NSF Centers’ Approach to the Integration of Research and Education

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Abstract - The rapid integration of cutting-edge, multidisciplinary research into the engineering curriculum is a challenge for educators. The National Science Foundation Engineering Research Centers have pioneered this type of integration since 1985. The goal for the Engineering Research Centers program is to educate engineers capable of integrating fundamental knowledge across disciplines to advance systems-level technology. Forty-three Engineering Research Centers have educated thousands of graduates who have proven to be effective in industry. The next generation of Engineering Research Centers currently under development have the mandate to provide opportunities for research and learning collaboration that will prepare graduates for leadership in innovation in a global economy. To accomplish this integration of research and education, Engineering Research Centers develop comprehensive education programs that provide learning opportunities across the learning continuum, from precollegiate levels through lifelong learning. Outreach activities, undergraduate curriculum and research opportunities, graduate programs, and continuing education for professionals are offered. Advances fostered through Center research activities are incorporated into learning materials appropriate for each level. To disseminate the most effective mechanisms to accomplish these goals, Engineering Research Center educators have developed a best practices manual.

Index Terms – Integration of research and education, Engineering Research Centers

INTRODUCTION

National Science Foundation (NSF) Engineering Research Centers (ERCs) developed from a meeting led by the Office of Science and Technology Policy of the White House in 1985. It was noted that while engineers were taught within the constraints of traditional disciplines, new advances were occurring at the boundaries between the disciplines. It also was noted that engineering education did not adequately prepare students for the team-based, interdisciplinary engineering actually practiced in industry. The Office of Science and Technology Policy report therefore called for the integration of research into engineering curricula. These recommendations were subsequently incorporated into the NSF Engineering Research Center Program’s mission. Under the assumption that cutting-edge, systems-level engineering problems require new problem-solving skills, NSF gives each Engineering Research Center a mandate to address entwined research and education problems. NSF envisions a complete integration between research and education in Centers, where the nature of the research demands new and swiftly implemented pedagogy, course content, and curriculum changes, and where the need to train students by making them partners in discovery requires research to be managed as an educational tool for students of all ages. In addition, NSF requires that Centers take proactive steps to insure that a diverse group of students and faculty participate in these programs. This is done through the development of a comprehensive program that offers educational opportunities across the learning continuum from postgraduate education down to the precollegiate level. This paper will discuss those education efforts at the collegiate level.

GRADUATE RESEARCH

Engineering Research Centers train graduate students through the conduct of interdisciplinary research in a team-based environment, and through courses that inculcate an interdisciplinary, systems approach to engineering problems. Students not only acquire the depth of a traditional disciplinary degree, but also benefit from increased breadth through exposure to the interdisciplinary environment characteristic of Centers. Centers recognize that this type of interdisciplinary training differs substantially from traditional disciplinary degrees, and they intentionally develop research projects that require problem-solving that crosses disciplinary lines. The thesis committees for ERC graduate students may include academics from different disciplines as well as industry researchers.

GRADUATE COURSES

In addition to the research experience, Engineering Research Centers typically develop new courses that reflect their research fields, and modify existing courses to reflect Center research. Much Center-generated knowledge is transmitted initially via “special topics” courses before finding a vehicle in more structured course sequences. Often these courses enroll both graduate and undergraduate students, are team-taught, and are developed by faculty at multiple institutions. Courses are generally institutionalized into the engineering curriculum and therefore are available to the wider student population and extend beyond the NSF funding cycle. It is also common for Centers to develop new degree programs (masters and/or doctoral), minors, or certificates. Between 1985 and 2003, 1,494 course modules...
for new and ongoing courses, and 119 new degree programs or certificates were developed by Engineering Research Centers [1].

**UNDERGRADUATE COURSES**

In many cases, Center research areas have not been traditionally taught at the undergraduate level because they cross disciplinary boundaries. For example, particle science had been virtually missing in the undergraduate curriculum until the Particle Engineering Research Center at the University of Florida in Gainesville established an introductory-level course for senior undergraduate students. In addition, the Particle Engineering Research Center leveraged additional resources to develop a particle product and process design course and computer-based modules in aerosols engineering. Aerosols were previously only taught at the graduate level and these modules are specifically designed for an undergraduate audience. It was determined that primarily senior students were being impacted by these courses that brought state-of-the-art Center research into the curriculum. Particle Engineering Research Center faculty looked for a mechanism to reach younger students to increase their interest in the field, and collaborated with the college to integrate a particle science module into an existing freshman-level introductory engineering course. This module introduces particle engineering to over 700 freshmen annually.

At the Center for Advanced Engineering Fibers and Films (Clemson University, Massachusetts Institute of Technology, and Clark Atlanta University) undergraduates can take “Introduction to Fiber and Film Systems,” an undergraduate technical elective that develops students’ systems-level understanding of fibers and films. The course teaches students to identify the steps in fiber and film production processes, explain the effects of process variables in a system on the structure and properties of fibers or films, and collaboratively create computer code to visualize the results of mathematical modeling. Because of the diverse educational backgrounds of the students, the course comprises both traditional lectures as well as modules. For example, students majoring in computer science take a module on polymer chemistry, while students majoring in chemical engineering take a module on visual programming language. The governing models for polymer extrusion, fiber spinning, film formation and structure property relationships are then presented in traditional lectures. Students teams undertake interdisciplinary projects that require an integrated approach to problem-solving. The course thus provides a capstone design experience much earlier in the students' careers than would be possible in the traditional curriculum. Furthermore, the course gives students the opportunity to develop an industrial perspective by arranging site tours of local fiber and film facilities. Industry personnel brief students on the processes and on technical issues.

In other cases, research at Engineering Research Centers has led to entirely new undergraduate curricula. For example, faculty at the Center for Advanced Engineering Fibers and Films (Clemson University, Massachusetts Institute of Technology, and Clark Atlanta University) have spearheaded a movement to restructure international materials education. The objective of the proposed changes is to train an engineer who considers molecular issues before designing the process or product, and then uses molecular information to increase the accuracy of the actual design.

In May 2002, an international workshop called “Touchstones of Polymer Processing” was held at the Polymer Processing Institute at the New Jersey Institute of Technology. The participants concluded that a new five-year undergraduate curriculum in molecular engineering and science was needed to prepare students for careers that combine molecular biology, complex fluids, polymer chemistry, polymer physics, chemical engineering, etc. In November 2003, CAEFF hosted a follow-up workshop at the University of Leeds to outline the new curriculum, develop syllabi for the required courses, and discuss multi-university implementation. The envisioned education reforms emphasize a fundamental understanding of molecular issues, molecular transformations, multiscale analysis, and a systems approach to process/product design.

**UNDERGRADUATE RESEARCH**

A successful way to bring research into the undergraduate curriculum is through undergraduate research experiences. Engineering Research Centers typically involve undergraduates as research assistants (either for pay or for course credit) during the academic year, and as summer interns. For example, the Particle Engineering Research Center has established the largest multidisciplinary undergraduate research program in the College of Engineering at the University of Florida. Over the past ten years this program has placed over 800 students from fourteen departments and three colleges on Center research projects. As is generally the case with these types of programs, it initially accepted only junior and senior students, but beginning in the third year of the Center, underclassmen were accepted.

In addition to integrating research into the undergraduate curriculum, undergraduate research serves other purposes. There is broad consensus in the engineering education community that undergraduate research is an important component of the engineering curriculum [2, 3, 4, 5]. A hands-on research experience is believed to better prepare students for graduate school, and perhaps equally important, to motivate them to continue beyond the bachelor’s level [6, 7]. A main rationale for these types of programs is that they can serve to increase graduate enrollments by increasing both awareness of and preparedness for graduate research. Faculty see the recruitment of graduate students as an incentive to participate in undergraduate research programs [8]. Programs that encourage students to pursue graduate degrees in engineering are especially important given trends showing a decline in the number of science and engineering graduate students [9, 10].
An additional benefit of undergraduate research may be
the role it can play in retaining undergraduate students in
the field of engineering through the bachelor’s degree.
Engineering educators are facing troubling statistics.
Enrollments and undergraduate engineering degrees are
down across all demographic categories [11]. Enrollments
of women and minority are even more problematic [12, 13].
The Commission on the Advancement of Women and
Minorities in Science, Engineering and Technology (SET)
Development called for a “national imperative” and “drastic
steps” to make the American SET workforce more
representative of the general workforce and cautioned that
the United States could find itself with a shortage of SET
workers. Significant numbers of students who indicate an
interest in pursuing engineering at the beginning of the
freshman year drop out of the field before graduation [14]. It
is also well documented that these rates are higher for
women and minorities [12], exacerbating the problem that
begins with lower enrollments from these groups. Studies
indicate that the dropout rate is very high during the
freshman year [14, 15].

The Board on Engineering Education of the National
Research Council in 1992 sought to identify successful
retention strategies and indicated that attitudes were more
important than academic factors. A longitudinal study of
women in engineering determined that a positive relationship
with an advisor and entering a department are critical factors
in retention for sophomore women. It has also been
theorized that technical experiences outside of the classroom
can enhance retention by helping students become integrated
into the institution [16]. A notable project was initiated at
Dartmouth College and adapted as the Penn State University
Women in Science and Engineering Research. This is a
program that was designed to use research as a retention
program for freshmen women, and rather than only involving
academically gifted students, it was designed to include
average students. This program placed women in three
semesters of research and reported a 50% reduction in
dropout rates among these students [17]. A research
experience is a vehicle that can provide students with the
positive relationships with faculty and integration into a
department, thereby enhancing retention in engineering
programs. Another retention problem identified is that
traditional engineering programs often include the basic
math and sciences classes in the first two years, but students
do not begin engineering classes until the third year [18].
Many students drop out before they get into the engineering
coursework. This realization spurred the development of
many lower-level undergraduate engineering classes. Early
research experiences can also address this issue.

Boasting approximately 26% minority and 35% women
students, the Particle Engineering Research Center
undergraduate research program has consistently
outperformed national numbers for the participation of
women and minority students. The Particle Engineering
Research Center conducted a study to identify the factors
that contribute to its success in attracting female students.
The Particle Engineering Research Center demonstrated that
participants in the research program reported a high level of
satisfaction. Analysis of the survey results indicated that
responses became increasingly positive as time spent in the
Center increased. As mentioned earlier, research shows
female students report a lower level of self-confidence, and it
is probable that self-confidence in the lab increases with
time. Therefore, laboratory experiences that last more than
one semester could serve as a mechanism to address the lack
of confidence reported by female engineering students.

Centers are also challenged to integrate research into the
engineering curriculum of students who do not attend the
Center institutions. The common mechanism for
accomplishing this is through a summer residential Research
Experience for Undergraduates (REU) programs. All
Centers place visiting students on interdisciplinary research
teams for up to ten weeks in the summer to allow them to
learn about research that would not be available to them on
their home campus. Program goals include providing
interdisciplinary laboratory experiences to undergraduates,
improving student competence in a laboratory, and
increasing the participation of women and minorities in
engineering. The PERC has provided 110 students with a
10-week program for the past eleven years through the REU
program and has developed a roadmap that can serve as a
model to other institutions that would like to offer a similar
program [19].

Research projects conducted by undergraduates in the
CAEFF REU program are tied to the Center’s study of fibers
and films. The Center envisions a new paradigm for
developing these materials through equations that couple
molecular and continuum information and through
corresponding three-dimensional images created in the
virtual domain. Verification of these mathematical and visual
models is achieved experimentally. REU projects, as an
integral part of the Center’s strategic plan, ideally comprise
all three of the intellectual focuses of the Center:
mathematical modeling, visualization, and experimentation.
An interdisciplinary perspective, a systems approach, and
industrial relevance – the hallmarks of ERC research – are
inherent in the REU projects. REU alumni develop many of
the skills necessary to function effectively on collaborative
materials design teams through activities that teach
laboratory safety and techniques; the nature of science and
the scientific method; the roles of observation, measurement,
and experiment in science; ethics in scientific research;
presentation skills and scientific communication; and team
building.

**Teaching Materials**

Another way research can be integrated into the graduate and
undergraduate curricula is through the development of
teaching materials, and Engineering Research Centers have
again led the way. Between 1985 and 2003, 163 textbooks
were published, as well as multimedia software on
immunology, electronic materials processing, cluster tool
design and semiconductor manufacturing processes [1].

**Diversity**
NSF further mandates that the integration of research and education should be accomplished by a diverse group of students and faculty, and that the Engineering Research Center integrative approach be disseminated to a diverse audience. As a result of proactive recruiting, Engineering Research Centers exceed national averages in engineering schools in the participation of women and minorities at both the student and faculty levels. This success resulted in the Deputy Director of NSF asking in 2003 that Engineering Research Centers ensure that students traditionally underrepresented in science and engineering have the opportunity to become trained in and contribute to Center research fields. Centers therefore forge partnerships with NSF human resource development programs such as the NSF Louis Stokes Alliance for Minority Participation program, which produces over 18,000 minority bachelors degrees every year, and the NSF Alliance for Graduate Education and the Professoriate, which helps prepare hundreds of minority graduate students in science, mathematics, and engineering for academic careers (http://nsfagep.org/). A more diverse, expanded workforce is thus being trained in the systems approach that NSF hopes will mold the future of engineering.

CONCLUSIONS

NSF Engineering Research Centers are uniquely positioned to provide both undergraduate and graduate education in cutting edge research by supplementing traditional disciplines with multidisciplinary experiences. This includes courses, new degree options, and research experiences. The mandate of the Engineering Research Center program and the length of the awards (ten years) allow strategic planning on how to bring Center research into all levels.

The legacy of the first ten years of the Engineering Research Center program is 1,080 bachelors degrees, 1,677 masters degrees, and 1587 doctoral degrees awarded to students trained in this environment [1]. A measure of the success of the integration of research and education was determined by surveys of Engineering Research Center graduate employers conducted in 2003 and 2005 that found that over 80 percent of supervisors rated Engineering Research Center graduates superior to non-Engineering Research Center students in their overall ability to perform their jobs, in their ability to work in interdisciplinary teams, and in both the depth and breadth of their technical understanding [20]. Additionally, a study was conducted to determine the degree to which the Engineering Research Center culture fostered institutional change on their campuses. It was determined that the most significant long-term impacts on these campuses were those related to engineering education [21].

The Centers have produced a best practices manual to assist others who are interested in using the Engineering Research Center model in their own institutions (http://www.erc-assoc.org/manual/bp_index.htm).

ACKNOWLEDGMENT

This work was supported by the Engineering Research Centers Program of the National Science Foundation under NSF Award Number EEC-9731680.

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Coimbra, Portugal
International Conference on Engineering Education – ICEE 2007
September 3 – 7, 2007


