ASU NAE GRAND CHALLENGES CONFERENCE

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INTRODUCTION

My assignment this afternoon: To somehow connect one of the themes of the
NAE Grant Challenges effort, "advancing personalized learning" somehow to
"engineering education".

So, what does NAE mean by "advance personalized learning"?

> "Personalized learning" recognizes the importance of tailoring learning to
> a student's individual needs. Personal learning approaches range from
> modules that students can master at their own pace to computer programs
> designed to match the way it presents contents with a learner's
> personality.

> What can engineering do to improve learning? Ongoing research in
> neuroscience is providing new insights into the intricacies of neural
> processes underlying learning, offering clues to further refine
> individualized instruction. Engineers can contribute to these complex
> challenges by enhancing technology for neuroscience and brain research
> and advanced instructional systems development.

Wait a second! How does this relate to what engineering does best?
- Develop brain research technology?
- Fiber to the forehead technology?
- Enders Game technology?

This sounds
- More like research and analysis than design and synthesis…
- More like discovery than innovation…
- More "micro" than "macro" or "mega"…
- More like "small think" than "big think"…

Where is the stuff that engineers do best?
- Synthesis and design?
- Systems thinking?
- Innovation?
- Paradigm breaking?

I see a couple of problems here:

1. COSEPUP Experience: For many years there has been a total disconnect between the extraordinary advances in neuroscience and cognitive science, and how we teach. Most of it has bounced off of our schools, colleges, and universities without making a dent either on pedagogy or the faculty. Sure, there have been advances such as CMU's "cognitive tutor" software, but this stuff just hasn't gained traction yet.

2. This disconnect has been compounded by just how radically learning paradigms are being changed by today's young people! Let me explain.

Today's students are citizens of the digital age.

They have spent their early lives surrounded by robust, visual, interactive media—not the passive broadcast media, radio and television of our youth, but rather Wii's, iPhones, Facebook, and virtual reality.

They are "digital natives", comfortable learning, working, and living in the digital world, unlike those of us who are "digital immigrants" who are

struggling to keep pace with digital technologies.

This is not an easy task for educators, who for the most part remain reluctant to embrace the new technologies in their teaching and hence are increasingly detached from today's students.

Today's students are no longer the people our current educational system was designed to teach.

Rather they learn by experimentation and participation, not by listening or reading passively. They are indeed the "plug and play" generation.

They embrace interactivity and demand the right to shape and participate in their learning. They are comfortable with the uncertainty that characterizes their change-driven world.

They master merging technologies that enable social networking to form learning communities and immersive virtual environments for simulation and play facilitate the "deep tinkering" that provides the tacit knowledge necessary to "learn to be", tools already embraced by the young if not yet the academy.

These students will increasingly demand new learning paradigms more suited to their learning styles and more appropriate to prepare them for a lifetime of learning and change.

From a broader perspective, our society increasingly values not just analysis but synthesis as the key to innovation, enabled by the extraordinary tools of the digital age. Increasingly, we realize that learning occurs not simply through study and contemplation but through the active discovery and application of knowledge.

From John Dewey to Jean Piaget, we have ample evidence that most students learn best through inquiry-based or "constructionist" learning. As the ancient Chinese proverb suggests "I hear and I forget; I see and I remember; I do and I understand." To which we might add, "I teach and I master!!!"

Today, learning has become a lifelong activity since a changing world will demand that students continue to learn, through both formal and informal methods, throughout their lives–what we might call both "lifelong" and "life-wide" learning.

Hence any strategic approach to "personalize learning" must account for paradigm changes such as those suggested by John Seely Brown, former Chief Science of Xerox's Palo Alto Research Center:

- Just in case to just in time to just for you
- Learning to know to learning to do to learning to be to learning to becoming
- Reflection to immersion to play to ephiphany
- Hanging out, messing around, geeking out!
- Homo Sapiens (knower), Homo Faber (maker), Homo Ludens (player)

So how can engineering approach such a complex and rapidly changing challenge such as the learning needs of our society? Let me give three examples that illustrate how engineers should approach such Grand Challenges:

1. Systems Thinking: A Master Plan for the Midwest

2. Big Ideas: The Future of the University

3. Radical Innovation: A Flexner Report for the Engineering Profession

EXAMPLE ONE: A MASTER PLAN FOR THE MIDWEST

Last year I was asked to develop a "master educational plan" for the Midwest states, similar to that developed by California in the 1960s. Here the challenge was perhaps best stated by a recent Brookings Institution study of the region:

"Still heavily reliant on mature industries and products, the aging workforce of the Midwest lacks the education and skills needed to fill and create jobs in the new economy. Its entrepreneurial spirit is lagging, hampering its ability to spur new firms and jobs in high-wage industries. Its metropolitan areas are economically stagnant, old and beat up, and plagued with severe racial divisions. Its landscape is dotted with emptying manufacturing towns, isolated farm, mining, and timber communities. It continues to bleed young, mobile, educated workers seeking opportunities elsewhere. Its legacy of employee benefits, job, and income security programs–many of which the region helped pioneer–has become an unsustainable burden, putting its firms at a severe competitive disadvantage in the global economy. And most important, the culture of innovation that made it an economic leader in the 20th century has long since vanished".

So, what to do? My challenge was to develop a plan for building a learning and innovation infrastructure for the Midwest region.

The plan needed to address the life-long educational needs of its citizens and the workforce skill needs necessary to compete and flourish in a global, knowledge-intensive economy.

In addition, it needed to address how to build the sources of new knowledge, innovation, and entrepreneurial spirit necessary to create world-class companies and a world-class living environment.

And it needed to accept the reality is that today's global knowledge-

driven economy really doesn't respect the usual geopolitical boundaries–municipalities, states, even nation. The economic concentrations of the global economy span regions characterized by common economic, demographic, and culture characteristics and anchored by world-class metropolitan areas.

My approach has been to adopt and adapt a common engineering approach used in high-tech industry, technology roadmapping.

Although sometimes confused with jargon such as environmental scans, resource maps, and gap analysis, in reality the roadmapping process is quite simple. It begins by asking where we are today, then where we wish to be tomorrow, followed by an assessment of how far we have to go, and finally concludes by developing a roadmap to get from here to there.

The roadmap itself then usually consists of a series of recommendations, sometimes divided into those that can be accomplished in the near term and those that will require longer-term and sustained effort.

Since the future of the Midwest states will be determined by the region's success in building a world-class learning and innovation infrastructure for its citizens, the effort began by asking three key questions:

1. What skills and knowledge are necessary for individuals to thrive in a 21st century, global, knowledge-intensive society?

Clearly a college education has become mandatory, for some at the associate level, for most at the bachelors level, and for many, at the graduate level. Beyond this goal, a region should commit itself to providing high quality, cost-effective, and diverse educational opportunities to all of its citizens throughout their lives, since during an era of rapid economic change and market restructuring, the key to employment security has become continuous education.

2. What skills and knowledge are necessary for a population (workforce) to provide regional advantage in such a competitive knowledge economy?

> Here it is important to stress that the concern is not longer competition among cities and states within the Midwest region for prosperity or with other states such as California or Texas or Arizona. More serious is the competition from the massive and increasingly well-educated workforces in emerging economies such as China, India, and Central Europe.

3. What level of new knowledge generation (e.g., R&D, innovation, entrepreneurial zeal) is necessary to sustain a 21st century knowledge economy, and how is this achieved?

> It has become increasing clear that the key to global competitiveness in regions aspiring to a high standard of living is innovation. And the keys to innovation are new knowledge, human capital, infrastructure, and forward-looking public policies.

> Not only must a region match investments made by other states and nations in education, R&D, and infrastructure, but it must recognize the inevitability of new innovative, technology-driven industries replacing old obsolete and dying industries as a natural process of "creative destruction" (a la Schumpeter) that characterizes the hypercompetitive global economy.

Clearly, the implications of a global, knowledge-driven economy for discovery-based learning and knowledge institutions–schools, colleges, and universities–are particularly profound.

> The knowledge economy is demanding new types of learners and creators. Globalization requires thoughtful, interdependent and globally identified citizens.

New technologies are changing modes of learning, collaboration and expression.

Rather than boring you with the environmental scan, resource mapping, visioning, and gap analysis, let me jump to elements of the resulting roadmap to give you a flavor of how an engineer would approach such a challenge:

1. Regional→ National → Global: While it is natural to confine policy to state boundaries, in reality such geopolitical boundaries are of no more relevance to public policy than they are to corporate strategies in an ever more integrated and interdependent global society. Hence the Midwest's strategies must broaden to include regional, national, and global elements. Put another way, we must act regionally but think globally!

2. Competition → Collaboration: Midwestern states, governments, and institutions must shift from Balkanized competition to collaboration to achieve common interests, building relational rather than transactional partnership most capable of responding to global imperatives.

3. All Students College-Ready: The Midwest region will set as its goal that all students will graduate from its K-12 systems with a high school degree that signifies they are college ready. To this end, all students will be required to pursue a high school curriculum capable of preparing them for participation in post-secondary education and facilitating a seamless transition between high school and college. State government and local communities will provide both the mandate and the resources to achieve these goals.

4. Restructuring K-12 to Achieve World-class Performance: To achieve a quantum leap in student learning, Midwestern schools systems will have to restructure themselves to achieve world-class performance, including extending the school year (from 180 to 240 days), developing and implementing rigorous methods for assessing student learning;

restructuring school organizations (including administration and governance), teacher qualifications, performance evaluation and incentives; and investing in state-of-the-art technology infrastructure.

5. Social Infrastructure: Beyond the necessary investments in K-12 education and the standards set for their quality and performance, raising the level of skills, knowledge, and achievement of the Midwest's workforce will require a strong social infrastructure of families and local communities, particularly during times of economic stress. To this end, state and local governments must take action both to re-establish the adequacy of the Midwest's social services while engaging in a broad effort of civic education to convince the public of the importance of providing world-class educational opportunities to all of its citizens.

6. Higher Education Engagement with K-12: Higher education must become significantly more engaged with K-12 education, accepting the challenge of improving the quality of our primary and secondary schools as one of its highest priorities with the corresponding commitment of faculty, staff, and financial resources. Each Midwest college and university should be challenged to develop a strategic plan for such engagement, along with measurable performance goals.

7. Demanding Zero-Defects Institutional Performance: All Midwestern colleges and universities should be challenged to achieve a "zero-defects, total quality" performance goal in which all enrolled students are expected to graduate in the prescribed period. This will require adequate financial, instructional, and counseling support but as well strong incentives and disincentives at the individual and institutional level (e.g., basing public support on graduation rates rather than enrollments, demanding that faculty give highest priority to adequate staffing of required curricula, and setting tuition levels to encourage early graduation).

8. Institutional Diversity: The Midwest should strive to encourage and sustain a more diverse system of higher education, since institutions with diverse missions, core competencies, and funding mechanisms are necessary to serve the diverse needs of its citizens, while creating a knowledge infrastructure more resilient to the challenges presented by unpredictable futures. Using a combination of technology and funding policies, efforts should be made to link elements of the Midwest's learning, research, and knowledge resources into a market-responsive seamless web, centered on the needs and welfare of its citizens and the prosperity and quality of life in the region rather than the ambitions of institutional and political leaders.

9. Social Inclusion: The Midwest must recommit itself to the fundamental principles of equal opportunity and social inclusion through the actions of its leaders, the education of its citizens, and the modification of restrictive policies, if it is to enable an increasingly diverse population to compete for prosperity and security in a intensely competitive, diverse, and knowledge-driven global economy.

10. Lifelong and Life-wide Learning: The Midwest should explore bold new models aimed at producing the human capital necessary to compete economically with other regions (states, nations) and provide its citizens with prosperity and security. Lifelong learning will not only become a compelling need of citizens (who are only one paycheck away from the unemployment line in a knowledge-driven economy), but also a major responsibility of the state and its educational resources. Furthermore, formal learning experiences should be augmented by broader learning opportunities that take advantage of emerging technologies such as social networking and open education resources.

11. Immigration: Immigration is vital to transforming the Midwest economy, as a source of both talent and energy and contributing to its innovation and entrepreneurship. The only immigration policy that will help the

Midwest is one that opens the door as widely as possible.

12. Increased Investment in Innovation: The Midwest must invest additional public and private resources in initiatives designed to stimulate R&D, innovation, and entrepreneurial activities. Key elements would include reforming state tax policy to encourage new, high-tech business development, securing sufficient venture capital, state participation in cost-sharing for federal research projects, and a far more aggressive and effective effort by the Midwestern state's Congressional delegations to attract major federal research funding to the region.

13. Innovation Infrastructure: Providing the educational opportunities and new knowledge necessary to compete in a global, knowledge-driven economy requires an advanced infrastructure: educational and research institutions, physical infrastructure such as laboratories and cyberinfrastructure such as broadband networks, and supportive policies in areas such as tax and intellectual property. The Midwest must invest heavily to transform the current infrastructure designed for a 20th-century industrial economy into that required for a 21st-century knowledge economy.

14. Technology Transfer: The Midwest's research universities should explore new models for the transfer of knowledge from the campus into the marketplace, including the utilization of investment capital (perhaps with state match) to stimulate spinoff and startup activities and exploring entirely new approaches such as "open source – open content paradigms" in which the intellectual property created through research and instruction is placed in the public domain as a "knowledge commons," available without restriction to all, in return for strong public support.

15. World-Class Learning: Colleges and universities should aspire to achieve world-class quality, nimbleness, innovation, efficiency, and the capability of providing our citizens with the higher order intellectual skills (critical

thinking, moral reasoning, an appreciation of cultural and human values, commitment to lifelong learning, adaptive to change, tolerance of diversity) necessary for achieving national prosperity, security, and social well-being in a global, knowledge-driven society.

Paradigm Shifts

For the longer term, the possibilities and uncertainties become even more challenging.

How will wealth be created and value added in this global, knowledge-driven economy?

While many regions (e.g., Bangalore, Shanghai) will prosper with exceptionally high-quality specialization in knowledge-intensive services and low cost commodity manufacturing, the United States is unlikely to be competitive here, whether because of our high standard of living (and high wage) requirements or population limitations.

Instead we will have to stress our capacity to innovate and create, derived from an unusually diverse, market-driven, democratic culture. Although we will still "make things", we will do so by organizing the financial and human capital on a global level.

Will increasingly robust communications technologies (always on, always in contact, high-fidelity interaction at a distance) stimulate the evolution of new types of communities (e.g., self-organization, spontaneous emergence, collective intelligence, "hives").

Suppose info-bio-nano technologies continue to evolve at the current rate of 1,000 fold per decade. Can we really prepare today's kids for the world of several decades from now when technologies such as neural implants, AI "mind children", stim-sim, and such may actually exist?

During the 20th century, the lifespan in developed nations essentially doubled (from 40 to 80 years). Suppose it happens again in the 21st century?

More generally, it is clear that as the pace of change continues to accelerate, learning organizations and innovation systems will need to become highly adaptive if they are to survive. Here, we might best think of future learning and innovation environments ecologies that not only adapt but mutate and evolve to serve an ever-changing world.

Such future challenges to the Midwest's prosperity and social well-being call for bold initiatives. It is not enough to simply build upon the status quo. Instead, it is important that the Midwest consider bolder visions that exploit truly over-the-horizon opportunities and visions.

To this end, we conclude our roadmapping exercise with a series of bolder proposals that would act as "game changers" to challenge and change the entire learning and innovation infrastructure of the Midwest region.

Lifelong Learning: In fact, we might even make the case that it is time for the nation to step up to its responsibility as a democratic society to enable all of its citizens to take advantage of the educational, learning, and training opportunities they need and deserve, throughout their lives, thereby enabling both individuals and the nation itself to prosper in an ever more competitive global economy. *Access to livelong learning opportunities should be essentially a civil right for all rather than a privilege* for the few if the nation is to achieve prosperity, security, and social well-being in the global, knowledge- and value-based economy of the 21st century. (Note: This was a key recommendation of the Spellings Commission, i.e., the National Commission on the Future of Higher Education.)

Learn Grants: To address this alarming inequities and provide strong incentives

for college preparation, the idea would be to provide every student with a 529-like college savings account, a "Learn-Grant" when they begin kindergarten. Although this account would be owned by the students (although invested in the equity market by the federal government or its agents), its funds could be used only for post-secondary education upon the successful completion of a high school college-preparatory program. Each year students (and their parents) would receive a statement of the accumulation in their account, with a reminder that this is their money, but it can only be used for their college education (or other post-secondary education).

Learn Grant Universities: Perhaps it is time for a new federal act, similar to the land grant acts of the nineteenth century, that will enable the higher education enterprise to address the needs of the 21st Century. The land-grant paradigm of the 19th and 20th centuries was focused on developing the vast natural resources of our nation. In a sense, the 21st Century analog to the land-grant university might be termed a *learn-grant university* designed to develop today's most important resource, our human resources, as its top priority, along with the infrastructure necessary to sustain a knowledge-driven society.

Universities in the World and Of the World: Globalization and the attendant emergence of the global knowledge economy are exerting tremendous pressures on universities around the world and reshaping some of their basic assumptions and activities. There is a strong sense that higher education, long international in participation, may now be in the early stages of globalization. New types of universities may appear that increasingly define their purpose beyond regional or national priorities to address global needs such as health, environmental sustainability, and international development, becoming *universities in the world but also of the world*.

Open Source Universities: Hence one might imagine the emergence of "open source" universities, committed to providing extraordinary access to knowledge and learning tools through open learning resources. In fact, some institutions might decide to remove entirely the restrictions imposed by intellectual property

ownership by asking all of their students and faculty members to sign a Creative Commons license for any intellectual property they develop at the University (at first copyright but eventually possibly even exploring other intellectual properties such as patents.) Perhaps this would even redefine the nature of a "public" university, much in the spirit of the "public" library!

One final observation: In assembling a "master plan" for education in the Midwest states, it is essentially to go beyond the approach of the California Master Plan, which focused on higher education, and extend it to encompass all educational needs and resources–cradle to grave! It is also important in today's rapidly changing environment to create a process that engages leadership groups over a long period of time to sustain the momentum of any plan. Here we are adopting many of the ideas developing in the Bologna Process, which is now in its second decade of integrating higher education throughout the European Union.

EXAMPLE TWO: THE FUTURE OF THE UNIVERSITY

So what might we anticipate as possible future forms of the university?

he monastic character of the ivory tower is certainly lost forever. Although there are many important features of the campus environment that suggest that most universities will continue to exist as a place, at least for the near term, as digital technology makes it increasingly possible to emulate human interaction in all the sense with arbitrarily high fidelity, perhaps we should not bind teaching and scholarship too tightly to buildings and grounds.

Certainly, both learning and scholarship will continue to depend heavily upon the existence of communities, since they are, after all, high social enterprises. Yet as these communities are increasingly global in extent, detached from the constraints of space and time, we should not assume that the scholarly communities of our times would necessarily dictate the future of our universities.

For the longer term who can predict the impact of exponentiating technologies on social institutions such as universities, corporations, or governments, as they continue to multiply in power a thousand-, a million-, and a billion-fold?

Paradigm Shift 1: Cyberinfrastructure

The information and communications technologies enabling the global knowledge economy–so-called cyberinfrastructure, the current term used to describe hardware, software, people, organizations, and policies (Europe calls this e-science)–evolve exponentially, doubling in power every year or so and amounting to a staggering increase in capacity of 100 to 1,000 fold every decade.

- It is becoming increasingly clear that we are approaching an inflection point in the potential of these technologies to radically transform knowledge work.

- To quote Arden Bement, Director of the U.S. National Science Foundation, "We are entering a second revolution in information technology, one that may well usher in a new technological age that will dwarf, in sheer transformational scope and power, anything we have yet experienced in the current information age."

Many leaders, both inside and outside the academy, believe that these forces of change will so transform our educational institutions–schools, colleges, universities, learning networks–over the next generation as to be unrecognizable within our current understandings and perspectives.

Ironically, while we generally think in terms of Terabit/sec networks and petaflop supercomputers, I believe the most profound changes may be driven not by the technology itself but rather the philosophy of openness and access it imposes on its users.

Paradigm Shift 2: Open Education Resources

Of particular importance are efforts adopting the philosophy of open source software development to open up opportunities for learning and scholarship to the world by putting previously restricted knowledge into the public domain and inviting others to join both in its use and development.

- MIT led the way with its OpenCourseWare (OCW) initiative, placing the digital assets supporting almost 1,800 courses in the public domain on the Internet for the world to use.

- Today, over 1,000 universities have adopted the OCW paradigm to distribute their own learning assets to the world, with over 7,000 courses now available online. (Check out iTunes U for a quick experience!)

- Furthermore, a number of universities and corporations have joined together to develop open-source middleware to support the instructional and scholarly activities of higher education, already used by hundreds of universities around the world (e.g., Moodle and Sakai).

- Others have explored new paradigms for open learning and engagement, extending the more traditional yet highly successful models provided by open universities.

To this should be added projects to digitize printed material such as the Google Book in which a number of leading libraries (26 at last count in 35 languages) around the world have joined together with Google to digitize a substantial portion of their holdings, making these available for full-text searches using Google's powerful internet search engines.

- For example, over 6 million volumes at the University of Michigan have been already been digitized, with our complete 8 million volume library now projected to be online by 2011.

- Google now has over 12 million books full-text searchable and has recently negotiated with publishers to provide full-text access to the vast volume of "orphan" works, no longer in print. Their goal is to eventually have digitized over 30 million titles, which happens to be roughly the number of books that scholars estimate now exist in the world!

- A number of U.S. universities (25 thus far) have pooled their digital collections to create the HathiTrust, currently at 5.5 million titles and adding over 400,000 books a month to form the nucleus of what could

become a 21ˢᵗ century analog to the "Library of Alexandria". ("Hathi" means "elephant" in Hindi…)

- While there are still many copyright issues that need to be addressed, it is likely that these massive digitization efforts will be able to provide full text search access to a significant fraction of the world's written materials to scholars and students throughout the world within a decade. In fact there has recently been a negotiation to provide access to millions of "orphan" works through an agreement with publishers similar to the music industry.

There are still other examples of what is now called social computing or networking:

- We all know well the rapid propagation of mobile technology, with over 3.5 billion people today having cell-phone connectivity and 1.2 billion with broadband access.

- Today's youth are digital natives, members of the Net Generation, comfortable with using the new techologies for building social communities–instant messaging, blogs, wiki's, virtual worlds, FaceBook, Twitter, Wikipedia (which even their professors use).

- Rather than access the vast knowledge resources provided through the open education resources movement through passive media such as books, this generation access knowledge and build social communities through 3-D virtual reality environments such as Second Life, the World of Warcraft, and Croquet in which all of the senses are faithfully replicated to enable human interaction at a distance.

  Paradigm Shift 3: The Future of the University? (Or something else?…)

Imagine what might be possible if all of these elements could be pulled together, i.e.,

- Internet-based access to all recorded (and then digitized) human knowledge augmented by powerful search engines,

- open source software, open learning resources, and open learning institutions (open universities),

- new collaboratively developed tools (Wikipedia II, Web 2.0); and

- ubiquitous information and communications technology (e.g., cheap laptop computers or, more likely, advanced cell phone technology).

In the near future it could be possible that anyone with even a modest Internet or cellular phone connection will have access to the recorded knowledge of our civilization along with ubiquitous learning opportunities.

- Imagine still further the linking together of billions of people with limitless access to knowledge and learning tools enabled by a rapidly evolving scaffolding of cyberinfrastructure increasing in power one-hundred to one thousand-fold every decade.

  This will not only challenge existing social institutions–corporations, universities, nation states, that have depended upon the constraints of space, time, laws, and monopoly,

  But it will enable the spontaneous emergence of new social structures as yet unimagined–just think of the early denizens of the Internet such as Google, MySpace, Wikipedia, …and, unfortunately, Al Queda.

- In fact, we may be on the threshold of the emergence of a new form of civilization, as billions of world citizens interact together, unconstrained by today's monopolies on knowledge or learning opportunities.

Perhaps this, then, is the most exciting vision for the future of knowledge and learning organizations such as the university, no longer constrained by space, time, monopoly, or archaic laws, but rather responsive to the needs of a global, knowledge society and unleashed by technology to empower and serve all of humankind.

And all of this is likely to happen during the lives of today's students…and, in fact, during the lives of most of you in this gathering this evening.

These possibilities must inform and shape the manner in which we view, support, and lead higher education. Now is not the time to back into the future!!!

A THIRD EXAMPLE: A FLEXNER REPORT FOR ENGINEERING

This same array of powerful forces that is so reshaping our economic–demographics, globalization, and rapidly evolving technologies–is also driving profound changes in the role of engineering in society.

> The changing workforce and technology needs of a global knowledge economy are changing dramatically the nature of engineering practice, demanding far broader skills than simply the mastery of scientific and technological disciplines.

> The growing awareness of the importance of technological innovation to economic competitiveness and national security is demanding a new priority for application-driven basic engineering research.

> The nonlinear nature of the flow of knowledge between fundamental research and engineering application, the highly interdisciplinary nature of new technologies, and the impact of cyberinfrastructure demand new paradigms in engineering research and development.

> Moreover, challenges such the off-shoring of engineering jobs, the decline of student interest in scientific and engineering careers, immigration restrictions, and inadequate social diversity in the domestic engineering workforce are also raising serious questions about the adequacy of our current national approach to engineering.

> Yet today engineering education remains predominantly dependent upon undergraduate programs increasingly challenged both by the relentless pace of new technologies and their declining ability to attract a diverse cadre of the most capable students compared to other professional programs such as law, medicine, and business administration.

Several years ago I chaired a major study of engineering research for the National Academies that provided input to the "Rising Above the Gathering Storm" effort and hence the America COMPETES Act.

Following this, NSF asked me to broad the study to analyze the changing nature of engineering practice, research, and education. More specifically, the study aimed at addressing the question of what our nation should seek as both the nature and objectives of engineering in the 21st century, recognizing that these must change significantly to address rapidly changing needs and priorities.

In a sense, this report asks questions very similar to those posed a century ago by noted educator Abraham Flexner when he examined implications of the changing nature of medical practice for medical education. Just as his premise that "If the sick are to reap the full benefit of recent progress in medicine, a more uniformly arduous and expensive medical education is demanded" drove a major transformation in medical practice, research and education, it is suggested today that the emergence of a global, knowledge-driven economy driven by technological innovation will demand a similarly profound transformation of engineering practice, research, and education.

Once again I employed the approach of *strategic roadmapping*, beginning with an environmental scan of the changing context for engineering and an assessment of the character and challenges of contemporary engineering practice, research, and education.

In view of these changes occurring in engineering practice and research, it is easy to understand why some raise concerns that we are attempting to educate 21st-century engineers with a 20th-century curriculum taught in 19th-century institutions.

The current paradigm for engineering education, e.g., an undergraduate

degree in a particular engineering discipline, occasionally augmented with workplace training through internships or co-op experiences and perhaps further graduate or professional studies, seems increasingly suspect in an era in which the shelf life of taught knowledge has declined to a few years.

There have long been calls for engineering to take a more formal approach to lifelong learning, much as have other professions such as medicine in which the rapid expansion of the knowledge base has overwhelmed the traditional educational process. Yet such a shift to graduate-level requirements for entry into the engineering profession has also long been resisted both by students and employers.

Moreover, it has long been apparent that current engineering science-dominated curricula needs to be broadened considerably if students are to have the opportunity to learn the innovation and entrepreneurial skills so essential for our nation's economic welfare and security, yet this too has been resisted, this time by engineering educators.

Nick Donofrio, former Vice-Chair of IBM, suggests innovation requires a new type of engineer he calls "T-shaped" as opposed to "I-shaped."

> I-shaped people have great credentials, great educations, and deep knowledge—deep but narrow. The geniuses who win Nobel prizes are "I-shaped," as are most of the best engineers and scientists.

> But the revolutionaries who have driven most recent innovation and who will drive nearly all of it in the future are "T-shaped." That is, they have their specialties—areas of deep expertise—but on top of that they boast a solid breadth, an umbrella if you will, of wide-ranging knowledge and interests.

> It is the ability to work in an interdisciplinary fashion and to see how different ideas, sectors, people, and markets connect. Natural-born "T's are perhaps rare, but I believe people can be trained to be T-shaped.

> The problem is that our educational system is still intent on training more "I's. We need to change that.

Hence the challenging is not so much *reforming* engineering education within old paradigms but instead *transforming* it into new paradigms necessary to meet the new challenges such as globalization, demographic change, and disruptive new technologies.

Our analysis has arrived at the following key conclusions:

1. In a global, knowledge-driven economy, technological innovation–the transformation of knowledge into products, processes, and services–is critical to competitiveness, long-term productivity growth, and the generation of wealth.

- Preeminence in technological innovation requires leadership in all aspects of engineering: engineering research to bridge scientific

discovery and practical applications; engineering education to give engineers and technologists the skills to create and exploit knowledge and technological innovation; and the engineering profession and practice to translate knowledge into innovative, competitive products and services.

2. To compete with talented engineers in other nations with far greater numbers and with far lower wage structures, American engineers must be able to add significantly more value than their counterparts abroad through their greater intellectual span, their capacity to innovate, their entrepreneurial zeal, and their ability to address the grand challenges facing our world. (Mention NSF's 5XME Project aimed at exploring how to make mechanical engineers 5 times more valuable that their global competition.)

3. It is similarly essential to elevate the status of the engineering profession, providing it with the prestige and influence to play the role it must in an increasingly technology-driven world while creating sufficiently flexible and satisfying career paths to attract a diverse population of outstanding students. Of particular importance is greatly enhancing the role of engineers both in influencing policy and popular perceptions and as participants in leadership roles in government and business.

4. From this perspective the key to producing such world-class engineers is to take advantage of the fact that the comprehensive nature of American universities provide the opportunity for significantly broadening the educational experience of engineering students, provided that engineering schools, accreditation agencies such as ABET, the profession, and the marketplace are willing to embrace such an objective.

- Essentially all other learned professions have long ago moved in this direction (law, medicine, business, architecture), requiring a broad liberal arts baccalaureate education as a prerequisite for professional education at the graduate level.

In summary, we believe that to meet the needs of the nation, the engineering profession must achieve the status and influence of other learned professions such as law and medicine.

- Engineering practice in our rapidly changing world will require an ever-expanding knowledge base requiring new paradigms for engineering research that better link scientific discovery with innovation.

- The complex challenges facing our nation will require American engineers with a much higher level of education, particularly in professional skills such as innovation, entrepreneurship, and global engineering practice.

To this end, we set the following objectives for engineering practice, research, and education:

1. To establish engineering practice as a true learned profession, similar in rigor, intellectual breadth, preparation, stature, and influence to law and medicine, with extensive post-graduate education and a culture more characteristic of professional guilds than corporate employees.

2. To redefine the nature of basic and applied engineering research, developing new research paradigms that better address compelling social priorities than those methods characterizing scientific research.

3. To adopt a systemic, research-based approach to innovation and continuous improvement of engineering education, recognizing the importance of diverse approaches–albeit characterized by quality and rigor–to serve the highly diverse technology needs of our society.

4. To establish engineering at the undergraduate level as a true liberal arts discipline, similar to the natural sciences, social sciences, and humanities

(and the trivium, quadrivium, and natural philosophy of earlier times), by imbedding it in the general education requirements of a college graduate for an increasingly technology-driven and -dependent society of the century ahead.

5. To achieve far greater diversity among the participants in engineering, the roles and types of engineers needed by our nation, and the programs engaged in preparing them for professional practice.

To achieve these, we offered the following proposals for action:

1. Engineering professional and disciplinary societies, working with engineering leadership groups such as the National Academy of Engineering, ABET, the American Association of Engineering Societies, and the American Society for Engineering Education, should strive to create a guild-like culture in the engineering profession, similar to those characterizing other learned professions such as medicine and law that aim to shape rather than simply react to market pressures.

The initial goal should be to create (actually, re–create) a guild culture for engineering, where engineers identify more with their profession than their employers, taking pride in being members of a true profession whose services are highly valued by both clients and society.

The necessary transformation is suggested by a transition in language:

* Engineers: from *employees* to *professionals*
* Market: from *employers* to *clients*
* Society: from *occupation* to *profession*

2. The federal government, in close collaboration with industry and higher education, should launch a large number of Discovery Innovation Institutes at American universities with the mission of linking fundamental scientific

discoveries with technological innovations to build the knowledge base essential for new products, processes, and services to meet the needs of society.

- *Discovery Innovation Institutes* represent a new paradigm aimed at linking fundamental scientific discoveries with technological innovations to create products, processes, and services to meet the needs of society.

- These new centers would be created through a partnership, very much in the same spirit as the earlier land-grant acts, involving the federal government, the states, industry, and higher education.

- These campus-based research centers would amount to "miniature Bell Laboratories", capable of conducting the long-term research necessary to convert basic scientific discoveries into the innovative products, processes, services, and systems needed to sustain national prosperity and security in an increasingly competitive world.

- The first round of these are the new "Energy Innovation Hubs" being created by the Department of Energy. The second round will be the "Regional Innovation Hubs" being proposed in the reauthorization of the America COMPETES Act.

3. Working closely with industry and professional societies, higher education should establish graduate professional schools of engineering that would offer practice-based degrees at the post-baccalaureate level as the entry degree into the engineering profession.

- Perhaps the most effective way to raise the value, prestige, and influence of the engineering profession is to create true post-baccalaureate professional schools similar to medicine and law, which are staffed with practice-experienced faculty and provide clinical practice experience.

- More specifically, the goal would be the transformation of engineering into a true learned profession, comparable in rigor, prestige, and influence to medicine and law, by shifting the professional education and training of engineers to post-baccalaureate professional schools offering two- or three-year, practice-focused degree programs (e.g., M. Eng. or D. Eng.).

- The faculty of these schools would have strong backgrounds in engineering practice with scholarly interests in the key elements of engineering, e.g., design, innovation, entrepreneurial activities, technology management, systems integration, and global networking, rather than research in engineering sciences.

- Students would be drawn from a broad array of possible undergraduate degrees with strong science and mathematics backgrounds, e.g., from the sciences or mathematics or perhaps a broader engineering discipline similar to the pre-med programs preparing students for further study in medicine.

4. Undergraduate engineering should be reconfigured as an academic discipline, similar to other liberal arts disciplines in the sciences, arts, and humanities, thereby providing students with more flexibility to benefit from the broader educational opportunities offered by the comprehensive American university with the goal of preparing them for a lifetime of further learning rather than professional practice.

- If the professional elements of an engineering education were shifted to a true post-graduate professional school, it might provide a very significant opportunity to address many of the challenges that various studies have concluded face engineering education today at the undergraduate level.

- In particular, removing the burdens of professional accreditation from undergraduate engineering degree programs would allow them to be reconfigured along the lines of other academic disciplines in the sciences, arts, and humanities, thereby providing students majoring (or concentrating) in engineering with more flexibility to benefit from the broader educational opportunities offered by the comprehensive university.

5. In a world characterized by rapidly accelerating technologies and increasing complexity, it is essential that the engineering profession adopt a structured approach to lifelong learning for practicing engineers similar to those in medicine and law. This will require not only a significant commitment by educators, employers, and professional societies but possibly also additional licensing requirements in some fields.

6. The academic discipline of engineering (or, perhaps more broadly, technology) should be included in the liberal arts canon undergirding a 21st-century undergraduate education for all students.

- Today we have a society profoundly dependent upon technology, profoundly dependent on engineers who produce that technology, and profoundly ignorant of technology.

- From this perspective, one could make a strong case that today engineering–or at least technology–should be added to the set of liberal arts disciplines, much as the natural sciences were added to the trivium and quadrivium a century ago.

- Here we are not referring to the foundation of science, mathematics, and engineering sciences for the engineering disciplines, but rather those unique tools that engineers master to develop and apply technology to serve society, e.g., structured problem solving, synthesis and design, innovation and entrepreneurship, technology

development and management, risk-benefit analysis, and knowledge integration across horizontal and vertical intellectual spans.

7. All participants and stakeholders in the engineering community (industry, government, institutions of higher education, professional societies, et. al.) should commit the resources, programs, and leadership necessary to enable participation in engineering to achieve a racial, ethnic, and gender diversity consistent with the American population.

We recognize that the resistance to such bold actions will be considerable.

- Many companies will continue to seek low-cost engineering talent, utilized as commodities similar to assembly-line workers, with narrow roles, capable of being laid off and replaced by off-shored engineering services at the slight threat of financial pressure.

- Many educators will defend the status quo, as they tend to do in most academic fields.

- And unlike the professional guilds that captured control of the marketplace through licensing and regulations on practice in other fields such as medicine and law, the great diversity of engineering disciplines and roles continues to generate a cacophony of conflicting objectives that inhibits change.

The stakes in such an effort are very high.

- Today neither industry nor the federal government are investing adequately in basic engineering research to provide the knowledge base necessary for technological innovation.

- Recent studies have well documented alarming trends such as the increasing tendency of industry to regard engineers as commodities, easy to replace through outsourcing and off shoring of jobs.

- Although most students interested in science and engineering have yet to sense the long-term implications of the global economy, as practices such as off shoring become more apparent, there could be a very sharp decline in the interest in engineering careers among the best students.

- Current immigration policies threaten our capacity to attract outstanding students, scientists, and engineers from abroad.

- And our failure to adequately diversify the engineering workforce poses a challenge in the face of the demographic certainty that 90% of the growth in the American population over the next several decades will consist of women, minorities, and immigrants.

If one extrapolates these trends, it becomes clear that without concerted action, our nation faces the very real prospect of eroding its engineering competence in an era in which technological innovation is key to economic competitiveness, national security, and social well being.

- Bold and concerted action is necessary to sustain and enhance the profession of engineering in America–its practice, research, and education. It is the goal of this report both to sound the alarm and to suggest a roadmap to the future of American engineering.

What happens next?

Option 1: Benign Neglect

One approach is to simply continue the status quo, accepting the current global market realities, reacting as best as one can to new requirements such as the need

for global engineers, and wait until conditions deteriorate sufficiently to stimulate bolder action.

Option 2: Evolution (Education and Persuasion)

A more proactive approach would involve the launch of a major outreach and education campaign aimed at convincing American industry, government, and the public of the importance of sustaining and enhancing domestic engineering capacity through additional investments in engineering education and research to raise the value-added by American engineers, as reflected in enhanced prestige and compensation for the engineering profession.

Option 3: Revolution (Politics and Cartels)

Here engineering professional societies would emulate the efforts of the medical and law professions (through the American Medical Association and American Bar Association) to seek legislation at the state and federal level to create a regulatory environment sufficient to empower the engineering profession.

Option 4: Punctuated Evolution and Spontaneous Emergence

Finally, one might simply take an opportunistic approach by keeping an eye out for possible tipping points that would drive–or at least allow–fundamental transformation of existing paradigms for engineering practice, research, and education, much as rapid climate changes drove occasional bursts of simultaneous co-evolution of biological species on Planet Earth.

Of course we could simply heed the advice of Thomas Paine:

"Perhaps the sentiments contained in the following pages, are not sufficiently fashionable to procure them general favour; a long habit of not thinking a thing wrong, gives it a superficial appearance of being right, and raises at first a

formidable outcry in defense of custom. But the tumult soon subsides. Time makes more converts than reason." (Paine, Common Sense, 1776)

Yet, unfortunately, the events of our changing world move ahead at a rapid pace despite our tendency toward procrastination. The future–indeed, the very survival–of American engineering demands the exploration of new paradigms of practice, research, and education today.