A Model for Graduate Crossdisciplinary Education

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Technology has evolved to require detailed engineering of chemistry, biology, physics and mathematics to describe and apply many of today's and tomorrow's innovations. Thus, experts are brought together to interact in teams at technology and research centers. These teams must be able to cross the boundaries of disciplines to succeed. An engineer in industry often does not carry a specialty label, even though they are educated through specialty-labeled engineering departments.

The National Science Foundation has recognized that a change is needed in both educational and research functions at the University level to reflect this industrial evolution. Thus, its Engineering Research Centers and Engineering Education Division has established Engineering Research Centers, Educational Coalitions, and Industry-University Research Centers. Nationally, universities have picked up this theme and established research centers in almost all areas of technology and science. The intent is to develop new technology, aid U.S. national competitiveness, and to create a "new generation" of engineer and scientist. Then-NSF Director Erich Bloch in 1986 stated "I believe that when we look at the Centers in several years we will find new and very significant examples of the flow of ideas and people back and forth across the disciplinary lines of science and engineering," and "continuing disciplinary strength is needed as well as continuing cross-disciplinary strength." At the same time, former NSF Director H.G. Stever stated "'A new generation of engineering students has to be educated to think and function in the cross-disciplinary environment." Thus, the policies of the Engineering Education and Centers Division of the Engineering Directorate at NSF require that each center develop, early in its evolution, very clear scientific objectives that lead toward practical engineering advances that enhance America's competitiveness. These policies are also aimed at changing the educational "culture" at American universities.

By combining the vision and the interdisciplinary instincts of our founder, Bill Characklis, and the policies of the Engineering Directorate of the National Science Foundation (NSF), the Center for Biofilm Engineering (CBE) has established a novel paradigm that allows us to crosstrain graduate students from ten academic departments in four different colleges without sacrificing disciplinary rigor or eventual employability.

The Research Center Model

Bill Characklis was the founding director of the Center for Interracial Microbial Process Engineering (CIMPE) which was established as an NSF funded Engineering Research Center (ERC) at Montana State University in 1990. Bill died in June of 1992 but, before his death, he conceived and began to implement a unique program of graduate student crosstraining. After Bill's death the ERC was renamed the Center for Biofilm Engineering and we have continued and expanded the education program that he established in our capacities as continuing Education Director and new Director for the center.

Bill's personality and philosophy both demanded that his students must have contiguous space for daily interaction and so, with the active encouragement of NSF, an entire floor of the engineering building was cleared and turned over to the Center and its crossdisciplinary mission.

The mission of the Center for Biofilm Engineering is to advance the basic knowledge, technology and education required to understand, control and exploit biofilm processes. In achieving this mission, the Center is meeting three major objectives: (1) demonstrate the basic scientific understanding and technological feasibility of systems and protocols that control and exploit biofilm processes, (2) create an engineering education based on teaching and research at the interface of life science and engineering, and (3) assist in the direct transfer of research discoveries from university laboratories to industry.

The graduate program of the Center for Biofilm Engineering (CBE) currently includes 45 graduate students in Engineering (26), Letters and Science (16), Agriculture (1), and Business (2), representing 10 different academic graduate programs. These academic programs all have different pedagogic traditions and their graduate degrees have different criteria but each student is registered in his/her home department and subscribes, with his/her thesis advisor, to the traditions of each discipline. Because the 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 the PI and the student are both from the same discipline and are both fully integrated into the CBE, the PI becomes the thesis advisor; graduate committee selection, the monitoring of research progress, and the thesis defense all proceed within the departmental framework with maximal involvement of CBE personnel. In peripheral disciplines in which the center has fewer faculty, or in cases in which faculty have drifted away from the CBE. students recruited by the Center must choose a thesis advisor from the academic department who agrees with the research direction to be taken and the interdisciplinary pattern of the proposed research training. In all cases the graduate student attends Center seminars, takes Center-oriented courses, and participates in an interdisciplinary research team in addition to full participation in similar activities in his/her home department. In the case of these peripheral students whose thesis advisors are not fully integrated into the Center, graduate committee selection, the monitoring of research progress, and the thesis defense is more complex and special vigilance is required.

The crossdisciplinary aspect of the CBE is further reinforced by the fact that the Center accommodates almost all of the 45 center graduate students in contiguous laboratory space and in PC equipped carrels. CBE education activities include weekly noon hour student seminars (BERP, Biofilm Experimental Research Program) and weekly research seminars given by PIs and visiting speakers, are organized by a full-time education specialist and coordinated by a centerwide E-mail network. All Center students must take the introductory biofilm course offered through Environmental Engineering and engineers also select the biofilm engineering course. Students take other courses offered by center-connected faculty in their home departments as well as traditional courses. However, the most effective crosstraining of CBE graduate students actually takes place in our interdisciplinary research teams that operate in our contiguous office and laboratory space. These teams consist of PIs, postdoctoral fellows, technicians and students and they conduct virtually all of our research in the three designated thrust areas of our NSF-funded research program and in the many independently-funded research projects that cluster around the CBE. In a few cases the most effective of these teams have become so integrated that students from either science or engineering have chosen a pair of coadvisors for their theses and these advisory teams are typically composed of faculty from Microbiology and from Chemical or Civil Engineering.

Typically these research teams are composed of engineers (primarily chemical, civil, or environmental) and scientists (mostly microbiologists with some chemists and physicists) with a strong emphasis on quantitation and modeling (mathematicians and computer scientists). The teams in general are led by engineers, all of whom have excellent credentials in experimental science. The actual process of cross-training is accomplished by intellectual osmosis between students from different disciplines working together towards a well-defined common objective. A simple case-in-point would be that a microbiologist would assist an engineer in the establishment and taxonomic mapping of a mixed species biofilm, and then the same engineer would assist the microbiologist in scanning this biofilm with dissolved oxygen and pH microprobe and/or a scanning vibrating electrode. Microbiological and biochemical data are integrated with electrochemical data, and an educational product is crosstraining and development of mutual respect between members of a new generation of engineers and microbiologists. Engineers learn how to clone specific bacterial genes, microbiologists learn mathematical modeling, civil engineers learn sophisticated confocal laser microscopy, mathematicians learn biochemistry, and everyone pools their perceptions and their techniques. The mysteries of time-of-flight SIMS or of ATR-FTIR slowly disappear if the microbiology student who attends weekly meetings with the team learns their underlying principles, their practical perils, and their perceptual power. In the CBE labs 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 CBE a very eminent microbiologist was convinced that two very brilliant young men defending a poster on trichloroethylene degradation by genetically engineered bacteria were microbiologists - they were in fact both chemical engineers!

The dynamics of interdisciplinary research teams often build interest in, and respect for, other disciplines in science and engineering. In addition, graduate students are exposed to these other disciplines from the firm vantage point of expertise in their own research area so that they begin to combine and synthesize. These techniques and approaches are assimilated without as much formal coursework as a total immersion approach.

Any arrangement where graduate students are deployed between their home department and a superdepartmental research unit must produce some problems and the CBE is not an exception. The most common problem occurs when the student is attracted away from his/her departmental base by the excitement of team research, by available equipment, or by relatively generous financial support, while the thesis advisor remains firmly in the home department. The student sees less and less of his/her thesis advisor and the student's research drifts away from the planned area. We have found it necessary to review each student's progress toward their declared research goals annually or semiannually, with their thesis advisor, and at least five cases have been detected in which the student's research emphasis had shifted to an extent that the thesis advisor was uncomfortable. In one case it was necessary to suggest to the student in question that he leave the CBE research team, to which he had made a very valuable contribution, so that he could return to his home department and finish his thesis research. He was successful, graduating six months later, and he was eventually able to use most of the research that he had conducted in the Center in his PhD thesis in Chemistry.

Application of the Model

The impetus and the resources that have enabled the CBE to develop this unique and successful program to crosstrain engineers and scientists were provided by the ERC program of the Engineering Directorate of NSF. A very large part of our annual grant is dedicated to graduate student support and to the development of our unique education program. But this high funding threshold should not in any way limit the proliferation of similar cross training programs in American universities.

Any Vice President of Research in any of the leading 250 research universities in the USA could build a similar crosstraining program for graduate students. What is needed is a firm commitment to interdisciplinary research and a critical mass of faculty and graduate students in an interdisciplinary area that can be designated as a superdepartmental research center. Such a center could be created by the use of university funds and/or by voluntary pooling of the research grants of the PIs in the designated area of research. A center must be provided with sufficient contiguous space to allow the accommodation of center students in suitable office space and laboratory space for the activities of interdisciplinary research teams. The creation of the center would at most entail only a very small increase in overall space requirements, and most of the space can be made available by redistribution from the contributing departments.

The director of the superdepartmental interdisciplinary research center must maintain excellent relations with the departments that contribute faculty and students to the center and he/she must always keep the students' interest uppermost in his/her priorities. The graduate students must be trained well in their home departments and then they must be integrated into interdisciplinary research teams with well defined scientific objectives. The research center may decide in favor of close ties to industry to increase financial support for its research and enhance the employability of its graduate students. The progress of center graduate students must be monitored very carefully, especially when their thesis advisors are not active members of the center. to detect cases in which students have drifted away from their departmental anchors. If they are properly established and intelligently run, superdepartmental research centers are ideal vehicles for the crosstraining of engineers and/or scientists.

Examples of a Research Center Team Approach

The Center's Industrial Associate Program is made up of 19 companies that each pay an annual subscription fee to be closely integrated into the CBE research and education programs. Center students work closely with industrial scientists and engineers on critical problems such as microbially induced souring (hydrogen sulfide production) 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 working in the field, serving as interns with member companies, and participating in planning and review sessions with sponsoring companies. Because our Industrial Associates are functional members of many of our research teams, and because their input and assessments are actively solicited, many of them develop close relationships with particular graduate students. Eleven of the 28 civil and chemical engineering graduates from our program have been employed by our Industrial Associates, typically by the same associates that hosted their industrial internship; nine went into academia or continued in a Ph.D. program.

Over the past three years, a group of six Microbiology, Chemical, and Civil Engineering students at various undergraduate and graduate levels of seniority have worked as a team to find answers to a very expensive and complicated problem for the oil industry - souring of petroleum reservoirs. The oil companies believed the CBE had just the right mix of engineering and microbiology to investigate the role that sulfate reducing bacteria might play in hydrogen sulfide production in oil recovery operations. Most importantly, the Industrial Associates wanted the Center researchers to study ways to inhibit this microbial souring process. Through company sponsorship and matching funds from the NSF, a three year research program was developed. Three Ph.D. graduate students, Satoshi Okabe, Mark Reinsel and Robert Mueller, were involved from the germination of the project when five Industrial Associate companies presented the Center with the opportunity to work on the souring problem. They worked to help develop program direction and used their experimental results for their Ph.D. theses, while playing a key role in managing the project and conducting the research. In fact, student contributions were an all-important factor in meeting the deliverables set out by industry. The research team met at least twice each year with the industrial sponsors to review and plan the research path. At these meetings, the students gave comprehensive presentations on their research progress. In addition to continuous collaboration with industry participants, the students had the opportunity to travel to the field to obtain bacterial samples. The students returned to the CBE to inoculate test-bed oil field cores with the suspect bacteria. Toward the end of the project Darla Goeres (a Center MS student) spent a week in a Texas production facility to test a CBE-developed agent for inhibiting the souring process. The project culminated in understanding the microbiological basis for souring and inhibition and resulted in an engineering patent application for the control agent and the CBE is currently working so that it is available to the oil industry as a solution to the souring problem. Two graduate students are named as co-inventors of the technology.

The souring research program embodies much of what the CBE strives for in the crosstraining of students - interdisciplinary team work, real world problems, scale-up engineering (from laboratory bench scale work to applications in the field), collaboration with industry, and emphasis on solutions tied to an understanding of fundamentals. But, this project is only one of many at the CBE that integrate students with key biofilm problems facing industry. In the past year, two thirds of the Industrial Associate companies have sponsored applied research projects that gave students opportunities to work directly on field relevant problems. In one project, the industrial sponsors mentor a class of graduate students that is working on bioremediation solutions to a gasoline spill site. In a series of projects investigating biofilms growing in water distribution pipelines and treatment plants, CBE students have collaborated with over 30 water utilities, participated in hosting several international conferences on biological regrowth in drinking water, and have worked on transferring CBE developed biofilm monitoring technology to drinking water plant operators.

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 the NSF support of the CBE and follows a course set-out by the CBE Strategic Plan. The Strategic Research Plan is the CBE charter for developing a baseline of fundamental knowledge on biofilms which is a prerequisite for addressing more specific, applied problems. But all problems are attacked with this team approach.

Summary

Most of us pay lip service to interdisciplinary research, certainly when we address our granting agencies, but the academic community really has not adopted one successful formula to accomplish this objective. The CBE has evolved a system that works, we have developed a monitoring system that detects problems, and we are caught up in the excitement of producing graduate students who are unique in their degree of crosstraining and who will easily eclipse the authors in our accomplishments as scientists and engineers. But perhaps the greatest satisfaction is encapsulated by a wise young department head who steers some of his students towards the CBE. He said that some elements of his academic community had become so inward-looking and specialized that their principle investigators could no longer get grants, and their students could no longer get j ohs, but that interdisciplinary research has moved both back into the mainstream of funding and employability. Established traditions meld when engineers and scientists cooperate and many very good things happen.

The pivotal lessons that we have learned are that the student must be a well-trained practitioner of his/her own discipline to be an effective member of an interdisciplinary team and that crosstraining is readily accomplished by graduate students working within interdisciplinary research teams in contiguous space with clearly defined scientific and practical objectives.

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J. WILLIAM "BILL" COSTERTON is Director of the Center for Biofilm Engineering at Montana State University. He holds a Ph.D. in Microbiology and he defined the modern field of Biofilm Microbiology in a pivotal article in Scientific American in 1978. Dr. Costerton has published more than 750 papers and reviews in refereed journals and has recently co-authored a book on Microbial Biofilms. His is cross-appointed in both the College of Engineering and the Department of Microbiology at Montana State University.

NICK ZELVER is Coordinator of Industrial Development at the Center for Biofilm Engineering. He has managed all technology-transfer activities at the Center since 1990. Under his direction, the Center's Industrial Associate Program has grown to a current membership of 19 companies that provide over $1 million a year for sponsored research. Mr. Zelver is co-principal investigator on a joint College of Business/Center for Biofilm Engineering project to develop a management model for introducing environmentally friendly technologies into U.S. manufacturing.