Transformation of Mechanical Engineering Education at M.I.T.

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It is my pleasure to be here today. I would like to thank Professor Raju for inviting me to give this talk. I would like to offer my congratulations to Professor Raju and his colleagues for their excellent contributions to engineering education. It takes dedication and hard work to accomplish the ambitious goals of the LITEE.

One of the hallmarks of our educational institutions is the serious effort made to improve undergraduate engineering education. Many engineering schools have done excellent work to improve the quality of their educational programs with remarkable success. Today, I would like to share with you how we have attempted to improve mechanical engineering education at MIT. Before I discuss what we have actually done, I would like to provide the rationale for the change, especially for the students in the audience.

Exciting Era for Engineers

We, the scientists and engineers, are living in an exciting era. We have both unique opportunities and challenges that were not existent for previous generations.

The rapid advances in science and technology have provided us with new opportunities to create new products and processes that were only possible in the realm of science fiction a few decades ago. Through science and technology, we have improved, and will continue to improve, the quality of life for everyone on this planet.

These opportunities for major advances in science and technology are in part driven by diverse societal issues that are challenging us. The issues that require technological solutions are related to energy, environment, health care, manufacturing, and socio-economic problems. They will require our ingenuity and hard work. They will also require that engineers work with socio-political economic sectors whose inputs will be critical in achieving rational solutions to these outstanding issues.

Exciting Technological Opportunities

There are many exciting opportunities for engineers. I will just give a couple examples. Recently I have been working with rocket scientists and other highly skilled engineers who are designing the Orbital Space Plane (OSP) that may eventually replace the Space Shuttle. The OSP will be launched in Year 2010. Figure 1 shows an artist rendering of an Orbital Space Plane. OSP will be launched using an expendable launch vehicle (ELV) — the rocket. In this scheme, the Orbital Space Plane is attached to ELV. The OSP may carry another smaller plane, which will be used to take the crew into orbit and to the international space station (ISS). The international space station has a capacity to accommodate seven people, but currently only three astronauts are stationed in ISS, because we can rescue only three astronauts using the Russian spacecraft Soyuz.

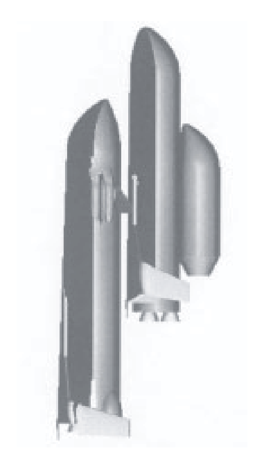

Figure 1 An artist rendering of the Orbital Space Plane

The opportunity and challenge in this "Project of the Decade" is that OSP must be developed in a systematic manner so as to satisfy the required performance of the OPS mission at minimum cost, maximum safety and unprecedented reliability. One of the astronautics companies has decided to use Axiomatic Design to improve the design and the development process, to increase the reliability of the OSP system, and to minimize the development and operational cost of the OSP. In the past, these complicated engineering tasks were achieved through a repetition of the design-build-test cycle, which tended to be expensive and unreliable. It was my privilege to be teaching Axiomatic Design – a rational design method for complex systems – to outstanding rocket scientists and engineers.

Another example is that of the manufacture of semiconductors, which is an equally interesting and complex project. One piece of equipment required to manufacture integrated chips (IC) is the photolithography machine, which optically prints electric circuits on the silicon wafer coated with photoresist. This piece of equipment optically reduces the image on a reticule down to a small size using a series of lenses, which are called projection optics, and activates the photo-resist coated on the silicon wafer. This is a major process in creating the memory de-

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* *Laboratory for Innovative Technology and Engineering Education*

vices or microprocessors. This equipment is used in conjunction with many other kinds of manufacturing equipment to make IC chips. The amazing thing about these machines is the precision required to produce very small dimensions to an extreme accuracy. The width of the circuit line, which is called the critical dimension (CD), of Pentium 4 is only 130 nanometers, that is, 0.13 microns. For comparison, a strand of human hair is 70 to 100 microns in diameter and therefore, on the cross section of our hair, we can put about 500 lines of electric circuits. Furthermore, in modern IC devices, many layers of these integrated circuits must be created to manufacture a functioning device. These lithography tools are very precise machines that must operate at high speeds for economic production of IC chips. To design this kind of machine, we need engineers with expertise in diverse areas with a strong background in engineering principles. They must have the capability to design complicated systems, understand the process physics and create reliable manufacturing processes, and to integrate diverse engineering disciplines to generate the best technology.

The challenge in semiconductor manufacturing is that the critical dimensions must be decreased further every two or three years to increase the storage density and the speed of microprocessors. Therefore, the industry is developing lithography tools, which uses 157 nm laser beams, which is a major challenge. Even with these advances in optical technologies, we may not be able to extend the optics-based semiconductor technology to dimensions smaller than about 30 nm during the next decade. Therefore, we need to consider alternative means of storing information and making "nano" processors. One of my colleagues, Seth Lloyd is working on a quantum mechanical computer, which is to use the electron spin around an atom to store information. It is an exciting idea that may someday become a useful technology. There may be other alternatives to information storage and processing, which should be investigated by engineers and scientists.

There are many other exciting technological opportunities that can significantly improve human capability and the quality of life. Engineering education must prepare students so that they can deal with these exciting opportunities, which is why we have changed our undergraduate education.

Engineering Education

The educational goal of our department is to create future leaders. To achieve this goal, we have decided that our department should implement changes to further strengthen our research programs, to improve the quality of our undergraduate educational programs through teaching excellence and innovation, and ultimately help in re-defining the discipline of mechanical engineering. We have also renovated the facilities and have undertaken ambitious book writing activities. One of the most important decisions we made was to broaden the discipline of mechanical engineering by hiring faculty members whose academic disciplines are different from those of traditional mechanical engineers, so as to complement traditional mechanical engineering subjects with those that are essential for future practicing engineers. We have been on this path for more than ten years. As a result of this effort, we have a new undergraduate curriculum, new teaching laboratories and modern lecture halls, and many new textbooks and professional books, and a strong faculty who collaborates across disciplinary lines. In addition, we have also initiated research in many new areas such as bio-instrumentaion, information, and micro- and nano-technologies as well as reinforcing the research in traditional areas.

Our educational goal has been to prepare our students for leadership roles by teaching them "how to think" and by providing them with a broader perspective of their career by introducing them to ideas and technologies that may shape the future of our society. Students are challenged to learn the basics of engineering science, mathematics, and natural science. Undergraduate students have the option of choosing their own interdisciplinary curricula that is tailor made to pursue their own interests. We give them a set of intellectual tools that will provide them with means of pursuing their own career goals. However, a majority of our students pursue more traditional mechanical engineering curriculum. Both the traditional and broader mechanical engineering curricula have been accredited by ABET.

A Need to Re-define the Mechanical Engineering Discipline

We have been attempting to re-define the discipline of mechanical engineering by transforming our department. We wanted to transform the field of mechanical engineering or the discipline of mechanical engineering from a discipline that has been primarily based on physics into a discipline that is based on physics, information and biology while maintaining a strong foundation in design.

From a historical perspective, the development of mechanical engineering can be traced back to the industrial revolution, but the heydays of modern mechanical engineering were from the 1930's to the 1960s when the automobile industry dominated the industrial development in the United States. At the time, the automobile and other heavy industries defined the field of mechanical engineering. Much of what we taught in mechanical engineering was done to provide the intellectual and technological knowledge of these industries. At the time, mechanical engineering education benefited a great deal from the technological innovation that these industries had pioneered. The basis of mechanical engineering – mechanics and thermal science – emerged during the last century as the core of the mechanical engineering discipline, largely based on the classical physics of the late 19th century and the eary 20th century.

Traditional mechanical industry has become intellectually mature and is no longer undergoing rapid technological changes. Thus the mechanical engineering industry is not providing the intellectual leadership that is associated with development and transformation of "mechanical" technologies. However, new opportunities for mechanical engineering are coming from other non-traditional mechanical engineering industries such as semiconductor manufacturing, microelectronics, aerospace, and bio-medical engineering. Our narrow focus on traditional mechanical engineering industry let us lose important opportunities for intellectual broadening and creation of new technologies. For example, in the 1960's mechanical engineering education missed an important opportunity to be involved in semiconductors and microelectronics by assuming that these fields are more in the domain of electrical engineering, although these industries depend on machines and processes that mechanical engineers must design and operate. The problems encountered by these industries require broadening of the mechanical engineering discipline by including more of information technology, biology, optics, and modern physics. The leadership for transformation of mechanical engineering has to come from academia, since we can combine the traditional discipline of mechanical engineering with these new topics without being bound by segmentation of the commercial business.

Emphasis of Academic Research

Research is an important element of research universities. Many universities measure the performance of their professors by counting the number of papers they publish. Since quality is difficult to measure, they depend on quantity. As a result, a large number of papers published are not read. Sometimes we get into endless arguments on the merits of research in terms of engineering science versus research in more applied end of academic research. I find that these arguments are not helpful in promoting excellence in academic research.

The research philosophy I have advocated is shown in Figure 2. The horizontal axis represents the research spectrum. The left end of the research spectrum represents the basic research or fundamental research. The research done at this end produces new fundamental knowledge that can in turn become the basis for further basic research or technological innovation. The right end of the research spectrum represents technological innovation. The results of the research at this end produce new technologies that can benefit people and society. Typically major innovations create opportunities for basic research, since early stage innovations create many questions. Some researchers work at both ends of the spectrum. Some may specialize at either end of the research spectrum. The vertical axis on the left is the amount of time and effort academic researchers spend in conducting their research, or the activity level. The vertical axis on the right represents the impact of research done at universities.

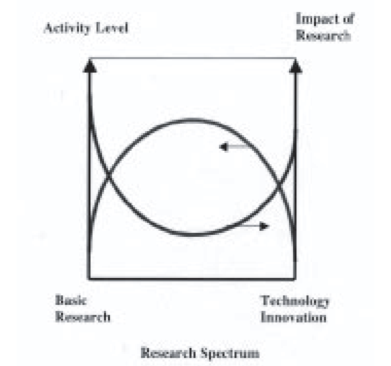

Figure 2. Academic research spectrum vs. activity level and impact of research.

Most academic research is done in the middle of the research spectrum — away from either the basic research end or from the technology innovation end. This situation may exist because the middle area is the easiest to do research in and publish papers. Fewer researchers conduct research at either end of the spectrum. Paradoxically, the impact made by academic research is larger when successful research results are produced at either end of the research spectrum. Therefore, when we look at this curve, we must wonder why people are working in areas that have the least an impact on the knowledge base or the technology base.

As part of the transformation of our department, we encouraged our younger professors to do research for the purpose of making important impact through their research rather than just to publish papers. Whether they choose to do research at the basic end or the technological innovation end of the research spectrum is strictly up to the researcher. Both contributions are equally important to society and to education. At either end of the research spectrum, our graduate students learn from the master how to make impact through their research. Ultimately, the excitement that comes with making impact will permeate through undergraduate education as well.

Faculty Composition

Since 1991, the Department of Mechanical Engineering has added 27 new faculty members, although the faculty size of the department has more or less remained constant at 60. This large number of new faculty appointments was possible because MIT has rather stringent requirements for tenure appointment. Of the 27 new faculty members we hired, 50% of them have doctorate degrees outside of mechanical engineering. Their Ph.D.s are in electrical engineering, computer science, physics, chemistry, mathematics, bioengineering, and other disciplines. This mix of faculty background enabled our department faculty to work in interdisciplinary areas with colleagues who have different disciplinary backgrounds. As a result, our faculty members are creating new research frontiers.

The research interests of our new faculty members are divided about equally between the basic research end and the technological innovation end. Some conduct research at both ends of the research spectrum. Important basic research is done as well as research that may generate new technologies. At this point, a large number of MIT's licensees are using the technologies that were developed in our department.

With the hiring of new faculty members, we had to create many new research laboratories. Since our department is in the original main building of MIT, they were rather old, requiring major renovations. Now our facilities are some of the best laboratories at MIT. We have also created endowment funds for chairs and book-writing activities. Our books are being published by Oxford University Press as MIT/Papallardo Series in Mechanical Engineering. There will be many books coming out every year. Then we have also changed our doctoral programs to accommodate the interest of our students who are working in new areas such as quantum mechanical computers.

New Research Areas

We have created many research groups. One of these is the information research group through the creation of the d'Arbeloff Laboratory for Information Systems and Technology. We hired outstanding new faculty members in communications, computer science and information to launch this effort. An important contribution of this new emphasis on information technology is the creation of the Auto ID Center, which was created by our new faculty members. Professor Sanjay Sarma, whose specialty is manufacturing, got together with Professor Sunny Siu, computer and communications specialists, and Dr. David Brock, another mechanical engineer, to establish this international center, which is supported by over 100 companies. They are developing the infrastructure and technology that uses RF tags for every product made so as to replace bar codes and eventually bring the commerce into the information age.

Our faculty in bioengineering decided that we should change the focus of our research in bioengineering from prosthesis related to bioinstrumentation. Our goal is to provide biology and medicine with new instruments with which to observe, measure and control biological samples and molecules. Instrumentation has been important in advancing engineering and science in all areas. For example, one of our young professors in this laboratory, who received his Ph.D. in physics, is using Two-Photon Microscopy to detect cancer cells below the skin without incision.

One research area that we have struggled the most was the energy related area. Finally we decided that we should conduct research that can make significant impact in the post-petroleum era, which will come when the demand for petroleum is greater than the supply. It is clear that during the 21st century, we will run out of petroleum-based energy. When we reach the point where the demand for petroleum becomes greater than the supply, it will be equivalent to having run out of petroleum because the price for petroleum will go up so high that we are not going to burn the petroleum to power automobiles and to get electricity. In addition, the burning of hydrocarbons creates environmental problems because of CO_2 generation. Our department is in the early phase of developing the Laboratory for 21st Century Energy.

The research in traditional areas are prospering as well. My colleagues in the field of manufacturing have created many new processes such as 3-D printing, Droplet Based Manufacturing, Microcellular Plastics, re-configurable die for stretch forming, and others. Our design group is also designing many products and pioneering the development of underlying design principles that can be taught to students.

Educational Effort

Our undergraduate curriculum is new. The development of this new curriculum was in part motivated by the need to enhance the confidence level of our students by providing them with a proper context for learning. Surveys indicated that our students are most confident when they first enter MIT, but by the time they graduate, their confidence level is low. This fact was not revealed by the course evaluation that we conduct twice a term in each course. These evaluations typically rate the professor and the course very highly, and yet the exit interviews with graduating seniors indicate that their confidence level — in what they think they can do — is only about 35%. This decrease in their confidence level indicates that we have done something wrong in educating our students.

Our curriculum is revised to achieve several goals. First, we decided to provide a better context for learning by integrating several subjects into one sequence. For example, in one integrated two-term sequence in thermal science, we teach thermodynamics, heat transfer and fluid mechanics in an integrated two-term sequence. In this subject, we teach the basic principles during the first term and apply them to different problems, similar to the way we peel onions. We have three other sequences: design and manufacturing sequence; dynamics, control and system sequence; and mechanics and materials sequence. We have designated professors who are jointly in charge of these subjects, who are developing these subjects and writing new textbooks. These books will be published by Oxford University Press in the MIT/Pappalardo Series in Mechanical Engineering. Using the endowment fund created by Mr. And Mrs. A. Neil Pappalardo, the department supports the book writing activities of faculty members.

We teach in three different ways, depending on the subject matter. One is what we call "just in time" teaching, which makes use of web based educational materials so that students will have access to the required knowledge as needed. Another teaching method is the "Socratic teaching", and the third one is called the "self-discovery mode of learning". To be able to teach in self-discovery mode, we created a new lecture hall with desks that can be converted into a lab table. During the lecture students may form a group to run experiments to test the principle taught in the lecture. We also created new undergraduate laboratories, which are modern and flexible. We emphasize *active learning* by students through their participation in class. Our new curriculum also emphasizes hands-on-experience and design. We offer design subjects from freshmen year to senior year. The last three of these design subjects are required subjects.

One of the interesting and highly successful subjects we have created is called "ME Tools". This is an intensive two-week, 80-hour sophomore subject taken by sophomores between the first and the second semester. In this course, all of our sophomores learn to use machine tools and computer software. This is done during the Independent Activities Period (IAP), which occurs in January when we do not have formal class. During the first week they learn all about standard computer tools so they will be able to use them during the rest of their undergraduate study, and during the second week they build a Sterling engine, using machine tools. All their engines are tested for speed at the end of the 40-hour session. This subject exposes our students to the essence of engineering and gives them an appreciation as to why they have to learn all the required engineering subjects.

Graduate Education

One of the most important ways in which we teach our graduate students is through their participation in research. All of our graduate students must write a thesis for their master's degree as well as for their doctoral degree. They learn from professors who supervise their research and from fellow students. The fact that we have multi-disciplinary faculty strengthens this learning process through independent research.

One of the things I have personally been trying to teach our graduate students is the rational design of complex systems. Although engineers design and manufacture complex systems, universities do not provide education on this important topic and industry build these systems through recursive "design-build-test" cycles. Through the use of axiomatic design, our students learn to design complex systems, often better than industrial people. For example, four of our masters' degree candidates designed and built the MIT CMP (Chemical Mechanical Polishing) machine shown in Figure 3 in less than two years, all on their own. This machine is about 9 feet long, 8 feet high, and 3.5 feet wide. This machine polishes semiconductors to nanoscale flatness. The interesting thing is that none of the four graduate students had any industrial experience. Three students designed the hardware, including a new sensing system that measures the end of the polishing operation. One student developed the instruments for measuring device. Two students developed the system architecture and key mechanical subsystems for a complex machine with over one hundred functional requirements (FRs) for the mechanical part and a few hundred FRs for the software/control part of the system. One student who is a mechanical engineering student built the entire machine control system including electrical circuits and the software system in fourteen months. They completed this project in less than two years. We spent two million dollars. This machine is more accurate than industrial machines.

What this project demonstrated is the fact that a university can play a major role in generating engineers who can rationally design complicated systems. What we teach is how to design complex systems without the use of traditional trial-and-error development processes for complex systems. If the company which sponsored this research had taken on this project it would probably have cost somewhere between 30 to 60 million dollars. It would have taken them much longer to develop the machine. Two of the students who worked on this project have taken on important assignments in an industrial firm. They are doing a great job and the president of the firm really depends on these young engineers.

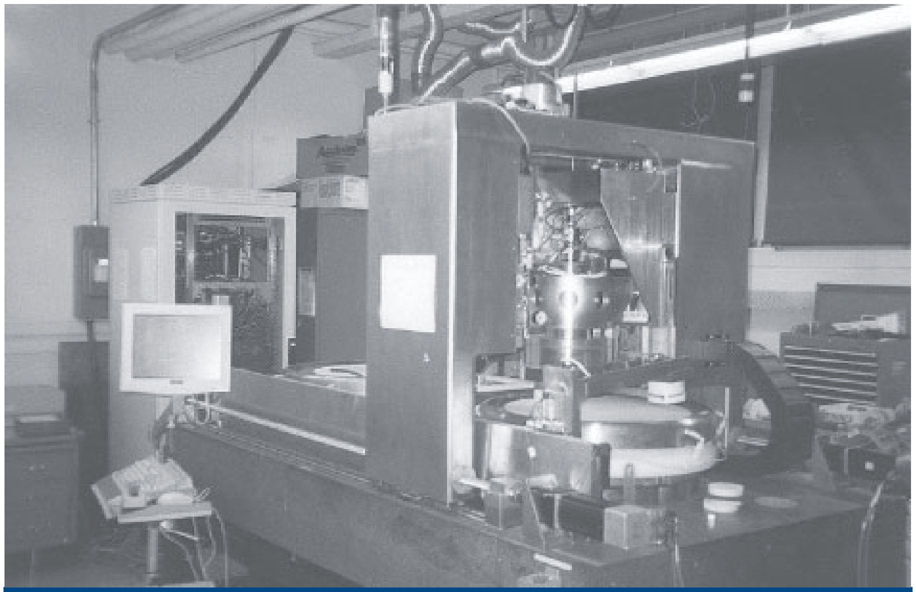

Figure 3. The MIT CMP machine

Concluding Remarks

We are fortunate that we live in an era where science and technology offers us a vast vista, where the limit is set by our ability to dream and by our vision. Engineering is an important instrument that enables us to improve the quality of life for everyone on Earth and to solve many societal problems through technology. This goal requires well-educated engineers. We transformed the Department of Mechanical Engineering at MIIT to prepare our students for their era and to improve the efficacy of education and research. Although it has taken a decade to bring about these changes, I feel that it was an effort well spent. Our job as engineering educators is to make sure that our students have a broad and deep understanding that can help them as they take on the responsibility and challenges during their professional careers. We must also provide meaningful research experience to our graduate students by giving the knowledge and exposure to diverse disciplines. Most of all, we must equip our students with the ability to learn on their own and to explore new ideas and fields based on their ability to think independently, define their own problems, synthesize solutions, and analyze what they have created.

Dr. Nam P. Suh is the Ralph E. & Eloise F. Cross Professor, and Director of the Manufacturing Institute at MIT. He was the Head of the Department of Mechanical Engineering at MIT for ten years from 1991 to 2001.

In October 1984, Professor Suh accepted a Presidential Appointment at the National Science Foundation where he was in charge of engineering. During his tenure at NSF, he introduced a totally new organizational program structure for supporting engineering research in order to strengthen engineering education and research and "to insure that the United States will occupy a leadership position in engineering well into the 21st century." He returned to MIT in January 1988.

Dr. Suh has received many awards and honors. He received three honorary doctoral degrees: Doctor of Humane Letters from the University of Massachusetts-Lowell in 1988, Doctor of Engineering from Worcester Polytechnic Institute in 1986, and Honorary Doctor (Tekn. Hedersdoktor) from Royal Institute of Technology (KTH), Stockholm, Sweden, in 2000. He also received the Gustus L. Larson Memorial Award, the Blackall Award, the Best Tribology Paper Award, and the William T. Ennor Manufacturing Technology Award from ASME; the F.W. Taylor Research Award of SME; an SPE Best Paper Award; Federal (NSF) Engineer of the Year Award from NSPE; and the American Society for Engineering Education Centennial Medallion. He was also awarded the National Science Foundation's Distinguished Service Award. In 1994, he was awarded the KBS Korean Compatriot Award for Scholarly Achievements. He is also the winner of the 1997 Ho-Am Prize for Engineering. In 2000, he was the recipient of the Mensforth International Gold Medal of the Institution of Electrical Engineers of the United Kingdom. In 2001, he received the Hills Millennium Award from the Institution of Engineering Designers of the United Kingdom.

Listed in Who's Who in The World, Who's Who in America, Who's Who in Science and Technology, and others, he is a Fellow of ASME. He is a member of Pi Tau Sigma, Sigma Xi, Phi Kappa Phi, ASEE, SPE, and AAAS. He is also a Foreign member of the Royal Swedish Academy of Engineering Science (IVA), a member of Collége International pour l'Etude Scientifique des Techniques de Production Mécanique (CIRP), and the Life Fellow of the Korean Academy of Science and Technology.

His research interests are broad, with current projects in the fields of design, manufacturing, tribology, and materials processing.

He is the author of more than 280 papers and five books, he holds about fifty patents, and he has edited several books.