Special Guest Editorial

Context and Challenge for Twenty-First Century Engineering Education

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The engineering workforce of tomorrow, and indeed that of today, will face profound new challenges. Every day the men and women of this workforce will face the stress of competing in the fast-paced world of change we call the knowledge-based global economy of the twenty-first century. They will also face even larger challenges because the nation and world will need to call on them to seize opportunities and solve global problems of unprecedented scope and scale.

The United States has long been King of the Hill in engineering education, especially at the graduate level, and certainly in the quality and accomplishment of our research universities overall. We have been the most technologically innovative nation on the planet. But things are changing rapidly in the twenty-first century.

The last half of the twentieth century was dominated by physics, electronics, high-speed communications, and high-speed long-distance transportation. It was an age of speed and power. The twenty-first century appears to be quite different, dominated by biology and information, but also by macro-scale issues like energy, water, and sustainability. These are things that should be strengths of U.S. engineers, but the context is rapidly evolving.

We once dominated all other countries in terms of expenditures on R&D, but today North America, Europe, and Asia each account for about a third of the world's R&D expenditures. Whereas, the U.S. is still on top, we are losing "market share" in every category used to evaluate R&D. From 1986 to 2003 the U.S. share of R&D spending dropped nine percent. The U.S. dropped eight percent in share of scientific publications, dropped 10 percent in share of new of science and engineering bachelors degrees, dropped two percent in share of U.S. patents, and dropped 30 percent in share of new science and engineering Ph.Ds. Now this is not all bad, because it largely reflects growth in other parts of the world, and we should celebrate the advances of other countries. Nonetheless, because we must depend on out-thinking and out-innovating others, these trends must be watched carefully.

The rise of production of engineers in China is unprecedented. China now educates about 250,000 bachelor-level engineers per year while the U.S. graduates about 60,000. Yes, there are still large quality differences, and numbers are not everything, but Floyd Kvamme, a highly experienced high-tech venture capitalist with Kleiner-Perkins, says that "Venture capital is the search for smart engineers." So we do have to worry about numbers, and we must note with deep consternation that fewer than 15 percent of U.S. high school graduates have sufficient math and science backgrounds to even have the option of entering engineering school.

Our engineers must work and innovate at ever accelerating rates. When the automobile was introduced into the market, it took 55 years, essentially a lifetime, until a fourth of U.S. households owned one. It took about 22 years until 25 percent of U.S. households owned a radio. The World Wide Web achieved this penetration in about eight years. Such acceleration drives an inexhaustible thirst for innovation and produces competitive pressures. The spread of education and technology around the world magnifies these competitive pressures many fold.

Globalization is changing the way in which engineering work is organized and in which companies acquire innovation. Today the service sector employs more than 70 percent of the U.S. workforce. The development and execution of IT-based service projects is usually accomplished by dividing the functions into a dozen or so components, each of which is carried out by a different group of engineers and managers. These groups are likely to be in several different locations around the world. In the manufacturing sector, this new distribution of work is even more dramatic. For example, the new Boeing 787 reportedly has 132,500 engineered parts that are produced in 545 global locations. Indeed, IBM CEO Sam Palmasano says that we have now moved beyond multinational corporations to globally integrated enterprises. An emerging element of this evolving engineering context is "open innovation." Companies no longer look just within themselves for innovation, nor do they just purchase it by acquiring small companies. Today they obtain innovation wherever it is found—in other companies, in other countries, or even through arrangements with competitors. Working in this evolving context requires a nimble new kind of engineer and engineering organization.

Perhaps even more dramatic than the changes brought about by globalization and competition in the Knowledge Age are the new engineering frontiers and grand challenges. I think of two frontiers of engineering, Tiny Systems and Macro Systems. Tiny Systems are those developed in the "Bio/Nano/Info" world where things get increasingly smaller, faster, and more complex. Here there is little distinction between engineering and natural science. Research and product development are done by teams of men and women from various scientific and engineering disciplines that rapidly move from reductionist science to synthesis and system building.

Macro Systems are of ever increasing size and complexity. Work at this frontier may be associated with systems of great societal importance: energy, water, environment, health care, manufacturing, communications, logistics, etc. Research, development, and the design and deployment of projects frequently require teams of engineers and people with backgrounds in social science, management, and communications.

Much of what will be exciting and valuable in the twenty-first century will be the work of engineers who will move tiny systems technology into macro systems applications. Here I have in mind the application of bio-based materials design and production, biomimetics, personalized predictive medicine, biofuels, nanotechnology-based energy production and storage devices, etc.

We also must think about what projects should engage the best of engineering talent and knowledge in the years ahead. The National Academy of Engineering formed a committee of 17 amazingly creative and accomplished engineers and related scientists and medical experts and asked them to define several Engineering Grand Challenges for the decades ahead. These challenges were to be such that accomplishing them would advance the human condition, and that the committee believed could actually be accomplished in the next few decades. The committee proposed 14 unranked Engineering Grand Challenges:[1]

- Make Solar Energy Economical
- Provide Energy from Fusion
- Develop Carbon Sequestration Methods
- Manage the Nitrogen Cycle
- Provide Access to Clean Water
- Engineer Better Medicines
- Advance Health Informatics
- Secure Cyberspace
- Prevent Nuclear Terror
- Restore and Improve Urban Infrastructure
- Reverse Engineer the Brain
- Enhance Virtual Reality
- Advance Personalized Learning
- Engineer the Tools of Scientific Discovery

These challenges involve energy and sustainability, medicine and healthcare, reducing our vulnerability to natural and human threats, and advancing our human capabilities and understanding of our world and ourselves. Meeting some of these challenges is imperative for human survival, meeting some will make us more secure, and all will improve quality of life.

My message here is that *the twenty-first century will be very different from the twentieth*. Engineering will be enormously exciting, and increasingly rich and complex in its context and importance. As we think about the challenges ahead, it is important to remember that students are driven by passion, curiosity, engagement, and dreams. Although we cannot know exactly what they should be taught, we can focus on the environment in which they learn and the forces, ideas, inspirations, and empowering situations to which they are exposed. Despite our best efforts to plan their education, however, to a large extent we simply wind them up, step back, and watch the amazing things they do.

In the long run, making universities and engineering schools exciting, creative, adventurous, rigorous, demanding, and empowering milieus is more important than specifying curricular details. Nonetheless, I hope that those who design curricula, pedagogy, and student experiences will profitably contemplate the new context, competition, content, and challenges of engineering.

[1]See http://www.engineeringchallenges.org/for further details.

Special Guest Editorial

The Human Face of Engineering

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Engineers…a sea of white faces, all male, all in white shirts with dark ties. This was both the image and the reality of mission control at NASA in the 1960s. We were reminded of that history in October 2007 during events and reporting surrounding the 50th anniversary of Sputnik. Perhaps it takes such a stark reminder to realize how far we have come in increasing the diversity of engineering and also how far we have to go before the task is accomplished! Many in that room were drawn there by the challenge to "put a man (sic) on the moon and return him safely to the earth"; others by a sense of patriotism born of the need to "defeat the enemy." What is striking is who was missing.

In 1970, women received less than 1 percent of bachelor's degrees awarded in engineering. By 2006 women earned almost 20 percent of these degrees. African Americans also received less than 1 percent of bachelor's degrees in engineering in 1970 and almost 5 percent in 2005. Hispanics received 2 percent of bachelor's degrees in engineering in 1973; by 2005 this had grown to 6.4 percent of bachelor's degrees. Native Americans grew from 0.1 percent to 0.5 percent of bachelor's degrees earned between 1973 and 2005, and Asian/Pacific Islanders swelled from 1.6 percent to 13.2 percent of bachelor's degree recipients in the same timeframe.

From 16 women and one African American engineering doctorate recipients in 1970 the numbers swelled in 2005 to 1,322 women and 111 African Americans. Clearly the times, the numbers, and the images have changed, becoming much more diverse, although not yet as diverse as the higher education or general populations available from which to draw talent. Collectively, women and minorities represent some 64 percent of all students in higher education institutions. These numbers promise to climb as minorities become an even larger component of the school-age population.

However, it has not been easy to move the engineering numbers. In the case of women and minorities, it took the civil rights movements for both groups to make the connection and affect the impact of taking rigorous courses in mathematics and science in middle school and high school. Special programs introduced young women and minorities to engineering professionals who looked like them and to the work of engineers. Minority students joined out of school and summer programs aimed at career education, at closing the information and preparation gap, and at getting students oriented toward college. Interestingly, these programs provided access and engagement one student at a time through "high touch" experiences that both supplemented and counter-acted the effects of schooling! Clearly, greater complementarity of formal and informal education would make the job easier. This includes internships and co-operative education programs that put students into the job environment, in the middle of real work.

These days it may be harder for institutions to put in place "special intervention programs" to introduce women and minorities to engineering without running into legal concerns. So creating learner-friendly environments must extend beyond projects to be embraced by individual faculty members, teams of faculty, departments and schools of engineering, drawing on the research and on what we learned from the "special efforts."

Today, several factors emerge more often in discussions about minority participation in engineering, including: adequacy of preparation, especially in mathematics and science; understanding of how to navigate higher education; and affordability of higher education. But these are not the only issues. Barriers to study and work in engineering perceived to be shared by women and minorities include: a faculty focus on what students lack rather than what they bring; an image of engineers and engineering as the purview of whites and males, involving work that is "object oriented" rather than "people oriented"; a lack of availability of accurate career information that reflects the real work of engineers in many different settings; different and/or lower expectations, including bias; and the nature of the curriculum and experiences provided in engineering programs.

In the future, engineering needs to offer a different face to students, especially if there is an interest in attracting females and minorities. For example, engineering provides real opportunities to enable sustainable well being in developing countries by addressing the need for portable water, quality sanitation systems, improved agricultural practices, better roads and bridges, and so on. Through work in organizations, such as Engineers Without Borders (EWB), a human face is put on the profession. Another example is the UNESCO-Diamler Mondialogo Engineering Awards. There, teams of students from developed and developing countries (or South–South teams) work together via the Internet (or other communications technology) to design solutions to engineering challenges in the developing country. The winning teams receive support by way of a monetary award to carry the design to the next level.

So what does all this mean for the engineering community?

Greater involvement in education at all levels. Failure by individual engineers acting as citizens or by the engineering community acting collectively to support and to affect the direction of K-12 education makes it difficult to shape student course choices and career options; this may include fighting to ensure access to the right courses! On the other hand, failure to consider the role of graduate education in the development of future faculty will ensure that the value of a diversity of perspectives, ideas, and performers will not be inculcated into the lifeblood of the profession.

Building relationships to the natural, social and behavioral sciences, mathematics and computational sciences. Engineering needs to offer perspectives on engineering and technology to other parts of the campus just as it depends on these other areas to offer courses and contexts to its students. While one might not find many engineering majors among the "undecideds" who might be attracted to such courses, it is essential to offer a vision of engineering and technology, their role in history and in the future of the globe to a much broader cross section of the campus community.

Closer articulation with community colleges. Whether due to costs, geographic considerations, or convenience, minority students (especially Latino students) who often begin their study in community colleges need assurance of smooth transitions to university programs. Failure to articulate these programs will disadvantage the very students we wish to attract, leaving them to spend more time and money to complete their education, increasing the likelihood that they will not.

Enlivening the engineering curriculum and connecting it to the need for a globally competent engineering workforce. Curricular changes need to reflect what we understand about the practice of engineering now and *into the future*. They also need to connect to what we know about our students, how they learn, what motivates and excites them, tapping into their idealism and concerns, including the role of engineering in serving human needs and preserving the health of the planet.

As we work to re-configure engineering education, policy makers will need to re-make our schools and colleges: introducing engineering principles at a much earlier level of schooling to attract, interest, and retain female and minority students before they are lost; moving engineering classes into the field, into international settings, into media and into local communities; and supporting study and work so that students can afford to pursue challenging courses of study, perhaps with a requirement for service, reinforcing the notion of engineering for public benefit.

Special Guest Editorial

Reframing Professional Development: A Systems Approach to Preparing Engineering Educators to Educate Tomorrow's Engineers

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The articles in this special issue present research on who engineering students are, how they learn, and what they need to know. The challenge to engineering education is that the answers to those issues are different now than they were just a few years ago, and they will inevitably continue to change. Due in part to the rapidly increasing power of technology, routine tasks that were traditionally performed by engineers are now performed by technicians using computers while engineers are called upon to develop innovative products and processes, exercise new and unfamiliar technical and professional skills, and function in an increasingly global environment. What it will mean to be an engineer in the twenty-first century and the incompatibility of current engineering curricula with that meaning have been the subject of many high-level studies. The debate so far has had little impact on engineering educators.

In view of the broadening and rapidly shifting scope of the engineering profession, it is imperative to shift the focus of engineering curricula from transmission of content to development of skills that support engineering thinking and professional judgment. Future engineers will need to adapt to rapidly changing work environments and technology, direct their own learning, broaden an understanding of impact, work across different perspectives, and continually revisit what it means to be an engineer. Traditional approaches to engineering education (chalk-and-talk lectures, individual homework, three years of "fundamentals" before an introduction to engineering practice) is incompatible with what we know from decades of cognitive and classroom research. Furthermore, research on student engagement has moved the boundaries of learning environments beyond formal classrooms to informal spaces such as student lounges, professional work spaces, and virtual community spaces. What remains crucial is the importance of social learning as students interact with others—e.g., peers, educators, campus administrators, and internship supervisors. As such, the teaching decisions engineering educators make can impact learning in and out of the classroom.

While these challenges may seem formidable, they present considerable opportunity for reframing what it means to be an engineering educator preparing tomorrow's engineers. Future engineering educators will have access to a variety of exciting new roles for enabling engineering education to dynamically respond to the evolving nature of the engineering profession:

- *Educational philosopher and provocateur:* Engage in the international dialogue about the content, skills, and values engineering graduates should be equipped with and how these should be addressed. Advocate new perspectives that challenge traditional views and enable innovative curricula, content and pedagogy.
- *Educational researcher:* Imagine educational and workplace environments as learning laboratories to delve into how, what, and why students are learning, and how engineers use this learning. Design experiments to develop, assess, and disseminate new instructional materials, methods, and learning environments.
- *Interdisciplinary educator:* Integrate engineering content with content from other STEM disciplines, economics and business, humanities, and the social sciences. Provide opportunities such as interdisciplinary projects for students to learn from peers in other disciplines.
- *Teaching leader:* Share effective instructional methods and materials with colleagues; help to adapt them for their own classes. Embrace opportunities to be a decision maker and change agent, build networks for making an impact, and have intellectually stimulating discussions with colleagues about good teaching practice.
- *Scholarly teacher and reflective practitioner:* Read the literature and attend education conferences to keep abreast of new education practices. Imagine links between research findings and teaching practice. Engage in collaborative and systematic reflection about what works and what does not (and why) as an essential part of life long learning and continuous improvement. These habits of mind might even be initiated as part of graduate training.

Engineering educators would not be expected to assume all these roles but gravitate to those they feel most comfortable, competent, and passionate; department heads would ensure that each role is filled by one or more faculty members. The idea is to encourage activities that facilitate greater synergy between being an *engineer* and being an *educator*. Ideally, all educators would assume a role of *scholarly teacher and reflective practitioner*.

How can we prepare engineering educators for roles that may not be part of their training or their experience? The inadequacy of current professional development approaches is abundantly clear. It is unfortunate and unnecessary that many new engineering educators have to figure out for themselves how to design syllabi and lesson plans and tests, motivate students to learn, teach effectively in small and large classes, help students who are struggling, and deal with classroom disruptions and cheating while at the same time building a research agenda, recruiting students, and meeting service responsibilities. Just as the education of future engineers must evolve to reflect new challenges within the profession, professional development must evolve to reflect new demands on engineering educators.

Reframing the professional development of engineering educators from a complex systems perspective could move the community beyond short term, quick-fix solutions towards longer term, proactive, integrated, adaptive, and relevant solutions. From a complex systems perspective, engineering education involves the engineering profession, the society it serves, educational institutions, educators, and students. The question becomes how to design for *intentionality*—to change the existing situation into a preferred one? One way is to consider educational institutions as learning organizations that focus on building a culture of innovation and continual learning, and emphasize the importance of systems thinking, dialogue, and reflective practice.

A particular challenge of conceiving higher education as a learning organization is finding ways to leverage academic freedom of the individual within the organization while maintaining a collective goal of quality of an education. The question of assessing and evaluating professional development is also a challenge at the individual and organizational level. How might the maintenance of competence and expertise be a joint responsibility of the individual professional and the organization? Providing accredited, award-bearing programs in higher education or including professional development outcomes in accreditation policies may create a system for continual development at the organizational and individual level. This might provide mechanisms for improving alignment between academic roles and academic rewards or incentives.

There are also implications for enabling synergistic cycles of research informing teaching and teaching informing research. Engineering educators do not typically read engineering education journals. A challenge for engineering education researchers is to find ways to communicate their work for use in practice and to respond to educator and practitioner needs to ensure they are conducting rigorous and relevant research. A challenge for education practitioners is to find ways to help form research agendas and provide feedback on research-informed instructional practice.

This volume delves into questions about who is an engineer, how they learn, how they come to identify as engineers, and what they need to learn. From a complex systems perspective, there would be parallel questions about engineering educators: who are they, how do they learn, how do they come to identify as engineering educators, and what do they need to learn? Finding answers to these questions is a substantial research agenda and requires creativity and serious scholarship. For example:

- *Becoming an engineering education professional:* What motivates continued professional development, what are deterrents, and how do they interact? What can stimulate a broad segment of the engineering faculty community to partake in professional development programs, participate in education-related professional societies, and engage in the scholarship of teaching and learning? What role might graduate education play in initiating this professional development?
- *Engineering education thinking:* What do engineering educators find convincing about existing education research and what informs their decisions about teaching? How do beliefs about teaching and learning co-evolve as engineering educators acquire expertise, and how does this impact an understanding of what constitutes engineering knowledge?
- *The engineering education culture:* What can promote better alignment between academic roles and academic rewards? What are strategies for integrating all the facets of academic careers—research, teaching, academic leadership—with personal life goals? What are the pros and cons of engineering-specific instructional development delivered by experts in both engineering content and engineering pedagogy, as opposed to interdisciplinary programs delivered to faculty from all STEM disciplines by experts in general pedagogy?
- *Theories to guide professional development of engineering educators:* What are exemplar models of professional development for supporting experienced, new, and future engineering educators (e.g., workshops, seminars, continuing education, mentorships, learning communities)? How much emphasis should be placed on general theories of pedagogy and learning, the scholarship of disciplinary teaching and learning, and practical tips on good teaching and assessment? What are implications of established teaching and learning theories for informing the professional development of engineering educators; what new studies should be undertaken?
- *Assessing and evaluating professional development:* What are ways to assess and evaluate professional development? What are approaches that integrate assessment with life-long learning (e.g., action research, critical learning communities, development of portfolios, and recording of life histories as emerging forms of research that incorporate reflective practice)? What role can engineering education programs or departments play in designing and assessing professional development programs for engineering faculty?

The challenges facing engineering education—globalization, increased blurring of traditional disciplinary boundaries, rapidly accelerating growth in the capabilities of technology in general and instructional technology in particular, and shifting college student demographics—are here to stay. Finding and evaluating new approaches in the face of a rapidly changing environment is nothing new in our field—it is what successful engineers have done and continue to do every day. Engineers appreciate complexity; they thrive on challenge and a passion to make an impact. Embracing the challenges as well as new roles for engineering educators is the ultimate opportunity to impact who becomes an engineer, how they learn engineering, and what they need to know to be tomorrow's engineers.