in theoretical physics in the senior year, the first being advanced mechanics (Goldstein, Marion) and the second electromagnetic theory (Marion, Jackson). In addition we offer one-term courses in optics and thermodynamics and statistical mechanics in alternate years during the third term. Most seniors and a lesser number of our juniors elect the third-term offering.

Our advanced laboratory program is wholly independent of any of our courses, and is spread over three terms (usually in the junior year) with a one-third course credit per term. The student may choose to work in a wide variety of areas—mechanics, electricity and magnetism, optics, thermodynamics, atomic and nuclear physics and solid-state physics. Not being tied to any specific formal course, projects in the laboratory may freely cross boundaries. The student is expected to elect a broad cross section. Working with modest direction, he must read extensively for background and frequently devise his own procedures. Often during the later phases of his laboratory experience he will initiate a larger project. A number of these projects have subsequently become regular advanced laboratory experiments. As part of this laboratory, the physics major must utilize Fortran programming of our IBM 1620 computer in the analysis of data in at least one of his experiments.

Research and comprehensives

Beyond these formal course arrangements, independent study and research projects are possible both during the academic year and during the summer. For our theoretically oriented majors, independent study has been undertaken in such fields as group theory, advanced topics in quantum mechanics, the special and general theory of relativity, etc. Experimental independent study has taken a wide variety of forms, and is often, but not exclusively, centered on faculty research interests. Summer research, often beginning or following an academic-year study, is always centered on staff research and usually involves one quarter to one third of our upperclassmen. With departmental recommendation and the approval of a special faculty committee, a student undertaking independent study may be awarded "honors" at graduation.

Finally every physics major late in his senior year must take an intensive comprehensive examination in physics. This examination embraces his entire undergraduate program in physics and consists of a six-hour written examination and a one-hour oral examination. A satisfactory performance is a requirement for graduation that parallels the usual grade-point and course requirements. Graduation "with distinction in physics" is given in recognition of an outstanding achievement.

Evaluation

The foregoing curriculum represents the distillation of the efforts of many people, some no longer at Carleton, over the past decade. It continues to be in a state of flux, and probably the next decade will bring as substantial a change as the past one. How successful is our present curriculum? One means of evaluation, the comprehensive examination, is at best a rather subjective one. Probably the best measure of our program is the subsequent performance of our majors in graduate study, that is, with what courses they begin their graduate study and how well they do. We have 8 to 12 seniors each year, 90% of whom do graduate work in physics, and most of the remainder study related fields such as biophysics or engineering. Feedback of their strengths and weaknesses in undergraduate preparation has been most helpful. With the wide distribution of our majors at "good-to-excellent" graduate institutions in physics, we thus have a more objective means of measuring our accomplishments. The most important factor is not the nature of the curriculum but the nature of the student body. □

Pomona College

Strong faculty involvement in research has led to undergraduate interest and participation that provides some of the excitement of graduate school often missing at a liberal-arts college.

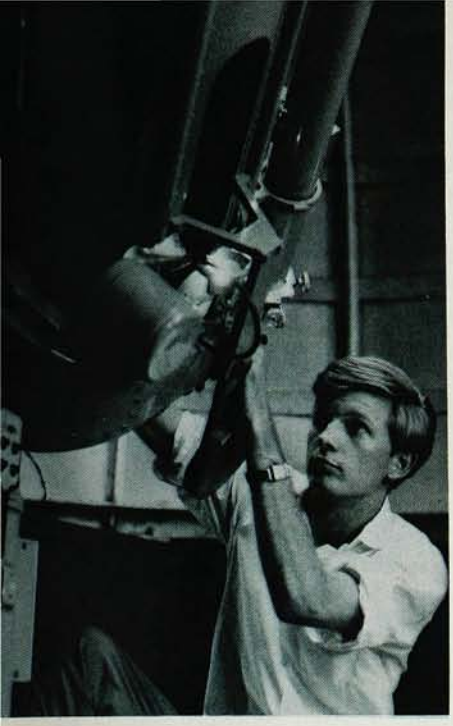
by Charles A. Fowler Jr

THERE IS A DECLINE in the productivity of small-college physics departments as a group. The necessary, if not sufficient, ingredients for a successful undergraduate-physics program are interested physicist-teachers and capable students, and the desire of many in each of these groups to "be where the science action is" has resulted in their gravitating toward the large universities. The physics department at Pomona College (Claremont, Calif.) offers no studies beyond the baccalaureate and would seem to typify that kind of department marked for oblivion by George Pake and others.[1,2]

But physics has flourished at Pomona to the point where the department's performance ranks creditably. The department has managed to attract and hold competent professors and good students. It has accomplished this by devising an undergraduate program that has much of the atmosphere and excitement of a graduate curriculum. The key factor contributing to this atmosphere is the existence of serious research projects by the faculty with active student participation.

Course design

The formal courses offered for the physics major have evolved over a period of several years and reflect the educational philosophies of the staff and the needs of the students, most of whom are professionally oriented. The essential subject matter is de-



signed for the two-semester calendar with a four-course student load. Under this system, all courses carry the same credit (one unit) regardless of the schedule of class and laboratory meetings. A few half courses exist, generally of a special kind. Requirements for graduation are 32 courses with limited overload occasionally allowed in the junior and senior years. The scope of these courses differs little from Curriculum R of the Second Ann Arbor conference.[3] The typical four-year sequence of physics and related science courses for the major appears in the table on page 28.

The general physics laboratory is one of the pioneer efforts to avoid the traditional one-a-week, cook-book variety of experiments.[4] It provides 12 challenging experimental problems during the year; each one requires from six to ten hours of lab work and the preparation of a satisfactory scientific report. Intensified project laboratories continue in the junior and senior years.

The entire physics faculty participates in the senior laboratory, and each member is responsible for developing one or more experiments and directing student work on these throughout the semester. The students work in teams of two and undertake four of the seven or more experiments offered. One afternoon per week for three weeks is scheduled for each problem, but considerable extra time in the lab is the standard practice. The students must submit a comprehensive report for each project that generally requires study of specialized reference books and research literature. The list of experiments at any time reflects both the major equipment available and the interests of the faculty but has generally included problems in x-ray diffraction, interferometry and laser optics, electron microscopy, cyclotron physics, magnetic resonance, cryogenics and certain aspects of astrophysics.

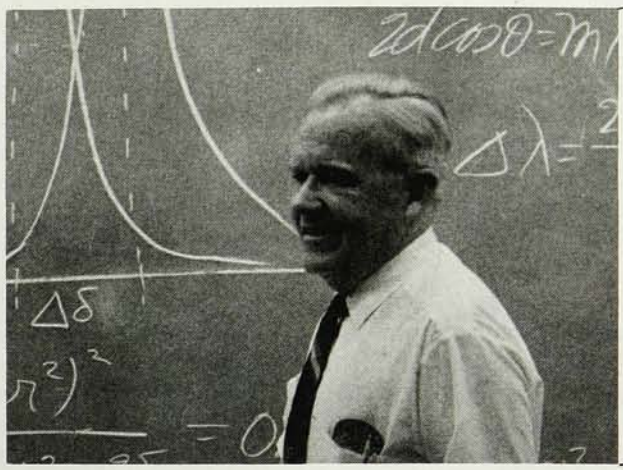
All senior majors are expected to submit a "thesis," and a half course in selected topics provides part of the time needed to prepare it. These senior papers may derive from independent library work, laboratory work, or in many cases meaningful participation in some departmental research project. Finally the candidate for graduation must pass an oral comprehensive examination before the faculty examining committee.

Mathematics through differential equations follows the standard sequence for four semesters. The fifth semester, taught by one of the physics staff, deals exclusively with the methods and techniques of mathematical physics (Mathews and Walker, Arfkens; see textbook table on page 60).

Research: modest beginnings

Serious productive research cannot be established in any department by edict, but must spring from the convictions and desires of its faculty, and this is particularly true in small undergraduate colleges with no publish-or-perish policy. Each member of Pomona's physics faculty (six physics and an astronomy PhD; one on leave annually) came to the college because of his deep interest in undergraduate education, but none ever entertained, even remotely, the possibility that his career would not include some continuing research. Thus despite the many well known obstacles, two modest research projects were begun shortly after World War II by the three-member staff; this research program has kept pace with the gradual growth of the department as each additional faculty member has subsequently initiated some project that he judged to be desirable and feasible. Such research projects include physics of ultrasoft x rays, magnetoöptics and magnetic domains, proton-produced soft x rays, optics of multiple thin-film layers, properties of liquid helium, and several projects in astrophysics and biophysics. The research has been sufficiently significant to justify publication in the *Physical Review, Review of Scientific Instruments, Journal of the Optical Society of America, Journal of Applied Physics, Journal of Chemical Physics, Astronomical Journal, Nature* and others.

At the outset the meager available facilities and other circumstances were scarcely suggestive of research at any level. One of the original projects was conducted by two professors with equipment borrowed from the electrical-measurements and the optics laboratories and was set up in a 7 × 15 foot closet. The second project was the final phase of the PhD research of the third staff member who was still a doctoral candidate at nearby Cal Tech. Space limitations made it necessary to set up the borrowed equipment in one corner of the general physics laboratory, and although this occasioned some wisecracks from visitors, it was



CHARLES FOWLER, professor and department chairman at Pomona, received his PhD from the University of California, Berkeley, in 1940. A participant in AAPT *functions, he was president of the southern California section in 1952–53 and member of an* AAPT–AIP *committee on physics faculties in colleges, 1962–65.*

in fact a blessing in disguise. Forced to do their routine laboratory experiments alongside operating research equipment, several young undergraduates became increasingly interested in the progress of the investigation; the faculty researcher on his part found in these students a highly receptive group eager, if not competent, to discuss every aspect of his problem. Occasionally the students handled modest subproblems within the research (specimen preparation and testing, electrical or optical calibration of components, graphical analysis of data, etc.) in place of their conventional laboratory exercise, and the resulting enhancement of their interest, industry, and learning was truly remarkable. Moreover although involvement with these relatively untrained helpers was frequently frustrating to the researcher, the jobs did get done and in satisfactory fashion. This accomplishment suggested to the faculty investigators—who in the absence of graduate students were faced with a manpower problem—that truly interested undergraduates might well be permitted to join the projects as apprentices and assistants and to assume increasing responsibilities as their knowledge and ability developed. The idea was tried, in a small way at first, and was so successful both in furthering the research and in inspiring and training the students that it has become an informal but most important feature of our instructional program. This feature has been decisive in attracting and holding good faculty and good students.

A productive environment

Even with a research-oriented faculty, projects do not appear spontaneously; rather they require a set of favorable circumstances for their generation and continued progress. The Pomona administration has kept salaries competitive, provided acceptable fringe benefits including sabbatical leaves, acted favorably on requests for reasonable instructional budgets and in general has shown a real respect for the judgment of its science faculty in educational matters.

Some research may indeed be possible even with poor facilities if other factors are favorable; physics at Pomona during the early fifties was an example. Nevertheless an entirely new scale of operation became possible in 1958 when the Millikan Laboratory for physics, astronomy and mathematics was completed.[5] Its facilities include well equipped teaching laboratories, modern lecture facilities, research areas arranged for great flexibility, a precision machine shop, student workshop, electronics-maintenance shop, digital computer (IBM 360, Model 40) and a departmental library with about 5000 reference volumes and 85 research periodicals.

The college has given strong support to research by recognizing that its investment in research equipment pays real dividends in educating its undergraduates. Sources of direct funding include several federal agencies, and the importance of this support cannot be overstated. On the other hand, some of the projects have been productive with only modest funds justified in the instructional budget.

Although student research was already established on a limited scale (two or three students per year) when the National Science Foundation undergraduate research participation program was first announced, grants under the program since then have permitted us to expand our instruction through research considerably. A typical summer program now involves from five to seven of the staff working informally with ten or more students in full-time effort. Some students are active on a project for two or more years, generally without academic credit, and their responsibilities and contributions often become of major importance. 18 of these undergraduates have published papers with their professors.

A small-college physics professor must reconcile himself to the fact that research will be done mainly in the summer. Nevertheless there are ways to alleviate the time shortage so that he and his student associates can make modest progress during the academic year. Of primary importance is technical help to perform the many routine tasks that confront the teacher researcher. The Pomona department has a laboratory-and-lecture-equipment curator and set-up man, a precision machinist and an electronic technician, all employed full time.

Pomona's four-course curriculum reduces somewhat the faculty's classroom commitments and also provides students with some extra time to participate in research. Restriction of general physics, with its heavy enrollment, to two semesters rather than a longer sequence substantially reduces the number of laboratory sections, thereby giving the faculty time for more personalized instruction and research with upper-class majors.

Lines of communication

The feeling of being far from the main stream of physics sharply reduces the attraction of the small college for many students and faculty. Pomona has kept the lines of communication with the scientific community open and active through visits to and by other researchers including extended stays by

Curriculum at Pomona College

	Courses	*Text*
First year	General physics Mathematics	Resnick and Halliday
Second year	Electromagnetic waves, physical optics, special relativity Atomic and nuclear physics Mathematics, chemistry	Jenkins and White; Feynman; Semat Goble and Baker
Third year	Linear networks, physical electronics, electromagnetism Classical mechanics Quantum mechanics Mathematics	Friedland, Wing and Ash; Corson and Lorrain Symon Powell and Craseman Schiff
Fourth year	Atomic, nuclear and solid-state physics Thermodynamics, statistical mechanics Mechanics Senior laboratory Selected topics; thesis	Leighton; Kittel Pippard; Kittel

postdoctoral personnel, exchange of ideas by research correspondence and participation by the faculty in professional meetings and research conferences. Frequent colloquia are shared by Pomona and the other associated colleges of the Claremont group.

Nearly every Pomona physics major functions as a laboratory assistant during his junior or senior year. Two are assigned to each general physics section under the close supervision of a professor who also works full time in that section. Inasmuch as printed instructional material is largely avoided, the three instructors must carry on a continuing dialog with their students about the experiment in progress. Student instructors profit enormously, both through a deepened understanding of their subject and through real involvement in the education of others. Moreover younger undergraduates readily identify with and respect them.

Having proved to our own satisfaction that serious research can be carried on in an undergraduate department with great benefits for participating students and faculty, we have resisted pressures to expand into some type of graduate program. It seems clear to our faculty that any such step would drastically reduce the opportunities now enjoyed by our undergraduates, since research equipment, space and faculty time would be preëmpted by graduate students. At a time when competition for good graduate physics students is almost desperate and with several eminent graduate schools located in Southern California, it would appear that we would be sacrificing distinction in undergraduate physics for mediocrity in the graduate field.

An appraisal

Pomona's average annual enrollment since 1950 has been less than 1200, of whom fewer than 300 are men majoring in science. In this period 170 students have been graduated in physics, an average of ten per year. Of these, 142 have continued with graduate study and 120 of them received first-year graduate fellowships and assistantships, including 18 NSF and five Woodrow Wilson fellowships. The graduate schools to which the students have gone include UC Berkeley (26 students), Cal Tech (17), Stanford (12), UCLA (10), Harvard (9), MIT (5), and 29 others with fewer numbers. Of those who entered graduate school between 1950 and 1963 with a PhD as the stated goal, 65% have achieved the doctorate and a few others are still candidates. For those of the last group who participated in research at Pomona, the PhD attainment was 80%.

In the same period the Pomona physics faculty has published 52 research papers, contributed frequently at American Physical Society meetings and special research conferences, and has delivered eight invited research reviews and digest articles. They have received seven fellowships for postdoctoral study and research.

In two areas only the Pomona physics department appears to have failed. Since 1950 it has graduated just six women and produced five high-school physics teachers.

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Reed College

Emphasis on an extensive senior-year special project forms part of a program designed both as preparation for graduate school and as training for immediate employment in industry.

by William L. Parker

IN TERMS OF A PHYSICAL ANALOGY our curriculum is certainly an example of dynamic equilibrium—at times almost unstable equilibrium. It is in such a state largely as the result of tensions: tensions between theorists and experimentalists, tensions between classical ideas and modern ideas both as to subject matter and methods of approach, and tensions between an abstract, conceptual treatment and a phenomenological treatment. All of these tensions exist within the department itself; in addition there are tensions with our mathematics department as to who shall teach the applied mathematics, and that tension common to all liberal-arts colleges between the need for a broad general education and the desirability of thorough specialized training in the major field.

The primary aim of Reed College (Portland, Oregon) is to graduate well trained physicists who are broadly educated. We do not think of ourselves as primarily a preparatory school for graduate work, although our graduates must be able to go on to graduate school, and most of them do. We like to feel, however, that the curriculum, although not being a terminal program, is sufficiently complete to allow a graduate to go out as a physicist into an industrial position without further formal education. Some do take industrial jobs, and they are successful. Before launching into the program for