The Urgency of Engineering Education Reform

by **William A. Wulf**

INCORPORATING A SET OF "NEW FUNDAMENTALS" into the engineering curriculum and encouraging faculty to practice their craft are among the steps needed to bring engineering education into the 21st century. I want to talk about what should be — but aren't yet — watershed changes in engineering education. I hope to communicate the urgency I feel for the need for these changes, as well as something of their nature. Most, but not all, of what I will say is contained in one or more recent reports (American Society for Engineering Education, 1994; National Research Council, 1995; National Science Foundation, 1995). So, much of my message is not "new news," but little of what these reports recommend has been implemented, and indeed there seems to be little sense of urgency. Quite the contrary, there is widespread complacency, in my view. And, in some areas, I feel even the reports don't go far enough.

I should make three introductory remarks before getting to the substance. First, a caveat: I am going to paint with a broad brush. I know there are exciting, innovative programs in a number of engineering schools. Perhaps most schools are trying one or two novel things. My remarks are an effort to generalize the status of the entire engineering education enterprise; this kind of approach will explicitly miss these "points of light."

Second, a word about my view of what an engineer does, since this colors my ideas of how an engineer needs to be educated. Science is analytic — it strives to understand nature, what *is*. Engineering is synthetic — it strives to create what *can be*. My favorite operational definition of engineering is "design under constraint." Engineering is creating, designing what can be, but it is constrained by nature, by cost, by concerns of safety, reliability, environmental impact, manufacturability, maintainability, and many other such "ilities." Engineering is not "applied science." To be sure, our understanding of nature is one of the constraints we work under, but it is far from the only one, it is seldom the hardest one, and almost never the limiting one.

An Accelerating Pace of Change

Third, the practice of engineering is changing. Indeed, those changes are what underlie the urgency I feel for a new approach to engineering education. Growing global competition and the subsequent restructuring of industry, the shift from defense to civilian work, the use of new materials and biological processes, and the explosion of information technology — both as part of the process of engineering and as part of its product — have dramatically and irreversibly changed how engineers work. If anything, the pace of this change is accelerating.

Although there are exceptions, in general, engineering education has not kept up with this changing environment. I think it is only a slight exaggeration to say that our students are being prepared to practice engineering in a world that existed when we were trained a generation or two ago. They are not being prepared for the 21st century.

So, what needs to change? A lot, I think! Most obviously, we need to focus on curriculum, pedagogy, and diversity. I will say a bit about each of these, but the need for change goes deeper. We need to question whether the B.S. should be the first professional degree. We need to scrutinize the current system of rewards for faculty. We need to consider seriously the need for formalized lifelong learning, the adequacy of student preparation in grades K-12, and the importance of technological literacy in the general population.

The list is long and the time short, so I will say only a few words about only some of these to give you a sense of both the vector of change that is needed and why I feel urgency about it. I am also going to jump around in this list because these issues are not independent of each other.

Most professions (e.g., business, law, medicine) do not consider the bachelor's degree a professional degree. Engineering does. Doing so is a misrepresentation, both to the student and employer. Let's consider just a few of the problems this causes:

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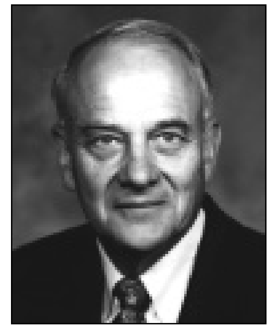

In 1988-90, he was also on leave while serving as assistant director of the National Science Foundation where he headed the directorate for computer and information science and engineering. He previously founded Tartan Laboratories, serving as its chairman and chief executive officer, and before that was a professor of computer science at Carnegie Mellon University.

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• The engineering B.S. program has bloated to over 130 credit hours and still doesn't cover requisite material.

• Companies generally invest one-to-two years in training new B.S. hires, completing the job left unfinished by our undergraduate programs.

• Liberal education in the humanities is being squeezed out of the engineer's undergraduate experience, as are courses in social and management sciences.

These problems are exacerbated as a number of states begin to mandate a maximum of 120 hours in the B.S.-degree track.

The squeeze caused by treating the B.S. as a professional degree provokes recitation of the mantra, "the undergraduate curriculum should teach (only) the fundamentals." Everyone agrees with that, pretty much. The difficulty comes when we try to decide which fundamentals are truly *fundamental*. The last major curriculum change in engineering, the move to what is referred to as "engineering science," occurred following World War II. Since then, the fundamentals have been seen largely as continuous mathematics and physics. But, as I said earlier, engineering is changing!

Performance-oriented professions . . . expect their faculty to practice that profession.

The new fundamentals include information technology (IT), which will be embedded in virtually every product and process in the future. That is, the "design space" for all engineers will include IT. Discrete mathematics, not continuous mathematics, is the underpinning of IT. Biological materials and processes are a bit behind IT in their impact on engineering, but they are closing fast.

Thus, the chemical and biological sciences are also becoming fundamental to engineering. In addition, the modern engineer must design under constraints that include global cultural and business contexts, so he or she must understand those constraints at a deep level. We can't just add these new elements to a curriculum that's already too full, especially if we still claim that the baccalaureate is a professional degree. We have to look critically at the current cherished fundamentals and either displace them or find ways to cover them much more rapidly.

I don't want to engage in the teaching-versus-research debate. I believe, as I suspect most of you do, that teaching and research complement each other and that, by and large, there is a high correlation between good teaching and good research. In my admittedly idiosyncratic career, the number of cases of genuinely good teachers who were not good researchers is very small.

But in engineering education I think we have an additional problem, and it's one I want to emphasize. Recall that my definition of engineering is design under constraint. I believe the process of design is a synthetic, *highly* creative activity. Can you think of any other creative field on campus where the faculty are not expected to practice or perform? Art, music, drama? Even if you don't buy that engineering is creative in the same way as art or music, performance-oriented professions such as medicine and law expect their faculty to practice that profession. Can you imagine a medical school where the faculty was prohibited from practicing medicine? Yet, this is just the situation we have in engineering.

Engineering faculty are, for the most part, judged by criteria similar to the science faculty, and the practice of engineering is not one of those criteria. The faculty reward system recognizes teaching, research, and service to the profession, but it does not give the same status to delivering a marketable product or process, or designing an enduring piece of the nation's infrastructure.

Of course, what you measure is what you get. For the most part, our faculty are superb "engineering scientists," but they are not necessarily folks who know a lot about the practice of engineering. At most schools, for example, it's hard to bring someone onto the faculty who has spent a career in industry, even though such people would be extremely valuable to the students; their resumes simply don't fit what the reward system values. Sometimes, it's even hard to get recognition for a sabbatical in industry.

Please understand that I am not criticizing the current faculty. I am one of them, and I respect my colleagues greatly. Rather, I am criticizing a *system* that prevents us from enriching faculty with a complementary set of experiences and talents. But, to close the loop, the current faculty are the folks with the largest say in the engineering curriculum. Given this, it should not be a big surprise that industry leaders have been increasingly vocal about their discontent with engineering graduates.

Work-Force Diversity

Now, let's explore the issue of diversity. We've leveled off at less than 20 percent of entering freshman being women, and the number of underrepresented minorities is stuck in single digits. That's unacceptable! By the way, this is not an equity issue, it's a work-force issue. As a creative field, without diversity, engineering cannot take advantage of life experiences that bear directly on good engineering design. A clever TV ad that depicts the trials of a woman in high heels trying to get out of her sport-utility vehicle illustrates the point: Until recently, the U.S. auto had been designed for the 50th-percentile male.

The situation is simply unacceptable and will become increasingly unacceptable to industries that need diversity among their engineers in order to compete in a global market. I have no silver-bullet solution, but it is obvious to me that there is a crying need to coordinate the many good programs at various universities, professional societies, and the like. We're not getting the "bang for the buck" that we should.

I'd like to briefly consider the long-term educational needs of engineers. The half-life of engineering knowledge — the time in which half of what an engineer knows becomes obsolete — varies by field, but is estimated to be in the range of 2.5 to 7.5 years. To be sure, job-

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specific knowledge is gained in the process of doing that job. But we must question the value of narrow specialization at a time when engineered systems are becoming larger, more complex, and involve components and processes from many more fields of engineering.

The notion of lifelong learning has not been part of the engineering culture, either among individual engineers or at engineering schools. This must change. Individual engineers have to take responsibility for their own careers, and part of that responsibility is to keep abreast of the new fundamentals. Merely taking training on the latest technology isn't good enough. The fundamentals you learned in college probably still are fundamental, but they now aren't the only ones in this rapidly changing profession.

I am especially concerned that continuing education, with some exceptions, is mostly relegated to non-top-tier schools and, increasingly, to for-profit organizations. Unlike business schools, where the best of the best have embraced executive training and where the best faculty vie to teach these courses, the best faculty at our best engineering schools studiously avoid involvement in continuing education.

The Role of IT in Pedagogy

Let me turn now to pedagogy. While it is tempting to devote this entire article to this subject, I want to focus on just one issue: the opportunity for information technology to fundamentally change and dramatically improve the effectiveness of learning. So far, this hasn't happened.

As someone who has watched the development of computers for nearly 40 years, I know that the first use of IT developments is always to automate, in basically the same way, what we are already doing. The important, even *profound,* uses are when we do something different and better. Educational technology seems mired in that first use — predominantly automated drill. A system, called Plato, developed at the University of Illinois when I was a graduate student there in the early 1960s, contained most of the ideas in today's computer-assisted instructional systems. I don't find it surprising that many professors still depend on overheads, whiteboards, and lecture for much of the teaching they do.

Yet, at the same time, we know from research in learning that the lecture format is far from optimal. An approach called "asynchronous learning networks" has shown that comparable or better results can be obtained among students and faculty who communicate only over computer networks. I interpret these results mostly as a condemnation of the lecture format, which is somehow failing to exploit the benefits of personal interaction.

The profound uses of IT, I suspect, lie in its ability to provide access to vast information sources, to support discovery-based educational experiences safely, and to more aggressively support peer-to-peer education. In particular, the team-oriented design projects used by many schools, and which I applaud, could be dramatically expanded through the use of simulation and virtual reality. While, in the end, it's important to get one's hands dirty, the material, cost, and other constraints of doing actual physical fabrication limit the number of such experiences a student can get. Virtual fabrication in a high-fidelity simulated environment can greatly enrich the undergraduate experience.

For many years, I have been a professor at the University of Virginia, which was founded by Thomas Jefferson on the conviction that we could not have a democracy without an educated citizenry. I think Jefferson would consider the current state of his democracy alarming. Technology is one of the strongest forces shaping our nation, and our representatives in Congress are called upon regularly to vote on issues that will profoundly affect the nation and whose roots are technological. Yet, both those representatives and the people who elect them are, for the most part, technologically illiterate. Every person with a "liberal education" needs to be technologically literate!

I am consciously saying "technologically literate" and not just scientifically literate because it's not enough to understand something of nature, what *is*. An understanding of the larger "innovation engine," the process by which an understanding of nature is converted into what *can be* — into a better, richer life — is critical. Engineering schools have not traditionally provided courses for liberal arts majors, but, in my view, they must. These courses will not be of the kind we are accustomed to teaching, since they need to relate technology and the process of creating it — that is, engineering — to larger societal issues.

In a recent article in *The Bridge* Jonathan Cole (1996) reported on an analysis of some popular modern American history texts. It turns out that most of them ignore the impact of technology on society. Yet, nothing, absolutely nothing, has had a more profound impact in the 20th century.

To conclude, our society is not only dependent on technology, it is addicted to technological change. If asked about the important events of the 20th century, most people will respond with the list of wars, the Great Depression, and so on. But, if one contrasts the life of an average citizen in 1898 with that in 1998, the profound differences are nearly all the result of the technology produced by engineers.

Engineering, the process by which our understanding of nature is combined with constraints to create artifacts and processes, is changing. It is changing very rapidly. Engineering education has to change, too!

We have studied engineering education reform to death. While there are differences between the reports I cited earlier and with my remarks here, the differences are not great. Let's get on with it! It's urgent that we do so!

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