Engineering Education
In The 21st Century:
An MIT View

John B. Vander Sande and Joel Moses

School of Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
U.S.A.
1. Introduction

We live in a time when the world is changing rapidly. The end of the Cold War; the global nature of competition; shifts in government spending patterns; the instability in the domestic economy and related changes in organization, staffing and approach taken in American industry; the integration of women and minorities in the work force; growing concern for the environment; the revolution in biological science; and the commensurate complexity of problems with which we must deal are all part of the picture. As a result engineering schools, and more generally all universities involved in research, are facing profound adjustments of a magnitude not seen since the 1940's when the considerable changes brought about by World War II led to the Engineering Science movement.

At that time, we engineers at MIT recognized that scientists and mathematicians were very well prepared to cope with the technical challenges of new technologies, such as radar, perhaps better prepared than were engineers! Vannevar Bush, MIT's first Dean of Engineering, was in charge of all the research activities during the war. His post-war writings emphasized the role of science, and led to the creation of the National Science Foundation. As a result of his work and the Engineering Science movement it fostered, there was between 1945 and 1968 a major increase in the time an undergraduate engineering student spent on basic science and mathematics. There also was a concomitant decrease in the amount of time students spent on laboratory work and relatively specialized professional education. To say that that approach was fruitful is to commit an understatement of truly global proportions. The successful effort to put humans in space, as well as the enormous strides in electronics, telecommunications and computers, are some of the better-known products of the strongly science-based engineering of the last forty to fifty years.

In Engineering Science one is given well-defined technical specifications, and uses basic engineering and science principles to produce a result. This result will be the same regardless of the context in which it is done. The results of a fundamental investigation in fuel combustion chemistry, for example, do not vary depending on who is asking the questions. The sea-change we are now undergoing comes from an understanding that the practice of engineering is to a greater and greater degree not context-free. To
continue the example, the combustion products of interest depend less and less on their intrinsic or theoretical significance and more and more on their role in the environment and their associated regulatory significance.

Education and research activities will have to be modified in a fundamental way to accommodate these changes. While we surely do not envision the elimination of the context-free view (much less the elimination of Engineering Science!), we do wish to emphasize the addition of some contextual influence on the process and the end-result of engineering calculations and designs. By context we mean to include the business and organizational context, the needs and desires of customers, and the social, political, economic, environmental and cultural context of the task.

If we as engineers and engineering educators do not take these critical considerations into account, others will do it for us, in the process defining a distinctly subordinate role for engineers. If we want our graduates to be leaders in the process of applying the promise of technology to today’s problems and challenges, we need to undertake some fundamental shifts.

Such a context-sensitive view of the nature of engineering leads to an emphasis on areas that were paid relatively little attention in engineering curricula as recently as a decade ago. These include manufacturing, design, engineering management, and the environment. Since we do not see a major reduction in the emphasis on basic science, mathematics and engineering science content, and especially since we have not discovered a more efficient way to present all this material, there is a need for additional time, not only in first professional degree programs, but also in subsequent educational programs for practicing engineers.

The context-sensitive view we espouse returns us to a view of engineering similar in some ways to that held prior to World War II. Application of handbook formulas dominated the practice of engineering in that era, an approach which was supplanted by the Engineering Science movement with its emphasis on the application of principles. Engineers, prior to the war, made up in breadth what they lacked in depth. We are deeper in our understanding of the fundamentals now, at the expense of some loss in perspective. Prior to World War II engineering faculties had very close relationships to industry and to the practice of engineering. These were partially lost during the Engineering Science era and need to be regained. Undergraduate engineering education as well as Master’s programs in the pre-war era were clearly largely intended to educate students for the practice of engineering, rather than to provide entrees to doctoral research programs as has often been the case during the Engineering Science era. First year engineering students tended to bring with them an unusual amount of hands-on experience with equipment, such as ham radios or automobiles. This experience has been increasingly lost in the past few decades (with the cardinal exception of students’ experience with the digital computer). This change in the students coming to us needs to be addressed in colleges and universities at the present time.

This essay is a synthesis of a large number of discussions that have occurred over the past two years in the School of Engineering at MIT. It summarizes the current state of the response we are developing to the “interesting times” referred to above that we face. This response is three-fold, and deals with undergraduate and First Professional Degree education, with graduate education and with research, the three traditional concerns of an engineering school.

II. First Professional Degree Programs

The discussions that led our Electrical Engineering and Computer Science Department (EECS) at MIT to its present Five Year First Professional Degree Program started in 1985. The concern then was an Engineering Science-based concern, namely, that there was insufficient time in four years of undergraduate engineering education to cover all the technical material that a practicing engineer should know. Thus much of the discussion went under the banner “Four Years are Not Enough.”

The nature of the Master’s thesis (S.M.) that co-op students complete was an important issue in these discussions. Under the Engineering Science approach, the usual on-campus S.M. thesis at MIT changed radically. A thesis that could formerly be completed in approximately one half of one semester in the 1950’s became a research project that averaged nearly two years in most departments in the School, and averaged three years in Computer Science. During the same forty year period the length of time required to complete a co-operative thesis with an industrial partner (co-op) changed hardly at all. Many of us have long felt that the vast majority of our S.M. students (those who graduate and go on to work in industry or the
public sector immediately thereafter), do not gain sufficiently from the research experience to justify its present length. By considering most of our undergraduates to be co-ops in essence, we could deal with this long-standing issue of the length of the SM program at the same time that we deal with other curricular concerns.

Another insight that arose out of discussions in EECS was the realization that one could restructure the undergraduate program in a more flexible manner. At MIT, nearly all freshmen take the same subjects emphasizing mathematics, science and humanities and social science. Certain engineering departments, EECS and Aeronautics and Astronautics in particular, have developed a common core of sophomores subjects that all their majors must take. Beyond this core students have some flexibility. The realization was that one can create several sequences, each consisting of three or four subjects, at the junior, senior and first year graduate level. Students can then choose the sequences they wish to take. This approach permits EECS undergraduates, for the first time, to major in EE or CS or even a mixture of the two, depending on the sequences they choose. In fact, it is now possible, in principle, to mix EECS sequences with sequences from other departments, for example a control sequence from Mechanical Engineering. Moreover, students who wish to leave with an accredited Bachelor's degree (S.B.) can simply choose not to take the graduate level components of the sequences in their program and still have a coherent program of a preprofessional nature. Such a four-year program would be excellent preparation for the professional schools, such as medical schools, as well as an entree to pre-professional engineering positions in industry or government. We believe that an undergraduate engineering education is destined to become a full-fledged alternative to a liberal arts education in the 21st century.

The complete redesign of the Electrical Engineering and Computer Science Department First Professional Degree program is now completed and is in its second year of operation. Its implementation necessitated the creation of a new Master's level degree, called the Master of Engineering (M.Eng.). The research-oriented SM degree is still available in EECS for students coming in with undergraduate degrees from other institutions. Other departments in the School will use the M. Eng. degree, but with variations on the approach. In particular, the Aeronautics and Astronautics Department will offer a year-long integrative design experience during the fifth year (first graduate year) of its program.

We also anticipate that the Civil and Environmental Engineering, Mechanical Engineering, Nuclear Engineering, and Ocean Engineering Departments will adopt the M. Eng. concept or the sequence approach to restructuring the undergraduate program in the next few years.

Although the five year programs were initially designed for Engineering Science-based reasons, they naturally satisfy many of the needs of context-based engineering. For example, the Aero/Astro year-long design subject will give students experiences close to the current practice of engineering. The added year in the five year programs gives the students additional time that can be spent taking professionally oriented subjects that broaden their perspective, such as subjects in technology and policy or the environment.

Perhaps the major impact of the new programs is that they will have a clear emphasis on preparing students whose aim is the practice of engineering, as distinguished from others whose aim is to continue on for the Ph.D. and thereafter seek careers in engineering research.

But whether the student is focused on a four-year experience leading on to graduate work in another field (e.g., law or medicine), the M. Eng. degree, or a research-oriented SM or Ph.D. degree, we owe him or her an undergraduate engineering education which is honest about the complexities and uncertainties of engineering as it is practiced.

The earlier-noted lack of hands-on experience of our entering students is a related--and major--issue in undergraduate engineering education. The School's Education Committee is now engaged in discussions of a possible school-wide "design-build-operate" requirement of sufficient depth and duration to provide hands-on experience in relating theory to practice, to require teamwork and working with others under conditions of ambiguity and uncertainty, and to introduce students to the design process and the nature of engineering practice. This renewed emphasis on hands-on experience is an important component of engineering education with a focus on engineering in context.

We are also considering the development of a new subject, "The Nature of Engineering." This subject is aimed at introducing students to the essence and framework of engineering inquiry: synthesis,
construction and control of physical systems. One possible way of offering this material is through small freshman seminars, with each faculty member tailoring the discussion to his or her field of specialty.

III. Second Professional Degree Programs

With the rise in importance of research after World War II, the SM degree at MIT, as noted earlier, became a research degree usually resulting in a publishable paper. This confusion of the role of the SM with that of the Ph.D. has been a boon for faculty research, but also led to the aforementioned increase in the duration of on-campus SM programs. The emphasis on research in graduate engineering education points to a fundamental problem: engineering schools have largely ignored the career needs of their graduates in industry. They have left it to business schools to provide the major mid-career boost for those destined for leadership. While engineers moving up the ranks in engineering management do need business-related education, gaining an MBA not surprisingly tends to reorient them toward professional management. They may turn away from technical involvement and in the process become poor managers of engineering.

While there are several periods in the life of a working engineer or engineering manager where additional education would be beneficial, the Second Professional Degree Programs (SPDs) described below are aimed at engineering graduates who have worked in industry for about five years, and are about to embark on careers that are different from those of 'bench' engineers whose orientation is more technical. These careers and their respective programs usually have a management component. "Pure" management education, as noted, is not the answer, at least in many cases. Engineering-oriented management is required; engineering schools need to recognize its value and significance, and thus meet the needs of engineers in industry. The program we are especially interested in involves the management of the design of large systems, such as planes, cars, ships and telecommunications software to name a few. As engineering faculty are beginning to understand, the product design and development process is closely related to the fundamental restructuring going on in business today, most prominently the flatter organization structure.

Industry leaders we have consulted believe that candidate students for the Second Professional Degree program we envision in large-scale design will not be able to spend as much as two years away from their jobs. They are sufficiently mature and valuable to their companies that both they and the firms will be seeking an arrangement whereby they can continue to contribute while enrolled in their course of study. Nor is it necessary that the course of study include the full complement of management subjects at this stage in their careers.

We have identified two major new components to the proposed SPD program. One is that the emphasis in the new program is on issues such as product development, systems engineering, and software architecture. It is interesting to note that different fields of engineering have developed different terms for what is basically a similar set of concepts and processes. In the aerospace industry the term systems engineering embraces many of the same issues that the automobile manufacturers refer to as product development and those in the telecommunications software industry call software architecture. Certainly there are differences among these three terms, but their commonality shows, we claim, that there is a need in industry that is unmet by universities which have not yet abstracted the common notions.

The second new component of the proposed SPD program is that an important mode of delivery of the new program will be TV, either live or on tape. Taped versions would enable teaching subjects using, for example, the Tutored Video Instruction mode popularized at Stanford University. In this mode a group of students and a tutor (usually a former student working at the company) watch a taped lecture. The tutor stops the tape whenever a question is raised and the entire class tries to answer it. This interactive mode can have very beneficial results.

We envision that students will begin their experience with one semester (summer, fall or spring) on-campus. This will help create a cohort of students with relatively similar experiences, albeit in somewhat different industries. Another fifteen to eighteen months will be spent at a company site, taking subjects remotely and working on a project under the joint supervision of a company mentor and a faculty member. The students will probably return to the campus for short periods of time, and the faculty will visit them
at their companies at least as often as they now do with co-op students.

We believe that by our working together with our Sloan School of Management we can create a joint program that will lead the nation in large scale design the same way that our program called Leaders For Manufacturing (LFM) has led in manufacturing. The proposed program will build on subjects developed for the LFM.

IV. Relations with Industry

A major corollary to the Engineering Science movement was the development of a relationship between engineering schools and the Federal government that is far deeper than that which existed prior to World War II. The Federal government in the first two decades after the war supported engineering research not just because of the needs of the military, but also for the general welfare, based in part on the arguments of Vannevar Bush. The School's faculty and staff presently have a total research volume of about $150 million, but industrial support is approximately a quarter of this amount. While both numbers are large, this is of little comfort since neither the Federal support nor the usual industrial support are likely to grow with inflation, and may in fact decline over the coming years, although for different reasons.

While universities actively engaged in research are undergoing profound changes in their relations with the Federal government, the changes in industrial research laboratories may be even greater. Time has become a greater constraint than ever before, and the ability of central research laboratories to help a company produce new products or processes quickly is coming into question. Industry is also undergoing a profound change in its approach to management, with increased emphasis on cooperation and teamwork. These changes have led to significant downsizing of central research laboratories, and the creation of cross-functional product development teams. In such teams researchers work closely with product developers, marketers and others. Not only do these teams create structural changes, but they also make necessary a cultural shift. Members of central research laboratories tended not to trust engineers in development divisions, and vice versa. Bringing people closer together is a necessary condition for trust. And increased trust is necessary for successful technology transfer.

Some people believe that the decline of the central research laboratories will lead to increased funding for research in universities. They argue that industry's current tendency is to outsource activities they no longer can support in-house, and that this presents an opportunity for universities. Such a shift in funding may indeed occur in some companies for a period of time, but it is not likely to be sustained. The same dynamics that have led to the decline of the central research laboratories will probably lead companies to conclude in similar fashion that university-based research is no more likely to yield marketable products. Only if we know how to be team members—insiders in the new approach—can we expect to maintain and build our base of industry research funding. It is also vital in terms of creating the experiences for our students which will best prepare them for the years ahead.

The process of technology transfer is at the heart of the matter. American industry will surely decline if we do not respond to the global challenge and speed up the R&D process. Many have noted that students are the universities' ultimate technology transfer mechanism. Unfortunately, the process by which we educate students is relatively slow. Moreover, unless academia keeps abreast of the issues most important to industry, further delay will be inserted into the technology transfer process because the education of the students will not be well matched to current needs.

There are two classic mechanisms by which faculty and students have kept abreast of these industrial needs. Co-operative programs are one such mechanism, as we have mentioned several times. The other is faculty consulting. The weakness of both of these approaches is that they usually involve only one person at a time, are often narrowly focused, and are also not usually an integral part of the education and research programs of engineering schools. What we believe is necessary in the future, for the health of both industry and academia, is closer cooperation between faculty members and their students with teams of developers, marketers and manufacturing engineers from industry. In particular, it is important for universities to begin working on problems that are critical to the success of their industrial partners.

Another issue is that critical industrial projects often involve company confidential information. Our engineering faculty and students have dealt with company confidential information for decades in consulting and co-op activities. In addition, it is not
unprecedented for universities to delay publication of papers and theses for some months in order to allow sponsors to purge those documents of company confidential information. In most such cases, the work has been done at the company site, i.e., off-campus. It is likely that the new mode of interaction that we suggest will also involve off-campus interactions, but possibly in university-sponsored development parks.

A related concern of industry is that universities have for at least a decade tended to retain title to university-generated intellectual property and grant a license to an industrial firm even if the effort was solely sponsored by that firm. A major argument for this is the need to keep 'march-in' rights that permit the university to give the license to someone else if the first licensee does not perform sufficiently well. This may work acceptably on peripheral matters, but it is not likely that companies would permit universities to keep title to work that is of critical importance to them.

At MIT, arrangements are under consideration whereby work done off-campus between cross-functional industrial teams and teams of faculty and students may be kept on a non-disclosure basis with title residing with the sponsoring company. Discussions have also been going on between MIT engineering faculty and various U.S. companies to determine which will become the first industries to interact with the Institute on such an experimental basis.

If these experiments prove to be successful, then the Institute may wish to broaden the initiative by creating a separate corporation to operate these new activities with industry. We wish to note that companies that participate in such activities with MIT do not simply gain from the R&D activities and the interactions with students and faculty, but also gain from the novel organizational structure. It may be that in the long run these organizational aspects will be the greatest benefit to industry.

V. Concerns and Observations

There is some concern that Engineering education and research accomplished with an enhanced focus on context throws out the baby with the bath water in its efforts to improve on the Engineering Science approach. While the concern is understandable we believe it can readily be addressed. We start from a recognition that the Engineering Science approach has been extremely successful in putting engineering on a firm foundation. We fully expect that engineering faculties will continue to teach and do research in this vein for the foreseeable future. The Ph.D. program will remain strongly based in engineering science. We would expect that many if not most new faculty hires would be in the Engineering Science mold.

Then what will be the source of the broader, more integrative view of Engineering? First, we will need some new faculty members with industrial experience. Certain issues, such as an understanding of large and complex systems, can only be gained at this time through long-term experience with such a system; such experiences are rarely obtained in a university setting. On the other hand, faculty members with extensive experience gained from a career in engineering education in the university may gain a broader perspective over time. As the areas of systems, design, and engineering management become better understood, a more abstract development of these areas will occur, along with more doctoral research leading to new junior faculty in these areas.

Finally, there are some fields (and some individuals) that are inherently multidisciplinary. In these fields, it makes sense to hire junior faculty members. Indeed, MIT has already responded to industrial/societal needs in the spirit of context-based engineering in certain such areas. Leaders for Manufacturing has already been mentioned, but programs such as the Technology and Policy Program take a systems approach and apply integrative thinking to the problem areas on which they focus. Thus the concept we are advancing here is one with which we should be familiar. It is time to apply it to the very core of what we do in the School of Engineering.

The implications of context-based engineering for faculty promotion and tenure need to be carefully considered, in the context in which such decisions are made. And of course, all that we are trying to do must take place in a time in which MIT is facing extraordinary needs to contain expenses, reduce the size of the faculty and staff, and harden faculty salaries, in light of research funding uncertainties and changes in government policies.

A recurring question concerns the extent to which developmental work will occur on or near the campus. Some worry that such work will displace the basic research in engineering and in other fields in the university. It is certainly true that certain resources have to be shared, and to that extent some existing efforts
Vrouwen in de techniek

opening academisch jaar 1994
drs W.J.M. Knippenberg,
voorzitter Universiteitsraad
5 september 1994


Elk jaar opnieuw kijk ik met interesse uit naar het percentage vrouwelijke instromers. Het is nu globaal 20%. Nu hoor ik vertegenwoordigers van sommige organisaties en stromingen weleens roepen dat dit getal te klein is. De redenering is als volgt. Vrouwen en mannen zijn gelijk. De helft van de mensen is vrouw, dus de helft van de techniek-studenten moet vrouw zijn. Grappig is dat. Als mannen vrouwen gelijk zijn, dan maakt het toch niet uit wie op deze Technische Universiteit zit?


Wat is er aan de hand?
De universiteiten staan zeer onder druk. Zeker financieel, want de instellingen krijgen minder geld. Voor de studenten is het nog erger