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ABSTRACT

Over the past half-century, engineering education in the United States has undergone a profound transformation, from a strong focus on engineering practice and design before World War II to the current emphasis on scientific fundamentals and mathematical analysis. This change was driven by the Cold War and the accompanying major federal investment in university research, which also produced a major shift in engineering faculty culture away from its traditional roots in professional practice toward an academic science perspective, with rewards based primarily on research achievement. Beginning in the 1980's, the emergence of global competition as the major driver for engineering employment, along with the rapid growth of information technologies, have focused increasing attention on the need for new forms of engineering education that will equip graduates with stronger skills in communication, teamwork, knowledge integration, and economic understanding, in addition to sound technical competence. Led by far-sighted educators and industry executives, engineering education is now beginning to adopt this new paradigm. However, academic culture changes but slowly, and some time will elapse before the new paradigm becomes dominant at a majority of U.S. engineering schools. Driving forces for change are discussed, including efforts of engineering professional societies, engineering college advisory boards, the National Science Foundation, private foundations, and the Accreditation Board for Engineering and Technology. (Contains 41 references.) (Author/ASK)

Engineering Education in the United States: Past, Present, and Future

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Abstract *- Over the past half-century, engineering education in the United States has undergone a profound transformation, from a strong focus on engineering practice and design before World War II to the current emphasis on scientific fundamentals and mathematical analysis. This change was driven by the Cold War and the accompanying major federal investment in university research, which also produced a major shift in engineering faculty culture away from its traditional roots in professional practice toward an academic science perspective, with rewards based primarily on research achievement.*

Beginning in the 1980's, the emergence of global competition as the major driver for engineering employment, along with the rapid growth of information technologies, have focused increasing attention on the need for new forms of engineering education that will equip graduates with stronger skills in communication, teamwork, knowledge integration, and economic understanding, in addition to sound technical competence. Led by far-sighted educators and industry executives, engineering education is now beginning to adopt this new paradigm. However, academic culture changes but slowly, and some time will elapse before the new paradigm becomes dominant at a majority of U.S. engineering schools. Driving forces for change are discussed, including efforts of engineering professional societies, engineering college advisory boards, the National Science Foundation, private foundations, and the Accreditation Board for Engineering and Technology.

Introduction

Like the world around us, engineering education has changed dramatically over the last half-century. At the time I enrolled as a freshman in 1947, engineering was, at most institutions, a highly practical subject, with little application of mathematics beyond elementary calculus and strong emphasis on design according to codes and other well-defined methods outlined in the standard handbooks. Most engineering faculty had significant industrial experience and/or close ties with industry. However, over the next ten years, U.S. engineering education underwent a profound transformation -- a so-called *paradigm shift*. The traditional handbook methods had proven inadequate to deal with the demands on the engineering profession imposed by new wartime technological developments such as atomic energy, radar, jet aircraft, anti-aircraft gun control, mass production of penicillin, synthetic rubber, high octane aviation fuels, etc. To contribute to these developments successfully, a much stronger foundation was needed in mathematics, basic sciences, and engineering sciences than had been provided by most pre-war curricula. Probably of greater significance was the decision of the Federal Government of the United States, shortly after the close of World War II, to support much of the Nation's basic research through contracts and grants at universities. The Cold War military/aerospace competition amplified the flow of federal research funds, accentuating the demand for engineering faculty with academic research credentials rather than experience as practitioners.

Engineering programs responded quickly. In the decade from 1950 to 1960, engineering education experienced a true paradigm shift from an applied, practice-oriented focus to a mathematical, academic, "engineering science" focus. Courses in machine shop, mechanical drawing, and (except in civil engineering) surveying disappeared, to be replaced by differential equations, control systems theory, and transport phenomena. At a number of institutions, the so-called engineering curriculum became hard to distinguish from one in applied science.

New Demands on Engineering Education

As this century draws to a close, the environment for engineering practice is changing dramatically and irreversibly, impelled by the shift from defense to commercial competition as a major driver for engineering employment, the impact of exploding information technology on education and practice, the globalization of both manufacturing and service delivery, and the imperatives of environmental protection and sustainable development. Few would disagree that the engineering science emphasis has produced graduates with strong technical skills. However, these graduates are not nearly so well prepared in other skills needed for success in today's engineering practice and in the development and management of innovative technology. Todd *et al.* in 1993 (1) reported results of a survey of engineering employers that summarizes frequently-cited industrial perceptions of the weaknesses of recent engineering graduates, which included the following:

- technical arrogance
- no understanding of manufacturing processes
- lack of design capability or creativity

- lack of appreciation for considering alternatives
- lack of appreciation for variation
- all wanting to be analysts
- poor perception of the overall project engineering process
- narrow view of engineering and related disciplines
- no understanding of the quality process
- weak communication skills
- little skill or experience in working in teams

Employers uniformly emphasize that success as an engineer increasingly requires, in addition to strong technical capability, skills in communication and persuasion, ability to lead and work effectively as a member of a team, understanding of the non-technical forces that profoundly affect engineering decisions, and a commitment to lifelong learning. The needed characteristics are well summarized in a recent paper by McMasters and Lang (2).

Acquiring such characteristics is unlikely with our traditional, passive, lecture-based learning and competitive reward structure. Most educational experiences, beginning in elementary school, emphasize individual achievement and penalize teamwork (we call it "cheating"). And yet, the first day on the job, the engineering graduate finds that she or he must work as a member of a team and that success may depend as much on the combined efforts of all team members as on those of any individual. Today's engineering graduates must be prepared to work effectively in a quality-oriented team environment.

An Impossible Dream?

A new engineering education paradigm is needed, characterized by active, project based learning; horizontal and vertical integration of subject matter; introduction of mathematical and scientific concepts in the context of application; close interaction with industry; broad use of information technology; and a faculty devoted to developing emerging professionals as mentors and coaches, rather than as all-knowing dispensers of information. An engineering education based on this vision should not only produce graduates better prepared to meet the needs of engineering employers, but could very well increase student motivation and interest, with a consequent reduction of the present high dropout rates.

But is such an approach realistic given the background of our present faculty and the financial pressures that force most large engineering schools to depend heavily on outside research funding to keep their doors open? Am I describing an impossible dream? Can one structure an engineering education about practice-oriented team experiences without depriving students of needed analytical skills and knowledge of the engineering sciences? Can one find enough engineering faculty with the interest and capability to develop case studies at appropriate levels, along with supporting instructional modules? Will industry be willing to devote the financial and human resources needed to work with faculty in developing and conducting case studies? Will enough faculty members be willing to forego their ego-stroking authority as lecturers and become coaches instead? Even if faculties are willing, can deans and department chairs allow them to devote so much of their time to efforts that are not likely to bring in extramural funds?

Drivers for Change

The answers to these questions are still unclear, but a growing number of individuals are working to develop new educational models that retain the strengths of the "engineering science" paradigm, while alleviating its weaknesses. An early example is the project-focused Engineering Clinics Program, which has flourished at Harvey Mudd College for more than 30 years (3,4). The model has been warmly received by industry, but has not been widely adopted at other institutions because of its faculty labor-intensive character and its inconsistency with the academic research culture that dominates most large U.S. engineering schools. However, the reform movement began to grow in the 1970's with the work of a few far-sighted educators and practitioners (5-7) and gained momentum in the 1980's and 1990's through a series of studies by organizations such as the National Research Council (NRC), the National Academy of Engineering (NAE), the American Society for Engineering Education (ASEE), and the National Science Foundation (NSF) (8-26). A principal result of these studies was a significant increase in NSF investment in engineering education reform.

The major current drivers for engineering education reform include:

- the industrial advisory boards of engineering colleges and departments
- engineering professional societies, especially the American Society for Engineering Education (ASEE) and the Education Society of the Institute of Electrical and Electronics Engineers (IEEE).
- private foundations, for example, the F. W. Olin Foundation (new Olin College, Needham, MA) and the Lemelson Foundation (National Collegiate Inventors and Innovators Alliance -- NCIIA)
- the National Science Foundation (NSF)

- the Accreditation Board for Engineering and Technology (ABET)

These organizations act in a variety of ways to influence the engineering educational process, as discussed in the following examples.

Advisory Boards

Most engineering colleges and larger engineering departments have industrial advisory boards composed of alumni and representatives of companies that employ significant numbers of the institution's graduates. Traditionally, many of these boards have functioned primarily to assist in private fund raising and only passively with regard to curriculum. However, such boards are now becoming far more activist in advocating change in the educational programs of the units they advise and are making it clear that unless needed curricular reforms are adopted they will employ new engineering graduates from other, more responsive institutions.

Professional Societies

Professional society publications and conferences, in particular the *ASEE Annual Conference* and the annual *Frontiers in Education Conference* sponsored jointly by ASEE and the IEEE Education Society, help engineering educators maintain awareness of engineering education trends and effective instructional techniques. The conferences often include in-depth workshops to help engineering faculty who would like to become proficient in using team-based collaborative learning, multimedia and web-based instructional support, collaborative educational projects with industry, etc. The *Journal of Engineering Education* was established by ASEE to give engineering faculty an opportunity to publish scholarly papers dealing with *educational* research; and a number of engineering schools recognize these papers as a scholarly contribution, on a level with purely technical papers, in meeting the institutional requirements for promotion and the granting of tenure.

In November 1997, the Educational Activities Board and the U.S. Activities Board of the Institute of Electrical and Electronics Engineers (IEEE) issued a joint position statement urging an active role for IEEE in moving engineering education toward the new paradigm (27).

Private Foundations

Private foundations in the United States have a long history of support for educational reform. Important recent initiatives include a new engineering college established by the F. W. Olin Foundation and the National Collegiate Inventors and Innovators Alliance (NCIIA) established by the Lemelson Foundation.

In 1997 the Olin Foundation announced a grant of over $200 million to endow a new engineering college to provide innovative undergraduate education that will prepare graduates for professional practice and management of technology in the 21st century (28). The new college, known as Olin College, will be located in Needham, Massachusetts, and will share resources with the adjacent Babson College, an independent college of business administration well recognized for its program in entrepreneurship. By starting afresh without an entrenched academic culture, Olin College hopes to develop an educational program built around active, project-centered learning; integration of subject matter; close interaction with industry; intense use of information technology; and committed faculty members as mentors. The college is now recruiting a president and a faculty and plans to admit its first class of students in 2001.

NCIIA was established by the Lemelson Foundation to foster invention, innovation, and entrepreneurship among college students across the nation as a way of creating new businesses and employment opportunities in the United States (29). Its headquarters are at Hampshire College in Amherst, Massachusetts. NCIIA promotes this goal through grants and resources for curriculum development and direct support to interdisciplinary student "E-teams," which work with faculty mentors to develop and commercialize innovative technologies and ideas.

The National Science Foundation

Although the National Science Foundation (NSF) began supporting innovative engineering education programs in the 1970's, (6,7) the impetus for such support increased significantly at the direction of the National Science Board (NSB) with the release of the so-called "Neal Report" (9) by the NSB in 1986. Since that time a variety of programs to support engineering education reform have been developed. The largest of these is the Engineering Education Coalitions program, which currently includes eight consortia or "coalitions" of engineering schools of diverse size and mission. Each coalition works to develop, implement, and evaluate forms of engineering education that reflect the new paradigm. The eight coalitions encompass more than fifty engineering schools, which annually confer more than one-third of the baccalaureate engineering degrees in the United States.

In addition to the coalitions, NSF supports a variety of programs that address aspects of the new engineering education paradigm, including Course and Curriculum Development (CCD), Institution-Wide Reform of Undergraduate Education in Science, Mathematics, Engineering, and Technology (IR); Instrumentation and Laboratory Improvement (ILI), Undergraduate Faculty Enhancement (UFE), Combined Research-Curriculum Development (CRCD), Research Experiences for Undergraduates (REU), Grant Opportunities for Academic Liaison with Industry (GOALI), Faculty Early Career Development (CAREER), Computer and Information Science and Engineering Educational Supplements and Educational Innovation Program, Engineering Education Scholars Workshops, and the educational components of the Engineering Research Centers. Major NSF investment in engineering education reform for Fiscal Years 1991 through 1996, exclusive of laboratory equipment awards, has been approximately $125 million. Additional funding through the Technology Reinvestment Project's Manufacturing Education and Training Program (TRP/MET), provided from other agencies and administered through NSF, has totaled over $40 million.

The results of these efforts have been extensively documented in the engineering education literature, especially in *ASEE Prism* and the *Journal of Engineering Education*, (a few examples appear in references 30-36) and in the proceedings of ASEE Annual Meetings and Frontiers in Education Conferences. A substantial body of electronic courseware has also been produced and made available to the engineering education community, for example through CD-ROM's distributed by the SUCCEED Coalition and through the National Engineering Education Delivery System (NEEDS) electronic courseware data base developed and maintained by the Synthesis Coalition (http://www.needs.org). An "Engineering Education Innovators' Conference" in April 1997 included a number of papers describing results of engineering education projects, with special emphasis on the CRCD and TRP/MET programs; a report of this conference is in preparation and will be available from the NSF. Information on many coalition projects can be accessed through the Engineering Education Coalitions web page (www.needs.org/coalitions). Among the positive results of these efforts are:

- Promising educational innovations are being developed, adopted, and transferred to institutional support at the originating schools and, in the coalitions, to other coalition schools.
- These innovations have been shown to increase learning, retention, and graduation rates, including those for underrepresented groups.
- Within the coalitions, diverse institutions are cooperating effectively, for example through two-way sharing of educational methods and courseware between major research universities and small, historically black institutions.
- Perhaps most significant of all, a community of young, enthusiastic engineering education scholars is developing.

However, while much progress has been achieved, more needs to be done to build on that progress, to consolidate the gains already achieved, and to institutionalize these gains both at participating schools as well as schools that so far have not been involved. Projects have tended to focus on developing innovative educational models, while evaluation, dissemination, and institutionalization of these models has too often received only limited attention. In the coalitions, significant administrative and communications effort is required to keep 5-10 engineering schools functioning together effectively, thus absorbing resources that might otherwise have been available to support educational projects. Furthermore, the ability of existing programs to effect lasting culture change in the engineering schools is still uncertain. Most observers agree that the current academic culture and reward system often discourage investment of faculty time in educational innovations and the adoption of new educational paradigms. It seems clear that additional efforts will be required to counteract these effects and break the "implementation barrier."

Until recently there has been little systematic effort to examine NSF engineering education investments from a holistic perspective to produce an integrated structure. In 1995 the NSF Engineering Directorate convened a workshop of approximately 50 leaders from engineering education, industry, private foundations, and professional societies to review progress to date in implementing the new engineering education paradigm and to recommend an "Action Agenda" to develop a follow-on strategy (37). Following additional internal study, the NSF issued in December 1997 a program announcement for an "*Action Agenda for Systemic Engineering Education Reform* (38)." The program employs an outcomes-based strategy, inviting proposals for effective actions to create engineering programs in which:

- *engineering faculty* view themselves as mentors dedicated to nurturing and developing students; develop and use advanced educational materials that promote student-based learning; provide learning experiences that meet the needs of students with different learning styles; integrate their education and research roles; stress active, collaborative learning with less dependence on lectures; integrate subject matter by showing relationships from the beginning of the student's program; utilize emerging information technologies and network communications; and develop students' capability and motivation to engage in lifelong learning.
- *engineering curricula* maintain a solid mathematical and scientific knowledge base; integrate subject matter by introducing fundamental principles in the context of applications; integrate the development of teamwork, communication, and group project

definition and problem-solving skills in learning experiences throughout the curriculum; address issues of cost and timeliness, quality, social and environmental concerns, health and safety, etc., in the context of engineering practice; recognize diverse learning styles and career goals; increase opportunities for international experience, possibly taking advantage of distance learning technologies; and integrate research and education

- *engineering programs* create an environment that increases the successful participation of underrepresented groups in engineering; develop effective linkages with elementary and secondary education, two-year colleges, dual-degree programs, and other transfer institutions; maintain regular, well-planned interaction with industry; support creation of a network of engineering education leaders; create, maintain, and disseminate a body of evaluation findings; increase the incentives to department chairs, deans, and institutional administration to reward faculty who develop or implement successful innovations in teaching and learning; and reduce the time and cost required to earn an engineering degree.

Special emphasis will be placed on multiple goal achievement, strong assessment and evaluation components, firm institutional commitments to integrate the project results into ongoing educational programs, and the extent to which proposed projects go well beyond course development and modest curricular changes.

The Accreditation Board for Engineering and Technology

Engineering programs in the United States are accredited by the Engineering Accreditation Commission (EAC) of the Accreditation Board for Engineering and Technology, Inc. (ABET). ABET is a federation of 28 engineering societies that accredits approximately 1500 engineering programs at 300 institutions; 750 engineering technology programs at 250 institutions (two-year and four-year); and 40 engineering-related programs at 30 institutions. ABET is recognized by the U.S. Office of Education to accredit Engineering and Engineering Technology programs in the United States. Most states require graduation from an ABET-accredited engineering program as one of the conditions for licensure as a Professional Engineer.

In the past, ABET accreditation has been based on criteria that emphasize detailed curricular content; these have often been criticized as rigid and unfriendly to innovation. However, ABET has now developed a new accreditation process specifically planned to encourage adoption of the new engineering education paradigm. The process has been pilot tested and is now being phased in, with full implementation scheduled for the fall of 2001. A new set of accreditation criteria, "Engineering Criteria 2000," developed with strong industry input, focuses attention on the goals of engineering education as expressed in the characteristics and abilities expected of graduates (39). These characteristics include:

- ability to apply knowledge of mathematics, science, and engineering
- ability to design and conduct experiments and interpret data
- ability to design a system, component, or process to meet defined needs
- ability to function on multi-disciplinary teams
- ability to identify, formulate, and solve engineering problems
- understanding of professional and ethical responsibility and the impact of engineering solutions in a global/social context
- ability to communicate effectively
- motivation and ability to engage in lifelong learning
- knowledge of contemporary issues
- ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

Each engineering program must define the specific measurable learning objectives required to achieve these goals, the educational experiences that will produce these objectives, the multiple ways in which attainment of the objectives will be measured, and how the measurement results will be used for the continuous improvement of the educational process. ABET's principal role will be to assure that the program's goals and objectives are consistent with the characteristics of graduates described in Criteria 2000, and that the continuous improvement process is functioning effectively.

The new accreditation process will not be easy or trouble-free. The concept of self-evaluation and continuous improvement is foreign to the academic culture, and engineering faculty, department heads, and deans must learn and grow if they are to apply these concepts successfully to their programs. A major challenge is to train enough visiting team members and chairs to apply accreditation criteria vastly different from those of the past. At the same time, ABET must set a high standard for the effectiveness of institutional processes, and not all programs will be able to meet them. However, in the final analysis, ABET's role is no different than that of a truly dedicated faculty member

-- to set high standards for achievement and then do everything in his or her power to help students achieve them!

Closing Thoughts

In all these developments, the role of industry is crucial. If, indeed, industry wants engineers who can not only function effectively in a culture of continuous improvement, but who can help form and lead such a culture, it must accept a significantly increased responsibility to commit financial and human resources to the education of such engineers. In today's strong anti-tax political environment, there is little chance that either public or private engineering schools can find the added resources to implement the new educational paradigm without such industrial assistance. Despite its increased interest in educational innovation, the bulk of NSF resources will continue to support research. The new paradigm requires close, active partnerships between engineering schools and industrial firms whose engineers can cooperate with faculty in case study development and actively participate as part of the instructional team. Direct financial assistance is also needed to help pay for the added faculty time, travel, and supporting materials required to develop and conduct the team projects. Furthermore, industry managers must be willing to support participation of talented engineers as ABET evaluators and leaders if accreditation under Engineering Criteria 2000 is to achieve its full potential. The engineering faculties, for their part, must recognize that professional schools cannot be ivory towers today and that they will need to seek out and work enthusiastically with their industrial partners to conceive and bring the new paradigm to birth.

As an incurable optimist, I believe that the dream *is* possible. NSF support is making educational scholarship and curriculum reform intellectually respectable at a significant number of engineering schools, and the current NSF leadership continues strong advocacy of engineering education reform (40). Accreditation processes are being changed in ways that seek to encourage innovation. The community of educational scholars is growing steadily, and an important cadre of educational reform leaders is developing. Influential deans are supportive, but entrenched academic culture will be difficult to change.

And the journey is still far from over. Those of us committed to engineering education reform must take as our motto the words of the New England poet, Robert Frost (41),

> "The woods are lovely, dark, and deep,
> But I have promises to keep,
> And miles to go before I sleep,
> And miles to go before I sleep."

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