Celebrating the Past by Imaging the Future of Engineering Practice, Research, and Education

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Happy Birthday!!! And congratulations on a century of leadership in mechanical engineering at Caltech. Yesterday provided a spectacular demonstration of just how special Caltech engineering is!

It is therefore not only enjoyable but very reassuring to return to Caltech every now and then, just to see how the institute has flourished. And besides, Michigan Avenue still leads back to the Caltech campus.

- I did manage to make it to Pasadena several times during the 1990s on New Year's Day as Michigan's president. In fact, I used to be introduced by the Tournament of Roses folks as the "ultimate Caltech Rose Bowl prank"…a Caltech alum leading a Big 10 team to its doom in the Arroyo Seco, year after year (although I actually managed to win twice in my five Rose Bowls!)

A centennial is a time to celebrate past accomplishments and experience the excitement of today. But it is also a time to look ahead at the challenges and opportunities for Caltech to provide leadership in engineering in the years ahead.

Yet, ironically, to look ahead in engineering, it is instructive to first look back a century to 1910, just about the time ME was starting up at Caltech, to the experience of another profession, medicine, which was facing challenges similar to those faced by engineering today.

- During the 19th century, medical education had evolved from a practice-based apprenticeship to dependence entirely upon didactic education (a year of lectures followed by a licensing exam), losing the rigor of training critical to competent health care.

- To become a doctor, one needed only a high school diploma, a year of lectures, and a few dollars to buy a license to begin practice as a physician.

- The changing health care needs of society, coupled with the changing knowledge base of medical practice, would drive a very rapid transformation of the medical profession, along with medical education, licensure, and practice.

- The Carnegie Foundation for the Advancement of Teaching commissioned noted educator Abraham Flexner to survey 155 medical schools over a yearlong period and draft a report concerning the changing nature of the profession and the implications for medical education.

The Flexner Report of 1910 transformed medical education and practice into the 20th century paradigm of scientific (laboratory-based) medicine and clinical training in teaching hospitals. (Flexner, 1910)

- Flexner held up Johns Hopkins University as the model against which he compared other programs, since it was the first medical school to require a baccalaureate degree as the entry credential, allowing a far more rigorous approach to medical education.

- In a sense, Johns Hopkins provided the existence proof, a model of a radically different approach to medical education that was rapidly accepted by a number of other universities and resulted in the rapid disappearance of most for-profit medical colleges at the undergraduate level.

- The shift of medical education to post-graduate university programs not only resulted in the closure of two-thirds of the nation's medical schools, but also the creation of the university medical center, combining education, research, and clinical practice.

Here it is interesting to note during his study of medicine, Flexner raised very similar concerns about engineering education even at this early period.

- "The minimum basis upon which a good school of engineering accepts students is, once more, an actual high school education, and the movement toward elongating the technical course to five years confesses the urgent need of something more."

During the past century there have been several efforts to conduct an analysis of engineering very similar in spirit to the Flexner Report, including

- the Mann Report of 1918 (sponsored like Flexner by the Carnegie Foundation);

- the Wilkenden Report of 1923;

- the ASEE Green Report of 1994,
- the NRC BEED Report leading to the ABET EC2000 program, and most recently the
- NAE *Engineer of 2020* study (Clough, 2004)
- As Bill Schowalter, former U. Illinois engineering dean, observes, "Appearance every decade of a definitive report on the future of engineering education is as predictable as a sighting of the first crocuses in spring." (Schowalter, 2003)

Over the past century other professions have changed very dramatically:

- Medical knowledge has been transformed from the skills taught through apprenticeship (e.g., the barber shop) to macroscopic science (physiology, epidemiology) to microscopic science (genetics, proteomics, nanotechnology). Medical practice is also continuing to evolve rapidly, from reactive (curing disease) to prescriptive (determining one's genetic deposition to disease) to preventive (wellness).
- The profession of law is also evolving rapidly because of the impact of information technology (e.g., the ability to rapidly search and analyze written material in digital form; new forms of evidence such as DNA analysis; and the evolution of computer-based pattern recognition and psychological profiling to detect lying).

Yet, although engineering is one of the professions most responsible for and responsive to the profound changes in our society driven by evolving technology, its characteristics in practice, research, and education have been remarkably constant–some might even suggest stagnant–relative to other professions.

- Most aspects of engineering, including engineering education and professional certification, remain much as they have for decades, despite the rapidly changing nature of engineering practice and technology needs of society.

- In particular, engineering education has remained remarkably stable–to be sure, adding more scientific content, but doing so within a four-year undergraduate program based primarily upon scientific problem solving.

- In fact, one might even suggest that today most of our universities are attempting to produce 21^{st} engineers with a 20^{th} century curriculum in 19^{th} century institutions!

Hence although perhaps foolhardy at a progressive place like Caltech, it occurred to me that you might be amused by an attempt to propose a Flexner report for engineering–a century after the founding of engineering at Caltech–and a century after the transformation of medicine from a barber shop skill into a learned profession!

Here I should stress, however, that since Caltech is far out on the tail of the Gaussian distribution of quality and innovation, most of what I'm going to talk about are the challenges faced by OTHER engineering programs (perhaps even that place in Cambridge…).

Actually, I don't have to visit 155 schools as Flexner did since there have been numerous recent studies suggesting the need for new paradigms in engineering practice, research, and education that better address the needs of a 21st century global, knowledge-driven society. Most prominent among these are:

- *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, National Academies (Augustine, 2005)
- *The National Innovation Initiative*, Council on Competitiveness (Council on Competitiveness, 2006)
- *Engineering Research and America's Future: Meeting the Challenges of a Global Economy*, National Academy of Engineering (NAE, 2005)
- *The Engineer of 2020 (Parts I and II),* National Academy of Engineering (Clough, 2004, 2005)
- *The Engineering Profession*, Carnegie Foundation for the Advancement of Teaching (Sheppard, 2006)
- *The Science and Engineering Workforce: Realizing America's Potential*, National Science Board (NSB, 2003)

Other more general or related studies include:

A Test of Leadership: Charting the Future of U.S. Higher Education, The Secretary of Education's Commission on the Future of Higher Education in America (ED, 2006)

Revolutionizing Science and Engineering Through Cyberinfrastructure, the NSF Advisory Panel on Cyberinfrastructure (Atkins, 2004)

The IT Forum, National Academies, Government-University-Industry Research Roundtable (Duderstadt, 2005)

The Federal Science and Technology Budget, Committee on Science, Engineering, and Public Policy (COSEPUP, 1999-2003)

Critical Choices: Science, Engineering, and Security, Department of Energy Task Force on the Future of Science Programs at the Department of Energy (Vest, 2003)

In addition, there are several efforts underway that are aimed at implementing several of the recommendations in these studies:

ABET's EC2000 Program (ABET, 1995)

The President's American Competitiveness Initiative (Marburger, 2006)

NSF's Cyberinfrastructure Program (Atkins, 2003)

This cacophony of reports and initiatives has converged into a chorus of concerns about the changing nature of engineering:

- 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 as 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.

Clearly these challenges facing our rapidly changing world are immense and require the skills of talented engineers to both address existing needs and to provide the innovative products, systems, and services necessary for prosperity, security, and social well being in the future.

- Yet these will require very significant changes in engineering–in its practice, its supporting knowledge base, and its education and training.

More generally, they raise 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 changing national needs and priorities?

- What is engineering–a discipline, an occupation, a career, or a profession?

- Who should be the primary clients of engineering–industry, government, the nation, the world, students, or the profession itself?

- Granted that engineering education should not be monolithic, but how can we achieve adequate intellectual depth, breadth, and rigor across a highly diverse engineering enterprise demanded by our changing needs as a society and as a nation.

So, let me leap into the fray, suggesting some of the flaws in American engineering today…and the challenges it must face and surmount tomorrow.

Engineering Practice Today

Engineering practice is changing rapidly.

In a global economy increasingly driven by technological innovation and the creation of new businesses, the role of the engineer as innovator and entrepreneur becomes even more important.

- While many corporations still require a large engineering workforce for product development and manufacturing, others are pushing their engineering activities off-shore to take advantage both of lower labor costs as well as the rapidly increasing engineering sophistication of nations in Asia and Europe making major commitments to science and engineering education for large populations.

- Multinational corporations manage their technology activities to take advantage of the most capable, most creative, and most cost-efficient engineering and scientific talent, wherever they find it.

- The rapid evolution of high quality engineering services in developing nations with significantly lower labor costs such as India, China, and Eastern Europe raises a serious question about the global viability of the United States engineer, who must now produce effectively five times the value-added to justify wage differentials.

- And, of course, this is a moving target, since while much of today's off-shoring of engineering involves routine, repetitive services, it is clear that the commitment of other nations to education in science and engineering, the strong work ethic and rising quality of their engineering talent, and the rapidly expanding size of their engineering workforce–particularly in Asia–will allow global sourcing to move rapidly up the value chain to product design, development, and innovation.

Clearly American engineers face the challenge of elevating their activities to a higher level of sophistication and value added if they are to be competitive in the global economy.

- The globalization of markets requires engineers capable of working in multinational corporations and NGOs. New perspectives are needed in building competitive enterprises as the distinction between competition and collaboration blurs.

- Both new technologies (e.g., info-bio-nano) and the complex mega systems with problems arising in contemporary society require highly interdisciplinary engineering teams characterized by broad intellectual span rather than focused practice within the traditional disciplines.

- Today's hypercompetitive markets demand a much faster pace of innovation, shorter product life cycles, lower prices, and higher quality than ever before.

- As technological innovation plays an ever more critical role in sustaining the nation's economic prosperity, security, and social well-being, engineering practice will be challenged to shift from traditional problem solving and design skills more toward innovative solutions imbedded in an array of social, environmental, cultural, and ethical issues.

Yet, despite the growing importance of engineering practice to society, the engineering profession still tends to be held in relatively low esteem compared to other learned professions such as law and medicine.

- The prestige of the profession of engineering in our nation requires particular attention, since most Americans tend to view engineers as employees of industry or government rather than learned professionals such as physicians and lawyers.

- We tend to portray engineers as problem solvers rather than creators and innovators who address the grand challenges of our time—environmental contamination, world hunger, energy dependence, and the spread of disease.

- Journalists report scientific achievements and engineering failures, as though engineering hasn't made profound contributions that have dramatically extended the human life span through public infrastructures.

- The low esteem of the engineering profession is also evidenced in the way that industry tends to view engineers as consumable commodities, similar to other white-collar employees such as accountants, subjecting to lay-offs or off-shoring whenever near-term financial pressures arise or discarding them when their skills become obsolete or replaceable by cheaper engineering services from abroad.

- In a recent survey few engineering managers acknowledged a shortage of new graduates in engineering as a problem.

    - Several admitted they were not allowed to increase “head count” in the United States at all; if they wanted to add engineers, then they had to do it off-shore.

    - Indeed, some managers said they would not recommend that their own children go into engineering, since they did not see it as a career with a bright future.

- The low public prestige of the engineering profession is also apparent in the declining interest of students in engineering careers relative to other professions such as business, law, and medicine.

Engineering Research Today

There is increasing recognition that leadership in technological innovation is to the nation’s prosperity and security in a hypercompetitive, global, knowledge-driven economy. (Council on Competitiveness, 2003)

- Our American culture, based upon a highly diverse population, democratic values, free-market practices, and a relatively stable legal and regulatory climate, provides an unusually fertile environment for technological innovation and entrepreneurial activity,

- But other nations are beginning to reap the benefits of such investments aimed at stimulating and exploiting technological innovation, creating serious competitive challenges to American industry and business both in the conventional marketplace (e.g., Toyota) and through new paradigms such as the off-shoring of knowledge-intensive services (e.g. Bangalore).

- Even though current measures of technological leadership—percentage of gross domestic product invested in R&D, absolute numbers of researchers, labor productivity, and high-technology production and exports—still favor the United States, a closer look at the engineering research and education enterprise and the age and makeup of the technical workforce reveals several interrelated trends indicating that the United States may have difficulty maintaining its global leadership in technological innovation over the long term.

These well-documented trends include:

- a large and growing imbalance in federal research funding between the engineering and physical sciences on the one hand and biomedical and life sciences on the other; (e.g., NIH = $30 B, NSF = $6 B)

- increased emphasis on applied and relatively short-term R&D in industry and government-funded research at the expense of fundamental long-term research;

- the erosion of the engineering research infrastructure due to inadequate investment over many years;

- the declining interest of American students in science, engineering, and other technical fields; and

- the growing uncertainty about the ability of the United States to attract and retain gifted science and engineering students from abroad at a time when foreign nationals account for a large, and productive, component of the U.S. R&D workforce.

One of the most critical—and today most neglected—elements of the innovation process is the long-term research required to transform new knowledge generated by fundamental scientific discovery into innovative new products, processes, and services required by society.

- In years past this applications-driven basic research was a primary concern both of major corporate R&D laboratories and campus-based programs such as engineering schools.

- However, in today's world of quarterly earnings pressure and inadequate federal support of research in the physical sciences and engineering, this longer-term, applications-driven basic research has largely disappeared both from the corporate setting and from the campuses, putting at risk the discovery-innovation process in the United States.

Engineering Education

The critical role of our engineering schools in providing human capital necessary to meet national needs faces particular challenges.

- Student interest in science and engineering careers is at a low ebb–not surprising in view of the all-too-frequent headlines announcing yet another round of layoffs of American engineers as companies turn to off-shoring engineering services from low wage nations.

- Cumbersome immigration policies in the wake of 9-11 along with negative international reaction to U.S. foreign policy is threatening the pipeline of talented international science and engineering students into our universities and engineering workforce.

- Furthermore, it is increasingly clear that a far bolder and more effective strategy is necessary if we are to tap the talents of all segments of our increasingly diverse society.

Of course, the United States cannot match the Chinese or Indians in numbers of new engineering graduates. Rather, the United States needs to develop new engineering paradigms appropriate for a rapidly changing, global, knowledge driven society.

Yet, despite the profound changes occurring today in engineering practice and engineering science and technology, we continue to educate and train engineers much as we have for the past several decades.

- In the curricula of our engineering schools we still stress analytical skills involving scientific and mathematical analysis to solve well-defined problems rather than the broader skills of engineering design, innovation, and systems integration.

- Bowing to industry and student pressure, we continue to pretend that one can become an engineer with only a four-year undergraduate education, despite the fact that the curriculum has become overloaded, pushing aside the opportunities for the broader type of liberal education required to address the changing nature of engineering practice.

- The current paradigm for engineering education, e.g., an undergraduate degree in a particular engineering discipline, occasionally augmented with workplace training 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 knowledge base has overwhelmed the traditional educational process.

- Moreover, it has also 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.

- Finally, we must make engineering education, engineering practice, and the profession of engineering itself more attractive to young people.

Clearly new paradigms for engineering education are demanded to:

- respond to the incredible pace of intellectual change (e.g., from reductionism to complexity, from analysis to synthesis, from disciplinary to multidisciplinary);

- develop and implement new technologies (e.g., from the microscopic level of info-bio-nano to the macroscopic level of global systems);

- accommodate a far more holistic approach to addressing social needs and priorities, linking social, economic, environmental, legal, and political considerations with technological design and innovation, and

- to reflect in its diversity, quality, and rigor the characteristics necessary to serve a 21st century nation and world.

- And, perhaps as important as anything, we must infuse in our students a new spirit of adventure, in which risk-taking and innovation are seen as an integral part of engineering practice, and where bold solutions are sought to the major challenges facing our world.

- (Here I should note that from the presentations yesterday, it is clear that Caltech is providing important leadership!)

Transforming the Profession

The first challenge is to transform engineering from an occupation or a career to a true learned profession.

- When physicians are asked about their activities, they generally respond with their professional specialty, e.g., "I'm a cardiologist" or "I'm a neurosurgeon." So too, lawyers are likely to respond with a specialty such as corporate law or litigation. In sharp contrast, when asked about their profession, most engineers will respond with their employer: "I work for Ford…Boeing…whatever…" Engineers tend to identify with their job rather than their profession.

- Part of the challenge is that there are so many types of and roles for engineers–from low level technician/draftsman to master engineers to engineering scientists to technology managers. Hence as we redefine the engineering profession it will be important to identify new career paths. For example, one might distinguish these by degree levels:

    - engineering (B.S.E.)
    - master engineer (M. Eng.)
    - engineering scientist (D. Eng.)
    - technology manager (M. Eng + MBA)

Hence key in any effort to elevate the educational requirements and thereby the value, prestige, and influence of the engineering profession will be an effort by engineering professional societies and higher education to break through the current resistance of employers and the marketplace.

- Put another way, the key is for the American engineering profession to shift from simply reacting to market pressure to a more concerted effort to define and control the marketplace, much like other learned professions.

Proposed Action: Transforming Engineering (Back) into a Guild

Hence perhaps the initial goal should be to create (rather, re-create) a guild culture for engineering, where engineers identify more with their profession than their employer, taking pride in being a part of a true profession whose services are highly valued both by clients and society.

Note the transition in language we are suggesting here:

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

But how?

- A century ago, the American Medical Association and the American Bar Association exerted strong political influence at the state and federal level to elevate the educational and licensing requirements for their professions.

- Yet in contrast with medicine and law, engineering is characterized by numerous disciplines and roles, many of which have their own professional societies. While there are broader organizations such as the National Society of Professional Engineers, the American Association of Engineering Societies, the Accreditation Board for Science and Technology, and the National Academy of Engineering, none has the influence to unite engineers behind a concerted and coordinated effort to break the stranglehold of employers and achieve radical transformation–at least yet.

Transforming Engineering Research

For over 50 years the United States has benefited from a remarkable discovery-innovation engine that has powered our economic prosperity while providing for our national security and social well-being. Indeed, it has been estimated that over 50% of the economic growth during that period came from new technologies.

Today it has become apparent that the nation's discovery/innovation engine needs a tune-up in the face of the profound changes driven by a hypercompetitive, knowledge-driven global economy and that further federal action is necessary to generate the new knowledge, build the necessary infrastructure, and educate the innovators-entrepreneurs necessary for global leadership in innovation.

Recently the National Academy of Engineering completed a comprehensive study of the challenges facing engineering research in America and recommended a series of actions at the federal level to respond to the imperatives of a flattening world.

We summarize the most important of these recommendations below:

- Federal R&D Budget: The committee strongly recommends that the federal R&D portfolio be rebalanced by increasing funding for research in engineering and physical science to levels sufficient to support the nation's most urgent priorities, such as national defense, homeland security, health care, energy security, and economic competitiveness.

- Long-Term Research and Industry: Long-term basic engineering research should be reestablished as a priority for American industry.

- Engineering Research Infrastructure: Federal and state governments and industry should invest in upgrading and expanding laboratories.

- Quality of the Technical Workforce: Considering the importance of technological innovation to the nation, a major effort should be made to increase the participation of American students in engineering.

- Diversity: All participants and stakeholders in the engineering community (industry, government, institutions of higher education, professional societies, et al.) should place a high priority on encouraging women and underrepresented minorities to pursue careers in engineering.

- Fellowship Programs: A major federal fellowship-traineeship program in strategic areas (e.g., energy, info- nano- and biotechnology, knowledge services, etc.), similar to the program created by the National Defense Education Act, should be established to ensure that the supply of next-generation scientists and engineers is adequate.

- Immigration Policies: Immigration policies and practices should be streamlined (without compromising homeland security) to restore the flow of talented students, engineers, and scientists from around the world into American universities and industry.

Responding to these technological challenges and opportunities and the changing nature of global competition and technological innovation will require changes—

- in the way our research is prioritized, funded, and conducted;
- in the way we attract, educate, and train engineers and scientists;
- in policies and legal structures that affect related issues, such as intellectual property;

- and in strategies to maximize contributions from institutions engaged in technological innovation and workforce development (e.g., universities, corporate R&D laboratories, federal agencies, and national laboratories).

The current challenges to the nation's prosperity and national security, as well as the opportunities for global leadership, call for a bold new initiative of magnitude similar to other federal actions such as the Land Grant Acts and the Government-University Research Partnership to break away from the status quo.

Proposed Action: Creation of Discovery-Innovation Institutes

Multidisciplinary *discovery-innovation institutes* should be established on the campuses of research universities to link fundamental scientific discoveries with technological innovations to create products, processes, and services to meet the needs of society.

- Like the agricultural experiment stations created by the Hatch Act of 1887, these institutes would be responsive to particular societal priorities and designed to stimulate technological innovation, educate a world-class high-technology workforce, and ensure U.S. economic growth.

- Like academic medical centers, they would bring together research, education, and practice.

- Like major corporate R&D laboratories, they would link fundamental scientific discoveries with the engineering research necessary to yield innovative products, services, and systems. Unlike industry laboratories, however, they would be focused on meeting long-term societal needs, as well as educating the next-generation technical workforce.

University-based discovery-innovation institutes would be funded through a partnership of federal, state, and possibly local governments, industry, foundations, and universities.

- Schools of engineering, management, medicine, law, and social sciences would all have a compelling interest in participating in genuinely interdisciplinary projects to address the complex challenges facing the nation.

- The institutes would compete for funding and would be responsible for producing both short- and long-term deliverables.

- They would engage both undergraduate and graduate students and would be expected to provide new curricular materials and engage in outreach activities.

- Because discovery-innovation institutes would be focal points of activity for participants from many disciplines and communities—faculty, students, engineers, industrial managers, legal experts, health professionals, and financial experts—they would provide a nurturing environment for entrepreneurship.

To ensure that the discovery-innovation institutes have a transformative impact, the committee believes they should be funded at a level commensurate with past federal initiatives and current investments in other areas of research, such as biomedicine and manned spaceflight.

- Thus, federal funding would build to a level of several billion dollars per year that would be distributed throughout the engineering research and education enterprise; comparable amounts would be invested by states, industry, foundations, and universities.

(By the way, Caltech already has a "discovery-innovation institute". It is named JPL!)

Transforming Engineering Education

Many nations are investing heavily in developing their engineering workforce within cultures in which science and engineering are regarded as exciting, respected fields by young people and as routes to leadership roles in business and government–in contrast to the relatively low popularity and influence of these fields in American society.

But the United States does have one very significant advantage: the comprehensive nature of the universities in which most engineering education occurs, spanning the range of academic disciplines and professions, from the liberal arts to law, medicine, and other learned professions.

- This stands in sharp contrast to the more focused educational institutions in Europe and Asia where the professions are frequently set apart from the liberal arts disciplines.

- American universities have the capacity to augment education in science and engineering with the broader exposure to the humanities, arts, and social sciences that are absolutely essential to building both the creative skills and cultural awareness necessary to compete in a globally integrated society.

- Furthermore their integration of education, research, and service–that is, learning, discovery, and doing–provides a formidable environment for educating 21st century engineers.

- By building a new paradigm for engineering education that takes full advantage of the comprehensive nature and unusually broad intellectual span of the American university, we can create a new breed of engineer, capable of adding much higher value in a global, knowledge-driven economy.

Ironically, to take advantage of this unique character of American higher education, its capacity to integrate learning across the academic and professional disciplines, perhaps we should consider separating engineering as an *academic discipline* from engineering as a *learned profession* through the following actions:

Proposed Action: Establish Graduate Professional Schools of Engineering

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

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 three-year, practice-focused degree programs (e.g., D. Eng. or Diploma of Engineering).

- 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 basic sciences or perhaps through a "pre-engineering" program (similar to the pre-med programs preparing students for further study in medicine.)

- The engineering professional schools would be augmented by university-owned engineering services companies capable of providing internship experiences in engineering practice (similar to the teaching hospitals supporting medical education).

Yet here we face a formidable challenge since we really have no existing models to build upon in the way that Abraham Flexner utilized Johns Hopkins University as his model for the future of medical education.

- Instead, most of our existing engineering schools are heavily discipline-based, providing the science, mathematics, and engineering science instruction that undergird engineering, but have very little of the professional training and experience that professional schools in other disciplines provide (e.g., moot courts or clinical rounds).

- Most engineering faculty today are, in reality, engineering scientists, focusing their professional activities on research rather than professional practice.

- We also have no analog to teaching hospitals or law clinics. As a result, today's engineering students must depend on summer employment, co-operative education, and early employment to provide their first exposure to engineering practice and training.

Speculating a bit about the structure of such schools, it seems clear that they would have to exist at the graduate level, requiring a B.S./B.A. in science, mathematics, or “pre-engineering”.

- While the M.Eng. degree programs developed by many engineering schools might be a first step toward such professional schools, much like the M.B.A. suffices for the business profession, a more extended program akin to law and medical education would have more impact on both student capabilities and the prestige of the profession.

- Clearly the educational content would be quite different from the engineering science curriculum characterizing most undergraduate engineering programs today.

- At the professional level, a practice-oriented and experienced faculty would be capable of developing topics such as design and synthesis, innovation, project and technology management, systems analysis, entrepreneurial and business development skills, and global engineering systems, as well as more abstract topics such as leadership and professional ethics.

- There are several possibilities for clinical experience in engineering practice, along the lines of the teaching hospital or law clinic. While sophisticated intern experiences in industry are certainly a possibility–if carefully designed and monitored by the faculty–it may be desirable to create specific opportunities more closely related to campus-based instruction.

- Here the discovery-innovation institutes mentioned earlier in this chapter would be one attractive possibility.

- Another approach would involve the creative of captive, for-profit engineering consulting or services companies, managed by professional engineers and staffed by student interns.

- Finally there are also several models of such professional engineering education we might look to for guidance. Many engineering schools already have developed professional oriented masters programs, substituting project work or an internship in place of a research thesis. Perhaps the most highly developed is MIT's David H. Koch School of Chemical Engineering Practice.

Proposed Action: Undergraduate Engineering Would Be Restructured as a "Liberal Arts" Discipline

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 much as 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.

- It could reverse the trend toward ever more narrow specialization among engineering majors that is driven largely by the reductionist approach of scientific analysis rather than the highly integrative character of engineering synthesis.

- Reframing undergraduate engineering as an academic discipline rather than a pre-professional training program would have another great advantage in better enabling future engineers to benefit from a truly liberal education.

The discipline of engineering would be taught by existing engineering schools through both degree programs at the undergraduate and graduate level and courses provided to all undergraduates as a component of a new 21st century liberal arts core curriculum.

- Because of the strong research interests and background of most current engineering faculty, the curriculum and degrees offered in the discipline of engineering would have more of an engineering and applied science character and would not necessary require ABET certification, thereby allowing more opportunity for a broader liberal education on the part of undergraduates.

- Engineering schools would continue to offer multiple degrees as they do now, e.g., ABET-accredited B.S. degrees in engineering, broader B.S. or B.A. degrees in engineering science, and of course an array of graduate degrees (M.S., M. Eng., Ph.D.).

- Students wishing an engineering background as preparation for further study in fields such as medicine, business, or law would continue to enroll in specific engineering majors, much as they do now.

- There would still be room for the old undergraduate engineering paradigms: Many students would continue to enroll in ABET-accredited engineering degree programs to prepare them for entry into technology-based careers, although as we have noted earlier, these would soon require further education and training to remain relevant. Other undergraduates would major in either ABET-accredited or engineering science degree programs in preparation for further graduate study in engineering science (M.S. and Ph.D.)

Proposed Action: The Academic Discipline of Engineering Would Included in the Liberal Arts Canon for the 21st Century

In a world increasingly dependent upon technology, it seems appropriate that the engineering discipline be added to the liberal arts core of a general education, appropriate for undergraduate students seeking a liberal education for the 21st century, much as the natural sciences were added a century ago to the classical liberal arts (classical languages, grammar, logic, rhetoric–the classical *trivium* and *quadrivium*).

- Recall that the liberal arts is an ancient concept that has come to mean studies that are intended to provide general knowledge and intellectual skills, rather than more specialized occupational or professional skills.

- In proposing that engineering be added to the liberal arts 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 entrepreneurialism, technology development and management, risk-benefit analysis, and knowledge integration across horizontal and vertical intellectual spans.

Primary 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. For engineering to play the role it must, it is essential to elevate the status of the engineering professions, 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 outstanding students.

3. To compete with talented engineers in other nations with far lower wage structures, American engineering 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.

4. From this perspective the key to producing such world-class engineers is to take advantage of the fact that universities in the United States are more comprehensive and hence capable of providing broader educations, provided engineering schools, accreditation agencies such as ABET, and the marketplace is willing to embrace such an objective. Essentially all other learned professions are moving in this direction (law, medicine, business), requiring a broad liberal arts baccalaureate education as a prerequisite for professional education at the graduate level, but not as an end in itself.

The Goals for 21st Century Engineering

1. To establish engineering practice as a true learned profession, similar in rigor, intellectual breadth, preparation, stature, and influence to law and medicine, with a extensive post-graduate education and 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 characterizing scientific research.

3. To adopt a systemic approach to the reform 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 as a true liberal arts discipline, similar to the natural science, social sciences, and humanities (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, and the programs engaged in preparing them for professional practice.

Clearly the resistance to such transformations will be considerable.

- Industry 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 slightest threat of financial pressure.

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

- And unlike the professional guilds that captured control 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 prevents change.

But here it is important to also remember and take comfort from those famous words of Thomas Paine:

> "Perhaps the sentiments contained in these pages (…rather, my talk…), 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)

And provides more opportunities for Caltech's leadership in engineering for the century ahead!!!