Engineering Enters New Cycle of Development and Definition

Kenneth C. Rogers

Summary. The profession of engineering is evidencing important changes under the impact of the microprocessor and the energy crisis. Societal considerations are altering the normative criteria of engineering while computerized manufacturing systems require entirely new engineering approaches. The trend is toward greater autonomy of engineering from the traditional basic sciences. Significant changes in engineering education will be necessary. The new technological environment requires closer links among academia, industry, and the professional societies—engineering's essential triad.

The centennial of *Science* finds the engineering profession entering a new period of change and redefinition, remarkably similar to the transformation that coincided with the founding of the magazine. That earlier transformation, which accompanied the rise of modern electrical technology, recast engineering into an analytical mode and established a new relationship between industry and scientific knowledge. For the first time, contemporary scientific discovery gave rise to new industries as exemplified by the emergence of modern electrical and chemical technologies.

The significance of these developments did not escape the notice of *Science*. In its very first issue the new relationship between science and industry was addressed in several articles, most notably in an excerpt from the writings of T. H. Huxley: "The value of knowledge of physical science as a means of 'getting on' is indubitable. There are hardly any trades, except the merely huckstering ones, in which some knowledge of science may not be directly profitable. As industry attains higher stages of development, the sciences are dragged in, one by one, to take their share in the fray" (*1*).

One century later, the cogency of Huxley's observations remains undiminished. Industry continues to attain higher levels of sophistication and complexity, and its progress rests firmly on scientific knowledge. Although this process of technological change continues, it now takes place in a totally altered social, cultural, and material context.

Engineering and Society

To satisfy the ineluctable need for "getting on" and to provide for the material wants of society has been a task of overriding importance, one that each generation of engineers has interpreted according to its own lights. All these interpretations have assumed that engineering is the "art of the possible," and that the duty of the engineer, acting in the best interests of society, is to seize every potentiality of available technology. In the past 10 years or so, the engineer's concentration on technical (and concomitant economic) advantage has been complemented by a broad set of societal concerns, such as the need to conserve energy and material resources, protect the environment, enhance the safety of the workplace, and conform to a growing number of governmental regulations.

In response to these societal concerns, an urgent drive to conserve and develop alternative sources of energy has spurred the growth of new technologies. Excellent progress in furthering conservation has already been achieved by industry. Progress in harnessing new sources of energy has not been as satisfactory. Many approaches to this problem are now being pursued, but it is doubtful that any single new energy technology will furnish a complete solution; nor must we overlook the possibility that the best near-term answer may well be the modernization of existing technologies, such as coal technology. In any event, the probable impact of these activities on the nature of engineering practice will be small, for even the most innovative approaches involve traditional engineering methods to a great extent.

The contrast between the social significance of the new energy technologies and their limited influence on engineering practice illustrates the distinction between what engineers do and how they do it. Every significant technological advance constitutes an important achievement in engineering. Every innovation affects engineering by enlarging its scope and giving new direction to the work of engineers. However, an important distinction should be made between engineering advances achieved through the application of classical engineering techniques and the generation of new technologies by totally new modes of engineering thought. The contemporary nuclear power industry, while employing thousands of engineers, has had little impact on the classical mechanical and electrical engineering disciplines. On the other hand, the digital computer industry has forced the engineer to adopt entirely new concepts.

In recent years, the commanding U.S. technological advantage has been lost in certain mature sectors, such as the steel and automobile industries. The revitalization of such industries is an important challenge. Unfortunately, this problem has often been attributed to a decline in engineering innovation, although such a charge is not sustained on close examination of the facts. Even in those instances where American industry is unquestionably behind, the failure cannot be attributed to engineering. For instance, more industrial robots are used in Japan than in the United States, but robots were first developed and marketed by U.S. firms, and the United States still leads in their production (Fig. 1). The decline in U.S. industrial innovation, with its consequent decrease in productivity, is not an engineering problem. It results from a lack of investment and venture capital, misguided tax policies, and administrative and managerial inertia.

Microelectronics Revolution

Although societal considerations are becoming increasingly important, engineering continues to be strongly affected by technological change. In particular, the impact of the microelectronics revolu-

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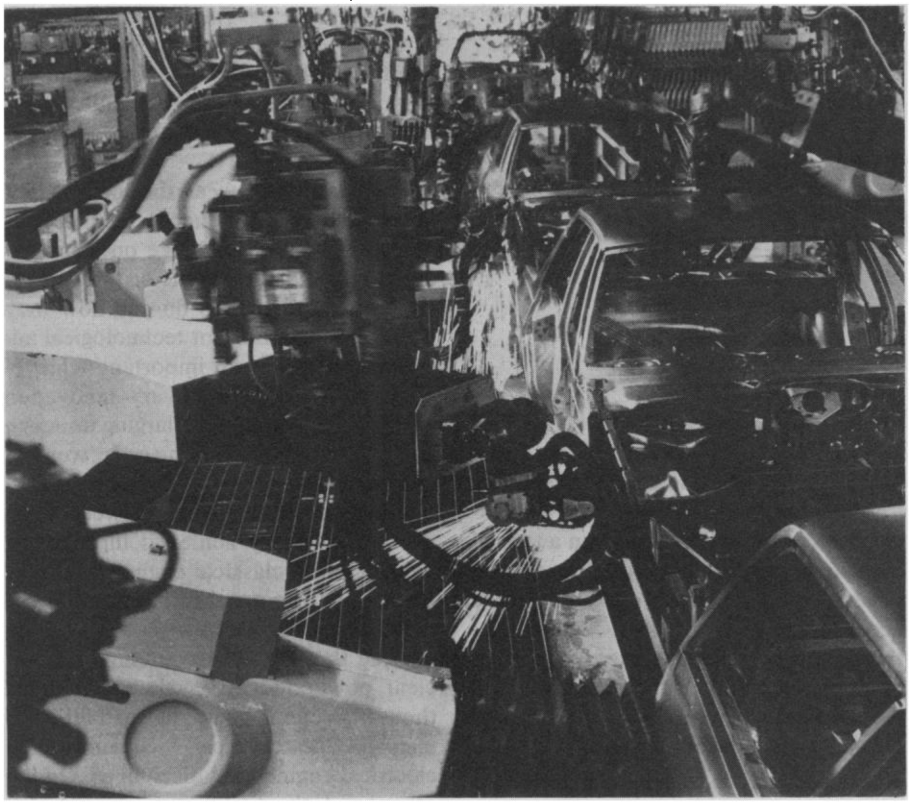

Fig. 1. Thirteen UNIMATE robots produce 450 welds in 50 seconds on car bodies at Chrysler Corp. facility in Newark, Delaware. The Respot Welding System supplied to Chrysler by UNIMATION, Inc., includes robots, supervisory control, and car body indexing conveyor. [Courtesy of UNIMATION, Inc.]

tion is everywhere manifest. It is evident in the new industrial systems, especially in the new instrumentation with its autocalibration, in-field diagnostics, and in-process testing capabilities; in the "intelligent" microsensors with their ability to sense the dew point or determine the most minute stress; in the "smart" robots with their multigrippers and manifold axes of articulation, working unattended on night-shift assembly lines. Within a few years, microelectronics will enter the office and the home, automobiles, washing machines, furnaces, and lawn mowers.

To service this enormous diversity comes Very Large-Scale Integration (VLSI) technology, heralded by the arrival of 16-bit microprocessors with 100,000 components, and a complete computer on a single chip, like the MAC-4 recently developed by Bell Laboratories. In the next 5 years, megabit memories are confidently expected, and it is anticipated that annual production will reach 10^{14} circuit components, or roughly the equivalent of a mainframe computer for every two people in the world (*2*).

The remarkable aspect of the microelectronics revolution is its total pervasiveness. Ultimately, no branch of industry, no aspect of American life will escape the impact of the microprocessor. It is this total pervasiveness which distinguishes the microelectronics revolution as one of those singular technological changes that ends up reordering the nature of engineering practice.

New Engineering Paradigm

The powerful impact of the microprocessor, superimposed on the constraints arising from the energy shortage and resource depletion, will work to recast both the conceptual framework and the normative criteria of engineering.

New criteria. Only time can tell what the ultimate character of new engineering criteria will be, but some important features are already discernible. Since the Industrial Revolution, engineering has been driven by the desire to maximize efficiency by increasing production at the lowest possible cost. However, in the past decade, that principle has been substantially modified. Economic cost as a measure of efficiency remains the primary criterion, but its definition has been enlarged to include the total cost of renewing depleted resources. The shifting balance between initial investment and maintenance expenditures has emphasized the importance of extending cost to cover entire life cycles, realistically taking resource uncertainties into account (*3*). In the future, as geopolitics intrudes more frequently into engineering criteria, economic efficiency may have to be sacrificed for greater resiliency against shortages of crucial materials.

Besides insisting on conservation of resources, the new engineering will place great emphasis on flexibility and versatility of function and will tend to arrange systems in hierarchical structures. These latter characteristics bear the obvious stamp of the computer. Flexibility and ease of reconfiguration are the essential features of the microprocessor, and ensure its broad adaptability (*4*). Hierarchical memories are characteristic of large data-base systems, and a similar trend toward hierarchical architecture is evident in the latest generation of microcomputers (*5*).

The pervasiveness of the computer has served to impress these traits upon the products of engineering generally, not only on stand-alone devices but also on processes and complex technological systems. Realization of these characteristics takes alternative forms. Sometimes it is achieved by intentional redundancy. More often, realization of these traits leads to the splitting of structures and systems into modular segments, which in turn are carefully articulated into complex, integrated arrangements.

Computer-integrated manufacturing. These trends are most evident in computer-integrated manufacturing. Versatility is attained through random scheduling of workpiece and classification of parts into generic families suitable for automatic processing. This technique is carried one step further in group technology processing, in which production occurs under a cellular system. Each localized cell produces a family of parts with close similarity in geometry or processing sequence. At the highest levels, computers coordinate the work of the individual cells, giving management full control over production (*6*).

Flexibility is also attained in machining centers where computer-controlled tools are programmed to perform turning, drilling, boring, and milling operations. It is exhibited in modular machines that manufacture, indifferently, six-cylinder or V-8 engines in accordance with programmed instructions (*7*), and in the new "virtual" instrumentation that on command can transform a spectrum analyzer into a sampling oscilloscope.

Materials. Engineering will also be influenced by new materials. In view of recent progress in materials science, it is now possible for development engineers to leave material characteristics open-ended in satisfying stipulated product criteria. Here, polymers and composite materials are bound to be very significant. With our present knowledge of molecular science, it is possible to breed straight-molecule polymeric structures with strengths approaching those of metals (see page 122). The new reactive injection moulding technology can generate car bodies, camera casings, and other parts at very low costs (*8*).

Primacy of design function. The integration of large articulated systems, whether they are VLSI circuits, complex manufacturing factories, or chemical processing plants, requires the most careful planning and design.

Computers are already radically shortening and simplifying certain aspects of design. Computer-assisted design (CAD) includes the replacement of drafting boards by cathode-ray tube computer-graphics terminals that automatically produce the descriptive geometry and orthographic projections developed so laboriously in the past (Fig. 2). The design and planning of manufacturing processes is also being facilitated by computer-based procedures. However, CAD acquires its fullest importance when used in concert with computer-assisted manufacturing (CAM). In the paperless factory of the future, design data will be communicated directly to on-line manufacturing machines and used to optimize and automate parts manufacture (*9*).

New more intimate relations between development and manufacturing will mature with the assistance of computers. Heretofore, the development cycle invariably entailed a long and expensive sequence: bench-model prototype, preproduction, and finally, production. The CAD/CAM system in principle allows production to take place directly from the designer's final product. This process will be facilitated by having all engineering handbook information immediately accessible from data bases, and design rules incorporated in the software itself. Paradoxically, then, the power and intelligence that computers contribute to the design process is expected to increase rather than diminish the role of the designer. Even though the computer removes some of the designer's traditional activities, it expands the designer's domain and scale of responsibility and judgment. Designers controlling computers will make decisions impinging directly on the total operation of complex systems. In the future, the role of the designer will be so enhanced by the computer that the designer will enjoy an unchallenged primacy in the industrial process.

The splendid accomplishment of the Gossamer Albatross shows that the computer need not displace human ingenuity. That design achieved a unique integration of materials, instruments and function, and led to realization of the ancient dream of human flight.

Software Science

Among computer users, the current catchphrase is "software dominates." In the narrowest sense, this refers simply to the high cost of debugging and maintaining complex software programs. More fundamentally, the assertion describes the trend toward software as a replacement for dedicated hardware. The flexibility and economy such replacement offers is already being exploited in such areas as industrial measurement and control. However, longer and more complex programs can require seemingly perpetual debugging and lead to apparently insoluble conflicts. To resolve this software crisis, various alternative solutions have been proposed, such as partitioning programming tasks and relying more heavily on modular programs.

Yet basic improvements will have to await a better understanding of software principles. Real progress will be made only through a complete understanding of such new multipath techniques as vector processing, or by embarking on new approaches, such as functional programming, in an effort to transcend the bottlenecks inherent in sequential von Neumann machines.

The discovery of fundamental principles that can be used to codify software development remains the ultimate goal. Ideally, a set of basic principles would generate formal techniques for standardizing and systematizing software, and would permit the development of programs of minimal complexity, free of contradictions. Admittedly, the existence of such principles can at present be posited only as an article of faith; but the goal is sufficiently important that its attainment must necessarily be an important task for universities and industry (*10*).

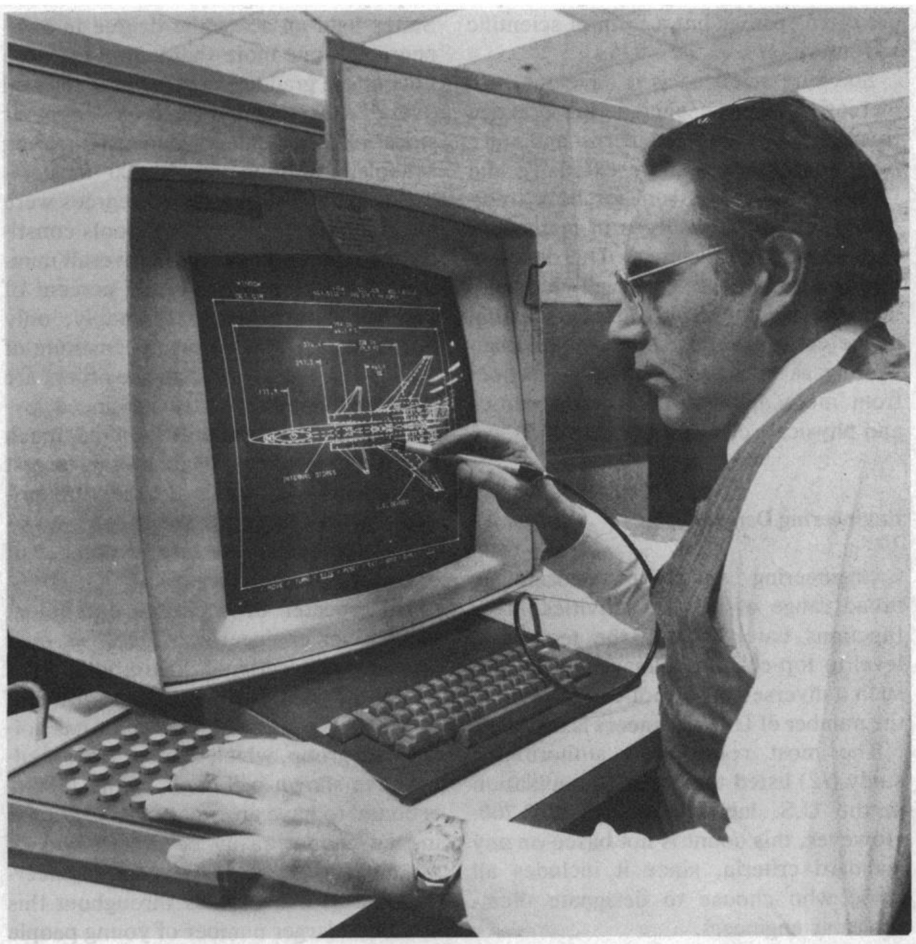

Fig. 2. Preliminary design engineer Frank Dellamura of Grumman Aerospace uses interactive graphics terminal to develop configuration for new military aircraft. [Courtesy of Grumman Aerospace Corp.]

Autonomy of Engineering

The ultimate effect of the microelectronics revolution on engineering may well be the rapid acceleration of its gradual movement toward greater intellectual autonomy. In modern times, engineering has been widely perceived as a subordinate discipline, since it employs the analytical tools of mathematics and derives its fundamental principles from physical science. Not surprisingly, the public tends to confuse the distinction between science and engineering, and ascribes every notable engineering achievement to science.

The confusion between science and engineering can be exemplified by the U.S. space program. Manned landing on the moon is surely this century's most thrilling feat of engineering, and the Apollo program has yielded a host of engineering benefits, direct and indirect. It furnished a proving ground for new techniques, materials, and devices; it spawned microelectronics and satellite communications. Just one such benefit, remote sensing, will reimburse the country for the entire cost of the space program. Yet these engineering triumphs are often seen as but a form of scientific adventure (*11*).

Software science, as it develops, will increasingly cause engineering practice to reflect methods, concerns and, ultimately, roots even more extensive and therefore different from its now traditional intellectual sources in mathematics and physical science. The development of software science will give engineering a new intellectual dimension and hence contribute to distinguishing engineering as an endeavor that is distinct from mere application of mathematics and physical science.

Engineering Demographics

Engineering spans an enormously broad range of human activities, from functions barely above the technician level to top-echelon management. Since such a diverse field is not easily defined, the number of U.S. engineers is in doubt.

The most recent and authoritative study (*12*) listed the engineer population in the U.S. labor force as 1,268,700. However, this count is not based on any standard criteria, since it includes all those who choose to designate themselves as engineers.

As late as 1976, there were only 6,700 women engineers and 24,900 engineers of minority origin in the United States (*13*). However, the number of women engineering students increased from 6,064 in 1973 to 34,518 in 1978—an increase of 570 percent. During the same period, minority students recorded a more modest gain, from 11,462 to 22,785 (*14*). These numbers are bound to increase even more in the future.

Engineering Educational Institutions

The educational needs of the engineering profession are served by 244 Engineers' Council-accredited schools of engineering, which offer over 131 different curricula (*15*). This great variety reflects our society with its emphasis on strength through diversity. American technology requires a vast multiplicity of educational institutions; its broad needs cannot be well served by any single engineering program. The national response must remain pluralistic.

As in the 19th century, many engineers are still apt to acquire their professional knowledge outside of degree-granting academic institutions. In 1970 only slightly more than half the people employed as engineers in the United States held an academic degree in engineering, while more than one-third were not college graduates (*16*). Last year well over 52,000 students, the largest number since 1950, graduated from engineering schools. Additionally, 16,000 master's degrees and 2,815 doctoral degrees were awarded. The ten largest schools constitute only 3.5 percent of the overall number, but they produced 16.7 percent of the bachelor's degrees. Notably, only one of these, Massachusetts Institute of Technology, is private; all the others are state universities. At the advanced levels, the private schools assume much greater importance. Half of the largest producers of master's degrees are private institutions, as are 5 of the 13 schools awarding the largest number of engineering doctorates (*17*).

The specter of declining enrollment hangs over engineering schools as over all other educational institutions. The well-publicized decline in the number of 18- to 24-year-olds, the traditional college age group, which demographic studies have shown will begin in the 1980's, is bound to have an effect; but its precise impact cannot easily be determined. If the present strong demand for engineering graduates continues throughout this decade, a larger number of young people will undoubtedly elect to enter engineering schools. But there are obvious limits to this, since not all young people qualified for college possess the inclination and ability to successfully pursue engineering studies.

The curriculum choices of undergraduate engineering students correspond closely to the distribution by discipline prevalent in the engineering profession, modified somewhat by expectations of the relative career opportunities to be afforded in the near future. Thus, electrical engineering is by far the most popular choice (25 percent) because of its association with computer science (*18*).

Despite the general decline in educational standards, the quality of engineering education has remained very high. With notable unanimity, spokesmen for American industry have expressed their satisfaction with the performance of recent engineering graduates. They have been uniformly praised for their intelligence, their thorough grounding in basic science, their familiarity with computers and mastery of analytical skills, and for their enthusiasm and devotion. However, their education has failed to develop their communication skills, and has encouraged an excessive preoccupation with analytical formalisms and a tendency to view every engineering task as a research project (*19*).

The quality of full-time engineering graduate students, as measured by their mean Graduate Record Examination scores, is also not in doubt. Their numbers have remained roughly constant since 1975, largely as the result of a balance between an increase in the graduate enrollment of foreign students and a corresponding decline in the enrollment of U.S. students. Approximately 30 percent of full-time graduate enrollments in engineering is accounted for by foreign students on temporary visas (*20*).

Education for Technical Leadership

Institutions aiming to educate the nation's technical leaders must correctly assess and address the future needs for technology. This requires knowledge of the new directions and developments in the basic sciences as well as an understanding of the needs of industry and society at large, which calls for close links between industry and engineering schools. These links can assume a diversity of forms. Schools have established research consortia and industrial associates programs and have formed collaborative research partnerships. They have met an important educational need through the mechanism of industrial clinical experiences. Under such arrangements, students perform an engineering task mutually agreed upon by their school and the industrial sponsor. During the project the student has access to company facilities and works under the joint supervision of an industrial manager and a faculty adviser.

All such arrangements provide important bonds between industry and the universities. The supportive role that universities can contribute is of undeniable importance. However, such activities must remain ancillary to the primary function of engineering schools: providing the intellectual sinews of engineering by developing the principles that underlie everyday engineering practice. Above all, engineering schools must take the lead in forming new intellectual attitudes required for the new engineering tasks.

In this regard an important caveat is in order. Universities can never assume the same relationship vis-à-vis engineering that they have had toward basic science. The zealous attempts to replicate the research models of the 1950's, with engineering substituted for basic science, cannot succeed. Most engineering research will continue to be conducted predominantly in its natural habitat, the industrial R & D laboratory. There is absolutely no way that the very large systems in which engineers increasingly have to function can be replicated on campus. This will have no serious educational consequences if closer links are forged between industry and academia so that students have the opportunity to become acquainted with contemporary industrial realities.

In the development of these strengthened relationships, industry's changing requirements will automatically have a major effect on the work of faculty and students. At the same time, it is important to interpose a degree of separation between industry and academia in order to provide institutional continuity and shield the schools from responding resonantly to the rapid variations characteristic of particular industries and technologies.

Nevertheless, in order to accommodate changes mandated by new engineering orientations, schools will have to make significant revisions in their curricula. In the future a more coherent basic engineering education will be required, one that is centered around a unified core of fundamental science, analytic skills, and common engineering practice (*16*). In a rapidly changing technological world, engineering graduates with a comprehensive education, capable of rapidly assimilating new techniques and responsibilities, are more likely to be leaders than those whose education followed more narrow specializations.

Engineering courses will undergo extensive restructuring. The dominance of software will have to be reflected in every engineering course. Nearly all engineering students will have to understand the architecture of computers, how software is put together and managed, and interactive synthesis involving hardware and software. Unfortunately the giant computer systems utilized in scientific research and industry will rarely be available on even the most affluent campuses, and new techniques will have to be developed to impart to students an understanding of the architecture and potentialities of large systems.

Additional emphasis will also have to be paid to teaching design. In building needed capabilities in engineering science over the past 20 years, most engineering schools lost sight of the need to give due attention to design. Today there is a much greater recognition by institutions that design must be an integral part of all engineering programs. Design must be taught from a comprehensive perspective that includes considerations of analysis, production, economics, and social impact, while still affording ample scope to the play of imagination and intuition. To build these considerations into undergraduate and graduate educational programs will require that engineering schools develop new faculty strengths and acquire new instructional equipment. Both are formidable problems on a national scale.

The existing shortage of engineering faculty of all types and the poor prospects for meeting that need will make it more difficult for engineering schools to move vigorously to reestablish design programs on their campuses. Today hundreds of engineering faculty positions across the nation are unfilled. Shortages have already been identified in energy-related fields of mechanical and chemical engineering (*12*), in software systems engineering, and in polymer engineering. This problem is exacerbated by the failure of engineering faculty salaries to keep pace with salaries in industry. The shortage of engineering faculty may build to catastrophic proportions in the late 1980's, when unusually large numbers of engineering professors are expected to retire (*16*).

Difficulties also exist with respect to engineering school facilities. Physical plants and equipment have been aging, so engineering schools today are not well equipped to work with industry. A recent survey of 14 independent engineering schools (not including California Institute of Technology and Massachusetts Institute of Technology) showed that at the average current expenditure rates, it will take these institutions 40 years to replace their present instructional equipment, which itself is estimated to have an average lifetime of 6.5 years. These institutions should be budgeting for new equipment $1500 annually per baccalaureate degree granted, but are unable to do so. If these numbers are applied nationally, U.S. engineering schools together should be spending $150,000,000 per year on instructional equipment. There does not appear to be any systematic program to meet this need (*21*).

Despite these problems, it is clear that engineering schools will move much closer to industry in the future and that engineering programs will change in ways that ultimately meet the future needs of U.S. industry while at the same time providing increasingly excellent educations for careers.

Engineers as Professional and Societal Leaders

Engineers constitute a rather special subculture that contributes enormously to the development and well-being of our society but does so largely anonymously. Engineers tend to maintain low personal profiles and function as corporate team players or through their professional societies. As a result, engineers have had few highly visible and articulate spokesmen; the superstars of scientific research, so prominent in the public eye, by and large do not have counterparts in engineering.

This lack of visibility has contributed to a feeling among engineers that their profession has not been accorded the recognition and status it deserves. Historically, engineering was not counted as one of the seven liberal arts, and to this day there is a tendency not to include it among the learned professions. It has been a heterogeneous group without identifying credentials held in common.

Professional registration. One response to the need for such credentials is professional registration of engineers. In 1978, between 25 and 30 percent of the nation's engineers were registered or licensed by state agencies (*22*). The National Society of Professional Engineers has worked hard and long, with increasing success, in establishing registration as the criterion for defining who is and who is not an engineer. However, it is by no means unanimously accepted that all engineers must be registered.

Industry considers the requirement of registration as an unnecessary form of governmental interference; managers argue that since industry's engineering relationship with the public is indirect, it does not require the same regulation as a small consulting firm or an engineer practicing independently. Many academic engineers, whose engineering practice usually consists of research and consulting for high-technology industries, are uninterested in registration, considering it irrelevant. Moreover, many registered engineers freely acknowledge that in many fields the licensing examination results do not predict the ability to do engineering work. Nevertheless, the trend toward greater voluntary registration of engineers will probably continue to grow.

Engineering societies. The more than 30 engineering professional societies have concerned themselves with many facets of engineering. They have created a system of educational program accreditation that is above reproach. They have led in developing codes and standards for engineering design, and have struggled to define an ethical code of professional practice. Through their journals, publications, and meetings, they have kept themselves informed of technical and other developments.

Despite this, until recently many engineers felt that they were talking largely to themselves, that society and often their own corporate employers did not recognize them as professionals, and that their expert knowledge and opinions were not given sufficient weight. Engineers have tended to avoid political and social controversy and have shied away from activities that require them to make decisions without adequate opportunity for careful weighing of alternatives. But recent events have forced them to alter this traditional posture. Increasingly, engineers view with deep concern the growing acceptance of the illusion that a risk-free world can be created by legislation. And they feel a responsibility to make the public aware that logical argument alone, unaccompanied by genuine technical knowledge, is insufficient for setting national policies affecting technology.

Consequently, engineering societies have become much more publicly active, espousing particular positions on technological questions having broad social consequences, such as nuclear power, regulatory reform, and productivity. These and other concerns have given rise to a much more aggressive political posture by the engineering societies. Political action committees have been formed to work for the support of House and Senate candidates whose positions on technological matters appear to have a sound technical basis (*23*). Also, there have been proposals to create a National Engineering Foundation (or to expand the National Science Foundation to a National Science and Engineering Foundation) and to strengthen the National Academy of Engineering (*24, 25*).

One development that may ultimately have a profound effect on the legislative influence and national stature of engineering is the formation, in late 1979, of the American Association of Engineering Societies (AAES), a federation of 37 societies (*26*). The AAES will maintain an active liaison staff in Washington so that the views of the new organization can be readily available to legislators. The technical content of much new legislation is very high, and AAES plans to provide unbiased, objective testimony to legislators and their staffs as an aid in the drafting of new legislation. The new association will also be in a position to alert the engineering profession quickly to new developments in government and public policy. The AAES will provide the single voice capable of being heard nationally that has been so urgently needed by the engineering community.

Engineering education. The greatest challenge to engineering education is the problem of continuing education. In many areas, rapidly developing technologies are rendering engineers' educations obsolete in less time than they spent studying as undergraduates. Keeping current is a serious problem for many registered engineers, especially those not located near large cities or other educational centers. The responsibility for providing continuing engineering education will probably have to be shared by universities, professional societies, and employers of engineers. However, the infrastructure necessary to carry out continuing education programs does not yet exist. Perhaps this is a problem that the AAES can help to solve.

The Essential Triad

All of the developments touched on earlier lead us to view engineering as a field scintillating with opportunities. However, if these opportunities are to be fully exploited, new economic, social, and managerial connections will have to be established among industry, academia, and the engineering profession—the essential triad. The most useful role of government would be to facilitate the development of these connections and (when no other mechanism exists) assist each member of the triad to develop the necessary strengths to participate effectively with the others. Governmental initiatives, however, must be balanced by governmental self-restraint. Directions and priorities should be allowed to evolve naturally if society is to obtain the maximum advantages that engineering can bring to it in the shortest possible time.

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