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Research and Dedicated Mentors Nourish Science Careers at Undergraduate Institutions

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Recent studies of undergraduate education in the US—such as those undertaken by the Carnegie Foundation for the Advancement of Teaching,[1] by a Faculty Task Force of the University of California,[2] and by the National Institute of Education[3]—describe a similar set of problems besetting the nation's undergraduate colleges and universities. They report, for example, an erosion in the preparedness of entering freshmen, a marked trend by students toward specialized courses that offer a vocational payoff and away from courses contributing to a liberal education, and widespread low-quality instruction by too often uninterested faculty. The Carnegie report found that many undergraduate institutions seem to be more successful in merely credentialing students than in offering them a quality education. It characterized undergarduate education in the US as "troubled,"[1] (p. 2) while the University of California study called its undergraduate program "something of a neglected child."[2] All paint a picture of decline, if not crisis.

In this essay I will focus on undergraduate science education in the US, on what recent reports reveal about its quality and future, and on some undergraduate institutions that are highly successful in producing science graduates. I will discuss the role of research in undergraduate education: student participation in research appears to have a captivating effect on many students who without this experience might well decide against a career in science. I will also discuss the contributions to scientific knowledge made by many faculty at primarily undergraduate institutions. While the emphasis here is on the US, foreign readers should also benefit from the message that large research universities cannot claim a monopoly on excellent scientific instruction or research.

Undergraduate Science Education in the US

In March 1986 the National Science Board (NSB), the policy-making arm of the National Science Foundation (NSF), published *Undergraduate Science, Mathematics and Engineering Education*, a study of the serious problems—"especially problems of quality"—in the US undergraduate science enterprise. The report warned that these problems create a "grave long-term threat to the Nation's scientific and technical capacity, its industrial and economic competitiveness, and the strength of its national defense."[4] (p. 1)

The chief areas of concern were three: poor laboratory instruction, often using antiquated equipment; unimaginative curricula and classroom instruction; and faculty who are not up-to-date on recent advances. These deficiencies, the report noted, have contributed to fewer students electing careers in science, to some specialties not attracting enough students of high quality, and to a decreasing supply of qualified science and engineering faculty.[4] (p. 2)

The report recommended that the NSF spend $100 million per year on undergraduate education in science, mathematics, and engineering by 1990 and leverage its contribution with state and private sector funds.[4] (p. 6) Congress recently acted on this recommendation by authorizing $70 million for undergraduate education in the NSF's 1988 budget in support of instrumentation and laboratory instruction, curriculum development (particularly in calculus and in engineering), faculty enhancement, and student research participation.[5] This is more than double last year's amount and represents a giant step toward the goal set by the NSB.

The renewed effort of the federal government is plainly overdue, as an array of statistics on the decline of undergraduate interest in science indicates. For example, 9.4 percent of all students receiving undergraduate degrees in 1975 chose majors in biology, chemistry, physics, or geology, but the number was only 7.5 percent for 1983 baccalaureates.[6] Whereas basic science lost ground as far as undergraduate interest is concerned, engineering and business attracted more and more students. This trend, as *Science Indicators: The 1985 Report* observed, is "consistent with the widespread perception that undergraduate education has become increasingly vocational."[7] It logically follows that fewer science baccalaureates translates into fewer graduate degrees in science being awarded: between 1975 and 1985 the awarding of science PhDs declined by 11 percent.[8]

Baccalaureate Origins of Science PhDs

Amid aggregate decline, however, there are certain schools that have produced a disproportionate share of science PhDs and certain primarily undergraduate institutions that have sent a disproportionate share of their baccalaureates on to study science in graduate school. Carol H. Fuller, research associate, Great Lakes Colleges Association, Ann Arbor, Michigan, recently undertook a comprehensive study of the undergraduate origins of PhD recipients in the US during the period 1951-1980.[9] Her ranking of baccalaureate schools is adjusted for the differing student populations at each institution and provides a weighted, or proportionate, ranking of the number of graduates who later earn a PhD.

The top 10 producers, proportionately, of baccalaureates who went on to earn a PhD in the mathematical and physical sciences are (here and elsewhere listed in descending rank order) Harvey Mudd College, California Institute of Technology (Caltech), Massachusetts Institute of Technology (MIT), Cooper Union, Webb Institute of Naval Architecture, Reed College, Rice University, Rensselaer Polytechnic Institute, Polytechnic Institute of New York, and Carnegie-Mellon University. The top 10 producers, proportionately, of baccalaureates who later earned a PhD in the life sciences are University of California at San Diego, Philadelphia College of Pharmacy and Science, Reed, Caltech, University of California at Irvine, Delaware Valley College of Science and Agriculture, University of Chicago, Swarthmore College, Harvey Mudd, and Wabash College.[9]

Elsewhere these two groups—physical- and life-sciences PhDs (1950 to 1980)—were analyzed together and the rankings turned out as follows: Caltech, Harvey Mudd, MIT, Reed, University of California at San Diego, University of Chicago, Swarthmore, Haverford College, Carnegie-Mellon, and Wabash.[10] (p. 40)

In a recent article, M. Elizabeth Tidball, professor of physiology, George Washington University Medical Center, Washington, DC, reported her study of the baccalaureate origins of recipients of doctoral degrees in the natural sciences—physical sciences and engineering (PS/E) and life sciences (LS)—1970-1979.[11] Tidball divided the data in various ways but focused on the baccalaureate origins of women PhD graduates in science. Tidball found that among the greatest producers on a per capita basis of PS/E and LS women PhD graduates were a number of women's colleges, including Bryn Mawr, Mount Holyoke, Smith, and Wellesley colleges.

What is remarkable about these and other such lists and what is perhaps surprising to many is the place that select liberal arts colleges hold in the rankings. Harvey Mudd, Reed, Swarthmore, Haverford, Wabash, Bryn Mawr, Mount Holyoke, Smith, Wellesley, and many other colleges are primarily undergraduate institutions, which lack the scientific hardware and financial resources, both public and private, of large research universities. Yet these select liberal arts colleges and others (for example, Oberlin, Carleton, and Pomona colleges) send more than their share of baccalaureates on to graduate study in science.

Role of the Liberal Arts Colleges

A group of 50 liberal arts colleges (listed in Table 1) was intensively studied in 1986 and was found to contribute significantly to the training of US scientists. Approximately 30 percent of the 1985 freshman class at these "science-active" colleges, as they are known, expressed the intent to major in science. This is double the proportion at highly selective public and private universities and six times the national average. The actual production of baccalaureates in science by these colleges matches closely the students' intent: in 1983 these 50 colleges graduated about a quarter of each class with science degrees.[10]

Of added interest is the number of women majoring in science at these select liberal arts colleges: they constitute about 45 percent of the freshman science majors at the science-active colleges. This is twice the proportion at the select research universities.

These findings are reported in *Maintaining America's Scientific Productivity: The Necessity of the Liberal Arts Colleges*[10] (March 1987), which is the latest report of Sam C. Carrier and David Davis-Van Atta, Oberlin College, Ohio. The report updates another published in 1985, *Educating America's Scientists: The Role of the Research Colleges*,[12] which was prepared for the first national conference on the Future of Science at Liberal Arts Colleges, convened at Oberlin in June of that year. *Maintaining America's Scientific Productivity* was prepared for the second national conference,

Table 1: The 50 primarily undergraduate institutions participating in "The Future of Science at Liberal Arts Colleges," a conference convened at Oberlin College, Ohio, on June 9-10, 1986.

Albion College	Kenyon College
Alma College	Lafayette College
Amherst College	Macalester College
Antioch University	Manhattan College
Barnard College	Middlebury College
Bates College	Mount Holyoke College
Beloit College	Oberlin College
Bowdoin College	Occidental College
Bryn Mawr College	Ohio Wesleyan University
Bucknell University	Pomona College
Carleton College	Reed College
Colgate University	Smith College
Colorado College	St. Olaf College
Davidson College	Swarthmore College
Denison University	Trinity College, Connecticut
DePauw University	Union College, New York
Earlham College	Vassar College
Franklin and Marshall College	Wabash College
Grinnell College	Wellesley College
Hamilton College	Wesleyan University
Hampton University	Wheaton College, Illinois
Harvey Mudd College	Whitman College
Haverford College	Williams College
College of the Holy Cross	College of Wooster
Hope College	
Kalamazoo College	

held in June 1986; it adds qualitative data to the earlier study.

These two Oberlin reports have demonstrated that many outstanding liberal arts colleges "rank at or near the top of all American institutes of higher education—including public and private multiversities and private research universities—in turning out scientists."[12] (p. 1) This productivity is attributed to high-quality, one-on-one teaching, which frequently includes undergraduate participation in research. There would seem to be some magic in this method, for while the total number of science baccalaureates declined by 17 percent since the mid-1970s, the number of science baccalaureates produced by these science-active liberal arts colleges remained essentially unchanged and actually increased on a per capita basis. In 1975 US liberal arts colleges contributed to the education of 42 per 1,000 US scientists, while in 1983 the number was 58.3 per 1,000.[8]

Regarding qualitative measures of scientists who graduated from liberal arts colleges, the 1987 Oberlin report lists the following institutions as those whose baccalaureate graduates in science have gained membership in the NAS at the greatest rate: Caltech, Harvard University, University of Chicago, Swarthmore, MIT, Reed, Wesleyan College, Carleton, Hamilton College, Amherst College, Princeton University, Columbia University, Cornell University, Haverford, Yale University, Pomona, Carnegie-Mellon, University of California at Berkeley, and Oberlin. This list was compiled by Rush D. Holt, Department of Physics, Swarthmore College, Pennsylvania.[10] (p. 40-1)

Holt also examined citation data—specifically the list of 1,000 contemporary scientists most-cited between 1965 and 1978 that I published in 1981[13]—to determine which undergraduate institutions accounted for the greatest number of highly cited scientists. The rankings this time were Swarthmore, University of Chicago, Harvard, Caltech, Columbia, Wesleyan, Haverford, Kenyon College, Yale, Carleton, MIT, Princeton, Union College, Oberlin, Cornell, Reed, Amherst, Williams College, and Hamilton.[10] (p. 40-1)

The 1987 Oberlin report also analyzes the baccalaureate origins of NSF graduate-study grantees, 1976-1983. The per capita rankings in this analysis were Caltech, Swarthmore, Harvey Mudd, MIT, Princeton, Harvard, Reed, University of Chicago, Yale, Pomona, Bryn Mawr, Haverford, Carleton, Stanford University, Oberlin, Macalester College, Earlham College, Brown University, and Whitman College.[10] (p. 40)

Thus, using NAS membership, citation data, and receipt of NSF graduate-study grants as rough measures of excellence or quality, it is plain that many liberal arts colleges stand alongside premier research universities in preparing the nation's best scientists. This determination is corroborated by other measures as well: number of baccalaureates who become members of *American Men and Women of Science* or are listed in *Who's Who in Frontier Science and Technology*.[10] (p. 40-1) Thus, both quantitatively and qualitatively, these liberal arts colleges are important producers of scientists in the US.

Selectivity is clearly one important element in the success of the elite liberal arts colleges in producing scientists. I suspect that even more important, however, is the greater likelihood that a close student-teacher relationship will develop in the setting of a small class than in a large lecture hall, such as is typically encountered at large universities. Moreover, close relationships among students, which seem more likely to develop in a small setting, also foster the research spirit.

Undergraduate Participation in Research

The Oberlin studies, as well as many other sources, have pointed with favor to undergraduate participation in research as a powerful way of attracting students to science and giving them a high-quality education that prepares them well for graduate study. The extent to which these 50 schools practice what they preach is impressive; for example, of 7,000 articles published by faculty of the Oberlin group of liberal arts colleges, 30 percent included an undergraduate student as coauthor.[10] (p. 43) At research universities the number is less than 1 percent.

The gospel of undergraduate participation in research has now reached beyond the elite undergraduate colleges. A cover story in a recent issue of the *Chronicle of Higher Education* reports a sharp increase in the number of undergraduates collaborating with their professors on research projects.[14] At the University of Delaware, Newark, two-thirds of the engineering students who participated in research as undergraduates went on to pursue doctoral degrees in the last two years, the article reports. This compares with a 10 percent nationwide average for engineering students. The University of Minnesota has also been emphasizing undergraduate research recently. And a few programs are long-standing, such as MIT's Undergraduate Research Opportunities Program, begun in 1969.

Participation in research or "active learning" attracts a student's interest and has a catalytic effect in enhancing both motivation and skills. Students who as undergraduates participate in research are more likely to pursue graduate studies. With the pool of students expected to shrink substantially in the 1990s,[15] the importance of attracting highly motivated and skilled science graduate students will be even more important than it is now.

As part of its increased funding for science education, Congress allocated $9 million in the NSF budget for fiscal year 1987 for a new and special effort to involve an additional 2,000 undergraduates in research.[16] The figure will be $18 million in fiscal year 1988 for the Research Experience for Undergraduates program, as it is known. And in March 1987, the US Department of Energy (DOE) announced that it will double its program to provide undergraduate science and engineering students (juniors and seniors) the opportunity to do research at one of five DOE laboratories (Argonne, Brookhaven, Lawrence Berkeley, Oak Ridge, and Pacific Northwest).[17]

In a recent editorial in *THE SCIENTIST*™, I emphasized the importance of undergraduate participation in research.[18] That editorial prompted a letter from Colin Eaborn, professor of chemistry, University of Sussex, Brighton, UK. Eaborn described how undergraduates at Sussex (as well as at the University of Essex) can obtain their baccalaureate degrees by research work. He wrote: "For 16 years we at the University of Sussex have offered, as an option, a degree program in chemistry called 'Chemistry by Thesis.' In this program, after six months at the university, students move into a research laboratory alongside postgraduate and postdoctoral research workers, and take up carefully chosen research topics." Research forms the chief activity of the students from then on, he explained, although to acquire sufficiently broad training, students also attend lectures. Furthermore, students are required to achieve a passing grade on a general examination.[19]

The program has been quite successful, Eaborn stated, and has produced "capable graduates with substantial problem-solving experience,...enthusiasm, self-reliance, and creativity, along with the maturity that comes from a close working relationship with postgraduate and postdoctoral students." He suggested that "one of the more enterprising American universities [might] contemplate setting up this type of program for the last two years of a four-year degree course."[19]

Council on Undergraduate Research

Give much of the credit for current US interest in this subject to the efforts of the Council on Undergraduate Research (CUR), a nonprofit organization founded in 1978 by Brian Andreen of the Research Corporation, a private foundation supporting basic research at universities and colleges, and 11 chemistry faculty members at small, chiefly undergraduate institutions. The CUR seeks to encourage research in the undergraduate environment. There are currently 71 faculty participants from chemistry, biology, physics, and geology departments at private and public undergraduate colleges and universities in the US. The CUR has published directories[20-22] of science programs at primarily undergraduate institutions and has organized conferences to increase professional and public awareness of the important role that research plays—both for students and faculty—at these schools. It also publishes the triannual *Council on Undergraduate Research Newsletter*, which covers a wide variety of news items and articles about support for and the effectiveness of research at undergraduate colleges and universities. (Its editor is Michael P. Doyle, who can be reached at the Department of Chemistry, Trinity University, 715 Stadium Drive, San Antonio, Texas 78284.) From 1981 to 1983, when NSF support for undergraduate science education and research involving undergraduates was in abeyance, the

CUR kept alive concerns about undergraduate research and played an important role in reviving support for such activity.

Faculty Research at Primarily Undergraduate Institutions

As mentioned, the CUR works not only to advance student participation in research but also to advance funding for research conducted by the science faculty of undergraduate colleges and universities. Despite limited federal funds for research grants (as well as for instruments and facilities), the absence of graduate students, and in general heavier teaching loads than at research universities, the faculty of this group of science-active colleges produce more publications than many would suspect. Of the 50 institutions in the Oberlin group, 60 percent of their faculty have averaged one article published in each of the past five years.[10] (p. 43)

Last year Jerry P. Gollub, Department of Physics, Haverford College, Pennsylvania, and Neal B. Abraham, Department of Physics, Bryn Mawr College, Pennsylvania, reported that the Research Corporation made 34 awards to principal investigators in physics at undergraduate institutions during 1985-1986. Faculty members at undergraduate institutions, they noted, receive support from the NSF, the Sloan, Guggenheim, and Fulbright foundations, and many other highly competitive sources.[23] A similar study, assessing the ability of chemistry departments at primarily undergraduate institutions to attract support, was recently conducted by Philip Myhre, Department of Chemistry, Harvey Mudd College, Claremont, California. Myhre concludes that "there has been a significant increase in annual funding in the form of individual research and equipment grants to faculty at predominantly undergraduate institutions."[24]

Recently, the NSF's Presidential Young Investigators award program, designed to encourage young scientists and engineers to enter and remain in academia, was opened up to faculty at undergraduate institutions. Previously only faculty members at PhD-granting universities were eligible for these awards. This is yet another sign of the growing recognition that science faculty at undergraduate institutions often conduct high-quality research and deserve support of the same sort given to faculty at the nation's large research institutions.

Although many primarily undergraduate institutions conduct excellent research and produce excellent graduates, their efforts have not been supported by the federal government on a level commensurate with their contributions. Research at undergraduate institutions has historically received low priority in funding by the NSF, the National Institutes of Health, and other federal agencies. Since 1983, however, the funding picture has brightened; from 1983 to 1987 there has been a three-fold increase in federal funding for research at predominantly undergraduate institutions.[25]

The documentation for the effectiveness of these institutions overwhelmingly supports a continuation and increase of federal support. I have been able only to touch upon the evidence. Also compelling are the numerous vignettes published about successful faculty at these smaller institutions—anecdotal but instructive stories that I recommend to the reader.[23,26] Meanwhile, I hope this brief overview serves to bring to the attention of scientists and science policymakers, here and abroad, the important role of the undergraduate institutions in training tomorrow's scientists and in advancing scientific knowledge.

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