

Cross-Training for Engineers and Scientists

An unusual graduate education program, involving four colleges and 10 departments, is a potent teaching force

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Because researchers trained in specific scientific and engineering disciplines usually must adopt interdisciplinary approaches to make progress in their work, there is growing recognition that young investigators will benefit if they are trained from the outset in several disciplines, instead of in the traditional manner emphasizing single disciplines. Many granting agencies and universities now subscribe to the notion that interdisciplinary training for young scientists and engineers is valuable, as do many individual researchers. Indeed, more and more researchers have undertaken interdisciplinary training the hard way—by taking crash courses in neighboring disciplines long after their formal studies were completed.

However, simplistic approaches to providing this training, such as creating multidisciplinary departments or encouraging graduate students to transfer frequently from one department to another, have been singularly unsuccessful. We believe that our Center for Biofilm Engineering (CBE) at Montana State University (MSU) provides an alternative approach to interdisciplinary graduate education that overcomes many of these problems and thus could provide a model for other programs involving their own assortments of specific scientific and engineering disciplines. Indeed, several environmental engineering programs for graduate education at other institutions now feature faculties that include members trained in several engineering and scientific disciplines.

The MSU CBE program allows us to cross-train graduate students from 10 academic departments in four different colleges without sacrificing disciplinary

rigor or eventual employability of the students who graduate from the program. In establishing this program, we have affirmed several pivotal lessons. For one, students must first be well-trained practitioners in their particular disciplines before they can become effective members of interdisciplinary teams. For another, graduate students can quickly begin to cross-train by working within interdisciplinary research teams that themselves have clearly defined scientific and practical scientific objectives.

CBE grew out of the vision and the truly interdisciplinary instincts of the founder of the program, the late Bill Characklis. Its development also depended very much on the enlightened policies of the Engineering Directorate of the National Science Foundation (NSF). According to NSF policies, engineering centers are asked to develop clear scientific objectives that lead toward practical advances to enhance U.S. economic competitiveness. These policies are also aimed at changing the educational culture at U.S. universities (see also p. 170).

Simplistic Approaches Proved Unsuccessful

Many academic researchers, especially those working on environmental problems, have been exposed to multidisciplinary departments that were created during the 1960s and 1970s. For the most part, those programs reflect a response to the perceived need for scientists and engineers with interdisciplinary training. These multidisciplinary departments, whose names could span an entire page in a university catalogue, often significantly diluted academic rigor at the undergraduate level.

Matters were often worse for graduate students, who typically were drawn from the same or similar departments. These students experienced a virtually cumulative lack of rigor in the course of their training,

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sometimes finding themselves badly equipped for doing research or finding other employment. While some such programs have produced useful graduates, we submit that even the best of these programs suffer from serious identity crises.

Another experimental strategy for interdisciplinary graduate training, known as the total-immersion approach, also proved less than successful most of the time. In this case, students who graduated from one particular department simply registered as graduate students in other departments in which they wished to be cross-trained. In practice, training was spotty, and professional resentments sometimes flared, frequently causing undeserved harm to students.

For example, several years ago one of us (B.C.) was seeking an expert in Fourier transform infrared spectroscopy to help in studying antibiotic penetration of microbial biofilms. Accordingly, a young woman with a B.S. in chemistry was recruited and became a graduate student in the Microbiology Division. Although she learned much about microbiology very quickly, she lost her poise when presenting her first seminar and misidentified a well-known bacterium. This episode proved so damaging that purists hounded her from the department, arguing that disciplinary muddling made her unfit for a graduate course in microbiology. Later, however, she completed a Ph.D. in microbiology elsewhere.

The Research Center Model Takes Shape

Bill Characklis was the founding director of the Center for Interfacial Microbial Process Engineering, an NSF-funded Engineering Research Center, at MSU. Before his death in 1992, he conceived and began to implement our graduate student cross-training program, which is part of the renamed CBE. He attracted colleagues from four engineering departments, four departments in letters and science, and one agriculture department, including 10 graduate students.

Characklis had impeccable interdisciplinary credentials, being at once a superb environmental microbiologist and a fine chemical engineer. To provide contiguous space for daily interaction with all his students, an entire floor of the MSU engineering building was turned over to his group of resolutely interdisciplinary colleagues.

The CBE research team now includes 23 faculty members from 10 departments; six postdoctoral fellows, research engineers, and professional staff members; 59 graduate students from 10 departments; and 29 undergraduate students who interact with the center in several different types of association. Faculty members in these departments represent different traditions, and requirements for their graduate degrees differ considerably. Nonetheless, each CBE student registers in his or her home department and is required to meet criteria defined according to the traditions of each discipline.

One MSU department head who steers some of his students towards CBE said that some elements of his

academic community had become so inward-looking and specialized that their principal investigators (PIs) could no longer get grants and their students could no longer get jobs but that interdisciplinary research has moved back into the mainstream of both funding and employability. Many very well established traditions are melded when engineers and scientists cooperate, and many very good things happen.

Because CBE involves faculty members in a wide spectrum of different degrees of involvement, from total integration to casual association, graduate students are usually recruited by the center and the appropriate academic departments. If a particular PI and student are both from the same discipline and are participating fully in CBE activities, the PI becomes the student's thesis advisor. Subsequently, graduate committee selection, the monitoring of research progress, and the thesis defense are carried on within the departmental framework but with additional involvement of CBE members.

For those disciplines that have fewer faculty members involved with CBE or in cases in which faculty members have drifted away from its activities, students recruited by the center choose thesis advisors who agree with the research direction and the interdisciplinary pattern of the proposed research training. In all cases the graduate students attend seminars, take courses, and participate in interdisciplinary research at CBE on top of similar activities in the respective home departments of the students.

CBE provides almost all of its 59 graduate students with computer-equipped carrels in a large central study area. CBE education activities include weekly noon-hour student seminars as well as weekly research seminars given by PIs and visiting speakers. These and similar activities are organized by a full-time education specialist and coordinated by a centerwide E-mail network. All CBE students must take the biofilm course offered by the center, and they may also select the center's biofilm engineering course or other courses offered by center-connected faculty members in their home departments.

The Core of Cross-Training Is Research Teamwork

However, the critical cross-training of CBE graduate students takes place when they join forces within our interdisciplinary research teams. These teams consist of PIs, postdoctoral fellows, technicians, and the graduate students. Currently 59 students are involved in all phases of research in the three designated thrust areas of our NSF-funded research program and in the many independently funded research projects that cluster around CBE. In a few cases the most effective of these teams have become so integrated that students choose coadvisors from microbiology and an engineering discipline.

Typically these research teams consist of engineers (chemical, civil, or environmental) and scientists (mostly microbiologists but also chemists or physicists).

There is a strong emphasis on quantitation and modeling (mathematicians and computer scientists). The three thrust area teams are led by engineers, all of whom have excellent credentials in experimental science.

Intellectual osmosis is the basis for cross-training, and it is most active when students from different disciplines work together, sharing information and otherwise educating one another as they work towards a well-defined common objective. For instance, a microbiologist may assist an engineer in analyzing the mix of species in a biofilm, and then the same engineer would assist the microbiologist by scanning the biofilm with microprobes that measure dissolved oxygen and pH or with a scanning vibrating electrode. Whenever these team members work together, the microbiological and biochemical data that they collect are automatically integrated with electrochemical data.

When research-oriented cross-training occurs, graduate students from different disciplines develop a natural sense of mutual respect in a process that is leading to a new generation of engineers, microbiologists, and scientists from additional disciplines. As part of this training, engineers learn how to clone specific bacterial genes, microbiologists learn mathematical modeling, civil engineers learn about sophisticated confocal laser microscopy, mathematicians learn biochemistry, and everyone pools their individual strengths as they work on learning new techniques.

In the CBE laboratories, disciplinary boundaries melt away but there is always a bona fide expert to help with any concept and any technique. During a recent NSF review of the program, an eminent microbiologist was convinced that two graduate students defending their research on trichloroethylene degradation by genetically engineered bacteria had to be bona fide microbiologists. In fact, they are chemical engineers who learned their microbiology on a CBE team!

Problems Can Arise

Any arrangement in which graduate students split their time between their home departments and a superdepartmental research unit is bound to produce some problems, and CBE proves to be no exception. The most common problem is that CBE tends to attract students away from their departmental bases for a variety of reasons, including the satisfactions of joining in team research, availability of specialized equipment, and CBE's relatively generous financial resources.

To address this overall issue, we review with the thesis advisor each student's progress toward their declared research goals annually. In at least five cases, the review indicated that the student's research emphasis had shifted enough to make the thesis advisor uncomfortable.

In one case, reviewers recommended that a student leave the CBE research team and complete his thesis research in the home department. This recommendation proved a success, with the student using most of the research that he had conducted in the center as

part of his thesis and graduating 6 months after the review.

Industrial Experience Boosts Employability of CBE Students

The center has developed an Industrial Associate Program (IAP) that brings faculty and students together with representatives from 17 companies. Each corporate participant is assessed an annual subscription fee in return for forming a close alliance with the CBE research and education programs. The center has tripled the funding provided by NSF's Engineering Research Centers program by attracting funding for specific projects from its IAP and from a wide variety of granting agencies.

Center students benefit because they work closely with industrial scientists and engineers on practical problems, such as microbe-induced souring of petroleum reservoirs, bioremediation of hazardous wastes, and biofouling and biocorrosion of industrial and drinking water distribution pipes.

Student involvement in these applied research projects includes field work, internships with member companies, and participating in planning and review sessions with sponsoring companies. Moreover, some IAP members join our research teams, and thus many of them develop close relationships with particular graduate students. IAP is helping students find jobs. For example, 12 recent graduates were hired by various IAP members, typically by the same associates that hosted their industrial internship.

Intellectual osmosis is the basis for cross-training.

Over the past 3 years, a group of six students with specialties ranging from microbiology to chemical and civil engineering worked as part of a team to address an important problem for the oil industry—microbial souring of petroleum reservoirs. The oil company participants believed that CBE had just the right mix of engineering and microbiology to investigate the role that sulfate-reducing bacteria play in hydrogen sulfide production in oil recovery operations and how that activity could be blocked.

Through multicompany sponsorship and matching funds from NSF, a 3-year research program was developed. CBE students helped to plan, conduct, manage, and evaluate the ongoing research project. Students also had opportunities to travel to field sites to obtain bacterial samples and to inoculate test bed oil field cores with bacteria suspected of being the souring agents. The project led to a patent application which includes two students as coinventors. The application describes a control agent that CBE is now trying to license to the oil industry as a solution to the souring problem.

The oil souring research program embodies what CBE strives for in cross-training students: interdisciplinary teamwork, real-world problems, scale-up engineering, collaboration with industry, and emphasis on solutions tied to an understanding of fundamental science. The project is only one of many at CBE that acquaint students with key biofilm problems facing industry. In the past year, two-thirds of the IAP companies have sponsored applied research projects that gave students opportunities to work directly on field-relevant problems.

Certainly not all CBE students work directly on applied projects or on industrially sponsored projects. Many of the students are involved in cross-disciplinary fundamental research which is funded through NSF and follows a course outlined in the CBE strategic plan, which calls for developing a baseline of fundamental knowledge on biofilms as a prerequisite for addressing specific applied problems.

Applicability of the CBE Model to Other Institutions

Any of the leading 250 research universities in the United States could build a similar cross-training program for graduate students. The main ingredient is a firm commitment to interdisciplinary research and a critical mass of faculty and graduate students in an interdisciplinary area that can be designated a superdepartmental research center. Such a center could be created by the use of university funds and by voluntary pooling of money from research grants held by individual PIs in the designated area of research. The research center may decide to forge close ties to industry to increase financial support for its research and enhance the employability of its graduate students.

To flourish, a center must be provided with sufficient contiguous space to allow the accommodation of center students in suitable office space and to provide laboratory space for the activities of interdisciplinary research teams. The creation of the center would entail only a very small increase in overall space requirements, and most of this space can be made available by simple redistribution of existing facilities.

The director of such a superdepartmental interdisciplinary program must maintain excellent relations

Several Graduates Exemplify MSU's Cross-Training Approach

Anne Camper trained in microbiology at MSU (B.S., 1975; M.S., 1977) and joined the center at an early stage of its development in 1987. She registered as a graduate student in civil engineering in 1992 and was awarded her Ph.D. and recruited into a tenure-track faculty position by the Department of Environmental Engineering in August of 1995. Her research involves the safety of drinking water.

Chris Wend came to CBE with training from Montana College of Mineral Science and Technology (B.S., 1987) and MSU (M.S., 1989) in mathematics. His interests in mathematical modeling extended to environmental and biological systems models. At the center, he studied environmental engineering (M.S., 1994) and subsequently joined the Battelle-Pacific Northwest Lab's Technology Planning and Analysis Center as a research engineer. Wend plans to rejoin CBE as a Ph.D. student.

Mike Abrahamson studied microbiology and environmental health at MSU (B.S., 1992). Subsequently he joined CBE, where he studied environmental engineering (M.S., 1995). He has developed several techniques for monitoring the transport of organic compounds through biofilms.

Britt Ide came to CBE in 1991 and 1992 in the summer undergraduate research program. She studied mechanical engineering at Ohio State University (B.S., 1993) but later returned to CBE to study environmental engineering. She has worked on a technology management project that focuses on regulatory issues pertaining to clean-air technology and plans to study for a law degree after finishing her CBE studies in 1996.

with the departments that contribute faculty members and students to the center. Moreover, the director must always keep the students' interest uppermost, as they must be trained well in their home departments and then be integrated into interdisciplinary research teams with well-defined scientific objectives. The progress of center graduate students must be monitored very carefully, especially when their thesis advisors are not active members of the center. If they are properly established and intelligently run, superdepartmental research centers can prove valuable for the cross-training of engineers and scientists. □