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New Approaches to Science and Mathematics Teaching at Liberal Arts Colleges

. . . the power of instruction is seldom of much efficacy, except in those happy dispositions where it is almost superfluous.

—Edward Gibbon, 1737–1794[1]

INTRODUCTION

RECENTLY, HIGH-SCHOOL STUDENTS were polled about which regional institution was most likely to have an award-winning introductory science program. The majority selected the state research university with a nationally ranked football team rather than the liberal arts college that created the program. People unfamiliar with four-year liberal arts colleges believe that one studies philosophy and classics at these institutions rather than science or mathematics.

Although liberal arts college faculty are justifiably proud of their role in nurturing prominent research scientists, only a small percentage of undergraduates actually major in science. Even in outstanding science programs, 70 percent or more of students enrolled in science and mathematics courses are nonmajors seeking to satisfy general studies requirements.[2] Participants at a recent Pew Higher Education Roundtable characterized traditional courses as primarily serving the needs of potential science majors. They felt that this approach ne-

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glects the needs of the majority of students for whom a basic knowledge of science is a primary tool for citizenship, future employment, personal enlightenment, precollege teaching, and parenthood.[3]

My own experience shows that basic science knowledge can have unforeseen value to nonscience majors. Take the case of the Dickinson College classics major who took a few computer science courses and put off the dreaded lab science requirement until her senior year. As a computer system manager for a midsized company, she found herself removing ceiling tiles and checking continuity in cables with an ohmmeter—a task for which she was prepared by her hands-on physics course sequence. She is now a global Internet consultant for Arthur Anderson. And about twenty years ago, two nonscience majors' career plans were altered by a project-based land-use course that a geology colleague and I taught. One is now a public interest lobbyist, the other specializes in environmental law.

In this essay, I augment Thomas Cech's account by highlighting the leadership role in science-education reform played by liberal arts colleges. This reform movement, which rests upon a set of fundamental principles, has been made possible by new federal funding strategies. Traditional liberal arts science and mathematics programs have unique strengths and weaknesses that can be judged in the context of fundamental reform principles. A new field of discipline-specific, science-education research has moved beyond general reform principles and has greatly enhanced the effectiveness of science curricula. Liberal arts colleges have taken a leading role in developing, implementing, promoting, and facilitating the use of reform-based curricula.

TRENDS IN SCIENCE-EDUCATION REFORM

Since 1983, over five hundred reports have been published dealing with the problems of science and mathematics education. These reports are so similar that one can easily extract a set of principles that define current trends. The principles of reform call for all students to have the opportunity to: learn science and mathematics actively by doing them in collaboration with peers and instructors; engage in extended research projects with faculty mentors; explore fewer topics in more depth; achieve scientific literacy by being able to ask and answer questions such as "How do we know . . . ?" and "What is the evidence for . . . ?";[4] relate scientific and mathematical understandings to contemporary social issues; and develop written and oral communication skills.

The reform community agrees with the view expressed by Edward Gibbon in the epigraph, that "instruction is seldom of much efficacy." Reformers believe that instruction should be replaced by active learning opportunities. They feel that a conceptual understanding of science and the processes of experimentation and theory-building are more important than a broader knowledge of accepted facts and theories. Since fewer topics can be covered, reformers believe that the topics selected should provide a foundation for self-actuated learning and be relevant to social issues and the workplace. These educators feel that collaborative work and the development of oral and written communication skills not only enhance learning but are also important ends in themselves. Their major goal is to help students "learn how to learn."

Multiple factors have shaped these principles, the primary one being the wisdom of experience developed by teachers about "what works" and what knowledge and skills seem most important. However, these principles have been influenced by understanding how students learn vital concepts in science and mathematics, an understanding that has emerged from educational philosophy, cognitive psychology, and discipline specific educational research. Finally, social and political agendas that exist in federal funding agencies and programs such as the National Science Foundation and the U.S. Department of Education's Fund for the Improvement of Postsecondary Education have contributed to the formulation of these principles.

Intellectual Precedents of Reform Trends

Precursors of many of the current ideas in science-education reform are found in the writings of several educators. Philosophers Alfred North Whitehead and John Dewey promoted education that guides the self-development of students through experiential learning.[5] Social psychologist Kurt Lewin believed that learning was best facilitated in a collaborative environment where active dialogue by members of a group is used to resolve tensions between immediate, concrete experiences and previously held conceptions.[6] Cognitive psychologist Jean Piaget focused on identifying stages of intellectual development in children and the role of experience in promoting intellectual growth.[7]

Since 1960, a number of cognitive psychologists have extended earlier work on the abstract reasoning abilities of children to college-age adults and beyond.[8] These extensions have been pivotal in helping educators identify common learning difficulties of undergraduate students in mathematics and science, and have contributed to the articulation of reform principles.

Arnold Arons has had a profound influence on trends in science and mathematics education. He taught physics at Amherst College from 1952 to 1968 as part of a required interdisciplinary studies program that he helped to develop. He had a deep understanding of the history of science and was a keen observer of the intellectual development of several generations of Amherst physics students. He wrote about the learning difficulties shared by a large percentage of introductory physics students in light of new research in cognitive development, and has been a relentless advocate of helping students achieve scientific literacy. Arons's notion of scientific literacy has much more to do with students understanding the basis of knowledge than with knowing facts. He spoke of the importance of allowing students to grapple with important concepts over and over again in new guises rather than being forced to study too many topics. His textbooks, expository books for physics teachers, and journal essays have served as the foundation for educational reform in science and mathematics.[9]

Recent History of Federal Funding for Undergraduate Reform

High quality educational research and research-based curriculum development is expensive. For this reason, federal funding is a major determinant of new trends in undergraduate science and mathematics teaching. There were no notable twentieth-century science-education reforms of any kind until the Soviet Union's 1957 *Sputnik* launch. The notion that the United States was behind in the space race inspired dozens of federally funded projects to develop instructional materials. Although many of the post-*Sputnik* curricular materials were inquiry oriented and involved students as active learners, most were designed for precollege students. Thus, these new programs did not directly influence undergraduate programs or have much lasting effect on teaching practices in primary or secondary education. Oft cited reasons include the lack of teacher training, the lack of detailed knowledge on how students at various grade levels learn specific topics, and a complacency that set in by 1969 when the United States landed astronauts on the moon.

During the early post-*Sputnik* era, undergraduate science programs at both liberal arts colleges and universities were growing rapidly without serious consideration of changes in the curriculum or teaching practices. College and university instructors based course offerings and teaching methods on those they had encountered in the research university programs where they served as graduate teaching assistants. The small amount of federal funding that existed in those years ended in 1981 when the Reagan administration greatly reduced funding for education.

The current wave of science and mathematics reform at the undergraduate level began in 1987, when the National Science Board's "Neal Report" on undergraduate science, mathematics, and engineering education was released.[10] The major goal of the report was to help the National Science Foundation make the programmatic changes needed to achieve excellence in science, mathematics, and engineering education. A social agenda was presented that envisioned implementing and expanding programs that would benefit "students in all types of institutions," improving "public understanding of science and technology," and mounting efforts to "increase the participation of women, minorities, and the physically handicapped in professional science, mathematics, and engineering." In addition, for the first time there was recognition that cognitive issues might be important. The Neal Report cited the need to stimulate creative activities in teaching and learning and to perform "research on them," analogous to basic disciplinary research.

Since World War II most federal funding for undergraduate science and mathematics education has come from the National Science Foundation (NSF). In 1986, the NSF expended almost $36 million to provide undergraduate departments with instructional equipment and to promote undergraduate research. By 1989 the Neal Report had helped stimulate the NSF to add several new programs, including one for course and curriculum development and another for the professional development of faculty. Since 1986 the NSF's annual budget for the support of undergraduate education programs increased fivefold. Thus, in the past twelve years, a number of major undergraduate reform initiatives in the basic sciences, mathematics, and engineering have been funded.

Back in 1986 the NSF seemed most interested in using funding to increase the number of college students majoring in science. Officials used a leaky pipeline analogy to describe the drastic decline of students interested in studying science and mathematics at each level of education. For example, at present fewer than half the students who enter college intending to major in science, mathematics, or engineering actually do. To add insult to injury, statistics show that the percentage of freshmen interested in majoring in the sciences declined from 12 percent in 1966 to 6 percent in 1988.[11] Significantly, the NSF's focus has shifted in the past twelve years from the leaky pipeline to the idea of improving the quality of education in science and mathematics for all students, especially women and minorities—not just for students majoring in science and mathematics. The fact that the pipeline is leaky is no longer deemed the principal challenge. The overall number of scientists and mathematicians now seems adequate, although there are shifts in student interest occurring among the disciplines. The medical sciences, electrical engineering, and computer science are currently in vogue. Thus, the number of physics majors is decreasing at the same time that undergraduate chemistry and biology departments are scrambling to develop new major programs in biochemistry.

The new focus of federal programs involves developing scientifically literate citizens, reducing science and mathematics phobias among students, and increasing the chances for success of all students who choose to take college-level courses in science and mathematics. It can be argued that this new science-for-all focus may benefit science majors more than would developing rigorous programs for committed science majors. In 1997, Elaine Seymour and Nancy Hewitt published an ethnographic study of 335 students majoring in science, mathematics, and engineering at seven undergraduate institutions.[12] The goal of the study was to determine why over half of these students do not complete their intended majors. The authors conclude that it is extremely important ". . . to improve the quality of the learning experience for all students—including those non-science majors who wish to study science and mathematics as part of their overall education."[13]

TRADITIONAL SCIENCE EDUCATION AT LIBERAL ARTS COLLEGES

Educators at liberal arts colleges frequently cite the many advantages they enjoy over large institutions: smaller classes; an emphasis on teaching, rather than research, that frees faculty for class preparation and attention to individual students; laboratory sessions led by faculty rather than graduate students; undergraduate research opportunities; and interdisciplinary courses relating science to social issues.

How does the quality of learning experiences in science and mathematics at liberal arts colleges stack up against those at larger universities? Do liberal arts colleges realize the full potential from their advantages? Would the application of reform principles enhance learning in the liberal arts setting?

Strengths

Liberal arts colleges have been national leaders in promoting undergraduate research. Extended senior research is often used as a capstone for highly motivated science majors; this experience has inspired many students to pursue graduate studies. Liberal arts colleges, especially the most selective, take great pride in the many students sent on to graduate school. Compared to other institutions, a larger proportion of liberal arts college graduates earn Ph.D.'s in science and mathematics.[14]

Faculty at liberal arts colleges often work closely with colleagues in other departments. For this reason, many liberal arts colleges have developed interdisciplinary general studies programs that include science and mathematics. One such program, at Drury College, is described below. The focus on interdisciplinary work is strongest at a handful of distinctive experimental institutions such as Hampshire College, the College of the Atlantic, and Evergreen College. The emphases on student research and interdisciplinary course work typical of liberal arts institutions are clearly consonant with the educational reform principles. Both highly motivated science majors and nonscience majors can benefit from these program elements.

Weaknesses

Science and mathematics pedagogy at the majority of liberal arts colleges mirrors that at large research universities. The content and teaching methods used center on the use of standard textbooks. Introductory science students typically attend several large-group lectures and one laboratory session each week. Upper-level courses, while smaller in size, still rely heavily on the lecture format. In mathematics, students attend small-group lectures each week. It is difficult to incorporate reform principles into traditional lecture and laboratory courses. Formal lectures do not provide opportunities for active learning, collaboration, investigation, or research. Lecturers often cover more topics than students can assimilate. Textbook expositions are boring and incomprehensible. Laboratory activities, rarely based upon outcomes of educational research, involve complicated procedures in which students "can't see the forest through the trees."

The disadvantages of traditional pedagogy more than offset the advantages of small class size when it comes to reaching nonscience majors. How often does the typical liberal arts college nonscience major talk about getting his science requirement "out of the way?" Liberal arts colleges also fail to retain their less-motivated science majors for the same reasons large universities do. Seymour and Hewitt identified reasons why approximately 50 percent of potential majors eventually leave the sciences. The students interviewed cited loss of interest, poor teaching, conceptual difficulties, and the overwhelming pace and load of required courses as primary reasons for switching majors. Seymour and Hewitt found that

> . . . in the small private liberal arts college where we expected to find conditions more conducive to good educational experiences in science and mathematics, the main concerns of switchers and non-switchers differed little from those of students at other institutions. Although some aspects of the teaching emphasis traditional in liberal arts colleges were discernable, they were more in evidence in the non-sciences than in the sciences.[15]

It appears that the liberal arts colleges are not succeeding at reaching nonscience majors or at retaining potential majors. Assessments of curricula based upon reform principles in a number of disciplines show enhanced student learning and improved attitudes towards science. Given the correlation between the application of reform principles and the quality of student learning, it is disturbing that many liberal arts colleges fail to embrace the principles of reform. This is particularly ironic since the liberal arts college environment is ideal for experimenting with and implementing new curricula and programs.

Curriculum developers at liberal arts colleges and elsewhere have incorporated the principles of reform into their work. Those who have been most successful in enhancing student learning have also taken advantage of developments in a new discipline-specific field of scholarship known as science education research. In the following sections, I will describe the emergence of physics and mathematics education research and exemplary reform efforts mounted by college faculty.

SCIENCE AND MATHEMATICS EDUCATION RESEARCH

Some of the most effective new curricula, especially in physics and mathematics, are based on a new style of discipline-specific educational research. It is helpful to understand the origin of this type of research and how it is used as a basis for effective curriculum development.

In 1968, Arnold Arons, whose work contributed to many of the principles of science-education reform, moved to the University of Washington to develop a course in the physics department for prospective elementary school teachers.[16] Lillian C. McDermott collaborated with Arons on this project, extending it to the development of a course for prospective middle- and high-school teachers.[17] This collaboration led to the formation of the Physics Education Group at the University of Washington. As part of McDermott's early work on teacher preparation courses, she began to investigate student thinking about certain physical phenomena in order to identify conceptual difficulties that interfere with learning. For example, most physics students believe that a ball tossed in the air hovers at the top of its path before descending, so that its velocity, acceleration, and net force are all zero. Mature physicists understand that the ball's position is changing continuously under the influence of a constant downward gravitational force exerted by the Earth. It never hovers; its net force and acceleration are never zero. Students who believe that the ball hovers have a difficult time understanding Newton's second law of motion and using it to explain common, everyday motions.

To identify student conceptual difficulties like that of the "ball toss," McDermott and other physicists often begin with individual student interviews. The results from these interviews are used to guide the design of written questions that are administered to large numbers of students. The information obtained from the interviews and written questions can then be used to develop curricular materials that enhance student understanding of various topics. The effectiveness of these instructional materials is assessed by comparing student performance on conceptual questions before and after the use of the curriculum.

McDermott's systematic research on learning difficulties was the genesis of a new field of scholarly inquiry for physicists: Physics Education Research. In 1973, McDermott began a new program in which graduate students could earn doctorates in physics for research on the learning and teaching of physics.

Under McDermott's guidance, the Physics Education Group has served as a model for discipline-specific educational research and curriculum development and has produced numerous trailblazing articles.[18] Similar physics education research Ph.D. programs have been set up at the University of Maryland, San Diego State University, Kansas State University, and North Carolina University. Basic research is also taking place at the University of Oregon and Tufts University. Related research, focusing on the differences between how experts and naive students solve physics problems, is being conducted by groups at the University of Massachusetts and Carnegie Mellon University.[19]

Discipline-based educational research is a bit newer in mathematics than it is in physics. Alan Schoenfeld at the University of California is a leading proponent of using the outcomes of cognitive psychology in mathematics education.[20] Ed Dubinsky from Georgia State University, a pioneer in mathematics education research, began his research as an extension of Piaget's work.[21] Dubinsky's work involves exploring the subconcepts students need to acquire in order to understand key mathematics concepts, and then designing activities, often computer-based, that help students acquire these subconcepts.

Commonly held notions that result in student's learning difficulties have been identified in other disciplines. Astronomy students often think that the weather is cold in the winter months because the Earth is farther away from the Sun. Even if they are taught that the Earth is closer to the Sun in the winter in the northern hemisphere, they will revert to thinking the opposite is true soon after the exam is over. Biology students typically believe that plant biomass is made primarily from material gathered up from the soil. Unless these students complete a well-designed activity such as growing plants using hydroponics, they will probably cling to their belief even if told otherwise. Many students who complete chemistry forget how to balance equations because they have not made a connection between the balancing procedures they have memorized and the law of multiple proportions, which states that the relative number of atoms of each type must be the same before and after a reaction. If they are asked to use this law to design a method for deciding how many molecules of each compound are needed for a given reaction, they will be more likely to remember equation balancing. Mathematics students have difficulty understanding the functional relationships between the linear dimension of an object and its area. In the absence of direct experience paying for and eating pizzas of various sizes, they cannot answer questions such as: "If the diameter of a pizza is doubled and its price tripled, should you buy the big pizza or three small ones?"

Discipline-based science-education research is an extraordinary tool for curriculum development; it is commonly used in new physics curriculum development and to a lesser extent in mathematics curricula. The Physics Education Group at the University of Washington has created an extensive body of research-based supplementary curricular materials for science and engineering students enrolled in introductory physics courses.[22] It has also developed a laboratory-based curriculum for the preparation of prospective and practicing teachers to teach physics and physical science as a process of inquiry.[23] Widely disseminated physics and mathematics curricula—based, in part, on physics education research—have also been developed at a number of institutions. Workshop Physics and Workshop Calculus developed at Dickinson College are of particular interest in the context of this essay and will be discussed in more detail in the next section.[24]

Although many astronomy, biology, chemistry, and geology curriculum developers are guided by the principles of reform, the notion of doing research on specific learning difficulties to refine curricular materials has not yet spread to these disciplines. There is no substantive science education research literature that developers in these disciplines can draw upon.

LIBERAL ARTS COLLEGE EDUCATORS AS LEADERS IN REFORM

Liberal arts college educators are having a profound impact on the course of reform throughout the science and mathematics education community. Educators have helped to create influential national organizations and served as leaders in curricular reform. Institutions such as Drury College and Hope College have implemented comprehensive science programs that embody the educational reform principles.

National Organizations

In 1979 Michael Doyle, a chemist from Trinity University, along with several other liberal arts college professors, founded the Council on Undergraduate Research to develop federal programs that promote summer research for undergraduates and help institutions acquire modern laboratory equipment. The Council also organizes national conferences and publishes a journal that allows students to present the results of their research. The Council has been instrumental in spreading interest in undergraduate research programs to universities and two-year colleges. In twenty years, membership in the Council has grown to more than 3,500 members representing over 850 institutions.

Jeanne Narum founded Project Kaleidoscope (PKAL) in 1989 for the purpose of strengthening science and mathematics education in the nation's liberal arts community. PKAL was initially led by a committee of liberal arts college presidents, deans, and science educators. Over the past nine years it has expanded to serve undergraduate science educators from all kinds of institutions through publications, workshops, seminars, and national conferences. PKAL facilitates faculty and administrators in almost every conceivable manner: designing new facilities, promoting undergraduate research, attracting women and minorities to the study of science, mentoring new faculty, and developing curricula based on reform principles.[25]

Curricular Reform

Liberal arts colleges are ideal environments for the development, classroom testing, and evaluation of curricular materials. The leadership taken by scientists and mathematicians from liberal arts institutions is not accidental. It flows from the confluence of many streams—the intellectual heritage of educational philosophers and cognitive psychologists, the by now widely known guiding principles of science education reform, a new wave of federal funding, the emergence of discipline-based educational research, and the availability of new computer technologies and instrumentation. It is an interesting coincidence that leading curricula in the four major sciences were developed at only two small colleges, Beloit College and Dickinson College. These curricula, examined below in detail, have been widely adopted at institutions of many different types.

The BioQUEST Curriculum Consortium (Beloit College). BioQUEST is a group of educators and researchers committed to providing students with biology research and research-like experiences. This project, deeply rooted in the liberal arts, was founded by John Jungck, editor of *The BioQuest Library*. The Consortium began with an initiative of the Commission on Undergraduate Education in the Biological Sciences, established by liberal arts college biologists in the 1960s. Since its inception in 1986, the Consortium has grown to a community of more than 4,500 educators representing a diverse range of subject areas and educational levels.

The BioQUEST philosophy emphasizes the acquisition of scientific literacy through the collaborative intellectual activities of problem posing, problem solving, and the persuasion of peers (the "three P's" of science education). A major project has been the development of computer simulations that help students understand fundamental biological concepts. For example, students studying genetics can breed fruit flies and observe the inheritance of characteristics such as eye color. They can then augment their laboratory experience with software that simulates the breeding of thousands of virtual fruit flies, leading the student to discover the laws of genetics. In addition, computer tools have been developed that help students transfer data, graphics, hypotheses, and analyses into word-processing, spreadsheet, and graphics software. Students then build scientific manuscripts that can be reviewed by student editorial boards and published in student-run journals.

To build the collection of computer tools, the Consortium established *The BioQUEST Library,* an electronic, peer-reviewed academic journal.[26] The BioQuest software collection received an EDUCOM award for distinguished curriculum innovation in 1992. The Consortium also conducts faculty-development workshops and distributes a free newsletter, *BioQUEST*

Notes, three times a year to interested members of the education community.

The ChemLinks Project (Beloit College). The ChemLinks project was initiated by Brock Spencer of Beloit College and developed with members of the Midstates Science and Mathematics Consortium. After receiving startup grants from the Pew Charitable Trust, the ChemLinks Coalition became one of five NSF-funded systemic initiatives in chemistry education. Chemistry educators at forty institutions collaborate to develop topical modules for introductory and intermediate college chemistry curricula. The majority of these institutions are Midwestern liberal arts colleges, including Beloit, Carleton, College of Wooster, Grinnell, Hope, Kalamazoo, Knox, Lawrence University, Macalester, Rhodes, and St. Olaf. The ChemLinks Coalition has recently collaborated with The Modular Chemistry Consortium centered at the University of California at Berkeley. Between the two projects, over a hundred faculty from more than forty two-year colleges, four-year colleges, and universities have developed and tested modules dealing with chemistry, the environment, technology, and life processes.[27]

ChemLinks modules cover topics relevant to contemporary issues and take three to five weeks to complete. Students are guided to develop the chemistry knowledge needed to deal with these complicated issues. Modules incorporate collaborative activities and inquiry-based laboratory projects that replace traditional lectures, exams, and laboratories. All of these approaches are consistent with the reform principles.

It is unlikely that ChemLinks could have been developed at a large research university. After overseeing the development of ChemLinks at institutions of all sizes, Spencer has become "acutely aware of how difficult it is for a large university with large lecture . . . and lab sections to experiment."[28] He points out that faculty in liberal arts programs can make significant changes without waiting for funding, and cites several examples of rapid, modestly funded projects initiated at liberal arts colleges: Grinnell's recent success in testing ChemLinks modules, Franklin and Marshall College's unfunded Middle Atlantic Discovery Chemistry Project, College of the Holy

Cross's development of Discovery Chemistry, and Merrimack College's microscale organic chemistry laboratory system.

The Workshop Physics Project (Dickinson College). Development of the Workshop Physics curriculum began at Dickinson College in 1986 with a grant from the U.S. Department of Education's Fund for the Improvement of Postsecondary Education (FIPSE). The curriculum was designed to provide activities for a two-semester course in calculus-based physics. In Workshop Physics courses, lectures and traditional laboratory sessions have been abandoned in favor of activity-based sessions that last for two hours and are held three times each week. The structure of these courses is based on a program of guided inquiry embodied in a workbook-style activity guide.[29] A major objective of Workshop Physics courses is helping students understand the basis of knowledge in physics as a subtle interplay between observations, experiments, definitions, mathematical description, and the construction of theories. Whenever appropriate outcomes of Physics Education research were available, they were used to inform the development of activities. Curriculum refinements were based on the results of pre- and posttests on known student learning difficulties.

The Workshop Physics curriculum makes extensive use of computer software and hardware tools for the collection, graphing, analysis, and mathematical modeling of data. These tools have been codeveloped by educators at Dickinson College, Tufts University, and Millersville University. They include a computer-based laboratory system,[30] tools to enhance spreadsheet performance,[31] and video analysis software.[32] Educational research by Ronald Thornton, David Sokoloff, and others has demonstrated that computer-based laboratory tools used with curricular materials based on educational research can help students achieve dramatic learning gains.[33]

Since the fall of 1987 over five hundred Dickinson College students have completed Workshop Physics courses. Research has shown improvements in student attitudes toward the study of physics; mastery of critical concepts; student performance in upper-level physics courses and in solving traditional textbook problems at a level as good as or better than that of students taking traditional lecture courses; and confidence working in a laboratory setting.[34] The Workshop Physics curriculum is now used at approximately fifteen residential liberal arts colleges as well as at thirty-five other institutions including universities, two-year colleges, and high schools. The computer tools that have been developed for use with the curriculum have been distributed to hundreds of institutions. Major portions of the Workshop Physics curriculum have been incorporated into RealTime Physics Modules designed for use in university and college laboratory programs.[35]

The Workshop Mathematics Program (Dickinson College). Nancy Baxter-Hastings, Allan Rossman, and Priscilla Laws began developing Workshop Mathematics courses in 1991 with grants from FIPSE and the Knight Foundation. Additional support has come from the NSF and FIPSE. Workshop Mathematics courses embody the reform principles. The courses are distinguished by their emphasis on active learning, conceptual understanding, real-world applications, use of computer and/or graphing calculator technology, and motivation of underserved populations. Students work in small groups to examine the behavior of mathematical systems in much the same way that science students explore natural phenomena. They are invited to make connections, pose questions, explore, and learn from mistakes. The Workshop Mathematics program was chosen by PKAL as one of ten "programs that work."

Workshop Mathematics contains four entry-level courses: Quantitative Reasoning, Statistics, and Calculus with Review I & II. Activity guides are being developed for all of the courses. The Workshop on Quantitative Reasoning teaches students to interpret and assess quantitative arguments. Topics are presented in the context of practical applications to motivate students, for example, estimating gasoline-tax revenues and interpreting the results of AIDS tests. Workshop Statistics is intended primarily for social-science and prehealth students. Students analyze genuine data, both from available sources and generated by the students themselves, on real-world problems. Workshop Calculus: Guided Explorations with Review is a two-course sequence for students unprepared to enter the regular calculus program. It integrates a review of basic precalculus concepts with the study of fundamental ideas encountered in a traditional first semester calculus course: functions, limits, derivatives, integrals, and an introduction to integration techniques.[36]

With no competing activity-based statistics curricula, more than thirty thousand copies of the Workshop Statistics activity guide have been distributed.[37] Approximately thirty institutions have adopted the Workshop Calculus program. Workshop Calculus and Workshop Physics share the distinction of being the only curricula described here that are explicitly shaped by outcomes of discipline-based educational research. Rigorous assessments of Workshop Calculus students have shown substantial improvements in their attitudes, learning, and retention of concepts.[38]

Other National Curriculum Projects

Several other well-known curriculum development projects are worthy of mention. Larry Marschall at Gettysburg College leads a group that has developed laboratory exercises illustrating modern astronomical techniques using digital data and color images (Project CLEA). Arnold Ostebee and Paul Zorn of St. Olaf College have authored a very successful two-volume set of calculus books entitled *Calculus from Graphical, Numerical, and Symbolic Points of View*. These books make creative use of symbolic algebra systems and graphing calculators to help students learn basic calculus concepts by engaging in innovative graphing activities. Several mathematics educators from liberal arts colleges were members of the consortium that contributed to the extraordinarily popular Project Harvard Calculus effort.[39]

Programmatic Reform in Science and Mathematics

Although many colleges are revitalizing their science and mathematics programs, PKAL and the NSF have identified a number of exceptionally successful institutions. Two, Hope College and Drury College, are especially noteworthy.

Holistic Reform at Hope College. In 1998 Hope College was chosen by the National Science Foundation as one of ten liberal arts colleges to receive a prestigious award for the integration of research and education. Hope's Division of Natural Sciences has developed an innovative curriculum that intertwines student learning and faculty development. Students are given the opportunity for collaborative work, and upper-level students mentor younger students. Approximately 85 percent of Hope's science majors undertake extended undergraduate research projects. For the 70 percent of students not majoring in science, Hope has developed a strong core curriculum of interdisciplinary courses that promote an understanding of science and technology. This is intended to help students excel in a technological culture. Courses in science and mathematics are taught in an experiential, hands-on mode that includes in-course research projects.

As a result of their institutionwide revitalization efforts, Hope College's program in science and mathematics is particularly successful at reaching nonscience and less-motivated science majors. About 30 percent of Hope's science majors enter graduate programs, much higher than the national average for liberal arts colleges. The faculty also benefits; it has an enviable record of producing quality publications in collaboration with students. With seventy-six NSF grants awarded since 1989, Hope science faculty rank third among more than 160 liberal arts colleges in the number of grants received.

Drury College's Integrated Math and Science Program. With a major grant from the NSF in 1995, Drury implemented a new integrated science and mathematics curriculum as part of its general education program.[40] The major goal was for students to achieve science and mathematics literacy, defined as "understanding how science and scientists work." The core program begins with a course entitled Mathematics and Inquiry, which is designed to develop quantitative and abstract reasoning abilities. Next, students take a longer interdisciplinary course, Science and Inquiry, taught by a physicist, chemist, and biologist. A case-study approach, involving real-world problems, is used. These courses prepare students for the culminating Undergraduate Research course, where students engage in a research project and present their results orally, in writing, and at a public poster session.

The program has a strong assessment component that focuses on both student attitudes toward and understanding of science. This assessment has shown a significant enhancement of attitudes toward the study of science, self-esteem, and self-confidence as scientific investigators. The college has recently received a second grant from the NSF to integrate its science and math curriculum with the rest of the general-education program. And there is evidence that Drury has applied its innovative philosophy towards its program for science majors; the physics department has successfully adopted Dickinson's calculus-based Workshop Physics curriculum.[41]

PROBLEMS AND CHALLENGES

Science curricula at many liberal arts colleges are still dominated by traditional textbooks and the lecture method. There is an urgent need for high-quality curricular materials developed according to the reform principles and refined with reference to the outcomes of systematic, discipline-specific educational research. This requires continued funding for both science education research and curriculum development in all disciplines. This blend of development and educational research presents exciting opportunities for collaboration between colleges and universities. At liberal arts colleges, small student-faculty ratios, teaching-oriented philosophies, and modern laboratory equipment provide a fertile environment for the development of new teaching methods and curricula. University graduate programs in the basic sciences, with graduate students specializing in educational research and access to large undergraduate populations, provide an ideal setting for educational research.

Ideally, every liberal arts college in the country would spend the time, effort, and money to develop or adapt exemplary programs for students completing general science requirements as well as for its science majors. Such programs would have innovative interdisciplinary courses linking science to social concerns, state-of-the-art equipment and facilities, and integrated undergraduate research programs. Faculty would take advantage of new principles of teaching and discipline-specific educational research outcomes.

But ideal programs are beyond the reach of mortal faculties. "First tier" liberal arts colleges, such as Oberlin, Carleton, Swarthmore, and Reed, have outstanding records when it comes to recruiting, retaining, and educating future research scientists and mathematicians. "Second tier" liberal arts colleges have collaborated with large universities to take national leadership in curricular revitalization based on reform principles and, where possible, research on student learning difficulties in the sciences. Still other liberal arts colleges have taken local leadership in revitalizing their own institutions. The creative ideas and successes of these institutions provide models to inspire colleagues to revamp their own programs.

Liberal arts colleges share common problems. Good teaching and conducting undergraduate research in student-centered programs is labor intensive. The time to keep abreast of new teaching methods and educational research and the money to maintain computer systems and apparatus are perpetually in short supply. Faculty become isolated from communities that could stimulate them to seek excellence in teaching based on educational principles and research, the supervision of undergraduate research, or participation in interdisciplinary courses. A balanced institution with experts in several disciplines in each of these areas would be able to mount a truly outstanding science and mathematics program.

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ENDNOTES

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[27]John Wiley & Sons is publishing a preliminary edition for use in 1999–2000, and the first commercial edition is scheduled for release in the fall of 2000.

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[30]The microcomputer-based laboratory system tools are available from Vernier Software, 8565 S.W. Beaverton-Hillsdale Highway, Portland, OR 97225-2429; telephone: (503) 297-5317.

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[39]These include Jeff Tecosky-Feldman of Haverford College, Patti Frazer Lock of St. Lawrence University, Eric Connally of Wellesley College, and Carl Swenson of Seattle University.

[40]Supported in part by the National Science Foundation Course and Curriculum Development Program under Grant 95–54960.

[41]Drury chemist Rabindra Roy must surely rank as one of the most productive undergraduate research mentors in history, averaging over four papers and ten conference presentations *per year* for over thirty years. He has copresented talks and coauthored papers with hundreds of his undergraduate students.