Today's Engineering Education at Carnegie Mellon—Innovative Yet Reflective of our History

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Abstract

The disciplines represented in many engineering colleges have their roots in the industrial needs at the end of the 19th century. Architectural, chemical, civil, electrical, mechanical or metallurgical engineering *practice* were typical engineering courses. Those names may sound familiar in today's engineering schools, but it is unlikely that an Institute of Technology student from the early 1900's would recognize significant aspects of Carnegie Mellon's engineering curriculum. It is not just the "tools" and the labs engineers use that would be unrecognizable, but the curriculum structure, too.

A century ago, engineering education meant training technologists in specific disciplinary specialties, where technical requirements crowded out classes in science, humanities and social science. As industry's needs changed during the Great Depression, engineers who were narrowly trained often failed to find employment outside their fields. The challenge was to *educate* students to become engineers, and not to merely train them. By the 1940s, radical curricular changes such as the Carnegie Plan were transforming engineering education. The ultimate goal was to teach engineers problem-solving skills, how to apply those skills in the context of larger social issues, and to understand the impact of technology on society. This approach, combined with an interdisciplinary climate, has been a driver of curricular change at Carnegie Mellon.

This paper will explore circumstances leading up to the transformation of engineering education at Carnegie Mellon 60 years ago and illustrate how this information is of value to today's educators. Throughout this paper, Civil and Environmental Engineering is used to illustrate the curriculum changes over a century. Emphasis will be placed on an emerging pattern of issues, including: preparedness of students, the necessity of practical hands-on experiences, the need to balance technical knowledge with humanities and social science knowledge, and how to prepare for a career where technology changes require constant upgrading of skills.

Professional Education for Engineers

> "The aim of professional education at Carnegie Institute of Technology is to equip students to go on learning after graduation and to grow throughout their

lives in professional and personal stature and in usefulness as citizens. Carnegie does not seek to *train* students to *be* professional practitioners at graduation but rather to *educate* them so that they will *become* professional men[1] of full stature.

. . .as the study of engineering advances, the scientific, the technological, and the social relations aspects of learning increasingly merge into learning to deal with complex problems as a whole." [1]

This quote could easily describe the engineering education philosophy in the 2004-05 undergraduate catalog. Surprisingly it is actually quoted from the introductory and concluding paragraphs of a visionary plan for engineering education published in 1949. The Carnegie Plan of Professional Education in Engineering and Science, initiated in 1936 by President Robert Doherty, represented a revolution in engineering education.

Doherty's vision for liberalizing professional education for engineers focused upon the fundamental need for content to be useful in later learning, rather than upon the amassing of particulars of knowledge and technique that can better be learned at the time of use. Doherty based his curriculum on the belief that understanding how to apply knowledge and the ability to communicate ideas was essential for professional engineers.[2] He believed that a successful engineer's growth in professional stature involves growth in stature as a human being and as a citizen.

As stated by Doherty, instruction is planned to help each student acquire:

- thorough and integrated understanding of fundamental knowledge in fields covered and the ability to use this knowledge;
- competence in analytical thinking to reach sound, creative conclusions;
- ability to learn so that after graduation the student will be able to grow in wisdom and keep abreast of the changing knowledge and problems of the profession;
- breadth of knowledge and sense of values which will increase understanding and enjoyment of life and will enable graduates to recognize the human economic and social problems of professional work [2]

Almost a century later, a National Academy of Engineering (NAE) report on revising undergraduate curricula to meet the needs of engineers in 2020 lists similar attributes:

> ". . .the engineering curriculum for 2020 so as to be responsive to the disparate learning styles of different student populations and attractive for all those seeking a full and well-rounded education that prepares a person for a creative and productive life and positions of leadership." [3]

The attributes identified by the NAE include analytical problem-solving skills, creativity and practical ingenuity, excellent communication skills, business management skills combined with

[1] The only contemporary change to this quote would be adjusting it for gender inclusive language. Women were not admitted in engineering until the early 1940s, but were admitted to the College of Fine Arts and the Margaret Morrison Carnegie College in the Bachelor of Science program . In academic year 1947-48 only 3 women were studying engineering.

leadership, high ethical standards and a sense of professionalism. Engineers of 2020 must engage in life-long learning not just because of the pace of technology development, but because successful careers will require knowledge of history, politics, business in a global marketplace.

Doherty applied his Carnegie Plan to the existing engineering curriculum that had evolved from the school's trade-school origins. The 120 members of the charter class of 1905 at the Carnegie Technical Schools enrolled in programs leading to three-year diplomas in the fields of architectural practice, chemical engineering practice, civil engineering practice, electrical engineering practice, mechanical engineering practice, and metallurgical engineering practice. (Those disciplines would map directly into the engineering disciplines a century later in Carnegie Mellon's engineering college.)

In 1912, the technical schools became a four-year degree-granting institution offering bachelor's and master's degrees. The early engineering curriculum was characterized as hands-on technical training in courses taught by faculty who were often practitioners.

The 1919-20 first year curriculum only included 12 hours in current issues and English, and Economics; in subsequent years, the Civil Engineering curriculum included 6 hours of modern language. The remainder of the curriculum was restricted to requirements in technical courses including fundamental math and science, mechanics, materials, surveying, hydraulics, structures, reinforced concrete, and 2 management courses, corporation operations and management, and a course in construction and estimating.

By 1928, engineering students faced a daunting array of technical course requirements leaving no room in the curriculum for additional humanities and social science courses. Carnegie Tech was training technologists rather than educating engineers. By 1929, engineers who were narrowly trained often failed to find employment outside their fields. [4]

Impact of the Carnegie Plan in Curricula from 1940-Today

It took until the appointment of Carnegie Tech's President Robert Doherty in 1936 before serious curricular reform was implemented. Doherty's *Carnegie Plan for Professional Education* emphasized an understanding of the fundamentals of science and engineering, creative problem-solving, and an appreciation of the humanities. The plan was inspired by Doherty's experience at General Electric, and his observation that colleges and universities were failing students by not educating them in problem-solving skills. Under his leadership, (it took over a decade), new courses in humanities and social leadership were added to the engineering curriculum. Engineers were educated to develop creative and analytical abilities.

The Carnegie Plan was significant not just because it emphasized problem-solving, but because it emphasized the need for engineering students to possess problem-solving skills in the context of larger social issues and to understand the impact of technology on society. In 1940, all first-year students at Tech were required to take a common curriculum that included humanities courses.

> “A *man*[2] who has spent fours years in college largely in acquiring information and in learning techniques is under a discouraging handicap if later in the crowded hours of professional practice, and without a guiding discipline, he must learn how to think for himself.
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> Professional work in engineering and science involves much more than exact mathematical application of engineering formulas or even of scientific principles. In so far as an engineer or scientist does truly creative work he must solve problems for which no formulations have been devised and make judgments from scientific principles in situations where mathematical manipulations cannot indicate the full solution. Even in less creative work he must deal with the materials and forces of the real world, and these do not coincide exactly with the abstractions of pure science. Again and again the professional scientist or engineer must work with intangible factors, and alternative and even speculative hypotheses.
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> An exclusively scientific and technological education would tend toward a narrowness of mind that would be a handicap in professional engineering work, even in its technological aspects. It is therefore important for the engineering or scientific student to take courses which expand his opportunities to learn how to think his way out when in his professional work he is faced with perplexities to which no existing formulations give means of solutions.
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> As an engineer or scientist attains professional stature and rises in his profession he must increasingly deal with people. As he becomes more important in his community he must assume greater responsibilities of citizenship. The social relations program is therefore also designed to assist the student to learn how to express himself effectively to others and how to apply to problems of dealing with people and with human institutions the engineering orderliness and thoroughness of thought. Finally it is designed to give him habits of appreciation and enjoyment of good reading, music or art which will assist him to enrich his life and broaden his understanding.” [1]

By 1945, Tech faculty were writing papers on the new curriculum and their assessment of its impact, and in 1948, faculty volunteered to evaluate their strengths and weaknesses in the classroom by having students complete rating sheets, a precursor of present day course evaluations.[4]

Further refinements to the plan are documented in the 1954-55 undergraduate catalog, which describes the aim of professional education in engineering science and management as teaching students to think and to equip them to grow throughout their lives in professional and personal stature and in usefulness as citizens.

[2] See footnote 1, italics added by authors

The catalog noted that the customary method of teaching engineering had been to present technical facts and to drill the student in calculation, manipulation of formulas and in following established procedures. But a fast-changing world caused much of the information thus acquired to soon go out of date. No four-year college program can give students all the information that they will need in the future. If engineers thoroughly understand basic principles and have the ability to use this knowledge, they will able to address unforeseen problems in the future. [5]

Goals of the curriculum in 1954:

- understanding of fundamental knowledge in a technical field, dealing with people and government;
- skill in independent analytical thinking, which enables effective decision making;
- commitment to life long learning;
- ability to communicate ideas

The catalog noted that Civil Engineering was moving from craftsman's art to "art-science" and that it takes more than mastery of science and technology to be an engineer. It went on to state that successful engineers should have a practical sense of what ought to be done and why, who can do it, how it should be done, when it should be done and at what cost. The 1954 engineering curriculum required nine courses in Humanities and Social Science, but did not allow students to choose any electives. By1964 the curriculum did include one technical elective.

By the 1970s, Carnegie Mellon's undergraduate catalog described the excitement (and challenge) for professionals in engineering and science. As the rapidly expanding context in which technical problems must be considered, it was acknowledged that a host of social, economic, and environmental considerations also enter into engineering problem-solving. As social and technical problems become more complex and their solutions become more interdisciplinary, engineering education must include non-technical subjects. Thus, the traditional degree programs began to include opportunities for students to choose among electives. The engineering college also introduced new dual degree programs between the traditional departments and the newly established department of Engineering and Public Policy. [6]

The 1980's curriculum included a minimum requirement of 8 Humanities and Social Science or Fine Arts courses. In addition, students in Civil Engineering were asked to choose up to 3 departmental electives and 2 technical electives. [7]

More Flexibility in the Curriculum

In 1990, the College of Engineering re-evaluated its undergraduate curriculum. Carnegie Mellon recognized that as the world becomes more complex, demands are placed on engineers to meet the increasing needs of society. We noted that our engineers were entering a profession that cuts across international cultures and markets. Important questions that helped shape the new curriculum included what kind of education allows engineers to contribute to the advancement of technology, while deriving personal career rewards; what kind of undergraduate education would provide the best background for graduates who wish to enter other professions, such as medicine, business or law?

The present engineering curriculum is an outgrowth of a college-wide discussion of the need to revise the undergraduate curriculum. It was felt that the undergraduate course load was often heavier than desired, especially in the first year; the connections between basic science and math prerequisites and subsequent engineering courses was not always clear to the students; and additional flexibility was needed to accommodate students with widely different backgrounds, and to allow students to prepare for increasingly varied career paths.

An important related objective was to construct a curriculum that was more gender neutral by providing early engineering experiences to all students, thereby leveling the playing field for those who did not have prior exposure to hands-on activities. Subsequently, a substantial curriculum revision was implemented beginning with the 1991 freshman class. This class, graduating in 1995, experienced a different first year for all students, a new set of designated engineering minors, and a very different set of course requirements in the most popular engineering major, Electrical and Computer Engineering.

Undergraduates were required to undertake two out of a set of six first year engineering courses. These courses were intended to provide hands-on engineering experience, to provide context for related courses in Science and Mathematics, to introduce the range of engineering practice and to introduce students to methods for engineering design and problem-solving. A goal of the curriculum was to allow students with varied experiences and preparation to quickly reach a common level of knowledge of engineering by exposing each student to meaningful engineering content.

Departmental curricular change soon followed, resulting in greater flexibility in course selection. An increased number of electives created the opportunity to introduce designated minors. Each of the minors required seven to eight courses with some inter-disciplinary exposure and could be completed within the structure of the degree program.

In the summer of 1995, the college performed a preliminary assessment of the curriculum changes. Key instruments used were retention statistics, faculty/course evaluations, senior student surveys, faculty surveys, and recruiter surveys. The college survey questioned students on communication skills, both oral and written, problem-solving abilities, ability to conduct fundamental analysis to solve technical problems, preparation for teamwork, preparation for life-long learning, and understanding of engineering and its concomitant ethical responsibilities. [8]

Comparing the experience of the 1995 class with the preceding class, students reported that the new curriculum had been very successful. Student retention improved, student satisfaction increased, faculty/course evaluation scores increased, faculty evaluation of student skills increased, and industrial recruiters reported satisfaction with the graduates' skills. The report also suggested that more opportunities for exercising communication skills and additional internship opportunities and teamwork assignments might be sought. After the publication of that report, the college hired a full-time senior lecturer to teach technical communication, and two departments added co-op/internship programs.

Building upon the college changes, the CEE 2005 curricula objectives for graduates with a BS are to have:

- graduates who are capable of meeting both routine and unique professional challenges in Civil Engineering;
- graduates who can work independently or as a productive member of a team;
- graduates who can communicate with other professionals and with society at large both in writing and in speech;
- graduates who aspire to leadership and who are prepared for a breadth of career challenges and for life long learning [9]

The Civil Engineering curriculum is intended to allow ample opportunity for students to pursue areas of personal interest. The opportunity for self-exploration requires careful advising to gain meaningful educational experiences. We believe that design and team-working experiences should occur at regular intervals in the curriculum, and that graduates should have appropriate "hands on" experience in laboratories and projects. Students are encouraged to participate in research projects and to pursue study or work abroad.

The educational outcomes for this program, expected of every graduate, have been worded to be consistent with those required for EC 2000 ABET accreditation, but are still true to the outcomes defined during the curricular revisions of the early 1990s. True to the Carnegie Plan, pre-1990s engineering students had 20% of their courses in the humanities and 80% in engineering, math and science. In the revamped curriculum, 65-70% of a student's courses are engineering, math and science related, leaving room to pursue other interests, or double majors or minors, many outside of engineering. More than half of the Carnegie Mellon engineering undergraduates now pursue a double major or a minor.

Evolving Organizational Issues

Just as the educational program has evolved from one noted for cramming too much knowledge into four short years into a curriculum that is flexible and addresses a variety of needs, organizational change also took place. The organizational structure that began as highly discipline-based has evolved into a multidisciplinary organizational structure and culture.

Engineering's interdisciplinary culture took root back in 1923, when the Metals Lab opened. In this lab, physics and chemistry were applied to metallurgical research. The lab was supported by industry and foundations and provided fellowships for graduate students. Decades later in 1967, Mellon Institute, a prototype of private applied research institutes in this country, merged with Tech to become Carnegie Mellon University. The purpose of this union was to develop a greater partnership between industry and science in the hope that academic research results could be shared with the public.

Before 1970, the university organizational structure could be characterized as departmentally (meaning discipline) focused; tenure-track faculty appointments were for the most part in one department; graduate education in one discipline; and space and facilities were allocated at the departmental level.

Today, departments are still the main organizational unit within the engineering college. Shorter term collaborations are handled through the creation of centers and institutes, which have been very effective mechanisms to establish interdisciplinary research programs at Carnegie Mellon. Tenure-track faculty from different departmental units come together to work on interdisciplinary problems by writing joint proposals, advising graduate students from their departments, and jointly publishing archival papers describing their disciplinary and interdisciplinary contributions.

The use of these centers enables the engineering college to maintain the traditional disciplines for academic purposes and to augment the department research missions to explore specific, though interdisciplinary, research challenges. Review of the mission and effectiveness of these centers and institutes by the Dean and the responsible department heads will typically take place every two years. New centers and institutes require approval by the Dean, but programs, consortia and laboratories can be initiated by departments. A new center is expected to make steady progress towards meeting minimum standards of faculty participation (at least three from a minimum of two academic units) and funding levels.

Currently, 26% of the faculty appointments involve two departments within the university. In addition, the university now recognizes two non-tenure faculty tracks, research faculty (established in 1987) and teaching (established in 1994). Many interdisciplinary Master of Science (MS) programs have also been recently introduced, such as the MS programs in Information Networking Institute (INI) that spans engineering, computer science, business, and public policy, and the Architecture, Engineering, and Construction Management (AECM) program that spans Civil and Environmental Engineering and Architecture.

While the doctoral research has remained firmly rooted in the departments, it has also remained a vehicle of interdisciplinary research; doctoral committees, where appropriate, are constituted to be highly interdisciplinary. Centers and institutes are often times the sources of these interdisciplinary committee members.

Implementation Challenges

The parallels in curricular design between Doherty's vision as formulated in the 1930s and the NAE vision for engineering education for 2020 are both frustrating and heartening. The parallels are frustrating because the ideas embodied in the Carnegie Plan have yet to be applied broadly within the engineering community. The parallels are heartening in that the NAE and its Engineer 2020 initiatives are calling for programs to move in directions similar to that defined by the Carnegie Plan. .

Some frustration may also stem from the challenges of recognizing and correcting for issues encountered during implementation of the plan. The increased flexibility of the curriculum requires attention to student advising to insure that students take advantage of curricular options. The conscious decision to pare the required courses to the fewest needed to address today's profession meant giving up legacy courses. As time goes on and new faculty are hired it is tempting to add additional required courses, leading to requirement creep. College and departmental committees engage in philosophical discussions of the need for stand-alone required courses to address non-technical subjects, such as communication or ethics, versus the value of reinforcing those topics by integrating them in technical courses from the first year through senior year.

An effective and efficient engineering curriculum requires cooperation and coordination with other colleges for course development and delivery, especially in providing depth sequences in the Humanities, or just-in time support in math and science. However, it also requires vigilance in engineering, where teaching assignments change and sometimes alter the content of a course.

Conclusion

Andrew Carnegie's philanthropy in establishing a technical school could hardly foretell the institution's innovative evolution and progress a century later. The engineering college is now an internationally recognized engineering program known for its interdisciplinary approach to problem-solving. Carnegie Mellon has always viewed the undergraduate program as a target of innovation, yet still demanding high quality standards. The present curriculum has evolved to meet the needs of modern engineers, while remaining true to the visionary Carnegie Plan for engineering education.

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Biography

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