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HOLISTIC ENGINEERING AND EDUCATIONAL REFORM

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Introduction

A recent report from the National Science Foundation projected that employment in science and engineering occupations will increase approximately 70% faster than the overall growth rate for all occupations between 2002 and 2012. [1] For engineers, this projection translates to the addition of 976,000 new jobs during this ten year period. In 2006, United States colleges and universities graduated approximately 74,000 new bachelor's level engineers [2]. Assuming that U.S. domestic production of engineers stays relatively constant, as it has over the last 20 years (see Figure 1 [1, 3]), by the year 2012, the U.S. will fall short of this projected need by more than 200,000 engineers. Over this same period, the global supply of engineers is expected to increase, due to increasing production in countries such as China (Figure 1). This trend, coupled with increasing economic globalization and the comparatively low percentage of students studying engineering or science in the United States (Figure 2), has led many to conclude that U.S.-based industry will globalize much of its engineering work for reasons of both cost and limited resource availability within the United States.

Much has been made of the impetus to pursuing science and engineering careers that was generated by the launch of Sputnik in October 1957. And many have attempted to fashion a similar call to action based on our national economic security. However, when one looks at the production of bachelors-level engineers, on a population normalized basis, it appears that the Sputnik "phenomenon" had little impact on engineering study. As the data in Figure 3 [1, 4-6] demonstrate, there was only a relatively modest increase in the production of bachelor's-level engineers in the late 1960s and early 1970s as the Sputnik generation came of age. Rather, the more significant increase occurred in the late 1970s and early 1980s, most likely corresponding to the energy crisis and the nascent environmental movement, both still prominent and socially-relevant topics of our times. Moreover, although data suggest rather static interest in engineering over the last 20 years (Figure 1), 1985 saw the peak in interest in engineering careers, most likely a result of the early promise of biotechnology and information technology – areas associated with engineering and very closely tied to the human experience.

While national comparisons of numbers of engineering graduates can be useful in assessing gross trends, they fail to account for the varied capabilities of foreign educated engineers and what a recent report [7] identified as two distinct groups of engineering graduates: dynamic engineers and transactional engineers. Dynamic engineers were defined as individuals capable of abstract thinking and high-level problem solving using scientific knowledge. Dynamic engineers lead innovation and typically have a minimum of a four-year engineering degree¹. Transactional engineers, on the other hand, are typically responsible for rote and repetitive tasks in the workforce. Transactional engineers are commonly trained at the associate, technician or diploma level in less than four years. Related to this, such numbers also fail to account for the size of the engineering workforce *per capita*, a potentially useful metric when comparing the production of engineers among nations. Figures 3 and 4 are illustrative of this point. When one normalizes the production of engineering graduates to population, the United States production is quite similar to that of China, but falls considerably short of other nations that have a stronger technological societal ethos, such as Germany and Japan.

Although the population of a country such as China translates into a significant engineering labor resource, the state of development of their infrastructure is far behind that of the US. Their needs to modernize and grow this infrastructure will likely create a significant domestic demand for engineers reducing the availability of Chinese and Indian engineering graduates who might help reduce the shortfall in the United States.

It is therefore critically important that we increase the representation of engineering graduates in the United States. There are many aspects that must be addressed to close the gap between the US engineering workforce demand and the current or projected supply. One critical topic, that is the focus of this paper, is engineering college curriculum reform. In order to better approach the levels of engineering representation in society similar to countries such as Germany and Japan, we argue that educational reform to increase the perceived and actual social relevance of an engineering education and career is needed. This reform must be grounded in a broader more holistic education of engineers. Several institutions have already embraced this approach and have proven to be very successful. This paper will review some background information and then highlight some salient features of programs with a holistic philosophy.

Background

The stagnant numbers of U.S. engineering graduates occurring at a time of record college and university enrollments have been attributed to [8]:

1. The failings of the US K-12 education system, especially its inadequacies in science and mathematics (Figure 5 [3]).
2. A declining level of interest in such fields among US students, especially among the "best and brightest", in part because of the relative difficulty of science and mathematics as fields of study.

¹ Figure 1 reports the number of dynamic engineers.

3. Inadequate knowledge among younger US cohorts of science and engineering fields as careers, or in the alternative of the science and math prerequisites required to pursue them at university level.
4. For women and minorities, a lack of role models in these fields, suggesting to younger cohorts that such fields are "not for me."

It is argued here that an additional reason might be the nature and structure of the extant engineering curricula that are offered at universities around the nation. The transformation of the U.S. labor force from one that was largely manufacturing-based in the middle of the twentieth century to one that is more than 80% information-based today [9] has created challenging opportunities for engineering programs. However, an investigation of university engineering curricula in chemical, electrical, and civil engineering from the 1950s, 1980s, and today suggests that in many cases, other than important but relatively focused modifications such as the addition of biology to meet science requirements and the elimination of military science, much in the engineering curricula has been essentially static over this period. Elements of all these factors combine to yield what one recent study of multiple engineering cohorts reported as graduation rates as low as 33% [10].

ABET 2000 has allowed universities to become more creative in attempting to better educate future engineers to address the challenging problems of the 21st century. Capitalizing on this opportunity, the National Academy of Engineering report entitled *Educating the Engineer of 2020* [11] called for universities to revise their engineering curricula to better prepare engineers to solve problems that Peter Senge [12] describes as having derived from yesterday's solutions. Indeed, a recent article published in the *Chronicle of Higher Education* entitled "Holistic Engineering" [13] argued for a new paradigm in engineering education; one focused more on engineering fundamentals and complemented with an array of broad topic courses. Consistent with the NAE report, the article suggested that this approach would enhance the engineers' ability to better contextualize their work within the greater needs of society and develop the creative, innovative and holistic solutions to the problems and challenges of the 21st century. This broader educational philosophy would allow engineers to play a more prominent role in policy and decision making and attract more individuals to the profession to meet the demands of the coming century. Quoting directly from the NAE report, a university's goal should be to graduate "technically proficient engineers who are broadly educated, see themselves as global citizens, can be leaders in business and public service, and who are ethically grounded" where "learning disciplinary technical subjects to the exclusion of a selection of humanities, economics, political science, language, and/or interdisciplinary technical subjects is not in the best interest of producing engineers able to communicate with the public, able to engage in a global engineering marketplace, or trained to be lifelong learners."

Although it is well accepted that a sound math and science background is a necessary prerequisite for a successful engineering career, there is also the critical and complementary issue of motivation. Ask a physician why she selected a career in medicine and you rarely hear: "I liked biology", rather, the more common response is: "I

wanted to help people.” [18] This predilection is evident in the proportions of women who have entered other professions that have manifest social relevance (e.g. medicine, law, business). Figure 6 [4] shows that looking back to the 1960s, the penetration of women into all the professions was scant. However, as society demanded better gender representation and integration in all its professions, engineering alone has languished at about 20% while medicine, law and business are approaching parity. Certainly the technical rigor required to enter medicine is comparable with that required to enter the profession of engineering. However, engineering has failed to make a sufficiently compelling case for social relevance. It is this sense of social relevance and context that must be the prime motivation for students to be successful in the negotiating the challenges of an engineering education.

Moreover, the creativity and innovation promise of careers in engineering are often not borne out during the undergraduate experience. The creative aspects of design are all too often reduced to choosing the correct beam, or determining the proper residence time for a reactor – and these aspects are commonly delayed until late in a student’s education. The senior design experience, which is often open-ended and offers the reward for which many students enrolled, is only a portion of the educational experience. This lack of emphasis on nurturing the creative aspects of our profession has resulted in a mind set where students believe that the objective of their education is to follow specific protocols and just go out and “get a job” rather than go out, be innovative and “create jobs”. But how does one teach creativity and innovation? These processes typically derive from considering problems from different perspectives. The art of discovery is not necessarily about visiting new lands but seeing with different eyes. The broader ones education and the more ways of thinking to which one is exposed, the more creative, holistic, and expansive is the solution space.

It is not surprising that when one looks at the percent of engineers with their highest degree in engineering employed who are practicing in a field close to their discipline (Figure 7 [1]), we find that that on average less than half (46%) of engineers are so employed after 35 years. As one might expect, the percent of engineers practicing close to their discipline of education generally decreases with time. However, more remarkable is the large percentage of virtually all engineering graduates that do not work in an area close to their educational training. This is very strong justification for providing a broad education to engineering students so that they may effectively pursue varied career options.

Educational Innovation

Four engineering programs, two nascent and two historic (Smith College, Olin College, Dartmouth College and the University of Vermont), have evolved unique approaches to the challenge of nurturing creativity and holistic thought and inspiring students to consider engineering careers. The two former programs started with blank slates and could create any form or structure of their choosing.

Olin College offers only three accredited engineering degrees: mechanical, electrical and general engineering. [14] The curriculum is based on three major components: science and engineering fundamentals, entrepreneurship and the liberal arts. To help students stay well-rounded and balanced, they are encouraged to pursue their personal artistic, humanistic, philanthropic, and technical interests through the college's Passionate Pursuit program. Students complete a final project at the end of each semester and receive non-degree credit for their efforts. Examples of recent Passionate Pursuits include The Art of Glassblowing, Jewelry Making, Russian Studies, Flute Performance, and Rock Climbing with Physics. [14]

Olin students are also required to complete a Foundations of Business and Entrepreneurship course and incorporate entrepreneurial components into design courses. There is a focus on active learning and interaction with minimal reliance on traditional lectures, on the use of student portfolios (purposeful collection of student work used to demonstrate mastery of the course measurable outcomes, and to provide a personal reflective tool for self-assessment), and on interdisciplinary courses. The Olin program's philosophy is to build connections among fundamental science, mathematics, and engineering; among different fields of engineering; among the arts, humanities and social sciences and technical disciplines; and among business, entrepreneurship, and technology. As a result, the Olin curriculum is conceived and taught in a highly interdisciplinary way. The curriculum culminates in SCOPE (Senior Consulting Program for Engineering) a final year-long engineering project for an industrial or corporate client.

Smith College was the first women's college in the United States and one of the few liberal arts colleges to establish an engineering program. The Smith program has a continuous emphasis on the use of engineering science principles in design and culminates in a final design clinic based project that incorporates broad-based societal aspects for an industrial or governmental client. Unlike Olin College or traditional colleges of engineering, Smith offers only one accredited undergraduate degree, in Engineering Science, the broad study of the theoretical scientific underpinnings that govern the practice of all engineering disciplines. The Smith decision to offer only one degree in engineering science was based on the recognition of pitfalls of overspecialization in a world of rapidly changing technologies and increasingly complex multinational markets. [15]

Not surprisingly, Smith also pays significant attention to the liberal arts, requiring its entire engineering student body to take a "Latin Honors" set of courses. That is, at least one course in each of the seven general areas of knowledge must be taken: literature; historical studies; social science; natural science; mathematics and analytic philosophy; the arts; a foreign language. This is particularly noteworthy for two reasons. Smith has no core curriculum and therefore the engineering students at Smith are the only majors required to have this curricular breadth. Secondly, one year of a foreign language is required of all engineering students, another unique feature of the program which helps prepare graduates to understand foreign cultures and practice in a global economy.

At Dartmouth College, where the Thayer School of Engineering is one of the oldest engineering programs in the country, the story is similar; undergraduate students are grounded in the liberal arts, rooted in the humanities, and learn engineering through an interdisciplinary systems-based engineering curriculum [16]. Students pursuing engineering at Dartmouth meet general education requirements identical to those of all other liberal arts majors with emphasis on humanities, sciences, and writing. In the engineering courses, there is an emphasis on a systems approach to engineering throughout, and the incorporation of team-based design projects from the outset. For example, in the first sophomore-level engineering course, an interdisciplinary offering entitled “Introduction to Engineering,” student teams are challenged to identify a practical problem in a general area addressing a contemporary problem (for example, “energy technology” has been chosen as one of the course themes for fall 2007), brainstorm to identify possible solutions, research the relevant patent literature, choose an approach, prototype, test, refine, conduct economic analysis, prepare a business case, and present and defend their results to a design review board – all in a single ten week term. Through this course, students take a systems-approach to problem definition and solution, rather than being restricted to the tools and language of a specific engineering discipline. Evidence for the success of this approach is provided by the nine student teams who have filed for patent protection on their term projects within the past 5 academic years, with one student team recently winning a national breakthrough award for their effort to develop an alternative to children’s training wheels [17].

The Dartmouth program described above typically culminates in the awarding of a Bachelor of Arts (A.B.) degree in Engineering Sciences as the students’ first degree. Students may then choose to pursue an ABET-accredited Bachelor of Engineering (B.E.) degree, also in Engineering Sciences but with more disciplinary emphasis, an emphasis based upon student choice of electives. The B.E. is typically earned through a fifth year of study, although 20% of B.E. recipients earn the B.E. and A.B. concurrently in 4 years. This combination provides students with both the breadth characteristic of a liberal arts education and the depth desired as the foundation for graduate study in an engineering discipline.

Finally, the University of Vermont College of Engineering and Mathematical Sciences has long offered a traditional engineering program, with accredited degrees in civil, mechanical, electrical and environmental engineering and an unaccredited degree in engineering management. However, it recently underwent organizational restructuring unifying historical engineering departments into a single School of Engineering. Consistent with and capitalizing on this transformation, the School of Engineering is also undergoing a major curriculum reform. The proposed curriculum (Curriculum 21) is based on the vision of how to best prepare engineering graduates for the 21st century and lifelong careers. The student educational experience will stress innovation and creativity in design and will be personalized, multidisciplinary, liberal, systems-oriented, integrated, and interactive.

Curriculum 21 was recently approved by the faculty. Key items of this reform include: (1) development of a common two-year core for all engineering students, (2) an 18-

semester hour elective focus area for all engineering students, (3) common multidisciplinary first year and senior design courses, (4) a professional seminar for junior-level students, (5) a proposal for a new Bachelor of Arts in Engineering program intended to serve as a bridge between engineering and the liberal arts and to provide opportunities for students who want to learn how to think like engineers but would like to pursue other careers (e.g. medicine, law, finance), and (6) a proposal for a new Bachelor of Science in Engineering Science program to allow students to pursue interdisciplinary studies in multiple engineering areas or in areas connecting engineering with mathematics, physical or life sciences, or business.

Interestingly, in all four cases² the programs elected to organize themselves in a structure that has no traditional academic departments or boundaries and stresses broad interdisciplinary education that is contextualized in a societal relevant framework and stress creativity. In all these programs, students are exposed to modes of reasoning beyond the science and engineering paradigms, allowing them the resources to consider more holistic approaches to solving what might otherwise have been considered narrow technical problems. If engineers are to move beyond a profession characterized by specific performance expected of the “sons of Martha” [18, 19] and move to a profession truly inspired by creativity and holistic systems thinking, we must move to a broader undergraduate preparation for our students.

Not surprisingly, the interest in these programs outpaces the national trends. For example, at the University of Vermont applications to the School of Engineering have increased by 64% since the announcement of the Curriculum 21 reform effort.

Summary

There are many traditional engineering programs in the United States and abroad. The dawn of a new century gives us pause to consider the strengths and weakness of these programs that have generally served us well in the past. The projected shortages of engineers in the United States are an indication that the profession’s attractiveness has not kept pace with the profession’s opportunities. Moreover, the challenges of the coming century will demand creative, innovative and holistic solutions that will require broader pre-professional preparation. This paper summarized several programs that have model curricula designed to address these concerns.

Curriculum reform is not without challenges and it is not suggested that all traditional programs abandon a departmental structure and seek an integrated organization and curriculum. However, a first step in moving toward a curriculum that can better educate holistic engineers might be to work toward true interdisciplinarity at both ends of the undergraduate experience. By structuring a first year design course that brings together students of varied interests and backgrounds, the profession of engineering can be contextualized within a societal framework inspiring students to seek creative solutions

² It is also worth noting that UC-Merced’s new School of Engineering is also devoid of traditional academic departments.

using the engineering method but unencumbered by traditional disciplinary protocols. This would serve to encourage students to continue with the rigors of an engineering education and concomitantly to seek a broad education to help them address the myriad of factors which the future will demand. Complementing the first year course, a unified senior design course that is truly interdisciplinary and involves engineering students of all disciplines together would better prepare our students to design the holistic, creative, and integrated solutions that will serve society's needs.

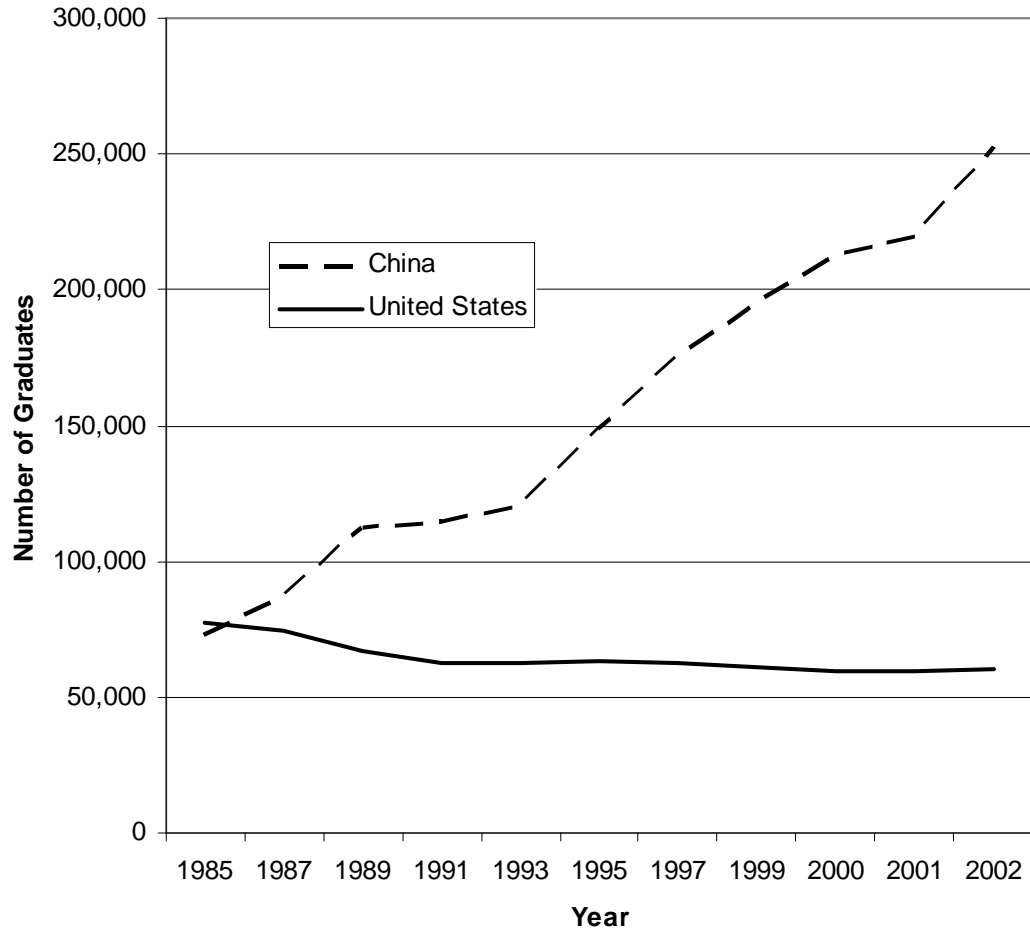


Figure 1. Engineering college graduates in the United States and China (adapted from data in reference [1]). Missing U.S. 1999 data approximated by the average of 1997 and 2000 data.

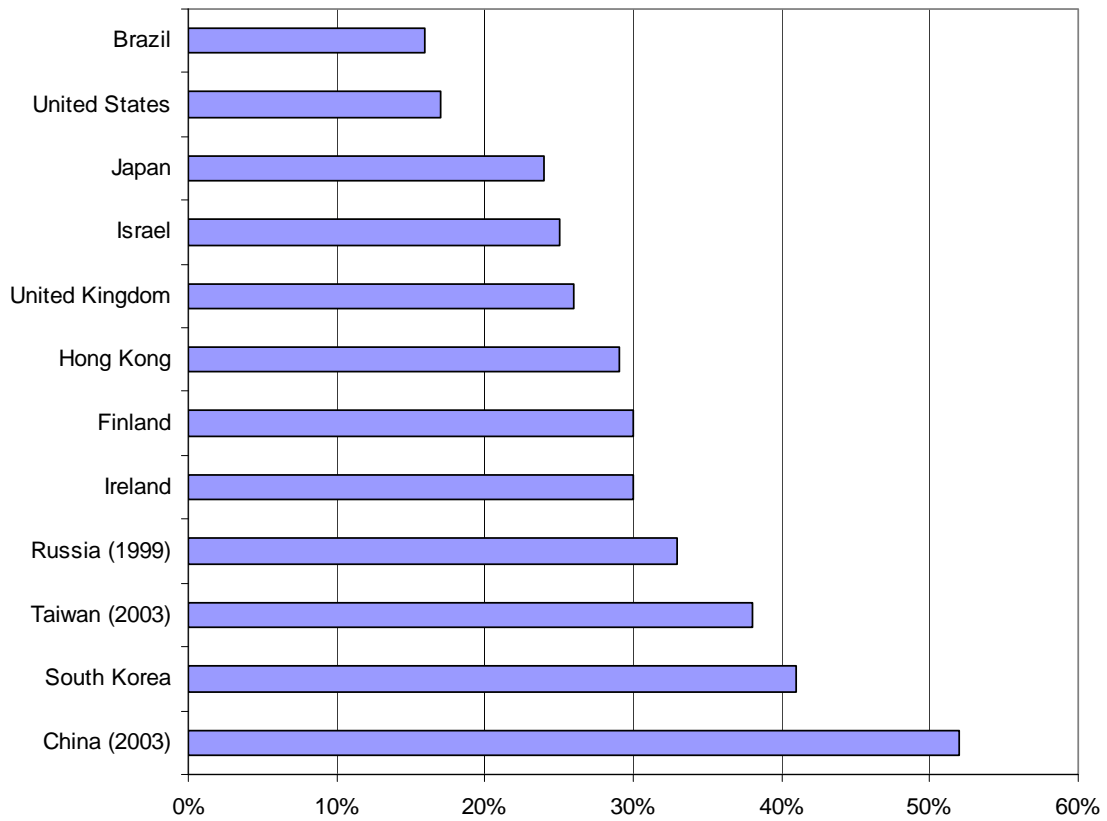


Figure 2. Percent of undergraduates receiving science³ and engineering degrees⁴ (adapted from reference [3]).

³ Science includes physical, biological, earth, atmospheric, and ocean sciences, agriculture, computer science and mathematics.

⁴ Data are for 2002 or year stated.

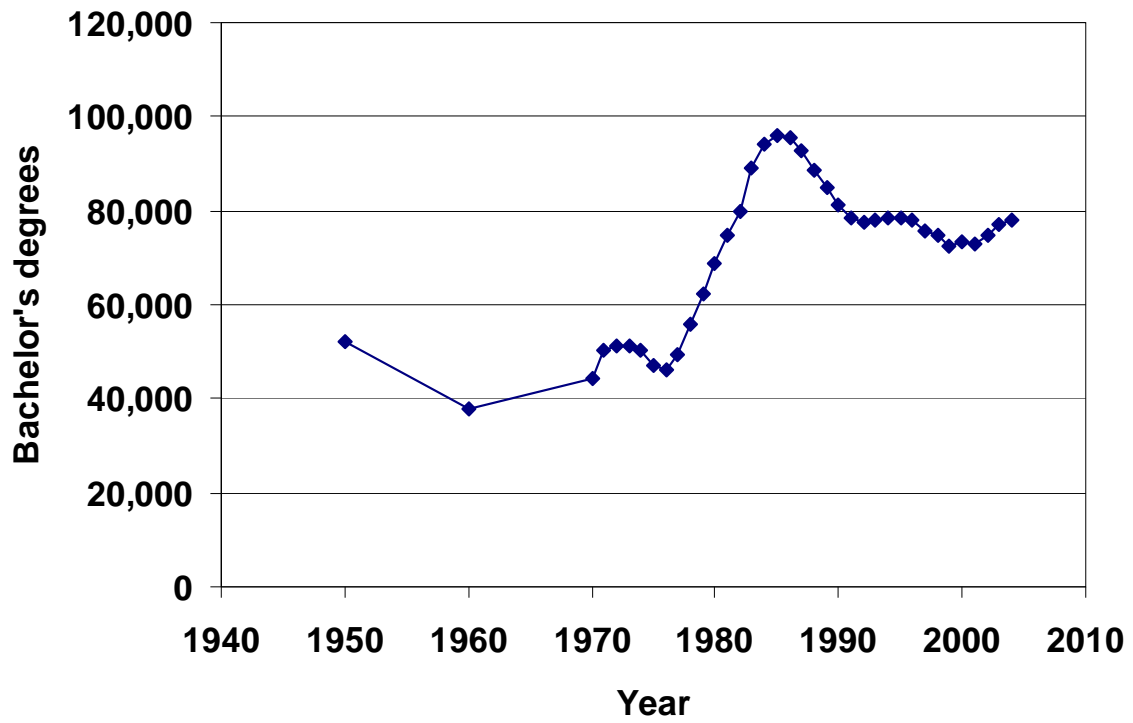


Figure 3: US Bachelor's degrees in engineering by year. Data source: US Department of Education, National Center for Education Statistics [4].

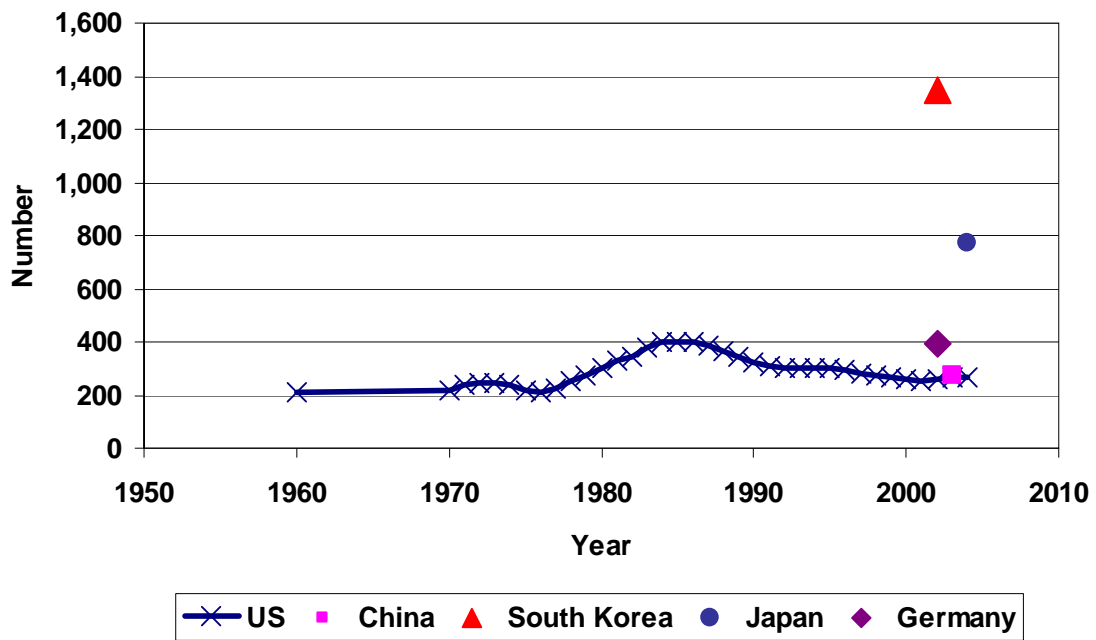


Figure 4. Number of engineering Bachelor's degrees or equivalent per million population. Sources: [1, 4-6].

U.S. Students Rank Poorly Compared to G8 and OECD Countries

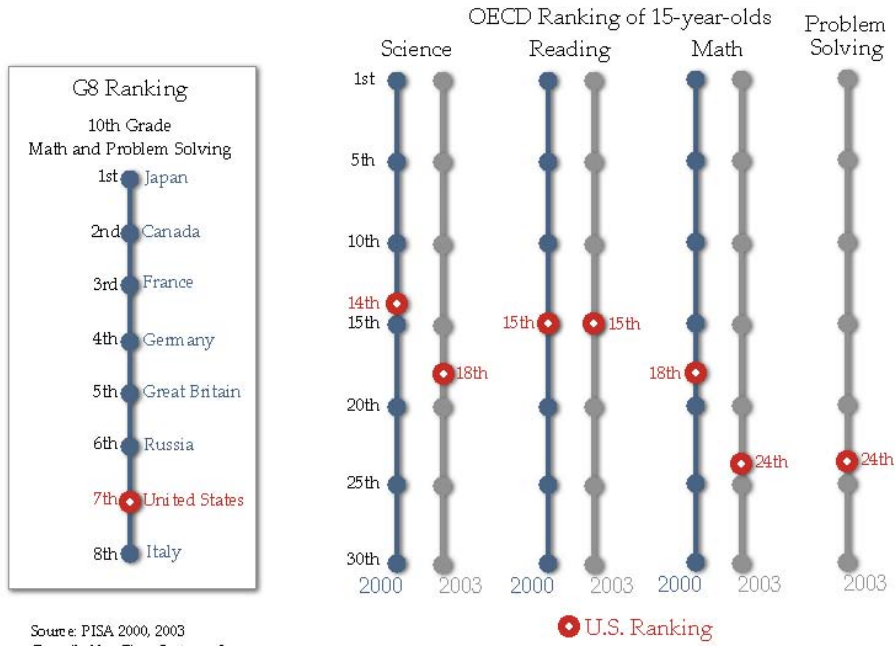


Figure 5. Ranking of 10th grader (G8 nations) and 15 year old (OECD) performance in various standardized tests. (reprinted with permission from reference [3]).

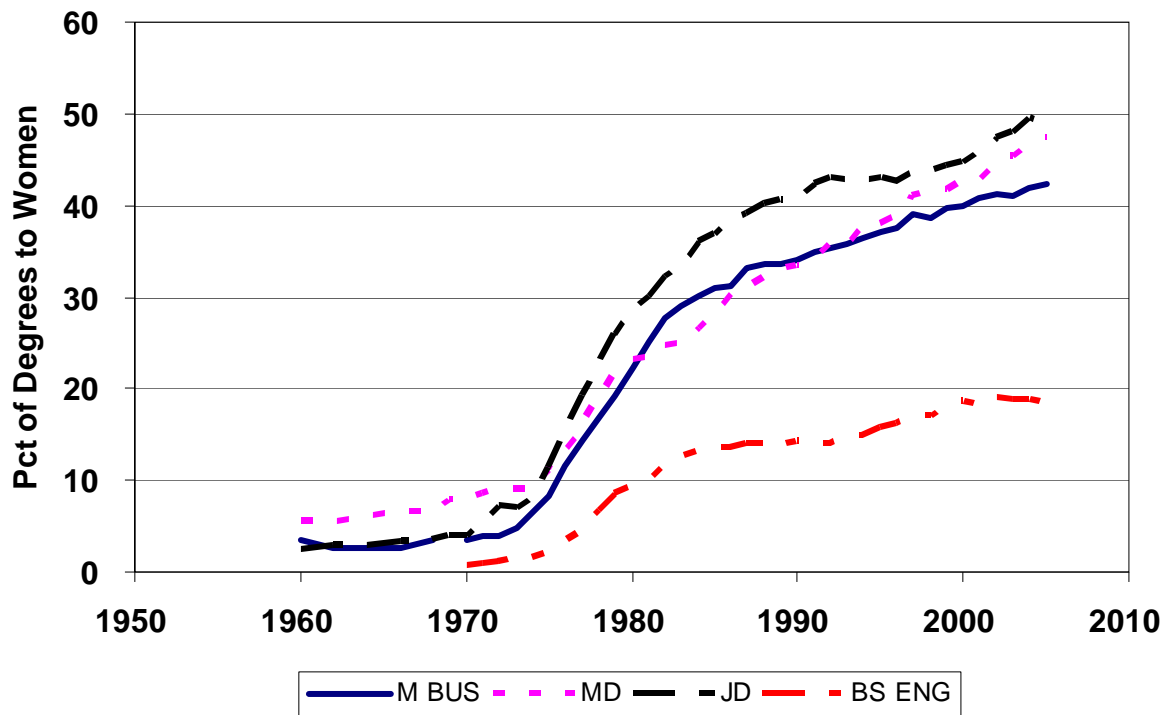


Figure 6. Percentage of U.S. degrees granted to women in business (all Master's degrees), medicine (Doctor of Medicine degrees), law (Juris Doctor degrees), engineering (Bachelor's degrees), 1960-2005. Source: selected tables from U.S. Department of Education, National Center for Education Statistics [4].

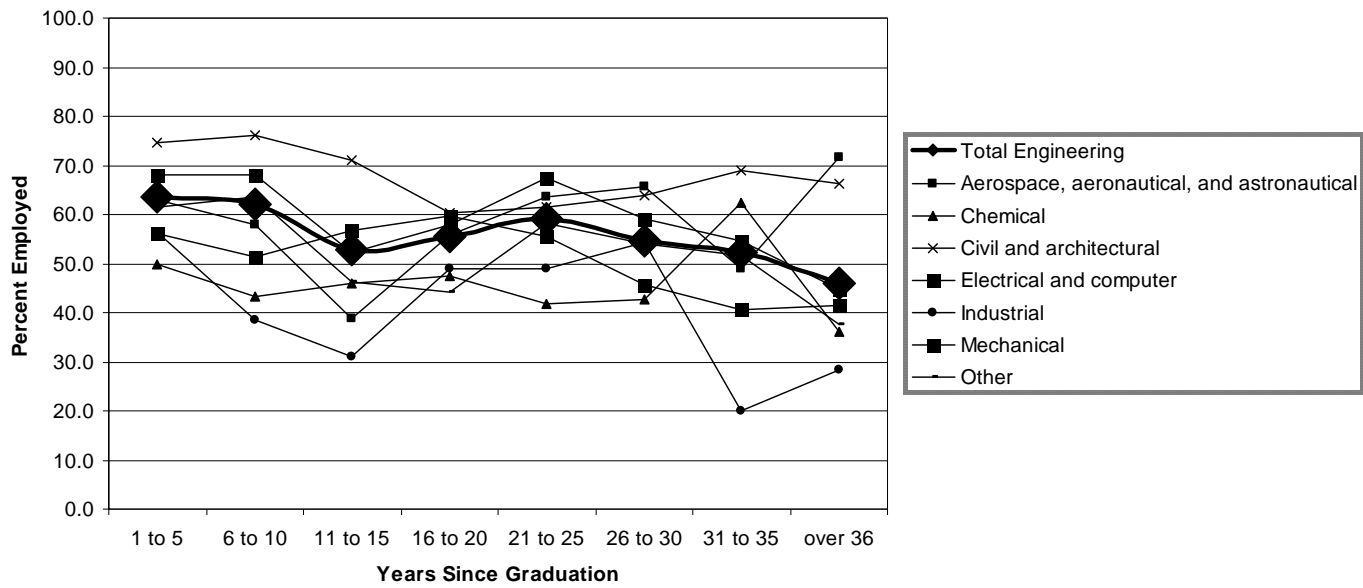


Figure 7. Employed individuals with engineering highest degrees whose jobs are closely related to field of highest degree, by years since degree: 2003 (adapted from data in reference [1])

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