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ABSTRACT

In an era when the U.S. educational enterprise, particularly in mathematics, physical sciences, and engineering, has been found to be seriously flawed and has come under criticism from many different sectors, it is essential for science and mathematics educators from the nation's predominantly undergraduate institutions to take the lead in confronting the issues and setting a new course for strengthening undergraduate science and mathematics. This report presents the goals of Project Kaleidoscope as well as a plan of action for the decade of the 1990's to meet these goals. The plan contains four major initiatives which involve changing undergraduate science and mathematics education through continued dialogue and partnerships between funders, policy makers, and science and mathematic educators. Specifically, the initiatives propose: (1) reforming the introductory course in undergraduate science and mathematics; (2) supporting the integrated teacher/scholar role of undergraduate science and mathematics faculty; (3) making disciplinary content and active learning central to the education of K-12 teachers of science and mathematics; and (4) developing partnerships focused on strengthening undergraduate science and mathematics. It is emphasized as well that in each of these initiatives, careful attention must be paid to underrepresented groups in science--women, minorities, and handicapped. Recommendations corresponding to each of these initiatives are given, and to illustrate the report's analysis of "what works" in this endeavor, a number of strong programs that address well-defined needs in liberal arts institutions are described. Chapters in this report include: "Forming Natural Science Communities," "Learning Science," Mathematics: The Foundation of Science," "Human Resources," "Faculty: Building a Community," and "Facilities: Supporting a Community." (PR)

ED351187

What Works: Building Natural Science Communities

A Plan For Strengthening Undergraduate Science and Mathematics

Volume One

In August 1989, The Independent Colleges Office (ICO), based in Washington, D.C., received a grant from the National Science Foundation (NSF) in support of a project to develop an agenda for strengthening science and mathematics in this nation's liberal arts community. Called Project Kaleidoscope, this effort paralleled similar NSF-funded projects focused on the undergraduate sector at two-year institutions, at public comprehensive universities, and at major research universities. The history and present condition of the nation's scientific and educational infrastructure, as well as the challenges facing this country's liberal arts colleges and other predominantly undergraduate institutions, established the context for Project Kaleidoscope. Designed from the beginning to be a catalyst for action, Project Kaleidoscope sponsored a National Colloquium at the National Academy of Sciences in February, 1991, bringing together over 600 persons committed to strengthening undergraduate science and mathematics. This report, "What Works: Strengthening Undergraduate Science and Mathematics," is the next step in the Project Kaleidoscope agenda.

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WHAT WORKS

The most important attribute of undergraduate programs that attract and sustain student interest in science and mathematics is a thriving community of students and faculty. Such "natural science communities" offer students a learning environment which is demonstrably effective:

◆ Learning that is experiential, investigative, hands-on, and steeped in investigation from the very first courses for all students through capstone courses for science and mathematics majors.

◆ Learning that is personally meaningful to students and faculty, that makes connections to other fields of inquiry, that is embedded in the context of its own history and rationale, and that suggests practical applications related to the experience of students.

◆ Learning that takes place in a community where faculty are committed equally to undergraduate teaching and to their own intellectual vitality, where faculty see students as partners in learning, where students collaborate with one another and gain confidence that they can succeed, and where institutions support such communities of learners.

Programs organized around these guiding principles motivate students and give them the skills and confidence to succeed. Thus empowered, students learn science and mathematics.

Can an effective program be proposed for discovering and developing scientific talent in American youth so that the continuing future of scientific research in this country may be assured?

New frontiers of the mind are before us, and if they are pioneered with the same vision, boldness, and drive with which we have waged this war, we can create a fuller and more fruitful employment and a fuller and more fruitful life.

- Franklin D. Roosevelt, 1944. Letter to Vannevar Bush, Founding Director, The National Science Foundation.

PREFACE

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.

The environment for reform must be based on a driving vision of what works.

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!

– Representative Robert A. Roe, 1989.

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.

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.

Project Kaleidoscope
Suite 1205-ICO
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May 1, 1991

Dr. Walter E. Massey, Director
The National Science Foundation
Washington, D.C. 20550

Dear Dr. Massey:

On behalf of my colleagues on the Executive and Advisory Committees of Project Kaleidoscope, it is a pleasure to communicate with you in your first weeks as Director of the National Science Foundation. Project Kaleidoscope has been an extended effort involving presidents, deans, and faculty in mathematics and the natural sciences from the nation's liberal arts colleges and other predominantly undergraduate institutions. We received NSF support from the Education and Human Resources (EHR) Directorate — Division of Undergraduate Science, Engineering, and Mathematics Education (USEME), with additional grants from the Exxon Education Foundation, The Pew Charitable Trusts, the Kellogg Foundation, and the Camille and Henry Dreyfus Foundation.

Our charge was to outline a plan for the coming decade for undergraduate science and mathematics education in the liberal arts setting; our report presenting this plan of action, "What Works: Building Natural Science Communities," will be published in June. We recognize that the NSF must take the leadership role if the nation's problems in undergraduate science and mathematics are to be addressed, and present here for your consideration our recommendations that pertain specifically to the NSF. This letter will be included in the report and thereby become part of the formal record of Project Kaleidoscope.

We began our work in the fall of 1989 convinced that undergraduate science and mathematics must be strong if the challenges facing this country are to be met — if we are to have 1) an educated citizenry that is scientifically and technologically literate, 2) adequate numbers of well-equipped scientists and mathematicians for the nation's academic and research communities, and 3) scientifically competent and confident primary and secondary school teachers. A strong undergraduate sector is critical if this nation is to attract more women and minorities into science and mathematics.

Both the forthcoming report and the Project Kaleidoscope National Colloquium, held at the National Academy of Sciences on February 4 and 5, 1991, have been based on our experience and analysis of undergraduate programs that succeed in attracting and sustaining student interest in science and mathematics. Over 600 persons participated in the National Colloquium, representing colleges and universities from across the country, federal and private funding agencies, and educational associations. Dr. Frank Press, in his welcoming remarks, called it perhaps the most important gathering at the Academy in twelve months. Our report will include summaries of colloquium activities, including presentations by Dr. James L. Powell, Congressman George E. Brown, Jr., and Dr. D. Allan Bromley.

We applaud your commitment to ". . . strengthen the research base and infrastructure and improve science education and opportunities for all students . . ." as expressed in your recent Congressional testimony. We believe liberal arts colleges and other predominantly undergraduate institutions offer an ideal venue for reform efforts. Because of their *size* — small enough to make change possible, their *institutional commitment* — strong enough to make change likely, and their proven *record of productivity*, these institutions provide an excellent place from which to start the reform of undergraduate science and mathematics.

This reform should be based on a clear understanding of *what works*. We are convinced that science and mathematics education works wherever it takes place within an active community of learners, where students work collaboratively in groups of manageable size, and where faculty are deeply committed to teaching, devoted to student success, and convinced that all students can learn. It works where learning is active, hands-on, investigative, and experiential, and where the curriculum is rich in laboratory experiences, steeped in the methods of scientific research as it is practiced by professional scientists. This approach works for women, for minorities, for all students.

We are convinced that 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 this approach. You and your colleagues in the federal sector can be assured of our intent to be active partners in the national effort to strengthen science and mathematics at all educational levels. Four initiatives must receive highest priority in the immediate future if this approach is to be implemented in schools and colleges across the country. The recent FCCSET report is consistent with these initiatives.

INITIATIVE I. REFORMING THE INTRODUCTORY COURSES IN UNDERGRADUATE SCIENCE AND MATHEMATICS.

INITIATIVE II. SUPPORTING THE INTEGRATED TEACHER/SCHOLAR ROLE OF UNDERGRADUATE SCIENCE AND MATHEMATICS FACULTY.

INITIATIVE III. MAKING DISCIPLINARY CONTENT AND ACTIVE LEARNING CENTRAL TO THE EDUCATION OF K-12 TEACHERS OF SCIENCE AND MATHEMATICS.

INITIATIVE IV. DEVELOPING PARTNERSHIPS FOCUSED ON STRENGTHENING UNDERGRADUATE SCIENCE AND MATHEMATICS.

You will find specific recommendations for the NSF in relation to these initiatives in the accompanying exhibit. Although each is described separately, there is a strong relationship among these four initiatives — each dimension of the undergraduate effort must be considered integral to the whole. Efforts will not succeed if the reform of introductory courses is seen as separate from faculty enhancement activities, or if teaching and research are seen in competition with each other rather than as integrated responsibilities of the undergraduate faculty member. Furthermore, such efforts will be unproductive if advances in scholarship, technology, and pedagogy are not linked explicitly to programs for instrumentation acquisition and curriculum development.

In each of these initiatives, careful attention must be paid to under-represented groups in science — women, minorities, and handicapped — whose lives would be enriched by greater achievement in these areas, and who would in turn make a significant contribution to the lives of us all. This is one reason why, in Project Kaleidoscope, there is strong participation of faculty and administrators from Historically Black Colleges and Universities. Everyone has much to learn from their successes.

We do not expect the NSF to meet all the needs of undergraduate science and mathematics with grant support; however, we do look to the NSF to set the parameters by which reform efforts are to be undertaken, evaluated, and disseminated, and to do this in concert with the community it seeks to serve. The graduates of institutions for which we speak have made and can continue to make a significant contribution to the nation's scientific infrastructure — as citizens, and as members of the academic and scientific communities. The liberal arts colleges need to be at the table as policies and programs affecting undergraduate science and mathematics are considered. Congressman Brown emphasized this in his presentation at the Project Kaleidoscope National Colloquium, saying that reform efforts need financial support, but more important, they need an environment in which people collaborate in working toward mutually agreed-upon goals.

Our work builds on that of many others — the National Science Board [The 1985 Neal Report], the work of the "Oberlin 50 Colleges," the Council on Undergraduate Research, and the member institutions of The Independent Colleges Office — in the effort to help focus attention on the significance of the undergraduate academic experience in the science and mathematics pipeline. We recognize that considerable progress has been made, and are grateful to Drs. Bassam Shakashiri, Luther Williams, and Robert Watson for their leadership. However, one challenge you face is to bring a clearer focus to undergraduate activities within the Foundation. We look to the NSF to mount a sustained effort to strengthen undergraduate science and mathematics, and urge you not to abandon programs before they have had time to work. It takes time to accomplish effective change.

Beyond the initiatives presented here, there are further issues we believe must be addressed.

First, a concern is that current discussions — about the relationship of teaching and research, about balance between big science and little science, as well as balance between educational sectors — may not be informed by a clear understanding of what the predominantly undergraduate institutions have to offer. An analysis of the membership of NSF policy and advisory boards reveals that predominantly undergraduate institutions generally, and liberal arts colleges specifically, are under-represented, given the disproportionate contribution these institutions make to the national scientific and educational enterprise. To meet the national goal to attract more students into science and mathematics, NSF support must be available to all sectors of the collegiate community that have documented productivity in the education of scientists and mathematicians. If this is to be accomplished, representatives of all such sectors must participate as policies and programs are developed.

Equally important, data analyzed by NSF should highlight sector by sector productivity — disaggregated by gender and race — as a basis for establishing policies and programs. Procedures should be put in place to gather such data systematically, within the context of grant applications and reports, as well as through normal research mechanisms. Over the long term, these would help to document the effectiveness of reform efforts across the board and within the different sectors.

A final concern relates to facilities. The magnitude of the facilities deficit at predominantly undergraduate institutions is known to us all. If needed reforms are to be made in introductory courses and meaningful research opportunities are to be provided for faculty and undergraduate students, our facilities must accommodate such reforms and programs. It is hard to imagine how predominantly undergraduate institutions across the country are going to tackle successfully the pressing facilities problem without the NSF as a major player. With its peer review process exerting quality control — eliminating pork barrel decisions about academic priorities — and with the leverage its support can bring as colleges seek funds for facilities from other sources, a facilities program at NSF is critical. The recent NSF program for facilities modernization (RFO) was a promising beginning; we regret that this program is not included in the current NSF budget request. Of particular value in the RFO program was the formula distribution of funds between educational sectors. This was a clear signal that each sector had much to contribute to the total national effort; this model should be continued as further NSF programs for facilities and for major instrumentation are planned.

We urge the NSF to take a leadership role on the facilities issue, and join with Congress and the nation's colleges and universities to determine how to balance the infrastructure needs of all sectors of the research and research-training communities. The current plan to provide support for major research instrumentation rather than for research and research-training facilities does not address the need for better balance in NSF support to the different sectors of the community. It would be particularly helpful if the NSF would establish a multi-year facilities program linked to course and curriculum development and the acquisition of instructional instrumentation. Colleges and universities could then build such an NSF program into their long-range plans for facilities modernization. A study of the needs of the undergraduate sector for teaching, research, and research-training facilities would assist in developing the necessary long-range plan.

Finally, let me say that all of us involved in Project Kaleidoscope look forward to working with you and your colleagues at the National Science Foundation to make this nation's science and mathematics enterprise one of the highest quality. We thank the National Science Foundation for the support that made our work possible. Warm regards.

Sincerely,

Daniel F. Sullivan
Chair, Project Kaleidoscope Executive Committee
President, Allegheny College

Exhibits: A. Initiatives and Recommendations

INITIATIVE I. REFORMING THE INTRODUCTORY COURSES IN UNDERGRADUATE SCIENCE AND MATHEMATICS.

◆ **Recommendation #1:** The FY 1993 Budget Request for Instructional Laboratory Equipment be increased to $33 million, with a continuing focus on introductory courses.

◆ **Recommendation #2:** The FY 1993 Budget Request for Course and Curriculum Development include an $18 million outlay for local improvements in introductory courses at colleges and universities, in addition to the outlay for comprehensive programs.

◆ **Recommendation #3:** These programs be housed, along with their budget authority, within USEME, with an administrative structure that addresses the need to coordinate programs and policies with the research directorates.

The transformation of introductory courses must be NSF's highest undergraduate priority over the next five years. A significant body of research and our own experience confirms that the first year of college is the point of a critical drop-off in numbers of students in science and mathematics courses.

Students acquire and confirm lifelong beliefs and attitudes about science and mathematics in their introductory courses. This is where they make the decision whether or not to major in these fields, whether or not to take further courses, whether or not it is important to be literate on science issues. When these courses are dull, consisting mainly of lectures and canned labs, when they keep students isolated and passive, and press on at breakneck speed for the sake of "coverage," when they are too big and faculty members are unwilling to support each student's progress, they slam the door on the positive attitudes toward science. The final formal experience of learning science is often one of frustration and failure. Courses labeled *introductory* turn out to be *terminal*.

Our own experience validates that the introductory course can be a pump instead of a filter. Introductory courses can give first-year students the pleasure of discovery and the opportunity to construct personal understanding of science and mathematics at a critical stage in their academic career.

The recommended funding levels given above are consistent with those in the Neal Report; they address the demonstrated interest at the local level to strengthen undergraduate programs, and they establish a more equitable balance in NSF support for research and education programs.

Several hundred proposals, requesting over $200 million, were submitted to NSF for the first competition of the expanded Course and Curriculum Program, excluding proposals in Calculus and Engineering. The available funds through USEME, for all disciplines, was $14 million. A similar level of interest is evident in the Instructional Laboratory Improvement (ILI) program, where each year proposals reviewed request almost four times the funds available from NSF. We are particularly concerned that the College Science Improvement Program (CSIP) — the ILI component for predominantly undergraduate institutions — has been level funded for the past three years.

We ask you and your colleagues to consider a new program for departmental development of lower-division courses — one that would include support for instrumentation, development time and supplies for new curriculum, and faculty expansion and enrichment opportunities. Such a new program would emphasize again the integral relationship of each of the parts of the undergraduate academic experience in science and mathematics. Moreover, it would establish a means by which the experiences and resources of predominantly undergraduate institutions can serve as models for strengthening undergraduate science and mathematics.

In all of these programs, one criterion in determining grants should be the impact that an award will have on attracting and sustaining student interest in science and mathematics. A more targeted focus on courses for science literacy for all students should be announced, perhaps supported jointly between the NSF, the National Endowment for the Humanities, and the Fund for the Improvement of Post-Secondary Education. The means by which the impact of the proposed projects would be evaluated and by which their activities would be disseminated to the larger community should also be a review criterion.

Parallel to the recommendations of adequate funding levels and expanded programs, we recommend that the NSF establish a budget line item for these programs, and hold a single office accountable for coordinating the distribution of grant funds. We recognize NSF's current rationale for cross-directorate programs; however, funds "targeted" within research directorates for undergraduate programs have often become the first casualty when available funds for research are not adequate. If we are to move with all deliberate speed to achieve the essential reformation in introductory courses at the undergraduate level, there must be within NSF a strong, highly visible office where these programs are initiated, integrated and coordinated. We believe that office should be USEME.

INITIATIVE II. SUPPORTING THE INTEGRATED TEACHER/ SCHOLAR ROLE OF UNDER-GRADUATE SCIENCE AND MATHEMATICS FACULTY.

◆ **Recommendation #4:** The Research Experiences for Undergraduates (REU) program be expanded so that more students from liberal arts institutions can be provided the opportunity to do research at their home institutions and to allow REU Supplements to be used flexibly to support student-faculty research in predominantly undergraduate institutions, especially for those groups under-represented in science.

◆ **Recommendation #5:** The programs for undergraduate faculty supporting professional growth, including research and other scholarly activity, be strengthened and broadened.

The hands-on, discovery-based, laboratory-rich approach we advocate requires that teaching faculty be actively engaged in scholarship. Faculty active in scholarship foster a culture that enhances the community of learners; these faculty are often the most productive leaders in curriculum reform and laboratory improvement efforts, locally and nationally. Faculty active in scholarship are the most effective role models for students, and faculty-student research partnerships have been shown over and over to be a critical pump in the career pipeline. The distribution of revised Important Notice#107, which requires researchers to document the ". . . effect of the proposed research on the infrastructure of science and engineering . . ." was a welcome step in recognizing that teaching and research should be integrated activities in the nation's colleges and universities.

We strongly support the REU program. However, because of the level of funding, only a small fraction of Site awards presently can be used to support students at their own institutions. This has discouraged significant numbers of highly qualified departments at undergraduate institutions from applying. Just as graduate departments use this program to recruit students to attend their graduate programs, undergraduate departments should be given the resources to use this program to recruit students into science and to retain them in science, mathematics, and engineering. The most successful graduate students are those who have a solid grounding in research techniques — who know what science is about.

The on-campus research programs of undergraduate faculty are supported through the NSF Research in Undergraduate Institutions (RUI) program. Maintaining and enhancing this valuable program is critical to the overall effort of strengthening the undergraduate academic experience. Given its distributed nature, strong oversight of RUI by a single office must be reinstituted to ensure that the importance and distinctive characteristics of undergraduate research continue to be recognized. We further recommend that you and your colleagues consider a simpler, streamlined award system for small-scale individual grants for undergraduate faculty. In addition, we recommend investigation of a modified program of start-up grants for undergraduate faculty, with criteria similar to those within the current Presidential Young Investigator Program, but at a level of support more appropriate to the needs and scale of research of faculty at predominantly undergraduate institutions.

We recommend further that the NSF establish a faculty development program that would support faculty exchanges between strong under-graduate institutions. In our studies we have found many successful teacher scholars in undergraduate institutions who can serve effectively as mentors and role models for colleagues at other undergraduate institutions. A program of faculty exchanges would provide important opportunities for joint curriculum development based on disciplinary, technological, and pedagogical advances. It would also assist in the development of partnerships working together toward the common goal of strengthening the undergraduate experience in science and mathematics. This award would parallel the current ROA program which enables undergraduate faculty members to do research at major universities.

The Neal Report recommended that the NSF spend $17 million by 1991 for programs focused on the enrichment of undergraduate faculty. The 1992 budget request for the Undergraduate Faculty Enrichment program, though increased over past years, is $6 million. This is inadequate. We take 400 as the base number of science-active undergraduate institutions. If the NSF is to have an impact at such institutions across the country, support for faculty enrichment programs must be expanded.

INITIATIVE III. MAKING DISCIPLINARY CONTENT AND ACTIVE LEARNING CENTRAL TO THE EDUCATION OF K-12 TEACHERS OF SCIENCE AND MATHEMATICS:

◆ **Recommendation #6:** NSF priorities for the pre-college sector include encouraging colleges to redirect the structure and content of their teacher preparation programs to focus more directly on science and mathematics — utilizing an active, investigative, hands-on, content-based approach.

◆ **Recommendation #7:** NSF support a wider range of pre- and in-service activities for K-12 teachers, making use of the resources of *all* colleges with strong undergraduate programs in science and mathematics.

The single most important determinant of what elementary and secondary students learn in science and mathematics is how much their teachers know. Teacher preparation must include substantial, deep exposure to the content of subjects they will eventually teach. Teachers for the nation's K-12 community must have pre-service and in-service involvement with a hands-on, laboratory-rich, active learning experience with science and mathematics. This must be the way they are prepared in their undergraduate courses, another reason why NSF's first undergraduate priority must be reform of introductory courses.

In setting NSF priorities for K-12 programs, we urge you to recognize that undergraduate colleges, particularly those in the Carnegie Liberal Arts I classification, graduate high percentages of their students with majors in science and mathematics. These colleges, whose faculty are committed to the hands-on approach to learning, are natural sources of a substantially increased stream of properly educated science and mathematics teachers. These colleges are also excellent resources for the development of new materials for science and mathematics at the pre-collegiate level.

A large number of the colleges for whom we speak have entered into formal and informal partnerships with schools, bringing teachers to campus as research associates, and providing opportunities for teachers to gain new understanding about disciplinary advances and pedagogical approaches. It is clear from the workshops at the Project Kaleidoscope National Colloquium, that the potential is great for effective collaboration in faculty/teacher development opportunities and in the design of new materials for the elementary and secondary levels. These cooperative opportunities should be expanded, including their incorporation into REU projects, and expanding the ROA program to include K-12 teachers. We see education as a "seamless web," and the undergraduate sector as a key strand in the web.

INITIATIVE IV. DEVELOPING PARTNERSHIPS FOCUSED ON STRENGTHENING UNDERGRADUATE SCIENCE AND MATHEMATICS

◆ **Recommendation #8:** The NSF provide opportunities for regular national and regional colloquia to discuss what works in undergraduate science and mathematics education.

◆ **Recommendation #9:** NSF guidelines outline specific criteria relating to partnerships between schools and colleges, colleges and universities, and colleges and the private sector, focusing on faculty and curriculum development activities, evaluation and dissemination.

◆ **Recommendation #10:** Discussions about the proposed super computer highway include linking undergraduate science and mathematics faculty so that they can communicate regularly about research and teaching interests and have access to regional and national computing centers. Pre-college teachers of science and mathematics also should be linked to this highway.

It is clear that each sector of the science and mathematics education community has a unique contribution to make in addressing national goals; it is equally clear that we can accomplish more by working together than by working separately. The NSF has the ability to develop and sustain such working partnerships on a national basis, and to model within its own structure how such partnerships can be developed and sustained.

The success of many of the current networks supported by the disciplinary organizations, educational associations, private foundations, and corporations, demonstrates that there are significant numbers of persons who are ready and prepared to work together to strengthen the nation's scientific and educational enterprise. The Project Kaleidoscope National Colloquium was another strong demonstration that there is a growing national consensus about what works in science and mathematics and a commitment to get on with the task of improving the programs for which we are responsible. We recommend that the model of the Project Kaleidoscope National Colloquium, bringing together institutional teams — including presidents, deans, faculty members and development officers — be considered in the planning of further colloquia.

Level of NSF funding is not the only way to identify strong programs. The networks to be developed should include representatives from all segments of the educational community. These networks should have at their center those colleges and universities that have a demonstrated productivity in undergraduate science and mathematics.

As one example, with support from the Kellogg Foundation, there was a large representation at the National Colloquium from the Historically Black Colleges and Universities. Their contribution during the colloquium was significant; equally significant, we hope, are the connections that were made for cooperative efforts in the coming months and years.

Tables: Federal Support

Table 1. FCCSET Committee on Education and Human Resources FY 1992 Budget Matrix *(dollars in millions)*

EDUCATION LEVEL/ MAJOR PROGRAM AREAS	FY 92 BUDGET REQUEST	AGENCY: NSF	ED	DOE	DOD	DOC	NASA	DOI	HHS	EPA	USDA
UNDERGRADUATE:											
FORMAL & INFORMAL	100.0%	27.7%	3.4%	6.3%	36.9%	0.4%	5.2%	1.8%	14.7%	0.9%	2.6%
Program Evaluation /Assessment	100.0%	----	----	74.1%	----	----	----	0.0%	25.9%	----	----
FOUR-YEAR: FORMAL TOTAL	100.0%	37.4%	4.8%	----	32.1%	0.5%	2.5%	1.0%	17.8%	0.1%	3.7%
Faculty Preparation/Enhancement	100.0%	99.4%	----	----	----	----	----	0.2%	----	0.4%	----
Curriculum Development, Total	100.0%	87.6%	8.7%	----	----	0.3%	2.4%	0.7%	0.2%	0.1%	0.0%
Curriculum materials	100.0%	81.6%	13.0%	----	----	0.4%	3.5%	1.1%	0.3%	0.1%	0.0%
Laboratory Equipment	100.0%	99.9%	----	----	----	----	----	----	0.1%	----	----
Comprehensive (Org. Reform)	100.0%	31.6%	----	----	17.4%	----	4.3%	1.4%	13.5%	----	31.9%
Student Incentives	100.0%	12.6%	5.1%	----	51.0%	0.8%	2.5%	0.7%	27.3%	0.1%	0.0%
Direct Student Support	100.0%	12.6%	5.1%	----	51.0%	0.8%	2.5%	0.7%	27.3%	0.1%	0.0%
Bridging Programs	----	----	----	----	----	----	----	----	----	----	----
Other	100.0%	48.0%	----	----	----	----	5.7%	35.9%	10.3%	----	0.0%

Taken from FCCSET-EHR Report

Table 2. FY 1988, 1989, and 1990 Actual Expenditures, 1991 Current Plan for NSF Undergraduate Programs *(dollars in thousands)*

PROGRAM		Appropriation FY to EHR	Appropriation To R&RA by Directorate*						Totals	
			BBS	CISE	ENG	GEO	MPS	STIA	R&RA	NSF
Instrumentation	88	11500	0	0	0	0	0	0	0	11500
& Laboratory	89	16000	957	635	3608	459	1728	0	7387	23387
Improvement (ILI)	90	15802	2120	739	1487	830	0	0	5176	20978
	91	23000	0	600	2000	0	1400	0	4040	27040
Undergraduate	88	2000	0	0	1000	0	0	0	1000	3000
Curriculum & Course	89	3977	0	71	1696	0	1106	0	2876	6853
Development (UCC)	90	4000	0	3778	5109	0	1017	0	9904	13904
	91	11000		2835	2030	0	1000	0	5855	16855
Undergraduate	88	3000	0	0	0	0	0	0	0	3000
Faculty	89	3000	0	0	0	0	0	6	0	3000
Enhancement (UFE)	90	2900	0	0	0	0	0	0	0	2900
	91	4000								4000
Research Careers	88	0	0	0	0	0	0	0	0	0
for Minority	89	0	0	0	2	0	0	1823	1825	1825
Scholars (RCMS)	90	3470	0	0	0	0	0	0	0	3470
	91	6600	0	0	0	0	0	0	0	6600
Research Experiences	88	0	2543	1258	2748	1650	3451	0	11650	11650
for Undergraduates	89	0	3649	1696	2766	1548	4135	249	14043	14043
(REU)	90	0	4105	1721	3290	1572	5158	295	16141	16141
	91	0	4000	1776	3300	1700	4100	0	14876	14876
Research in	88	0	7407	556	930	2224	5007	0	16135	16135
Undergraduate	89	0	8089	898	1158	2410	5211	49	18715	18715
Institutions (RUI)	90	0	9129	1277	884	3365	5615	2	20272	20272
	91	0	5000	825	1000	2500	5200	0	14525	14525
Research	88	0							1500#	1500
Opportunity	89	0	630	71	133	135	653	54	1676	1676
Awards (ROA)	90	0	540	80	539	110	674	88	2031	2031
	91								1500#	1500
Career Access,	88	850	0	100	0	0	0	0	100	950
NSFNet, and	89	2612	0	1092	0	1039	0	0	2131	4743
Other	90	3767	110	2070	0	1250	0	0	3430	7197
	91	8000			6550	1000			7550	15900
Total Funding	88	17350	9950	1914	4678	3874	8458	0	30385	47735
	89	25591	14225	1466	9363	5591	12833	2175	48653	74241
	90	29939	16004	9665	11309	7127	12464	395	56954	86893
	91									101,296

* R&RA figures do not add horizontally because not all totals are apportioned to the listed directorates.
\# Not attributed in FY88.
\#\# Not yet apportioned.
NSF data.

National Context

In 1983 "A Nation at Risk" awakened this country to serious problems in its educational system. This alarm, like the one sounded twenty-six years earlier by the beeping of Sputnik, drew particular attention to deficiencies in learning science and mathematics. Indeed, dozens of reports and studies during the past six years have affirmed that this nation has deep-seated problems of equity, quality, and quantity in science and mathematics education:

- An alarmingly low level of scientific and technological literacy in the general population.
- A projected critical shortage of well-equipped scientists, mathematicians, and engineers.
- Severe inequities in the access of minorities and women to science and mathematics fields.

The rising concern over our nation's shortcomings in science and mathematics education established the context for Project Kaleidoscope. Current studies document numerous challenges facing the entire educational continuum, reaffirming the necessary connections between schools, colleges, and universities.

The U.S. education enterprise, particularly in mathematics, physical sciences, and engineering, is seriously under-performing.

These studies also project the substantial investment required if undergraduate science and mathematics is to be strengthened over the long term. We cite here a few indicators of the distressing state of science education:

- National assessments show that only about 7% of U.S. adults and about 20% of college graduates are literate in science.
- The number of entering college freshmen planning to major in physical sciences declined by 61% in 16 years, from 7.3% in 1967 to 2.4% in 1983.
- The percentages of Ph.D.'s in the mathematical and physical sciences awarded to Americans has declined significantly in the last thirty years. These percentages are now less than 70% in the physical sciences, 50% in mathematics, and 45% in engineering.
- Whereas Blacks comprise 12% of the population, they receive only 4% of the science and engineering baccalaureates and 2% of the doctorates.

It is clear that the U.S. education enterprise, particularly in mathematics, physical sciences, and engineering, is seriously under-performing. Measures of trade balances, patent activity, technical specialists per capita, and research and development expenditures reveal that this nation incurs serious penalties from these failings.

This report concerns baccalaureate level education in science, by which we mean education in mathematics and the natural sciences — astronomy, biology, chemistry, geology, and physics. We will be only peripherally concerned with the social sciences and engineering, not because they are any less important, but simply because the mission of this project is to examine the natural sciences and mathematics.

We need action soon. More and more, America's competitiveness depends directly on the men and women who develop and apply new technologies. Our health depends on researchers finding new ways to cure disease. The quality of our environment depends on scientists and engineers finding new ways to protect our planet. So many of the questions we face today require scientific and technological answers. We need to ensure that we have the men and women [educated] to provide those answers.

— Senator Albert Gore, 1990.

The institutional environment clearly matters. Elements of students' experiences that encourage pursuit of the Ph.D., such as early research experience, the emphasis that [certain undergraduate institutions] place on teaching, and their small student-faculty ratios, could be replicated at other institutions. OTA concludes that to increase numbers of Ph.D. scientists and engineers, it would be worth studying [those] techniques ... and encourage other institutions to adopt similar strategies and values.

– Office of Technology Assessment, (OTA) 1988.

The Undergraduate Context

The undergraduate years are critical for strengthening our nation's science and mathematics capacity. It is in college where future scientists and college faculty are recruited and prepared for graduate study; where our nation's elementary and secondary teachers, educators of America's youth, are equipped; and where tomorrow's leaders gain the background with which to make critical decisions in a world permeated by vital issues of science and technology. It is also at the undergraduate level where many able young people — particularly minorities and women — decide to discontinue their study of science and mathematics. The result is a serious loss of talent to the service of the nation, a loss that we cannot afford if we are to remain competitive in a global economy.

Undergraduate education is carried out in four sectors of higher education. Three sectors comprise institutions that offer bachelor's degrees: private predominantly undergraduate colleges and universities, public predominantly undergraduate colleges and universities, and doctorate-granting universities. The fourth sector, two-year colleges, enrolls 30% of the nation's nine million full-time-equivalent (FTE) undergraduates, many of whom later receive baccalaureates. In this report we examine science education in the independent predominantly undergraduate schools, a sector that includes many historically Black institutions and women's colleges. Over 85% of the 1100 schools in this category have enrollments under 2500 and nearly ninety percent are coeducational.

Small, independent liberal arts institutions consistently produce significant numbers of graduates who go on to careers in science and mathematics. Over the past thirty years America's liberal arts colleges have produced science and mathematics baccalaureates at a rate over three times the national average. Moreover, their graduates earn Ph.D.'s in science and mathematics at over twice the national average (twelve per thousand as compared with six per thousand on average). Especially productive are the 140 private colleges in the Carnegie "Liberal Arts I" category. These colleges are second only to independent Research I Universities in the rate of Ph.D.'s in science and mathematics awarded to their baccalaureate graduates. The same is true for women baccalaureates.

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Small, independent liberal arts institutions consistently produce significant numbers of graduates who go on to careers in science and mathematics.

Even more significant is the disproportionate production of science and mathematics majors by these undergraduate colleges. Again, as a percentage of bachelor's degrees awarded, independent Liberal Arts I colleges rank first overall and first in the production of women science and mathematics graduates. These colleges, with 3% of the undergraduate enrollment, award nearly 10% of the nation's total baccalaureate degrees in the natural sciences and mathematics. In addition, the absolute number of undergraduate science and mathematics majors produced by these colleges is larger than the number produced by independent Research I Universities. It is not uncommon to find liberal arts colleges graduating more majors in basic sciences or mathematics than nearby universities that are ten times larger. Among the smaller institutions that produce relatively large numbers of science graduates are women's colleges and Historically Black Colleges and Universities. This is particularly significant given the continued under-representation of the groups they serve. These liberal arts colleges are indeed highly "science-active."

These analyses demonstrate clearly that aggregate outputs of science and mathematics graduates and Ph.D.'s in science and mathematics from liberal arts colleges are large. Because of the high level of attention these institutions pay to science and mathematics, liberal arts institutions make a disproportionate contribution to improving the nation's science and mathematics education. These institutions must be at the table when science policy is made in the United States.

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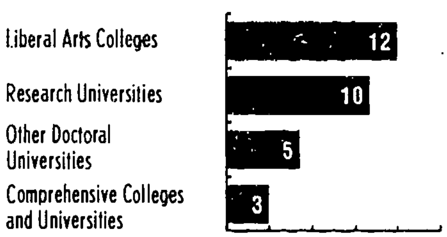
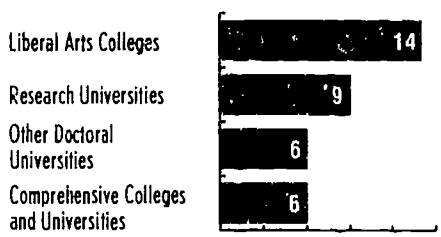
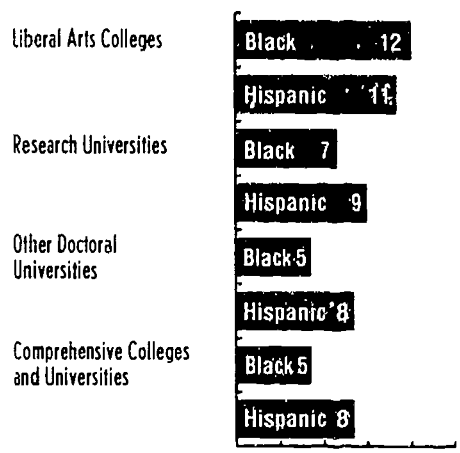
Liberal arts institutions must be at the table when science policy is made.



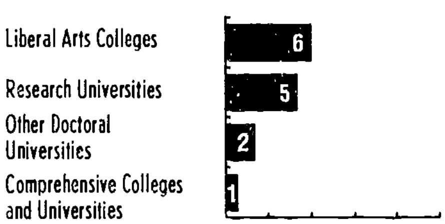
Natural Science Ph.D.'s Earned by Graduates of Each Type of Institution. Number of Ph.D.'s Per 1,000 Graduates.



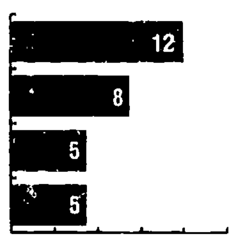
Mathematics and Science Baccalaureate Degree Granted by Type of Institution. Science Degrees Per 100 Graduates.



Mathematics and Science Baccalaureate Degrees Granted to Black and Hispanic Graduates by Type of Institution. Science Degrees Per 100 Black or Hispanic Graduates.



Natural Science Ph.D.'s Earned by Women Graduates of Each Type of Institution. Number of Ph.D.'s Per 1,000 Women Graduates.



Mathematics and Science Baccalaureate Degrees Granted to Women by Type of Institution. Science Degrees Per 100 Women Graduates.

– ICO - PKAL: Department of Education Data; NRC Data.

I believe a liberal education is an education in the root meaning of liberal — liber, "free" — the liberty of the mind to explore itself, to draw itself out, to connect with other minds and spirits in the quest for truth. Its goal is to train the whole person to be at once intellectually discerning and humanly flexible, tough-minded and open-hearted; to be responsive to the new and responsible for the values that make us civilized. It is to teach us to meet what is new and different with reasoned judgment and humanity.

—A. Bartlett Giamatti, 1988.

The Liberal Arts Context

Project Kaleidoscope focuses not just on undergraduate science education, but particularly on the practice of science and mathematics education in liberal arts colleges. Our aim is to identify the essence of science and mathematics learning in the liberal arts colleges, to deduce from exemplary practices a model of how students — majors and non-majors alike — best learn science and mathematics, and to examine implications of this learning model for U.S. policy in science education. We believe conclusions can be drawn from the lessons learned at these liberal arts institutions for a broader set of educational endeavors.

The ancient tradition of liberal education, the core around which most universities were organized, survives most clearly in the nation's small liberal arts colleges. These colleges emphasize education for life rather than narrow preparation for a profession. They encompass basic studies in a variety of traditional disciplines, and they insist on study in depth as well as breadth.

Science and mathematics, comprising three of the four courses of the ancient Quadrivium, have been part of the liberal arts curriculum since it was re-established in the medieval European universities. The tradition that every educated person should know science and mathematics continues strongly in most liberal arts colleges today. Such institutions form a primary repository of successful experience in the struggle to create a scientifically literate citizenry.

Undergraduate education in our nation's liberal arts colleges provides students with wide-ranging experiences that:

- ◆ Encourage curiosity, intellectual adventure, and an affinity for quality and integrity;
- ◆ Aim to develop a sense of the whole, of the interconnections between fields of study and larger realities;
- ◆ Provide a sense of both the unity and diversity of human knowledge while guarding against narrowness of outlook;
- ◆ Promote diversity, skepticism, and debate.

Liberal education, as a college president said recently, "views the world as changing, not fixed. It asks not only what but why. It insists that we make judgments rather than have opinions, that we treat ideas seriously, not casually, that we be committed instead of indifferent."

Because of the profound impact that the scientific enterprise has had on almost every aspect of life over the last hundred years, broad education in the liberal arts and sciences is even more critical for present and future generations of students. Not only has science assisted in creating a powerful technology, it has influenced the very way we view the world and ourselves. This argues for a well-balanced curriculum that attracts more people into scientific professions while simultaneously providing students with a broad working scientific intelligence about issues that both enhance and threaten the condition of life on earth.

Liberal arts colleges are places where teaching and research come together in practice as well as in theory, where senior professors are actively engaged in classroom and laboratory teaching, and where the commitment to teaching is supported by institutional procedures related to hiring, tenure, and promotion. They are distinguished by educational environments that offer students small classes and regular study groups. Many of these institutions offer students plentiful opportunities to work one-on-one with faculty, a curriculum that strives to be lean but lab-rich, and abundant opportunities for hands-on research. Because of their traditions, size, and lack of bureaucracy, these institutions can serve as testing grounds for new approaches to teaching and learning; they have flexible curricula and support faculty who break away from established disciplinary norms. Liberal arts institutions are appropriate settings for innovation and testing of new approaches to teaching and learning.

Liberal arts colleges are places where teaching and research come together in practice as well as in theory.

Building Connections

Liberal arts colleges have no monopoly on programs that work in undergraduate science education. Institutions of all kinds have achieved successes in baccalaureate science education; not all independent colleges have succeeded at science and mathematics education; and even the best colleges have failed with certain students. The art of education is never easy. Anyone who has been involved seriously in education kr... that one must deal constantly with imperfection even while keeping one's eye on the ideal.

Over seventy years ago, Alfred North Whitehead offered a critique of education that is still useful in shedding light on what is wrong with much of today's science and mathematics education. In his famous 1917 essay "The Aims Of Education," Whitehead criticizes what he termed "inert ideas," ideas that "are merely received into the mind without being utilized, or tested, or thrown into fresh combinations." Tolerance of inert ideas, in Whitehead's estimation, was the prevalent form of futility in education in his day; it may be also in ours.

"The solution which I am urging," Whitehead wrote, "is to eradicate the fatal disconnection of subjects which kills the vitality of our modern curriculum. There is only one subject matter for education, and that is Life in all its manifestations. Instead of this single unity, we offer ... Algebra, from which nothing follows; Science, from which nothing follows; History from which nothing follows."

The fields in which we educate have advanced and multiplied since Whitehead's time, but his criticism is instructive as we look for clues to what works today. It is still connections that make a science or mathematics course interesting, meaningful, and exciting, whether the connections are to social, historical, or personal contexts, to scientific phenomena, or to elegant argument and compelling logic. Students can engage the subject — get beyond the tiring experience of rote learning — only by "making sense" of it through connections. The achievement of meaning by the learner is absolutely essential in learning science.

The achievement of meaning by the learner is absolutely essential in learning science.

Educators manifest many ways of thwarting meaningful learning. We do so in our curricula by packaging science and mathematics in air-tight, bite-sized units that are "clear" to students, free of messy entanglements, and easy to test with routine examinations. The methods by which the knowledge we teach was won are rarely presented as fit for testing against nature or alternative formulations. Seldom are they presented as relevant to investigations in the world or as products of lively personal or historical dramas. In short, the science we teach is not very scientific.

Many factors contribute to poor learning and low interest in science and mathematics by American students today. Many educational environments pose high risk of student failure, especially where busy faculty take little time for questions from inquisitive students, where the faculty reward system does not recognize that scholarship and teaching are integrally related,

Connections make a science or mathematics course interesting, meaningful, and exciting.

or where spaces inhibit the development of communities of learners, establishing barriers between faculty and students.

Other factors contributing to educational weakness have little to do with the educational system. Many children in our country are losing ground. Some are homeless, others move often to follow the harvest, and still others are in educational systems that approach "melt-down." Who among them has a good chance to become a scientist or mathematician ... or a philosopher or a lawyer? If colleges and universities are to be anything other than institutionally self-centered, they must acknowledge some responsibility for these broad societal issues, however remote they may be from traditional institutional missions.

Forming Communities

The best college science courses, from introductory to advanced levels, are conceived and run in a partially investigative mode. Investigation, the natural arena for using and solidifying one's knowledge, may be manifest in open-ended laboratory and library projects or in small research projects made available to students. The personal and social attributes of learning science in an investigative mode extend to the whole of the student's experience. Having professors in undergraduate laboratories means that they get to know their students and their capabilities exceedingly well. This close contact is important in the process of becoming a scientist.

These are the circumstances in which students should use science libraries, computers, laboratories, instruments, class materials, study areas, and class and seminar rooms. The great pedagogical payoff of having a science building occupied and used by students at all hours is that they develop a learning community. Advanced students help beginners learn how to function efficiently in their particular campus environment. The student network disperses knowledge of where materials are, how instruments work, what is in the library, how to use computers, and who is an expert on what. Most importantly, students receive the kind of feedback that engenders the confidence and inquisitiveness of a secure identity.

Many liberal arts colleges — especially selective co-educational colleges, historically Black colleges, and women's colleges — have been unusually productive of minority and female baccalaureates, many of whom go on to receive doctorates in science. The wisdom of practice and the preponderance of evidence show that the formation of inclusive learning communities is the primary reason for this success. Both Uri Treisman's award-winning work at the University of California at Berkeley and the experience of many Historically Black Colleges and Universities demonstrates that creating a learning community is a crucial factor in fostering improved learning of science and mathematics by under-represented groups.

Communities for teaching and learning are established also through active research and scholarship embedded in undergraduate science departments. Research helps keep faculty members current in their fields, professionally connected, and psychologically rewarded. It also helps to keep the instrumentation, facilities, and library holdings current by providing a continuing rationale for support of these scholarly tools. Scholarship lends priority and conviction to the choice of what to

Vicarious knowledge is not enough: a truly educated person should be able also to generate ideas and solve real problems.

teach and how to teach it. It demands discipline in a deep sense of both faculty and students. Scholarship implies to students that vicarious knowledge is not enough, that a truly educated person should be able also to generate ideas and solve real problems.

Whereas basic research that is publishable in mainstream journals can be of great benefit to a department's educational effort, it is not the only type of research that is good for undergraduate science education. Some productive departments have a research or honors program oriented strongly to student-originated research. Results of such research are not often published, but asking a student to conceive and attack a problem is a powerful stimulator of interest, especially if faculty provide enthusiastic counsel and support. Applied research on problems related to health, industry, or environment may also provide an arena in which material learned in courses is put to work. The indispensable thing is that each department develop suitable opportunities for research and scholarship in which both students and faculty collaborate.

Science as practiced in liberal arts colleges is generally lean in number of courses offered and in formal requirements for the major. A student aspiring to a career tied to the major will fulfill requirements for that career as interest quickens. The crucial thing is to get the student to start aspiring, to enter on the process of learning the discipline. This end is best served by introductory courses that involve investigation and by streamlined requirements for the major; elaborate majors that anticipate every contingency by requiring arrays of lock-step courses are recipes for depopulated departments. Faculty in liberal arts colleges generally concentrate, therefore, on making a limited number of courses superb, well-integrated, and important rather than laboring to create a varied menu of courses that provides an exhaustive survey of the discipline.

In summary, science instruction at liberal arts colleges is a case of "less being more." There is less formal content in the curriculum, less total expertise and specialization in the faculty, and perhaps fewer holdings in the library and the instrument rooms. There is, however, more exposure of students to real science: to the research-like modes of taking initiative, figuring things out, working with others, asking questions and discussing, making things work, using the library, and thinking and writing critically about procedures and results.

Developing Partnerships

Project Kaleidoscope was created as a mechanism to move from analysis to action. We began with certain convictions:

◆ The nation's leadership role in science and technology is severely compromised by deficiencies in the educational system, and by a lack of a mutually agreed-upon plan of action for all those who must be involved in addressing those deficiencies.

No one believes that NSF, or even the federal government as a whole, can change American education by itself. Our system of education is diffused, with responsibility divided among the states and local governments, and public and private institutions, as well as the federal government ... A cooperative effort involving all these players and the students, parents, teachers, and others directly involved will be necessary to really solve the problem.

– Former NSF Director Erich Bloch, 1990.

Dr. Luther Williams

Assistant Director, Education and Human Resources — The National Science Foundation.
Project Kaleidoscope National Colloquium, February 5, 1991

There are several "new circumstances" that affect planning for reform of undergraduate science and mathematics:

◆ The President and the nation's governors have issued a call for immediate and sustained action on education.

◆ Many federal agencies are cooperating to attack the problems of education. The Federal Coordinating Council on Science, Engineering and Technology (FCCSET) and the interagency Committee on Education and Human Resources have formulated a single program and budget request for FY 1992.

◆ There is increased formal coordination and collaboration among agencies such as the NSF, the Department of Education, and the Department of Energy to address challenges facing the educational community.

◆ The National Endowment for the Humanities has proposed general education requirements, which encompass requirements in mathematics and the sciences.

◆ A frequently cited Office of Technology Assessment (OTA) report calls for a coordinated approach to education from grade school to graduate school.

◆ Congress is showing increasing concern for demonstrable progress in reform efforts, encouraging comprehensive efforts, even if they are radical, as means to reach the nation's education goals.

◆ Some members of the science and engineering communities are concerned that the basic research enterprise and undergraduate science and mathematics education are not strengthening one another as much as is desirable.

◆ The explosion of knowledge has put great pressure on the system. The nature of scientific knowledge now demands that much more attention be paid to areas lying across the boundaries between disciplines. The individual historic disciplines no longer can stand totally alone; science education should reflect these new needs and divisions.

◆ The non-science students must be better served.

Following up the 1986 studies by the National Science Board, several disciplinary groups recently considered the state of U.S. science education. Their recommendations included several that reinforce the approaches taken by Project Kaleidoscope: (a) develop new and improved introductory labs emphasizing "hands-on" approaches to excite students, (b) give high priority to creating new materials and approaches for the introductory courses, (c) strive to improve access to careers in science for women and under-represented minorities, and (d) involve undergraduate science and engineering majors in research experiences as soon as possible.

In response to the above "new circumstances" and recommendations, the NSF is funding programs to develop undergraduate curricula, expanding the Research Experiences for Undergraduates Program, doubling expenditures for instrumentation, opening the program to more schools, and starting new programs to improve undergraduate teaching, and supporting certain special initiatives aimed at under-represented groups. In pursuing its goals, NSF will work directly with other parts of the federal government in planning and executing improvements in undergraduate science and mathematics.

◆ Each educational institution needs to evaluate its programs regularly, within the larger context of national need, to determine strengths and weaknesses, and to set priorities focused on areas of opportunity for distinction that are central to its institutional mission.
◆ Many institutions have developed successful undergraduate science and mathematics programs. These institutions can serve as models for others in the national effort to address the crisis in science and mathematics.

To strengthen undergraduate science and mathematics education, many groups — college and university presidents, deans, science faculty, governing boards, representatives of federal and state agencies, private foundations — must form new partnerships based on a strategic plan for reform.

Such partnerships would parallel similar efforts that arose during an earlier challenge to the nation's leadership in science and technology. One response during the 1960's shock of Sputnik was renewed national attention to science and mathematics at the undergraduate level and the consequent awareness of the need for concerted efforts to improve. In physics and chemistry, for example, the Sputnik period brought the direct mobilization of Nobel laureates, research university and liberal arts faculty in a major effort to revise high school and undergraduate introductory courses. Similar efforts also took place in other sciences. Heavy federal investments, mostly from NSF in the form of small grants to a large number of institutions, supported professional growth and refreshment of faculty, undergraduate research, curriculum and course improvement, instrument acquisition, and facilities renovation. The nation became richer because of that investment.

◆

The challenge is for all of the partners to join together on a commonly-agreed strategic plan and then to move quickly from analysis to action.

As the nation benefited from this earlier investment in undergraduate science, so now it is experiencing the consequences of a generation of inconsistency and neglect — of erratic support, inadequate planning, and divisive argument. After the Sputnik surge of federal support in the 1960s, NSF support for education diminished, moving through a precipitous decline at the end of the 1970s until educational programs for undergraduate activities were completely eliminated in the early 1980s. It is a sad reflection on our society that it takes a crisis, real or perceived, to galvanize coordinated efforts to support undergraduate science and mathematics education in a consistent manner. Just as the cadre of scientists and mathematicians attracted into science careers during the 1960s nears retirement age, the national need for scientific personnel and for a scientifically-literate populace has become acute.

Everyone suffers when efforts for reform are piecemeal, faddish, and inconsistent; when such efforts address single segments of the community or one aspect of the scientific enterprise; when "big" science is in conflict with "little" science, and when research is in conflict with teaching. The challenge in strengthening undergraduate science and mathematics education is for all of the partners to join together on a commonly-agreed strategic plan and then to move quickly from analysis to action.

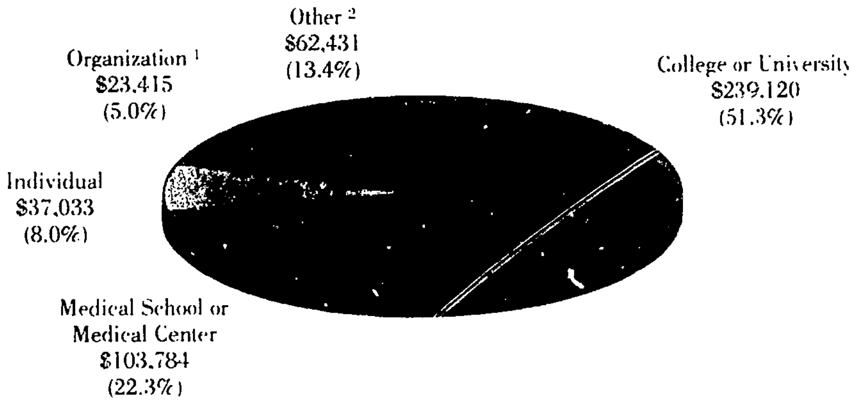
The Federal Government

Any partnership to strengthen undergraduate science and mathematics must recognize the critical leadership role of the National Science Foundation. Only NSF has the capability and the statutory responsibility to build a broad consensus on how to improve the quality of science and mathematics programs at all educational levels. NSF's mandate is to identify areas of need, to set priorities to address those needs, and to develop, coordinate, and implement programs that address these national priorities.

The crucial role of NSF in addressing needs on the undergraduate level was clearly outlined in a 1986 Report of the National Science Board, commonly known as the "Neal Report." This report recognized that NSF support for undergraduate education must be tied to a coherent, long-range plan. In particular, it recommended that NSF:
◆ Bring undergraduate programs into a better balance with activities in the pre-college and graduate areas.

Science grants by recipient type, 1986

Foundations with total giving of $1 million or more (thousands of dollars)



TOTAL: $465.78 MILLION

[1] Includes health organizations, professional societies, and science organizations.
[2] Includes independent research institutes, museums, foundations, educational centers, and other organizations.

Science grants by recipient type and purpose, 1986

Foundations with total giving of $1 million or more (thousands of dollars)

	RECIPIENT TYPE					
PURPOSE	College or University	Medical School or Medical Center	Individual	Organization[1]	All Other Recipients[2]	All Recipient Types
Facilities and Equipment	$93,375 67.9%	$27,258 19.8%	$0 0.0%	$963 0.7%	$15,906 11.6%	$137,502 100.0%
Research	42,874 39.3%	27,790 25.5%	15,656 14.3%	7,830 7.2%	15,012 13.8%	109,162 100.0%
Fellowships and Scholarships	28,756 54.0%	9,872 18.5%	10,488 19.7%	890 1.7%	3,261 6.1%	53,267 100.0%
Faculty Development [3]	18,708 40.5%	15,746 34.1%	3,840 8.3%	5,457 11.8%	2,479 5.4%	46,230 100.0%
Program and Curriculum Development	23,106 63.9%	4,002 11.1%	10 0.0%	1,102 3.0%	7,951 22.0%	36,171 100.0%
General Operating Expenses	8,354 28.9%	12,516 43.3%	0 0.0%	680 2.4%	7,339 25.4%	28,889 100.0%
All Other Purposes [4]	1,232 10.5%	103 0.9%	7,039 60.1%	826 7.1%	2,505 21.4%	11,705 100.0%
Purpose Unknown [5]	22,715 53.0%	6,497 15.2%	0 0.0%	5,667 13.2%	7,978 18.6%	42,857 100.0%
All Purposes	$239,120	$103,784	$37,033	$23,415	$62,431	$465,783

[1] Includes health organizations, professional societies, and science organizations.
[2] Includes independent research institutes, museums, foundations, educational centers, and other organizations.
[3] Includes endowed chairs.
[4] Includes scientific publications, educational literature, conferences, and seminars.
[5] Purpose was not recorded in original data sources and could not be obtained directly from the relevant foundations.

– Howard Hughes Medical Institute Report: 1991

- Implement new programs and expand existing ones for the ultimate benefit of students in all types of institutions.
- Develop an appropriate administrative structure and mechanisms for the more effective coordination of undergraduate programs.
- Support a variety of efforts to improve public understanding of science and technology.
- Foster creative activity in teaching and learning, as it does in basic disciplinary research.
- Stimulate states and the private sector to increase their investments in the improvement of undergraduate science, engineering, and mathematics education, and provide a forum for consideration of current issues related to such efforts.

The Neal recommendations laid the foundation for a revitalization of undergraduate programs at NSF. (Project Kaleidoscope and three related projects focused on different types of institutions are one outcome of these recommendations.) In addition to programmatic and organizational recommendations, the Neal Report recommended a significant increase in the annual NSF investment in undergraduate education. An analysis of recent NSF budgets indicates both the need for increased funds for undergraduate programs and welcome momentum in that direction.

The impact of NSF support at undergraduate institutions across the country can be illustrated by looking at one NSF program — the Instructional Laboratory Improvement Program (ILI). Modest in size by research grant standards. these grants have helped to transform science and mathematics departments across the country. As significant as the ILI financial support for instrumentation is. there are further benefits of this program. The proposal guidelines request applicants to outline a plan for improvement that fits into institutional, disciplinary, and national contexts. Both winners and losers benefit from such an exercise, and from the subsequent peer review process. However, the high ratio of proposals reviewed against awards made and the relatively high scores of rejected proposals indicates clearly that the ILI program merits an infusion of funds if it is to meet its goal of reshaping introductory courses by providing more effective approaches to laboratory and field-based instruction.

The work of the Federal Coordinating Committee for Science, Education, and Technology (FCCSET), designed to coordinate the science and mathematics

An analysis of recent NSF budgets indicates both the need for increased funds for undergraduate programs and welcome momentum in that direction.

education activities of NSF and the Department of Education, the Department of Energy, the National Institutes of Health, and other mission-oriented federal agencies, augers well for the development of partnerships at all levels. Of particular significance is the increase in programs that support links between colleges and the pre-collegiate sector. Those interested in strengthening undergraduate science and mathematics need to be alert also to funding possibilities at a wide variety of federal agencies, including the Fund for the Improvement of Post-Secondary Education (FIPSE), the National Endowment for the Humanities, and the Department of Education.

The Private Sector

It is heartening to note that in the past fifteen years, as federal support has ebbed and flowed, grants from private foundations and corporations have moderated the absence of stability in federal support for undergraduate science programs. An analysis of support for a select group of science-active liberal arts colleges reveals that over the past five years, private support for undergraduate science and mathematics has greatly exceeded the support from federal agencies. There is good reason to believe that this is true for most liberal arts colleges.

Several private foundation and corporation grant programs have served as catalysts for much of the creative reform that has taken place throughout this country in undergraduate science and mathematics in the past two decades. Some of these have been local initiatives, with support generated by the vision and persistence of a single faculty member on an individual campus. Other projects, such as the Sloan New Liberal Arts Program, The Pew Clusters, the Howard Hughes Undergraduate

The importance of private philanthropic support, thoughtfully applied, can be seen in numerous examples of scientific discovery and educational improvements.

– Howard Hughes Medical Institute, 1991.

Economy consists not of saving, but in selection.

— Edmund Burke

Science Initiative, the Kresge Challenge Grants, the Kellogg Science Initiatives, and The Keck Consortial grants, seek to build structures for systemic change.

The Research Corporation and Petroleum Research Fund of the American Chemical Society have long served undergraduate institutions with support for faculty-student research at schools that have limited access to federal research support. The Camille and Henry Dreyfus Foundation offers individual faculty and departments in chemistry new opportunities for development and growth. Significant support for summer research for undergraduate students has also come from industrial and corporate sponsors.

Institutional Responsibilities

This call for action is directed at academic institutions, as well as at governmental agencies and corporate foundations, at faculty as well as at presidents, deans, development officers, and at those who shape policy and provide support to implement those policies. Our analysis suggests the need for a paradigm shift in the way colleges approach their development activity. It is clear that liberal arts colleges forego many potential sources of support if they do not have someone in their development office who understands science and can speak its language. Everyone concerned with collegiate education, including development officers, must work together to forge new partnerships.

To make progress in reform of undergraduate science and mathematics, colleges and universities need to set goals and establish appropriate yardsticks by which to measure progress toward these goals. Measuring the success of efforts to reform undergraduate science and mathematics is not easy; accurate baseline data on historic and current productivity and on the present and future needs of undergraduate programs are not readily available. Rarely will currently-available national, state, or local data be appropriate to this kind of task.

One deficiency is that current data on science and mathematics enrollments and degrees conferred are not consistently disaggregated by race, gender, or discipline. Another is that the diversity of undergraduate institutions is not recognized as data are collected, analyzed, or used to set policy or evaluate programs.

Faculty and administrators should consider how admissions policies, curriculum, student services, and physical spaces on their campus support or distort the development of natural science communities.

As a consequence, national programs are often focused too narrowly to address the broader challenges facing the nation.

To measure success from the perspective of an individual institution, faculty and administrators should consider how admissions policies, curriculum, student services, and physical spaces on their campus support or distort the development of natural science communities. Individual campus teams should analyze the separate facets of such communities to see if and how they connect in a pattern suitable for strategic reform. The analysis of needs and accomplishments on each single campus should also reflect the larger context of national needs and national goals.

The portrait of leakage in the national science and technology pipeline given on page 77 can serve as a basis for analysis as science and mathematics faculty, deans and presidents, campus planners and grants officers develop strategies and set priorities for reform. Each campus should develop a plan that addresses key issues of local accountability for scientific and mathematical education:

- How does the institutional profile for the undergraduate years compare to the national profile?
- What is the institution's current record of productivity of minority baccalaureates in science and mathematics? What about women?
- What would it take in institutional commitment to increase graduating majors in science and mathematics by 20%, focusing on women and minorities?
- What institutional commitment would it take to graduate women and minority science and mathematics baccalaureates in proportion to their percentage in the population?
- At what points in the science and mathematics pipeline can this institution make the biggest difference?

Local action by many institutions can have significant effect on national needs. We urge each college and university engaged in undergraduate science and mathematics education to undertake four key actions:

- Restructure introductory courses in science and mathematics for all students.
- Set specific goals to increase minority and women baccalaureates in science and mathematics.
- Establish a long-range plan to sustain a campus-wide natural science community.
- Make formal connections with teachers and students in nearby elementary or secondary schools.

We believe that the national profile in science and mathematics would be greatly improved if these things were to happen. We strongly urge institutions to address these important issues promptly and vigorously.

Some Say It Can't Be Done

Despite evidence of "what works," some faculty and administrators argue that education of the sort we advocate is more the exception than the rule. They sincerely believe that it just can't be done:

CRITICISM: Lean, lab-rich curricula cannot be implemented without hiring more faculty; this approach is just too expensive.

After eighteen months of looking at the Black students at Berkeley, we discovered that these students had the wrong idea about how to succeed at the university. It was as if they believed that you can be a mathematician or a scientist by doing homework responsibly; that effectively, the route to engineering, to physics, to chemistry and mathematics was taking a certain number of courses from a prescribed list.

All of our processing of students ... our catalogues, advising and our lack of interaction with students ... reinforced this mistaken notion. We came to realize that our solution had been to create learning centers and to hire *others* to deal with these problems. Of course none of us thought to ask "If they are the learning center, what are we?" Then we created adjunct workshops that didn't actually change the structure of the courses either. We did not think to change the *courses* themselves or more generally the capacity of our departments to serve our students.

— Uri Treisman
Project Kaleidoscope
National Colloquium
February 4, 1991.

RESPONSE: The "lean" part of "lean and lab-rich" is crucial to the success of this model. Some coverage will in fact have to be sacrificed to get teaching to be more "hands-on," but it is worth it. Testimony from those who have tried this approach is very convincing: it leads to more majors and more students taking upper-level science courses. We believe that by insisting on a lean curriculum, colleges and universities can reshape curricula without adding faculty.

CRITICISM: Liberal arts colleges are too insignificant to have much impact nationally.

RESPONSE: These colleges are major players at the undergraduate level. They can have a significant impact just by getting better. But they can have an even larger impact if they use their potential for leadership to help reform science and mathematics teaching at the collegiate and pre-collegiate levels. If they apply their deeply-rooted belief in quality teaching to problems of science education, their national impact can be substantial.

CRITICISM: Hands-on, lab-rich curricula require small classes, hence they cannot work in universities.

RESPONSE: Some universities have already adapted the lean, lab-rich, community-based approach to introductory courses. Universities can choose to do this kind of teaching if they wish. It works best in small classes, but even large classes can benefit from movement toward this kind of pedagogy.

CRITICISM: The real problem with science and mathematics education is at the pre-college level; major resources expended at the collegiate level would not be cost-effective.

RESPONSE: Teachers are most likely to teach as they were taught, not the way their methods courses say they should teach. Reform at the pre-college level will *never* occur unless changes in college teaching occur. The collegiate level demands serious, sustained attention.

CRITICISM: The capital costs of a lab-rich curriculum with pervasive computing are too high.

RESPONSE: Even though funding has been tight, the National Science Foundation (with strong pressure and support from the Congress) has greatly increased its annual level of investment, and there is evidence that science and mathematics education is becoming a focus of support in some states as well. Resources have been increasing in recent years and could continue to do so, at least at the federal level, because this need is so small relative to other huge budgets. In addition, good planning on the part of colleges and universities can go a long way toward making a successful case for finding needed resources. Sophisticated equipment and computing is necessary no matter what kind of pedagogy is adopted.

CRITICISM: Current faculty cannot and will not change to a new pedagogy: small college faculty don't do sufficient research, and research university faculty don't care enough about teaching.

RESPONSE: The Kaleidoscope effort has made it clear that a significant number of faculty, in institutions of all kinds, are engaged in reform efforts, linking teaching and research. Faculty development resources can help those not now capable of teaching in an interactive, context-rich manner, and strong presidential leadership emphasizing teaching can shift the balance at the research universities.

CRITICISM: Sacrificing coverage to achieve depth of understanding will reduce student performance on standardized tests.

RESPONSE: Students educated in a lean, lab-rich curriculum will perform well even on traditional tests because they will reason better, solve problems better, and think better scientifically. Moreover, the authors of the GRE and other exams are modifying them to stress the same goals of higher-order problem solving, rather than just rote knowledge.

Project Kaleidoscope offers the nation examples of effective undergraduate science and mathematics education. Our investigations demonstrate the effectiveness of lab-rich science taught within a learning community. We know that it can be done.

THE PROJECT KALEIDOSCOPE NATIONAL COLLOQUIUM was held on February 4 & 5, 1991 at the National Academy of Sciences. The goals of the National Colloquium were to:

- inform the educational and scientific communities what our project had discovered;
- encourage an atmosphere in which more informed decisions can be made regarding undergraduate science and mathematics;
- provide a forum for cross-disciplinary dialogue involving science and mathematics faculty and administrators from institutions of liberal learning across the country;
- spotlight the national need to build and sustain strong undergraduate science and mathematics programs;
- initiate the development of partnerships for continued strengthening of undergraduate science and mathematics, and
- make a public statement about the crucial contribution that undergraduate institutions of liberal learning make to the nation's science and mathematics infrastructure.

Excerpts from four National Colloquium presentations follow.

Dr. James L. Powell

Introduction. It is a great honor to have been chosen as the first speaker of this important and timely gathering. This morning I want to cover two major policy issues in science: the appropriate balance between teaching and research in our colleges and universities, and the impact that funding of Big Science is apt to have on Small Science. I will conclude with some specific and what I hope will be provocative recommendations.

Teaching And Research In Colleges And Universities

James L. Powell, President, Reed College Director Designate, The Franklin Institute, Philadelphia

Project Kaleidoscope National Colloquium February 4, 1991.

In thinking about the relationship between teaching and research, somewhat to my surprise I remembered a line from Geoffrey Chaucer. In *The Canterbury Tales*, he said of the Clerk of Oxenford, "And gladly would he lerne and gladly teach." (Chaucer also noted that:"...he [had] but little gold in confre... nowher so bisy and man as he ther nas, and yet he semed bisier than he was.")

Research Benefits Teaching. I like to imagine that when Chaucer referred to gladly learning, he was describing the attitude of the most successful researchers today. The joy of learning what no one has known before is surely the primary motivation of most scholars.

But what about that Chaucerian connection —"AND"? He did not say, "Gladly Learn *or* Gladly Teach." Is it true that one should be glad to learn, which here I am equating with doing research, "AND" be glad to teach? To answer affirmatively implies that teaching and research are at least complementary.

Let me try to show why I think they are that and more. I cite three ways that research supports teaching and learning:

First, faculty who only pass on knowledge that others produce tend in time to become out-of-date, and the information they are transmitting becomes less and less current and useful. Faculty who are active in research, on the other hand, remain engaged with their disciplines — through involvement with the peer review process in seeking grants, through reading journals and attending professional meetings, and they therefore continually replenish their stock of knowledge. They will be the better informed teachers.

Second, to be able to do research today, when all are busy (and indeed, when some do seem busier than they are), requires a dedication that almost always is the product of a sincere and deep curiosity. A person with that kind of dedication and interest is usually the better teacher. As Rosovsky says in *The University: An Owners Manual*. ... "By far the healthiest and most efficient method of fighting burnout is research."

The third point is that when faculty bring students into their research projects, the students not only help to make a contribution to that research, they also learn firsthand what research is about, and something about the life of the researcher. As an old Chinese proverb is alleged to say, "I hear, and I forget. I see, and I remember. I do, and I understand." Through participation in research, students are able to apply the knowledge gained in their coursework. Mathematics, for example, becomes not an exercise, but a tool necessary to address a particular research problem. Some students will discover that science is the life for them; others will discover it is not; all will be better off for discovering this about themselves early on.

Teaching Benefits Research. Rosovsky, writing from Harvard, explains eloquently how research benefits both faculty and students at research universities. He does not examine whether teaching aids research, but I believe that an even stronger case for this can be made, at institutions of all types.

First is that having to explain one's research to students is a useful and healthy exercise. A faculty member who cannot make a senior major understand at least the basic idea of a research problem may not be thinking that clearly himself or herself. Many flashes of insight have occurred as a researcher attempts to explain a complicated research problem to a student. Another Chinese proverb might have said, "I teach, and I learn; I teach well, and I understand."

A second reason is less immediate, but more important: the continual creation of new knowledge requires a supply of new scholars to whom previous knowledge has been transmitted and on which they can build. Tomorrow's researchers are being taught in today's colleges and universities. Over time, therefore, the ultimate purpose of scholarship is served — equally well and necessarily — by both teaching and research. To put this in human terms, with few exceptions, behind every successful scientist lies an inspiring teacher. For confirmation, read the biography of almost any famous scientist. Or, let us have a show of hands in this room. How many of you can trace your interest in science back largely to one key person? In my case, it was Miss Frederickson, fifth grade teacher at Knapp Hall in Berea, Kentucky, known naturally as "Freddie."

The final reason I wish to cite is by far the most fundamental. Before expressing it let me acknowledge that at the undergraduate level, in contrast to the graduate, involvement of students in faculty research projects often in the short run actually detracts from research productivity. It may take as long or longer to explain a research technique to an undergraduate than it would simply to do it yourself. Yet we must take the time and explain, for this simple reason: we are being paid for doing this. Teaching, good teaching, thus is the foundation of our academic house. If it is seen as weak, not only the foundation, but all that stands upon it, is threatened.

A profession that needs and wishes to receive continuing support from society will have to deliver on its promises, both implicit and explicit. Either through tax-based support of public institutions or through tuition at private ones, Americans pay colleges and universities to educate the youth of this country. It is reasonable of them to expect that professors will profess, and tolerably well.

Luther Williams, Assistant Director for Education and Human Resources, NSF speaking to Colloquium participants.

Project Kaleidoscope National Colloquium

Mounting Criticism. Today, however, we must acknowledge a mounting perception that, in most of our universities there is a significant imbalance between research and teaching. Because of this, higher education comes in for mounting criticism, from the public as well as from inside our community.

Our own national science honor society, Sigma Xi, had this to say in its recent excellent report:

> Undergraduate education is trapped in an infrastructure that rewards research and denies those same rewards to those fulfilling the mission of undergraduate programs. The practices of the research community, college and university administrators, state and federal governments and agencies, and private foundations have created and reinforced the value system that produced and sustained this dichotomy.

The National Governor's Association, which is working hard on educational issues at all levels, states:

> The public has a right to know what it is getting... the right to know and understand the quality of undergraduate education. They have a right to know that their resources are wisely invested and committed.

Research and the Government. To find the answer to how the tilting of the balance in our universities so strongly in favor of research come about, one has to trace the history of the ever-tightening bonds between the American University and the Federal Government after WWII. The best place to start is with Vannevar Bush's famous report, "Science: The Endless Frontier," which was commissioned by Franklin Roosevelt but presented to Truman, and which eventually resulted in the establishment of the National Science Foundation.

Project Kaleidoscope National Colloquium Workshop

Science had become the business of government during the war, and would continue to be in peacetime. If not done in the university, modern research, requiring large facilities, expensive equipment, and teams of researchers, would have to be done either in industrial or in specialized government laboratories. These would have the advantage of being able to concentrate on specific problems, but they would also have several disadvantages. Both industrial and government labs would focus on applied research: industry would need to withhold results for commercial advantage. In federal labs, it would be the government, not the scientists, that would tend to set policy and direction. An equally important objection was that, since both industrial and government labs would be *sans* professors and students, they would not be able to help much with the all-important of all, only in the university could basic research, that type on which most scientific progress had been based, be done unfettered by the demands of competition, profits, and government interference. Only under a system of academic freedom and tenure could researchers be free to follow their research wherever it led, a necessary condition for the scientific method to function at its best.

Dr. Bush concluded, and persuaded Roosevelt, that science — which one could argue had won the war — could also win the peace, contribute to the economy, and provide miraculous benefits to mankind.

> Science can be effective in the national welfare only as a member of a team, whether the conditions be peace or war. But without scientific progress no amount of achievement in other directions can insure our health, prosperity, and security as a nation in the modern world.

One finds an abundance of evidence in his seminal document, "The Endless Frontier," that Vannevar Bush and his colleagues were not discussing research alone. They plainly saw the interconnections between research and teaching, and the necessity for supporting both. They recognized explicitly that the researchers of tomorrow are students today and need to be well taught.

> Publicly and privately supported colleges and universities... are charged with the responsibility of conserving the knowledge accumulated by the past, *imparting that knowledge to students*, and contributing new knowledge of all kinds.

The complementarity and importance of teaching AND research are most clearly and significantly demonstrated in the charges that Bush drew up for the agency that was to implement his vision. He called it the National Research Foundation, but his very first words show that he had more than research in mind:

> It is my judgement that the national interest in scientific research and scientific education can best be promoted by the creation of a National Research Foundation ... [which] should develop and promote a national policy for scientific research and scientific education... [and] should develop scientific talent in American youth by means of scholarships and fellowships...

We can see Dr. Bush's lasting influence by comparing this statement with the first words of the Charter of the National Science Foundation, which came into being five years later:

> The Foundation is authorized and directed to initiate and support basic scientific research and programs to strengthen scientific research potential and science education programs at all levels....

The results of Vannevar Bush's vision for university-based research have exceeded what must have been his dreams, and have led to an American university system that is without any doubt the finest engine of research in the world. The graduate programs of our leading research universities are one part of our educational system of which we can surely be proud. On the other hand, the availability of large sums of government funds to support university research has, equally without doubt, changed the culture of American higher education.

In his book, *The Degradation of the Academic Dogma*, Robert Nisbet shows how, in the years since WWII, the university had come to depend more and more on sponsored research, and, how, inevitably, the reward structure for faculty had altered so that the garnering of research grants, and the quantity of publications (necessary in order to compete for the next grant), have become the coin of the realm. The emphasis on research and publication has now extended to all academic disciplines, even those with little chance of outside support.

It is only common sense that people behave in what they perceive to be their interest. If advancement and tenure depend on research grants and resulting publications, then anything that detracts from research is a load, and time that can be spent on research is a precious opportunity. Can one blame professors who allocate their time rationally? The real fault must lie somewhere else: I would ascribe it to the university itself and to the funding agencies that have largely defined the modern university.

Project Kaleidoscope National Colloquium Workshop

Some Recommendations:

◆ The reward structure should be changed on an institution by institution basis so that professors will teach, if not gladly, then at least willingly. This will take time, as did the present state of affairs to develop, but it can be done.

◆ Good teaching needs to be defined, and rigorously sought out and promoted, on each campus.

◆ We need to work harder at evaluating teaching. One of the principal obstacles on many campuses is the unwritten rule that faculty members of evaluation committees and departments should not attend the classes of colleagues being evaluated. Scholars making judgements should not be satisfied until they have all the evidence they can fairly get.

◆ Each person with the title Professor should profess. To ensure this result, each institution should set a minimum expectation for the amount of teaching that must be done by each faculty member. That expectation would vary with institution; I would say that it is reasonable that each professor should teach at least one course each term, and at least one undergraduate course each year.

◆ The importance of teaching performance will vary from community college to research university, but even at the latter it should count for at least a defined fraction, perhaps 40%, in the tenure decision.

◆ Colleges and universities review the performance of tenure-track faculty members, but often the scrutiny of faculty who have earned tenure is more relaxed. This needs correction. The teaching performance of each tenured faculty member should be reviewed by the appropriate persons on a regular schedule, perhaps every five years. Teaching level and performance should play a defined, minimum role in determining the promotion and salary level of tenured faculty, even at research universities. If we say, "publish or perish," we might also say to tenured faculty members, "fail to teach well, fail to flourish."

◆ In performance evaluations, faculty members should be asked to show evidence that they are up-to-date. Publication in reference journals is the best, but not the only, evidence.

◆ At institutions where a record of publication is required, faculty members being evaluated should be asked to present, not all the papers they have written, but only a small number, perhaps five, that they believe to be their most important. NSF should continue its recently-adopted practice of asking proposers to list only their most significant papers.

◆ At institutions where research is not emphasized, we need to work harder to provide opportunities for faculty members to remain up-to-date and active as scholars.

◆ Federal agencies, such as NSF and NIH, should review policies in which faculty members are provided salaries in order to release them from some or all teaching. For example, the NIH Career Development Awards buy out the teaching duties of promising researchers, thus diverting their careers directly away from teaching. Such policies may prove to be desirable, but it needs to be demonstrated that they do not overly detract from the educational mission of institutions.

◆ Finally, an in-depth analysis, one that goes well beyond what I have attempted today, needs to be made of the relationship between teaching and research. To what extent are they in competition, and to what extent, and where, are they complementary? The Education and Human Resources Committee of the National Science Board is planning such a study and should be encouraged and assisted.

Project Kaleidoscope
National Colloquium Opening Session

Frank Press, President,
National Academy of Sciences

James Powell, President, Reed College

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Big Science, Small Science

Vannevar Bush was a prescient man. I doubt, however, that he predicted, and I am certain he would have strongly disapproved of, the cultural change that would cause professors to advance fastest by professing least. He also undoubtedly saw that scientific projects would grow larger and more complex, as they had, but one can wonder whether he could have foreseen the enormous level and scale of the class of projects that today we call Big Science.

Background. To espouse the interconnection of teaching and research means that, like Vannevar Bush, one espouses research done in academic settings. This kind of research had traditionally been what is called Small Science. Over the years since *The Endless Frontier* was written, science had grown larger and more sophisticated and expensive. It would be comforting to be able to say that all scientific projects, Big or Small, are good, and leave it at that, but in 1991 that is a naive and untenable position. Today, whether we like it or not, Big Science has a major impact on Small Science. Those who care about Small Science have to make themselves heard, and it is in that spirit that I continue. I wish to make an unabashed case for Small Science.

Recently the Congressional Research Service reviewed all Big Science projects since WWII, using a cost floor of at least $25 million. The 1950s saw nine projects above that floor, at a total cost of $260 million and an average of $28 million. In the 1980s, 34 such projects cost $6.7 billion, for an average of $200 million. The constant dollar comparison shows the average project in the 1980s to have been about 4 times as costly as those thirty years ago.

Current Projects. An unprecedented number of Big Science projects (defined as national science, engineering, and technology projects costing more than $100 million) are on the drawing boards, or are under construction today.

The current estimate of the construction cost for these projects combined is $65 billion. Studies of large projects, however, have shown that they cost much more than initially planned: on average 50% more. Overruns of that size would take the total construction cost for the projects currently planned to over $90 billion. The estimated operating cost is $100 billion.

Lest the prediction of a 50% escalation over the original estimate in a big project seem unfair, take the Superconducting Supercollider as an example. The original estimate in 1986 was $4.4 billion; last September, the Department of Energy estimated that it would cost $11.7 billion, an increase of $7 billion or 165% (and the project has several years to go before completion).

This latest estimate for construction of the SSC is over four times the total budget of NSF for 1991. The SSC detectors alone will cost $1 billion, half of NSF's current budget for research. It will cost $313 million annually — approximately equal to the current budget of the Education and Human Resources Directorate at NSF — to operate the SSC. Over its projected 30 year life, operation of the SSC will cost $9.4 billion in 1990 dollars.

To repeat, we will spend as much to construct this one Big Science facility as we will spend in four years on NSF; it will cost the same amount as we spend on education at NSF annually just to operate it.

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Appeal of Big Science. One reason that supporters of Small Science have to speak up is that Big Science projects are inherently more attractive and draw more powerful advocates. Why is this so?:

◆ Big Science holds the promise of remarkable scientific progress; in some fields, of real breakthroughs. Often the projected results capture the mind and imagination in a way that Small Science seldom does.

◆ Size alone attracts human attention and interest.

◆ A project that is big enough can have something for nearly everyone: the state and county in which it is located; contractors and subcontractors; many universities; several federal agencies and sub-parts of agencies.

The result of all of these factors was noted by Lewis Branscomb, former chairman of the National Science Board: the more the cost of a scientific project, the less the scrutiny.

Cost of Big Science. Obviously, Big Science has genuine benefits. But in arriving at a balance of support, good policy would indicate that the benefits need to be weighed against the costs:

◆ Big Science may drain brainpower from Small Science disciplines, even those that might turn out to be more important in the long run.

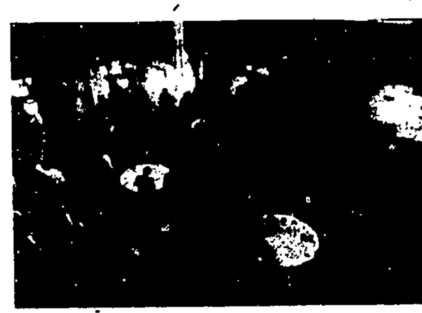
◆ The bigger the project, the more prone it is to disaster. One little thing can go wrong — a few pieces of lint, a millimeter error in grinding a mirror, a failed magnet — and much can be lost.

◆ Big projects take so long that the need changes, allowing them to be superseded by advances in other areas. Some say that much of what can be seen by the Hubble can be seen as well by ground-based telescopes that use adaptive optics to get rid of the effects of atmospheric turbulence.

◆ Even when the needs and conditions alter, Big Science projects sometimes go ahead anyway. So much is riding on them that they develop a momentum that makes them impervious to change.

◆ Big Science can squeeze out funding for Small Science. It is already happening, of course. With one hand, Congress subtracts from the plan to double the budget of NSF in five years; while with the other it spends far greater sums on Big Science.

◆ A final potential cost of Big Science is that a few public failures or perceived boondoggles will contribute to a loss of public confidence in science and scientists generally that we can ill afford. The sorry state of science education already is a scandal or tragedy or both. Further, several recent revelations have done more than tarnish the reputation of science, they have begun to etch into the metal itself. I am thinking of the cold-fusion sham; the public and congressional attention to misconduct in science (which as we know is extremely rare); the recent, visible failures of NASA.



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Advantages of Small Science. In this context, it is important for us to note that, in comparison, Small Science has a number of important, indeed essential, characteristics:

◆ Having much less mass, once moving, Small Science projects have less momentum, making it much easier to shift direction as the results dictate. Thus Small Science lends itself to application of the Scientific Method at its best.

◆ Small Science projects are more apt to be conceived, designed, described, reviewed, conducted, and published by working scientists.

◆ As Vannevar Bush recommended, Small Science projects tend to be done in academic settings, rather than in government labs or in specialized facilities. This allows Small Science to help more in growing the next generation of scientists, including women and minority scientists.

◆ Each Small Science project is peer-reviewed twice: before the work is done in a research proposal, and afterwards in a paper submitted for publication. Some say that the converse of Branscomb's law is true as well: the lower the cost, the more the scrutiny.

◆ Small Science works. For example, of the ten Nobel Prizes awarded in physics during the 1980s, one was in theory, three were in Big Science, and six were in Small Science. Almost all those in Chemistry and Medicine were in Small Science. We have only one year to go on from the 1990s: the three prizes in physics were in Big Science; the one in chemistry was in Small Science.

Many of the most important technological advances since WWII did not come from Big Science: the transistor, antibiotics, TV and VCRs, the computer, lasers, monoclonal antibodies, CD.s (my favorite).

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The burden of proof of the spin-off debate ought to be on the supporters of Big Science. But, some say, even if Small Science has worked better in the past, the easy discoveries have now been made. Fields have been "mined out," and in order to advance today we need Big Science. Of course, there is truth in this. But just when one begins to believe the argument, along comes superconductivity, or the supernova (which may have been Big Science by some definition, but was discovered by an astronomer working at a typical land-based telescope), or the paradigm shift in the earth sciences. You can name examples from your field.

Small Science: Not Optional. Without adequate support for Small Science, the research infrastructure in our colleges and universities will decay even further, perhaps beyond the point of repair. It is in the setting of Small Science — the colleges and universities — that tomorrow's citizens take their last science course, the one on which their ability to participate as intelligent voters depends. Most important of all, funding for Small Science represents the life-giving water that the seen corn — the next generation of researchers — must have if it is to live and flourish. Thus, I submit: support of Small Science is not optional; it is a requirement vital to every interest of our nation, even to the ability of our democracy to function. Although I would support some Big Science projects, I for one cannot see Big Science overall in the same life or death terms as I see Small Science.

Some Recommendations:

Some Big Science projects may be justified, though it is hard to think of a single one that is universally supported within the science community, and some will take place whether or not they are justified. The key is to ensure that an overview takes place so that an appropriate balance is struck and the interest of Small Science is protected.

◆ One way of accomplishing this would be to have funding for Small Science be indexed, however roughly, to spending for Big Science. I believe that Congress or the Office of Science and Technology Policy could develop such an index. For every increase in spending on Big Science, a proportionate increase would occur in the budgets of NIH and NSF. This would instantaneously put NSF back on the doubling track and reverse the alarming decline in the success rate of proposals to NIH, and comparatively would cost peanuts. For example, it would take only $100 million to put *the NSF research budget back on the path to doubling in five years, or about 4% of the 1991 request for the Space Ship* Freedom. Four percent!

◆ Another useful step would be to require each Big Science project to show how it would help improve the state of the human and physical resources of the nation's science base. As Frank Press has said, the highest priority has to be people. Next, we have to maintain and improve the infrastructure of teaching and research. Big Science projects can and should be required to make a significant contribution to these needs. For example, the SSC project is funding a good deal of research in academic settings; for another, one of Reed's faculty members spends summers and leaves at SLAC; far more of this sort of thing should be done.

◆ During the 1980s the United States doubled the defense budget, but in 1990 we found ourselves ill-prepared for, and unable to pay for, Desert Shield. We asked other countries to help, and, with varying degrees of reluctance, they have come through. Why should one country alone pay for advances that will benefit all countries and all peoples? Why should not the wealthy nations of the World — Germany and Japan, for example — pay a fair share of the cost of Big Science? If we must pay for War jointly, why not Science? It is gratifying to see that the SSC and the new 8 mm telescopes are garnering this kind of international support; let them be examples.

Conclusion

Nothing is wrong with science education that common sense, professionalism, and adequate financial support cannot repair. I submit that we have all three in this country, yes, even the money, if we would direct federal support for science where it ought to go. Let this gathering put us firmly on the road toward making science education at all levels, K-12 and undergraduate, the source of the same kind of pride as American graduate education.

In closing I use a metaphor of Ernest Boyer's: Let us make all of science education at colleges and universities a "seamless web" of quality; let the threads running in one direction intertwine in a beautiful, carefully-balanced conjoining of teaching and research; let those in the other be a harmonious, considered blend of support for all science, Big and Small, according to its benefit to mankind.

Project Kaleidoscope National Colloquium General Session.

Dr. Shirley Malcom

What is different about those institutions that have proven to be effective with students from groups currently under-represented in the sciences? How have they come to be effective with those students? In the spirit of the day, let's take a little "True-False" quiz about what works to get women and minorities into science programs, keep them there and get them out with the degree.

Shirley Malcom
Director, Education and Human Resources Programs
American Association for the Advancement of Science (AAAS)

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(1) **TRUE OR FALSE?** Success in science with women and minority students is just a matter of selecting the smartest students to attend your institution – high SAT scores and high GPAs.

FALSE. Many HBCUs accept students with less than stellar indicators of prior academic achievement and yet nurture them into scholars. On the other hand, many highly selective institutions attract high achieving minority students who subsequently under-perform in key gatekeeper courses (such as calculus and introductory chemistry and physics). Many women and minority students who enter declaring an interest in science find faculty who are unwilling to accept their interest and ability, who expect little or who subject them to demeaning class environments.

Having a poor background does not mean you're unable to achieve in science. Bringing in an excellent record is no guarantee of success. It's not just the student. There's something about the institution, too.

(2) **TRUE OR FALSE?** If women and minority students do not stay in, it is their choice and their problem.

FALSE. If these students do not stay in, it is your problem, too; and often "choice" has little to do with their decisions. Dwindling numbers of majors will make it increasingly difficult to justify and support upper level courses or faculty positions. Few departments aspire to be service units for those majors that are thriving. As women and minority students become a larger proportion of the college-aged population our ability to retain these students as majors may mean the survival of our fields.

(3) **TRUE OR FALSE?** There is nothing wrong with the science and mathematics courses as they are now.

To determine if this is true or false (a) count the number of students enrolled at the end of the term and compare this with the number at the beginning of the term. (b) Count the number completing the course; compare this with the number who take the subsequent courses. (c) What was the gender make-up of your freshmen majors: of your graduating majors? Do the same calculation for racial/ethnic minorities. (d) Have exit interviews conducted with your leavers. Perhaps they have come to realize that they really wanted physical education over physics. On the other hand they may have been made to feel unwelcome.

I saw a recent bumper sticker that conveys the right sentiment. "Humpty-Dumpty was pushed." Perhaps students who leave feel they too have been pushed out.

(4) **TRUE OR FALSE?** There is nothing college faculty can do about students' problems since the students come like this from high school (everyone knows there are problems in the K-12 system). (While we might be willing to admit the problems in the K-12 system, we would again point out that some institutions take the students, problems and all, and move them to a higher level of performance.)

FALSE. There are many things you can and must do about this. Reach out to K-12 teachers and work with them in addressing these issues. Vow to turn out teachers who will make you proud when they tell others that you taught them everything they know about science. Teach them as you want them to teach their students.

(5) **TRUE OR FALSE?** In order to keep more students you have to lower standards. You cannot have equity and excellence at the same time.

FALSE. Programs that provide meaningful context and rigorous content attract and hold students. It is hard to imagine how a quality program could be defined by the number who fail rather than by the number who are enabled to succeed. It is impossible to have an excellent program that is not equitable. It is not possible to have an equitable program that gives students less than what they'll need to be successful.

(6) **TRUE OR FALSE?** Some students just do not have what it takes to make it in science and their absence is evidence of this.

FALSE. There is no evidence to support biological determinism — that is, any genetic basis for some group's participation or non-participation, performance or achievement in science and mathematics. Complex social and cultural factors, opportunity to learn, and the availability of resources have likely interacted to produce the current distribution of groups in science fields. The existence of programs which can alter the "inevitable" support the idea that there are many interventions we must exhaust before we are allowed to claim biology. Let nurture take its course.

How does the environment of our colleges support the pursuit of science literacy and science careers by people from groups with weak traditions toward these fields? What works?

We must help students see themselves as part of the community of science. But that means we must be able to envision them there ourselves first. We have to help them find their understanding by sharing ours and by respecting their need for context. We must begin to see our introductory courses as an opportunity to recruit, not a place to weed out. If this is our last shot at providing a future President or a future Member of Congress with a view of science, what image do we want them to have? What do we want them to remember? I think we would agree that we want them to understand the quest, the dynamism and the energy of science, its place in our lives and its capacity to empower.

Project Kaleidoscope National Colloquium - lunch with Einstein.

Women and minorities are the miner's canary signalling deeper problems in our programs. We must recognize that as the demographics change we are playing to a "tougher house." If we do nothing to rethink our programs and depend on old strategies of weeding we face a troubled future. For not only are we not drawing proportionately from the disenfranchised majority, we are losing the interest of traditional participants as well. I began this presentation pointing out a nearly 50% decline in male interest in the physical sciences.

But we can take heart in the fact that we know quite a bit about what works for these groups which if applied, can revitalize our programs. What works to bring these groups into science seems to work for everyone.

The Four R's

Borrowing from concepts outlined in a recent OTA report, *Educating Scientists and Engineers: Grade School to Grad School*, I would like to focus on factors that affect science participation. The OTA report mentions recruitment and retention. I would add to either side of those the ideas of readiness and reconstruction.

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By readiness I refer to the set of K-12 experiences that maintain students' ability to choose college majors in science, mathematics or related fields or that permit students to successfully matriculate in college level science courses.

By recruitment I refer to the set of activities that attract students to science or related majors or to elective (interest based) course taking in science and mathematics.

By retention I refer to the set of actions and programs that seek to hold student interest in science as a career, to use science in their everyday life and/or to prepare a base for lifelong learning in science.

By reconstruction I refer to the process by which students are encouraged and assisted toward further study and toward contributing to the development of science as it incorporates the broadest base of human experience. That is, their participation reshapes the processes and structure of science.

A number of programs exemplify these elements as we undertake efforts to increase the participation of women and minorities in science.

Project Kaleidoscope National Colloquium Workshop.

The Honorable George L. Brown, Jr.

I am extremely pleased to be here. Your task of creating a reformation in undergraduate science and mathematics education across the nation is both formidable and necessary. The aims and objectives that you have outlined fo: Project Kaleidoscope show perception as well as persistence.

I want to quote from your own materials to begin my remarks because you have articulated so well what I believe to be the underlying concept of successful change.

> Effective reforms take money, to be sure, but of primary importance is an environment for reform that encourages strategic planning, fosters creativity, and rewards innovation.

Whenever we consider change, be it small or sweeping, we must be cognizant of the context in which that change must take place. The global, the national, and the immediate context should be understood, if what we desire to change has a chance to occur.

George L. Brown, Jr.
Chair, Committee on Science, Space and Technology
U.S. House of Representatives welcomed by Executive Committee members Daniel Sullivan and Thomas Cole, Jr.

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The Global Context. I will not belabor you with myriad statistics on the changing world. I will only mention what all of us already know in broad generality. Today's world, and surely, the world of tomorrow, will be based increasingly on the combination of technology and information. To that, I will add only four statistics for the global context: American students average 20 absences from school a year as compared to Japanese students who average three a year. Swiss and German students watch 60 percent less TV than American students. The length of the American school year ranks among the shortest of the industrialized nations. And 70 percent of U.S. produced goods are in active competition with foreign products, products which come from nations whose children repeatedly out-score our own children in math, science, geography and other skills.

The National Context. I think it is crucial to understand the demographic patterns that are evolving in America. Dramatic changes are occurring in our school-age population. In the 1980s the population growth among minorities was three times the rate, 21% versus 8%, of the rest of the population. Soon, we will be educating a majority of minorities. Most of these children are at the bottom of the educational and the economic ladder. Although American schools have been successful in the twentieth century in assimilating wave after wave of children who presented new and different challenges, we cannot take this ability for granted. We must prepare our public schools and our teachers for the enormous task ahead. It is an interesting phenomenon that science and technology have dramatically transformed almost every facet of our society except our schools. The nation's schools and the way that we teach in them have been almost impervious to this change.

The Immediate Context. We turn next to the undergraduate student when he or she graduates with a baccalaureate degree. Over half of college graduates do not take their first jobs in an area directly related to their majors. In addition, these students, over a lifetime, will work in five to seven occupations. Those occupations will be so diverse that there will be a continuing need for education and training. Many of today's students will eventually hold jobs that do not even exist today.

I believe that for this profile of the emerging undergraduate, we need to train students for strong adaptability to change. The most versatile and enduring preparation for the future is to be able to respond creatively to unpredictable change. We also need to teach students good predictability skills so that they can successfully forecast what changes might likely come. Skillfully managing change requires an ability to make judgements and to change attitudes. The more comprehensive a perspective we can build for our students, the better their judgements and the more flexible their attitudes will be.

Much of this will come from the humanities where the course of human events over thousands of years can put our own changes into a broader outlook. Properly designed science and math curricula could move us strongly toward this development.

To complete this analysis of the immediate context of your reformation, one has to examine a series of significant changes that have impacted the undergraduate schools in America.

First, the student bodies have changed and they will change more radically in the future. The demographic changes that are in the beginning of the pipeline now, at the elementary school level, will hit the undergraduate schools in less than fifteen years. The mandate of colleges and universities has changed to include a major role in "continuing education." Some schools may be looking at a future where this role eclipses the more traditional role of the school by virtue of its growing enrollment.

The proliferation of community colleges has altered the university equation even further. Many students come to a senior college from a community college where they have already completed their general education. As more heterogeneity is built into the undergraduate system, it will be more difficult to use academic credits as a measure of learning.

Finally, the push of undergraduate schools to abandon their teaching mandate in search of a research mantle is changing undergraduate education in detrimental ways. The undergraduate school is the backbone of higher education in this country. If these schools abdicate their fundamental task, we have no institutions to take over this comprehensive responsibility.

Convergence and Cooperation. Here then we have the context for the science and mathematics reformation in our colleges. Here also is the context for the larger educational Renaissance that needs to take place in our nation. Until perhaps the early 1970s, the major sectors of American society — government, industry, and education — had reasonably defined roles of autonomous behavior. Each segment could operate independently as a separate hemisphere.

Project Kaleidoscope National Colloquium

The monumental changes that have occurred in the world have dictated not only that changes be made within each separate sector, *but also that the three sectors develop a new relationship to each other.* The autonomy that was so cherished and promoted is now being discouraged. We are advocating convergence and cooperation. While this is altogether appropriate and necessary, it is not eminently simple.

Booth Gardner, the Governor of the State of Washington, said in a recent speech that, "People tend to cling to what is familiar, even when it is obviously dysfunctional." This instinct is as deep-seated in institutions as it is in individuals. Despite that, the important collaborations among government, industry, and education have occurred in other countries and the results are well-documented successes. The anxiety of change is inevitable. The goal is to prevent it from making us immovable.

I firmly believe that in order for your task to have ultimate value, we must find ways to make all of our youngest children feel confident and capable in science and math. If we do not learn how to broaden the base of competence in elementary school, we have immediately limited our possibilities and our potential for the nation. No matter how good a job we are doing to reform undergraduate science and math, we must simultaneously fight to convince every elementary school child that he or she can do math and science. This task will be a formidable challenge for decades to come.

As Chairman of the House Science Committee, I will dedicate myself to exploring every idea and working with any constituency committed to improving science and math education, and all education across this land.

Our goal must be to collaborate with each other. Our tasks are too great and our time is too short for any other approach. Perhaps the greatest idea that America has given the world is the idea of education for all. If we work together we can insure that ~~continues~~ to happen.

Project Kaleidoscope National Colloquium Poster Session.

Dr. D. Allan Bromley

D. Allan Bromley
Assistant to the President for Science and Technology
Director, Office of Science and Technology Policy

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This is a particularly fortunate day for me to be meeting with you, because I have just come from participating in the press conference releasing the report, "By the Year 2000: First in the World." The report was put together by the interagency Committee on Education and Human Resources, chaired by the Secretary of Energy James Watkins, under the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET). FCCSET is a group of Cabinet secretaries, deputy secretaries, and agency heads that meets to review, coordinate, and help implement the nation's science and technology policy; the Committee on Education and Human Resources is one of seven umbrella committees under FCCSET.

The report is a major step forward in the federal government's approach to science and mathematics education. It seeks to describe exactly what the federal government is doing in this area, and to outline a strategy that will maximize the effectiveness of the federal contribution to American science and mathematics education.

All three levels of science and mathematics education — pre-college, undergraduate, and graduate — are addressed in this report. Pre-college education is given highest priority, because this is where the greatest problems are and where much work must be done to meet the six goals established by the President and the governors. But the report also gives substantial attention to undergraduate and graduate education, recognizing that without a strong position in research and development — and without a much greater degree of scientific literacy among the population at large — America's competitiveness in world markets will be in jeopardy.

The FCCSET Education and Human Resources Committee focused on two central questions regarding undergraduate education:

1. Are we producing enough U.S. college graduates in science, mathematics, and engineering to ensure that our future economic and technological needs are met?

2. Are undergraduate students, both majors and non-majors, receiving the education in science, mathematics, and engineering that is necessary to meet those needs?

The members of the FCCSET Committee on Education and Human Resources concluded that the answer to both of these questions is very likely "no."

The number of college-age students is only about 80 percent of what it was a decade ago, and the fraction of these students who graduate with bachelors' degrees in science, mathematics, and engineering remains stubbornly stuck at about 4 to 5 percent. Unless we can find ways to raise this average, this country is going to be producing fewer science and mathematics graduates just at a time when the need for those graduates is growing.

One way to increase the percentage of students who major in science and engineering is, of course, to attract groups that have traditionally been under-represented in those fields, including minorities, women, and people with disabilities. The low level of these groups in science and engineering verges on the scandalous. Blacks constitute about 12 percent of the U.S. population, but they earn only 5 percent of all degrees in science, mathematics, and engineering. Women, who make up half the population, earn only about 30 percent of these degrees. We do not compare at all with other developed nations, and we cannot afford this wastage of very important talent.

Even among the student population at large, interest in science and mathematics had been falling. Over the past 20 years, interest, as registered by entering freshmen, in science and engineering majors had decreased by a third. Interest in mathematics had dropped by a quarter over the 1980s, and interest in computer science, an area where the greatest shortages are predicted, had dropped by fully two-thirds over the last five years. Even among those who express an interest in majoring in science and engineering as freshmen, more than 50 percent fail to complete degrees in science, mathematics, or engineering. The nation can no longer afford these kinds of losses.

In addition to these questions of quantity, the committee notes, many questions have been raised about the quality of the undergraduate experience in science and mathematics, and I know that this is an issue that had occupied much of your last two days. Much of the undergraduate curriculum is dull, uninspired, narrowly focused, and out-of-date. Undergraduates will always sleep through some classes, but many courses do not give them much reason to stay awake.

For reasons of both quantity and quality, the undergraduate area is going to be a key factor in determining whether the shortfalls of trained personnel predicted for the 1990s and first decade of the 21st century materialize. If we can reach undergraduates today, we will have graduate students emerging by the end of the decade. In that respect, there is no more important area in which to focus our attention.

Furthermore, the undergraduate level is the last formal exposure most graduates will have to science and technology. The quality of those courses may therefore have more than a little to do with the dismal state of scientific literacy in this country. In one recent study, half of the adults questioned did not know that it takes one year for the Earth to orbit the sun. Fewer than half of the adults in the United States believe that human beings evolved from earlier species of animals. Indeed, the public's understanding of science and mathematics recalls the story of Yogi Berra going to a pizza parlor and ordering a large pizza. When he was asked if he wanted it cut into four pieces or eight, he answered, "You'd better make it four. I don't think that I can eat eight."

In my opinion, in a democracy like ours it is absolutely essential that our citizens at least be able to understand the broad issues that confront the nation, even if they are not going to be able to participate in a direct way in resolving those issues. Lacking that understanding, they tend to become alienated from society, something which we cannot afford. Literacy, both verbal and numeric, is the foundation on which we must build the future of this nation.

Project Kaleidoscope
National Colloquium Keynote Presentations
Uri Treisman, Professor of Mathematics, University of California, Berkeley;
Priscilla Laws, Professor of Physics, Dickinson College;
Lynn Steen, moderator.

An Action Strategy for Undergraduate Education

Recognizing the importance of undergraduate education, the committee developed an undergraduate action strategy with four program elements.

◆ The first is to develop better curricula and learning materials and to improve laboratories. This focus on laboratories is particularly important. We cannot continue to send students to laboratories where the equipment they use is older than they are, and in many cases older than their instructors. Students must have access to modern laboratories and equipment, especially since many of them will be entering the workforce directly after they graduate.

◆ The second is to enhance the teaching skills of faculty. Faculty are the only ones who can create a classroom environment where students and teachers are true partners in learning. To do this, we must give faculty a chance to spend time on teaching and enhance their teaching skills. In particular, we can use many of the federal government's laboratories and other facilities to increase the skills and knowledge of faculty.

◆ The third is to attract and retain students in undergraduate programs in science, engineering, and mathematics. The means taken to do so range from scholarships to cooperative education to student research experiences. For example, the ROTC scholarship program is a significant component of this effort. A new component is the National Science Scholars Program, which was proposed by the President and will start this year. This program will provide four-year scholarships for up to 570 high school graduates each year who have excelled in science, mathematics, or engineering.

Project Kaleidoscope National Colloquium Panel Discussion: Chair: Carol Guardo, President-Great Lakes Colleges Association. Panel: PKAL Committee Members James Gentile, Etta Falconer, Sheldon Wettack, Daniel Sullivan.

◆ And the fourth, and perhaps most ambitious, is to work for comprehensive and systemic reform of the undergraduate experience, to give a new degree of vitality to the undergraduate system. These are multifaceted programs that are meant to spark new thinking and complement the more traditional approaches under way. An example is the Alliances for Minority Participation at the National Science Foundation, which promotes the creation of regional alliances between school districts, colleges, government, and businesses to attract and retain minority students to science and engineering. The ultimate goal of the program is to ensure that 50,000 bachelor's degrees and 2,000 Ph.D.'s are earned by under-represented minorities each year.

Partnerships for Reform in Pre-college Education

It is also important to recognize that the difficulty starts far back in the educational system — far before anything having to do with colleges or universities. I have often pointed out in the past that, at the graduate level, the United States leads the world in educational quality: the education we provide to foreign students who then return home is one of our most important exports. At the undergraduate level, because we are one of the few industrialized countries that has no central control over what constitutes a college education, we have peaks of excellence and valleys of mediocrity. At the pre-college level, the situation is frankly scandalous. For the first time in modern history, we are providing our children with a worse education than their parents received.

The FCCSET report points out that the greatest need is to increase the number and skills of pre-college teachers in science and mathematics. This is an area where new partnerships such as those you have been discussing are particularly crucial. The federal government had made a major commitment to attract more individuals to pre-college mathematics and science teaching and to increase the skills of those teachers. Now we need colleges and universities to join in fully in this endeavor.

The need for action is clear, and directions in which we must move are equally clear. Now it is a matter of marshalling the collective will to make changes. The old proverb says "If we do not change our direction, we are very likely to end up where we are heading." We have seen the direction in which we are heading in this country, and it is one fraught with peril for our continued international leadership. Now is the time to strike out in a new direction.

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,

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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 humility 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.

– Presidential Science Advisor D. Allan Bromley, 1990.

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Hamilton College

Basalt contains the mineral pyroxene, but not quartz. Or is it the other way around? And who cares — what difference does it make?

To professional geologists, of course, it makes a big difference. Basalt is a key component of the earth's crust, and understanding its mineral makeup gives insight into the processes that literally shape our world. But to students taking introductory geology courses, basalt, pyroxene and quartz are all too often just three more terms they need to memorize for the final exam.

That's not the case at Hamilton College in Clinton, New York. Beginning students there, says geology professor Barbara Tewksbury, "have the opportunity to do what geologists do, not simply learn what geologists know."

Geology majors at Hamilton have always had that opportunity. Many have gone on research expeditions to such far-flung locations as Antarctica, the Galapagos Islands, and Tasmania. They've also taken advantage of the diverse local geology. (The college is located on a sequence of Paleozoic sedimentary rocks and only a few hours' drive from the great deformed rocks of Appalachia.) However, the department — five faculty sharing four full-time positions — was concerned about students' first impression of the subject.

"How can we expect to attract students to science if, in our introductory courses, we don't give them a taste of what science is all about?" says Tewksbury. "We can't continue to imply to our students that, when they've learned enough information, sometime in the future they'll be able to tackle an exciting problem. By then, we will have lost them."

In 1986 Tewksbury and colleagues decided to "stop tinkering" with their introductory courses, and instead rethink their whole approach. What they came up with inverts the traditional order of things. Instead of one semester of Physical Geology, with emphasis on vocabulary and classification, followed by a semester of Historical Geology, students now start with a course on one of several global topics, such as plate tectonics, oceanography, or environmental geology, and then delve into the details of mineral identification, rock-forming processes, etc. in a second course. The global framework of the first course establishes the "big picture" while the second course introduces the nuts and bolts.

First-year labs have also been overhauled. For example, to accompany the plate tectonics course, Tewksbury has designed a lab course in which students use complex maps from the U.S. Geological Survey to analyze the geology of Indonesia, one of the most spectacular tectonic regions on earth. "In many respects, it is a highly directed research experience in which the students are doing the kind of science that makes geology exciting to scientists," she says.

The introductory courses at Hamilton are not watered-down versions of geology, Tewksbury contends, noting that average grades are lower than both the overall college average and average in other first-year courses. In spite of this — or should we be optimistic and say because of this? — students now flock to these courses. Enrollments are up from less than 70 students per year 5 years ago, to nearly 200 per year. Moreover, the number of majors has risen from 4 graduating in 1986 to 14 expected in 1992.

Did all this overhauling take massive amounts of money and outside grants? No. While the department receives NSF and other support research activities (which also involve undergraduates), the geologists at Hamilton sought no special funding to restructure the introductory courses. Explains Tewksbury: "This is a teaching institution, and we thought it was part of our job."

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 administrators and grants officers seeking general or long-range institutional improvements. A cognitive model is particularly appropriate for describing the learning of science and mathematics because scholars in these areas presuppose that the subject matter is logical and consistent, i.e., that one can know it and realize that one knows it without recourse to authority, doctrine, or personal predisposition.

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.

The prominence of the community of learners in the experience of science learning at liberal arts colleges indicates that it is one important component of effective science education. We are also impressed with the frequency and power with which lack of community has been emphasized by recent studies as a crucial shortcoming in college learning. Learning, motivation to learn, teaching, and the practice of science are all deeply social phenomena. 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. An able scientist becomes that not because of endowments conferred at birth, but because others cared enough to nurture and inform that person and enmesh him or her in a healthy social interaction that created a sturdy sense of identity.

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.

— Association of American Colleges, 1988.

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.

– *"The New Liberal Arts,"* *1981.*

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 1990's, 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 skimps 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

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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.

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

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 ...

– *Pew "Policy Perspectives," 1990.*

Morehouse College

The biology department at Morehouse College in Atlanta is taking an aggressive approach toward recruiting more minority students into research careers in science. With funding from many sources, including the David and Lucile Packard Foundation, the Hughes Foundation, and the National Science Foundation, Morehouse has established a range of programs that bring students into direct contact with researchers in the laboratory and guide them toward graduate school.

The concern at Morehouse is with the virtual absence of Blacks among Ph.D.'s in the natural sciences. The statistics are telling. In 1986, for instance, fewer than 100 Blacks received science Ph.D.'s: 64 in the life sciences, and 25 in the physical sciences. In 1990, Blacks accounted for a mere 1% of the Ph.D.'s given to U.S. citizens in mathematics — 3 men and 1 woman out of total 401.

When you're dealing with such small numbers, a difference of 1 can be substantial. And the biology department at Morehouse aims to make a bigger difference than that.

They are doing so by emphasizing research. The biology department made a "conscious decision" in the late 70s to emphasize research among its faculty, according to department chair John Haynes. That emphasis has carried over into the curriculum, which has been designed to get students into the laboratory early in their academic careers.

"Once we established our own laboratories, we could start giving research experience to students," explains Haynes.

Students can spend from a semester to two years or more working in a lab with someone from the Atlanta University Center, a consortium of institutions including Morehouse, Spelman College, Clark Atlanta University and Morris Brown College. Some receive formal credit through two research courses: a sophomore-level course called Experimental Biology and a junior/senior-level course, Biological Problems. Others work in the labs on a non-credit basis.

The department also runs a weekly seminar series which brings in outside speakers. Students in the research courses attend these seminars and write critiques which summarize the presentation and briefly analyze it. The seminars introduce students to diverse areas of research in biology, as well as expose them to minority scientists who serve as role models. In addition to speaking in the seminar, visiting scientists talk with students about research careers and graduate programs.

A key component of the Morehouse effort is the Research Careers Office, which opened in 1988 with the express purpose of increasing the number of students who go on to graduate school in the sciences. The office has recorded upwards of 100 students per year who are interested in summer research programs, and a smaller number looking into graduate schools.

"There's been a significant increase in the number of students who are interested in research" since the office opened, according to Director Rosalyn Patterson, who is also an adjunct professor in the biology department.

Some of that interest is due to summer research programs in which Morehouse students work at institutions such as the Massachusetts Institute of Technology, the National Institutes of Health, and Brown University. Some of it also stems from a summer science institute for high school students, which Morehouse began in 1984. That program has grown from five students its first year to nearly 20 in recent summers. Approximately 85% of them have gone on to major in science or mathematics.

The secret, says Haynes, is to put good faculty and good students together. At Morehouse, he adds, they have both.

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 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.

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

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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

[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."

– *Sheila Tobias, 1990.*

... 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.

The Community of Learners

Our model for learning science expresses an ideal that no instructional program or institution manifests perfectly. It reminds educators of three qualities — community, personal character, and context — that must be sought constantly to

The implications of "community" for institutional and departmental policies are profound.

make instruction in science and mathematics effective. It says that membership of the learner in a community of learners is crucial. Adoption of this standard for science education would immediately give most science instructors dozens of things to work on.

Science educators have traditionally assumed students to be isolated individuals. This assumption is most clear in the design of the introc... tory 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 upperclass 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 though 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 Laws
Project Kaleidoscope
National Colloquium,
February 4, 1991.

Our enterprise is both exhilarating and exhausting. It requires a partnership among students, faculty, administrators, professional organizations, private foundations, legislators and government agencies. It represents a blending of new and old ideas about learning with new laboratory tools. A new philosophy of science education is emerging. It is epitomized by a proverb which serves as the Workshop Physics motto:

I hear, I forget.
I see, I remember.
I do, I understand.

– Priscilla Laws
Project Kaleidoscope
National Colloquium.
February 4. 1991.

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.

Investigation should be invoked throughout a science curriculum.

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,

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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

I ... would ... do away with introductory chemistry lectures completely, and build a first-year course entirely around experiments.

— *ACS Priestley Medalist Harry B. Gray, 1990.*

American Chemical Society (Mt. Union College)

Global warming. Acid rain. Nuclear power. How can people make informed decisions about issues such as these without a basic level of scientific literacy?

The short answer: They can't. Scientific literacy is essential if society is to respond effectively to the myriad environmental and technological challenges of contemporary life. It's not enough to train scientific "experts" to solve all the problems; it also takes broadly knowledgeable people in all walks of life, from the individual motorist and homeowner to decision makers in industry to leaders in local, state, and federal government, who understand science well enough to make intelligent decisions — decisions that will determine our future.

The American Chemical Society has set out to raise the level of scientific literacy in its own specialty. Since 1988, the ACS has focused a curriculum initiative on college chemistry for students who are not science majors. The primary product of the initiative is a textbook, "Chemistry in Context," which is currently being pilot-tested at Macalaster College in St. Paul, Minnesota, Mt. Union College in Alliance, Ohio, and The Catholic University in Washington, D.C.

An earlier ACS initiative, begun in 1981, produced a high school text, "Chemistry in the Community," with a similar aim. Published in 1988, "Chemistry in the Community" has sold more than 100,000 copies to date.

The main goals of "Chemistry in Context," says Conrad Stanitski, one of six authors working on the text, are to teach students the fundamental concepts of chemistry, help them discover the theoretical and practical significance of the subject, show them how to locate information that addresses technical issues, and develop their ability to think critically and analytically in such matters as the assessment of risks and benefits.

But it's the book's approach to reaching these goals that sets it apart.

Instead of putting principles first and postponing applications to optional sections, "Chemistry in Context" starts with issues such as global warming or the economics of pollution controls, and brings in the pertinent chemical principles strictly on a "need-to-know" basis. If there's chemistry that's needed to understand an issue, says Sylvia Ware, director of education at the ACS, "we teach it as it comes up, rather than as an introductory unit."

The issues orientation of "Chemistry in Context" means that chemistry is not presented purely as cut-and-dried series of technical exercises with answers at the back of the book. "We try to move [students] away from the idea that science always has a 'right' answer," Stanitski says. Instead, there is an emphasis on decision-making in the face of uncertainty. "We try to get students involved in some kind of informed decision," Stanitski explains, stressing the word "informed."

Could such a course wind up widening the gap between majors and non-majors? Ware doesn't think so. If anything, the majors could benefit from a bit more context to the content of their courses, she says: "I hope that the kind of thinking that shows up in 'Chemistry in Context' begins to influence the way majors are taught."

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 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.

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

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.

– *Jon D. Miller, 1989.*

It seems that no universally recognized crisis exists today. The energy crisis, the trade and budget deficits, acquired immunodeficiency syndrome, and the greenhouse effect are profoundly serious and deeply troubling issues with long-lasting consequences, but not one has provided the coalescing influence concerning courses of action that wars provide. One issue does seem to be emerging in the national consciousness to a degree that might provide a coalescing influence for concerted national action. I refer to the crisis in American education and, in particular, its effects on the nation's ability to remain competitive in a rapidly changing world.

— NSF Director Walter E. Massey, 1989.

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, February 4, 1991.

Swarthmore

Lawyers might not like surprises on the witness stand, but scientists live for them in the laboratory. It's when something unexpected happens that you learn something — if not about nature, then at least about what it takes to run an experiment.

That's the message Barbara Stewart has brought to the introductory biology labs at Swarthmore College. Stewart and colleagues have designed a series of "investigative" labs in which students take an active role in designing their own experiments. Not everything goes as planned — and that's where a lot of the learning takes place.

By contrast, students in a standard "demonstrative" lab follow a cookbook set of instructions designed to produce results that are known in advance. All too often, students in such a lab are more concerned with getting the "right answer" than with learning science.

"If students write up the [experimental] protocol themselves, then they're more interested in what they're doing," Stewart explains, adding that "we also found it was important to let them go ahead and make mistakes." The open-ended nature of the labs and the fact that the teacher doesn't always know what the students are going to find appeals to the students, she says. "They're intrigued that they're getting new data."

Stewart's labs typically require two periods each. The first period focuses on learning basic techniques and data recording procedures. For example, to study properties of tyrosinase, the enzyme that makes potatoes, mushrooms, and other produce turn brown when exposed to oxygen, students learn to extract the enzyme and measure the rate of discoloration using a spectrophotometer. The students then split up into small groups of two or three to design a protocol for the second week's lab, which might be to investigate the effect of temperature of pH on tyrosinase activity. The planning may take much more time than the lab itself — that's a good sign, Stewart says. Their protocol is checked for gross technical errors at the beginning of the second period, and then they get to work.

That's when the surprises happen. A student may discover, for example, that when you put a cold test tube into a warm spectrophotometer, you get condensation on the outside of the test tube that makes it impossible to get a reading. Or the enzyme may denature in a bath of hot water. "These surprises confound and intrigue students and compel them to alter their experimental design," Stewart says. "These unexpected occurrences always are remembered by the students and contribute greatly to their education."

The Swarthmore biology department has also added a formal writing requirement to the investigative labs. Students not only design and run their own experiments, they also report on them in a professional scientific style. To make the writing component work well, the department hired a writing consultant, who comments on students' first drafts, confers with them as needed, and generally dispenses advice and wisdom.

The investigative labs and the writing component go well together. "Students appear more enthusiastic about writing a scientific paper that informs the instructor of the methods and results of their own experiment because they realize their data is unique and will contribute to the instructor's knowledge and, indeed, to the discipline," Stewart says. The upshot: Students learn "a lot more biology."

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 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.

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

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 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

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

We want our faculty members to teach science to students, not to teach about science to students.

– Bucknell University President Gary Sojka, 1990.

I distinguish two aspects of science: content and enterprise; one is classified knowledge, the other is the way in which scientists work and think. The one way in which we write up our results, in papers and books, in the passive voice, gives the impression that we start with precise measurements and proceed by strict logical steps to incontrovertible conclusions. The way we really do it — starting with hunches, making guesses, making many mistakes, going off on blind roads before hitting on one that seems to be going in the right direction — that is science in the making.

— Berkeley chemist Joel Hildebrand, 1957.

classroom presentation. Good curricula should emphasize big and important ideas. The who, what, where, when, and how of these ideas should be considered in detail, so that students taste the logic, the power, and the excitement of knowing.

The personal experience of the instructor in investigation provides useful insight to make hard curricular choices. The instructor who loses sight of the uses students have for disciplinary knowledge has no scalpel for shaping the curriculum. The instructor innocent of investigation has no firsthand sense of what is truly important and what can be learned later if the need arises. Undisciplined curricula can be exceedingly costly, sometimes difficult to detect from outside, and of little benefit to student learning.

The sign posts to a healthy curriculum point in the direction of a lean and lab-rich environment. The lean curriculum has been pruned by the experience of its instructors in disciplinary investigation and their expectation that the curriculum ought to prepare students to use what they learn. A lean curriculum provides students and faculty with the time and resources to have a lab-rich curriculum which personalizes lessons and connects ideas to the investigative process. Laboratories are essential to such experiences, but valuable investigation can occur as well in stairwells of science buildings, at field stations and museums, in front of computer terminals, in discussions, recitations, and problem sessions, and in lecture demonstrations. "Lab-rich" refers to the property of a curriculum that provides experience in the subject matter, and many settings can do this.

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 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.

Arkansas College

"Undergraduate student-faculty research is the highest form of education," states Bert Holmes, a chemistry professor at Arkansas College in Batesville, Arkansas. But can a small college with only a few hundred students afford to start up an undergraduate research program?

The answer is an emphatic "Yes," according to Holmes. "All it takes is one person who's really dedicated," he says. That, and the support of the college administration to develop a systematic plan to acquire the funds, faculty, and facilities it takes to establish a first-rate program.

"After all," says Holmes, "if undergraduate student-faculty research is sound educational pedagogy for students at larger colleges, it should also be a noble cause at any college."

Holmes came to Arkansas College in 1983, with the specific mission of initiating student-faculty research. A chemist whose research interests run to gas phase kinetics, Holmes joined a science division with four faculty members, including one chemist. The number of chemistry majors fluctuated between 1 and 3 graduates per year. (The school had approximately 400 students at the time.)

All those numbers have increased. There are now 11 science faculty, including 3 chemists. The college (with an enrollment of approximately 560 students) is currently averaging 5 chemistry graduates per year, with roughly half going on to graduate school. That may not seem like much, but considering the number of small colleges, there is potential for a sizable impact. "If every small college could add just 4 or 5 more graduates, that would be 2000 more chemists each year," Holmes points out. These colleges "represent a vast resource of potential chemists that should not be ignored," he adds.

The driving force has been the student-faculty research program. Since 1984, Holmes and colleagues have worked with more than two dozen students on summer research projects in biology and chemistry. The program has grown from 4 students working with 2 faculty members in 1984 to 10 students and 4 faculty in 1990. Many more students participate in research during the regular school year, including the college's January interim.

"They're real success stories," division chair Robert Carius says of the students researchers. One student, for example, worked four straight summers in Holmes's lab on the kinetics of fluorocarbons. His work paid off with a paper in the Journal of Physical Chemistry. The student, who graduated with a major in chemistry and mathematics, continued with graduate studies in chemistry at Stanford University. Other students have gone on to graduate school at places such as Berkeley and Rice.

Holmes's "grand scheme" involved a five-year plan to obtain research-quality instrumentation, drum up funds to support students during the summer, expand the college library's collection of chemistry journals, and recruit new faculty committed to undergraduate research. The college is now at work on a renovation plan for the science building.

Timing is critical in any such program, Holmes says. But an even more critical quality, he adds, is "persistence — you have to have someone who believes in it so much that they won't accept 'No' for an answer."

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 program — 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.

MATHEMATICS: THE FOUNDATION OF SCIENCE

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

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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 justly 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.

— *"Everybody Counts," 1989.*

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.

– *"Challenges for College Mathematics," 1990.*

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, 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.

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 to children equal opportunities to learn. It is imperative that colleges avoid similar mistakes by perpetuating the stigma of remediation. For example, precalculus courses all too often do little more than

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.

– *"Challenges for College Mathematics," 1990.*

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.

University of Houston-Downtown

Mathematics is often seen as the most difficult discipline to whip into shape, as far as giving students practical, hands-on experience with problems of more than a textbook nature goes. The logical development of the subject neither needs nor lends itself to "real world" applications — and anyway, you have to study a lot of math for a long time before you can do anything with it. Or so goes the argument.

The University of Houston-Downtown doesn't buy it. Math majors there have an opportunity to round out their studies with a senior practicum which has them work on very real problems with people at such very real places as the Johnson Space Center, the Texas Medical Center, and the Center for Population Dynamics.

The mathematics program at the University of Houston-Downtown (a strictly undergraduate campus, with approximately 8500 students, occupying a single building in the heart of Houston's business district) is designed so that students can take a bachelor's degree and put it right to work. The program "emphasizes immediate employment," according to chairman Richard Alo. That means emphasizing the applicability of mathematics. It also means emphasizing communication skills, especially writing — another thing that is often not associated with math.

The senior practicum is a "capstone" course taken by about two-thirds of the majors each year. The participants are carefully screened and chosen on the basis of their overall abilities. They work with a faculty member from the mathematics department and two others from elsewhere in the university and in local industry. The entire group of practicum students meets weekly with Alo, who guides them in writing assignments and discussion.

The practicum involves "a lot of writing," Alo says. And the results pay off. Outside evaluators have said that many of the final reports written by practicum students could qualify as Master's theses. Some have even turned into published professional papers.

"Students go into this enthusiastically," Alo says. No wonder, considering the types of problems they have to choose from. At the Johnson Space Center, for example, students have developed new techniques for robotic arms to work as retrievers in space. They have also worked on flight simulators for astronaut training and "fuzzy logic" — a new mathematical approach to decision making in the face of uncertainty. At the Texas Medical Center, students have analyzed blood chemistry and height-weight data in order to establish the equations needed to determine the level of drug delivery for cancer patients undergoing chemotherapy.

The practicum is preceded by a one-semester seminar taken by all math majors. The aim of the seminar, Alo explains, is to synthesize the students' previous mathematical training and help them "become better aware of the breadth and depth of their mathematical education." Even for students who do not go on into the practicum, the result is a broader outlook on mathematics and better preparation for bringing their mathematical skills to the workplace.

Mathematics may be the only discipline that bases its instruction on hundreds of exercises of five minutes or less. It is no wonder that students respond by doing without thinking, flushing everything as soon as the test is over, and never seeing the connections. It is a lousy way to teach, and almost anything that breaks that pattern is a good idea.

– *"Priming the Calculus Pump," 1990.*

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.

Few students learn a mathematical idea well the first time they encounter it.

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 statistics and computing, and as public demand has risen for college graduates to be quantitatively literate, the time may now be at hand to explore a new first year mathematics curriculum that belongs fully to neither the calculus nor the statistics tradition. The question is simple: how can one best introduce first-year college students to mathematics, rather than just to

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.

— "*A Call for Change*," 1991.

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
February 4, 1991.

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.

— *"Priming the Calculus Pump," 1990.*

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.

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

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. The benefit of close student-faculty contact that comes from such work is similar to the benefit conferred by small classes — but more intense: when both student and instructor are focused on the same problem, with neither knowing just how to solve it, there develops a shared experience in the excitement of discovery that can stimulate a student's long-term interest in a scientific or mathematical career.

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

Pomona College

All too often, students come out of science courses knowing loads of factual minutiae and able — more or less — to work their way through simple problems, but without the slightest idea what the big picture is. Or even that there is a big picture.

Physics professor Thomas Moore at Pomona College is out to see that that doesn't happen in first-year college physics. Moore is developing a two-semester course he calls "Six Ideas That Shaped Physics."

Moore's course is one of several model courses endorsed for development by the Introductory University Physics Project (IUPP), a coordinated effort of the American Association of Physics Teachers, the American Institute of Physics, and the American Physical Society. Like the "Lean and Lively" calculus reform movement in mathematics, IUPP seeks to trim down the content of introductory physics in order to achieve a pace that more students can keep up with — removing tangential topics and what Moore calls "conceptual noise." A second IUPP goal is to incorporate concepts from contemporary physics into the first-year curriculum (but without abandoning the first goal in the process). A third goal is to organize the content around "story lines" that will motivate students and highlight the main concepts.

Moore's "story lines" are provided by the "six ideas." In order of presentation, they are: 1) The universe is a mechanism of falling bodies — an introduction to the kinematics of a particle responding to an external force; 2) Conservation laws constrain the mechanism — a further study of interactions between particles; 3) Some quantities are relative, but laws are absolute — a modern presentation of special relativity; 4) Some energy flows are irreversible — a unit on thermal physics, emphasizing the statistical interpretation of entropy; 5) Electricity and magnetism are fundamentally linked — an introduction to electromagnetism and how special relativity ties together the effects of electricity and magnetism; 6) Macroscopic models don't fit microscopic physics — a basic unit on quantum mechanics.

Moore's approach, though, goes beyond a rearrangement and paring down of topics. "It's a full package, not just a revised syllabus," he says. The full package includes a pedagogical approach that emphasizes qualitative as well as quantitative reasoning and encourages active, collaborative learning in class. Computers enter in also, and the laboratory program is divided into informal "minilabs" that focus on individual concepts (and sometimes preconceptions), and longer, more formal "project labs." Finally, the Pomona physics department offers a weekly series of evening lectures on topics ranging from cosmology to superconductivity; these lectures are aimed at undergraduates, and Moore's course uses them to expose interested students to topics beyond what fits in the course itself.

As part of IUPP, Moore's course will be pilot tested by a development team at several different schools. The final goal, says Moore, is to create a physics course that is "exciting enough to attract majors and relevant enough so that non-majors carry away something useful." That hasn't happened enough in the past.

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.

Computing changes what is taught as much as how we teach.

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.

– Sheila Tobias, 1990.

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.

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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,

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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

St. John Fisher College

The problem faced by the chemistry department at St. John Fisher College is a common one: they seemed to be teaching two different classes in their freshman chemistry course. On the one hand, they had half a class — maybe two dozen students — whose eyes glazed over whenever the instructor went beyond the lesson to talk about some interesting chemistry; on the other hand, they had half a class who grew bored when the instructor went over the details of an elementary calculation. So they did the obvious thing: They made two classes out of one.

But they didn't do it in the obvious way.

The obvious way would have had a lower, "remedial" track left in the dust by an accelerated upper track. The obvious way would have looked to the upper track to produce majors and not expected much from the lower track.

Instead, the St. John Fisher chemists designed two separate courses — one keeping the name General Chemistry and one called Principles of Chemistry — that "converge" by the end of the year, so that students from both tracks are ready for the rigors of Organic. At St. John Fisher, a chem major can come from either side of the tracks.

That's not to say that students in the two courses come out knowing the exact same amount of chemistry. General Chemistry covers more ground, exploring certain topics in greater depth. For example, while both courses include the ideal gas laws, General Chemistry may also examine non-ideal gases. (At the same time, the Principles course may cover some material not found in General Chem.) However, students seem to do equally well on overlap portions of the final exams, according to department chairman Clarence Heininger. There's "no discernible difference" in their performance, Heininger says.

The two-tiered approach at St. John Fisher only started in 1988, so it's still too early to know for sure how well it does at producing majors from both tracks. However, Heininger notes that approximately a third of the students from his 1988-89 Principles class have declared science majors. This is far better than before, when nearly half the students who started General Chemistry never completed the full two-semester sequence.

How do students know which course to take? The main factor is their mathematical preparation. Students who scored well on the SAT (or New York equivalent) and/or are ready to take calculus are advised to sign up for General Chemistry, while students enrolling in college algebra are steered toward Principles of Chemistry.

"What it really requires is that you really try to find out what your students are capable of doing at the beginning," Heininger says. It also requires a department dedicated to support students' efforts. Says Heininger: "A lot of these people would not have persevered if we had not encouraged them to keep going."

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.

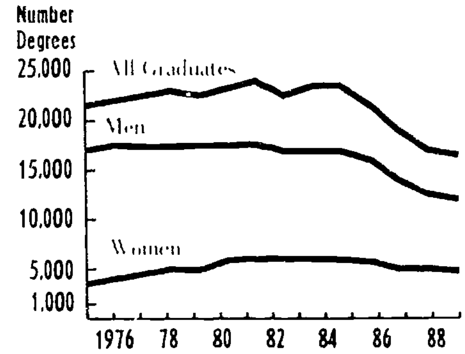
Private Liberal Arts I colleges — both coeducational and women's colleges — have been especially productive of women science and mathematics graduates and of women graduates who subsequently earn a doctorate in science or mathematics. Indeed, these colleges produce a higher percentage of women science 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.

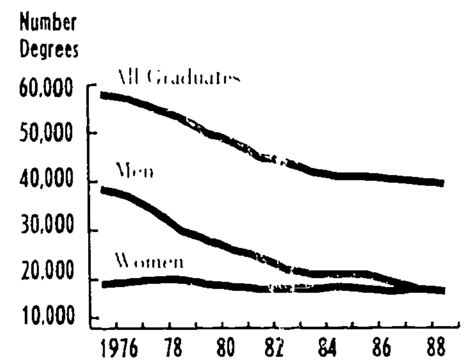
It is now clear that women can succeed in great numbers in science and mathematics. The success of women in science and mathematics is greatest in settings — both single-sex and coeducational — characterized by the kinds of learning communities described in this report. These settings warm the chilly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

Where Minorities Succeed

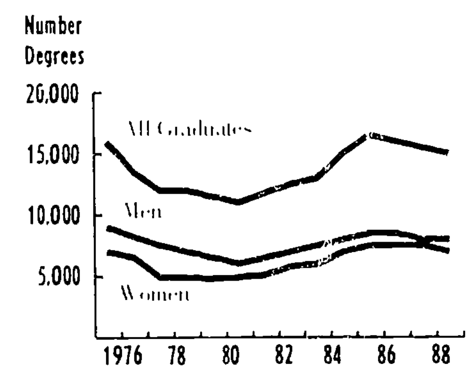
All analyses of the rates of participation of Blacks and Hispanics confirm a picture of severe under-representation in science and mathematics at all levels of our system of education. Nevertheless, there are



Physical Science Bachelor's Degrees by Gender.



Biological Science Bachelor's Degrees by Gender.



Mathematics Bachelor's Degrees by Gender.

ICO-PKAL: Dept. of Education Data.

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.

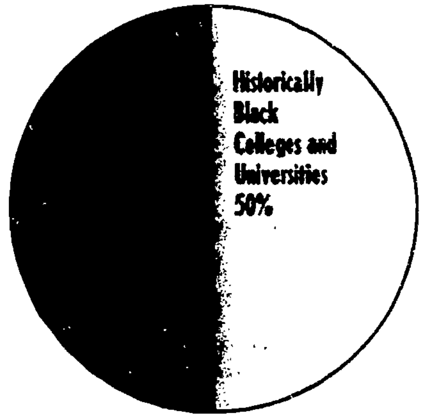
for collegiate success — a supportive community and "social connectedness" — are the same for all students. A great number of predominantly White colleges also

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

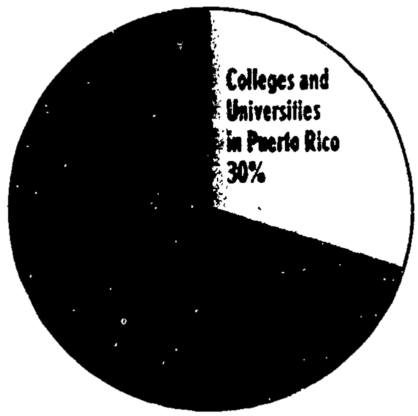
provide these kinds of communities, but Black students who attend such colleges seem to gain access to these majority-dominated communities less reliably and less often. Studies show that Blacks are more likely to persist at HBCUs due to a greater degree of involvement in campus life and a greater growth 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

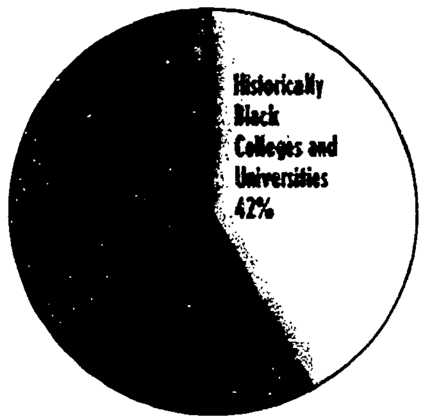
Mathematics Bachelor's Degrees.
321 Hispanic Graduates: 159 Institutions.



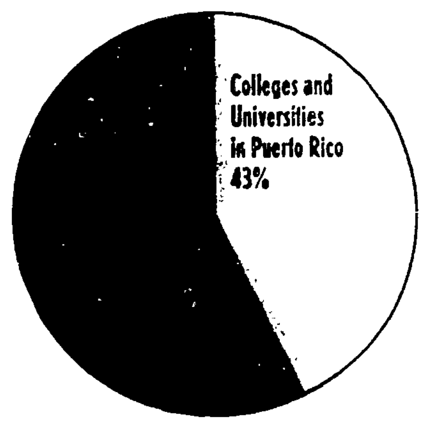
Mathematics Bachelor's Degrees.
834 Black Graduates; 289 Institutions.



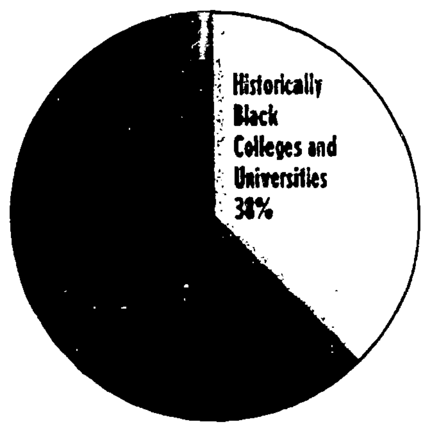
Physical Science Bachelor's Degrees.
585 Hispanic Graduates: 212 Institutions.



Physical Science Bachelor's Degrees.
823 Black Graduates; 309 Institutions.



Biological Science Bachelor's Degrees.
2146 Hispanic Graduates: 339 Institutions.



Biological Science Bachelor's Degrees.
1890 Black Graduates: 486 Institutions.

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.

— *"Education that Works: An Action Plan for the Education of Minorities QEM," 1990.*

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 for 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 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.

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

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

Juniata College

Every morning Tom Spicher climbs into the cab of the Juniata College ChemVan and takes off to visit one or more high schools in the six central Pennsylvania counties surrounding the college. Spicher, a certified chemistry teacher, will deliver and help demonstrate sophisticated equipment not otherwise available in the small, mostly rural schools.

The ChemVan is part of an effort at Juniata College to support high school science teachers in their teaching of chemistry. The effort got under way in 1985, with the formation of the Central Pennsylvania Association of Chemistry Teachers (CPACT), a cooperative partnership between college and high school teachers. The Juniata program includes summer workshops and research opportunities, seminars during the school year, and frequent faculty visits to high school classrooms. The ChemVan hit the road in 1988.

"The whole project started with the objective of trying to provide a complete support system for high school teachers" in chemistry, says project director and chemistry professor Donald Mitchell. "The things we do in Central Pennsylvania were chosen by the teachers, and they're done because these were things the teachers wanted."

The Juniata program treats high school teachers as colleagues, not clients. It encourages chemistry teachers to see themselves as chemists. That's critical for the underlying objective of the program: to get students fired up about science. "The excitement of science is most convincingly conveyed to students by those who perceive themselves to be scientists," explains Mitchell.

The summer workshops are a key ingredient. Teachers attending the two-week workshops get hands-on experience with modern equipment. They develop experiments that they and others can take back to their high school classrooms. And thanks to the ChemVan, they'll have access to the equipment there as well.

The ChemVan is a 16-foot truck, like what you might rent from U-Haul. But inside it's been equipped with padded shelves to protect its cargo, which includes a variety of spectrophotometers, gas chromatographs, analytical balances, pH meters, and other provisions of modern chemistry. The truck visits each school at least six times a year.

The program has grown dramatically. It now includes 27 schools and more than 50 chemistry teachers in the local, Central Pennsylvania area. Mitchell estimates that over 2000 students each year are affected by the program. The growth is especially notable in the summer workshops. "We started with one two-week workshop the first year," Mitchell says. It had 10 people — in fact we had to scrape to get 10 who were brave enough to come. Now we have two two-week workshops and we have 20 in each workshop — and we have a waiting list."

The program is also set to expand into the Pittsburg area, and Mitchell has an eye on Harrisburg as well. "This kind of project can have an effect anywhere," he claims. Pittsburg was chosen in part because it's an urban setting. As for Harrisburg, Pennsylvania's state capital, Mitchell has a further reason: "We sort of want to do it under the nose of the department of education."

In the matter of physics, the first lessons should contain nothing but what is experimental and interesting to see. A pretty experiment is in itself more valuable than 20 formulae.

— *Albert Einstein.*

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

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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.

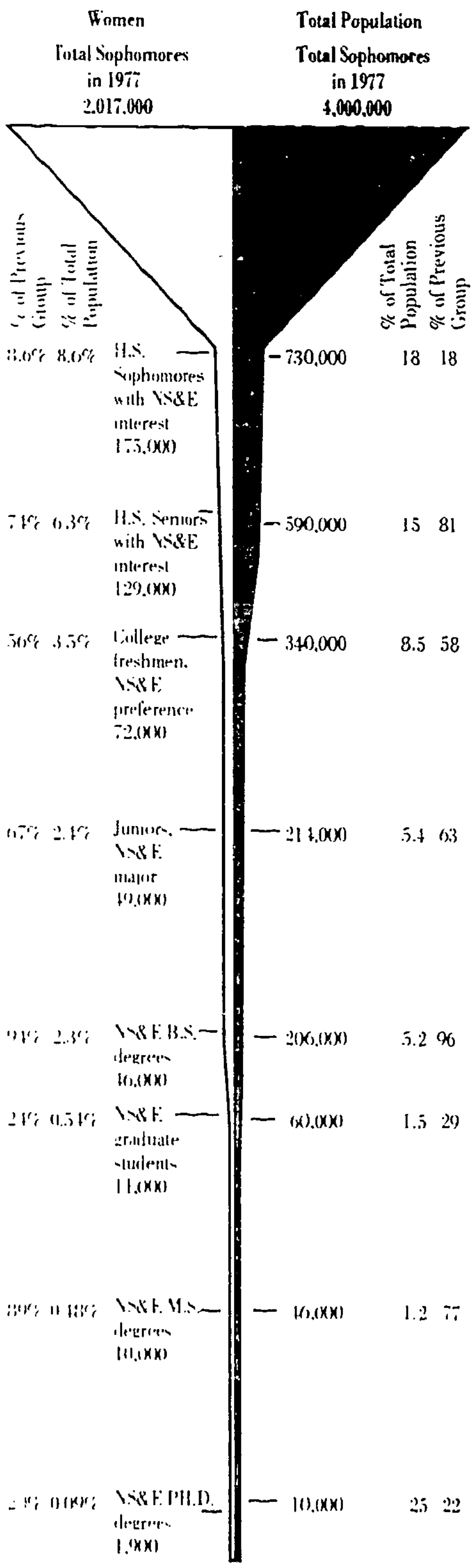
Broad-based science communities can be fostered through creative partnerships between pre-college teachers and college faculty members who together design a curriculum that introduces high school students to real college science (which may well receive college credit) and introduces college students 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

Interest and Participation in Natural Science & Engineering



Canisius College

The 1983 report "A Nation At Risk" not only got Ed Kisailus thinking — it got him doing something.

Kisailus, a biology professor at Canisius College in Buffalo, New York, started small: a discussion group with three colleagues from the biology department at Canisius and five high school science teachers. Over the last eight years that group has evolved into a full-fledged summer and Saturday program, with seminars, workshops and laboratories involving several hundred teachers from Western New York and other regions.

Dubbed BIG/PIE, for Biology Interaction Group/Partnership in Education, the Canisius undertaking aims at improving the in-service training of teachers, mainly by giving them hands-on experience in the laboratory. The program runs a series of two-week workshops each summer in subjects such as cell biology, comparative anatomy and physiology, and biochemistry methods. During the school year, several one-day workshops on "What's Working in Science Education" explore a variety of topics of interest to teachers. Typical topics are writing across the science curriculum and on-site visits to local industries. Kisailus is especially pleased with a recent workshop on special education which drew 28 teachers — 24 of them new to BIG/PIE.

The emphasis at BIG/PIE has been working with teachers, and not just telling them what they should be doing. "We design things around the needs of the teachers," Kisailus explains of both the program's variety and its success. Father Edmund Ryan, Executive Vice President for Academic Affairs at Canisius, agrees. The program "was not top-down, but bottom-up," he says. "They listened to the teachers."

But BIG/PIE is only a piece of the pie at Canisius. In 1985, the seminar program spun off a separate program named SEEK, for Science Education Eighth to Kindergarten. (Kisailus has a penchant for acronyms: when the Canisius chemistry department began a collaboration with pre-college teachers and industry, he bequeathed them the name LEAP, for Laboratory Equipment Assistance Program.) From 1987 to 1990, BIG/PIE and SEEK received NSF funding, which permitted them to pay stipends to participants in the workshops. These stipends were important, Kisailus notes: When the funding ran out, participation went down.

Nor is SEEK the end of Canisius's involvement with pre-college education. "Teachers are beginning to bring their students to the college for science experiences that they are not able to provide in their own school districts," Kisailus says. Since December, 1990, Canisius has hosted advanced-placement biology students for full-day, hands-on workshops on molecular biology and biotechnology. More than 200 students from 7 school districts have attended — one district alone sent 100 potential scientists.

Kisailus is also "just now tinkering with the idea" of science summer camps for grades 5-8. He already has a half dozen undergraduates — the BEES (Bettering Elementary Education in Science) — who spend two hours each Friday morning at one of three magnet schools working with children in grades 2-4.

What do his colleagues think of his work with pre-college teachers and students? "I used to have a lot of scoffers," Kisailus says. "Some of those people are now running their own programs." As for those who have no interest in pre-collegiate education, Kisailus has this advice: "Go ahead and do your own thing — just don't get in my way."

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 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.

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

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 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.

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

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

Beloit College

"We're trying to solve the problem of getting good tools out to students," says biologist John Jungck of Beloit College in Beloit, Wisconsin.

Jungck heads Project BioQUEST — Quality Undergraduate Educational Simulations and Tools in Biology — a nationwide effort to produce an introductory biology course based on computer "modules" that simulate biological systems and processes. More than 30 BioQUEST developers at a score of colleges and universities from Massachusetts to California have participated in writing, testing, and evaluating the project's 17 modules to date. The project has recently negotiated a commercial contract with Addison-Wesley publishers.

The BioQUEST modules allow students at many levels — from grade school to grad school — to explore topics in genetics, physiology, biochemistry, ecology, and evolution. There are also modules devoted to data collection and organization, statistical analysis, and report writing. The modules run on Macintosh computers, taking advantage of HyperCard stacks to unite the software.

Modules 10, 11, and 12, for instance, comprise a unit on the biochemistry of enzymes. In the first module, students practice purifying an enzyme from a limited quantity of starting material. In the second module, they go on to sequence the amino acid chain, while the third is aimed at exploring kinetic properties of enzymes. There are similar biotechnology modules for cloning and sequencing genes, and a "genetic counseling" module which combines technical science with personal and societal implications of the new technology.

While software has been the main product of the BioQUEST effort, it's not the main issue, Jungck says. "The central goal of the Project BioQUEST is to demonstrate the generality of content-based problem solving as an approach to learning biology. We believe that empowering learners, establishing group learning situations, engaging teachers as collaborators, and employing open-ended problems, are essential ingredients to a transformed education in science," according to *BioQUEST Notes*, a newsletter for participants in the project. Adds Jungck: "We're not replacing laboratories, we're supplementing laboratories."

Jungck preaches the "3 P's of science": problem posing, problem solving, and persuasion. Persuasion, he explains, is the bottom line of writing up results and convincing colleagues that those results are reasonable. Students need to learn from the beginning that it's not enough just to do an experiment, it's also important to write it up clearly. With that in mind, BioQUEST includes a "Persuading Peers" module that introduces students to the philosophy of science.

BioQUEST is not for everyone, Jungck points out. It puts new demands on the instructor, who must stop being the "walking encyclopedia" of facts and take a more collaborative approach to working with students. (It puts demands on the students as well, who must give up the passive role of note taker and fact memorizer for the more pertinent role of problem solver.) For many, however, the approach is "natural and nice and what they've been waiting for," Jungck says. "We had initially hoped to reach about 5% of the biology faculty," he adds. "I think we underestimated it."

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.

FACULTY: BUILDING A COMMUNITY

It is a hard fact, reluctantly confronted, that remodeling a curriculum inescapably implies remodeling a faculty. When the culture itself changed slowly, and when liberal arts education itself was a modest enterprise, evolution could take place almost imperceptibly and almost painlessly. To put the matter with perhaps indecent brutality, professors then became extinct at about the same pace as the courses they taught.

– *The Sloan Foundation "The New Liberal Arts," 1981.*

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.

A vital community of learners can be built and sustained only if there is commitment at all levels within an institution.

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.

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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.

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.

— *"Scholarship Reconsidered," 1990.*

Lawrence University

Can a quarter of a million dollars buy happiness?

Maybe not. But it can buy one heck of a laser laboratory. And that can bring with it student and faculty enthusiasm, increased enrollments, new courses, and abundant opportunities for meaningful undergraduate research.

The physics department at Lawrence University in Appleton, Wisconsin, has proved it's possible. With funding from a number of sources, including the National Science Foundation, the Sloan Foundation, and several corporations, the Lawrence physics department has built a "Laser Palace" that project director John Brandenberger says is "unequaled in any other liberal arts college in the country."

The Lawrence "Laser Palace" (the name was jokingly coined by a dean of the college; it caught on, to the point of being emblazoned in the form of a huge red neon sign) consists of four laboratories stocked with a variety of lasers, optical equipment, and electronic instrumentation. These labs are used by students in course work and for research projects. There are two additional labs reserved strictly for research. They also contribute to the teaching program, in that some of the more advanced students have been involved in research programs at these labs.

The Lawrence laser program has brought with it increased physics enrollments. Part of the increase is due to a recruitment program based on a laser physics workshop for high school students. The college brings in 40 high school seniors from around the country for a weekend of laser physics. A good many of these students — upwards of 25% — wind up as undergraduates at Lawrence.

As a result, the number of physics majors has more than doubled, from 5 or 6 graduates per year in the mid 1980s, when Brandenberger first started planning the Laser Palace, to more than a dozen in 1991, with approximately half of them heading toward graduate school. Several of these students have engaged in ambitious undergraduate projects, Brandenberger says, and one recently co-authored a refereed physics paper with him.

Why lasers? In fact, Brandenberger says, a good program can be built around any of a number of areas in physics. What it mainly takes is a faculty member active in research; in his case, laser physics made the most sense. However, he notes, lasers are a good choice, because they permeate so much of modern science — more than a third of the papers in experimental chemistry and physics these days report on the use of lasers, Brandenberger points out — and because they are based on physical principles that are accessible to college students.

"Laser physics and laser spectroscopy are good areas for undergraduate emphasis and undergraduate research, because undergraduates have more exposure to the underlying physics of this field than to most other subdisciplines in physics," Brandenberger says.

Does it really take a quarter of a million dollars? No, says Brandenberger. The Lawrence laser lab was funded as a pilot program, intended to showcase the possibilities of undergraduate laser physics. A 1989 report on the Lawrence project suggests three levels of laser physics for other interested colleges, from a $16,000 "entry level" package that puts minimal demands on staff and space, to an ambitious $160,000 package. The one absolute requirement: "A faculty member or two who are research active in the area," Brandenberger says.

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.

– *Pew "Policy Perspectives," 1990.*

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*
Project Kaleidoscope National Colloquium, February 4, 1991.

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 Robert Edwards; CUR-1985.

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.

In liberal arts colleges, successful faculty are those who understand that undergraduate students play an important role in the intellectual community of learners.

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.

It is of paramount importance for institutions to recognize the importance of departmental chairs and to cultivate their leadership abilities.

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 ...ical 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 <u>and</u> as scholars as they undertake their work with undergraduate research colleagues.

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 time for working with students as individuals, for building community, and for growing professionally — always taking into account the different needs of faculty at various stages of their careers. New faculty especially face not only the excitement of developing courses, but also the challenge of developing their own scholarly endeavors; established faculty face different types of teaching and scholarly challenges as their careers evolve. A key strategy to create time for faculty is the establishment of lean curricula shorn of excessive devotion to narrow aspects of the discipline.

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FACILITIES: SUPPORTING A COMMUNITY

The facilities gap (for research and research training), and the many factors contributing to it, have been documented in a succession of studies dating from the early 1970s. Consensus now exists in government and industry, as well as academe, that the situation has reached a point where it threatens the strength of the nation's research enterprise and the quality of education of new scientists.

– *Research Roundtable, 1990.*

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.

One principle undergirding this report is that public policy should encourage and support indigenous science and mathematics education. The physical and human resources necessary to support and maintain science and mathematics communities of learners must be made

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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 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.

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 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, underclassmen 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.

Facilities need to support serendipity.

To emend an aphorism of Louis Kahn, we might describe laboratories as buildings that both serve and are served by science. Laboratories are both a means to advance science and the product of modern technology.

— *Progressive Architecture, "Inquiry: Science Laboratories," 1989.*

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 out-dated, 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 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.

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

If we are serious about sustaining our [scientific] vitality, ... we must make a better claim on public and private understanding and on public and private dollars.

– 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 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.

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

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 nation'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.

We cannot meet facilities needs with mirrors. Something must be done to facilitate the necessary acquisition of capital.

Independent colleges, as the 1990 NSF facilities study clearly shows, pay for almost all of their construction and renovation costs though 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 suppo[illegible] 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.

APPENDICES

Project Kaleidoscope National Colloquium Workshop Presenters:

Women and Minorities in Science
Etta Falconer, Director, Science Programs and Policy, Spelman College
Elita Pastra-Landis, Chair, Department of Chemistry, Wheaton College (MA)
Annette Bower, Chair, Biological Sciences Department, Mount St. Mary's College (CA)

Geology: The Development of a Lean, Lively, Investigative Curriculum
Jeffrey W. Niemitz, Associate Professor of Geology, Dickinson College
Barbara J. Tewksbury, Chair, Department of Geology, Hamilton College

Literacy in Science: What do we mean and how do we attain it?
Stephen D. Baker, Professor of Physics, Rice University
Timothy D. Champion, Professor of Chemistry, Johnson C. Smith University
Conrad Stanitski, Vice President for Academic Affairs and Dean of the College, Mount Union College

Chemistry: The Development of a Lean, Lively, Investigative Curriculum
Esther Gribbs, Assistant Professor of Chemistry, Goucher College
Bert Holmes, Professor of Chemistry, Arkansas College
Julia M. Jacobsen, Project Manager, Women in Chemistry Program, The College University Resource Institute, Inc.

Effectiveness in Undergraduate Mathematics
Richard A. Alo, Professor and Chair of Mathematical Sciences, University of Houston Downtown
Kenneth R. Hoffman, Professor of Natural Science, Hampshire College
Armand E. Spencer, Professor of Mathematics, Potsdam College of the State University of New York

Facilities: Critical Components of Undergraduate Science Education
Richard Green, Director of Research Facilities Office, National Science Foundation
Daniel Guthrie, Professor of Biology, The Claremont Colleges
Harold Jones, Professor of Chemistry, The Colorado College
Charles Weiss, Coordinator of Grants and Research and Professor of Psychology, College of the Holy Cross

Partnerships that Improve Science Education
D. Kenneth Baker, President Emeritus, Harvey Mudd College, Consultant Pew Charitable Trusts
Alice Brown, Director, Appalachian College Program, University of Kentucky
John Jungck, Professor of Biology, Beloit College
Ryan LaHurd, Vice President for Academic Affairs, Augsburg College
Surrendra P. Singh, Professor of Biology and Health Sciences, Kansas Newman College

The Research Based Curriculum
J.K. Haynes, Professor of Biology, Morehouse College
Don O'Shea, Professor of Mathematics, Statistics, and Computation, Mount Holyoke College
Rabinda Roy, Professor of Chemistry, Drury College
Rexford Adelberger, Professor of Physics, Guilford College

Multiple Entry Points in Science and Mathematics Curricula
Clarence G. Heininger, Professor of Chemistry. St. John Fisher College
Carl Sheperd, Professor of Chemistry and Physics, Northland Pioneer Community College

The Role of Colleges and Universities in Addressing the Needs of Pre-Service and In-Service K-12 Teachers
Audrey Champagne, Professor of Education, State University of New York-Albany
Edward C. Kisailus, Associate Professor of Biology. Coordinator. Biology Interaction Group – Partnership in Education. Canisius College
Diane Ebert-May. Director, Science and Mathematics Learning Center. Northern Arizona University
Katherine K. Merseth, Director, Comprehensive Teacher Education Institute, University of California at Riverside

Innovation in Undergraduate Mathematics
Harriet Pollatsek, Professor of Mathematics. Mount Holyoke College
Wayne Roberts, Chair, Department of Mathematics and Computer Science. Macalester College
Diane Driscoll Schwartz, Associate Professor of Mathematics, Ithaca College

The Funding of Undergraduate Science and Mathematics Education
Robert Lichter, Executive Director, The Camille and Henry Dreyfus Foundation
Harold Gene Moss, Program Officer, The Kresge Foundation
Robert Watson, Director, Undergraduate Science and Mathematics Education Division, EHR Directorate, National Science Foundation
Eugene Steele, Manager, 3M Education Contributions, The 3M Foundation

Faculty: Key Components to Success
John R. Brandenberger, Professor and Chair of Physics. Lawrence University
Dorothy M. Feigl, Vice President and Dean of Faculty, Saint Mary's College (IN)
Michael Zimmerman, Associate Dean and Professor of Biology, Oberlin College

Biology: The Development of a Lean, Lively, Investigative Curriculum
Alan B. Hale, Assistant Professor of Biology, Cedar Crest College
Grayson S. Davis, Associate Professor of Biology, Valparaiso University
Barbara Y. Stewart, Associate Professor of Biology, Swarthmore College

Physics: The Development of a Lean, Lively, Investigative Curriculum
Charles Holbrow. Professor of Physics, Colgate University
Thomas Moore, Assistant Professor of Physics, Pomona College
Lyle Roelofs, Associate Professor of Physics, Haverford College
David Sokoloff, Associate Professor of Physics, University of Oregon

College-School Interactions to Improve K-12 Education
Richard E. Stephens, Director, University/School Partnerships, Department of Energy
Gerald R. Franzen, Associate Professor of Chemistry, Thomas More College
Donald J. Mitchell, Professor of Chemistry, Juniata College
Antoine M. Garibaldi. Dean of Arts and Sciences. Xavier University of Louisiana

Arm-Chair Tour of Science Facilities
Martin J. Harms, AIA, Senior Associate. MPB Architects
Christopher Fitting. Associate, Hayes Large Architects
J. Richard Fruth, Principal, Hayes Large Architects
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Project Kaleidoscope Volume II: "Resources for Strengthening Undergraduate Science and Mathematics" will be available in the fall of 1991. This volume will contain background materials to assist in the planning, implementing, and evaluating reforms in undergraduate science and mathematics. It will include:

Part A: Research and Comparative Data on bachelor's and Ph.D. productivity in the sciences and mathematics.

Part B. Bibliography.

Part C. Facilities for Undergraduate Science and Mathematics.

A. Research.

The research report describes the trends over the last decade for baccalaureates earned in mathematics, and the biological and physical sciences. The data are analyzed by field, by gender, by race, by sector and by institution. The analyses included data for all four-year institutions. The baccalaureate sources of recent Ph.D.'s earned in these fields are described for all graduates, and for doctorates earned by women.

The national data summarized over all institutions describe the serious national problem in the declining numbers of students receiving degrees and entering careers in scientific and technical fields, and the continued under-representation of minorities, women and the handicapped. However, the national data reveal that the overall decline in science and engineering degrees is not equal for all fields, for all population groups, or for all institutions. There are institutions that continue to attract and retain students in these fields, including certain colleges that have high rates of participation by women and minorities.

There are various statistics that can be used to measure the degree to which a particular group is represented in science. Typically what is used is the proportion of the degrees in a field that are earned by a particular group. This statistic is meaningful, but may obscure important information. In the biological sciences, women earned a third of the baccalaureate degrees in 1976, and one half in 1989. However, this higher proportion results entirely from the dramatic decline in the number of degrees earned in this field by men. The number of degrees earned by women has remained about the same through this period.

There are important differences in the trends over fields. The total number of science and engineering baccalaureate degrees has declined. However, mathematics and physics have experienced increases in recent years, in contrast to declines in chemistry, geology and the biological sciences. The rates of participation by women and minorities are much higher in some fields than in others. For example, Hispanics earned 2% of the mathematics degrees in 1986-87 but 5.5% of the biological science baccalaureates.

The liberal arts colleges continue to have the highest proportion of their graduates earning baccalaureate degrees in the natural sciences, and have the highest rate for graduates who go on to earn doctorates in these fields. Several of these colleges are among the most productive institutions in the absolute number of natural science baccalaureates and doctorates, as well as in the proportion of their graduates who earn baccalaureates and doctorates in these fields.

The number of institutions awarding baccalaureate degrees in mathematics and natural science to Hispanics or to Blacks continues to be very small. A large proportion of the degrees earned by Hispanic graduates and by Black graduates are conferred by the colleges and universities in Puerto Rico and the Historically Black Colleges and Universities, respectively. The HBCU's have demonstrated that institutions can take students with inadequate academic preparation and turn them into fully trained mathematics and science graduates.

B. Bibliography.

The bibliography will have two major sections. In the first, we will describe those works that are likely to have the most impact on undergraduate mathematics and science during the next decade. Since 1983, there have been over 300 policy studies of education, with a great number of these focusing on the practice and substance of mathematics and science education. A brief overview will be presented of some of the most salient of these.

A "recommended reading list" will be given, suggesting those works most likely to have a significant impact on reform efforts in undergraduate science and mathematics. In particular, references that examine the concept of "community of learners" will be described.

In the second section, we will present a bibliography organized in the following categories:

1. Women in Science
2. Minorities in Science
3. K-12 Connections
4. Curriculum
5. Faculty
6. Research
7. Exemplary Projects
8. Institutional Change

This section will include an overview of the references we have collected, a description of the methods used to assemble the bibliography, and suggestions about how the bibliography can be used.

C: Facilities for Undergraduate Science and Mathematics.

This part will expand on the material presented in the facilities chapter in Volume I and in the related workshops at the National Colloquium. It will include an outline of options for long-term planning for facilities, and a series of case studies giving examples of newly-constructed and renovated facilities for teaching and learning in the sciences and mathematics at the undergraduate level.

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