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Physics in the colleges

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Undergraduate institutions train a large proportion of the students who eventually earn PhDs in physics; research enhances the education of their students and the professional life of their faculty.

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Institutions that focus primarily on undergraduate education produce a surprisingly large fraction of the bachelor's degrees awarded annually in physics in the United States. More than half of the students majoring in physics in 1984–85 were at the 577 institutions that do not award doctoral degrees,[1] which we will refer to as "colleges." About 40% of US citizens starting graduate study in physics in 1985–86 came from US colleges.[2]

The role of colleges in training professional physicists is strong and may be getting stronger. Recent surveys indicate that some colleges are disproportionately successful in attracting students into physics and encouraging them to continue with graduate study in physics. At 48 research-oriented colleges included[3] in a recent survey, the number of physics majors had increased 49% since the early 1970s—a period in which total undergraduate enrollment in physics declined. Of the 50 institutions having the largest percentages of graduates who go on to earn PhDs in the physical sciences, 20 are colleges.[4] The health and vitality of physics in the colleges is thus a matter of some importance for the future of American physics.

In this article we consider the state of physics education in the colleges. Our perspective is based primarily on experiences at private colleges. We note, however, that with the growth of publicly supported higher education, a number of public colleges have become increasingly important.

We especially emphasize the contributions that vigorous research programs are making to the professional development of faculty and to the education of students. We realize that many physicists are skeptical about the possibility of doing successful research in the college environment. Heavy teaching loads, the absence of graduate students and limited financial support are assumed to preclude significant research programs. We believe that view to be incorrect, and as evidence we describe the substantial research programs that are in place at many colleges. We also consider some of the problems colleges face in encouraging research and some ways in which these difficulties are being addressed.

College curricula

Probably the most significant curricular difference between physics programs at the smaller colleges and those at the larger universities is that college students typically take fewer courses in their major subject. The difficulty of preparing students adequately for graduate study in the small-college environment may help explain why physics achievement test scores of even outstanding college students are sometimes unimpressive. Yet colleges provide undergraduate training for some of the best science students in the country. For example, six colleges (Swarthmore, Oberlin, Carleton, Pomona, Reed and Harvey Mudd) are among the top 50 producers of students winning NSF Graduate Fellowships.[4] Considering how small these institutions are, this is a remarkable achievement.

College students benefit from the breadth of their training. They often are articulate, write well and are conscious of the relationship of physics to other disciplines. In some institutions it is not uncommon for students to develop interdisciplinary strength by undertaking two majors, one of which may be outside the sciences. Many students develop close apprentice relationships with faculty members through research participation. This also occurs at universities, but there it tends to involve a smaller proportion of the students and may require more initiative on their part.

Introductory courses tend to be less differentiated at the colleges. Some universities offer an impressive range of options, each targeted at a particular group of students—premedical, engineering, prospective majors and so on.

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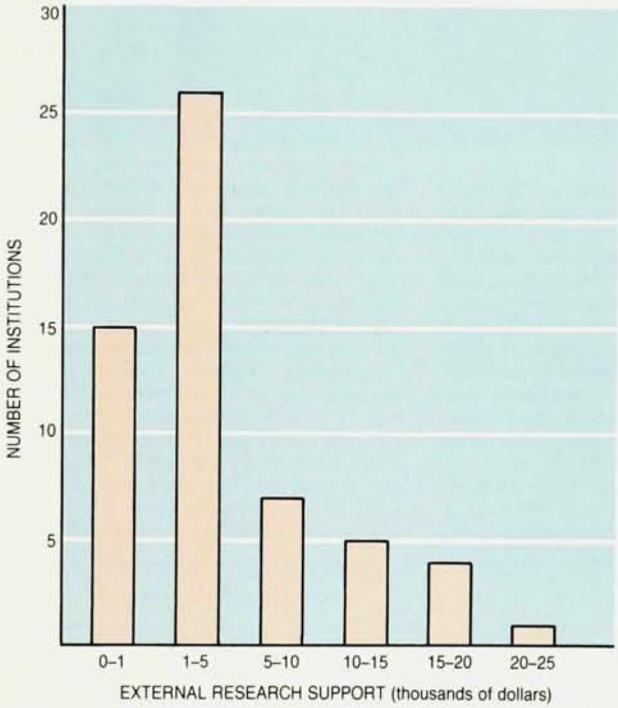
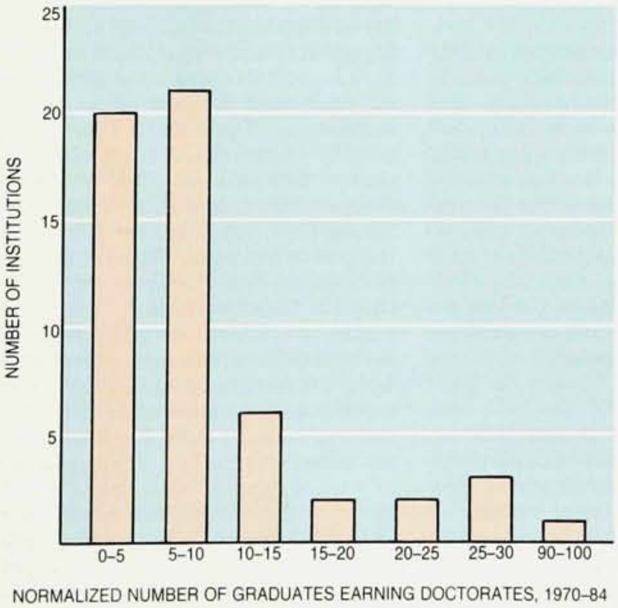
Colleges, with less staff, generally offer fewer options. Their student populations, however, tend to be more homogeneous, so the need for differentiation may be less. Some colleges do not even separate physics majors from other students, choosing to provide a single, calculus-based introductory course for all, including premedical students. The avoidance of early tracking seems to attract some students to the physics major who otherwise would have been unlikely to major in science.

Colleges seem to be somewhat more successful in graduating women and minority physics majors than the universities. Of physics graduates between 1951 and 1980 at the 48 colleges in the Oberlin study, 23% were women,[3] compared with 14% nationally.[5] Two-thirds of black and Hispanic physics majors (66 out of 95) earned their degrees at colleges in 1983–84.[5]

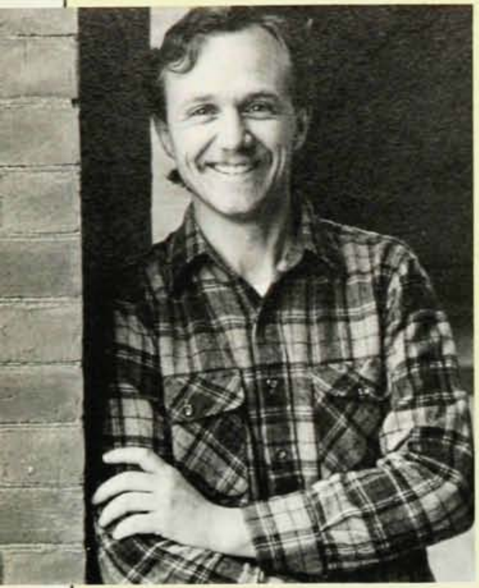
Probably the single greatest challenge that college departments face is providing an adequate diversity of upper-level offerings while reserving sufficient time for meaningful research by faculty and for participation in research by students. This problem can be critical when there are only three to five full-time faculty members. Institutional cooperation sometimes can make a major dent in this problem. Haverford and Bryn Mawr, for example, coordinate upper-level offerings so that burdens are reduced. Courses such as



Research support raised by college faculty members from external sources varies widely. The data plotted here are based on a survey[6] of 58 diverse institutions. At one institution the average faculty member raises \$20 000–\$25 000 per year, while at 26 institutions faculty members raise \$1000–\$5000 per year on average. Figure 1



The productivity of colleges in training future physicists also varies widely.[6] For every 1000 students currently enrolled, 20 institutions produced 0–5 graduates who went on to earn physics PhDs between 1970 and 1984. At the other extreme, one institution—Harvey Mudd—produced more than 90 students (per 1000) who went on to earn physics PhDs. Figure 2



Larry R. Hunter is an assistant professor of physics at Amherst College. His thesis work at Berkeley (supervised by Swarthmore College graduate Eugene Commins) and subsequent postdoctoral research at the École Normal Supérieure in Paris were on measurements of parity violation in atomic decays. His research is in atomic physics and fundamental symmetries. Current projects include precision measurements of oscillator strengths and level lifetimes, a search for the electric dipole moment of the electron via studies of cesium, and Stark-interference measurements. His work has been reported recently in *Physical Review*, *Physical Review Letters* and *Optics Communications*. Typically one or two undergraduate students participate in this research during the year or in the summer. Hunter describes their participation as essential to his research and beneficial to them, especially in applying for fellowships, graduate school or jobs. (He notes that research participation had not been easily available to him as an undergraduate at Columbia.)

Hunter's research has been supported by grants from the Research Corporation's Cottrell College Science Program, start-up funds from Amherst, the Hewlett Foundation and the NSF Research in Undergraduate Institutions Program. He was recently awarded one of the two annual National Bureau of Standards Precision Measurement Grants.

He has avoided the problem of small-college isolation in various ways. A graduate student from the University of Massachusetts has begun thesis work on the electric dipole-moment experiment under a Five College cooperative arrangement. Hunter collaborated initially with a colleague in atomic physics at Amherst and has received advice and loans of equipment from colleagues at Williams, Yale and Berkeley. He has returned for a summer to Paris and will soon start a sabbatical year under a special Amherst Trustee Fellowship. Amherst has also contributed funds to support a visiting research associate who will collaborate with Hunter.

Hunter noted that the career of a physicist at a college is both challenging and tiring. "It would be dishonest to say it's easy at a small place. The college expects that you will teach well and do research. Both are full-time jobs, but the research is a way of energizing the teaching and this makes it all an exciting opportunity."

advanced mechanics and solid-state physics alternate between the two colleges. Other institutions, such as the Five Colleges in Massachusetts, also have established cooperative arrangements.

The amount of truly creative instructional innovation may not be greater in colleges than it is in universities. But colleges do tend to be more concerned with measuring and promoting teaching effectiveness and student satisfaction. Considerable attention is lavished on individual students, and college faculty members generally keep in touch with at least some of their graduates. Colleges thus tend to attract students who value personal attention and encouragement.

Laboratory programs

A second major challenge faced by colleges is the development and maintenance of first-rate programs of laboratory instruction. Developments in electronic technology and laboratory computers have so changed the nature of scientific computing that older instrumentation must be replaced almost completely. This has created some financial strain for colleges, as it has for universities. Many of the financially sturdier colleges have been able to keep up by making substantial budgetary allocations for equipment, by seeking grants from corporations and foundations, and by using some sophisticated equipment for both research and instruction. The level of Federal support for instructional equipment, currently provided by NSF's College Science Instrumentation Program, is too low to provide for more than a small fraction of the need. As a result many institutions are currently relying on obsolete instrumentation.

Effective laboratory programs obviously require a human investment as well. University laboratory programs sometimes flounder because the investment of time in their improvement is not adequately valued. Colleges generally value faculty commitment to laboratory improvement, but typically no individual has time to devote a major fraction of his or her effort to such work. One reason for this is that colleges have been reluctant to delegate any teaching functions, including laboratory instruction, to non-faculty staff members. Some institutions, however, have recognized that staff support—for example, a BA-level laboratory assistant—can substantially aid faculty members in upgrading laboratory programs.

Many colleges have elegant advanced laboratories offering semi-independent work at a near-research level. Such work allows much room for student creativity and initiative and serves as an effective preparation for senior research. It also takes advantage of the major strength of the colleges—the one-to-one relationship between physicist and student.

Research at colleges

There are many active research programs at colleges. While it is difficult to assess their quality quantitatively, we note that the Research Corporation has made 34 awards to principal investigators in physics at undergraduate institutions in the last two years. (The Research Corporation is a private foundation that gives grants for research in basic science at both colleges and universities.) These awards were all subject to peer review. The grants for 1985 are listed in the right-hand table on page 33.

The National Science Foundation currently supports at least 18 projects in physics departments through its Research in Undergraduate Institutions Program. Awards in the Physics and Materials Research Divisions of NSF are shown in the left-hand table on page 33. These awards are administered by the regular program offices and are subject to normal peer review, but are restricted to non-doctoral institutions.

Many other college research pro-

Robert Warner has had an active career in nuclear physics at Oberlin College since 1965. His undergraduate work at Antioch College included research on glow discharges in rare gases. His graduate studies at the University of Rochester were followed by faculty positions at Rochester, Antioch and Manitoba. His research is concerned with multi-particle breakup reactions between light nuclei, especially cluster structure, velocity distributions and unusual reaction mechanisms. He performs this work during summers and recesses at the Indiana University cyclotron and the Notre Dame tandem Van de Graff accelerator in collaboration with groups from various universities. Undergraduates invariably participate in running the experiments, help analyze the data and coauthor the resulting papers. Most of these students eventually go on to earn PhDs in physics.

Warner has had continuous NSF support for his research at Oberlin since 1985. He suggests that colleges seeking to maintain a research presence need to hire committed individuals, because it is easy to fall into a comfortable pattern that does not include research.

Over the last 12 years Warner has developed and taught a popular course on the physics of music, which is particularly welcome at Oberlin because of its renowned conservatory of music. In the process, he has learned to play many instruments. Warner also has a small consulting practice in forensic physics, with an emphasis on accidents and brawls.

grams are funded by NSF grants in which the nature of the institution is not restricted. The total amount awarded by NSF to colleges in all sciences is about four times the amount funded by NSF's Research in Undergraduate Institutions Program alone.

College research programs cover the full range of physics and astronomy, including experimental high-energy physics, in which researchers mix trips to national laboratories with software or instrumentation development at home. The two tables provide examples of this breadth.

The American Physical Society, with support from the Research Corporation, recently established an Award for Research in Undergraduate Institutions. The research programs of individuals nominated for this award included studies of experimental nuclear physics at Oberlin College, ion–molecule interactions at the University of Missouri at St. Louis, nonlinear dynamics and pattern formation at Haverford College and low-temperature condensed-matter physics at John Carroll University, and a search for quarks at San Francisco State University.

As a measure of the success of colleges in involving undergraduates in first-rate research, we note that the APS Apker Award for undergraduate research has been won by graduates of Amherst and Macalester Colleges; Swarthmore and Reed College seniors have been finalists. Nominees from all types of institutions compete for this award on an equal basis.

College physics faculty members have occasionally won Guggenheim, Sloan and Fulbright Fellowships. Some are regularly invited to deliver papers at international meetings and to write review articles. At least 100 of the physics faculty members at the 48 selected colleges mentioned earlier publish papers regularly.[3] On the other hand, at many colleges resources, time, historical factors or institutional values preclude significant research activity.

Some college research is first-rate and makes a contribution to physics as a whole. It measurably enhances the educational experience of some students, enables faculty members to develop professionally and assists colleges in attracting outstanding faculty members and students. Four college faculty members who have established substantial research programs in physics and astronomy are profiled in the boxes on pages 30–32. There are many others at other colleges whose work is equally impressive.

Benefits from research

In our experience, research participation provides students with a way to achieve a special degree of excellence in science within the liberal arts environment. We know many students who have come to understand the practice of science by experiencing it in small groups or in a one-to-one relationship with a faculty member. The same kind of maturation that occurs during graduate thesis research occurs at the undergraduate level given the right combination of circumstances. Research experience helps students to assess their strengths and decide whether they wish to continue in physics. It also helps institutions to which they apply for graduate study to assess their talents.

Research experience enhances employment opportunities for students who do not wish to undertake graduate study or wish to postpone it. Science graduates are in high demand now, when the general pool of job applicants does not meet the academic or industrial needs of our country. Science graduates with liberal arts backgrounds, who have traditionally been valued for the breadth of their intellectual training, are even more eagerly sought when they have had scientific

Priscilla Benson is a member of the astronomy department at Wellesley College. She graduated in physics from Smith College in 1962 with an honors thesis on thermal conductivity in tin at low temperatures. She undertook graduate work and an academic career after investing some years in raising a family. She received her PhD from MIT in 1983. Her research consists primarily of microwave observations of interstellar dark clouds, especially those with ongoing low-mass star formation, and infrared observations of young stars and protostars.

Undergraduates have participated in this research each academic year and each summer. Current projects include programming a statistical equilibrium model for HC_3N to determine line shapes and strengths for different transitions, and measuring and fitting line spectra of ammonia. She has done experimental work in radioastronomy at various national and international facilities, including Haystack Observatory, the Max Planck Institute for Radioastronomy (West Germany), Kitt Peak Observatory, the Multiple Mirror Telescope and the NASA Infrared Telescope Facility (Hawaii).

Financial support has come from the American Astronomical Society, the Dudley Observatory, the Research Corporation and Wellesley College. She notes that the college provided indirect support in the form of contributions to travel expenses, page charges, secretarial support and free computer time. She admits that she finds it a struggle to do research during the term and finds that she must "zero in on research in January and in the summer." Her position at Wellesley is currently part time; she describes it as satisfactory because it is tenurable and gives her more time for research.

Richard E. Crandall is a member of the physics department at Reed College, an institution where all physics majors write undergraduate theses. He graduated from Reed, obtained a PhD from MIT and was director of environmental technology for a New York corporation before returning to Reed as a faculty member. His research is primarily in the area of quantum theory, especially path integration and nonlinear theory. However, his work is diverse, and he particularly enjoys the opportunities for collaboration with chemists and biologists that occur at a college such as Reed. One collaboration led to an exact solution of a quantum three-body problem. Crandall sponsors both theoretical and experimental student research. A physics senior whose thesis work was supervised by Crandall was one of four finalists for the Apker Award of The American Physical Society in 1983. The research used low-noise instrumentation to determine an improved experimental bound on the photon mass. Crandall has published seven articles with student coauthors.

Crandall is also technology director for Reed's master plan for computing resources. In this capacity he has developed an "iconic" approach to instrumentation that allows many standard laboratory instruments to be simulated inexpensively through a host computer with sophisticated graphics and simple hardware. This has led to innovations in laboratory instruction that are now being used at many other institutions. He comments that it has not been difficult to obtain corporate financial support for his work on computer technology in the laboratory. He emphasizes the importance of the stimulation he has received from having an active and exciting group of colleagues.

research experience. Trained to work and reason independently in the laboratory, some of them have gained several years in practical scientific maturity over their counterparts who lack research experience.

Research opportunities are also an essential part of the package of responsibilities and activities that attract young physicists to college faculties. Many colleges can offer young faculty members an environment in which good teaching is valued, close relationships with students can develop, interactions with colleagues occur across disciplinary boundaries, and scholarly freedom is paramount. Nevertheless many of the best young physicists would not choose this environment if opportunities for serious research were unavailable. Recognizing this, an increasing number of colleges have actively sought to raise the level of research by setting higher standards for hiring, promotion and tenure.

We believe that colleges are justified in seeking this higher level of research activity. Research at colleges, like university-based research, promotes the kind of long-term intellectual growth in faculty members that is critical to their ability to provide an excellent education. Institutional pressure on faculty members to do research recognizes that their vitality and their ability to remain abreast of current knowledge are at stake.

Some problems

We have painted an optimistic picture of the current state of physics education at some colleges and of their ability to sustain active research programs that attract outstanding physicists and students. There is, however, extremely wide variability among colleges. Teaching responsibilities range from two to four courses per semester. For those at the upper end of this range, research is clearly confined to the summer months. Some find it impossible to do sustained research under these circumstances. Clearly, colleges need to strive for consistency between what they expect young faculty to do to earn tenure and the time and resources available to such faculty.

Financial constraints also are quite variable. Internal financial support for research varies from zero to $5000 per faculty member per year. For external support, the median institutional figure is only about $2000 per faculty member per year, but a small number of departments have raised an average of more than $10 000 annually per person over the period 1980–84, as shown in figure 1. The data in this figure come from a set of 58 extremely diverse institutions included in a new directory of research in physics and astronomy at undergraduate institutions published[6] by the Council on Undergraduate Research.

Educational quality is not easily measured, but it is evident that there is wide variability in the success of colleges in training future physicists. For example, a histogram of the productivity of the same 58 institutions[6] in training future PhDs in physics is shown in figure 2. It demonstrates that a small number of institutions are dramatically more productive than most of the others. We note that geographical isolation and small faculties make it especially difficult for certain colleges to sustain the intellectual contacts needed to nurture research.

Even if financial resources are found and research time is available, some physicists find that the involvement of undergraduates in research is not an unmixed blessing. The time spent in training students sometimes outweighs their helpful contributions, partly because their involvement rarely extends beyond one or two years of part-time effort.

Enhancing college research

Any field of physics can be pursued from a position at a college, though some fields may require more innovation and imagination in adapting to constraints than others. Many colleges are currently promoting on-campus experimental work because of the ease with which undergraduates can be involved. Undergraduates also can take part in computational physics at computer centers, applied research in collaboration with industry, astrophysics experiments at national facilities and sometimes theoretical research at national laboratories. Many national labs actively encourage the involvement of students and faculty members from undergraduate institutions.

The traditional method used by colleges and universities to attract new experimenters is the offering of "starter grants." Several colleges have recently offered up to $50 000 to attract new condensed-matter investigators, though much smaller amounts are typical. Clearly even the most affluent colleges cannot compete directly with major universities and industrial laboratories, which sometimes offer much larger amounts. Instead colleges must seek candidates who like the atmosphere and responsibilities of the college environment. They need to do a better job of conveying the message to job seekers that strong research programs are indeed quite feasible at a college, and that modest external funding is not especially difficult to obtain.

Modest research grants can go a long way in the college environment. Machine shops and secretarial and com-

RUI grants to physicists

A new method to search for the electric dipole moment of the electron—Amherst College

Trapping of hydrogen isotopes by lattice defects in metals—Augustana College

Calibration of the Collider Detector Facility—Haverford College

Pattern formation from interfacial instabilities: dendritic solidification—Haverford College

Probing heavy ion reactions with light charged particle emission—Hope College

Optical refractory dispersion in the blue and isotropic phases of cholesteric liquid crystals—Kenyon College

Acquisition of an electroreflectance spectrometer—University of North Carolina at Asheville

Conversion electron Mössbauer study of advanced conducting materials—Northern Illinois University

Studies in classical chromodynamics—Reed College

Preparation and characterization of quasi two-dimensional molybdenum oxide bronzes—Rider College

Experimental studies of excess $1/f$ noise in SQUID systems—San Francisco State University

Low frequency acoustic losses in low loss metals at ultralow temperatures—University of Santa Clara

Investigation of the lambda–nucleon interaction in P-shell hypernuclei—Vassar College

Calculation of the electronic structure of alkali metal amalgam graphite intercalation compounds—Wake Forest University

This list is a sampling of recent grants to physicists under NSF's Research in Undergraduate Institutions Program (Physics and Materials Science Divisions only).

Research Corporation grants

Turbulence and binary liquid mixtures—Amherst College

A new method to search for the electric dipole moment of the electron—Amherst College

The effects of temperature and pressure on the optical spectra of cuprous oxide, various indium compounds and vanadium oxide—Benedictine College

Interdiffusion studies of metal–semiconductor and metal-oxide–semiconductor interfaces by polar angle-resolved Auger electron spectroscopy—Bethel College

High temperature elastic properties of silver halides—Davidson College

Systematic photometric and spectroscopic observations of semiregular stars—Grinnell College

Dynamic light scattering in non-equilibrium fluids—Haverford College

Surface phase transitions: adatom interactions, commensurate–incommensurate transitions and unregistered binding—Haverford College

Optical rotatory dispersion in the blue and isotropic phases of cholesteric liquid crystals—Kenyon College

Time-resolved fluorescence spectroscopy—Lawrence University

Nuclear matter sizes for several tin isotopes—University of Redlands

Generation and propagation of infrared surface electromagnetic waves at interfaces with macroscopic and microscopic structures—Rider College

Percolation at a surface by Monte Carlo invariant embedding—St. Lawrence University

Molecular beam electric resonance spectroscopy—St. Olaf College

Preparation and characterization of short xanthan fragments—Wake Forest University

Photoelectron spectroscopy of highly excited semiconductors and insulators—Wake Forest University

A search for supernovae in nearby galaxies—Wheaton College

Interstellar deuterium at the VLA and its cosmological implications—Williams College

Laser spectroscopy of excited triplet states in diatomic sodium—Williams College

This table lists the Cottrell College Science Grants awarded by the Research Corporation in 1985.

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puting services are often provided without charge to the scientists. Undergraduate student salaries are lower than those of graduate students. Finally, faculty members need not pay part of their own academic-year salaries with research funds.

To further enhance possibilities for research at primarily undergraduate institutions, colleges can:

▶ Budget funds for equipment to be used jointly in advanced instructional laboratories and in research programs.

▶ Take institutional responsibility for some of the expenses of providing research opportunities for undergraduates so that the burden of fund raising is not entirely on faculty members.

▶ Provide for maintenance and repair of electronic equipment by funding a department technician or setting up a special account for contracting such services.

▶ Cover travel expenses for attending conferences, seminars, and special schools and workshops.

▶ Offer new faculty members lighter teaching loads and paid student teaching assistants to free up time for initiating research programs.

▶ Give paid research leaves after several years of teaching to compensate partially for heavy teaching loads. Such leaves can facilitate inter-institutional collaborations in which faculty members do part of their research on campus and part elsewhere.

NSF recognizes the advantages of such links and encourages its grantees to collaborate with college faculty members through its program of Research Opportunity Awards. Funding for these collaborations can often be obtained from NSF with a minimum of paperwork. Many faculty members use this program for regular summer research work, while others use it for occasional or sabbatical support to learn new techniques.

Very often, major campus computing facilities are underutilized at certain hours and may be used free of charge during those hours. Support personnel capable of providing advice on software and hardware are widely available at colleges.

Colloquia and seminar programs are standard means of broadening horizons and stimulating discussion. The Society of Physics Students maintains a directory of speakers willing to visit colleges for the cost of travel expenses, and many university departments encourage their physicists to visit colleges to publicize their graduate programs. Colleges have found that visits by prominent researchers can help faculty members develop relationships with their university colleagues and industry counterparts.

While not many colleges do all of these things, such measures go a long way toward making successful research a realistic goal for many college faculty members.

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