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Reengineering Engineering-Education: Paradigms and Paradoxes

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Engineering education is at a challenging crossroads. Some see it as a crisis; others as an opportunity to position our community and our society for the 21st century. It would be fair to say, however, that no one is satisfied with the status quo or with the prospects for the near term.

The world is undergoing unprecedented change that is affecting not only governments and national boundaries, but institutions of higher education, as well. Colleges and universities that specialize in engineering education, in particular, face many threats.

First, our product is too costly-your customers simply can't afford it. The quantity of financial aid awarded by private universities is staggering, and it escalates year after year. Second, the promise of security and a good job has become less certain. Third, the resources once available to carry out much of the educational enterprise have shrunk dramatically. Fourth, interest among our young people in a technological, liberal education is wavering.

To understand these issues, it is necessary to first examine the historical and social contexts of engineering education.

Historical Context

History shows that our roots and our values can be traced to many different lands. In the U.S., we are heirs to the French and British cultures, in particular. The French were the first to view engineering as an elite profession. In fact, the French word ingenieur stems from genie, meaning genius. This is quite different from some of the connotations Americans tend to associate with engineering.

Louis XV established a civilian engineering corps, the Corps des Ponts et Chaussees, to oversee the design and construction of bridges and roads. In 1747 the corps created a school to train its members--Ecole des Ponts et Chaussees, the world's first civil engineering school.[1] This led to the. founding in France of other technical schools--the Grands Ecoles.

The French recognized early on that engineering is a noble profession that prepares future statesmen and leaders. The mathematician Laplace wrote that the Ecole Poly-technique's goal was to produce young people "destined to form the elite of the nation and to occupy high posts in the state."[2] Over the years the graduates of the Grands Ecoles have proven their "power" by occupying posts in the highest economic strata of French society.

The evolution of engineering in Britain took a quite different path. The English upper class believed in a more classical education. There was no meaningful governmental funding of higher technical education during the Industrial Revolution. In fact, it was not until the early 1900s that both Cambridge and Oxford universities established chairs of engineering sciences. Some argue that Britain's decline as a world power is attributable to its failure to appreciate the importance of engineering education.[3]

In large measure, the Industrial Revolution, in Britain was driven by ingenuity and entrepreneurial initiative. Knowledge was gained pragmatically in workshops and on construction sites. Young men became engineers through apprenticeships. As Sam Florman has characterized it, "In France engineering became associated with professional pride and public esteem, with leadership at the highest level. Whereas in Britain, engineering was considered a navvy occupation--the original navvies being the laborers on canal construction jobs."

Both of these cultures permeate the roots of American engineering education. During its early days, the United States had virtually no engineers. When construction of the Erie Canal began in 1817, there were fewer than 30 engineers in the entire nation. We had no choice but to adopt the British apprenticeship model. The canals and shops, and subsequently the railroads and manufacturing factories, became the institutions where surveyors and mechanics developed into engineers. During the same period, the heritage of the polytechnicien was also unfolding in America.

West Point was founded in 1802 as a school for engineer officers. Sylvanus Thayer, appointed its superintendent in 1817, visited the Ecole Polytechnique and emulated much of what he learned there. Similarly, in the 1840s B. Franklin Green visited Ecole Polytechnique and assimilated what he learned into the philosophy of Rensselaer Polytechnic Institute. Norwich University, founded in Vermont in 1819 on the principles of the citizen soldier, was a hybrid of the military and the polytechnicien. Founder Alden Partridge believed in the importance of a leader of society also serving the nation.[5]

Interestingly, when Thayer, upon his retirement, endowed an engineering school at Dartmouth College, he conceived of a two-year graduate program through which students would become professional engineers only after completing a four-year pre-professional college course. Thayer believed engineers should be "gentlemen" before embarking on a professional education. He wanted the Thayer School to prepare engineers for the most responsible positions and the most difficult service, much in accord with Laplace's concept of the Ecole Polytechnique.[6]

In the 1860s, MIT and WPI were founded. It is interesting to note that WPI's motto, Lehr and Kunst, "theory and practice," bridges the principles of these two cultures. In that same decade, America launched a new era of higher education with the passage of the Morrill Act, better known as the Land Grants Act. This law authorized the federal government to aid the states in establishing colleges of agriculture and the so-called mechanic arts, thereby providing an education for the industrial classes. In the process, engineering became linked with the mechanical arts and American engineers lost the elitism of the French polytechniciens.

Slowly, the values of the profession were eroded. In time, engineering education was set apart from--and to some degree, below--education for other professions, such as law, medicine and science. The enormous growth of American industry--during and after the Industrial Revolution--and the appetite of industry for engineering employees led to engineers being placed in many sub-professional jobs, further reducing the social status of the profession in America.

During World War II we saw much growth in the technology base of our nation. After the war the masses were educated via the GI Bill. In the postwar period, Vannevar Bush and others were instrumental in establishing the National Science Foundation, which funded the enormous growth in the infrastructure of our research universities. The establishment of the Department of Defense and the growth of the military-industrial complex further fueled this growth, producing engineering graduates who specialized in fairly narrow fields.

The Grinter Report of 1955 was a significant document in that it provided a framework for American engineering education and influenced its revitalization. Its authors assumed that while it would be difficult for colleges to incorporate all of the report's recommendations into a four-year course of study, somehow it could all be packed in. The recommendations did not leave much room for the liberal side of education.

In 1957 the launch of Sputnik and the establishment of NASA spurred an avalanche of interest in science, technology and engineering. In more recent years, we have seen the end of the Cold War and significant shifts in the nation's demographics. These changes present formidable challenges and lead us to question whether the educational process that has served society in the past is still relevant today. Will it serve us well as we enter the third millennium?

Social Context

From a global perspective, it is crucial that America remain a major competitor. To achieve this, we will need a world-class educational infrastructure. In the early days of this nation, Noah Webster claimed that democracy will succeed only if the people have economic hope and educational hope. They are closely interlinked.

The Competitiveness Policy Council recently forwarded to the White House these goals for the nation:

* Raise national productivity growth to an annual average of 2 percent from the 0.7 percent rate of 1973-91

* Achieve annual economic growth of at least 3 to 3.5 percent and create more high-wage jobs to restore full employment and a higher standard of living

* Eliminate our external balance of trade deficit and halt the buildup of foreign debt that has turned us into the world's largest debtor nation

The council included the following recommendations to the federal government for meeting these goals:[8]

* Through various tax credits and their "competitive life" depreciation allowance, raise private investment permanently by at least 5 percent of GNP

* Develop a major new export expansion strategy to increase export credits, eliminate export controls, and maintain competitive exchange rates

* Improve the education and training of the work force through sweeping reforms throughout the educational infrastructure

K-12 Education

The K-12 education system, the pipeline to our institutions of higher learning, has some shortcomings. First, consider the school calendar. The three-month summer break was established to enable boys and girls to work on the family farm. In fact, the school calendar was designed to be in sync with the agricultural calendar.

Second, the average American high school senior has about one-third fewer school hours under his or her belt at graduation than his or her counterparts around the world. It's not a great surprise that U.S. test scores are one-third lower; if you work one-third less, you learn one third less.

Finally, there is a critically important disparity in what students within our nation's schools learn. More and more, we are coming to realize that females and minorities are not being tracked into science-and math-oriented curricula. As a society, we will be committing suicide if we do not invest in the technical education of all the members of our society.

Technical Literacy

The technical literacy of the populace is another serious issue. Test scores and other evaluations point out that our youth fare quite poorly in this area (as well as in basic reading, writing and comprehension skills) when compared with their counterparts in Europe and the Pacific Rim. This is not acceptable; our system must respond.

Demographics

As we look at the demographics, it is clear that we in engineering education have our work cut out for us. The numbers are quite embarrassing and represent a major loss of human potential in our society.[9] For example,

* Women, who make up 51 percent of the population and 45 percent of the work force, made up only 7 percent of the engineering graduates between 1950 and 1989.

* Asians, who represent only 2 percent of the population, held 8.6 percent of all bachelor's degrees in engineering and 7 percent of all Ph.D.s in science and engineering.

* At 8 percent, Hispanics represent a growing sector of the population, though only 3 percent of graduates

with bachelor's degrees in engineering in 1989 were Hispanic.

* African-Americans, who make up 12 percent of the population, made up just 3.4 percent of the bachelor's degree holders in engineering in 1988.

Our educational institutions must provide a nurturing environment for all students, irrespective of color, gender or race.

Image and Professionalism

The image of engineering must change to reflect the concepts of Thayer and Laplace. I'd like to share with you a story told to me by the CEO of a major French transnational corporation. This CEO is based in the U.S and was returning from France with his senior American staff. As they were going through U.S. customs, he was stunned to see that while he, with a great deal of pride, listed himself as an engineer on the customs form, his staff members, many of whom were engineers of high distinction with Ph.D.s from some of our most famous research universities, had written in "executive" or "manager."

Engineering is the only profession that does not require universal statutory and mandatory licensing as a measure of minimal qualification to practice. Medicine, law, pharmacy, architecture, public school teaching--they all require licensing in addition to an accredited education. Either we must present a clearly defined, unified image to the public, or we should require of all engineering practitioners legally defined mandatory qualifications.

It would be interesting to draw a parallel between engineering education and the concept of the teaching hospital. At a teaching hospital, practitioners teach and the next generation learns from those who actually practice medicine. However, at most of our universities, the majority of the engineering professors have not actually practiced engineering.

Perhaps we should consider adopting the German model, wherein distinguished engineers from the industrial sector have a duty to teach a course at a university as part of their normal activity, and academicians have close ties to the industrial sector.

Globalization

In constant dollar terms, the U.S. accounted for half of the $2 trillion Gross Domestic Product of the world economy in 1970. Twenty years later, our share of the world's total GDP, now $15.7 trillion, had dropped to one-third, a reflection of the ferocity of global competition.

Industrial globalization should perhaps be measured in terms of the percentage of revenues derived from outside the "home country." Ronald Zarrella '71, president and COO of Bausch and Lomb, has addressed this issue (see "Globalization: The Next Big Wave" Spring 1993 WPI Journal).

"For America's 100 largest industrial companies," Zarrella wrote, "the percentage of non-U.S. revenues grew from 14 percent in 1970 to almost 40 percent in 1990. For Japan's largest companies, the percentage is 57 percent; for Germany's it is 69 percent. Furthermore, for U.S. companies, those revenues have shifted from largely being derived from exports to being derived from manufactured products from outside the country."

There is no doubt that we have a responsibility to ensure that our future engineers can function in transnational companies and can work in a global economy. Because corporations manufacture and sell globally, future engineers must be able to function in such settings.

Imperatives for Under-graduate Education

The societal and historical contexts I've outlined lead to an inescapable conclusion: we must change. Our greatest obstacle is fear of change. As George Bernard Shaw said, "Progress is impossible without change; and those who cannot change their minds cannot change anything...."

In 1962 Gordon Brown, then dean of engineering at MIT, wrote a seminal piece titled "New Horizons in Engineering Education." Questioning the lack of integration in engineering education, he wrote, "Can our present educational structure meet the test of the times? If we assert that we want our students to become men of breadth and vision, able to integrate knowledge, we would ask ourselves whether we are giving them the opportunity to see knowledge in its totality. I believe we are not..."[10]

Integration and synthesis in engineering education is a topical issue. There are several initiatives at various universities and engineering colleges addressing this challenge. At Drexel University, for example, the National Science Foundation in 1989 funded the Enhanced Engineering Education Experience ([E.sup.4]). The experimental curriculum is integrated around engineering principles and provides students a fresh perspective. The experiment was a success, and Drexel recently adopted this new approach throughout its College of Engineering.

The motivation for the creation of the WPI Plan was the acknowledgement of the deficiencies of the so-called passive learning that occurs in conventional classrooms. The weaknesses of the conventional program are many. For example,

* By their nature, conventional courses usually present knowledge in long, isolated corridors, but professional achievement requires extensive integration and application of knowledge.

* A rigid academic program offers few opportunities for students to assume responsibility for defining their personal objectives, but students' success after graduation depends on this ability.

* Classroom experience is usually passive, but career development requires self-activation.

* Formal classes usually treat students as isolated learners, but practice involves personal interactions, shared experiences, mutual understanding, and effective communications.

The philosophy of the WPI Plan was best captured by one of the Plan's founders, Dean Emeritus William R. Grogan '46. He said, "Engineering education must take much more seriously those components that deal with the human dimension: communication skills, management abilities, and significant exposure to social and cultural fields of endeavor."

Nurturing the development of professional values requires immersing students in real-world issues, as the required projects at WPI do so well. Project work not only requires a mastery of the technical disciplines, but a command of scheduling, teamwork and communication skills.

As part of the Plan, each student must complete three projects before graduation. During each of the last three years, the student carries out a project, often as part of a project team. The first of these is devoted to the humanities and the arts. To complete the Sufficiency, the student takes five thematically-related courses and writes a research project on that theme. The underlying theme of the Sufficiency is that there is purpose and context for the student.

During the junior year, the student learns about issues relating to the impact of technology on society through the Interactive Qualifying Project. It requires students to define, investigate and report on a topic of their choice that raises questions about the social and human values associated with specific technologies. The IQP provides students in the junior year a unique opportunity to question policy issues, ethical issues and the important experience of assuming the societal impact of technology.

During the senior year, the student is immersed in the Major Qualifying Project, which is concentrated in his or her major field. This project provides a culminating experience in the discipline, develops self-confidence, enhances communication skills, and ensures the synthesis of fundamental concepts.

Each of these projects earns the student credits equivalent to one-third of a year's effort. In other words, the equivalent of a full year during the last three years is devoted to project-based learning.

In 1988, an NSF workshop on undergraduate engineering education noted that the primary goals of the engineering educational process are to develop, in as individualized a way as possible, certain capabilities in each student.[11] They are

* integrative capability, or the ability to recognize that engineering is an integrative process in which analysis and synthesis are supported by sensitivity to societal need and environmental fragility.

* analysis capability, the critical thinking skills that underlie problem definition--these derive from in-depth understanding of the physical, life and mathematical sciences, the humanities, and the social sciences.

* innovation and synthesis capability, the ability to create and implement useful systems and products, including their design and manufacture.

* contextual understanding capability, the appreciation of the economic, industrial, political and international environment in which engineering is practiced, and the ability to provide societal leadership effectively.

These are critical issues that the faculties of many institutions are addressing. The WPI Plan is an example of a "re-engineered" program that works, though it is labor-intensive and requires tremendous faculty involvement. The underlying theme of the Plan is that, from the student's perspective, there must be meaning and purpose. As T.S. Eliot wrote, "The definition of Hell is a place where nothing connects with nothing." By connecting different kinds of knowledge, the Plan provides a meaningful educational experience.

Imperatives for Graduate Education

Our nation's graduate schools are the envy of the world. The infrastructure put in place after World War II allowed us to build some of the best research facilities and enabled us to recruit the brightest minds. It is a system that has worked well and served the nation well. However, with the societal changes taking place, there are serious challenges facing graduate education.

Curricular Issues

The issues of integration and synthesis, which I've discussed with regard to undergraduate education, are relevant to graduate education, as well. Moreover, our graduate curriculum should include exposure to organizational behavior, finance/management, global issues, and industrial internships.

We expect that our graduates assume leadership positions, so it is imperative that they have a knowledge of the workings of organizations and have been engaged in discussions of current ideas, such as those expressed by Peter Senge in Fifth Discipline or Hammer and Champy in Reengineering the Corporation. I am not suggesting that our engineering graduate students should also be MBAs. However, rather than viewing these two disciplines as separate cultures, we should look at them as points along a continuum.

In a similar vein, it is difficult to believe that in a capitalist society, we routinely award doctorates to students who cannot critically assess a corporate annual report. Our system has allowed students to concentrate on a narrow path without developing a macro view of the world in which they will acquire and use their knowledge base.

I believe our educational system does not serve students well if they don't acquire the rudimentary lexicon needed to operate in the business world. It is important to emphasize that I am not questioning the depth one needs for graduate education; I am merely suggesting that the present focused program can be complemented with a few courses or experiences (or even internships) that give students the needed background and knowledge base to succeed in and lead corporate America.

Global competitiveness is also pertinent for graduate education. To alleviate these major gaps, we also need to implement in our curricula concepts that are emerging in manufacturing, such as product realization.

Supply and Demand

Graduates of our engineering graduate programs have been sought principally by the industrial sector and the nonprofit sector (universities and the federal government). As we shift from a defense-oriented economy to a civilian one, a major restructuring is taking place in our corporations, government and universities. The idea is fast disappearing that one can graduate with a Ph.D. and work in R&D at an industrial laboratory for the next 30 years.

Our graduates have the opportunity to enter the marketplace and start their own companies and corporations. We in engineering education should promulgate Noah Webster's concept of educational and economic hope. There are entrepreneurial opportunities for those who've acquired the knowledge base developed in our laboratories; the challenge is to contribute to society by creating wealth and employment opportunities.

To adapt to such a paradigm shift, we must change our modus operandi. Let us examine how the ideas and concepts for the research programs at our universities evolve. Much of what the NSF does is on target and has served our nation well. But a larger chunk of the federal budget that funds research at our universities is defense oriented (ONR, AFOSR, ARO, ARPA etc.) Is the mission of these agencies to strengthen the knowledge base for the nation's commercial sector? I am not certain.

A case in point is what happened to Craig Fields when he attempted to have the Defense Advanced Research Projects Agency (DARPA; now ARPA) be responsive to key commercial and industrial sectors to help strengthen U.S. competitiveness. His concepts were not accepted and he left the Pentagon. The industrial sector, which is (and should be) the "customer" of the "product" graduate schools produce, should help universities identify research needs and projects/ programs. This will require a much stronger alliance between faculty members and the industrial sector.

Resource Funding and Support Mechanisms

The industrial sector needs to be the funding source for our future graduate students. This is not an original idea. Many of my colleagues and I initiated industrial internships in the early 1980s. These, however, were the exceptions, not the norm. Of the 20 Ph.D.s who have studied with me, four carried out industrial internships. Their thesis topics evolved from in-depth discussions with our counterparts in industry. The student's financial support came from industry, and the students made extensive use of industrial laboratories. Upon meeting the residency requirement, some of these students spent nine to 12 months in internships at the industrial laboratory.

Initially, our concern was that such doctoral theses, carried out in industrial laboratories, would not be as "pure" as those done by traditional students. Our concerns were not founded; these were, in fact, some of the best doctoral theses, with much relevance and merit. Furthermore, the students developed in a different milieu, one very much connected to the mainstream.

In Germany there is a strong alliance between universities and industry. Much of the research activity is funded by industry and experts from industry hold academic titles and have the responsibility to "profess" their expertise. It is a model that should be further studied by U.S. engineering educators.

Below is an example that illustrates how this model is being applied in WPI's Manufacturing Engineering Program:

Manufacturing Engineering at WPI

Typical M.S. Student Time line July to August: Company Location

* Learn company processes

* Develop project/thesis proposal September to December: WPI

* Control and monitoring of manufacturing processes

* Engineering analysis of manufacturing processes

* Two elective courses January to April: WPI

* Computer integrated manufacturing

* Design for manufacturability Two elective courses May to December: Company Location

* Full-time project/thesis with active faculty supervision

Program Expenses

	Traditional Student	Company Employee
Salaries:		
Faculty	$12,000	$12,000
Student	18,000	*
Tuition	16,000	16,000
Supplies/ Travel	6,000	6,000
Benefits	3,000	3,000
Indirect Costs	21,000	9,000
	$76,000	$46,000

*Salary paid by company payroll

A two-year master's program is carried out by spending a significant portion of the two years at an industrial site. The graduate student is either a person previously unknown to the company--the traditional student mode--or an employee pursuing graduate work while on the company payroll.

The industries that have participated in this program have realized many benefits:

* High-quality, reasonable-cost engineering talent directed at specific company problems

* Opportunities for proprietary work

* The opportunity to review potential hires in-house

* Faculty and students brain-stoming on company problems

* Enhancing skills of existing engineering workforce with thesis concentrated on company specific problems

Graduate engineering education has an exciting future. Many of us who have been involved in internship programs and have benefitted from closer alliances with industry have become converts. With the emergence of a civilian economy, these concepts are more relevant than ever. A paradigm shift has occurred, and we in the academic sector need to respond with a renewed enthusiasm.

Conclusions and Implications

Where do we go from here? As a community of scholars, we should consider these recommendations:

National Purpose

Americans have always been individualists, but we have also had a strong, common purpose at our core. We have relied on a common will and a shared culture. We need to rejuvenate and strengthen our national purpose and ensure that our national agenda reflects our values.

Ability to Respond

Apathy and negativism can become self-fulfilling prophecies. We need to respond to the challenges we face in engineering education in an organized manner and with excitement and vigor.

Change of Culture

As educators, we are privileged to be members of a noble profession. We are charged with opening the minds of our students, and challenging and stretching their imaginations. We must not be afraid to open our own minds, as well, and we certainly should not be afraid of the changes we need to undergo. For the fact is, those changes will require courage and a sense of purpose. We need to change the role of the faculty and the reward system to value the integration, synthesis and application of knowledge, as well as the discovery of new knowledge. Alliances need to be established with the industrial sector, though they will not occur overnight.

Change in Image

We need to take proactive steps to continuously broadcast the value of a liberal technical education in preparing men and women to accept leadership positions in a society that is becoming more and more technological. And we must be sure that the education we offer the next generation emphasizes the importance of studying the impact of technoloqy on society.

We must also vigorously seek to improve our societal view of engineering. Recently, when a light bulb in my hotel room needed to be changed, I called housekeeping and was told, "Our engineer will be there right away." That does not match my image of engineering.

Celebrate Diversity of Cultures

As a nation--and as a profession--we must recognize the extraordinary opportunities that exist in global alliances. We must teach our students to appreciate the beauty of diverse cultures, just as the brilliance of a tapestry comes from the blending of many colors of thread. And we must emphasize the importance of learning languages in our increasingly global economy.

We must respond to these exciting challenges; too much is at stake to let these opportunities pass. We need to pave a path for the next generation, giving them hope and high aspirations. The job before us will require enormous energy and leadership. And there is no time to lose. As the Red Queen says to Alice in Through the Looking Glass, "Now, here, you see, it takes all the running you can do to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!"

RELATED ARTICLE: New Education Yearbook due in July

The 33rd edition of the Education Yearbook will be available in July. The yearbook is used to locate potential consultants, as networking opportunities for educators and researchers, and as a guide in locating undergraduate schools/universities.

The 215-page reference book lists colleges and universities that offer four-year and advanced degree programs in metallurgy/materials, ceramics, and polymers (U.S. and International Schools). The yearbook includes department chair, addresses, phone numbers, faculty, and their specialties.

The yearbook is produced and distributed through the support of Dr. Kali Mukherjee, senior editor, and ASM's Student Outreach Program. The cost is $15 for members and $35 for non-members. For information, circle 110.

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Abstract:

The disadvantages occurring due to historical and social changes in the engineering field are overcome by combining the industrial sector and educational institutions, resulting in better opportunities to engineers. The industrial sector provides funds to the students and trained engineers from the sector educate students at the universities. The merger of the two fields provides useful computer integrated engineering courses and ensures successful job opportunities.

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