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HOLISTIC ENGINEERING

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The Golden Gate Bridge, the longest suspension span in the world when it was completed, in 1937, is widely recognized as an engineering marvel and a symbol of technology in harmony with its surroundings. When the bridge opened to a ceremonial trickle of cars, it would have been hard to imagine that an estimated 100 million tons would eventually cross annually between San Francisco and Marin County. Even less foreseeable, however, were the nearly two suicides per month, on average, facilitated by this testament to the power of engineering thought. As we say in the profession, the bridge has exceeded its design specs.

The Golden Gate Bridge is a useful metaphor in considering the scope of the challenge faced by every engineer beginning a design project: how to design for a specific objective without creating unintended consequences. Avoiding unintended consequences has never been more difficult or important than it is today, as population soars and technology, ever more complex, becomes increasingly embedded in human experience.

In this evolving world, a new kind of engineer is needed, one who can think broadly across disciplines and consider the human dimensions that are at the heart of every design challenge. In the new order, narrow engineering thinking will not be enough. American higher education is in an unusual position to create the 21st-century engineer.

Engineering and technical education are very much in the public eye now. For more than a year, Congress has debated how to best respond to the National Academy of Engineering's report "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future." The report is powerful in its statement that the "scientific and technical building blocks of our economic global leadership are eroding at a time when other nations are gathering strength." Among the recommendations it proposes are increased investment in research and education in technical disciplines. In response to the report, President Bush announced, in his 2006 State of the Union address, the American Competitiveness Initiative, which Congress has been considering in various versions ever since.

But investing resources in simply encouraging a technical-education paradigm developed in, and best suited to, the 20th century would be shortsighted and ineffectual. Congress might be well advised to use the opportunity to encourage the major transformation that the new century demands — and that American engineering schools are distinctly positioned to supply.

In the global marketplace, engineers are proliferating at an astounding rate. The past decade and a half has seen the rapid economic development of half a dozen countries in Asia and Eastern Europe once mired in poverty or slow-growing controlled economies. Now millions more people are embracing capitalism, and with it the technological engine that drives it. A previously untapped global human resource is being extracted like oil from new wells, yielding first a manufacturing capability, and now a staggering number of new engineers and scientists. According to some estimates, Asia alone graduates more than 10 times as many engineers annually as the United States does, many of them as qualified as our top graduates.

The emergence of a new global engineering work force and its threat to the U.S. economy have been the topic du jour in engineering and business circles, but responses tend to focus on increasing the number of traditional engineering graduates so we can go head-to-head with other countries in the technological marketplace. Such a goal alone, however, would do little more than drive down the price and value of engineering services, leaving the United States no better equipped than other nations to solve the increasingly complex problems facing society.

The answers lie in the quality of the product rather than in the quantity of output. The crucial question facing academe is whether we are adequately preparing our future engineers and designers to practice in an era that requires integrated and holistic thinking, or are needlessly limiting their solution spaces to those that contain only technological answers, with scant or passing consideration of the myriad other influencing and dependent factors.

Where should educators turn in preparing high-quality engineers who are better equipped to serve in the changing global marketplace? As engineers are often taught, solutions to new problems are found in returning to first principles. In that context, "first principles" means examining the definition and role of the engineer in their purest forms.

For centuries, society's problems have been sufficiently linear, mechanistic, and discrete to be served by engineers responsible for "solving problems through the application of math and science," the classic definition of engineering that has served us well — until now. By many accounts, 80 percent of our economy is now information-based. Yet if one were to pursue an undergraduate engineering degree from a typical state university, the result would be courses not significantly different from those offered during the middle of the past century, when we were largely a manufacturing-based economy.

Pursuing the holistic concept of the "unity of knowledge" will yield a definition of engineering more fitting for the times ahead. The unity of knowledge — first proposed by James Marsh, president of the University of Vermont in the early 1800s, and resurrected by the Harvard sociobiologist E.O. Wilson in his book *Consilience: The Unity of Knowledge* (Knopf, 1998) — is fundamentally about integrating knowledge across disciplines to deal with complex problems and better serve humanity. Many thoughtfully constructed versions of core curricula, sometimes referred to as general-education requirements, attempt to teach multiple modes of reasoning or ways of knowing. However, colleges rarely take the next step and encourage

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students to understand the connections among their courses and to integrate, or “unify,” their learning.

In engineering, a discipline that purports to design for humanity and improve the quality of life, the unity of knowledge should be a sine qua non that asks engineers to look outward, beyond the fields of math and science, in search of solutions to entire problems. To better serve humanity, engineers must at least attempt to understand the human condition in all its complexity — which requires the study of literature, history, philosophy, psychology, religion, and economics, among other fields.

Such a perspective on engineering education need not be restricted to the undergraduate curriculum. The educational philosophy embodied in the unity-of-knowledge approach also has a research analog in one of the most promising areas of investigation today: complex-systems analysis (recently identified in the National Science Foundation draft strategic plan, “Investing in America’s Futures,” as an area of focus and investment). Typically, complex systems are those that change with time, don’t vary in linear pattern, and demonstrate “emergence” — that is, behavior that cannot be predicted in advance from constitutive parts. Complex systems are different from merely complicated ones, such as jumbo jets or fine Swiss watches, whose behavior, though characterized by the intricate interrelationship of many parts, is determined and reproducible. While advanced mathematics is a necessary tool for working in the field of complex systems, so too is an understanding of human nature. Complexity is especially evident when human decisions play a role in the system — for example, in the dynamic functioning of the electric-power grid.

Educating engineers more broadly will not only make them better designers but will also give them the tools to work productively alongside the other problem solvers they will be increasingly required to collaborate with: lawyers who resolve conflicts, economists who find the incentives and disincentives that promote positive change, historians who elucidate the present through knowledge of the past, artists who have an appreciation for form and function, and politicians who reach compromise. The ability to model and incorporate elements of economics, sociology, psychology, and business to identify possible solutions to pressing problems will be a major part of the future of engineering.

Consider a rather simple example: acid rain, which results in large part from burning coal. Environmental engineers and scientists worked hard on technologies to curb the pollution, but it was economists who developed the “cap and trade” permit program — which, through tradable pollution permits, has allowed market forces to create incentives for companies to cut pollution and reduce acid rain in the Northeast. Were the mathematics in that economics program beyond the capabilities of engineers? Or did their preparation not allow them to consider all the possible solutions, which is to say, the ones that did not depend exclusively on technology?

When Stockholm was considering ways to transport more people into and out of the city, the concept of adding one more bridge to the 57 that already connect the 14 main islands that constitute the city would have been the natural engineering extension of past practices. Stockholm retained IBM — a company with a not-insignificant number of engineers. However, prompted by an economic realignment in the United States from manufacturing and industry to services and innovation management, IBM has already moved beyond traditional engineering thinking. Specifically, the company has embarked on a research-and-business model that applies technological and manufacturing models to the holistic delivery of services.

To solve Stockholm’s traffic problem, IBM designed a “tax and drive” system, in which autos are fitted with transponders and drivers are charged a fee based on the time of day their cars are in the city. In the first month of operation, the system yielded a 25-percent reduction in traffic, removing 100,000 vehicles from the roads during peak business hours and increasing the use of mass transit by 40,000 riders a day. Stockholm needed no new bridge and gained the concomitant benefits of reducing pollution and conserving energy. London has taken similar steps.

In a world where applied science and technology are available to practically anyone for a few rupees or yuan on the dollar, we have to ask ourselves: What will the U.S. engineer have to offer that is not available in the global market for a fraction of the cost? If we decide to compete with other countries using the traditional definition of engineering, we will certainly succeed in converting engineers into a commodity.

A better response lies in changing the scope and significance of what engineering is and, perhaps more important, who engineers are — namely, technically adept people who serve humanity through the application not simply of math and science, but of a wide array of disciplines. This new breed of engineer will be not only a truly comprehensive problem *solver,* but a problem *definer,* leading multidisciplinary teams of professionals in setting agendas and fostering innovation.

If, as many glossy college brochures say, engineers are problem solvers, we must open their eyes and minds to the range of problem-solving approaches that go beyond math and science. That is not to say that engineers must stay in school for 20 years to learn multiple disciplines in depth, but that they should experience the richness of a broad undergraduate education. It is not uncommon for only about 15 percent of the typical engineering curriculum in the United States to consist of electives. There is no question that our engineering graduates are well versed in the technical aspects of their profession. But it is equally clear that many of them graduate without the breadth they’ll need to think through the solutions we need.

Given that many rote engineering tasks can be easily outsourced, and that engineering organizations, including the National Academy of Engineering, are calling for the master’s degree to be the first professional degree in engineering, it is time to consider a major overhaul of the undergraduate engineering curriculum. At the end of the 19th century, law schools concluded that they could no longer teach all of the vast number of laws that had accumulated over time and decided instead to teach students how to think like lawyers. So, too, at the beginning of the 21st century, should undergraduate engineering schools focus on teaching students how to think like engineers.

Building quantitative-reasoning skills should still be a top priority for American engineering education, but that rigor should be complemented with developing students’ ability to think powerfully and critically in many other disciplines. To be sure, it will be a challenge, but a challenge with tremendous benefits.

Recently the Golden Gate Bridge, Highway and Transportation District selected an engineering firm to develop a plan to create barriers (physical or otherwise) to suicide attempts. With any luck, a well-considered and holistic solution to the human dimensions of the challenge will present itself, not one that creates unintended new problems born of the myopia of a purely technical approach.

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