Re-Engineering Engineering Education for the Challenges of the 21st Century

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INTRODUCTION

Engineering education and the profession are confronting a challenging crossroad. Some of us see it as a crisis, others, as an opportunity for positioning our community and our society for the 21st century. It would be fair to say, however, that none of us are very satisfied with the status quo and what seems to be facing us in the near term. As Charles Dickens cited in the opening of *A Tale of Two Cities*, "It was the best of times, it was the worst of times".

Author and journalist Thomas Friedman has declared that the world is now flat.[1] Globalization of the economy has amplified the impact of technology on modern societies in ways that could not have been predicted. The connectivity provided by the Internet has generated new markets for products and services, but has also made available labor that is often both educated and cheap. This is likely to have a profound impact on the distribution of wealth in both the developed and the developing parts of the world and may, in particular, alter the socio-economic structure of countries where the general wellbeing of the population has been taken for granted. That education plays a role in the prosperity of nations is not debated, but many authors, like Landes[2] for example, argue that it is specifically the presence of both knowledge and know-how that determines how well off societies are. The education of engineers is therefore critical to every nation to ensure the prosperity of their citizens.

The modern professional identity of engineers emerged in the early 18th century with the establishment of the Ecole Polytechnique in France and the foundation of professional engineering societies in England. The current way of educating engineers, including the structure of the curriculum, was already established by the early 20th century, but the course content has, of course, changed significantly since then. The last major shift in engineering education in the United States goes back over half a century when the role of science in the educational program increased significantly.[3] Although some evolution certainly has taken place, those changes are relatively modest and the basic structure and course content of a modern engineering program is very familiar to someone educated in the sixties.

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The time for another major re-examination of engineering education is overdue. Countless committees, task forces, panels, and commissions have already addressed the need and eloquently emphasized that the competitiveness of the country and therefore the general standard of living hinges on the ability to educate a large number of sufficiently innovative engineers [See, for example References 4–8]. Figure 1 clearly shows the concern with respect to manufacturing production, especially when one compares the production in the United States to Japan and China.[9] This is even more concerning when one considers that creation of wealth is related to a nation's ability to make products that other nations want to purchase.

That the world has changed in fundamental ways during the last decade or two is self-evident. Computers have completely altered the way we live and work. They have, in particular, transformed our ability to deal with information and data. We are now moving rapidly toward a world where, for all practical purposes, we can process information infinitely fast, store infinite amount of data, and transmit data instantaneously, to paraphrase a statement made by Henry B. Schacht, the first chairman and chief executive officer of Lucent Technologies Inc. in his commencement speech at Worcester Polytechnic Institute (WPI) in 2001.

As a result of the emergence of the Internet, knowledge has been "communalized." Everybody has access to information about anything and, perhaps equally importantly, knowledge is no longer "owned" by the experts. High school students can, and do, write articles on Wikipedia, just like the professors. This change has already transformed industries and raised fundamental questions about authorship and ownership of information and scholarly works. Computers have also empowered the average man and woman to create products that previously required large corporations with significant resources. In many aspects of digital media we have now reached the point that if we can imagine it, we can create it. As computer speed and software advances, this trend will continue and in 20 years or so it is very likely—almost certain, actually—that a high-school student with a laptop, and a little bit of time, will have the capability to create a full-length animated movie with virtual actors of the quality currently only produced by major moviemakers. The same transformation is likely to happen to the creation of engineered artifacts, although the time frame may be somewhat longer. Ordering components through the web and receiving them in the mail is now part of everyday life and e-manufacturing—where the customer sends an electronic description of a part to a manufacturer, who makes it and mails it back—is emerging.

The globalization of the world economy affects everyone. The movement of labor-intensive but low-skill industries to countries with low labor costs is, of course, not new. Such transfer has been largely responsible for the low cost and abundance of most manufactured goods and the rising importance of service over "stuff." Today, however, the rise in education in nations where salaries are low and the connectivity that makes this cheap and educated talent available worldwide are gradually changing the nature of jobs that move oversees. Skill is rapidly becoming a commodity that can be bought from low-cost providers anywhere. It does not matter what you know how to do; someone else knows it too and is willing to do it for less.

The mechanization of labor and advances in transportation taking place during the last century, coupled with the more recent information revolution and globalization of the economy, have brought unprecedented opportunities and challenges. On the positive side is that the increase in our material wealth makes it realistic, for the first time in history, to talk about eliminating extreme poverty.[10] On the negative side is the possibility, for the first time in history, that human consumption of materials and energy may irreversibly damage the entire global environment (Reference 11, for example). Engineering in the new world is therefore both a daunting and an exciting undertaking!

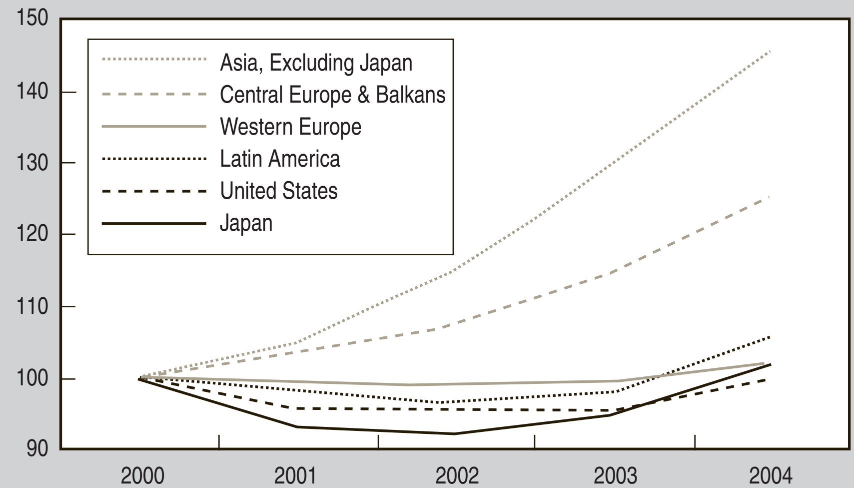

Figure 1. Manufacturing production by region of the world.[9]

HISTORICAL CONTEXT

History shows that we in the United States took our roots and our values from many different lands, and, in particular, we became the heirs to both the French and British cultures.

Louis XV established a civilian engineering corps to oversee the design and construction of bridges and roads in France. In 1716 he established an organization called the Corps des Ponts et Chaussées, which subsequently established a school to train its members. In 1747 Ecole des Ponts et Chaussées was founded in Paris—the first engineering school ever. This led to the founding of other technical schools in France known as the Grandes Ecoles. The famous Ecole Polytechnique of Paris was founded in 1794 by Napoleon. The French recognized engineering as a noble profession that prepared the future statesmen and leaders of their society. In fact, the word ingenieur stems from the word genie meaning genius, which is quite different from some of the connotations with respect to engineering and engines. The famous mathematician Laplace wrote that the Ecole Polytechnique's goal is to produce young people "Destined to form the elite of the nation and to occupy high posts in the State." The graduates of these Grandes Ecoles have over the years proven their "power" by occupying posts in the highest economic strata of French society.[12] To say the least, in France the "polytechnicien" reigns supreme.

On the other hand, as one reviews the evolution of engineering in Britain, we will see a very different path. The English upper class believed in a much more classical education wherein the bright young males sought careers in the church or in the army. There was no meaningful governmental funding of higher technical education during the industrial revolution and it was not till the early 1900s that Cambridge and Oxford universities established chairs in engineering science. Much of the industrial revolution was driven by individual ingenuity and entrepreneurial initiative. Knowledge was gained pragmatically in workshops and on constructions sites. Apprenticeships became the way young men went into engineering. As Samuel 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 navy occupation—the original navies being the laborers on canal construction jobs."[12,13] Both of these cultures, the theoretical foundation emphasized by the French Ecoles and the practical hands-on attitude of the British, permeated across the Atlantic and impacted the development of engineering education in the United States. Although it is possible to argue that the marriage of theory and practice played no small part in the phenomenal successes of U.S. engineering in the 20th century, finding the right mix occupied engineering educators throughout the century.

As engineering education has changed in the past to adjust to the needs of society, the evolution must continue and change is needed to address the needs of the 21st century. With many approximations and generous error bars, we can summarize major trends in engineering education by the following classification (for a more fine-grained classification see Reference 14):

19th Century and First Half of the 20th Century: The Professional Engineer

As engineering became a distinct profession, early engineering programs focused on providing their graduates with considerable hands-on training. However, the role of science and mathematical modeling slowly increased and gained acceptance.

Second Half of the 20th Century: The Scientific Engineer

By mid-century, technological progress, including the successful harnessing of nuclear energy, as well as geopolitical realities as materialized by Sputnik drove home the need for engineers to be well-versed in science and mathematics and the engineering curriculum adjusted to the changed needs. This structure has, to a large degree, continued until the present time, although design content increased slowly. In the early 1990s it was clear that more than science was needed and many schools started to emphasize non-technical professional skills such as teamwork and communications.

The 21st Century: The Entrepreneurial/ Enterprising Engineer

The rapid changes occurring in the world coupled with changes in engineering education starting to take place in the 1990s are likely to result in an extensive re-engineering of engineering education. While the new structure will, almost certainly, continue to be based on a solid preparation in mathematics and sciences, it is likely to emphasize the professional role of the engineer and then demand new qualifications suited for the new world order.

THE ENGINEER OF THE 21st CENTURY

We cannot, of course, say what the engineering profession will look like 100 years from now. The intense discussions that are currently taking place[4–8] among leaders of the profession and educators suggest that innovation will be a central theme. The premise is that skill is a commodity and that routine engineering services will be available from low-cost providers that can and will be located anywhere in the world. The engineering education therefore has to add value beyond just teaching skills. That skill is or will become a commodity does, of course, not mean that future engineers do not have to possess skills. Quite the contrary, they will have to be even more technically proficient than those making a living today practicing narrowly defined tasks. The engineers of the 21st century must constantly be able to gather information and decide on a course of action, including what tools are needed for a given task. The technical skills, the people skills, and the innovation required of the future engineers can be summarized—with only modest exaggerations—as follows:

The entrepreneurial engineer of the 21st century

- Knows everything—can find information about anything quickly and knows how to evaluate and use the information. The entrepreneurial engineer has the ability to transform information into knowledge.
- Can do anything—understands the engineering basics to the degree that he or she can quickly assess what needs to be done, can acquire the tools needed, and can use these tools proficiently.
- Works with anybody anywhere—has the communication skills, team skills, and understanding of global and current issues necessary to work effectively with other people.
- Imagines and can make the imagination a reality—has the entrepreneurial spirit, the imagination, and the managerial skills to identify needs, come up with new solutions, and see them through.

How do we educate someone barely into their adult life to possess these qualifications? Or, for that matter, do such generalized statements mean anything concrete? Our contention is that they do and that first of all, these goals translate into specific curricular requirements and second, that we are well on our way to achieving some of these goals—or that we at least see how to proceed.

The first goal—knowing anything—is relatively easy. We can now "Google" any concept and the probability is that we will have an abundance of information in a matter of seconds. And as search engines become more sophisticated the probability that the information is relevant will increase. The transformative effect of being able to access information instantaneously cannot be overemphasized. We all "know more than we know" because in addition to knowledge we possess we also know where to find information about specific things. Most of us know how to fix our computers, not by knowing so ourselves, but by knowing whom to ask. The introduction of the Internet expanded this network of contacts to literally every piece of information that exists. However, while finding information is already trivial, the communalization of knowledge will make it essential for the professional engineer to be able to judge the quality of the information that he or she has. Thus, teaching how to deal with an abundance of information and how to judge the relevance and the quality of the information at hand will be the educational challenge.

Engineers have always learned as they tackle new challenges. The explosion in the availability of tools to do nearly everything does, however, suggest that engineering educators must rethink how students are prepared in the foundation of their disciplines. Computer programs to do virtually anything, from conducting simple calculations to simulating complex systems to design a complete engineered artifact, empower the modern engineer to do more than his or her predecessors could ever imagine. These tools do, however, not only require that the engineer knows how to use them, but also require him or her to be able to first to assess what tool is appropriate for a given task and then to be able to evaluate the result in a critical way. "To err is human, but to really screw up you need a computer," so the importance of common sense will be even greater when design and analysis are done exclusively on the computer. While teaching engineering students how the physical world works is at the core of engineering education today, re-examining how we teach the fundamentals of engineering science to students is needed. Knowing the scale of phenomena and the distribution of knowledge over multi-scales are critical attributes.

In addition to the changes in the technical skills engineers must possess, their non-technical professional skills must be suited for the modern way of doing engineering. Considerable progress has already been achieved in the United States to make communication in the broadest sense an integral part of the engineering curriculum.[12,15] Most programs now require their graduates to exhibit proficiency in oral and written communications and to be able to work on diverse teams. Engineering, possibly more than most professions, requires accurate and efficient communications—I have to understand what you are saying and vice versa for the design that we both are working on to function. The surprising thing about communications is not that engineering schools have recently started to emphasize it (motivated by ABET,[15] in some cases), but that there ever was a need to remind educators that engineers need to communicate! However, in a flat world the ability to communicate takes on a much broader meaning. Not only are engineers frequently working on products that will be made in a different country and marketed to people of different cultures, but product engineering is increasingly done by teams consisting of people located in different countries and with diverse cultural background. Such interactions obviously have enormous potentials for misunderstanding and conflicts. To make the case, we quote Ron Zarella, chief executive officer of Bausch and Lomb, who said, in a speech that he gave at WPI during a globalization workshop: "We make a product called interplak. The electromechanical design for this home plaque-removal device is done in Germany and Japan. The batteries are supplied from Japan, the motors are built in the Peoples Republic of China, the charging base is made in Hong Kong, the precision molded plastic pieces are manufactured in Atlanta, Georgia, the brush head is made in Ohio, and the final assembly is done in Mexico."

Preparing young engineers to work in a flat world is no longer something that engineering schools can treat as an extracurricular activity, available only to those with the time and resources to spend an extra semester abroad. Every student must now develop the attitudes and skills necessary to function globally, right from the time they first enter the workforce.

With skill becoming a commodity, the engineer of the future must be able to do more than just perform technical tasks. There have always been extraordinary engineers who have had the imagination, vision, dedication, and endurance to change the way we live. Those who have not have, however, in the past been able to make a living performing routine engineering tasks. The young engineers of the future must, on the other hand, all be extraordinary. They will not be able to enjoy the comfort of well-paid jobs where routine tasks are performed more or less unchanged year after year. More and more the engineer of the future will be responsible for creating new ideas and solutions and seeing them through. Innovation has already been identified as one of the most important factors in the future prosperity of both nations and individuals.[1,2,7,8] The engineering challenges are, however, even greater. Not only must the engineer innovate, he or she must be able to help the innovation become a reality. Thus, the education of the engineers of the future must prepare them to see new opportunities as well as to give them the skills needed to marshal the resources to realize their ideas.

CONCLUSION

It is unthinkable that U.S. society can remain competitive and can sustain its present standard of living without a large number of people with the knowledge and know-how to innovate.[1,2] In the early days of the nation, Noah Webster claimed that democracy succeeds and prevails only if the people have economic and educational hope, and that these two are closely interlinked. To educate engineers ready to face the challenges of tomorrow we must appreciate how profoundly the world has changed from just a few decades ago. Thus, we need to examine the curriculum from a new perspective and accept the possibility that changes that go beyond minor tweaking are needed. Here, we have attempted to set up a framework to do so. We have tried to be general, but we believe that the suggestions made here have very specific implications for engineering curricula. The actual implementation, however, remains a topic for further study.

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