Report of

The "5XME" Workshop:

Transforming Mechanical Engineering Education and Research in the USA

May 10-11, 2007
National Science Foundation, Arlington, VA

Edited by A.G. Ulsoy

P. Eibeck, R. Buckius and A. Bement at the 5XME Workshop

Executive Summary

The National Science Foundation (NSF) sponsored a workshop, held May 10-11, 2007 in Arlington, VA, and entitled *The "5XME" Workshop: Transforming Mechanical Engineering Education and Research in the USA*.[1] The ambitious goal of the workshop was to lay the foundation for transformative change in mechanical engineering education and research in the USA. Motivated by the fact that the science-based engineering education taught at our engineering schools has become a commodity, available to students all over the world, including low-wage markets. Global companies employ such world-class engineering talent, often at 20% of the cost in the USA, and are moving manufacturing, design and even research activities to such locations. *The challenge for engineering schools in the USA is how to educate a mechanical engineer that provides five times the value added when compared to the global competition, i.e., the "5XME."*

Informal Discussions During Break at 5XME Workshop

The transformation needed in mechanical engineering education must embrace societal priorities, and become an exciting and attractive leadership opportunity for a diverse pool of talent from all segments of our society. Such a transformation will require a new infrastructure, and new methods of educational delivery, that develop the specific abilities of diverse students, to achieve the attributes that graduates must possess, e.g.:

[1] NSF Grant # CMMI-0647197

1. Broad grounding in fundamentals
2. Flexibility and agility
3. Innovation and creativity to benefit society
4. Global focus
5. Teamwork and leadership
6. Communication skills

In education: Engineers must be broadly educated, not simply to solve problems others have set for them, but to identify problems and issues and to provide the technological leadership needed to benefit society. We must fully develop the potential and all the skills of our students to develop the new renaissance engineer, and bring the successful research and project focus of graduate education to undergraduate students in engineering.

In research: Engineers must practice concurrent discovery and innovation to fuel the economy, and benefit society, in a time of accelerating technological change. Emerging areas, such as macro systems (e.g., innovation, energy, environment, enterprises, service industries, health care, complex systems), micro/nano systems, bioengineering, information technology and cognitive engineering present new opportunities.

While the participants in the workshop were primarily mechanical engineers, the recommendations from the workshop are broadly applicable to all fields of engineering. The recommendations included changes that were needed in engineering education, but also what further studies were called for, and how to move ahead with the recommended changes. Specifically, those recommendations can be summarized in terms of three broad categories:

1. Key Observations. Consistent with other recent studies on engineering education, major changes were recommended in all stages of engineering education:

a. In today's global knowledge economy, mechanical engineers educated in the USA must be able to add significantly more value than their counterparts abroad, through the breadth of their intellectual capacity, their ability to innovate, and their leadership in addressing major societal challenges.

b. Transformative changes are needed at each of the five major stages of the education of an engineer. These stages include: (1) primary and secondary education, (2) bachelors, (3) masters, (4) doctoral, and (5) lifelong learning. Discussions during the workshop focused only on stages (2) through (5).

c. The bachelors degree should introduce engineering as a *discipline*, and should be viewed as an extension of the traditional liberal arts degree where education in natural sciences, social sciences and humanities is supplemented by education in the discipline of engineering for an increasingly technological world.

d. This bachelors degree in the *discipline* of engineering can be viewed as the foundational stem upon which several extensions can be grafted: (1) continued professional depth through a professional masters degree in engineering, and (2) transition to non-engineering career paths such as medicine, law, and business administration.

e. The masters degree should introduce engineering as a *profession*, and become the requirement for professional practice. This is where educational institutions and professional societies can build an awareness of the profession, as opposed to producing graduates who view themselves merely as employees.

f. Doctoral education in engineering is essential to national prosperity, and global competition is rapidly increasing. The doctoral degree in engineering, while indisputably the best in the world, needs to be enhanced and strengthened with an emphasis on breadth as well as depth, linking discovery and innovation, and improved leadership and teaching skills.

g. Lifelong learning programs in engineering, including executive education, need to be developed and delivered to engineers at all stages in their professional development.

2. Proposed Studies. Although many studies have been done on various aspects of this topic in recent years, it was felt the following studies would be valuable for moving ahead with the recommended changes:

a. There is a need for a national market study for engineers. What are the various career opportunities for engineering graduates, and what are the various programs that best prepare the students for different markets (e.g., corporate employment, entrepreneurial companies, academic positions). This can help shape the content for the new bachelors, masters and doctoral degrees in recommendation 1 above.

b. A study to benchmark engineering education in the USA vis a vis the rest of the world. This would complement the recent NRC study of mechanical engineering research in the USA compared to the rest of the world (see Appendix D).

c. A study of the doctoral engineering degree pipeline, including its economics, sources of students, and placement of students, is needed. Such a study will be important to ensure that this degree remains in a leadership position worldwide.

d. A compilation and assessment of existing engineering programs that currently implement some aspects of the recommendations in 1 above, e.g., a liberal arts engineering bachelors degree, a 5-year professional masters degree, teaching of innovation, etc.

3. Proposed Pilot Programs. The changes recommended are transformative, thus, difficult to implement. To move forward, identifying and/or establishing pilot programs, and using assessment to benfit from those experiences, was recommended, e.g.

a. Programs that focus on societal relevance in engineering to attract a diverse student body.

b. Development of courses and curricula in engineering for teaching innovation.

c. An understanding of incentives that support the transformations in recommendation 1 above.

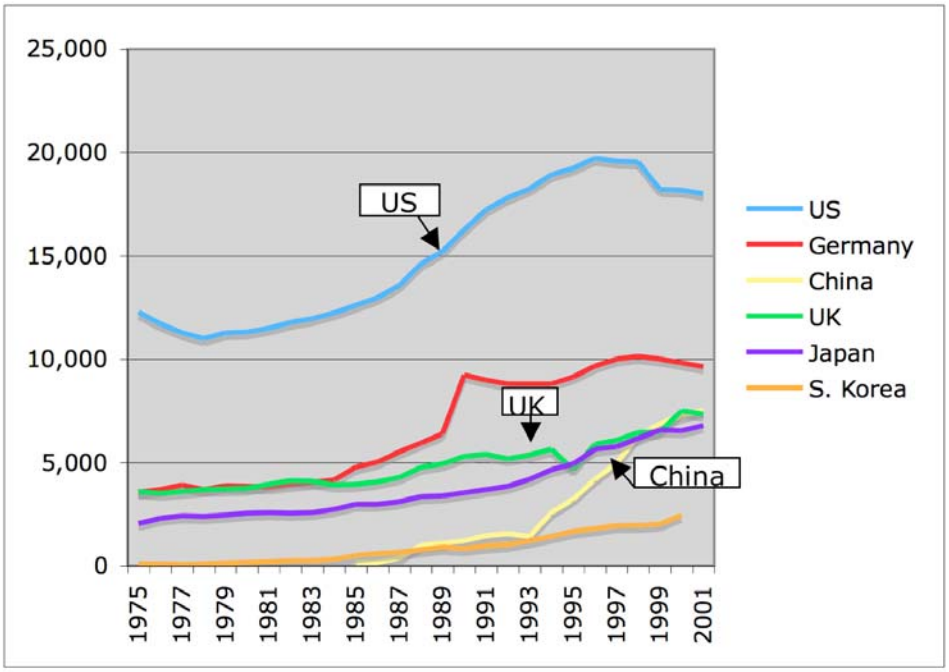
d. A collaborative effort among organizations, such as ASME, NAE, ASEE, etc. to move forward on some of these recommendations.

e. A collaborative effort with medical, business and law schools to establish a common cause among professional schools.

f. A follow up to the workshop, for in-depth discussion and further development of these topics, to be held at the Mechanical Engineering Education Conference sponsored by ASME International, to be held in Galveston, Texas during April 4-8, 2008.

Introduction

The launch of the first artificial satellite, Sputnik, by the USSR in 1957 precipitated a transformative change in engineering education in the USA, towards a science-based engineering curriculum focused on fundamentals. For example, mechanical engineering education emphasized thermodynamics, heat transfer, fluid mechanics, solid mechanics and dynamics. Topics from mechanical engineering practice, such as internal combustion engines, heat exchangers, automotive body structures and machine tools, became viewed as applications of those fundamentals. This emphasis on fundamentals empowered engineering students, and enabled graduates to apply their knowledge and skills in a variety of different industries, and in emerging new technologies (e.g., aerospace, nuclear, computer, biomedical). However, this same emphasis on fundamentals has led to a weak link to engineering practice, and a lack of emphasis on industrial innovation and commercialization of technology.

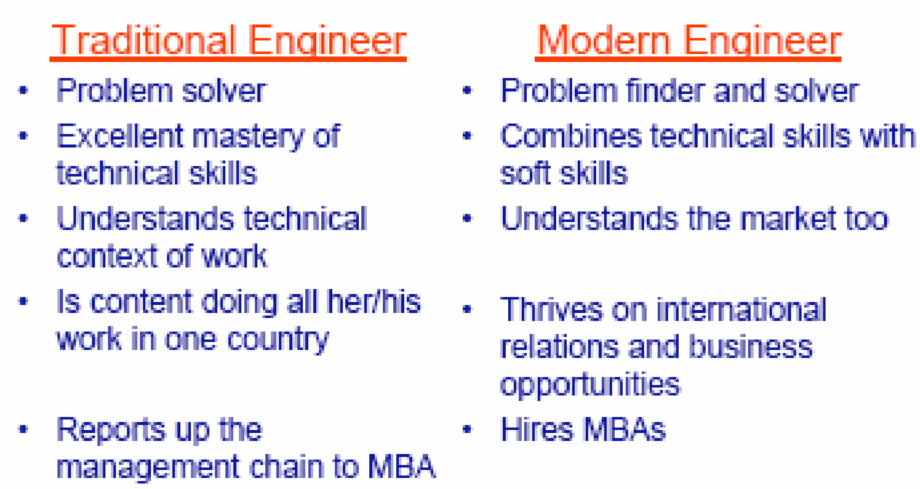


PhD Degrees in Science and Engineering from Plenary Presentation by A. Akay (see Appendix D)

Globalization, with the open flow of information, goods and people all over the world, brings significant benefits to all. However, it also creates challenges for the nation. In engineering education many countries now emulate the very successful USA engineering schools and their science-based curricula, and are making investments that produce an order of magnitude more engineers, and of comparable quality. Global companies employ such world-class engineering talent, often at 20% of the cost in the USA, and are moving manufacturing, design and even research activities to such locations. Furthermore, the national investment in mechanical engineering research, which has fueled the economy for decades with breakthrough technologies (e.g., CAD systems, MRI machines, non-destructive evaluation methods), is also being emulated by other nations around the world, which are recognizing the importance of engineering for economic prosperity, and are making the societal investments in engineering research and education. However, given current societal values, the USA is unlikely to significantly increase taxes for further public support of engineering education and research; in fact such public support has been eroding over the past 50 years.

We now face a national crisis more dramatic than the launching of Sputnik in 1957, and one that will require a creative and transformative response in terms of engineering education. The economy and prosperity of the nation will depend on our ability to respond effectively to such a changing environment, especially in core engineering disciplines like mechanical engineering. Mechanical engineering, which is often viewed as a mature discipline, is in fact rapidly evolving to encompass emerging areas such as mechatronics, MEMS, biotechnology, medical devices, cognitive engineering and nanotechnology. Furthermore, it retains a strong focus on design and manufacturing and remains one of the largest engineering disciplines in terms of undergraduate degrees and enrollments. *The challenge for engineering schools in the USA is how to educate a mechanical engineer that provides five times the value added when compared to the global competition, i.e., the "5XME".*

Mechanical engineering education and research in the USA will need to link more closely with engineering practice and the commercial world to generate the necessary market pull and resources for such a transformation. However, the current emphasis on engineering fundamentals cannot be sacrificed. To achieve the "5XME," mechanical engineering education must be transformed to embrace both fundamentals and practice; both the procedural knowledge of the problem-solving engineer as well as the declarative knowledge of the applied scientist. A similar transformation occurred in the automotive industry when some companies realized that they could beat the competition by producing vehicles that were *both* high in quality and low in cost. Also analogous is the transformation in medicine that occurred with the Flexner report in 1910, which led to a medical education based upon both scientific and clinical training.



Traditional vs Modern Engineer from the Plenary Presentation by N. Farvardin (see Appendix D)

The transformation needed in mechanical engineering education must embrace societal priorities, and become an exciting and attractive leadership opportunity for a diverse pool of talent from all segments of our society. Such a transformation will require a new infrastructure, and new methods of educational delivery, that develop the specific abilities of diverse students, to achieve the attributes that graduates must possess, e.g.:

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In research: Engineers must practice concurrent discovery and innovation to fuel the economy, and benefit society, in a time of accelerating technological change. Emerging areas, such as macro systems (e.g., innovation, energy, environment, enterprises, service industries, health care, complex systems), micro/nano systems, bioengineering, information technology and cognitive engineering present new opportunities.

Similar to the change that occurred in engineering, to become a science-based discipline, after the launch of Sputnik in 1957, we are now looking for another transformative change to engineering education; this time in response to the global competition, and specifically to the fact that a science-based engineering education has become a commodity available to students all across the world, including low-wage markets. We urgently need to identify the attributes that the mechanical engineering graduate in the USA must posses to compete successfully in a global marketplace, where global companies hire engineering talent and establish engineering services, anywhere in the world. We need to identify the mechanisms (e.g., courses, curricula, internships, projects, engineering clinics) by which those students will acquire such attributes. We also need to develop a strategy, tactics and resources to move ahead with such a transformation on a national scale.

The National Science Foundation (NSF) has sponsored (Grant # CMMI-0647197) a workshop, held May 10-11, 2007, to discuss these important and urgent issues, and to initiate the process of transformation (see http://www.umich.edu/~ulsoy/5XME.htm). This report summarizes the results of that workshop. A workshop planning committee (i.e., Mary Good, Marshall Jones, Lee Matsch, Dan Mote and Galip Ulsoy) had met earlier, during July 2006, with Adnan Akay and Richard Buckius from NSF, and drafted the white paper included in Appendix A of this report. They also intentionally coined the provocative title *The 5XME Workshop: Transforming Mechanical Engineering Education and Research in the USA* to convey a sense of urgency, and to emphasize that the goal of the workshop was to look for "big", i.e., transformative, ideas in mechanical engineering education and not to discuss continued improvements to our current educational paradigms in engineering, which have already been identified in numerous reports (see Bibliogrpahy).

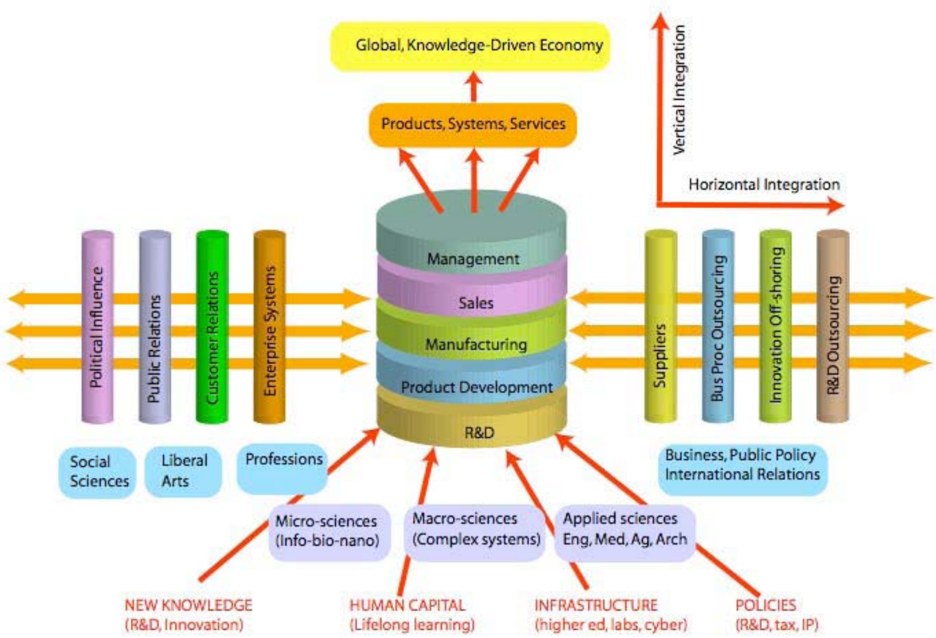
Welcoming Address by A. Bement, Director of NSF at 5XME Workshop

The "5XME" workshop began with plenary presentations on the morning of the first day, and then continued with small breakout sessions to discuss specific topics. The workshop agenda (including breakout groups and topics) is given in Appendix B, and the list of participants is in Appendix C. Furthermore, Appendix D of this report includes all the plenary presentations from the workshop:

- *Welcoming Remarks*, Arden L. Bement , Director, National Science Foundation
- Opening Remarks, Richard O. Buckius , Assistant Director, Engineering Directorate, NSF
- *Summary of 5XME workshop white paper*, A. Galip Ulsoy, W.C. Ford Professor of Manufacturing, University of Michigan

- *The need for a renaissance in engineering education – BS to PhD*, Adnan Akay, Director, Division of Civil, Mechanical and Manufacturing Innovation, NSF
- *NRC panel on benchmarking US research competitiveness in mechanical engineering*, Ward O. Winer, E.C. Gwaltney, Jr. Chair of the Woodruff School of Mechanical Engineering and Regent's Professor, Georgia Institute of Technology
- *Globalization and engineering education*, Nariman Farvardin, Dean and Professor of Electrical and Computer Engineering, University of Maryland.
- *Reinventing engineering for the 21st century*, James J. Duderstadt, President Emeritus and University Professor of Science and Engineering, University of Michigan

Following sections of this report will summarize, from the workshop discussions, the Needs and Opportunities, Possible Initiatives, and the workshop Recommendations.



The Global Knowledge-Driven Economy: A Systems Perspective from Plenary Presentation by J. Duderstadt (see Appendix D).

Needs and Opportunities

In the previous section it was discussed how the science-based engineering education of the second half of the 20th century is becoming a commodity, available anywhere in the world. At the same time, the needs of the global knowledge economy are demanding far broader skills from the engineer than simply mastery of scientific and technological disciplines. Thus, in today's global knowledge economy, mechanical engineers educated in the USA must be able to add significantly more value than their counterparts abroad, through the breadth of their intellectual capacity, their ability to innovate, and their leadership in addressing major societal challenges.

In our current global, knowledge-based, economy it is technological innovation that provides nations with a competitive advantage and leads to peace and prosperity. Technological innovation is the transformation of knowledge into products, processes and services and requires preeminence in engineering. Due to rapidly accelerating technological change, it is becoming more essential than ever to link engineering research (i.e., discovery) with innovation. Engineers must understand and manage the process of innovation, much as they currently understand and manage engineering problem solving, engineering design, and engineering research. Thus, engineering, which transformed our lives in the 20th century, promises to even more profoundly effect every aspect of society in the 21st century. This systems perspective is captured in the figure above, from the plenary talk by J. Duderstadt (see Appendix D).

However, despite the opportunities it affords for societal impact and leadership, engineering is held in low regard by many people. There is a decline in students interested in engineering, and the engineering student body does not reflect the diversity of the larger society. This lack of prestige for engineering as a profession, is grounded, in part, in perceptions that:

- Engineers are employees, replaceable and disposable commodities, not leaders and decision-makers
- Engineers focus on narrow technological problems, and not broader societal needs
- Engineers are narrowly educated in scientific and technological disciplines

Consequently, there is an opportunity to enhance the prestige of engineering as a profession, by educating engineers more broadly across all disciplines, by strongly linking engineering to societal needs, and by establishing engineering as a true learned profession, like medicine, law and business administration.

Gardner and Shulman [2005] state that "In our view, six commonplaces are characteristic of all professions, properly construed: a commitment to serve in the interests of clients in particular and the welfare of society in general; a body of theory or special knowledge with its own principles of growth and reorganization; a specialized set of professional skills, practices, and performances unique to the profession; the developed capacity to render judgments with integrity under conditions of both technical and ethical uncertainty; an organized approach to learning from experience both individually and collectively and, thus, of growing new knowledge from the contexts of practice; and the development of a professional community responsible for the oversight and monitoring of quality in both practice and professional education."

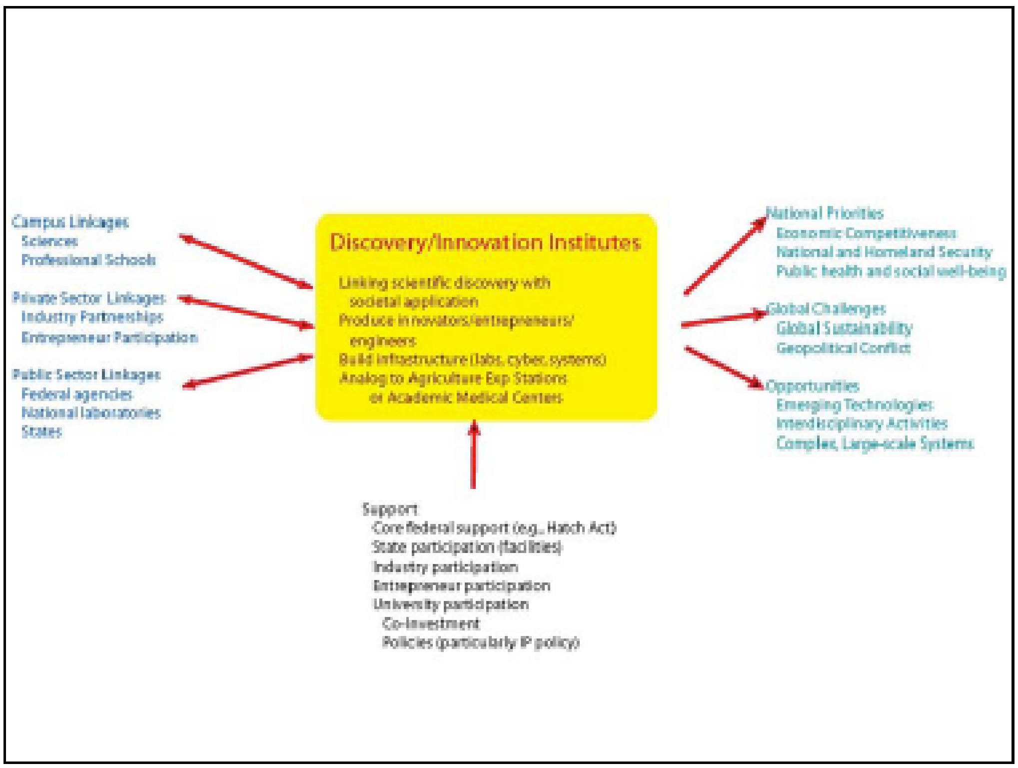
Possible Initiatives

Many ideas, and possible initiatives, were put forth by the workshop participants during the plenary and breakout sessions over two days. In this section, based upon the notes provided by the breakout session recorders, an unstructured summary of such possible initiatives in given. These were then, during the second day of the workshop, distilled by the participants into recommendations. The workshop recommendations are given in the next section of this report, as well as in the Executive Summary.

- *Leadership* was a major topic of discussion, since in an increasingly technological society engineers need to be educated for leadership positions. Engineering education must focus not only on the ability to solve problems correctly, but also to formulate the correct problems that fully consider the societal and human dimensions of technological decisions.
- It was recognized that engineering education must focus on *societal benefits of engineering*, and educate students for societal impact and leadership. This in turn will help to elevate the prestige of the profession, and to attract students that traditionally have shied away from engineering careers, especially women and minorities. Considerable discussions on how to attract diverse students focused on the need to understand the motivations, values and interests of young people.
- The need to *engage non-engineers in technology* (societal superproblems such as global warming, human interactions with technology), was also discussed, and the role that might be played in this regard by departments of engineering education.
- It was concluded that is necessary to *educate students broadly*, by expanding the traditional liberal arts education to include engineering and technology. Such a broad education will serve well both students who then pursue professional engineering careers, as well as students who need a foundation in technology for other careers, such as medicine, law, and business.
- The need to *elevate the prestige of the engineering profession* was also discussed in the context of other professions such as medicine, law and business. A professional masters degree in engineering, which builds upon the bachelors degree, was felt to be necessary.
- Significant discussion focused on *innovation and entrepreneurship*, since engineering is viewed as key driver for economic prosperity. Engineering students should be comfortable with business and commercialization plans as well as technology plans.
- The process of innovation, and its management and teaching, was a major topic of discussion. It was argued that the *innovation process*, like other procedural knowledge in engineering (e,g, the engineering design process, research – or the process of discovery) can be taught in a structured manner to engineering students.
- In the current environment of rapid technological change, the need to closely link *discovery and innovation* was emphasized. The concept of discovery-innovation centers, located at major universities, modeled on teaching hospitals and agricultural extension services, was put forth. The importance of project (or research) based learning was discussed, and its effectiveness in graduate education reiterated. An environment that supports practice and project experience, based upon case studies, as part of engineering education, is desirable.
- The last revolution in engineering education, during the 1960's, marked a transition from experience-based to science-based engineering, which relied heavily upon mathematical models of engineered systems. Discussions centered on what might be the next frontier in terms of such sweeping methodological change sin engineering. One

candidate area discussed was *self-diagnosing and self-healing engineered systems*, or so-called "immune systems engineering."

- Other discussion topics included the need to focus engineering education on *systems*, rather than components; the need for access in mechanical engineering to major national experimental facilities via a shared cyberinfrastructure; the fact that there are centers that study how people learn, and how we might take advantage of this.
- In summary it was felt that the new "5XME" can only be achieved through a *sweeping transformation*, with significant enhancements at all levels:
  - Liberal bachelors degree (broadly educated)
  - Professional masters (depth and disciplinary expertise)
  - Enhanced doctoral degree (quality, leadership, teaching)
- There was also considerable discussion on how we might move ahead with such a sweeping transformation. Some aspects of our recommendations might already be in *implementation*, and others might need to be undertaken as *pilot studies.*



Discovery-Innovation Institute Concept from Plenary Talk by J. Duderstadt (see Appendix D)

Recommendations

While the participants in the workshop were primarily mechanical engineers, the recommendations from the workshop are broadly applicable to all fields of engineering. The recommendations included changes that were needed in engineering education, but also what further studies were called for, and how to move ahead with the recommended changes. Specifically, those recommendations can be summarized in terms of three broad categories:

1. Key Observations. Consistent with other recent studies on engineering education, major changes were recommended in all stages of engineering education:

a. In today's global knowledge economy, mechanical engineers educated in the USA must be able to add significantly more value than their counterparts abroad, through the breadth of their intellectual capacity, their ability to innovate, and their leadership in addressing major societal challenges.

b. Transformative changes are needed at each of the five major stages of the education of an engineer. These stages include: (1) primary and secondary education, (2) bachelors, (3) masters, (4) doctoral, and (5) lifelong learning. Discussions during the workshop focused only on stages (2) through (5).

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g. Lifelong learning programs in engineering, including executive education, need to be developed and delivered to engineers at all stages in their professional development.

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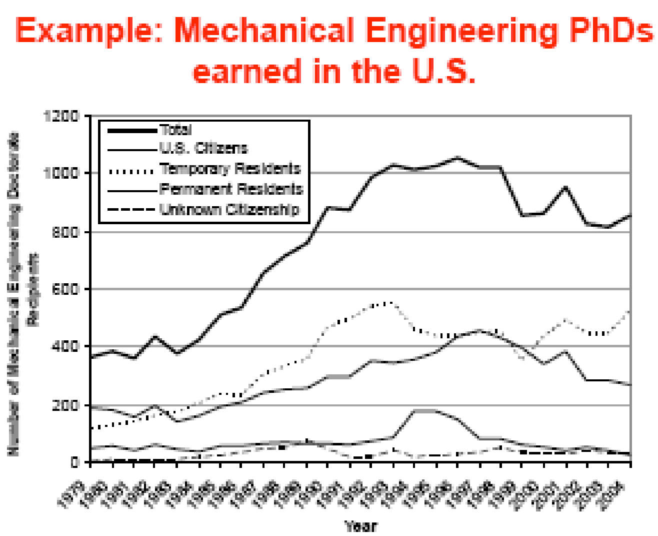

PhD Degrees in Mechanical Engineering from Plenary Talk by W. Winer (see Appendix D)

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{Please send additional key references to ulsoy@umich.edu}

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Appendices

A. White Paper

B. Agenda

C. Participants

D. Workshop Plenary Presentations

Arden L. Bement , Director, National Science Foundation

Richard O. Buckius , Assistant Director, Engineering Directorate, NSF

***Summary of 5XME workshop white paper,* A. Galip Ulsoy, W.C. Ford Professor of Manufacturing, University of Michigan**

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***Reinventing Engineering for the 21st Century,* James J. Duderstadt, President Emeritus and University Professor of Science and Engineering, University of Michigan**