Issues in American Engineering Education: A Selective Review of the Literature

A Draft Report
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by

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I. Project Description and Summary of Findings.

1. The objectives of this study and the structure of presentation.

The objectives of this study are:

(a) first, to place current concerns about engineering education in the context of a historical review of perceptions within the engineering community of problems and issues in engineering education;

(b) second, to identify the distinguishing characteristics of engineering and engineering education in relation to science and science education, again, as perceived by engineers and engineering educators;

(c) third, to relate engineering education and practice to the broader processes of technological innovation, and to the competitiveness of American industrial production with that of other nations.

The study is divided into three parts, the first of which describes the project, provides a timeline of significant events in engineering education, and summarizes the findings. The second part is a discussion, also divided into three parts, following the order of the objectives listed above; the third is a bibliography of the materials on which this report is based.

Social scientists are notorious for their methodological preoccupation, but their professional self-consciousness pales alongside the relentless self-examination pursued by the American engineering community since the first World War. This study is a review of the literature cited in the bibliography, which is only a small fraction of the materials that have been generated in the course of that self-examination. It is neither a critique of that literature nor a systematic interpretation. No attempt has been made to integrate disparate characterizations into a coherent whole or to reconcile inconsistencies: for example, between a concern that undergraduate engineering education be matched to industry's immediate needs and a concern that, to avoid being mere instruction, engineering curricula need to be buffered from industry. All of the characterizations that follow --of engineering education and practice, of engineering professionalism, the engineering community, science and the scientific community, technological change, the social impacts of engineering and technology, and of engineering in relation to industrial production and competitiveness-- are abstracted from the articles, reports and books listed in the bibliography and have been organized around a set of categories and sub-categories matching the objectives above.

As a result, the conclusions that can be drawn from this study are bound to the bibliography: if the materials studied are a representative selection of the engineering community's perceptions of engineering education and practice, then the findings of this study can serve as a guide in responding to current criticisms of engineering education and in distinguishing engineering and science. Because all of the major studies of engineering education --from the 1918 Mann report, "A Study of Engineering Education", to the 1985 National Academies of Science and Engineering multi-volume study, "Engineering Education and Practice in the United States"-- are included, together with scores of articles, smaller scale reports, conference proceedings and some book-length studies on a wide range of relevant topics and from a variety of individuals and institutions, it is likely that the bibliography indeed is representative. This conclusion is reinforced by a consideration of the scope of the categories and subcategories of Part II of the report. The apparent exhaustiveness of these, together with their derivation from the literature reviewed, reinforce the representativeness of the bibliography.

At the same time, it must be acknowledged that the total body of literature relevant to the objectives listed above is vast. In the time available, it was not possible to survey systematically the contents of the American Society for Engineering Education's Journal of Engineering Education, or that of its predecessor, the annual Proceedings of the Society for the Promotion of Engineering Education, yet these contain thousands of essays on, and analyses of, engineering education extending back almost 100 years and constitute a "real time" record of engineering education concerns.

Historical, philosophical and sociological studies of engineering, science and their respective communities of practitioners have, primarily since the 1960s, multiplied greatly in number and increased in sophistication and disciplinary specialization, making access doubly difficult. This literature, too, has barely been sampled here, but as its authors are as a rule neither writing as engineers nor for the engineering community, this is less likely to skew the inferences of this review than would be a non-representative selection of materials explicitly addressing engineering education.

Especially since Sputnik, institutions such as the National Science Foundation, the National Academies of Science and Engineering, the Departments of Education, Labor, Commerce and Defense, among many other groups inside and outside of government, have had almost continuous occasion to convene studies of engineering education in relation to issues touching on national security, equality of opportunity, industrial production technologies, research and development, and economic prosperity, as well as of engineering education itself and in relation to primary and secondary education.

Together with the almost continuous examination of engineering education pursued by the American Society for Engineering Education and other education-centered organizations, from the Accreditation Board for Engineering and Technology (ABET) and the Carnegie Foundation for the Advancement of Teaching to the National Association of State and Land-Grant Colleges and Universities, these efforts have generated a formidable body of materials that would need to be studied before one could claim to have exhaustively reviewed characterizations of engineering education in relation to American society.

The further question --beyond those of the state of U.S. engineering education and the nature of engineering practice and professionalism-- of the relation of engineering to technological innovation and its social, economic and political consequences, introduces still another large body of literature. The findings of this study in relation to these issues are necessarily more tentative than in relation to the preceding questions, first, because the subject is itself unsettled, and second because the items reviewed here are a significantly smaller selection from the relevant literature and cannot with the same degree of confidence be supposed representative. The findings on engineering and competitiveness must, therefore, be taken in the first instance as sounding a cautionary note not to acquiesce unreflectively in stereotypical characterizations (of the relation of engineering education and practice to innovation). These may not be critically defensible in light of our evolving understanding of the complex networks of interdependency linking technical knowledge-bases and their commercial exploitation.

With these qualifications in mind, the findings of this study offer an opportunity to apply to current calls for reform of engineering education the wisdom of the historical record. Which current concerns are truly new and which are truly problems? Which proposed solutions have already been attempted and with what success? What patterns can be discerned when the present is perceived in developmental context?

2. Timeline of significant engineering education events.

[An expansion of 1977: Grayson]

1833 - First U.S. engineering degrees awarded (West Point)

1852 - American Society of Civil Engineers founded.

1862 - Morrill Land Grant Act initiated explosive growth in engineering education, from some dozen degree-granting programs in 1862 to 70 just 10 years later to over 100 on the eve of World War I and some 260 today.

1867 - Reorganization of American Society of Civil Engineers, attempting to maintain its position as the one, comprehensive, engineering society.

1871 - American Institute of Mining and Metallurgical Engineers founded, initiating break with ASCE and reflecting the growing diversification of engineering curricula, practice and notions of professionalism.

1880 - American Society of Mechanical Engineers founded.

1884 - American Institute of Electrical Engineers founded.

1885 - Decisive shift of engineering curricula to "scientific" base begins: laboratory courses in place of shop; science and mathematics.

1893 - World's Engineering Congress, concurrent with the (Chicago) World's Columbian Exposition, put engineering education on a par with engineering disciplines as a subject for papers.

- First graduate engineering program, Harvard (electrical).

1894 - Founding of the Society for the Promotion of Engineering Education (SPEE) after the Engineering Congress, the first volume of its Proceedings being the papers presented at the Congress.

1903 - First engineering experiment station created by University of Illinois, followed by Iowa State and eventually all land-grant engineering colleges.

1904 - Evening courses introduced at Polytechnic Institute of Brooklyn.

1906 - Cooperative education introduced at the University of Cincinnati.

1907 - SPEE created Joint Committee on Engineering Education to conduct comprehensive examination of the state of engineering education in the U.S., at the time widely regarded as the finest system in the world.

- Wyoming inaugurated state licensing of engineers.

1908 - Carnegie Foundation for the Advancement of Teaching agreed to fund proposed SPEE-Joint Committee study, chaired by Charles R. Mann.

- First industrial engineering curriculum, at Pennsylvania State College.

1913 - Creation of National Association of Corporation Schools, later the American Management Association (1923), initially by 35 companies, today over 200 with at least 10% granting formal, fully accredited, doctorate degrees.

1918 - Publication of the Mann Report, "A Study of Engineering Education", urging: return to fundamentals and unification of then-fragmenting curricula; union of theory and practice in coursework; introducing "real work", including "values and costs" into teaching engineering problem-solving; retention of shop experience; lab and industrial training, cooperative and Summer work, as part of curriculum; English mastery; repair isolation of technical from its human and social setting; closer university-industry linkage, especially in relation to research, to improve productivity and thereby national well-being; attention to developing discipline for work and "lifelong" study; selection of faculty based on teaching ability and work experience, not just research excellence.

1923 - SPEE created another committee to study engineering education, chaired by William Wickenden of A.T.& T., with H.P. Hammond as co-chair.

1930 - Publication of volume 1 of the Wickenden report, "Report of the Investigation of Engineering Education 1923-1929".

1932 - creation of Engineering Council for Professional Development (ECPD), first national accreditation agency for engineering curricula.

1934 - Publication of volume 2 of the Wickenden report, containing summary (pp. 1041-1116): no further fragmentation of curricula; promotion of graduate engineering education and continuing education for 5 years after graduation; development of other forms of technical education than enginering colleges; functional rather than professional model for engineering education; design project for 2nd and 3rd year students with substantial writing component (not lab notes), 3rd year based on project teaching, 4th year honors option; strengthen high school preparation; with industrial help, promote lifetime learning as expected of engineers; professional certification by engineering societies independent of state licensing; higher faculty standards; highlight engineering method, resting on pure and technological sciences, economics and social sciences and mastery of English; teach how society works and nature of values so engineers can understand social impact of engineering and determine their own responses.

1939 - (H.P.) Hammond report for SPEE, "Aims and Scope of the Engineering Curriculum", recommending: diversification of curricula; parallel technical and humanities/social sciences (HSS) "stems", the latter to amount to 20% of curriculum independent of composition and business courses; reconsideration of 4-year curriculum, possible move to 5 or even 6-year program.

1941 - SPEE created Technical Institute Division.

1944 - (H.P.) Hammond Report for SPEE Committee on Engineering Education After the War: reaffirmed 1939 report; promoted expanding technician programs to fill industrial needs then being filled, non-optimally, by engineers and teaching focus on "art" of engineering, distinct from scientific method.

1945 - Vannevar Bush report "Science: The Endless Frontier".

- ECPD began accreditation of associate degree programs at technical institutes. By 1987, 195 institutions offered 731 accredited 2- and/or 4-year degree programs in engineering technology and 28% of ASEE members were primarily in this area.

1946 - SPEE changed its name to the American Society for Engineering Education (ASEE).

1947 - Publication of "Endless Horizons" by Vannevar Bush, reinforcing his 1945 report in a format for a mass audience.

1950 - Creation of National Science Foundation.

1955 - (L.E.) Grinter "Report on the Evaluation of Engineering Education" for ASEE, the final report shaped by the active participation of 122 engineering colleges responding to earlier drafts, recommending: five "stems" --HSS, mathematics and basic science, generic engineering science, engineering specialty subjects, electives; two track undergraduate curriculum, one to immediate employment, the other to graduate study; twin goals for engineering education --technical (analysis and "creative design"; construction, production, operation) and social (ethics, general education, leadership in technological action); improve high school preparation and articulation, admission standards; integration of graduate education and research-oriented faculty into undergraduate curriculum; requirement of industrial experience for tenure and sound teaching ability; programs for gifted students; improve facilities; drop shop and upgrade labs; retain 4-year curriculum but encourage experimentation; focus on design as distinguishing feature of engineering; base curriculum on engineering science, not contemporary engineering practices; include social and economic factors in solutions to technological problems; unify analytical methods in all branches of engineering; lifelong learning.

1956 - Publication of (E.S.) Burdell report, complementary to Grinter report, "General Education in Engineering - Report of the Commission for the Humanities--Social Research Project" (of the ASEE). Conclusions: more HSS needed; widespread, but groundless, fears that this will either weaken engineering education or lead to superficial treatment of HSS.

1959 - Report to President Eisenhower by Lee DuBridge, Chairman of PSAC, "Education for the Age of Science" urging: enhance image of teaching profession; improve high school education as preparation for science and engineering careers; curricular reform by unifying along basic scientific principles common to engineering specializations, teaching relation of engineering to social and governmental problems instead of parallel HSS stem; promote Ph.D. for engineers; special programs for gifted students; expand technical institutes; faculty retention efforts.

1962 - ASEE created Technical Institutes Council (now Engineering Technology Council) parallel to Engineering College Council (today, 28% of ASEE members are primarily in engineering technology education).

1963 - ASEE launches "Goals of Engineering Education" study, Eric Walker, Chairman.

1964 - National Academy of Engineering (NAE) founded, added to charter of the National Academy of Sciences (NAS).

1966 - Project Hindsight report by NSF: together with Department of Defense TRACES study, it called into question direct relationship of basic research to innovation.

- Engineers Joint Council response to Interim (ASEE) "Goals" Report: integrate teaching of engineering practice into its social context, preparing students for leadership in technological action; focus on fundamentals, not current information; do not standardize curricula or accreditation; increase student-faculty interaction; promote lifetime learning within curriculum; expand role of engineering professional societies in linking education to state-of-the-art practices.

1967 - Initiation of B.S. degree in Engineering Technology (enrollment increased from 23,700 in 1967 to 58,000 in 1976 then levelled off).

1968 - Publication of Final Report of five-year ASEE study "Goals of Engineering Education": endorsement of Grinter Report on engineering science as basis of engineering education; add one year of graduate study to basic engineering education; limit prerequisites and open the engineering major to transfers; expand cooperative and interdisciplinary programs; reduce credit hours for graduation; improve teaching of social and economic factors influencing, and influenced by, technology by integrating HSS into the engineering curriculum, not tacking it on; integrate research and undergraduate teaching; hire faculty with industrial experience, regardless of degrees; expand technician programs; expand industry funding of engineering research; promote advanced engineering education (Ph.D.), continuing education, lifelong learning, professional registration by faculty; predictions --M.S. will become basic engineering degree; fewer programs/institution; increasing use of engineering to solve social problems; 1/7 B.S. graduates will go on to Ph.D. by 1978 (1978 forecast: 50,000 B.S., 32,000 M.S., 8000 Ph.D.); need for 1.37 million engineers by 1970.

- Olmsted Report for ASEE: integrate HSS into 4-year programs, basing it on providing developmental and value context of technological action, not on utilitarian/cultural grounds; improve quality of general education; retain good HSS faculty who drift away from engineering schools; reduce the number of electives while retaining breadth.

1972/73 - Engineering doctorates peak at 3775 (having risen from 100 in 1943), decline to 2600 in late '70s and climb past 300 in mid'80s.

1975 - Center for Policy Alternatives report (J. Herbert Holloman, Chairman), "Future Directions for Engineering Education: System Response to a Changing World", provoked by "precipitous decline in engineering enrollments" and of America's global dominance: engineering education too responsive to "transient" changes; prepare for declining enrollments; restore art of engineering to curriculum by expanding teaching of design, requiring work experience, coop education; integrate HSS into engineering curriculum, also consciousness of "culture" of the sciences, as opposed to their techniques; include teaching changing constraints on engineering deriving from social, economic, political and legal factors; expand 2- and 4-year technology programs; promote continuing education in engineering, as opposed to management-related studies; expand evaluation; promote engineering major as generic preprofessional training; use industry more as a resource and sponsor.

1979 - ECPD changed its name to Accreditation Board for Engineering and Technology (ABET).

1981 - NAS Committee on the Utilization and Education of Engineers (E.M. Cortright, Chairman) recommended a comprehensive study of by NAS-NAE of engineering education and practice in the U.S.; it defined the need and identified what the parameters should be. The result was Engineering Education and Practice in the the U.S. (EEPUS), published in 1985/6 under the general chairmanship of J.A. Haddad.

- Foreign recipients of engineering doctorates from U.S. institutions exceeds 50%.

- freshman engineering enrollment peaks at 115,000.

1982 - "The Quality of Engineering Education", prepared by the National Association of State University and Land-Grant Colleges, John D. Kemper, Chairman: overenrollment, faculty shortages, serious equipment, space and facilities inadequacies threaten quality of engineering education; increase faculty salaries; pursue increased industry support and major government funding to upgrade infra-structure.

- Creation of National Technological University by 15 universities and 12 major corporations.

1983 - 9566 women receive B.S. in engineering disciplines, up from 358 in 1970. In the same year, almost 19,000 women were enrolled as freshmen engineering majors.

1985 - EEPUS publication begins, seven volumes (see Bibliography).

- NSF charter amended to increase support for engineering education and research.

- B.S. degrees in engineering peak at 78,000.

- NAE report to the NSF "New Directions for Engineering in the NSF", Peter Likins, Chairman.

1986 - National Conference on Engineering Education, convened by ABET. Consensus recommendations (>75% support): update undergraduate engineering education as follows --math concentration in probability, statistics and numerical analysis, more breadth in basic sciences, expand HSS and communication skills with close engineering college monitoring of effectiveness, focus on design with attention on socio-economic factors included, intensify utilization of computers, introduce interdisciplinary coursework in real-world problem contexts, set admission standards that obviate need for remediation; strengthen faculty, requiring industrial experience and teaching effectiveness for tenure, continuing education, advisory committee of practicing engineers for each engineering education unit, fellowship stipends at 1/2 industry starting salary to attract U.S. citizens to graduate study; tighten link of engineering education to engineering practice; encourage longer than 4-year curriculua but do not mandate them; engineers should play a role in competitiveness imrpovement efforts, not just executives, economists and politicians.

- Final Report, ASEE study, "Quality in Engineering Education Programs", W. Edmund Lear, Project Director: overenrollment severely straining institutions, insufficient and obsolete lab equipment, facilities shortage and deterioration require massive new funding; research values have overwhelmed production values in engineering education with increase in Ph.D./research oriented faculty; make industrial experience and teaching effectiveness conditions of tenure, on a par with research; require test of spoken English for teaching assistants; institute structured continuing faculty education; implement new educational technologies now, especially intensive utilization of computers; expand production of technicians; improve lab teaching, assigning senior faculty to it.

- "The Quality of Engineering Education II", follow-up to 1982 report, James E. A. John, Chairman: enrollment pressure eased slightly; promote U.S. citizen graduate study by raising fellowship stipends to 1/2 industry starting salary; large scale facilities improvement needed as well as maintenance endowments; Ph.D. faculty can only be held if campus provides research environment; far too few technicians.

- "Engineering College Research and Graduate Study: A 20 Year Statistical Analysis", W.J. Fabricky, J.E. Osbourne and R.C. Woods.

- Creation of first Engineering Research Centers by NSF.

1987 - ASEE convenes Task Force on a National Action Agenda for Engineering Education, chaired by Edward David; report in preparation.

3. Summary of findings.

It is possible to abstract from the engineering education literature two types of issues --new ones and perennial ones-- and a set of assumptions that recur in many of the reports without critical examination. By "new issues" I mean those that have emerged primarily since the mid-1970s. Perennial issues are those that were already identified in the Mann and Wickenden reports and have reappeared in most, if not all, subsequent studies.

A striking finding of this review is the number of issues of current concern that are perennial. A fuller account of both types of issues is given in the discussion section of the report (II, 1-4), but a number of general observations are here appended to the following brief listing of issues and assumptions.

A. A summary of perennial issues in U.S. engineering education.

1) Articulating a rationale, and making a place, for humanities and social science courses in the undergraduate engineering curriculum.

2) Integrating humanities and social science courses into the engineering curriculum in a way that communicates an understanding of the social context of the practice of engineering.

3) Determining the appropriate balance between courses in mathematics and physical science on the one hand and specifically engineering courses on the other.

4) Determining the appropriate balance between generic engineering science courses and specialized, disciplinary, engineering courses: a corollary of this is the problem of the fragmentation of curricula - at various times it has been considered desirable to have more, or fewer, curricular tracks to the B.S. degree.

5) The competence of engineering faculty vis-a-vis the "real" world practice of engineering: understanding, for example, how engineering problem-solving is constrained in industry by profit and market-related factors.

6) Continuing education and professional development for engineers, including engineering faculty, to maintain currency of competence; building life-long learning as a norm into the undergraduate engineering learning experience.

7) The limitations of the 4-year B.S. program and the desirability in principle of adding at least one more year.

8) Making the M.S. the first professional degree in engineering, with the B.S. serving only as an entry point into engineering as a profession (by analogy with law and medicine).

9) The proper role of state licensing and/or certification by an engineering professional society, in addition to job performance, as determining membership in the professional engineering community.

10) The distinctiveness of engineering vis-a-vis science.

11) The role to be played by industry in shaping the content of engineering education so that new B.S. recipients will be usefully employable as quickly as possible.

12) The undergraduate engineering curriculum as providing an education and not merely vocational instruction.

13) The responsibility of the engineer to society, at times in conflict with the responsibility to his/her employer, given the social impact of technological innovation and a recognition of the value-laden character of engineering judgement and design as shaping that impact: a coordinate problem is how to integrate a treatment of engineering ethics and the value structure of engineering judgement into the undergraduate curriculum.

14) Using technology, and ipso facto engineers, to solve social problems, implying the need to integrate into the undergraduate curriculum an understanding of the social context of engineering, especially of the ultimately dominant role of non-technical constraints on engineering problem-definition and solution.

B. New issues in engineering education. [The order of listing is not intended as a measure of significance. It follows, roughly, the chronology of their identification.]

1) Enrollment in engineering and the number of engineers in the American work force.

2) Recruiting women and minorities (especially Blacks and Hispanics) into engineering.

3) A demand for greater numbers of engineers with doctorates in engineering.

4) A dramatic shift away from engineering practice, and such distinctively engineering tasks as design [see the discussion, below], toward engineering theory as exemplification of scientific theories, methods and principles.

5) The emergence of cross-disciplinary engineering teams as the norm in industrial research and development, and the perceived need to incorporate preparation for this practice into the undergraduate curriculum.

6) Engineering faculty shortages, as market conditions improved dramatically in the late 1970s and engineering enrollment soared to historic highs in the early 1980s.

7) Growing concern that engineering faculty lacked understanding of the industrial context within which approximately 80% of engineers worked as engineers.

8) A sharp increase in the number of foreign, especially Asian, students enrolled in graduate engineering degree programs, constituting, by the early 1980s, more than half of the TAs, RAs and doctoral degree recipients in engineering.

9) A perceived weakness in engineering lab teaching, in part a reflection of faculty shortages such that graduate students are assigned to lab teaching, in part a reflection of the low professional prestige associated with responsibility for lab sections, and in part an expression of the time, skill and special knowledge needed to make an engineering lab into an accurate experience of engineering problem-solving rather than technical busywork.

10) Equipment and facility problems, especially at the so-called "second tier" institutions that produce half the B.S. engineering degrees in the U.S..

C. Recurring assumptions in reports on engineering education.

1) That engineering drives technological innovation and thus bears ultimate responsibility for the social, economic and political impacts of technology.

2) That U.S. global preeminence in science, engineering and industrial competitiveness is the norm, such that its absence implies a failure on the part of some person(s) --for example, educators, workers or managers-- or of some institution(s) --for example, the home, the family, the school system, Wall Street, corporate management, governmental policies, or the functioning of some agency of the Federal government.

3) That industrial competitiveness is a consequence of technology-driven production systems which are the direct product of engineering applications of basic science, which in turn rest on excellence in science and engineering education;

4) That education relevant to engineering and technology is the preserve of the nation's system of public and private schools, colleges, institutes and universities, effectively ignoring the enormous number of corporate education programs. In the process, an opportunity is lost for learning from these programs much that bears on industry's need for engineers and on the preparation industry would like them to have: for example, that industry has been providing, de facto, a fifth year of engineering training supplementary to the B.S..

5) That the engineer is an autonomous professional, obscuring the complexities introduced by the fact that some 90% of the people who work as engineers are employees of government or industry and as such lack the autonomy and freedom professionals are traditionally supposed to possess to judge when to act in accordance with values transcending employer interests.

6) That the intense, and intensely scientific, research orientation of graduate engineering programs benefits undergraduate education.

7) That U.S. engineering education, as well as U.S. research, innovation, production and even trade (except for the purposes of statistical comparisons) can be analyzed and responded to as national issues, without having to adopt an international perspective.

8) That engineering education should be directly responsive to anticipations of employability on the part of students (and doubtless their parents as well) and that the curriculum should be shaped by the employment needs of industry.

9) Virtual absence of any discussion of attracting to the engineering major students who do not begin their college careers as engineering majors or of special efforts at retaining the very large number of drop-outs from engineering (typically, 40% fewer degrees granted than freshmen who began as engineering majors, with an average B.S. completion time of approximately nine terms); of novel approaches to utilizing engineers (for example, by stopping the drift out of engineering proper into supervision and management) or to utilizing non-engineers to perform tasks currently performed by engineers or engineer-technologists (for example, by using workers and easing the schooling requirements for designation as technician, para-engineer or assistant engineer).

10) Absence of a recognition of the recruitment value of advocating a unit on engineering/technology at the high school level, and of the need for college level engineering courses for non-engineers and for engineering outreach programming so that the general public will understand enough about engineering to appreciate technology policy issues in which they must participate as citizens.

D. General observations.

1) Undergraduate engineering education in fact is strongly tied to the immediate needs of industry, which are unpredictably variable, and it is strongly influenced by public perceptions of the market for engineers. As a result, engineering enrollment as a whole, and the distribution of enrollment between engineering disciplines, varies widely even within time spans as short as five years. The creation of new institutional mechanisms as responses to short-term variations in enrollment thus seems inappropriate. It would appear to be more appropriate to address the more fundamental issue of the proper role of industry and its short-term needs as influences on engineering curricula.

2) Concern over the number of engineers in America should be seen in the historical context of 100 years of a doubling of the number of engineers every ten years. It hardly seems surprising that this rate of increase should have decreased at some point, as it did in the 1960s. Had it continued at its historic rate, the number of engineers today would be

approximately 5 million, instead of the actual 1.7 million. As shortages of engineers today are narrowly localized (in computer and aerospace engineering) and the starting salaries of engineers at all degree levels (in con(in constant dollars) are no higher than they were 25 years ago, it seems reasonable to conclude that the marketplace could not have assimilated the historic growth rate.

Furthermore, there remains an indeterminate, but almost certainly very large, elasticity in the pool of people capable of performing the tasks industry calls on engineers to perform. It has only been since World War II that as many as half of the people employed as engineers had a college degree of any kind and even today not much more than half of the people employed as engineers in durable goods manufacturing have engineering degrees. Thus, the historic growth rate of the number of engineers was fueled to a significant degree by identifying as engineers people who were not college trained. Correlatively, the decline after 1960 in the historic growth rate was at least in part a consequence of a tightening of the determinants of who is an engineer.

It seems reasonable to conclude, therefore, that if people with degrees in engineering were truly in short supply, skilled workers could once again serve many (but obviously not all) production-related engineering functions. This conclusion is buttressed by two other facts about the utilization of engineers in the U.S.: that a substantial percentage (>20%) move out of engineering into managerial, as distinct from supervisory engineering, positions, and that the ratio of technicians to engineers in the U.S. is far lower than in other industrialized countries. Taken together, these imply that, except for particularly esoteric expertise, the supply of engineers is globally more than adequate to cope with demand at least on the timeline of the responsiveness of the educational system: 3-5 years, both for major structural changes in curricula and for enrollement shifts in response to market perceptions.

3) The current concern with the number of engineers in, or available in the near-term to enter, the U.S. work-force seems misplaced. For one thing, given utilization patterns, the quality of engineering college preparation, especially in state-of-the-art related skills, seems of far greater consequence than the absolute number of engineers. For another, the pool of potential engineers is vastly larger than is reflected in engineering community studies of engineering.

On one hand, this claim is based on the evolution of how people are identified as engineers, in particular, on the growing formalization of the requirements for professional status. People employed as engineers today almost universally have degrees from accredited institutions either in engineering or in physical science. This was not the case prior to World War II, a period overlapping the "Golden Age" of American engineering, and although technical knowledge has become much more esoteric and specialized since then, there are unquestionably many production- and construction-related jobs filled by college-educated engineers for which talent and experience are the equal of an undergraduate engineering degree, the only degree possessed by the overwhelming majority of engineers.

Little effort has been made to institutionalize mechanisms by which appropriately talented workers can move up to engineer or "para-engineer" status, outside of corporate training/educational programs, which are generally ignored or patronized in the enginering education literature. This stands in sharp contrast to longstanding mechanisms in other industrialized countries (for example, England, France and Germany) to this end and may be a reflection of the elitist and management-linked professional self-image of the engineering community. It may also explain the failure of technician, technologist and engineering technology curricula to attract as many students as had been anticipated.

On the other hand, even within the formal accreditation scheme, the pool of available students overwhelms the predicted decline of engineering enrollment based on demographic changes. The drop out rate for engineering majors is on the order of 40-50% and unlike comparable drop-out rates for humanities and social science majors, it cannot be made up by crossover transfers except with very great difficulty because of the density of the 4-year curriculum, yet very little effort has been made to retain these students, many of whom have been identified as of high caliber. Engineering colleges make no effort to attract into engineering students who do not begin their careers as engineering majors, which makes enrollment almost totally dependent on career decisions made in high school: surveys consistently indicate that the overwhelming majority of freshman engineering majors chose to major in engineering by their junior year in high school. These decisions are clearly sensitive to a host of emotional, intellectual and social experiences capable of modifying them. In addition, it makes engineering enrollment dependent on still earlier decisions to take mathematics and science courses in pursuit of a career in engineering that is very poorly understood, in part because no systematic effort is made to present engineering to high school students as a discipline and a profession distinct from the physical, life and social sciences.

4) The rate at which women choose engineering as a major/profession has increased dramatically since 1970: from 800 freshmen and 350 B.S. degrees to 17,000 freshmen and 9000 degrees. Although some today express disappointment with the current levelling off of this figure, it is an astonishing success story, especially compared to the significant but much less dramatic results of intensive recruitment efforts aimed at the Black and Hispanic communities. Understanding the factors underlying this turnabout seems very likely to be of great value for efforts at increasing the rate at which high school students of all kinds choose to major in engineering.

5) The view persists in the engineering education literature that the supply of engineers is directly related to technological innovation and the competitiveness of industrial production. A consensus exists among technology studies scholars, however, to the effect that managerial decision-making dominates the innovation process and that competitiveness is determined by a wide range of corporate, political and social policy decisions that make the coupling of innovation and competitiveness to engineering education very weak.

Improving either the quality or the quantity of engineering graduates, on these views, would have little or no impact on innovation successes or the competitiveness of American industry in the absence of relevant policy changes, while policy changes by themselves would almost certainly affect competitiveness and in the process precipitate complementary changes in engineering education.

6) Graduate education generally is widely perceived to be the great strength of the American educational system. That many foreigners are attracted to graduate engineering programs here is not surprising and has only become a matter of concern because of the growing proportion of full-time doctoral students and graduate assistants they have come to represent. Americans were attracted into doctoral engineering programs in growing number since World War II and especially during the period of greatest federal research expenditures, peaking in the mid-seventies. Given the rate of growth of doctoral degree awards from the early 1940s (approximately 100 degrees/year) to the mid-1970s (3700/year) a decline cannot be simply attributed to some failure in the system to maintain that rate. Industry has no obvious need for substantially more engineering doctorates than are now available (as indicated by salaries offered) and academic positions are unattractive at a time of a dynamic industrial market, tight research money (compared to the '60s and '70s) and great teaching pressure because of very high undergraduate enrollment. The creation of industry-linked academic centers for engineering research, for example, the small number of NSF-funded Engineering Research Centers and the many anticipated local variations on them, may alter the perceived attractiveness of an academic career more than simply increasing graduate stipends to half the B.S. starting salary, as many recent reports have called for doing.

7) Many of the currently perceived problems with undergraduate engineering education are related to the intensification of the science model for engineering that took hold in the 1960s and '70s with the explosive growth of doctorate-level enrollment. The growth of Masters-level enrollment has been steady and strong since before World War II and its significance has not been pursued, another sign perhaps of an elitist bias. The Masters degree is an essential component of the profession, the number of degrees awarded amounting to 20-25% of the B.S. degrees in any given year. The doctorate, however, exerts a different influence on the profession and on engineering education because it imports into engineering values, concepts and methods derived from science. This seemed uncontroversial through the early 1970s when industry took engineering for granted and the historic Western bias for science (as knowledge) and against engineering (as "mere" know-how) reinforced it. In such an environment, the rapid growth of engineering research, alongside and in conjunction with scientific research, made it almost inevitable that scientific research norms would be taken as a model for engineering. The turnabout in industry's sensitivity to engineering with the onset of loss of market for manufactured goods has now called into question the value for industry of this model.

At the same time, undergraduate engineering education has been influenced by the conceptual orientation of growing numbers of faculty who possess doctorates earned during the '60s and '70s and who are now perceived as lacking an understanding of the relation of engineering to industrial production. This is said to be reflected in the reduced role commonly accorded design in engineering coursework and in the absence of relating the solution of engineering problems to the creation of successfully marketable products. Given the attention currently being focused on this issue, and the historic relation between engineering education and the orientation of industry, this would appear to be a problem in the process of correcting itself.

8) Current concerns, from a historical perspective, suggest three areas for federal policy in engineering education:

(1) large-scale infrastructure aid to "2nd tier" institutions;

(2) pressing further recent NSF efforts to promote industry-linked interdisciplinary academic engineering research, including funding for undergraduate curriculum development projects aimed at improving laboratory teaching, restoring design and project-based coursework to the curriculum, and bringing interdisciplinary engineering R&D in an industrial context into the undergraduate curriculum;

(3) creating a small number of academic centers for the purpose of developing exemplary curricular materials in the areas of design and engineering practice, and in the use of new educational technologies.

The rationale for claiming that the federal government ought to support the modernization of "2nd tier" institutions is based on the fact that they graduate half of all American B.S.-level engineers. If maintaining at least the current engineer training capability is an objective, then these institutions need to be kept open and they must be able to provide the quality of education necessary to move into industry or graduate school. There would seem to be little alternative to the federal government as a lead funding source, given the sums involved (perhaps as much as $2 billion dolllars on a one-time basis and then continuing support to avoid a repetition of large-scale obsolescence) and the experience that infrastructure modernization is extremely difficult to fund from private sources.

Through its massive support for science and engineering research and its active promotion of the engineering doctorate during the 1960s, the federal government played a large role, albeit an indirect one, in moving the undergraduate engineering curriculum further in the direction of analysis, and away from design, than had been the case earlier. The connection between the two was provided by the migration of engineering Ph.D.-holders onto engineering faculties, bringing with them a strong science-based research orientation. As the federal government brought this situation about through earlier policies, it ought now to undo the imbalance in the undergraduate curriculum that followed in their train. [This conclusion reflects accepting the judgements that scientific analysis is overrepresented in the undergraduate curriculum and that engineering Ph.D.-holders by and large have internalized scientific research norms and values. Both of these claims are discussed in II.]

Finally, it seems extremely wasteful for scores of institutions to pursue, independently of one another, generic curriculum development projects in engineering design, and in the implementation of new educational technologies. A small number of centers funded through the NSF, possibly in conjunction with the National Technological University, perhaps employing year-long rotating appointments to involve many institutions, would seem to offer significant economies.

II. Discussion.

1. Current Engineering Education Issues in Historical Context.

(a) Precollege preparation and recruiting.

With few exceptions, students come to college having decided to major in engineering. For the majority (between 70 and 80%), this decision was made by the second or third year of high school [1969a: Perrucci and Gerstl]. The most important consequence of this state of affairs is that college engineering curricula have been designed to reflect it. That is, because this is the case, the engineering major can begin in the first term of the freshman year with course requirements that are prerequisites to increasingly sophisticated engineering science and disciplinary engineering courses.

This would appear to be one way in which the 4-year engineering curriculum has been maintained in the face of growing pressures on it, but the price paid for this is substantial. For one thing, because of the early prerequisites and the sequential flow of the technical coursework, a student who wished to choose an engineering major after their freshman year could do so only with considerable difficulty: less in the case of a physics or chemistry major, more in the case of a social science or humanities major. On the other hand, transfers between humanities majors, science majors and even between humanities and science majors are common with moderate or no penalty until the second half of the junior year. Another "cost" of beginning the engineering curriculum in the freshman year is that it makes the size of the pool of potential engineering majors subject to poorly understood personal, social and intellectual factors rooted in students' high school experiences.

While it is tempting to suppose that students are attracted as high school sophomores and juniors to commit themselves to a career in engineering as a result of science and mathematics courses they have taken, it is not at all clear that this is in fact the case. With few exceptions, high schools do not teach anything in or about engineering. Somehow, students make this decision on the basis of other inputs: relatives, parents of friends, movies, television programs, books, imagination. It should hardly be surprising that so many drop out of engineering after their freshman year and their first exposure, not even to what engineering as a career is all about, but to what preparing for a career in engineering entails. That students also modify other career choices they make before college once they start college has a different impact on other disciplines than on engineering. Students can modify these other choices relatively painlessly by moving between majors on the basis of experiences in and out of college. The engineering major, however, can only lose students in the course of this maturational process because of the great difficulty of transferring into engineering.

Yet another price exacted by keying the engineering curriculum to students who arrive as engineering majors, is that high school science and mathematics preparation levels play a decisive role in determining the ability of students who choose engineering majors to function comfortably in lower level college courses. Inadequate preparation not only can discourage some students from considering engineering as a career, but it must play a significant role in the very high drop-out rate of engineering majors after the first and second year of college.

Finally, the fact that engineering curricula address only students who come to college having chosen the engineering major means that no effort is made at the college level to introduce non-majors to engineering with a view to attracting them into engineering. A corollary of this is that virtually no engineering courses exist of a general education nature, analogous to courses in the physical and life sciences, which can be required of liberal arts and business majors. As a result, there is almost total ignorance even among the college-educated public of the nature of engineering as a profession and a problem-solving discipline distinct from the sciences.

Weakness in high school science and mathematics preparation has been of concern to engineering educators at least since the Mann Report of 1918, and with growing urgency since the 1955 Grinter Report and the 1959 report to President Eisenhower by Lee DuBridge in the wake of Sputnik. In the 1980s, there was added to concern about the quality of preparation a recognition of the dramatic inadequacy of the numbers of certified high school science and mathematics teachers.

The retrospective judgement of many educators and observers is that the 1960s-era response to the quality concern, in the form of NSF-funded Summer Institutes, was successful in accomplishing significant teacher development. This program was, however, dropped by the NSF and has not yet been restored. Improvements in the shortage of certified teachers have, in the interim, been to the working of market mechanisms.

In addition to concerns about the number of students passively recruited into engineering by self-selection during high school, there grew during the 1960s a demand that women and minority group members, primarily Blacks and Hispanics, be actively recruited. The results of responses to this demand are of considerable interest, yet have provoked little study for the lessons they may hold.

On the one hand, the selection of engineering as a career by women increased dramatically between 1970 and 1986. Where women were awarded 358 B.S. degrees in engineering in 1970, they received 9566 in 1983 [1986: Purdue]. Freshman enrollments of women peaked in the early 1980s at almost 19,000, stabilizing at 17,000 --approximately 16% of total engineering enrollment at its historic high-- for the mid'80s. That some critics choose to focus on the levelling off should not obscure how astonishing a change this is in a long-standing behavior. Understanding this change could well illuminate the mechanisms of career selection at work in the vast population of students who are today ignoring engineering as women did prior to the 1970s. At the same time, the number of women in tenure-track engineering faculty positions is so low --between 100 and 200 nationwide!-- that further dramatic increases seem possible if women faculty reflected in their numbers the prevalence of women among recent graduates. Can the change in high school women's career selection plausibly be attributed solely to recruitment efforts whose success it reflects?

At a minimum, answering this question requires comparing recruitment efforts aimed at women to concurrent, and seemingly much more intense, recruitment efforts aimed at Blacks and Hispanics. These have resulted only in modest increases in the number of engineering students from these groups (though the percentage has doubled), while the extraordinary efforts made have created a substantial burden of remediation programs within engineering colleges [1986: National Congress]. Oriental-Americans, however, without any special attention, have over this same period of time become a much larger proportion of undergraduate engineering majors than their representation in the general population.

The upshot of these results would appear to be that we understand only poorly, if at all, why high school students make the career choices that they make. Because those who choose engineering represent only some 4% of graduating seniors, the potential for attracting more students into engineering if these ~~influences~~ were understood is enormous, far outweighing projected declines in the number of high school students over the next 5-7 years.

Recent reports [1986: EEPUS Infrastructure; EEPUS Engineering Undergraduate Education; EEPUS Foundations] continue to call for improving high school science and mathematics preparation, further efforts to recruit women and minorities and, more specifically, for the introduction of high school career guidance by engineering professional societies. While no impact on minority recruiting or retention is claimed for educational technologies used in special programming, some claim to see cognitive science as being on the threshold of generating new technologies of value for improving pre-college learning [1985: Outlook].

(b) The engineering major as an "attractor" in college.

The timing of the selection of engineering as a major is the primary determinant of the number of students electing engineering. For the overwhelming majority of students today, this is a decision made in the second or third year of high school, which means that little impact on this decision can be made by activities at the college level. On the other hand, retention efforts hold the potential for materially increasing the number of B.S. degrees awarded in engineering, as graduates typically number 40% less than their freshman class. Furthermore, reports over the last 20 years have observed that many students who drop out of engineering do not do so because of lack of ability. They may, in fact, possess significant creative ability that is currently thwarted by an initial exposure to engineering through mechanical introductory courses.

The pool of potential engineering majors could, however, be increased dramatically by broadening the time frame for choosing the major. This would entail making the engineering major more accessible to students transferring from other majors and/or choosing engineering after their freshman year. Limiting prerequisites is one measure that would improve access, albeit a passive one. Active measures would include promoting the choice of engineering as a major, for example, by offering an introduction to engineering course, interdisciplinary courses dealing with "real world" engineering problem-solving, promoting engineering as a career choice and as preprofessional education. All such efforts, however, require making the engineering major easy to adopt through the sophomore year. One way to do this would be to promote a common freshman year for all majors at an institution, or to require that science and mathematics requirements for non-science and non-engineering majors be satisfied in the first three terms of a student's college career. Picking a science/engineering major after the freshman year would not then entail having to take a cluster of basic courses at a time when the student's interest had been aroused in engineering proper.

Another pool of students potentially available to engineering programs is made up of students in two-year technician/technologist curricula. Cooperation with these institutions and better articulation of course content and requirements between curricula at two- and four-year institutions, could make it more likely that talented students who begin a technician or technologist program would see tranferring to an engineering program as a viable option for them.

Taken together, and without even considering the efficiency with which engineers are utilized in industry, the potential for swelling the number of undergraduate engineering degrees awarded through improved recruiting, retention, and transfers into engineering both within a given institution and between two- and four-year institutions/programs, is substantial. The numbers of students who could be brought within the scope of these programs is so large that it could more than outweigh projected engineering enrollment declines based on demographic changes, even assuming none of the recruiting, retention or major selection timing changes such as those above. Currently, one-half of engineering B.S. degrees in the U.S. are granted by only 45 of the approximately 260 engineering degree-granting institutions. Fourteen of these 45 are in New York, Pennsylvania and Massachusetts where a 40% decline is projected in the high school age population by 1992; 27 of the 45 are in frost belt states where the decline is projected to be 22%.

There has been concern since the Sputnik period that American schools were not producing enough engineers. More recently, the concern has been that to compete with Japan and western Europe we need to produce more engineers, yet there is no clear evidence that engineers are, or soon will be, in short supply.

For one thing, starting salaries for engineers in constant dollars are virtually unchanged over the past twenty-five years, at every degree level. For another, variations in undergraduate enrollment and B.S. degrees awarded have been sharp over short time periods since 1950. For example, freshman enrollment between 1965 and the present has varied from 79,000 to 52,000 to 110,000 to 98,000, while degrees awarded have varied from 36,000 to 77,000. In addition, the distribution of enrollment among the various branches of engineering also varies sharply. As a result, it is very difficult to interpret the absolute significance of enrollment and degree statistics, especially in the absence of market indications of supply-demand mismatches. On the contrary, the stability of starting salaries strongly suggests that, sharp variations notwithstanding, supply and demand are relatively well matched within the time required to produce a B.S. "generation", namely, four and one-half years.

It is worth noting that as recently as 1982, no federal agency targeted funds specifically for undergraduate engineering education. A total of 38 programs in 11 agencies spent $240 million on engineering education in fiscal year 1981, but more than 80% of this was student loan guarantees and a little over 10% went to the Merchant Marine and Coast Guard Academies [1982: GAO].

(c) Technician and Engineering Technology Programs.

The Wickenden Report in 1934 emphasized the need for America to pursue other forms of technical education than just engineering colleges. Many reports from that time to the present have echoed this advice, but to little avail: 1944, Hammond; 1955, Bevis; 1959, DuBridge; 1986, EEPUS "Foundations"; 1987, Engineering Research Centers. In 1941 SPEE created a Technical Institutes division and in 1945 ECPD began accrediting associate degree programs. In 1951, 68 institutions granted 2- or 4-year technician or technologist degrees. By 1983, there were 195 institutions with 731 accredited programs (460 of them 2-year) in which a total of 60,000 full time and 24,000 part time students were enrolled. This represents a doubling of part-time students and a 50% increase in full-time students over the preceding decade, but with little growth since then. The 4-year Engineering Technology degree was first awarded in 1971 and by 1983 9200 were granted, amounting to almost 12% of the B.S. engineering degrees in that year.

There is nothing in the American educational system comparable to the establishment institutions created in England, France and Germany in the 19th century to provide mobility into engineering jobs for skilled workers lacking formal education. On the contrary, the tension between the shop culture of early American engineering (dominant through 1885) and the lab culture of science-based engineering (dominant by the early 20th century) has been maintained in the steadily growing gulf between engineers with degrees and knowledgable workers without them. It is only since the late 1940s that as many as half of those people employed as engineers had college degrees of any kind; and in durable goods manufacturing today the percentage of engineers with degrees is not much more than 60%, if that. Technical institutes are underutilized.

It seems clear that the history of engineering in the twentieth century includes the progressive restriction of the title "engineer" to those with formal credentials. Many in the profession would like to see this restriction extended further, to exclude those with only a B.S. and no professional license or advanced degree, generally in addition to experience. Meanwhile, it is clear that outside state-of-the-art engineering employing mathematical models, there are many skilled workers possessing the same kinds of expertise that won people the title "engineer" prior to World War II, but not today. A corollary of this is that engineers are frequently employed in industry in capacities that do not utilize well their formal training, but have them perform jobs which could easily be done by expert workers. The situation suggests the existence of yet another pool of people who could swell the ranks of the engineers if demand for the latter significantly exceeded the supply.

(d) Corporate education activities.

If technician and technologist training is paid short shrift in the U.S., education outside the formal educational system is paid no shrift at all. American corporations in 1984 spent in excess of $30 billion on in-house employee training programs ranging from orientation to company procedures, to fully accredited doctoral degrees [1985: Eurich]. An additional $10 billion was paid out as tuition for employee enrollment at "official" educational institutions, either in traditional courses and degree programs, or in courses specifically designed to meet a particular company's needs. In 1984, for example, GM contracted with 45 community colleges around the country for automotive technician training courses, with the college faculty receiving specialized training at GM.

This sum dwarfs federal educational outlays of approximately $10 billion (in 1984) and is a sizable fraction of total public expenditures on education of approximately $100 billion. Nevertheless, recent studies of American education by the Heritage Foundation (" Blueprint for Jobs and Growth", 1984) and the Hoover Institute ("To Promote Prosperity", 1984) do not mention corporate education programming at all. Nor do such popular books about American corporate culture as "In Search of Excellence" and "The 100 Best Companies to Work for in America" [1985: Eurich].

Corporate education expenditures correlate very strongly with R&D investment and ranking in the Fortune 500 list of the largest American corporate enterprises. Increasingly, these outlays go to support courses of a remedial and general education nature at one end of the spectrum, aimed at improving the basic skills of the work force, to highly technical courses and seminars at the other end, aimed at maintaining the currency of scientists and engineers in state-of-the-art developments. Somewhere in between are programs aimed at providing upward mobility for skilled workers to "para-engineer" or assistant engineer status, at enhancing the skills required to perform existing or new job assignments, or at providing career growth opportunities.

Although it is not included as a corporate educational expense, it seems appropriate to add the first year of employment of new engineering graduates. It is a commonplace that new graduates cannot do useful work at the engineer level until they have had 6-12 months of on-the-job training, learning new skills or learning how to apply the theoretical knowledge they acquired in school. This seems to be a kind of "fifth year" of undergraduate education whose cost is borne by first employers. To be sure, even students who are graduated from 5-year engineering programs, such as the one at Dartmouth, cannot immediately do productive work. Company orientation and familiarization with equipment, procedures and techniques are necessary in any event. But the 6-12 month period generally acknowledged as the breaking-in period for new engineers suggests that this is yet another means [in addition to beginning the major in the freshman year, essentially restricting it to those who choose engineering in high school] by which the 4-year curriculum has been maintained: namely, by pushing the "finishing" process off onto the graduate's first employer.

The history of corporate education provides valuable insights into evolving U.S. attitudes towards education, industry and the workforce. From its mid-19th century inception, public education was strongly oriented toward providing students an education that would serve the needs of industry. This was reflected in the prevalence of skills training in high schools, including mandatory shop. By 1910, 29 states required some form of industrial education in the public school curriculum.

Today, the rhetoric of educating to serve the needs of industry is the same, but the focus has shifted to providing industry with the scientists, engineers and managers it needs. This entails shaping the public education system to identify those students with the ability to become scientists, engineers and managers and then channelling them into the college system and professional careers. At the same time, a hue and cry is raised that the blue collar work force is undereducated and holding industry back from productivity improvements, but no special efforts are being made to shape public education in ways that are likely to improve worker skills. For obvious social reasons, this would be very difficult to do today, given our comprehensive public school system, except by way of non-discriminatory generic course requirements.

Corporate education programming offers a wide range of opportunities for traditional educational institutions to pursue articulation agreements based not on short term company-specific objectives, but on the broader educational objectives of in-house corporate training programs. For example, in the period 1980-1982, 186 2-year colleges were linked to district offices of the Small Business Administration at the initiative of the American Association of Community and Junior Colleges and the Small Business Training Network. Analogously, 15 universities and 12 corporations in 1982 created the National Technological University, with headquarters in Boulder, Colorado. The primary mission of NTU is to disseminate specially developed science and engineering courses to technical staff at participating corporate and educational centers, using satellite transmission. The expertise of technical professionals can by this means be kept current without the disruption and loss of availability occasioned by leaves of absence for learning, or having to fit learning into campus schedules.

In addition, NTU hopes to instigate the creation of exemplary materials by spreading the very considerable cost of development over a much wider audience than any single institution, relying on local attendance, could hope to achieve. In general, corporate education programs are far more concerned with educational efficiency than are schools and colleges. They spend far more time and money on evaluation and on experimentation with different teaching and learning formats than colleges. They are, therefore, a potentially valuable resource for colleges as colleges experiment with implementing educational technologies and techniques about which industry may already have accumulated a great deal of data.

(e) The undergraduate engineering curriculum.

i. Criticisms of the technical component.

Historically, criticism of the technical component of the undergraduate engineering curriculum has centered on the relationship between science and engineering materials, and on the fragmentation of engineering curricula. After 1885, American engineering curricula moved steadily toward resting engineering coursework on a foundation of mathematics and basic sciences, with the laboratory defining the "space" in which the three converged. It was in the laboratory that engineering problems were encountered, defined, analyzed and solved. This contrasted sharply with the shop as a defining "space", one in which engineering problems, analyses and solutions took a very different form than in the laboratory.

By 1918 there was widespread concern that the mathematics and science coursework was redefining engineering in its image. The Mann Report [1918] urged that engineering theory and practice be taught in a unified way, not as science and mathematics first, in one set of courses, and then engineering in a separate set. Teaching in this way communicated the mistaken notion that engineering practice in some way simply derived from mathematical science, a view that is rooted in Victorian-Baconian depictions of technology as the "fruit" produced by the "tree" of scientific knowledge. In place of the sequential presentation of theory and practice, Mann suggested that engineering educators develop analogues of the case study method then being introduced into the Harvard Law School curriculum by Langdell. Furthermore, these cases needed to have built into them cost considerations and the kinds of value judgements encountered in engineering problem specifications, in order for students to appreciate that these were natural constraints on engineering problem definition and solution and not arbitrary, as they would be in science.

The Mann Report also had something to say about the fragmentation of curricula. It recommended a common core for the first two years and then specialization.

It is possible to trace these same two concerns right up to the present, with remarkably little change in the rhetoric as well:

engineering education has a character of its own, based on design and engineering judgement (reflecting a selective synthesis of theory with a set of constraints peculiar to a particular problem), so that engineering is not simply applied science;

as far as possible, overlap between engineering curricula should be eliminated, but curricula should not be standardized;

engineering education is founded on engineering science, but engineering science is not simply science applied to engineering problems, it has a character of its own which uses scientific and mathematical knowledge as means to engineering ends;

engineering students must encounter "real world" problems in something like their full complexity, either in engineering labs or in project-based learning, not problems idealized in the manner of science problems;

engineering students should recognize the industrial context of engineering problems and that a solution that is not matched to that context is not a solution.

(A counterpoint would be the view, commonly expressed by physicists, that engineering was simply applied science and that engineering curricula could all be combined into a very few, or even one [1944: Jewett; 1959: DuBridge].)

In the course of the 1970s, there emerged a new set of concerns alongside the persistence of the historic ones. The "scientization" of engineering faculty took on a new intensity with the explosive growth of engineering research and the engineering doctorate in the 1960s and '70s. To a much greater degree than ever before, engineers choosing an academic career had internalized many of the values and norms of scientific research and this was perceived to have pushed the engineering curriculum still further away from the "art" of engineering to scientific analysis. [See II (c), below.] What was needed was an integration of the research interests of the faculty with their teaching.

At the same time, the growing complexity of the new technologies of the '70s made interdisciplinary research and development the norm even in industrial settings, let alone in research labs, but this was still not influencing the undergraduate curriculum by the mid-1980s.

A third current criticism is that laboratory courses have become routinized and mechanical to the point that they are not fulfilling an educational function, at least not as engineering courses. This is, in fact, a severe problem the solution to which implicates structural features of undergraduate engineering education. Laboratory teaching assignments are anything but prestigious to many faculty and are often given to graduate students. To be effective, lab courses should make engineering students engage problems in the way that they will engage them in engineering practice: as open-ended problems for which there is no single correct solution. But to do this requires that a great deal of thought be given to the kinds of problems posed for the students and a great deal of attention paid to the way that each student chooses to approach their problem. A common problem with a common solution for a section of an engineering course is almost by definition not an engineering problem. The alternative, however, requires the talent and the time of committed faculty.

According to some critics, much too little use is currently being made of new educational technologies that some believe will both increase the productivity of engineering teaching and improve its quality. Others claim that, while new technologies need to be explored and computers integrated into the curriculum, productivity increases are very likely to come, if at all, at the price of quality.

ii. Criticisms of the humanities/social science component.

For the past seventy years, to no avail, critics of engineering education have almost with one voice called for a strong and broad set of humanities and social science courses to be integrated into the teaching of engineering. The objectives of this requirement were to be English mastery and an understanding of the social context and relations of technological action. That is, long before C.P. Snow's "two cultures" and the creation of science, technology and society (STS) studies, the engineering community possessed individuals who recognized that engineering, unlike science, was inextricably linked to social, institutional and personal values that constrained it.

To accomplish these objectives, it has been argued in Mann, Wickenden, Hammond, Grinter, DuBridge, Burdell, the ASEE Goals Report and the Engineering Joint Council assessment of it, Olmsted, Holloman, the National Science Board, the National Research Council, and the National Congress for Engineering Education that the teaching of engineering must be integrated with the teaching of humanities and social sciences and that the engineering college must play an active role in seeing that this integration is effective. Grinter and Burdell [1955; 1956] recommended that the humanities and social science component of the undergraduate curriculum should amount to 20% of the whole, not counting composition and business courses. This is substantially less than the percentage required by ABET, and is taught without any systematic effort at illuminating the practice of engineering as influenced by, and influencing, its social context. Thus, in spite of being required to take a set of humanities and social science courses, engineering students are not acquiring an understanding the mechanisms by which influences are exchanged between engineering and society. [This is not to ignore STS courses that continue to grow and spread; but they are nowhere integrated into the engineering curriculum.]

iii. Criticism of equipment and facilities.

In the early 1980s, spurred by the intense enrollment pressure of the largest engineering freshman classes in American history, institutions revealed the substantial degradation of the infrastructure of education facilities that had taken place during the preceding decades. Laboratory equipment was obsolete and in extremely short supply, classroom and lab space were inadequate, buildings needed major renovation or replacement. Especially at institutions that were not major recipients of corporate and research support, primarily the "2nd tier" institutions, so called, that produce half of the B.S. engineering graduates, infrastructure support had evaporated. Even where current equipment was available as a result of corporate gifts, funding was often not lacking to maintain, insure or repair it. The easing of enrollment pressure in the last three years (1984-87) does not resolve the problem. It remains the case that a very large number of engineering institutions are training students with little or no "hands on" experimental experience, in overcrowded laboratories, using equipment so obsolete it bears no resemblance to what the students will encounter when they graduate.

The unanimous recommendations of recent studies of the problem are for major federal fund commitments and sharply increased state and corporate contributions to institutions whose primary mission is undergraduate engineering education [1982: Kemper; 1986: Pings, John].

(f) Cooperative and work study programs.

Virtually every study of engineering education, from the Mann Report to the present [1986: Quality in Engineering Education Programs; EEPUS "Engineering Technology Education", "Engineering Undergraduate Education", "Foundations of our Techno-Economic Future"], has urged a more widespread adoption of cooperative education or, at a minimum, some systematic, monitored, form of Summer work experience. College-based cooperative education programs for engineering students began in 1906 at the University of Cincinnati and almost immediately afterward at the University of Pittsburgh. Today, one-third of U.S. universities and colleges have cooperative education programs, but only 2% of their students participate: 220,000 students (in all disciplines, not just engineering) and 30,000 participating employers.

The major obstacles to expanding co-op programs are finding the requisite number of jobs, continuity of employer commitment to keep administration within practical bounds, and monitoring both the relevance of the work assigned to the student's major and the quality of the student's performance. That these truly are major problems is reflected in the constancy of the percentage of students involved, in spite of the widespread recognition of the desirability of expansion. For colleges and universities, co-op programs entail substantial administrative burdens requiring personnel devoted specifically to those tasks noted above, together with advising before, during and after the co-op experience. For employers of engineering students, a special effort must be made to provide an opportunity for a student to do useful work that will advance their professional education. This is not a simple matter, given that even new graduates typically require 6-12 months before they become productive. None of the calls for expanded cooperative education programs contain suggestions for how this is to be accomplished.

(g) Beyond the B.S.

In 1918, Charles Mann wrote that there was universal agreement that the 4-year engineering curriculum was "congested beyond endurance". By 1939, H.P. Hammond wrote that the time had come to move from a 4- to a five- or even a six-year B.S. program. The 1955 Grinter report repeated the desirability of a longer curriculum and urged institutions to experiment with them. The 1965 report "Engineering in Transition" branded the 4-year program flatly inadequate to preparing engineers and the 1968 ASEE "Goals" report predicted that the 4-year degree program would soon be superseded, for example, by a 3+2 program, in which the basic and engineering science and HSS courses cluster in the first three years and disciplinary engineering courses in the last two, or by making the M.S., or a new Master of Engineering degree, the entry degree into the engineering profession (by analogy with architecture).

It remains the case, nevertheless, that the 4-year B.S. program is nearly universal in spite of its manifest limitations. The 1986 National Congress for Engineering Education convened by ABET could only recommend consideration of a longer program: the attendees would not support a call for making one mandatory. The 4-year program has been buttressed by beginning the major in the freshman year and by limiting the specific engineering material taught in favor of generic engineering science, which imposes on the first employer of new graduates the burden of completing their education by teaching them how to apply the theoretical learning they have acquired. Along with specific engineering materials, courses in design and project-based laboratory courses have been contracted or eliminated in favor of more courses in analysis and artificial problem-based lab courses.

All of these accomodations have revived the concern that the B.S. is not the entry-level degree to the profession of engineering, though it does provide entry to the practice of engineering. By analogy with law, medicine and the ministry, engineers concerned with the professional character of engineering have called for making an advanced degree, or professional society certification, the mark of entering the engineering profession. This would appear to have significant consequences for the status of engineers. It could lead to bolder initiatives in the area of professional codes of ethics, perhaps to codes that could effectively buffer the individual engineer-employee from the decisions of his/her employer when these ran counter to sound engineering judgement. There is, however, little evidence in the literature of support from the mass of practicing engineers for this kind of professionalization of engineering. As revealed in such histories of engineering as Layton [1969] and Calvert [1967], the nature of engineering professionalism and mechanisms for measuring it have been the stuff of controversy since the founding of the ASCE. There is no sign that recent developments in engineering have resolved these controversies.

Quite apart from concerns over the adequacy of the 4-year B.S. to prepare new engineers and over the proper degree marking entry to the engineering profession, is the issue of a need for continuing education, indeed for lifelong learning, to avoid the obsolescence of technical knowledge. In the 1960s and '70s, it was estimated that the "half-life" of engineering knowledge was 10 years and shrinking [Ernst Weber in 1977: NAS/NAE] and that the technical complexity of engineering assignments peaked shortly before an engineer reached 40, on average [1975: Holloman]. In point of fact, that the rate of generation of new technical knowledge made it necessary that engineers continually re-educate themselves is a staple of every engineering education report since that of Mann in 1918. Wickenden had called for formal part-time continuing education programming for the first five years after the B.S., to be supported in part by industry and Grinter [1955] echoed this.

In addition, virtually every engineering education report urged that undergraduates be taught that lifelong learning was integral to engineering professionalism [1965: Engineers Joint Council]. Where continuing education programs aim at disseminating specific knowledge, "lifelong learning" refers to an attitude that needs to be nurtured in engineering students that will motivate them to participate in continuing education programs. In particular, it is necessary to attract engineers to continuing their technical education rather than taking management-related courses, which seem to make up a very large percentage of continuing education activities [1975: Holloman; 1986: EEPUS "Continuing Education"].

One suggestion for accomplishing this [1980: Issues] is to create 2-year post-B.S. programs for engineers with the aim of stimulating advanced study, rather than leading to a degree. This would require colleges to create new re-entry points into advanced engineering education for working engineers, for example, through non-credit short courses, workshops and seminars [1973: NAE, and 1986: EEPUS "Support Organizations"]. Unfortunately, this is perceived to be a low university priority because of academic prejudices against such non-degree-oriented learning. To circumvent this, federal funding has been urged in order to create incentives for continuing education on the part of individual engineers and to subsidize the development of new relationships between academic institutions and working engineers.

(h) Engineering faculty.

Concerns about engineering faculty fall into three categories: staffing problems because of shortages; the competence of engineers who become faculty members; and professional development activities. Faculty shortages first became an issue in the late 1970s and early '80s as a precipitous decline set in in the number of engineering Ph.D.s awarded, while undergraduate enrollment unexpectedly swelled still more precipitously and the job market for new engineers improved dramatically.

As discussed below, in (j), an influx of foreign-born graduate students resulted in a rise in the number of doctorates such that foreign-born recipients were more than 50% of the total in 1981 and won 45% of engineering faculty appointments made between 1981 and 1985. Nevertheless, it remains the case that even now, with gently declining undergraduate enrollment, 8-10% of budgeted engineering faculty "slots" are unfilled.

The loudest recent criticisms of engineering faculty have focused on their assimilation of scientific research norms and values through their doctoral research, as a result of which the "art" of engineering has been supplanted in the undergraduate curriculum by scientific analysis. This is perceived to be a consequence of federal R&D funding in the 1960s and '70s which made science-based research the frontier of engineering to the detriment of teaching on the one hand and close linkages to industry on the other.

As a result, it has been urged by many that engineering faculty appointments be made only after industrial experience, or that industrial experience be made a condition of tenure; also, that demonstrated teaching effectiveness be made a condition of tenure and not research accomplishments, valuable though these are.

Indeed, just such a concern over a growing divorce of theory-oriented engineer-researchers from the industrial context of the practice of engineering, with harmful consequences for undergraduate engineering education, was noted by Mann in 1918. He stated that research excellence was an "equivocal measure" of excellence as an engineering faculty member and this has been a near-constant refrain of post-World War II reports, especially Grinter [1955], the ASEE "Goals" report [1968], David [1977, in NAS/NAE], Low [1981], Felder [1982] and the National Congress for Engineering Education [1986].

The 1986 ASEE study "Quality in Engineering Education Programs" concluded that research values had swamped production values in engineering education and that there was a pressing need to restore as the "natural end" of good engineering, involvement with manufacturing processes. Earlier, George Low [1981] had concluded that a proclivity for science rather than technology was detrimental to industrial production and to technological innovation. [See 2c and d, below.]

Common to all of the above reports has been the recommendation that engineering faculty have industrial experience. In the more recent of them, it is urged that industrial experience be a condition of tenure and that experienced engineers with relevant expertise who are willing and able to teach should be given faculty appointments regardless of degrees achieved. This is especially appropriate for "2nd tier" institutions which graduate half of the B.S. engineers and at which undergraduate teaching is the primary faculty focus.

The 1986 NAE-sponsored report "Engineering Graduate Education" [in the EEPUS series, 1985/6] concluded that there was neither a basis in fact nor a present need for requiring that all engineering faculty have a doctorate or a research orientation. Practical experience, properly exploited, could be as valuable as the Ph.D. in the context of engineering education. As discussed above, in (e), the research orientation of Ph.D. faculty is believed to be responsible for problems with the content and teaching of engineering laboratory courses. The parallel EEPUS report "Engineering Undergraduate Education" called for the creation of Professorships of Professional Practice as a means of bringing experienced expert engineers into teaching and at the same time of anchoring industry involvement with undergraduate programs through the sharing of these engineers.

Faculty professional development objectives center on maintaining currency with advancing science and technology. As with students, the ideal means for accomplishing this is by faculty internalizing the value of lifelong learning which will motivate remaining current. Practically, however, the suggestions for accomplishing this are traditional: Summer institutes, sabbaticals, short courses.

For any of these to have more of an impact than they now do will take much more in the way of resources devoted to them and in the scope of the participating agencies. Ideally, such programming should be joint efforts specifically targeted on faculty devlopment involving colleges, ABET, professional societies, ASEE, industry, government and foundations [1986: "Quality"].

The EEPUS report "Support Organizations" [1986] urged that the cultivation of professional standards and codes of ethics be promoted as one dimension of faculty professional development, while the EEPUS "Foundations" report [1986] urged faculty activism in and on behalf of engineering professional societies.

(i) Graduate engineering education:

The promotion of graduate education has been a persistent theme in reports on engineering education since the Wickenden Report. Wickenden urged graduate education as a means to the ends of continuing education and lifelong learning. DuBridge [1959] expressed concern that the 650 engineering doctorates then being awarded each year was insufficient, given the nation's high technology R&D needs in the Cold War and post-Sputnik environments, together with a need for more engineering faculty with a grounding in scientific research methods and values. The 1962 report of the Presidential Science Advisory Council forecast a severe shortage of graduate engineers by the end of the decade, especially of Ph.D. engineers, even as the number of doctorates continued its startling growth from 650 a year in 1957 to 3700 a year in the early 1970s. PSAC notwithstanding, engineering doctorates were perceived to be a "drug on the market" in 1972 and the NSF predicted, in 1971, a 40% oversupply by 1980. In the event, there would have been a substantial shortage in 1980 if not for the sudden increase in the number of foreign-born engineering graduate students. It seems likely that the decline in American Ph.D.-level enrollment throughout the middle- and late-'70s is related to contemporary predictions that the market for Ph.D.s in engineering was glutted.

The 1968 ASEE report "Goals of Enginering Education" urged the importance of a Ph.D. for appointment to engineering faculty positions, encouraged industry's growing interest in hiring Ph.D. engineers and called for the creation of a Master of Engineering degree, both as a first professional engineering degree and as a means of encouraging continuation of engineering education beyond the B.S. The "Goals" report, extrapolating from contemporary trends, predicted that by 1978 engineering Ph.D.s would number 1/7th of B.S. degrees, a figure more than twice as large as the number of doctorates actually granted that year. The Likins report [1985] identified expanded academic engineering research with the strengthening of engineering education at all levels and with the means to improve American industrial performance. The latter connection between expanded graduate engineering education and the "competitiveness problem" was echoed in the 1986 "Federal Actions" report, which called for establishing a Master of Engineering degree explicitly linked to productivity-enhancing R&D.

From the perspective of relieving faculty shortages, the rising chorus of calls for more American engineering students to pursue graduate education at the doctoral level clashes with growing criticism of the consequences for undergraduate engineering education of the assimilation into engineering, through the Ph.D., of scientific research norms. The burden of the criticism is that engineering is rooted in design and synthesis, not analysis, and that the increasing focus on analysis in engineering curricula in the past thirty years has come at the expense of teaching design. Through learning design, which is acknowledged to be much harder to teach than analysis because design is non-algorithmic and cannot itself be modelled formally, engineering students learn that the engineering problems involve parameters deriving from applications contexts. This serves to link engineering to the "real world" of products and markets. Scientific analysis, by contrast, causes engineers to identify problem formulation and solution with idealized systems that lend themselves to compact, formal analysis and closed, unique solutions.

At the same time, the argument that graduate engineering education should be tied to productivity-enhancing R&D has evoked concern over the harmony of interests between academic and industrial research. Among these concerns are problems posed by proprietary attitudes toward information generated through a company's funding and for its use, the differential expectations of the timeline of research results, funding schedules which for academics are linked to graduate student support but which for a company are likely to be tied to much shorter-term pragmatic considerations, continuity of funding, free and timely publication of results.

The shortage of engineering faculty today, together with the completion rate and the percentage of graduates who choose academic careers, suggests a need for approximately 1000 additional beginning full-time Ph.D. students a year. The problem is one of attracting American engineering students into full-time doctoral study: the number of M.S. degrees awarded has climbed steadily from 4800 in 1949 to over 30,000 today and can be considered a structural feature of contemporary engineering.

The most commonly identified obstacle to increasing the American enrollment is financial. On the one hand, starting engineering salaries are typically more than three times graduate fellowship stipends. On the other, starting salaries for engineers with the Ph.D. are not enough higher than B.S. salaries to motivate the time, effort and lost income required to obtain it. In fact, in constant dollars, Ph.D. starting salaries are lower than they were 25 years ago. Furthermore, there is a widespread perception among engineers that the real success "track" in industry lies in management and that appropriate preparation for this is not the engineering Ph.D., but the M.B.A. As a result, recent studies of engineering education have called for raising the stipend for doctoral engineering fellowships, presumably only those offered to American citizens, to one-half the B.S. starting salary.

It is impossible to deny that money is a significant factor, but it may be only part of the explanation for the decline in American enrollment. There is no obvious basis for industry's sudden "appetite" for Ph.D. engineers in the 1960s and '70s. In some areas of engineering, the science-based modelling skills of Ph.D. researchers are useful in industrial research laboratory environments, but many non-Ph.D. engineers work in these environments as well, on the basis of expertise acquired through experience. Especially in the absence of student work experience, many B.S. engineering graduates are too eager to finally practice engineering, after four years of preparation, to begin school again. Furthermore, once at work the motivation to pursue the Ph.D. strictly on careerist grounds is not strong, given the lure of management (noted as long ago as the Wickenden report), the discovery that only a small fraction of engineers (about 5%) do research and the realization that non-Ph.D. engineers can participate at all levels of R&D.

The lure of the Ph.D. for Americans would seem to be largely intellectual. It is attractive to those for whom an academic career is attractive, and/or a career on the frontier of an engineering discipline. In both cases, the attraction is likely to be enhanced by having graduate engineering research emulate the interdisciplinary industry-related environment of state-of-the-art engineering research laboratories in government and industry. The creation by the NSF of Engineering Research Centers has the potential for accomplishing this, especially if they become models for other institutions with graduate programs than the small number designated. This should enhance the attractiveness of graduate research by making it more engineering than science, and of an academic engineering career by making the academic setting a more exciting place in which to do engineering. Such a development would appear to be more likely to be reinforced by raising stipends than the other way around, namely, that raising stipends alone will make academic or research careers more exciting.

(j) Foreign users of the U.S. educational system.

In the course of the late-1970s, as engineering Ph.D.s began a steady decline from a peak of 3700 a year to 2700, a sharp increase began in the number of foreign-born full-time graduate students, especially at the Ph.D. level. This pushed the Ph.D.s awarded back up to, and over, 3000, but by 1981 half of these were being awarded to foreign nationals.

In 1985, foreign-born students made up 47% of full-time M.S. enrollment and 53% of full-time Ph.D. enrollment at U.S. engineering institutions. These students provided 47% of the Teaching Assistants, 50% of the Research Assistants and 75% of post-doctoral Research Assistants. Over 80% of these students were from Asia, primarily eastern Asia, India and Pakistan, and the Middle East. A comprehensive survey of over 400 department chairmen [1987: Barber and Morgan] revealed no complaints about performance other than English language skills in teaching assignments. On the contrary, many chairmen reported that these assistants were more assiduous than American students and thoroughly satisfactory.

Teaching problems posed by foreign TAs with limited spoken English skills were exacerbated in the early 1980s by the sharp and unanticipated increase in engineering enrollment to historic highs of over 100,000 freshman each year. Together with engineering faculty shortages of approximately 10%, the pressure to use all available personnel with plausibly relevant skills was great. As the pressure eased with gently declining enrollments in the mid-'80s, so did the teaching problem, though requiring demonstrated mastery of spoken English on standardized tests is widely called for. That this is a minimal requirement is suggested by the fact that in the period 1981-1985, 45% of engineering faculty appointments in the U.S. went to foreign-born Ph.D. recipients. Given the nearly universal recommendation that demonstrated teaching effectiveness ought to be a criterion of tenure for engineering faculty regardless of research accomplishments, the fact that many foreign-born graduate students will go on to become faculty members makes an early demonstration of English proficiency on the part of graduate students a reasonable, if not a necessary, requirement.

Data on the career plans of foreign-born students who study engineering in the U.S. are, understandably, imprecise. Approximately 75% plan on returning to their home countries, but 2/3rds remain in the U.S. immediately after receiving the Ph.D. and approximately 50% seem to settle into careers here. Short of introducing a quota system to limit enrollment, it is hard to see how foreign graduate students could be controlled, nor is it clear why their numbers should be controlled. Their presence is a sign of the perception of the quality and the accessibility of technical graduate education in the U.S. That they carry away with them, sometimes abroad, possibly to competitor nations, technical knowledge that bears on improving industrial productivity would until recently have been considered a virtue rather than a vice.

(k). Foundational issues in engineering education.

i. The nature of the technical in engineering education.

What is the purpose of an engineering education and with what mix of technical courses is it best served? [A discussion of the place of non-technical courses follows.]

Through much of the nineteenth century, the answer to these questions was: to produce graduates useful to those entrepeneurs and institutions with a need for civil, mechanical and mining engineering skills. As the complexity of engineering projects increased, in these areas and with the addition of electrical, metallurgical and chemical engineering, the philosophy of engineering education shifted, from teaching directly usable skills to teaching the fundamental principles of a branch of engineering. At a time of rapidly changing technology, with the state-of-the-art constantly being redefined, practical skills taught in college were likely to be out of date not long after graduation. Fundamental principles, on the other hand, could generate new techniques as new problems were encountered [1955: Grinter; 1970: Forrester, in NAE].

This shift in philosophy went hand in hand with the introduction of training in mathematics, physics, chemistry and the experimental method as the basis of generic analytical skills that were then applied to specific branches of engineering. Always the engineering "heart" of the curriculum was design and the application of theory to practice, but as the 20th century proceeded, the analytical component of the curriculum expanded. By the Grinter Report of 1955, it was urged that engineering curricula rest on the engineering sciences, that is, the basic sciences and mathematics together with their adaptation to engineering disciplines. In a 4-year curriculum, this entailed restricting sharply the portion of the curriculum given over to a concrete study of the student's chosen engineering discipline as practiced. If it were possible, this could usefully have been the basis of a fifth year of study.

Through the 'sixties, the analytical-scientific foundation of engineering education came increasingly to dominate the curriculum. This growth was reinforced by the growth of engineering research and the migration of Ph.D. engineers into faculty positions. Concurrently, a consensus slowly began to grow that the engineering in engineering education was being sacrificed to a vision of science that was mistaken. Forrester [1970: NAE] argued that the focus of undergraduate education should be on the methodology of engineering problem-solving not on teaching analytical solutions. Ferguson [1977] called for the restoration of design to centrality in engineering education. Felder [1982] argued in detail how misplaced the emphasis on analysis was in the engineering curriculum and called for a return to a design perspective. The EEPUS report "Engineering Undergraduate Education" identified as the core of engineering education, engineering methods applied to realistic problems and processes, in preparation for which students should learn the scientific principles underlying engineering and their employment in a specific branch of engineering, but with the emphasis on engineering methods. Guy [1986: in National Congress] claimed that undergraduate engineering education needed to be rescued from the scientific research-based influence of graduate education. Schmitt [1986: National Congress] portrayed engineering education as having lost a sense of its proper relation to industry, a relation that could be restored if the curriculum moved from a theoretical focus to a focus on design that incorporated a realistic set of marketplace constraints.

ii. The place of the humanities in engineering education.

Almost from its inception, engineering education in the U.S. internalized a fundamental duality of character that it still carries and that, for the past 100 years, has complicated defining its mission [1977: Walker in NAS/NAE]. On the one hand, engineering institutions have claimed to provide for their students an education, rather than vocational training. This was particularly true after 1885, with the rapid spread of curricula basing engineering education on the laboratory, in place of the shop, and on mathematical-scientific, not experiential, foundations. After the Mann Report, it was essentially universal.

[It is suggestive to relate the Mann Report and its conclusions to a broad reconceptualization of professional education in the U.S., affecting medical and law schools as well as engineering schools and in similar ways: namely, that they needed to have formal, rigorous, scientific, curricula. The Carnegie Foundation funded the Mann Report and was influential in the contemporary Flexner Report that transformed medical education in the U.S. Mann himself urged educators to incorporate into the engineering curriculum project-based teaching modelled after the case study method just then being introduced into the Harvard Law school curriculum by Langdell.]

In a very large number of instances, engineering curricula were institutionalized within, or in explicit emulation of, liberal arts colleges. As a result, what "education" means in the phrase "engineering education" has always been subject to contemporary notions of liberal arts education. At a minimum, this carries with it vague notions of self-realization and -development, of "culture", values and "the world of ideas"; somewhat more precisely, at least some study of language, history, philosophy, literature, art and music. As a matter of fact, all engineering institutions have dutifully wrestled humanities, and social science, courses into engineering curricula although, as 70 years of reports on engineering education attest, without integrating them into those curricula.

While engineering institutions claimed to be educating their students, however, they made it clear that their primary commitment was to providing the technical training necessary for students to find and usefully fill a job immediately upon graduation. In the context of the continuously changing technology of the past century, this has required that the closest attention be paid to industry, overwhelmingly the largest "customer" for the student "products" of these institutions. And that, of course, makes the engineering curriculum seem to be driven by the kind of vocational orientation that is belied by the term "education" taken in its liberal arts sense [1969b:Perrucci and Gerstl].

Over the years, the rationale for crowding non-technical courses into curricula already filled with technical material has changed. Before the Mann Report, the justification for what came to be called the humanities and social science "stems" was extrinsic to engineering. For many, these courses provided a veneer of culture that was necessary if engineering students were to be counted among educated young men and women. After the Mann report, and doubtless reflecting the influence of Taylorite management science notions, a new rationale steadily grew. In order to occupy the managerial positions their technical expertise mandated (in an optimal production system), engineers needed a mastery of written and spoken communication skills and of the principles underlying business. Furthermore, as Mann insisted and Wickenden later argued at length, engineering intrinsically involved the blending of technical knowledge with constraints derived from the context of its application, including such constraints as costs and social, political and legal values.

As the 1920s and '30s unfolded, it became a commonplace to say that engineering was central to national prosperity, that engineering was a force transforming society and an enterprise closely linked to society as science, for example, was not. This served to reinforce the insistence that room be made in the engineering curriculum for the study of society, its values, institutions and processes, its history and its ideas, in order to engineer well. This rationale carried through from the Wickenden Report --"Social orientation bids fair to take an equal rank with scientific discipline as an essential basis of [the engineer's] training"-- and the Hammond reports of 1939 and 1944, to the Grinter and Burdell reports of 1955 and '56, and Lee DuBridge's report to President Eisenhower in 1959.

In the course of the 1960s and their anti-establishmentarian turbulence, the essentially social nature of engineering began to be asserted within the engineering community [1965: Engineers Joint Council; 1968: Goals; 1970: Beranek; 1975: Grayson; 1986: "Engineering Undergraduate Education"]. The hostile critics of engineering argued that engineering was a social enterprise and was therefore subject to social control. The friendly critics argued that engineering was an expression of social values and socially set agendas, and that it could be applied to the solution of social, no less than of corporate, problems if that was what society wanted. The 1968 ASEE report "Goals of Engineering Education" predicted that engineers would increasingly be called upon to solve social problems and they needed to know how to do that. The "engineer of the future...should be provided with a fuller and richer understanding of the social and economic forces that will influence and be influenced by his technology".

2. Professional Identification Issues.

(a) Counting Engineers.

How many engineers there are in the U.S. is a difficult question to answer. It is an important one, however, if we are concerned with whether there are enough engineers now and for the near future; and if we are concerned with identifying the population pool from which engineers are drawn. How many engineers there are today by comparison with how many there were at various times in the past 100 years is even more difficult, in spite of statistics telling us that the number of engineers doubled in every decade from 1880 to 1960 (from 7000 to 800,000) and then doubled again by 1985. In both cases, the difficulty derives from the absence even today of a precise definition of "engineer" and from changing conceptions during this time of who ought to be counted when counting engineers. (The NSF, for example, puts the current number of engineers at well over 2 million, while the figure generally found in the engineering education literature is approximately 1.7 million.)

The NAE report "Engineering in Society" [1986: EEPUS series] begins with an unambiguous criterion: some one is an engineer if they hold a degree in engineering from an ABET-accredited institution. This is unambiguous, but it does not conform to the facts of the workplace. It would, for example, exclude large numbers of physicists and still larger numbers of people without degrees at all, who by universal consent do engineering. The supplemental criteria that follow repair the exclusions, but at the price of fuzziness. Someone is also an engineer, the definition continues, if they are a professional-level member of an engineering professional society; or if they are licensed by a government agency as an engineer; or if their job classification implies that they routinely perform professional-level engineering work. The clear implication of this definition is that engineering, at least, can be identified unequivocally, that it can be distinguished from scientific work on one side and from "merely" technical work, however complex, on the other.

This is implausible on its face. The boundary between engineering and science is vague and constantly shifting. More than half of all B.S. graduates in physics who take industrial jobs are classified as engineers, as are smaller but still significant numbers of chemists and mathematicians. Recent developments in opto-electronics and superconductivity suggest that this situation will at least continue. In the not too distant future, it is probable that biology graduates will have job classifications as engineers in a wide range of biotechnology industries and, if cognitive science and artificial intelligence research develop as enthusiasts predict, so might psychology graduates, in the commercialization of expert systems technologies. Indeed, this situation already exists, but it is sufficiently unusual, given current conceptualizations of engineering, and the scale is still so small, that professional identification is not yet an issue. The separation of chemical engineering from chemistry in the early twentieth century, as chemical process industries grew dramatically in size and number, may be a model for developments in biology and psychology.

The other side of this coin, so to speak, is that in many areas of physics, chemistry, biology and applied mathematics, people whose job descriptions imply that they are doing science or mathematics in fact are doing work whose application-orientation would ordinarily qualify as engineering work if the scale were larger, or if the same work were integral to the production of a commercial product. This strongly suggests that the border between science and engineering is far from well-defined. Technological innovations and venture capital have the potential to "convert" large numbers of scientists into engineers as commercial opportunities overtake research and development activities.

The border between engineering and technical work performed by non-engineer skilled workers, is still more amorphous. Historically, it has only been since World War II that the majority of people employed as engineers had college degrees. As the number of engineers with degrees increased, the kinds of technical work --for example, building, maintaining, modifying, supervising, and even designing complex machinery-- that qualified as engineering changed accordingly. In almost all cases (durable goods manufacturing and facilities maintenance for utilities are partial exceptions), the borderline shifted in the direction of skills associated with formal schooling. [An analogous situation developed in physics, where applied and experimental physics were steadily forced to incorporate more and more theory, in order for practitioners to retain professional identification as physicists.] During the "Golden Age" of American engineering, from the late nineteenth century to the depression of the 1930s, only a minority of people employed as engineers had engineering degrees, yet as the number of degreed engineers increased, the same kind of work that had been characterized as engineering and performed by people whose credentials were skills based on experience, was either appropriated to degree-holders or re-classified as craftsmanship.

The implications of these observations for the size of the engineering work force, and its potential for growth, are manifest. Such considerations should complement the collection of engineering manpower data, which is itself in disarray. A 1973 NAE report, "Engineering and Science Manpower", recommended continuous and uniform data collection permitting the creation and monitoring of a profession-wide "flow diagram" that would provide an accurate description of the present and at least near-term future manpower situation. Episodic and non-uniform data collection abounds: by the NSF, in a valuable longitudinal survey, for the period 1970-78, "Employment of Scientists and Engineers", in its Professional Manpower Survey, and in a graduation survey, Resources in Science and Engineering; by the Bureau of Labor Statistics in its Occupational Employment Survey; by the National Research Council, the Bureau of the Census, the Engineering Manpower Commission, and the National Center for Educational Statistics [1986: Infrastructure].

In the early 1980s, the NAE Committee on the Utilization and Education of Engineers, which recommended and oversaw the creation of the nine-volume series Engineering Education and Practice in the United States [1985/6], developed a flow diagram for the engineering profession and a simulation linked to systematic uniform data collection. Implementing this was one of the major recommendations of the EEPUS reports.

(b) Utilizing engineers.

How engineers are utilized, especially in industry, is significant for dealing with anticipated shortages or surpluses, for engineering education and for engineering professionalism.

Between 75 and 80% of all U.S. engineers are employed by industry. Of these, only 5-7% are employed to do research, while over 20% enter management. The majority are employed (in descending order) in development and design, planning and supervision, production, and sales. Approximately 12% of engineers work for government agencies at all levels: 6% for the federal government in institutions ranging from regulatory agencies to the over 700 federal laboratories. Academic institutions employ 4% of engineers. The remaining 5-9% are self-employed or employed in advising and consulting work.

It is estimated that 22% of people holding degrees in science or engineering work outside of science or engineering, exclusive of engineers whose careers shift from engineering to management within industry. Roughly one-third of all scientists and engineers are employed in defense-supported enterprises in government and in private industry, but recent studies have concluded that the current increase in defense-related employment has not drained engineers from the "civilian" sector [1986: "Impact of Defense Spending"]. Together with the weakness of starting engineer salaries, in constant dollars, compared to 1962, this is another indication that there is no evidence in the marketplace of an overall shortage of engineers. This is confirmed by the figures published by the Job Offers Index of the College Placement Council as well as the High Technology Recruitment Index of Deustch, Shea and Evans, Inc.

As of 1969, over 70% of all U.S. engineers were employed by just 1% of the companies (including government) that employed engineers. At the same time, 300 of the firms employing large numbers of engineers accounted for 80% of all industrial research, 60% of the sales of manufactured goods in the U.S. and 61% of total manufacturing employment [1969a: Perrucci and Gerstl. This concentration of engineers in a relatively small number of very large enterprises that dominate the manufactured goods sector of the economy, if still valid today, bears directly on the dynamics of engineer employment. It suggests a substantial slack in the engineering employment system such that more efficient utilization could overcome short-term market shortages of engineers, the existence of a large pool of experienced engineers that can be tapped by new small companies that need immediate expertise, and the constant prospect that a large number of engineers are at any given time candidates for retraining [1986: "Impact"].

(c) Distinguishing science and engineering.

i. The engineering method.

There is an overwhelming consensus among writers on engineering education that the engineering method is fundamentally different from the scientific method. Where the latter is essentially analytical, the former is based on design, expressing a synthesis of general theory and specific technical knowledge with relevant pragmatic judgements of workable means of achieving predetermined objectives.

Oboukhoff [in 1944: Proceedings] argued that science was incapable of generating a solution to an engineering problem. Science was abstract and Platonic where engineering was concrete and Pragmatic. Koen [1985] argued that the engineering method was fundamentally unscientific, resting on the use of heuristics that were fallible, not justifiable scientifically and not unique. They were one engineer's (or group of engineers') best educated guess at one way to solve the given problem in the terms posed. Layton [1984] argued even more forcefully that the "universe of design" was open-ended and indeterminate, non-scientific and permeated with values. Designs were in principle non-unique and the method for generating designs was non-algorithmic, but rather a chain of decisions each of whose links was a value judgement. "From the point of view of modern science, design is nothing, but from the point of view of engineering, design is everything" [1976: Layton].

"Design means thinking out plans for accomplishing actions that always permit alternative combinations. There is no deterministic or scientific way to design a machine...design is never fully subject to logic or rule" [1983: Hindle]. But neither is design monolithic. It differs in different branches of engineering [1986: Vincenti]. Nevertheless, technological innovation necessarily "depends on the relatively unstructured conceptual activity" of high-level managers translating "often ill-defined commercial or military needs into a concrete technical problem for the level below" [ibid]. The design problem acquires specificity through a process of interpretation that mirrors Layton's metaphor of design as a chain, each of whose links is a value judgement. Only at the lowest level does the individual engineer encounter a well-defined, well-circumscribed problem to which technical knowledge can be directly applied. But even there, the most obvious technical solution may not match expectations at higher levels of what the solution needed to accomplish given a broader perception of the problem, leading to its return for re-engineering.

For others, "the essence of engineering is not design [but] the application of engineering judgement" [Louis Guy: 1986 National Congress; also, 1944: Proceedings, essays by Young and by Everitt]. It is the fact that engineering design is an open-ended form of problem-solving, one with no uniquely correct solution, that gives engineering its character and defines its creative dimension [1970: Beranek; 1985: Koen; 1984: Layton; 1977: Ferguson]. What constitutes a solution to a particular engineering problem is not a statement about the way the natural world is, as it would be in the case of a scientific problem. It is instead a statement about the context within which a proposed solution is judged to be satisfactory, or not.

The "solution space" of engineering design problems, then, is defined by the interests of the (actual or projected) client for whom the design exercise is being carried out, together with the available technical knowledge base: from formal theories of matter and energy to machining capabilities. Scientists, by contrast, pursue patronage but, even for the radical sociologists of scientific knowledge, do not explicitly factor into the solutions they propose to scientific problems the expressed demands of their patrons, or of their peers.

ii. The value-laden character of engineering practice.

The consequences of these contrasting "solution spaces" for the practice of engineering as distinct from the practice of science are profound. Values are revealed to be an ineluctable concommitant of engineering practice, manifesting themselves in the social relations of the institutions through which engineers and the public interact. The study of values and of the ways that values enter into and shape engineering practice thus find a natural place, in principle, in engineering education. [This is not a tendentious interpretation. It is explicitly argued in Mann, Wickenden and Hammond, Grinter and subsequent ASEE reports, Grayson [1974], the EEPUS reports and many, many others. It is one of the staples of the engineering education literature, in spite of the fact that it is virtually ignored in practice.] By contrast neither the social relations of scientific research institutions, nor the study of the flow of values-based influences between science and society are acknowledged by the scientific community as a whole as relevant to the study or practice of science.

The EEPUS study "Engineering Undergraduate Education" [1986] called for building into the undergraduate curriculum an "understanding of social and economic forces and their relationship with engineering systems, including the idea that the best technical solution may not be feasible when viewed in its social, political or legal context". Louis Guy, speaking at the 1986 National Congress for Engineering Education, said: "It is not enough for engineers to know how to do the thing right; we must also know what is the right thing to do. Otherwise our education has failed us."

Both the EEPUS study and Guy were echoing William Wickenden who wrote, in 1934, that the engineer was a social pragmatist who followed the "apostolic injunction, `Test all things; hold fast to that which is good'", but for that very reason needed to "formulate some scale of social values in order to judge what is good". Simply accepting prevailing values uncritically, Wickenden wrote, meant reducing the engineer "to a mere servant of vested interests".

The integration of teaching about values into the engineering curriculum remains, 70 years after the Mann Report, in the realm of recommendations and proposals. It is also the widespread opinion of critics of engineering education that the teaching of design has suffered greatly in the last thirty years and the two may be related.

Design has been subordinated to the teaching of more and more analysis and the undergraduate engineering laboratory has increasingly become the scene of mechanical exercises instead of an encounter with something like a "real world" engineering design problem. This retreat from design as the centerpiece of engineering education is perhaps related to the degree to which the (ostensibly) value-free character of science has been a model for engineering. Design cannot be taught in a value-free way. What distinguishes design from analysis are, precisely, the arbitrary constraints on its "solution space" that derive from the values underlying its objectives: arbitrary, at any rate, from the perspective of a value-free scientific approach to problem definition and solution. But "chaos results when design is assumed to be primarily a problem in mathematics" and if courses in design are simply dropped from the curriculum, as they have been, then "we can expect to witness an increasing number of silly but costly errors that occur in advanced engineering systems" [1977: Ferguson].

The intentionality of engineering practice, the fact that the formulation of an engineering problem entails internalizing a value-laden set of criteria from outside the technical knowledge base of the engineer, manifests itself in different ways. Brooke Hindle observes that, historically, invention has always been responsive to needs "but it often looked for the need after a possible invention had arisen in the mind" [1983]. This can lead to the expenditure of considerable energy and resources on crystallizing the perception in others of a need that will be satisfied by the invention: a case in point is the consumer video-cassette recorder. When new values are internalized, engineering solutions to "the same" problems change, as described by Kemp in the context of highway design controversies in the 1960s [1986: in "Technology and Culture"]. But, of course, designing a highway between two cities is not at all the "same" problem if the engineers do/do not take into account non-user, alternative use and environmental values when performing a cost-benefit analysis.

Finally, perhaps the most radical-sounding response to the recognition that the foundations of engineering are in design and that design is value-laden, is Paul Goodman's argument that engineering is, properly, a branch of moral philosophy, not the "fruit" of science as many, especially scientists, continue to depict it. Engineering is a highly deliberate form of action. As such, it needs to be guided, as all human action must from a moral perspective, by the criterion of Prudence which is a synthesis of forethought, caution and utility. The contrast with science implied by this is total. Where the objective of science is explanatory knowledge, which may or may not have implications for our personal and our social values, for our self-conception and our ways of living, engineering is always linked to action and thus to prevailing notions of how to act [1944:Oboukhoff, in Proceedings].

iii. Engineering and science as two types of knowledge.

The essence of engineering is widely claimed to lie in (though it may not be identical with) design and the exercise of engineering judgement. One consequence of this characterization is that engineering is different from science in that both the formulation and the solution of engineering problems are explicitly contextual and value-laden enterprises. The centrality of design further distinguishes engineering from science as two different kinds of knowledge.

Layton [1973 and 1984], Ferguson [1977], Hindle [1983] and Billington [1984] argue that spatial thinking, visualization, synthetic thinking that is intellectual but neither discursive nor mathematical, and emulation are fundamental to engineering problem-solving. Indeed, Grinter [1955] had already urged an emphasis on graphics in engineering education because of the centrality of visualization in engineering thinking.

Technology is its own kind of knowledge, not simply applied science [1973: Layton]. Where engineering seems to be to science as the specific is to the general, this is only superficial. In fact, engineering assimilates scientific knowledge, transforms and extends it in its own characteristic way and to its own ends. That technological knowledge is derived from scientific knowledge "is a bit of modern folklore that ignores the many non-scientific decisions...made by technologists as they design the world we inhabit [1977: Ferguson; 1980: Forrester, in "Issues"]. The current model of the relationship between science and engineering is rooted in a persistent ideological interpretation of science promoted in America first by Joseph Henry and then by Vannevar Bush. Attempts by engineers to argue different models have proven ineffective [1976: Layton].

Science takes as its subject generalized idealizations of natural objects and processes, which gives scientific knowledge a necessary character. Engineering takes as its subject man-made and thus contingent objects and processes. Scientific knowledge is compact, general, solvable and formal. Engineering subordinates all of these to local judgements of functional solutions to its problems. The world of the engineer is much more complicated, because much more concrete and specific, than the world of the scientist. So much so, that it is not merely poetic to say that the engineer and the scientist perceive different worlds. As a result of using the world differently, they come to know it in different ways and can thus be said to perceive it differently, even when ostensibly looking at "the same" thing.

To be sure, in practice science and engineering do not merely overlap, but are mutually interpenetrating. The scene of this interpenetration is the interdisciplinary industrial R&D laboratory, which Layton calls the "most significant institution for modern technological development". The flow of their characteristic forms of knowledge between physicists and electrical engineers is described by Bromberg [1986] in relation to early research in masers and lasers, and between physicists and aeronautical engineers by Vincenti in relation to volumetric analysis [1982] and aerodynamic theory [1986]. But, on the basis of this interpenetration, to assume the underlying identity, or even the continuity of science and engineering "involves a conflation of form and substance". Engineering science "often differs from basic science in important particulars. Engineering scientists often drop the fundamental ontology of natural philosophers, though on practical rather than metaphysical grounds" [1976: Layton].

iv. Engineering and science as distinct cultural communities.

The upshot of these elementary distinctions between the practices of science and engineering, distinctions which are captured in the notion of design and its implications, is that science and engineering are institutionalized differently and thus constitute distinct communities. These communities have their own reward systems, their own societies, their own journals, their own values, languages, rituals and beliefs [1969b: Perrucci and Gerstl; 1976: Layton]. The engineering community, as it developed in the late 19th and early 20th centuries imported values and norms from the scientific community. These were incorporated into the reform of engineering education that then took place, basing it on mathematics, scientific theories and laboratory experimentation, and into at least the form and the rhetoric of engineering professional societies and journals.

The spread of these norms and values within engineering education and, especially in the 1960s, within engineering research has progressively restricted dealing with engineering as practiced, with the "art" of engineering, in the undergraduate curriculum. Part of the reason for this would seem to be the transformation of the engineering faculty in the period after 1960. Faculty appointments have since then shifted almost exclusively to Ph.D. holders, a situation made possible by the explosive growth in the number of Ph.D. degrees awarded. This growth, in turn, was made possible by the enormous sums of federal R&D money available at that time. [The decline in the number of American Ph.D. students after the early 1970s correlates well with the decline in federal research money.] As a consequence, engineering research emerged as a fundamental feature of engineering practice, but one that was strongly influenced by the prevailing physical science-based research norms and values. This is now perceived to have created a conduit for a further scientization of the engineering curriculum at the expense of traditional engineering values, in particular, of the relation of engineering to industrial production [1982: Felder; 1986: Roland Schmitt, in National Congress Proceedings].

Science-based values underlie a persistent but mythic professional image of the engineer that also has a negative impact on engineering education, namely, the folklore of the engineer as an autonomous individual. The reality is that the overwhelming majority of engineers, approximately 90% of them, are either corporate or governmental employees. In either case, they are locked into bureaucratic structures which define and limit in terms of institutional objectives the impact that the engineers' technical knowledge can have. Meanwhile, the strong scientific cast of engineering education, together with popular depictions, combine to create an image of the engineer as an autonomous individual analogous to a master architect, that is, an expert in control of the form that the application of their expertise will take [1981: Forrester].

Related "primordial but mythic" professional images of the engineer are those of the engineer as the agent of social change in modern societies and thus responsible for progress and national well-being, and of the engineer as a logical thinker, free of bias and thus, like the scientist, non-ideological. The non-unique and necessarily value-laden character of engineering analysis and design reveals the vacuity of depicting the engineer's thinking as logical in the commonly understood sense of the term and as free of bias. That engineering is indeed ideological is arguably a consequence of its appropriation to the objectives of the institutions whose interests it serves. A corollary of this subordination of technical knowledge to the context of its application is that it is a mistake to identify either science or engineering as agents of social change and progress. Instead, the true agents of social change are the institutions that selectively employ technical knowledge to achieve objectives deriving from the perceived best interests of those institutions. The key to understanding technology-related social change, then, is the value-structure of managerial decision-making in institutions that employ technical knowledge as a means [1984: Goldman]. The further determination of which changes are to be identified as progressive is a judgement whose roots would appear to lie in the relationship between social values and the values operative in the institutions effecting social change.

(d) Distinguishing science and engineering education.

A summary of the preceding comments on the distinctiveness of science and engineering as professional practices, in spite of their functional interpenetration, suggests the following:

science education is fundamentally analytical, that is, analysis is integral to the explanatory end of science;

the content of science education is driven by the prevailing conceptual framework and theoretical models, which dictate the tools and skills that students as potential practitioners need to acquire;

science education instills in students a conviction that the object of scientific inquiry impersonally determines the correctness of solutions to scientific problems;

engineering practice is substantially dependent on scientific analysis, but only as a means to an end unique to engineering, namely, generating context-dependent solutions to engineering problems;

engineering education must include acquiring the necessary analytical skills to practice engineering, but should subordinate them to the exercise of engineering judgement as the essential "art" of engineering;

engineering judgement is only teachable through design exercises which have the potential to communicate the non-algorithmic, creative, thinking characteristic of engineering at its best;

a thorough understanding of engineering judgement and design entails understanding the contextual determinants of engineering problem specifications and acceptable solutions, which requires integrating into engineering education the value structure of the relationship between engineering practice and its social context;

on balance, "analytical courses have proliferated at the expense of courses attempting to teach design" [1977: Ferguson; 1986: Nam Suh, in National Congress Proceedings] and have had the effect of uncoupling undergraduate engineering education from the industrial context within which its graduates will practice;

re-introducing design courses and/or project-based teaching using close to "real world" projects and constraints (on solutions), also an expansion of cooperative education programs or a work experience requirement for graduation, would return the focus of engineering education to engineering;

engineering education would benefit from a requirement that faculty have significant practical experience, in industry or an industry-related R&D laboratory, as a result of which they would integrate into their teaching an appreciation of the application-contexts of engineering practice.

3. Engineering, Technology and Competitiveness.

Engineering, technology and the strength of U.S. industry are clearly connected, though the nature of the connection is far from clear. Mann had called for closer ties between industry and American universities because increased production had become (by 1918) a national necessity. The newly created industrial research laboratories, he said, made it desirable to link academic expertise to industry's needs through the medium of engineering research [excellence at which he thought an equivocal criterion for faculty appointment!]. Wickenden wrote that the engineer had wrought an overwhelming revolution in social institutions, and that the Great Depression had made society see in the engineer the "controlling hand in the whole scheme of economic production".

Forty years later these sentiments were still to be heard [1969b: Perrucci and Gerstl: "...engineering has indeed become a revolutionary force in society; 1972: Carter, "Engineers are the keystone of our industrial structure"], but they have been challenged with increasing vigor in recent years [1977: Layton]. It is not engineering that drives social change, but rather the institutions that use engineering, and science, selectively, in pursuit of institutional objectives. The dominant factor in this process of translating technical knowledge into products and processes is managerial decision-making [1982: Outlook; 1984: Goldman; 1986: Guile; 1987: Guile and Brooks].

The term "managerial" is used somewhat idiosyncratically here, to refer to executives and civil service bureaucrats whose decision-making activities are guided by policy objectives in whose formulation they may or may not have played a role. The crucial element is the internalization of policy and the subordination of technical expertise to it. Vincenti [1986] wrote of the increasing specification of engineering problems as they moved down the managerial hierarchy. At each level, the responsible manager interpreted the broader objectives of his or her superior and specified in terms relevant to their sphere of responsibility and expertise how their subordinates were to realize them. These policies determine to a considerable degree what technical knowledge is available to an institution and how it is to be used.

It is increasingly recognized that technical knowledge by itself does not play a decisive role in a nation's industrial strength or competitiveness in international trade. "The belief that scientific preeminence goes hand in hand with technological leadership is clearly false" [1979: Outlook]. "The ability of a nation to generate technological advances is insufficient by itself, and may not even be essential for improving the national competitiveness position" [1987: Guile and Brooks]. While the technical infrastructure of skilled workers, engineers and scientists is of major significance, micro- and macro-economic factors including interest rates, tax structures, currency exchange rates, capital costs, domestic technology transfer rates and manufacturing improvements are of at least equal significance [ibid].

This list does not even allude to the formulation of company policies, upon which the listed factors impinge as relevant boundary conditions. The decision by SONY management to create a consumer appliance out of the video recording technology invented by Ampex is a case in point. So are the decisions by CBS to pursue instead a photochemical video image storage process invented by Peter Goldmark, or the RCA decision to pursue a proprietary playback-only videodisk technology (on the ground that consumers would not find video recording all that attractive). CBS could not bring its technology to the marketplace and the RCA videodisk failed in the marketplace, generating combined losses well over $100 million. In the end, American manufacturers, who certainly possessed the engineering expertise, in principle, to market a videocassette recorder, had to settle for putting their names on machines manufactured by the Japanese.

Layton [1977] cites an OECD study that concluded that from 1945-1970, the period during which America dominated world trade, the U.S. edge was not in invention, but in market-oriented innovation, precisely what many see as the Japanese edge now. This conclusion is reinforced by the NSF Hindsight study (for DOD, but contradicted by DOD's own TRACES study) which found little support for direct connections between basic research and marketable products, and research such as that by Walker and Hollander, which found that, much more often then not, productivity improvements at U.S. Steel and DuPont plants they studied either came from workers or were bought from outside inventors.

Lehnerd [1987: in Guile and Brooks] offers another view of how managerial decisions, not the technical knowledge available to the managers, determine innovation. Black and Decker power tools were a classic set-up for "victimization" by foreign manufacturers imitating their performance at lower production costs. The Black and Decker line had grown over decades without systematic engineering rationalization of functionally identical or related components in different models. Management decided to make the investment in such rationalization and set their engineering staff to the task. The result was profitability in the wake of enormous reductions in labor costs, time of assembly and raw materials and energy used.

This is just one illustration, but it is being repeated in many variants almost daily in the popular and professional business literature. This is not to deny the persistence of the counterpoint, that preeminence in science and engineering is in fact the key to competitiveness [1982: Outlook; 1986: Federal Actions; 1987: Merrifield, in Guile and Brooks]. It is, however, difficult to take this literally given the success of the Japanese and the fact that we ourselves, in the recent past, succeeded in exploiting technologies developed by others, most notably by the British: for example, printed curcuits, jet engines, the turbojet passenger 'plane, continuous steel casting, nuclear magnetic resonance machines. Given the very strong prejudice in England and America for science and against engineering --one manifestation of which is science teaching in elementary and high school and science requirements in college, but not engineering -- it is perhaps not surprising that people cling to the notion that engineering excellence is dependent on excellence in basic science, in spite of evidence to the contrary.

The extent to which science drives engineering, and the rate at which knowledge is transferred between the two, is a function of managerial policies, if only because engineers are, overwhelmingly, employees of managers. At both ends, then, in relation to scientific research and in relation to commercial product or process design and development, how engineering resources are to be allocated would appear to play a central role in innovation. Possessing resources by itself has no such implications, if management decides to pursue profitability elsewhere, as RCA did when it bought CIT Financial Services with capital that could have built a vcr plant, or then-U.S. Steel when it bought Marathon Oil with capital that could have been invested in steel making.

Even a commitment to using engineering resources does not mean that the outcome will be determined by the expertise available. The IBM PC was not a reflection of the capabilities of IBM engineeers and that computer model's enormous success had far more to do with marketing strategies than technical performance. Again, Tracy Kidder's Soul of a New Machine reveals how the design of Data General's first 32-bit minicomputer was driven by management's interpretation of market expectations and then constrained by managerial decisions that limited what the design engineers were permitted to do.

In general, it seems reasonable to conclude that ignorance of engineering, of its relation to basic research on one side and to technological innovation on the other, together with a misestimation of the role played by managerial policies in affecting all three, underlies glib claims that more engineers and better engineering will resolve America's current "competitiveness crisis". Guy [1986: in National Congress Proceedings] claimed that America's competitiveness problem stemmed from the movement of non-engineers into industrial management, but this is surely simplistic. If engineers move into management but in the process "put on their managers' caps", that is, internalize the prevailing value-structure of managerial decision-making, there is little reason to believe that anything will change. The teleconference exchange among Thiokol engineers and managers the night before the Challenger explosion gives pause for thought that this is indeed what happens customarily. Layton had long since concluded that when engineers moved into management they shed their identification as engineers. More generally, engineers have a strong reputation for identifying with their employer's objectives even while still functioning as engineers [1986: Florman, in "Technology and Culture"]. Sinclair [1986: ibid] showed the prevalence of this phenomenon 50 years ago in his review of a satire performed in 1933 by the Engineers Club of St. louis, "Everyman an Engineer", though it is clear from Layton [1971] that this was true almost from the creation of the engineering professional societies.

However the competitiveness problem is to be solved, then, it is extremely improbable that it can be solved simply by producing more or better engineers (whatever "better" means in this context). Given more engineers and/or more engineers trained in design and industry-sensitive engineering problem-solving, then if management utilized engineers more effectively there would likely be an impact on productivity and innovation. Of course, there is reason to believe that a great deal could be accomplished just with the pool of science and engineering talent already available, if it were applied more effectively to relevant tasks.

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