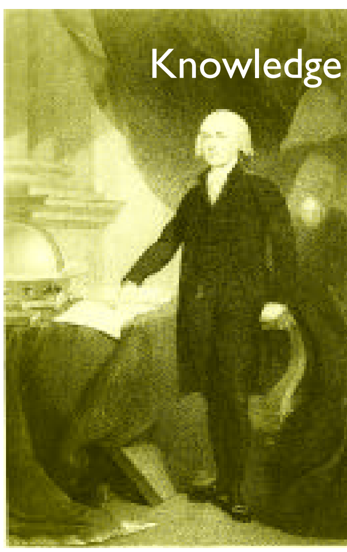
U.S. Engineering: Enabling the Nation's Capacity to Perform

by Joseph Bordogna, *Pennsylvania Delta '55*

ENGINEERS HAVE HISTORICALLY TAKEN a vigorous interest in education and, not surprisingly, have a particular interest in educating engineers. Today, many consider that pursuit to be *decisive* to our nation's future—and I am one of them. Educating engineers has occupied the greater part of my life—as an engineering student, as a naval officer, as an engineer in industry, as a professor and dean of engineering, and now in my role with the National Science Foundation (NSF).

As a steward of the health of our nation's science and engineering enterprise, NSF works at the frontier of research and education, where risks and rewards are high and where potential benefits to society are most promising. This is familiar territory for engineers. More than most, engineers have opportunities to ride the crest of the wave and arrive first at new shores. I say "opportunity" because exploring new frontiers is exhilarating and deeply satisfying. We can realize our personal aspirations as we also advance the collective future of our society and nation. It doesn't get any better than that!



Knowledge GOVERNS Ignorance

"Knowledge will forever govern ignorance; and a people who mean to be their own governors must arm themselves with the power which knowledge gives."

James Madison, 1822

From an engineer's point of view, we are the ones responsible for getting things done and out the door in our society. We make stuff, and we make it right. At our best, we also make the right thing. That has always been the role and responsibility of engineers in the continuing progress of society.

One particular application of those skills is the *making of U.S. engineers*. Of course, making engineers means *educating* engineers. Our design of the educational process manifests our intent for society. Thus, we must be very conscious of what we do and the path we take. Viewed in this light, the question of central importance becomes this: How do we make the *right engineers* for our times and for the future?

The amazing transformations that new knowledge and technology continuously trigger in our contemporary world bring education squarely into the limelight. In our knowledge-based economy and society, education is an investment in our nation's future. Engineering education *in particular* is an investment in our nation's capacity to perform. This is an awesome responsibility, ranging from an everyday improvement of society's operative underpinnings to responding smartly to sudden change.

Society's appetite for high performance in every sector is expanding. Standing at the fulcrum of scientific and technological change, engineers are expected to foster progress toward a daunting array of ends—creating new knowledge, artifacts, and systems; stimulating economic development; creating wealth and jobs; sharpening the nation's competitive edge; raising our prospects for more productive and satisfying lives; caring for the environment; and strengthening our national security.

Engineering education is at the very heart of these issues. Demands are increasing for a holistic breed of engineers—graduates with the skill to work across intellectual, social, and cultural boundaries. This integrative capability is key to successful performance in an increasingly diverse and complex international work environment.

But that's how it is and *should* be. Society's demands on us arise from a desire to provide our youngsters with the skills they need to thrive and our society with the wherewithal to understand and solve its problems and capitalize on its opportunities. They come from a reawakening that would resonate with the founders of our nation. Education plays a vital role in realizing our common purpose, now more integrated within a global context. Increasing expectations are a healthy sign that our core values have not changed.

Although some might quibble, most would agree that U.S. engineering education is *the best in the world*. The frontier research, cutting-edge tools, and skill sets that characterize our nation's engineering schools are the modern equivalent of Alexandria in the days of the great library.

Our schools of engineering are intellectual magnets, drawing students from every nation of the world. Today's global engineers are contemporary versions of the mobile scholars of classical times—diffusing new knowledge and technology and thus contributing to our common future on the planet. Science and engineering have always been international, democratic, and collegial in this sense.

But this raises an obvious and sobering question. If U.S. engineering education is the best in the world, why aren't U.S. students flocking to the engineering fold?

For some years, this question has been a serious concern and focus for the National Science Foundation, as well as for engineers. More recently, it has become a hot topic well beyond the engineering and scientific community. Industry, academe, government at all levels, and parents want to know if we are on the right track.

Will our youngsters have the skills needed to thrive in a competitive global economy driven by innovation and rapid technological change? Will there be a robustly capable supply of knowledge workers to meet increasing demands for them in our society and workplace? Will foreign nationals trained in U.S. engineering schools increasingly return to their home countries, depleting the ranks of engineers in the U.S.? Will an exodus of international talent, combined with growing numbers of engineers trained in other nations throughout the world, dull the competitive edge we enjoy in the United States? In academe, we worry about losing half of our engineering research capacity if international talent disappears from our graduate programs.

There is growing clamor to recruit more of our native talent to the engineering fold. And believe me, you'll find the NSF among the loudest advocates. Unequivocally, we need more U.S. women and under-represented minorities in our engineering workforce. This is a strategic as well as equitable manifestation of our intent in the design of engineering education. We need their talent and their perspectives. Without them, we will one day awaken, like the fictional Rip Van Winkle, to a world that has passed us by.

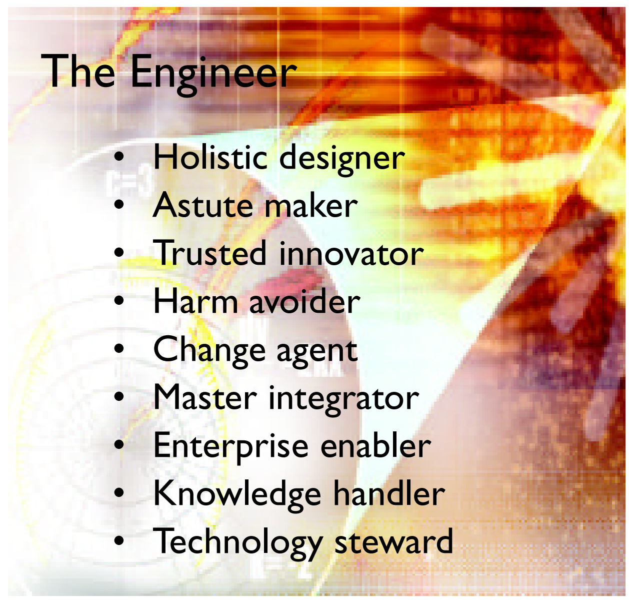
I won't repeat here the familiar litany of numbers that are deployed to demonstrate what some have called a *looming crisis* in U.S. engineering talent. We certainly need to be vigilant in understanding these trends; there is much we have yet to learn about their causes and consequences.

But as astute designers of our engineering future, we realize that the numbers are only part of the story. There is a deeper, abiding issue at stake. In 1822, James Madison wrote:

> *"A popular Government, without popular information, or the means of acquiring it, is but a prologue to a farce or a tragedy; or, perhaps, both. Knowledge will forever govern ignorance; and a people who mean to be their own governors must arm themselves with the power which knowledge gives."* [1]

Madison's words are still fresh and instructive today. They are the most fundamental rationale for an open-door policy to an engineering education. Let's advocate an open-door policy that educates and enables our own citizens to be contributing participants in our great democratic system, as well as continuing the successful policy of embracing those from abroad.

This new perspective on an old policy will make us a genuine welcoming nation to both talent from abroad and from the nation's women and underrepresented minorities. It can never be one or the other. The Statue of Liberty's torch must light the way for those within our borders as well as those from outside. If we engineers aspire to be leaders, this is the challenge we must accept and meet.



This challenge requires a transformation—a continuing revolution, if you will—in engineering education. Our engineering education must *go beyond best* to confront the new global realities. We need a model of engineering education suitable to a new world in which change and complexity are the rule, a world continuously transformed by new knowledge and the technology it makes possible, a world linked globally, where differences and divisions that have not been integrated can have immediate and large-scale consequences.

We must understand how to make the *right* engineers for our times and our future. Only then can engineering careers become a promising and appealing choice for more of our young people.

Here is one take on how we will identify engineers in the future. They will be: holistic designers, astute makers, trusted innovators, harm avoiders, change agents,

New Capabilities

- *Terascope*
- *Nanoscope*
- *Complexity*
- *Cognition*
- *Holism*

master integrators, enterprise enablers, knowledge handlers, and technology stewards. I am sure more characterizations can be added to this list.

This may seem a daunting repertoire of skills and talents, but it is by no means beyond our ability to achieve. The best engineers in all eras have lived up to this description, and more. However, in our own times, we have moved to a whole new threshold of capabilities that breach with the past and that will catapult us beyond today's horizons. They are nanoscope, terascope, cognition, complexity, and holism.

Each is characterized by a fertile research frontier. They also overlap and interweave in subtle and intricate ways that add tremendous power to our engineering tool kit. This newly minted synergy is what enables us to vastly enrich the scope and span of our knowledge and design the world of the future.

Ubiquitously available terascale computing—terascope for short—is computing technology that takes us three orders of magnitude beyond prevailing computing capabilities. Crossing that boundary of 10^{12}—one trillion operations per second—launches us to new universes.

Terascale is only one aspect of a much broader transformation. Our vision here is to reach *terascope* competency and catapult capability into a whole new era of science and engineering. In essence, we want to create a *tera universe or era* for science and engineering and a freshly robust national cyberinfrastructure. Within this infrastructure, we'll enjoy tera-ops power, terabyte storage, terabit connectivity, and tera-instrument interfaces. What an addition to our engineering tool kit!

Components of a Holistic Engineering Education

Vertical (in-depth) thinking	Lateral (functional) thinking
Abstract learning	Experiential learning
Reductionism-fractionization	Integration-connecting the parts
Develop order	Correlate chaos
Understand certainty	Handle ambiguity
Analysis	Synthesis
Research	Design/process/manufacture
Solve problems	Formulate problems
Develop ideas	Implement ideas
Independence	Teamwork
Technological-scientific base	Societal context
Engineering science	Functional core of engineering

The new *nano* capability brings together many disciplines of science and engineering to work in collaboration. As you know, nano-*scale* is three orders of magnitude smaller than most of today's human-made devices. Here, too, our vision is nano-*scope*: to create an overarching, enabling field, not unlike the role of information technologies today.

Nanotechnology gives engineers the ability to manipulate matter one atom or molecule at a time. We will be able to make a wish list of qualities and characteristics to build into a new material or machine. Nanostructures are at the confluence of the smallest human-made devices and the large molecules of living systems. We are now at the point of being able to connect machines to individual living cells.

Our tera and nano capabilities open vistas that were barely visible only 20 years ago. They vastly expand our options for designing our future. For that reason, they have raised new questions about the choices and directions we should take as we move forward.

Enter cognition, the third arrow in our quiver. The dictionary defines cognition as the mental process by which knowledge is acquired. Most of us would simply say, this is learning. But learning is anything but simple.

Cognition encompasses a panoply of individual human competencies—acquiring knowledge, solving problems, making decisions, communicating, and creating, among others. A rich knowledge base in cognitive science is being developed jointly by linguists, psychologists, philosophers, computer scientists, engineers, mathematicians, neuroscientists, and others.

Like tera and nano, the scope of this capability takes us to new territories. Cognition illuminates the full gamut of human and social dynamics that characterize our institutions at all levels of complexity. We already speak of *learning organizations* in this context. We are now beginning to address the complexities of large-scale change, for example, democratization, globalization, and the causes of war—as well as how we design engineering education. For these reasons, NSF has recently announced a competition to create *science of learning centers*. This brings us to the fourth capability, complexity. Mitch Waldrop, in his book *Complexity*, writes about a point we often refer to as "the edge of chaos." That is, "where the components of a system never quite lock into place, and yet never quite dissolve into turbulence either . . . . The edge of chaos is where new ideas and innovative genotypes are forever nibbling away at the edges of the status quo. . . ." This territory of complexity is *a space of opportunity*, a place to make a marriage of unlike partners or disparate ideas. It allows us to explore interdependencies on vastly broader scales and across traditional boundaries. It provides a window on the heart of change in all its myriad forms.

Holism, the fifth of our new capabilities, is closely linked to complexity. If complexity enables us to understand broader connections, holism teaches us that combinations of things have a power and capability greater than the sum of their separate parts. It spurs the search for new synergies and enables us to investigate and anticipate emerging structures and systems.

The hallmark of these new capabilities is their potential to transform. They help to connect, recompose, and expand core science and engineering disciplines. Each is nothing short of revolutionary, but in combination they are truly breathtaking in scope. They enable us to find solutions in unlikely places. One of the super chargers of our current age of cross-boundary discovery is the ability it gives us to shift from one context to another with agility, borrowing concepts and models along the way.

That's only for starters. As we integrate these new capabilities into engineering education, they will transform the very nature of learning environments. These new capabilities have the power to raise engineering education to a new dimension, to go beyond best to a newly transformed excellence.

I don't want to give the impression that we must abandon what we already know how to do so well in preparing engineers. We can't afford to jettison the tried and true. I envision the skills we routinely teach our students as paired with newly emerging ones. Both are components of a holistic engineering education. We might be tempted to perceive these pairs in sharp contrast, but they are actually complementary and, thus, enable one another.

Several have close ties to the new capabilities I've described. Take the pair "develop order-correlate chaos" for example. In his book, *Perfect Symmetry*, the physicist and explorer Heinz Pagels suggests some of the linkages between our new knowledge and the skills needed to realize their potential. He says: "The capacity to tolerate complexity and welcome contradiction, not the need for simplicity and certainty, is the attribute of an explorer."[2] We can also relate this directly to another pair: *understanding certainty—handling ambiguity*.

Seeing What's Visible 21st Century Academe

Conventional	***Emerging***
Department based	Topic based
Campus centric	Global reach
Building-block course	Holistic curriculum
Few links to industry	Robust industry partnership
Research vs education	Integration of research & education

Above all else, we are experts at teaching the technological-scientific base that engineers require. We do less well presenting the societal context in which engineers perform. In a broad sense, engineers will be required to design much of the societal change that will shape our future. They will envision artifacts, systems, networks, infrastructures, and tools for a new way of living and prospering. Our new cognitive capability will help us integrate human and social dimensions with our engineering knowledge base. The connections among complexity, holism, cognition, and *teamwork* are less obvious but even here progress is occurring.

The management guru Peter Drucker began talking about the need for knowledge workers and pervasive innovation at least 40 years ago. Years later, when asked how he could be so prescient, he replied: "I never predict. I just look out the window and see what's visible—but not yet seen."[3]

We can already see some of what is ahead for academe in the not too distant future. We are making progress in integrating research and education. Industry-campus partnerships have taken root in the fertile soil at the frontier of knowledge. Other changes are slower in coming. We are struggling to find a fit between the global reach of our new information and communications technologies and our campus-centric systems.

The baseball great, Yogi Berra, once said, "When you come to a fork in the road, take it." As we set out to revolutionize engineering education, there will be disconcerting moments when our vision of the end is not crystal clear, but the need to move forward is compelling. That is

Seeing by Looking

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Peter Drucker

one of the characteristics of working at the frontier and of innovation in its many manifestations.

At such times, we may need to deploy a strategy known as *constructive ambiguity*. This concept originated in the world of diplomacy and geopolitics, where it has a checkered history. But never mind the baggage. We can appropriate what is valuable in this concept as it resonates with our own subject.

Accepting ambiguity gives us tremendous power and flexibility. We can move ahead without knowing precisely where we are going, while making subtle course corrections along the way. And we can take advantage of entirely new developments and points-of-view to enrich and broaden our vision.

We can learn to recognize those contexts in which greater definition may close doors prematurely on future options. This is the *constructive* part of constructive ambiguity. There are times when working on parallel tracks provides the space necessary for innovation until it is ripe for integration.

John King of the University of Michigan recently offered comments on strategies for implementing the NSF's cyberinfrastructure vision.[4] I want to share one of his thoughts because it applies directly to our emerging vision for engineering education.

> *"The trick in evolving the capability for providing emergent infrastructure is the selective use of established models and the rapid generation and testing of new modes. This is a process of institutional and organizational learning, and the ability to learn rapidly is itself a kind of social infrastructure that is required to pursue the cyberinfrastructure vision."*

Substitute *engineering education* for *cyberinfrastructure* and you have a compelling strategy for the work that lies ahead. We need plenty of elbowroom and tolerance for experimentation with new structures and ideas. But we can't afford to dawdle. When we see a fork in the road, we need to take it.

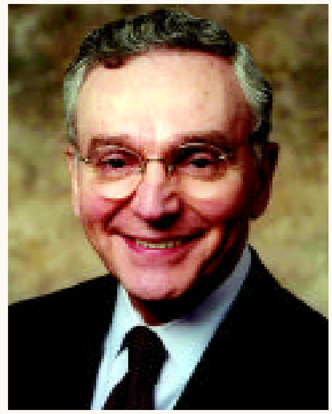
Forty years ago, in times of great national purpose similar to our own, President John F. Kennedy described the core of the educational enterprise in these words:

> *"Let us think of education as the means of developing our greatest abilities, because in each of us there is a private hope and dream which, fulfilled, can be translated into benefit for everyone and greater strength for our nation."*

We are closer than ever before to making this a reality in engineering. If we want to be leaders, we should welcome transformation and renewal, with all the risks and rewards they promise. If we do so, we will be well on our way to making the *right* engineers for our times and for the future.

To help us keep our focus on the inflection points in our progress—that is, to anticipate changes in our learning curve—I end with a quote from that great guru of human and social dynamics—William Shakespeare.

> *"The day shall not be up so soon as I, to try the fair adventure of tomorrow."*[5]



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He is a fellow of the AAAS, the ASEE, the International Engineering Consortium, and is a fellow and past president of the IEEE.

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