A 21st CENTURY ENGINEERING EDUCATION FOR LEADING CONCURRENT DISCOVERY AND INNOVATION

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Abstract

Engineering in the 20th Century has been successful in providing economic, health and security benefits to society. Modern engineering education is the foundation for these advances. However, modern engineering education has not seen major changes since the infusion of engineering science into the curriculum in the 1960's. Furthermore, a modern engineering curriculum has now become a globally available commodity. Currently the USA awards over 60,000 engineering bachelors degrees per year, the European Union awards over 170,000, Japan awards over 110,000, and major developing nations (i.e., China, Eastern/Central Europe, India) award over 500,000 degrees annually. In the 21st Century we are experiencing an explosion of new knowledge, increasing globalization and significant social and demographic change. It will be essential for engineering to develop the new innovations that benefit society, almost concurrently with the discoveries that enable those innovations. To continue providing benefits to society in the 21st Century, engineering education will need to undergo significant change. This paper argues that we must reinvent the renaissance engineer, based upon sound educational principles, who can provide not only technical expertise but strategic leadership for a highly technological society. The 21st century engineer will first of all need to be an agile and independent learner, who can acquire new knowledge as needed to tackle new problems. The curriculum to support such a transformation will emphasize fundamentals (e.g., science and mathematics, principles of design and manufacturing) as well as the ability to research new topics, skills in communication and teamwork, and strategic, economic, social, artistic, environmental and global perspectives.

Keywords:
Engineering, Education, Learning

1 INTRODUCTION

The 20th Century was transformed by engineering achievements that led to longer and better lives for people all over the world [1]. These include amazing advances in the constructed environment (e.g., affordable housing, home heating and cooling, skyscrapers, roads, bridges and tunnels), in mobility (e.g., automobiles, trains, aircraft), in communications (e.g., telephones, television, satellites, internet), in productivity (e.g., electric power, computers, automated machines, home appliances), and health (e.g., water distribution, sanitary sewers, medical devices and imaging). During the 20th century the average human life span increased by 30 years, from 45 to 75 years; the majority of that increase came not from advances in medicine, but from the widespread availability of clean drinking water and sanitary sewers.

So what exactly is engineering, and how has it had this profound effect on society? A key insight is provided in this quote from the distinguished fluid mechanician, Theodore von Karman :

> *"A scientist studies what is, whereas an engineer creates what never was"*

Thus, engineers create, and innovate, based upon an in-depth, quantitative understanding of the latest developments in mathematics, science, economics, etc. Engineers also conduct research, to develop methods and tools, that enable practicing engineers to solve problems more effectively, systematically and efficiently. Engineering education at the undergraduate level is focused on imparting the knowledge and skills required to practice engineering, and at the graduate level to ensuring the development of a knowledge base for the development of new engineering methods and tools.

As we begin the 21st century, there are important societal trends that effect the environment in which engineering education must take place [2]. Notable among these are the explosion of new knowledge, increasing globalization and demographic change. It is now widely acknowledged that investment in research and development fuels economic development [3-5]. Many countries, and many corporations, to remain globally competitive, are investing not only in improved productivity, but also in discovery and innovation for the next generation of technologies. At the same time, of the top 100 economic entities in the world today, 42 are global corporations. Thus, established technologies and products are rapidly becoming commodities, and being relocated to lower cost regions of the world. This is schematically depicted in Figure 1. As manufacturing processes and equipment become commodities the manufacturing jobs move to other areas of the world with lower direct labor costs [6].

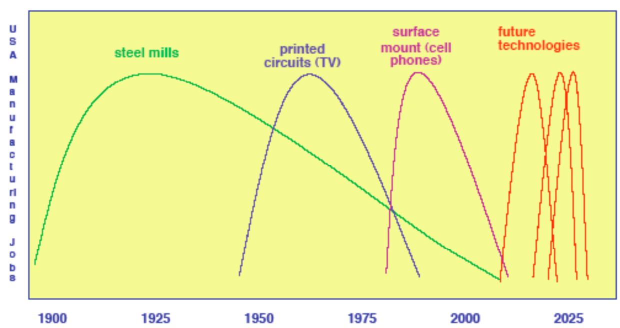

Figure 1. A Qualitative Depiction of USA Manufacturing Jobs Over The Life Cycle of a New Technology [6].

The rate at which new manufacturing technologies mature is accelerating, so the need is to develop those commercialization opportunities concurrently with the discovery of the new technology. For example, the steel industry provided good manufacturing jobs in the USA for decades before most of those jobs moved overseas. However, the surface mount manufacturing technologies used in the consumer electronics industry, rapidly became commoditized and moved to lower cost regions within a decade. Future technologies (e.g., nanomanufacturing, biomanufacturing) are expected to develop rapidly in centers of research, and then to quickly migrate their manufacturing to lower cost regions of the world.

The investment in research and development is important for economic competitiveness in an environment in which the rate of generation of new knowledge is accelerating. Forgac's Law [7-8] represents this reality in the form of an equation, based on based on correlation over many companies in many sectors and many countries:

$$\frac{R\,\&\,D\ expense}{Sales\ revenue}(\%) = \frac{16}{Marketable\ product\ life\,(yrs)}$$

Consequently, high research and development expenditures, as a percentage of sales, are needed for market leadership as marketable product lifetimes become shorter due to customer preferences, global competition, and new technology. Increasingly, economic and societal well-being are tied to excelling in engineering innovation [4-5, 8].

The purpose of this paper, in light of the preceding comments, is to review some current trends and issues in engineering education, with a focus on the USA. The trends in enrollments and degrees are presented, and the pathways to an engineering career are discussed. The preparation that engineers will need to be effective in the coming century is described. The challenge is to prepare the next generation of engineers to take on leadership roles in an increasing technological society where the pace of technological change is accelerating.

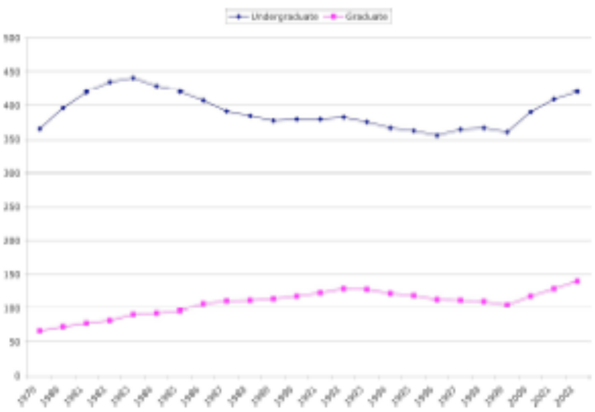

Figure 2. USA Engineering Enrollments for Undergraduates and Graduates in Thousands [9].

2 ENROLLMENT AND DEGREES

As illustrated in Fig. 2, USA engineering enrollments had been declining at the undergraduate level since the early 1980's, but have increased recently to near historic highs. At the graduate level, enrollments declined during the 1990's, but have recently risen to historically high levels [9-10]. Doctoral degrees in engineering peaked in 1997, and are again increasing (see Fig. 3) [10-11]. A large and increasing fraction of engineering doctoral degrees are being awarded to foreign students (see Fig. 4). While there has been some increase in the graduate engineering degrees awarded to underrepresented minorities (i.e., African-Americans, Hispanic-Americans, Native-Americans) the percentages remain small and the increase has been slow.

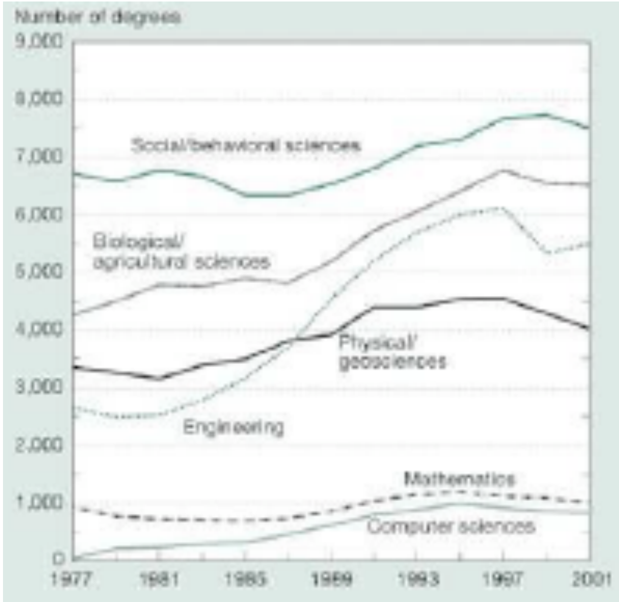

Figure 3. USA Science and Engineering Doctoral Degrees Awarded [11].

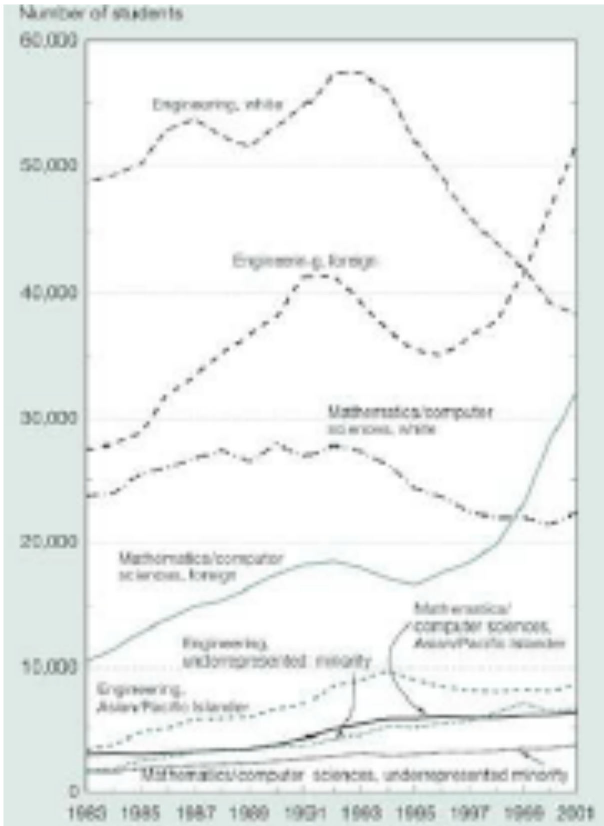

Figure 4. USA Graduate Enrollment Diversity and Citizenship [11].

Along with certain minorities (i.e., African-Americans, Hispanic-Americans, Native-Americans), women are also underrepresented in engineering [10-11]. In 2003 in the

US women earned 20% of bachelors, 22% of masters and 17% of doctoral degrees in engineering. In the mid 1970's these percentages were about 2%. However, it has taken nearly 3 decades to achieve this tenfold increase in the participation of womenin the engineering profession. Furthermore, while 17% of doctoral degrees in engineering were awarded to women, only 10% of engineering faculty are currently female, and only 5% of full professors in engineering are female. Similarly, only 3% of engineering faculty are Hispanic-American, and only 2% are African-American [10-11]. Consequently, the engineering workforce in the USA does not currently reflect the diversity of its overall population, and fully capitalize on the available talent.

Figure 5 shows the population of 20-24 year olds by race/ethnicity and shows the non-white categories converging with the white category over the next 15 years. This demographic fact makes participation of underrepresented groups all the more imperative in building the strength of the USA engineering workforce. Furthermore, this lack of diversity is even more pronounced among engineering faculty, who interact with engineering students and serve as a role model for the next generation of engineers.

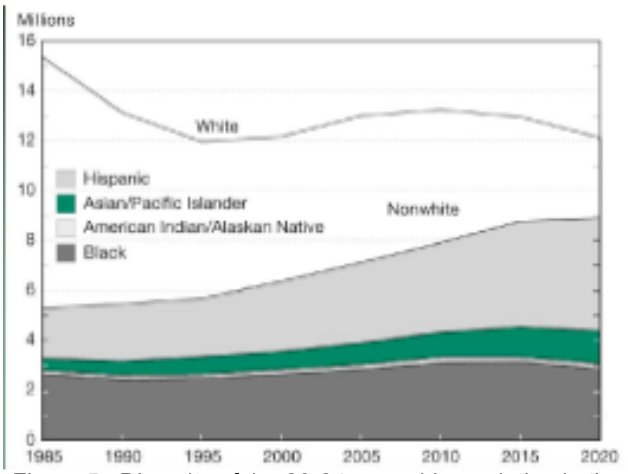

Figure 5. Diversity of the 20-24 year old population in the USA [11]

3 PATHWAYS TO ENGINEERING

The USA Bureau of Labor Statistics has projected strong growth in the demand for engineers, and expects engineering employment to grow 7.3% from 2002 to 2012 [12]. This growth is expected to be especially pronounced in certain engineering fields, such as environmental (38%) and biomedical (26%) engineering. At the same time, however, unemployment rates for engineers in the USA are unusually high. In 2003 the unemployment rate for all engineers in the USA was 4.3%, compared to 5.6% for all workers. In some fields, like computer hardware engineers (7.0%) and electrical and electronic engineers (6.2%), the unemployment rate, for the first time in history, exceeded the rate for all workers. The median salary for all engineers working in industry in 2002 was $73,550, which was up 5.5% from 2000. Faculty salaries in engineering continue to increase, but only at about the rate of inflation. Engineering, and Computer Science, faculty are near the top of the salary scale when compared to other disciplines, at over $88,000 per year [10].

Figure 6 shows the number of engineering degrees awarded by country. It is noteworthy that the USA awards approximately 60,000 engineering degrees, while Japan awards twice, and Europe three times, that number. It is also noteworthy that China, Central/Eastern Europe, Russia and India combine to award approximately 500,000 engineering degrees, or about ten times the number awarded in the USA. Many developing countries (e.g., China and India) are now educating excellent engineers in large quantities. The debate about whether the USA produces sufficient quantities of engineers is becoming less relevant, as global companies seek engineering talent around the world [13].

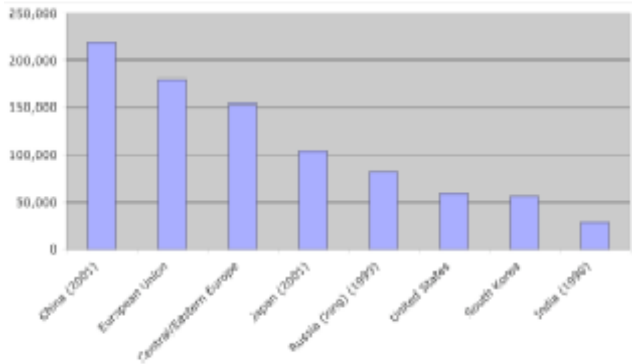

Figure 6. Engineering degrees awarded by country [11]

Despite the recent increase in engineering enrollments shown in Fig. 2, the degrees awarded in engineering in the USA relative to other fields are decreasing (see Fig. 7). Among the many reasons for this decline of interest in engineering, is the relatively poor preparation of high school students in mathematics and science in the USA [10, 14-15]. Also a factor is the emphasis in engineering education on technology, as opposed to emphasizing the societal benefits of that technology. The lack of emphasis on societal benefits in engineering education is also considered a major factor in the continued underrepresentation of women and minorities in the engineering profession [10, 14-15].


Figure 7. Percent of total USA bachelors degrees awarded that are in engineering [11].

This emphasis on technology has led to a perception in the USA of the engineer as technocrat (e.g., the image reinforced in the popular Dilbert cartoons). It is not widely recognized that an engineering education prepares the student for a variety of careers, including business, medicine, law, entrepreneurship, academia, art, etc. A recent survey of alumni of a mechanical engineering department showed that 10 years after graduation over 70 percent had used their engineering education as the basis for a variety of careers outside engineering [16]. The most common undergraduate degree among the Fortune 200 CEOs is engineering; 22% of those CEOs have engineering undergraduate degrees [10]. It is also not widely recognized that many practicing engineers enter the profession in the USA through unconventional paths, such as community colleges, or first degrees in mathematics or sciences. These unconventional routes are especially popular with women and minorities.

In our highly technological society, increasing the number of engineers becomes important. Furthermore, it becomes essential to educate societal leaders that have a strong foundation in engineering principles. It is also necessary to infuse technological literacy into the high school curriculum, and into other non-engineering disciplines at the university level.

4 PREPARING ENGINEERS FOR THE 21ST CENTURY

What does the engineer of 2020 need to be successful? Recent studies have noted that the engineering curriculum has not undergone any major transformations since the infusion of engineering science in the 1960's [10]. Most agree, however, that major changes in engineering curricula are needed, and are occurring, or will occur in the near future (see Figure 8) [17-18].

Conventional	Emerging
• Department-based	• Topic-based
• Campus-centric	• Global reach
• Building-block courses	• Holistic curriculum
• Few links to industry	• Robust industry partnership
• Research vs. education	• Integration of research and education

Figure 8. Emerging changes in engineering education.

The 21st century engineer will first of all need to be an agile and independent learner, who can acquire new knowledge as needed to tackle new problems. Such an engineer will need to be strongly grounded in fundamentals, which may now include science and mathematics topics such as biology, statistics, discrete-mathematics. These new fundamentals will also include principles of design and manufacturing, the ability to research new topics, skills in communication and teamwork, as well as strategic, economic, social, artistic, environmental and global perspectives.

Important changes are occurring, not only in engineering curricula, but also in the way curricula can be accredited [19]. The so-called "Engineering Curriculum 2000 (EC2000)" is now being fully implemented by the Accreditation Board for Engineering and technology (ABET). EC2000 brings concepts similar to ISO 9000 from the quality engineering movement. It is no longer an accounting of how many credits are allocated to various subjects, but now focuses on desired outcomes, their quantification, and the processes to assess if the measurable outcomes are being met. ABET has now also introduced the notion of "substantial equivalency" to recognize the quality of many engineering curricula outside the USA. ABET is certainly not a leader in terms of driving curricular change, however, it has developed an approach that supports change while ensuring quality. Furthermore, professional organizations, such as the American Society of Civil Engineers (ASCE), have focused on identifying the "body of knowledge" that will be needed by 21st century civil engineers [20].

In recent decades, it has also become clear that the "customer" for an engineering education, is not the industry that hires these graduates, but the students themselves. An engineer, during her or his professional life, will certainly have several jobs, probably have several employers, and perhaps even several careers. For example, while an automotive company may want to hire a student with detailed knowledge of spark-ignited internal combustion engines, they will be glad the student has strong command of fundamentals, when they assign the student to work on fuel-cell technologies. The engineering education of the 21st Century must enable the graduate to work on technologies that had not yet been invented while they were in school, and will certainly involve high-quality and efficient lifelong learning.

The renaissance engineer for the 21st century must ideally be a holistic designer, an astute maker, a trusted innovator, a harm avoider, a change agent, a master integrator, an enterprise enabler, a knowledge handler and a technology steward. Except for extraordinary persons, like the original renaissance engineer Leonardo Da Vinci, most of us can aspire to but not achieve such lofty goals. Clearly, engineering will continue to be a collaborative effort, with teams of individuals who have specific exemplary and complementary expertise, plus the skills to work together effectively. Nevertheless, the need is for a broad education that enables leadership in a technological society.

Research in education, by Howard Gardner and others, points to the importance of understanding the role of multiple intelligences in learning [21-22]:

(1) linguistic,
(2) logical/mathematical,
(3) musical,
(4) spatial,
(5) bodily-kinesthetic,
(6) interpersonal,
(7) intrapersonal, and
(8) naturalist.

For effective learning it is desirable to understand these multiple intelligences, and to nurture their development in each individual student according to their abilities. In traditional engineering curricula, although this is now changing, the focus has been primarily on the second of these intelligences, with little attention paid to the others. Another educational research study, with significant implications for engineering undergraduate education, is the work of the Carnegie Foundation's Boyer Commission [23]. They also focus on the individual learner, in the context of a research-based undergraduate curriculum. While such a curriculum is quite common in graduate studies in engineering, it is rarely employed in engineering undergraduate studies. They argue that a research-based curriculum, so successfully employed in graduate studies, is a desirable approach to undergraduate education as well.

5 CONCLUDING REMARKS

The 20th Century has provided ample evidence that engineers bring amazing benefits to society (e.g., sanitary water distribution, electrical power, aircraft, medical imaging, computers). The engineering education that has provided the foundation for those benefits has not changed significantly since the infusion of engineering science into the curriculum in the 1960's. The current engineering curriculum has now become a global commodity that is widely available in developing as well as developed countries. However, there are important societal trends that mandate a need for change if engineering is to continue bringing amazing benefits to society in the 21st century. These trends include the accelerating rate of new knowledge generation, increasing globalization and changing demographics.

What is our vision for the 21st Century engineer? A technocrat like the cartoon character Dilbert, a renaissance engineer like Leonardo Da Vinci, or both, or perhaps neither? We must have a vision, and based upon sound educational principles, develop an engineering education and curriculum to support that vision.

The 21st Century engineering curricula will need to develop engineers who can provide leadership in an increasingly technological society. Consequently, based on sound educational principles, these curricula will develop all the needed intelligences, not just the logical and mathematical. Such curricula will certainly attract to the profession a more diverse cadre of students, including minorities and women, than we do to today. In an environment of accelerating knowledge generation and global competition, concurrent discovery and innovation will be essential for success. Consequently, these curricula will be research-based, and will emphasize the importance of acquiring the knowledge needed to tackle new problems as they present themselves. Most importantly, the focus of the 21st Century engineering curriculum will be on the individual student, and the full development of the potential within each student. I conclude with a quote from Harvard psychologist Howard Gardner [22]:

> *I want my children to understand the world, but not just because the world is fascinating and the human mind is curios, I want them to understand it so that they will make it a better place.*

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