OPTICS EDUCATION:

Encouraging an Integrated Approach

By Dennis G. Hall and Richard C. Powell

Optics has traditionally fallen under the academic disciplines of physics and engineering. But with optical technology playing an increasing role in modern life, the need for individuals studying and universities teaching optical science and engineering as its own discipline is growing.

Far from being an unchanging enterprise, higher education exists in a state of continual evolution. Prior to 1850, colleges in the U.S. focused for the most part on a classical curriculum composed of ancient languages, mathematics, chemistry, and natural and moral philosophy.[1] Over time, more specialized or practical degree programs, such as business, education, science, and engineering, were added as options to meet the needs and expectations of a changing world. In 1960, the light emitted from the first laser signaled the arrival of a new era in light-based science and technology. Today, 38 years later, we have laser-based optical systems inside CD players, telephone calls carried on beams of light confined within thin strands of glass, national defense and healthcare exploiting optical technologies in many ways, and laser bar-code scanners as visible symbols of modern optics in the consumer world.[2] As optical science and engineering, or optics, takes its rightful place as one of modern society's technological pillars, higher education must accept its traditional responsibility. It is incumbent upon universities to gather and organize the knowledge and understanding that together constitute the intellectual core of any new human endeavor, and to synthesize that core into a coherent academic discipline. This work, unique to universities, is essential for the orderly transfer of knowledge and understanding from one generation to the next.

Traditionally, the majority of U.S. colleges and universi-

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ties electing to emphasize optics have done so within the broader academic disciplines of physics or electrical engineering. These have been accompanied by chemistry, mechanical engineering, materials science, and other departments active in optical spectroscopy, metrology, and materials. All are successful approaches that recognize the importance of optics in a number of scientific or engineering disciplines, but the growing pervasiveness of optics has created a genuine need at all degree levels for individuals educated broadly in the fundamental principles, laboratory and measurement techniques, and applications of optics. Meeting this need requires the establishment of comprehensive educational programs that treat optics as a coherent discipline. The Institute of Optics at the Univ. of Rochester and the Optical Sciences Center at the Univ. of Arizona[3] (see sidebar, page 20) are examples of comprehensive programs that offer optics degrees at all levels, while there are several higher-education programs that offer degrees at either undergraduate or graduate levels (*Editor's Note:* For examples, see sidebars throughout the features in this issue).

Degrees in optical science produce graduates whose coursework has covered the generation, propagation, manipulation, and detection of light, the interaction of light with matter, and their applications. It is important that programs define optics as a field spanning the continuum ranging from fundamental through applied science to engineering (see Fig. 1). Traditional science and engineering departments are organized along the horizontal in Figure 1, with those focusing on basic science, like physics departments, located lower on the fundamental-to-applied vertical axis than those focusing on more applied subject matter, an electrical engineering department, for example. A given department is represented by a characteristic width along the vertical axis, reflecting the way that department defines itself. In each case, a traditional department organizes its coursework and research into a collection of subfields distributed along the horizontal; the few examples appearing in Figure 1 serve only to illustrate the point. Appropriately, optics appears as a subfield of both physics and electrical engineering.

By way of contrast, the optics programs at universities such as Arizona and Rochester are organized along the vertical axis, not the horizontal. While the two programs have comparable spreads along the horizontal axis, reflecting research and coursework in allied subfields such as atomic and condensed matter physics and communications and electronics (which have close natural ties to classical and modern optics), within that spread, the teaching and research is organized along the full expanse of the fundamental-to-applied continuum.

Faculty are drawn from an expanding set of specialties including physics, engineering, and materials science, to cover this broad intellectual territory, and against the backdrop of traditional academic disciplines, the programs can be described as multidisciplinary. Among the benefits of this type of comprehensive education are career mobility and flexibility, breadth of perspective, and the recognition that basic science, applied science, and engineering are interlocking elements in a common culture. It is not at all uncommon for a person's career to change as the years pass. At the doctoral level, a career might begin centered on basic research, shift later to applied research or advanced development, and then shift again later still into systems considerations or management. A comprehensive educational program prepares an individual for either a focused or an evolving career. A broad understanding of all aspects of traditional and modern optical systems, as well as of the basic properties of light and its interaction with matter, is valuable for all career choices at all degree levels, providing a well-rounded point of view. With coursework that exposes students to important ideas and

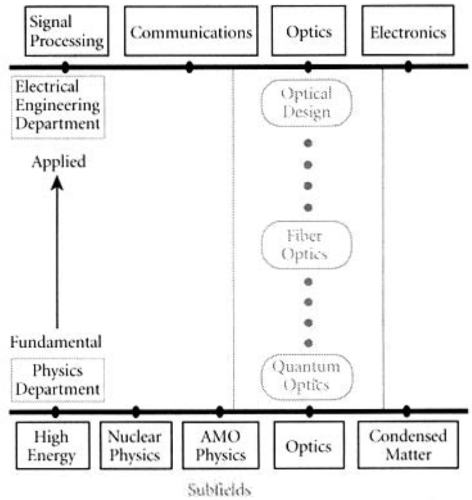

Figure 1. The educational and research programs of The Institute of Optics and the Optical Sciences Center span the fundamental-to-applied continuum. (AMO Physics denotes Atomic, Molecular, and Optical Physics).

Institut d'Optique Théorique et Appliquée/École Supérieure d'Optique

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Institut d'Optique, located at the Université Paris-Sud in Orsay, France, is a government subsidized institution devoted to higher education and research in the broad field of optics. The teaching division, known as École Supérieure d'Optique offers the degree of optical engineering, roughly equivalent to an American M.Sc., and a doctoral curriculum. Optical engineering students are selected at the level of the third and fourth years of higher education, after completing undergraduate training in basic physics and mathematics.

The engineering course is organized in three academic years (or two, for those entering after four years of higher education). While extensive training in optical physics, optical engineering, and optoelectronics forms the core of the curriculum, advanced courses in physics and electronics are included as well, as is general training for engineers, such as languages and economy. The optics courses offer a balanced combination of lectures, exercise classes, and laboratories. About 60 optical engineer degrees are awarded annually. Internships are required at the end of the last two years.

The doctoral course, organized jointly with Université Paris-Sud, Paris VI, Paris VII, Versailles St. Quentin, and École Normale Supérieure de Cachan, is open to physics, applied physics, and electrical engineering students having completed a full undergraduate degree (French maitrise or equivalent). The program consists of one year of combined directed research in a laboratory and course work, followed by three years of full-time laboratory research leading to the degree of docteur en sciences. The laboratories at Institut d'Optique comprise an Applied Research Laboratory and the Laboratoire Charles Fabry de l'Institut d'Optique.

For more information visit www.iota.u-psud.fr.

B.S. to Ph.D.: Two approaches

A particular university's approach to optics is often embedded in the program's (and university's) history. To illustrate the often overlapping and sometimes divergent approaches, The Institute of Optics (www.optics.rochester.edu) at the Univ. of Rochester and the Optical Sciences Center (www.opt-sci.arizona.edu) at the Univ. of Arizona are compared.

Because The Institute of Optics is an academic department residing within the college structure of Rochester, The Institute administers its own B.S. in optics, a degree first awarded in 1932 to Arthur Ingalls. Because the Optical Sciences Center is a stand-alone unit residing outside Arizona's college structure and reporting directly to the Arizona provost, its B.S. program in optical engineering is administered in cooperation with the Center by Arizona's Department of Electrical and Computer Engineering (ECE), which treats it as a specialization within the electrical engineering B.S. The Arizona program began admitting students in 1989.

In both programs, students take a core set of lecture and laboratory courses covering geometrical and instrumental optics, interference and diffraction, physical and Fourier optics, electromagnetic theory, quantum mechanics, electronics, lasers, radiometry, and detection, supplemented by a number of electives. A course covering optical fabrication and testing is a requirement at Arizona; at Rochester, testing is required, but optical fabrication is an elective. The Arizona program currently requires more courses on electronics than its Rochester counterpart, reflecting the former's connection with the ECE program. Rochester offers an undergraduate elective on thin-film optical coatings and its undergraduates take a bit more mathematics than their Arizona counterparts. At both universities, students supplement their optics studies with courses in the humanities and social sciences, along with technical courses taken in other science or engineering departments.

Approximately 25% of the B.S. graduates from both programs elect to attend graduate school in optics, physics, or electrical engineering, while the remaining 75% find employment opportunities in large and small companies or government laboratories. All things considered, the similarities between the two programs far outweigh the differences.

Arizona (Optical Sciences)	Rochester (Optics)
Probabilitity and Statistics	*Mathematical Methods*
Electromagnetic Waves	*Electromagnetic Theory*
Radiometry and Detection	*Radiometery and Detection*
Diffraction and Interferometry	*Physical Optics (Fourier Optics)*
Fourier Optics	*Geometrical Optics*
Introduction to Optical Design	*Instrumental Optics*
Introduction to Optical Physics & Lasers	*Lasers & Laser Systems*
Solid-State Optics	*Quantum Mechanics for Optics*

Comparison of the eight core courses required for the Ph.D. degrees at the Universities of Arizona and Rochester.

Rochester and Arizona awarded their first optics graduate degrees in 1938 and 1968, respectively. Both programs are the sole administrators of their M.S. and Ph.D. programs. Both doctoral programs are based on eight-course core curricula, with more specialized and advanced elective courses in optics or allied subjects and research leading to a written dissertation. Both programs also require students to pass written and oral examinations to be admitted to candidacy for the Ph.D. The eight core courses establish a relatively broad foundation upon which all Ph.D. students build their specializations. This means, for instance, that every student who graduates having pursued thesis research in quantum optics will have studied geometrical optics, lens aberrations, Fourier optics, and interferometry, just as every student who graduates having specialized in optical design will have studied lasers, electromagnetic theory, and the quantum-mechanical foundations of light and its interaction with matter.

As with the Ph.D. programs, the M.S. programs have much in common, with one distinct difference. The Arizona program is based on the idea of complete flexibility: there are no core coursework requirements, except that each student's program must include two laboratory courses. Students work with an advisor to define the set of courses that best serves the student's interests, needs, and career objectives. Rochester requires that each M.S. student's program include four graduate-level core courses: physical optics (Fourier optics), geometrical optics, radiometry and detection, and an intensive optics laboratory course; the remaining courses are electives. Both programs offer thesis and non-thesis options; the vast majority of students complete their M.S. in 18 months or less.

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techniques in both the fundamental and applied arenas, graduates develop both a sense of unity about the field and of belonging to a closely knit community.

As with all areas of science and engineering, several points are central to an education in optics. First, a student must gain sufficient knowledge and understanding in the field and sufficient awareness of the available reference literature to be able to function as a professional and continue learning throughout his or her career. Second, a student must learn the fundamental tools of the trade. In optics, this means acquiring facility with mathematics, computer modeling, laboratory equipment, and measurement techniques. Third, a student must gain experience using this knowledge and these tools to solve scientific or engineering problems. In the ideal case, this last step will lead students to develop skills in creative thinking. Being able to generate innovative research ideas, engineering solutions, or design concepts is just as important for a successful career in optical science or engineering as in any other technical field.

The key to establishing and maintaining an effective educational program in optics is to ensure the program contains all of the above-listed elements, although the emphasis will vary with degree level. Bachelor of Science programs need to focus heavily on developing basic knowledge, understanding, and a facility with tools, whereas Ph.D. programs need to emphasize research and creative thinking. Integrating research experiences with classroom studies is important for students at all levels. Research universities were recently criticized in the Boyer Commission report issued by the Carnegie Foundation for the Advancement of Teaching[4] for inadequately including undergraduates in the leading-edge research conducted on their campuses. This criticism does not seem to apply to optics programs, which in our experiences have regularly included undergraduates in ongoing research projects, even relatively early in their academic experience. This should continue and be expanded wherever possible.

But being organized along the vertical in Figure 1 can be described as a balancing act. For instance, maintaining an appropriate balance between the fundamental and applied aspects of a curriculum and ongoing research programs is a continuing challenge. Basic science, applied science, and engineering all have their own constituencies, some of whom can be quite vocal about their expectations. And because students admitted to graduate school in optics come from a variety of science and engineering backgrounds, it can be difficult to teach all the core courses at a level well-matched to every student's preparation. Maintaining balanced coverage between traditional and newer specialties represents still another challenge. Relatively few universities cover in-depth subjects such as geometrical optics, optical system design, interferometry, or thin-film optical coatings, so it is important that we educate and train (via research) students in those areas to help meet national needs. But optics has become so pervasive that newer subjects such as lasers (of all kinds), electronic imaging, and diffractive, nonlinear, quantum, and fiber and guided-wave optics have become extremely important and merit attention. Further, the technical community has a great interest in having institutions provide tutorials and technology updates as short courses, a form of instruction