In the process, college and high school faculty can learn from each other about pedagogy and content.

### From School to College

A big leakage of potential science students occurs between the senior year of high school and the first year of college. Moreover, nearly 50% of first-year college students with interest in natural science and engineering do not survive to a baccalaureate degree in one of those areas. These data indicate poor articulation between the secondary and post-secondary curricula. Additionally, secondary school science and mathematics teachers are in short supply, and many teachers in the field — especially elementary teachers — need professional enhancement. It is also distressing to learn that only 7% of U.S. 17-year-olds have the competence to achieve well in college science courses. Moreover, 40% of senior high schools offer no trigonometry, 70% offer no calculus, 10% offer no chemistry, and 20% offer no physics. Only 7% of high school graduates have taken trigonometry, 6% calculus, 24% chemistry, and 11% physics.

If the learning model we propose were incorporated in primary and secondary school instruction in science and mathematics, the percentages of students taking courses in these areas and persisting...
in them would increase. As one mechanism for doing this, we observe that teachers tend to teach as they were taught. Several colleges have recently made strong commitments to increasing their activity in teacher preparation. Liberal arts colleges can be excellent sources of teachers who have learned science and mathematics in the manner in which it should be taught to others.

All colleges should mount projects that draw their own science faculty into contact with school teachers. All colleges should take it as their responsibility to provide formal and informal means of teacher enhancement in their regions. The payoffs would be many. College faculty would learn more accurately the prior experience of their students, and could adjust their

All colleges should mount projects that draw their own science faculty into contact with school teachers.

introductory curricula accordingly. Contacts would also improve the placement of high school students in college settings that best suit their needs. High school teachers would benefit by acquiring a stimulating professional association in the discipline that would provide guidance for hands-on work for students and other enrichment.

One important mode for interaction is to involve secondary school teachers in scientific research groups during summers at nearby undergraduate institutions, based upon the model of the NSF Research Opportunity Award program for

It is critical that teacher preparation and enhancement initiatives currently underway be supported and expanded.

undergraduate faculty. We think that this mode has the potential for many synergistic effects. Enmeshing the teacher in the informal and personal laboratory setting rather than the classroom means far more personal contact; direct experience with real science, scientists, and apparatus; and a natural, continuing connection to on-going activities of the research group. It is likely to be a source of stimulation to the teacher, perhaps prompting some investigational activity in that teacher’s classroom. Having a mature collaborator in the form of a secondary school teacher would also be a fit and welcome addition to the research effort. The mixing of undergraduates with high school teachers in summer programs may also serve to interest some capable students in teaching careers.

Proper preparation of new school teachers and appropriate support of existing teachers are essential elements for achieving the joint goals of ensuring a scientifically and mathematically literate citizenry and attracting the people we need into professional careers in science and mathematics. It is critical that teacher preparation and enhancement initiatives currently underway be supported and expanded.

Fortunately, there is now a consensus on principles for effective teacher preparation and enhancement programs in science and mathematics:

- Teachers should have a strong command of the subject areas in which they will teach, and of relationships between their principal discipline and other disciplines.
- Teachers should develop strong communication skills that enable them to explain to others the concepts of their discipline.
- Teachers should understand science and mathematics not as facts to be learned but as ways of thinking and investigating which involve making conjectures and testing hypotheses.
- Teachers should know how to learn, how others learn, and how to adapt teaching methods to fit individual differences.
- Teachers should be familiar with recent research in mathematics and science curricula and pedagogy.

Teacher preparation and enhancement undertaken with these principles will create a system of science and mathematics education that pumps rather than filters, that cultivates rather than weeds.

The colleges who participated in this project are a natural source for such teacher preparation and enhancement; they are productive of science and mathematics majors; they are attentive to science and mathematics literacy throughout the
general curriculum; and they care deeply about teaching and learning. If we wish a new generation of primary and secondary science and mathematics teachers to embrace a hands-on, experiential, laboratory-rich, problem-solving pedagogy, that is what prospective teachers must experience in their collegiate years.

The independent predominantly undergraduate colleges are already major players in undergraduate

**Insufficient commitment is generally a greater barrier to success than inadequate resources.**

science and mathematics education. Because theirs is a teaching rather than research mission, they are constituted in ways that enhance the approach to science and mathematics teaching and learning advocated in this report. What works in these colleges is transferable, both to other types of undergraduate institutions and to pre-college education. While this kind of teaching and learning is in some ways more expensive than other less effective modes of instruction, insufficient commitment is generally a greater barrier to success than inadequate resources. This sector of higher education has enormous capacity to expand its outputs in important ways — in the production of more science and mathematics majors, in the enhancement of scientific and quantitative literacy, in expanded preparation of well-educated science and mathematics teachers, and in professional enhancement of current teachers.

**Partnerships for Education**

Those seeking to transform primary and secondary science and mathematics education will find a wealth of effective examples among the science-active undergraduate colleges. Effective responses will require the creation of new partnerships between colleges and schools. Anticipating this need, a great many colleges — some with the support of government, private foundations, or corporations — have begun to extend their reach to become part of the larger national effort to revitalize school science and mathematics education.

Creating and sustaining partnerships not only extends the reach of individual institutions, but also gives participants a sense of being part of a larger vision, of being a piece of the solution to a national problem. Partnerships help sustain attention on issues which require long-term effort; they motivate faculty and teachers to effective

**Support for partnerships should be a high priority for public and private funding sources for science and mathematics education.**

action; and they create wider recognition and reinforcement of local successes. Support for partnerships should be a high priority for public and private funding sources for science and mathematics education.
Strong faculty are indispensable to healthy learning communities. In addition to providing excellent teaching, faculty serve as role models for their students, provide intellectual stimulation for their colleagues, and catalyze all aspects of the academic process. To draw people into science and mathematics, careers in these disciplines must be seen to be attractive and rewarding. Faculty who are satisfied with their careers, who enjoy teaching, and who are excited about scholarship serve as dynamic models of the kind of persons we hope to graduate from our colleges.

The demographics and mobility of faculty in non-doctoral institutions are important characteristics of the current scene. The 1960s was a period of rapid expansion in U.S. higher education during which the number of science and engineering baccalaureate degrees more than doubled. Growth created many opportunities for upward mobility of faculty into jobs that better matched the person to the institution. Mobility is no longer a significant feature of the academic scene. Science and engineering baccalaureates in 1988 were just 17 percent higher than in 1970, providing an expansion rate of less than one percent per year. This means that the employer of a college faculty member who reaches tenure is now more likely to be that person’s employer at retirement. Hence colleges, science-related agencies, and faculty themselves must all work synergistically to keep these long-term relationships healthy and productive.

In successful academic communities, people work together to model the diversity that we want our students to experience. Institutions must recognize the diversity of talents that exist within a department and promote ways for faculty members to develop their different talents. Scholarly activities should be expected of all faculty, since active scholarship promotes excellent teaching. However, scholarship must be viewed broadly, including creativity in educational endeavors as well as in traditional academic research.

A vital community of learners can be built and sustained only if there is commitment at all levels within an institution. Faculty and administration must possess similar visions of the institutional mission, and everyone must work cohesively to achieve common goals. Federal agencies and private foundations are also key partners in the development of academic communities. By working with colleges and universities to develop new initiatives, they provide both intellectual and fiscal resources that are the lifeblood of faculty development.

The interactive combination of teaching and scholarship that is most satisfying to a teacher-scholar in undergraduate science or mathematics will also result in the most instructive and engaging education for students. This ideal of
the professionally active teacher should, therefore, shape our understanding of how faculty are brought into the community, how faculty development occurs within the community, and how the sense of community can be sustained and extended.

The Role of Scholarship

We have seen through repeated examples how natural science communities play a central role in the success of liberal arts colleges in attracting students to the study of science and mathematics. Faculty catalyze the formation of these communities by playing the combined role of teacher and scholar. Whereas in many research universities the roles of teaching and research often compete for time, energy, and resources, in liberal arts colleges they are essential and natural allies.

Public concern about the dominance of research priorities over undergraduate teaching in many universities has led to an unfortunate misconception about the appropriate relation between teaching and scholarship. Various national commentators and policy leaders have expressed concern that emphasis on research will result in diminished quality of undergraduate teaching, as if the environment of teaching and scholarship were a zero-sum game. The experience of effective science education in the productive liberal arts colleges exposes these concerns as profound misunderstandings.

It is surely possible for faculty to stress research at the expense of teaching, or teaching at the expense of scholarship; both extremes diminish learning by separating instruction from authentic, investigative, community-based science education. What the science-active liberal arts colleges have demonstrated so well is that between these extremes lies a productive synergism of teaching and scholarship in which student and faculty learning thrives.

Scholarship and research are pursued together in liberal arts colleges as forms of undergraduate teaching, just as in research universities they are pursued as forms of graduate and post-doctoral teaching. The symbiosis of research and teaching that has made U.S. universities an international magnet for graduate education is focused in liberal arts colleges on their unique mission — undergraduate education. In these institutions one finds faculty committed to the combined role of teacher and scholar and administrations committed to consistent support of a natural science community of learners.

What we urgently need today is a more inclusive view of what it means to be a scholar — a recognition that knowledge is acquired through research, through synthesis, through practice, and through teaching.

Recruiting Faculty

One of the biggest challenges facing colleges today is hiring new science faculty. The anticipated shortage of professors has provided impetus for many institutions to develop new ways to attract and retain qualified candidates. The most common response is to offer more money. While salary is certainly an important consideration, it is by no means the only factor in the employment equation. Working conditions and the general quality of life in the college community are critical factors, especially for scientists or mathematicians interested in the kind of undergraduate environment this report envisions.

Undergraduate science education is most successful when the commitment to teaching is personal and deep.

Individuals looking for academic careers in science and mathematics will be attracted to colleges that support the realistic development of such careers. Where collaborative learning is prized in the sciences and mathematics, its labor-intensive character must be reflected in faculty expectations. As they recruit new faculty members in science and mathematics, undergraduate institutions must be forthright about the importance of teaching and the commitment of time and energy that such a commitment entails. Any misrepresentation of the nature and priority of teaching betrays the mission of a college and misleads prospective faculty members. To support the student-faculty community that is essential for effective learning, course assignments, tenure, and promotion must encourage a broad view of educational scholarship.

Prospective science and mathematics faculty members must be equally clear about their own commitment to teaching. Undergraduate science education is most successful when the commitment to teaching is personal and deep. Faculty must understand that teaching is a meaningful and important responsibility and that scholarship is as important for their department’s curriculum as it is for their own professional development. The synergism of teaching and research provides faculty with a unique opportunity to open up the minds of their students and concomitantly to cultivate their own professional identity.

Faculty Responsibilities

Commitment to both teaching and scholarship combine in the undergraduate setting to provide first-rate education for students in the sciences and mathematics. With that commitment, responsibilities become opportunities; without it, they become onerous obligations. Committed faculty members teach to increase their students’ “hands-on” connections to the sciences and mathematics. They view their own activity as professionals always with an eye to the impact such activity can have on their teaching.

Creating a market for good teaching begins with having the faculty assume shared responsibility for the sum of their teaching activities ... in the end, that means individual faculty members coming to know firsthand how their colleagues teach.


We must, as teachers, transform ourselves from authorities who reveal truth, to facilitators who design creative learning environments for our students in which they can use the full range of talents and intelligences that they bring to the study of science. We must inspire ordinary people to become extraordinary.

— Priscilla Laws
You scientists need better cooperation across departmental lines ... to project equipment needs farther into the future ... and determine what must be reserved for unexpected visitors, research operations, and other opportunities. We presidents and deans need to work more effectively with you. You tend to be rather better at describing in excellent detail ... an opportunity for a matching grant ... than at laying out a five-year program of instrumentation and facilities needs.

—Bowdoin College President

In liberal arts colleges, successful faculty are those who understand that undergraduate students play an important role in the intellectual community of learners. Learning is not a uni-directional endeavor, but one in which faculty learn new ways of looking at old questions from the students they teach. Fresh student perspectives infuse faculty with new insights into the scientific endeavor and promote a shared approach to understanding scientific questions. A positive “esprit de corps” between undergraduate students and faculty helps students aspire to career goals in science and mathematics.

One must admit that circumstances sometimes make development of community difficult. Frustrated faculty members sometimes blame students for lack of a proper work ethic, for lack of enthusiasm and, most unfortunately, for lack of proper background. Students often blame science and mathematics faculty for antiquated teaching methods, dry lectures, and draconian grading systems. Such frustrations by students and faculty can easily undermine the foundation of a learning community. They must be resisted and reversed if science education is to thrive.

One of the most fundamental necessities of a good teacher is to respect students. Students who resist science, perhaps because of a residual fear, need nurturing that can be provided only by faculty members who are committed teachers. Faculty who respect students as individuals will learn to recognize the unique gifts of students who are unsure of their interests or who lack sufficient background or confidence to excel immediately. Success in cultivating scientific and mathematical talent and interest will prove to be the ultimate measure of effectiveness of the science and mathematics programs.

Supporting Scholarship

The role of departmental chairs is pivotal to program success, to faculty development, and to general support of scholarship. In addition to individual responsibilities such as teaching, scholarship, advising, and committee work, chairs are responsible for departmental curriculum needs, budget construction and supervision, public relations, and recruitment of students and faculty. Chairs also have responsibility for mentoring faculty, distribution of teaching opportunities, encouraging scholarship, and conducting performance evaluations. Beyond these duties, chairs serve as a vital liaison between the faculty and the administration. It is of paramount importance for institutions to recognize the importance of departmental chairs and to cultivate their leadership abilities.
Regular development of proposals for professional work is another essential component of the undergraduate science and mathematics environment. Writing proposals allows for invaluable peer evaluation of ideas and promotes the development of personal long-range plans. Faculty must be committed to the process of proposal development as part of their own long-range professional planning; deans and department chairs must encourage these endeavors and institutions must provide appropriate tangible support through their development offices. Proposals and publications frame and sustain the entire spectrum of scholarly endeavor, contributing both to the foundation of the discipline and to the scholarly community on campus.

While grant writing by faculty should be encouraged by college administrations, grant awards must not become the measure of success. College administrations must not allow federal or private organizations to become surrogate tenure and promotion committees. They should, instead, promote faculty grant writing as scholarly achievement of value for itself.

Faculty participation in professional and educational conferences is a critical dimension of teaching and scholarship that combats the sense of isolation often felt at a small college. By sharing teaching and research insights with one’s peers, a faculty member can more readily sustain pedagogical vitality and professional self-confidence. Such work also models for students a significant aspect of the scientific and mathematics community.

The learning model envisioned in this report cannot be limited to the contact hours assigned to lectures and laboratories. Collaborative research, consultation with students, and advising about a host of related concerns vie for a faculty member’s time along with such activities as course preparation, curriculum development, and other traditional collegiate responsibilities. Working with undergraduate research students during the summer is another important priority that needs to be supported by faculty, departments, and institutions. Student-faculty scholarly partnerships are powerful learning arrangements for both parties, but only work well if both commit time and energy to it. Faculty must find self-satisfaction in the fact that they are functioning as teachers and as scholars as they undertake their work with undergraduate research colleagues.

**A key strategy to create time for faculty is the establishment of lean curricula shorn of excessive devotion to narrow aspects of the discipline.**

**Developing Academic Careers**

To remain vital, faculty need support throughout the development of their academic careers that reflects changing, complex, multi-dimensional perspectives. Dynamic faculty undertake new challenges, teach different subjects, and engage in varied types of scholarly endeavors. Focused achievable goals for faculty are important stimuli that help shape academic careers. The formulation of these goals should be encouraged and aided by their departments and institutions.

Perhaps the most pressing need of faculty at any institution is time — the time necessary for work, for reflection, and for meaningful deliberation with students and colleagues. Time is necessary to encourage the informal associations that are vital to the development of community upon which the integrity of learning depends. Faculty development programs must allow...
The experience of successful science and mathematics programs in predominantly undergraduate institutions offers an important contribution to the national dialogue about infrastructure needs that are required to implement the kind of science and mathematics teaching and learning advocated in this report. It is clear that a highly interactive, hands-on, experiential, lab-rich, problem-solving program for natural science communities places special demands on infrastructure. Facilities, equipment, computing, libraries, and technical support must be adequate to the job if we are to achieve the fundamental reform of science and mathematics education needed by this country.

A second principle is that policies should address both long-term and short-term goals. Sustaining an adequate infrastructure is a costly proposition. Faculties, deans, development officers, and presidents, as well as staff of governmental and private funding agencies, need to be clear about the long-term implications of decisions made to solve immediate problems. Too often effective programs are abandoned before they have achieved their purposes. Commitment to long-term sustained effort is absolutely crucial if change is to be productive.

Appropriate Spaces

The problem of inadequate facilities has two dimensions: one is the limitations on programs caused by deteriorating, worn-out facilities. The other is that existing spaces do not necessarily support active, investigative communities of learners.

Architecture and facilities must support good teaching and learning: “... we shape our spaces and then they shape us.” We have come to recognize a widespread mismatch on most campuses between the pedagogy supported by existing facilities and the pedagogy we seek to encourage. Why this mismatch between architecture and curriculum? In part, because architects are often unfamiliar with the approach to undergraduate science and mathematics education described in this report. Faculty, furthermore, have few models of building design which translate these functions into form.

Public policy should encourage and support indigenous science and mathematics education. Available on individual campuses. Locally-based research supports student-faculty partnerships that enhance the learning community, reinforces faculty professional activities, and exemplifies to students the dynamic that sustains the undergraduate teacher-scholar.

A program of undergraduate science and mathematics education that seeks to attract students rather than weed them out needs spaces organized differently from the kinds of spaces built in the 1950s and 1960s. These earlier spaces, with large lecture halls and relatively cramped laboratories, envisioned a science education characterized by passive rather than active learning. Ironically, just as experimental research in science became more collaborative, our methods of teaching science became less so.

Serendipity — the chance discovery of an idea — is common in the daily practice of science and mathematics. Facilities need to support serendipity, to have spaces spread throughout where spontaneity can be exploited on the spot through informal discussion with peers, using a computer in a common study hall, or doing late-night laboratory team-work.

Colleges need space for science that will support a blend of teaching styles linked more tightly to the laboratory, space for student and faculty research, space that encourages interdisciplinary uses of major instrumentation, and classrooms wired for multi-media presentations and computing. Computing — for data collection, data analysis, word-processing, graphic display, simulation, modeling, and information retrieval — must be pervasive: students and faculty must have access to computing where they work. Science and mathematics are increasingly social, as opposed to solitary, activities. Our buildings must reflect the social character of science and mathematics by providing spaces for exchanges among students and faculty.

A department needs also to consider seriously the “hospitality” of its space for students and its role in fostering community. With certain restrictions, the science building should be accessible and useful to students after normal business hours. Of course safety and security matters have to be considered, but having the department’s own majors around the building usually means less rather than more mischief. Students will be attracted by such

Facilities need to support serendipity.

amenities as carrels where they can work and leave their books, scientific instruments, tutoring sessions, computers and printers, a telephone, a coffee pot and pop machine. They will make good use of research laboratories, science libraries, a general purpose room where homework, test answers, class references, reference books, models, and slides are stored. A department that makes such facilities available will soon find its quarters populated at all hours and on weekends; students will know each other, undergraduates will be coming by to get informal help with assignments, and everybody will have some sense of what is going on in the department. This type of environment develops a learning community and pays rich dividends in learning, persistence, and recruitment of students into science.
Deteriorating Buildings

In addition to spaces that are ill-equipped to support an active, hands-on, research-oriented communal learning experience for students, we are faced with space limitations caused by deteriorating structures. Excerpts from a description of one institution's chemistry building could describe outdated, worn-out facilities in countless institutions across the country:

- Fume hoods are located on interior walls in violation of federal safety requirements.
- Ventilation system provides insufficient air exchange.
- The entire building, including all laboratory space, lacks fire suppression sprinkler systems.
- Plumbing fixtures and laboratory gas lines are corroded and require replacement.
- The mechanical system is insufficient to maintain adequate temperature control.

Many institutions are now seeking to design spaces for a highly interactive, hands-on lab-rich science and mathematics education program. The 1990 NSF Research Facilities Modernization Program is part of a rejuvenated federal effort to help institutions plan appropriate new and renovated spaces for research and research training. This program is drafting a guide to planning science and mathematics research facilities that is designed to alert faculty, administrators, architects, and planners to critical architectural and engineering requirements in the design and redesign of research facilities. There is, however, no similar document that focuses on criteria for facilities to foster interactive science and mathematics learning. We hope to change this. Formation of a network of representatives from colleges planning to build new science facilities, or planning modernizations and renovations, would be an excellent way to diffuse architectural innovations which foster an interactive learning model.

The total need for new construction, renovation, and major repairs of science and mathematics facilities at the science-active predominantly undergraduate institutions is on the order of $1.5 billion.

In 1990 NSF issued a stark report estimating the magnitude of the facilities deficit facing higher education. Although this report focuses only on facilities for research and research training, it provides a basis for a similar — and much needed — study of facilities for undergraduate science education. There are approximately 30 million net assignable square feet of science and mathematics teaching and research space in the nation’s liberal arts colleges, concentrated mostly in the colleges with the most active science programs. If one uses the same construction and renovation cost estimates as in the 1990 NSF study, these undergraduate institutions need something like $250 million per year for new construction of science and mathematics facilities, and $90 million for repair and renovation. In addition, the NSF estimates that for every $1 of new construction actually undertaken, there will be $4.25 deferred. Under this formulation, the total need approaches $700 million per year in new construction and $350 million in renovations and repairs.

By these rough estimates, the total need for new construction, renovation, and major repairs of science and mathematics facilities at the science-active predominantly undergraduate institutions is on the order of $1.5 billion. While this figure represents only about ten percent of the total required for research facilities, it is nonetheless a very big number and a pressing problem at the institutions described in this report.

Instrumentation

A community of science and mathematics learners engaged in active learning in a lab-rich and research-based curriculum requires faculty and student access to state-of-the-art research instrumentation located where students and faculty work. Fortunately, the revolution in electronics has made this access possible. Instrumentation which was not even available at many advanced research centers just ten years ago can now be acquired and maintained by predominantly undergraduate colleges. Excellent, relatively robust, repair-free instruments are available in mid-priced models.
In addition, it is no longer as necessary to choose between securing expensive service contracts and requiring faculty members to spend considerable periods of time maintaining and repairing delicate instruments. The cost of owning and operating state-of-the-art instrumentation is decreasing, and therefore the ability of smaller colleges to provide this important resource to students and faculty has increased.

Recognizing the importance of adequate instrumentation, in 1985 NSF reinstated a program that provides matching grants for the acquisition of instruments to be used to develop new or improved laboratory courses in science, mathematics, and engineering as the nations predominantly undergraduate institutions. As significant as this ILI program has been, available funds have fallen far short of demand.

It is significant, we believe, that the ILI guidelines identify as activities eligible for support exactly the type of active, lab-rich instructional environment that supports the learning model we have described and advocated in this report:

- Projects that seek creative improvements to introductory level courses.
- Projects aimed at acquainting non-majors with the principles and methods of science, mathematics, and engineering, or with the impact of science and technology on society.
- Projects concerned with the undergraduate science and mathematics education of prospective teachers.

- Projects to improve laboratories for majors.
- Projects to up-grade obsolete or unreliable equipment, but with plans that significantly improve instructional capabilities.
- Projects that allow access to computer networks which provide greater capabilities than are available locally.
- Projects to improve undergraduate honors programs, student research, and independent study.

The NSF equipment program, matched with support from private foundations, corporations, and charitable individuals, has allowed many colleges to strengthen greatly students’ learning experiences by leveraging numerous modest grants for equipment and program. Attentive faculty use the ILI peer review process as an almost continuous outside review of the department. In this way faculty at

**Attentive faculty use the grant peer review process as an almost continuous outside review of the department.**

smaller institutions far removed from major research centers can use the extended contact with peers provided by the NSF competition to embed them in the world scientific community. A more adequately funded NSF equipment program could benefit a much larger number of colleges.

— Bowdoin College President Robert Edwards; CUR-1985.
Estimates of the funding required for instrumentation are difficult to make, but data obtained from several sources indicate that colleges wishing to maintain state-of-the-art instrumentation for a research-based curriculum must expend about $5,000 per faculty member per year. Thus the 400 or so science-active independent colleges, each with approximately 25 science and mathematics faculty, should be spending $50 million annually to support instructional and research instrumentation for this sector of the undergraduate community. If the NSF were to participate in financing this to the extent of 50%, the annual bill would be about $25 million. This is a feasible national policy goal.

**Computers and Library**

Contemporary science and mathematics programs must have pervasive, powerful, decentralized computing capacity for data collection, data analysis, word-processing, graphic display, simulation, modeling, and information retrieval. If students and faculty are to be in the laboratory, as we say they must, computing must be there and nearby also.

Colleges must take advantage of the revolution in computing technology, especially of modestly-priced multi-tasking workstations of great power and sophistication. Workstations allow presentation of a wide variety of information — including text, pictures, graphs, animation, video, music, and simulations — on a single screen. They offer efficient transfer of information among

Colleges must take advantage of the revolution in computing technology, especially of modestly-priced multi-tasking workstations of great power and sophistication.

several applications running at the same time to create high-impact teaching and learning applications. They enable faculty to model complex phenomena to increase student understanding. When connected to a local or national network, they enhance access to specialized information both on and off-campus, thus facilitating communication. Appropriate exploitation of this new technology at the undergraduate level will stimulate dramatic improvements in students’ analysis, synthesis, and quantitative problem-solving skills.

A vexing problem on all of our campuses is how to provide students and faculty with necessary and efficient access to the scientific and mathematical literature. The cost of journals is growing faster than that of books, and the capital cost of maintaining shelf space and providing timely and easy access to students and faculty is high. So, we have discovered, is the cost of bringing our libraries “on-line.” On the other hand, growing numbers of scientific journals will be available as databases, and if networked computing were available on our campuses, then bringing journals to local workstations electronically would be much more a marginal cost than a basic cost. NSF could play a major role by assisting with the conversion of key resources from paper to machine-readable form and with the building of networks to permit access to these databases.

The key is to encourage publishing in machine-readable form, and to maintain journal databases in a standard format accessible through a national network. This is a wonderfully appropriate role for government, with major impact on research as well as education. It would also provide a powerful incentive for colleges to create the workstation networks they need anyway for science and mathematics education. The cost of building and maintaining a journal collection in science and mathematics would then be reduced, and resources thus freed could be invested in campus-wide computing power and networking.

We greatly applaud the leadership NSF is already providing to estab-

NSF could play a major role by assisting with the conversion of key resources from paper to machine-readable form and with the building of networks to permit access to these databases.
lish a national data communication network. This investment in critical communication infrastructure, like the federal highway system, is something government can do especially well. The National Research and Education Network (NREN) will be a key to many of the partnerships envisaged in this report. For example, one can confront the isolation felt by many faculty directly by supporting national computer networks linking faculty of similar interests. Such networks could link, for example, women graduate students with women scientists, minority students with minority faculty role models, and those addressing reforms in introductory courses with individuals engaged in similar endeavors.

Policy Options
If colleges are serious about improving undergraduate science education, they must provide opportunities for faculty who teach undergraduates to grow and develop as teacher-scholars. To do this, colleges must make a better claim on public and private dollars that are available for science and mathematics education, and must be aggressive in helping foundations shape programs that are directed at undergraduate science and mathematics education.

As in other areas of science and mathematics, NSF must take a leadership role in supporting and stimulating institutions to meet their facilities needs. The job is daunting, but it is hard to imagine how institutions across the country are going to successfully tackle the critical facilities problem without NSF as a major player.

With its peer review process exerting quality control (eliminating the need for pork barrel decisions) and with the leverage its support can provide as colleges seek funds for facilities from other sources, NSF help is crucial.

The new NSF program in support of facilities renewal is a promising beginning, but its limitations overwhelm its potential: its restrictions to renovation and to spaces for research and research training, its inadequate recognition of our country’s critical need for new and renewed spaces for teaching, and its woefully inadequate level of funding are truly dismaying.

Different federal programs for support of science education operate with quite different objectives, for example, to identify exemplary programs, to establish model programs, to leverage support from other sources, or to support necessary activity. It is clear from the preceding analysis that NSF could reach effective leverage level for instructional scientific equipment through normal budget processes. However, to reach such a level for facility construction and renovation would require a major reprioritization of federal science policy goals.

The continuing propensity of the President and Congress to make the raising of capital from private donations more and more difficult compounds the problem of facility construction and renovation. Several years ago new and major constraints were placed on the ability of institutions — especially private institutions — to borrow capital in tax-exempt markets.

Limits on total borrowing, arbitrage interest, and holding time before spending have driven the cost of managing construction cash flow greatly higher. Proposals currently being discussed to limit the tax-deductibility of charitable gifts, especially by major donors, threaten to choke off the principle sources of capital required to tackle the huge facilities construction and renovation problem faced by independent institutions.

Independent colleges, as the 1990 NSF facilities study clearly shows, pay for almost all of their construction and renovation costs through charitable gifts and institutional funds. Were there plans for a significant federal grants program to support construction and renovation of science and mathematics teaching facilities, prospects for the future would not be so bleak. But no such program is even contemplated.

We cannot meet our facilities needs with mirrors. Something must be done to facilitate the necessary acquisition of capital. Incentives available to donors to make capital gifts must increase; the cost of borrowed capital must be reduced; and federal and state grant support must become available. Abundant
evidence of need can be found in the 1986 NSB report on undergraduate science education. Absent all, or at least some, of these changes, the science and mathematics facilities at independent colleges will only deteriorate, and the nation will lose.

**Actions**

Several key groups have a stake in investing in academic research facilities: academic institutions, state and local governments, the federal government, private industry, foundations, and individuals. If significant progress is to be made in meeting facility needs, these groups must share in the responsibility and increase their efforts. Each has a different interest and role to play, yet all must work cooperatively to leverage their efforts and funds for maximum impact. In particular, each group must determine where facilities needs fit relative to other priorities, since facilities support will necessarily compete for funding resources against other high priority programs.

A recent report from The Government-University-Industry Roundtable (NRC) outlined options such as the following:

- Colleges must prioritize their needs and employ more effective strategies for facilities planning; such plans, based on both short and long-term needs, should include mechanisms for budgeting, maintenance, management, and utilization, and should explore opportunities for greater use of debt financing.
- State and local governments must recognize the science facilities needs of undergraduate institutions. They should determine priorities, explore mechanisms to increase support, encourage partnerships and consortia, develop joint programs and initiatives, and consider additional incentives to encourage support for facilities.
- The federal government should play a more active leadership role in developing a systematic and balanced national approach to institutional facilities. Agencies must recognize the importance of such facilities, the need to provide support, and the priority of this need.
- Industry must strengthen its overall commitment to support academic science facilities. It should also consider and identify actions that would increase industry’s incentive to provide such support.
- Private foundations should consider initiatives, including cooperative programs among themselves and with others, to leverage their support.
AFTERWORD

In an era when higher education has come under criticism from many different sectors, it is essential the science and mathematics educators from the nation’s predominantly undergraduate institutions take the lead in confronting the issues and setting a new course for strengthening undergraduate science and mathematics. Many creative programs that address well-defined needs are being developed and implemented in liberal arts institutions. Too often exceptional education reform efforts go unnoticed either because they occur in places out of the public eye, or because faculty and students consider such programs as “status quo” and do not fully realize that other institutions are looking for models upon which to reform their own programs. Some of these programs are cited in this report and were highlighted at the National Colloquium; there are many more.

Our goal is that Project Kaleidoscope be the starting point for the evolution of a newly invigorated approach to undergraduate science and mathematics, and that it contributes the continued dialogue and partnership between funders, policy makers, and science and mathematics educators as they work together to shape the tools and provide the necessary support. Several further Project Kaleidoscope activities are in the planning stage. We look to all committed to “WHAT WORKS: BUILDING NATURAL SCIENCE COMMUNITIES” to be involved in this effort.