The Other Re-engineering of Engineering Education, 1900–1965

BRUCE E. SEELY
Department of Social Sciences
Michigan Technological University

ABSTRACT

Many engineering colleges in the 1990s are busily revising the style and substance of engineering curricula to provide increased attention to design. The intent is to redress what many reformers see as an imbalance caused by too much emphasis on the analytical approaches of engineering science. In effect, current reforms are responding to changes made in American engineering colleges in the years immediately after World War II, when engineering curricula first fully embraced an analytical mode of engineering science. This paper examines how and why this earlier "re-engineering" of engineering education came to pass. It begins by summarizing the state of engineering education in the late 19th century. Then the paper discusses the role of European-born and educated engineers such as Stephen Timoshenko, Theodore von Kármán, and Harald Westergaard, who after 1920 prepared the ground for the later transformation of engineering curricula. The paper next discusses the efforts of leaders such as Solomon Cady Hollister and Eric Walker to introduce changes after 1945, and concludes by noting how their initial visions of curricula based on engineering science were altered during implementation.

I. INTRODUCTION

A recent article in *IEEE Spectrum* began with the following words:

"On their first day at Drexel University, in Philadelphia, engineering students are ushered into a large auditorium—but not just to sit there passively and listen to a welcoming speech. Instead, Robert Quinn, a professor of electrical and computer engineering, teams the freshmen up in threes and instructs each team to design a model bridge using a toy construction set called Connects … From then on, these students will have to devote as much attention to building the skills they will need in the new team-oriented, multidisciplinary industrial environment as to learning differential calculus and circuit analysis."[1]

Such activities are not uncommon in the 1990s as engineering educators revamp their curricula, "re-engineering engineering education," as the author of that *Spectrum* article phrased it.[2–4] Central to the indictment of traditional educational approaches by many reformers is the charge that large numbers of engineering students leave college without the skills essential to professional engineers. Often topping the list of missing capabilities is problem-solving ability, or what engineers have called design experience. An editor of *Machine Design* argued, "Schools are being charged with not responding to industry needs for hands-on design talent, but instead are grinding out legions of research scientists … As a result engineering schools are producing entire generations of engineering faculty who have never practiced engineering."[5] Similarly, two engineering educators from the University of Delaware concluded in a 1987 essay in MIT's *Technology Review* that "Design has fallen so low in the order of educational priorities that many engineers—especially young ones and students—do not understand its meaning."[6] Indeed, in 1975, MIT had sponsored a conference to discuss how design could be brought back into the classroom, thus reintroducing the "art of engineering" to students.[7]

In other words, for at least twenty years some American engineering educators have been advocating a substantial adjustment in the nature of engineering education. What happened to bring about this situation? The culprit, according to some, was engineering science, for those courses assumed dominance in college curricula just as design began to slip away. As MIT aeronautical engineer Eugene Covert noted about his own discipline, "Recognition of the classical scientific foundation of aerospace engineering has led many educational programs in this field to become biased toward engineering science."[8] Drawings in that 1987 *Technology Review* essay capture the essence of this formulation, albeit in an exaggerated fashion. (See figures 1 and 2.)

Recent efforts to re-emphasize design in engineering schools and develop a better balance with engineering science actually fit into a history that extends further into the past than two decades. By stepping back fifty years or more, current calls to re-introduce design exercises into classrooms begin to be understandable as more than the latest fad in a long line of efforts to revamp engineering education. In fact, the changes being proposed in the 1990s seek to undo an earlier "re-engineering" of engineering education in the United States, an effort that dominated the first half of this century. Those earlier changes culminated in a substantial reworking of engineering education in the period 1945–1965, and brought into place the style that current reformers wish to overturn, or at least modify. It was only after World War II that American engineering colleges completely embraced engineering science as the foundation of engineering education. That decision led to sharp reductions in the time and coursework devoted to practical skills such as drafting, surveying, and other traditional features of engineering curricula. Replacing them were courses in fundamental sciences, mathematics, and engineering science. But how did this change come about? A better understanding of this earlier re-engineering of engineering education might add some important perspective to current reform efforts.

II. AMERICAN ENGINEERING EDUCATION IN 1900

Perhaps the most constant feature of American engineering education has been the demand for change. As late as the 1870s, most engineers entered the field after serving an apprenticeship in the field or in a machine shop. But by the 1880s, what one historian has called the "shop culture" slowly began to give way to the "school culture."[9,10] Even so, engineering colleges long retained the flavor of the

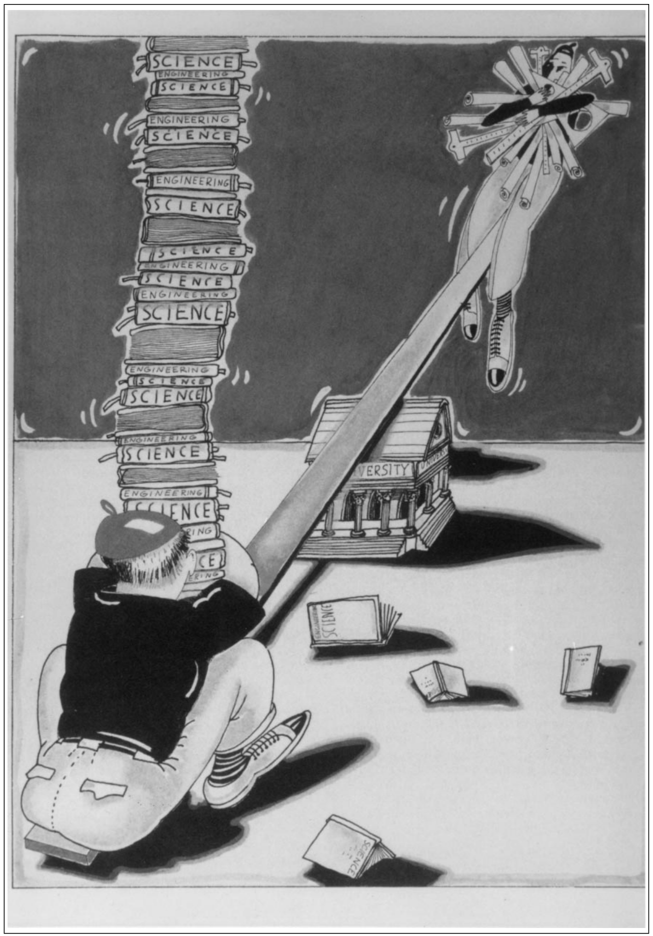

Figure 1. This illustration accompanied an essay in Technology Review in October 1987 to reinforce the author's contention that engineering curricula were giving too much emphasis to engineering science. Used by permission of Eugene Yelchin.

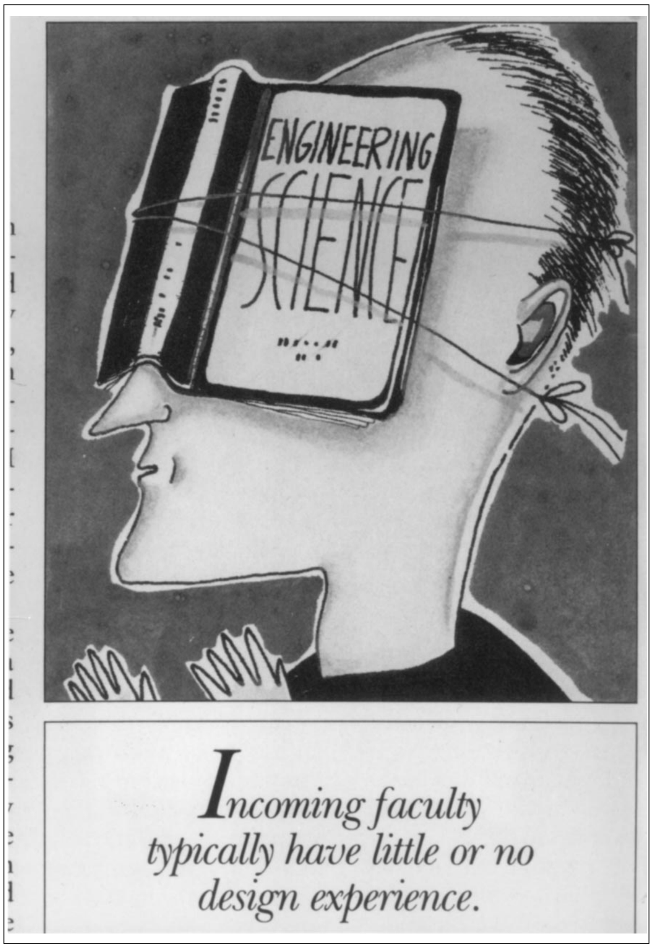

Figure 2. This illustration from the same issue of Technology Review suggested that faculty also were less well-prepared as engineers because the dominance of engineering science within engineering curricula displaced design activities. Used by permission of Eugene Yelchin.

earlier hands-on style of training. As the 1872 engineering college catalog for the University of Illinois stated "This school is designed to make good practical engineers…."[11]

Engineering education as delivered at the University of Illinois in the 1870s suggests how book learning and practical experience were first combined in some engineering schools. Stillman W. Robinson, the first, and for a time the only engineering professor at Illinois, directed that effort. He had grown up on a Vermont farm and apprenticed in a machine shop before earning his civil engineering degree at the University of Michigan in 1863. Robinson joined the Illinois faculty after holding several engineering jobs, and taught everything from physics and geodesy to mechanical engineering. Later he inaugurated laboratory work in physics and new courses on materials and hydraulics. Robinson always combined systematic classroom instruction with practice in laboratories and shops, but his practical tendencies showed when he designed, and his students built apparatus for classroom demonstrations in materials courses, a steam engine for the machine shop, and a tower clock for the union. Robinson also patented a rock drill, a lawn mower, and a sewing machine. In 1878, he moved to Ohio State University as dean of engineering and remained until 1895, when he left to develop shoe making machinery, an endeavor that amassed him a fortune.[12]

Clearly, Robinson sought to balance practical activities with formal classroom studies. Many engineering faculty, however, were less inclined than Robinson to install formal learning in science as part of engineering education. According to the president of Rensselaer Polytechnic Institute, Palmer C. Ricketts, most engineering schools in the 1890s imparted "a smattering of so called practical knowledge" and produced "surveyors, and … mechanics, rather than engineers."[13] A few engineers, most notably Robert Thurston, head of Sibley College of Mechanical Engineering at Cornell University after 1885, sought to alter this situation. Thurston borrowed heavily from European engineering schools, cutting back the hours spent in the machine shop to make time for "calculations" and basic courses in science; he also emphasized research.[14–18] But even Thurston could not completely abandon shop work and other practical elements of the curricula, and other schools changed much more slowly.

The point is that even in the most progressive institutions, an older, practical tradition remained embedded in the engineering colleges at the end of the 19th century. The efforts of civil engineer William H. Burr exemplified the retention of traditional practical approaches to educating engineers even in university classroom settings. Burr graduated from Rensselaer Polytechnic Institute (RPI) in 1872 and worked for a bridge building company and the

Newark, New Jersey, water works before returning to RPI as an instructor in mechanics. [Information on Burr can be found in references 19–23]. In 1876, he was named William Howard Taft Professor of Rational and Technical Mechanics. Burr believed that students needed to know *why* things worked as much as *how* they worked, and prepared textbooks on bridges and materials that showed them.[24,25] Both books presented the basic principles underlying those subjects and provided students with mathematical tools for structural analysis. Yet, Burr's goal was the construction of better bridges, not the generation of better theories of bridge design or materials behavior.

Indeed, in 1884 Burr left RPI to become assistant to the chief engineer of the Phoenix Bridge Company in Phoenixville, Pennsylvania. He remained until 1891, reaching the position of general manager and helping Phoenix Bridge make the transition from iron to steel as its primary structural material. He developed standards for steel bridges and superintended design and construction of large structures, including a three-span railroad truss bridge across the Ohio River at Cincinnati in 1888 with a record-length center span of 550 feet.

In 1892, Burr returned to teaching, spending a year at Harvard and then moving to Columbia University in 1893. As before, he stressed a combination of theoretical understanding and practice, and he authored additional texts on stress computation and bridge design.[26–28] Burr claimed with pride that he was the first American engineering professor to teach practical design work in iron and steel construction, to offer analytic designs of draw bridges, and to introduce a rational theory of earth pressure in the design of masonry arches.

But while Burr's interests ranged from the practical to the theoretical, in the end he devoted much more time to practice. For example, Burr consulted on many projects, including the Nicaraguan canal project (1890s), New York City's Harlem River Ship and Barge Canal (1893), Harlem River Drive (1895–98), and water supply system (1902), the Panama Canal (1902), the New York State Barge Canal (1911), and various projects for the New York Port Authority. Students and Columbia University Presidents Seth Low and Nicholas Murray Butler occasionally complained that he spent too little time on campus! More obvious evidence of Burr's priorities could be found in one of his textbooks, *The Elasticity and Resistance of the Materials of Engineering*. He divided it into sections headed "Rational" and "Technical," a layout that caused another engineer to accuse Burr of being too theoretical. But Burr made his stance clear in the introduction, arguing that the "rational" section was important, but "a great number, and perhaps all engineers in active practice … [will find it] unnecessary."[29,30]

Burr's approach to engineering typified the outlook of most American engineering faculty at the turn of the century. He wanted students to utilize mathematical analysis as a tool in bridge and structural design, but never doubted that good designers relied as much on experience gained through practice. He recognized the value of a more systematic and mathematical approach to engineering—indeed he taught essential structural calculations for bridge builders—even while remaining tied to traditional goals.

An engineer a few years younger than Burr showed that this pattern carried into the 20th century. Comfort Adams was an 1890 graduate of Case Institute of Applied Science, where he served as a laboratory assistant to physicist Albert Michelson and helped construct the large interferometer used in Michelson's famous ether experiment.[31,34] Adams' first jobs were with Cleveland's Brown Hoisting and Conveying Machine Co. and Brush Electric Co. Then in 1891, he moved to Harvard University and remained there for 45 years; from 1914 to 1936, he was Gordon McKay Professor of Electrical Engineering. At first, Adams focused on the theory and design of electrical machinery; publishing three very important articles in *Harvard Engineering Journal* between 1902 and 1904 on alternators, synchronous motors, and induction motors. These showed his ability to bring together physical principles, mathematical analysis, and practical considerations. But during a very productive professional career, Adams most often applied his analysis to industrial problems. He advised Babcock & Wilcox, for example, on the design of high-frequency steel melting furnaces about 1900. He also helped American Tool and Machine Company produce electric motors and worked with the Okonite Company on electrical cables for fifty years, about as long as he consulted for General Electric.

Adams' interest in hands-on engineering showed most clearly in his contributions to welding. By 1900, he was helping Babcock and Wilcox develop what may have been the first large-scale alternating-current welding machinery. This equipment later welded the three-inch thick steel penstocks at Boulder Dam. Adams also helped establish the American Welding Society. For his many accomplishments, Adams received the AIEE's 1940 Lamme Medal and the Edison Medal in 1956, and both citations pointed to his work in the theory and design of alternating current machinery and in welding.

The activities of both Burr and Adams suggest that American engineering education in the years after 1900 had changed since the 1870s. Even so, these men were not necessarily typical engineering faculty. Both were much more active in professional circles outside their campuses than many professors. More importantly, they understood better than most engineering professors the utility of mathematics and the value of scientific study. But even Burr and Adams did not carry their views very far. In other words, change came slowly to American engineering colleges, held back by the diverse educational styles within the engineering schools themselves, the uneven preparation of students, and the weight of tradition. In addition, industrial employers desired graduates who could step right into jobs. Thus, practical knowledge continued to matter as much as science. Faculty were expected to have practiced in industry before they began teaching. Machine shops and the drafting table consumed much student time. Student projects had a real-world flavor. For example, Embury A. Hitchcock, Professor of Experimental Engineering at the Ohio State University, assigned seniors to calculate heat balances on steam locomotives on the Hocking Valley Railroad, while students at Cornell tested street railway motors and generators on Buffalo streets in 1899 and textile engineering students at Georgia Tech operated a real factory.[35–38]

Moreover, research was not a normal activity for most engineering faculty, thanks to crushing teaching loads. Only after 1900 did a few engineering schools begin to expect faculty to conduct research as part of their professional lives. And that research almost always was highly practical. Projects focused on the needs of local and regional industries, or the problems facing local and state government officials. Industrial funds were rarely available before 1920, and then at only a few schools. But when industrial sponsors supported research, they expected practical results, not theoretical studies.[39]

Under these circumstances, even the best faculty in American engineering education early in the 20th century still weighted *how* more heavily than *why*. Burr and Adams had moved beyond Stillman Robinson, but the overall tone remained one of practicality. And that tone was firmly rooted, as can be seen in a disparaging comment by another leading engineering educator of the period, electrical engineer Harris J. Ryan of Stanford. Ryan conducted an active research program on high-voltage transmission systems, an early example of industrially-sponsored university research, yet he once commented that "The spirit of engineering can not be acquired through academic life."[40] In addition, in 1920, a report published after French scientist Maurice Caullery toured a number of American universities confirmed that Ryan's outlook was not unusual:

"There is nothing in the United States comparable to the preparation in our courses of the *École Polytechnique* or the *École Centrale*. The first-year students, the freshmen, of the engineering schools, are very weak. It is none the less true that the American engineer gives abundant proof of all the qualities which are expected of him ... He is first of all a man of action."[41]

III. CHANGES FROM EUROPE, 1920–1950: TIMOSHENKO, VON KÁRMÁN, AND WESTERGAARD

After 1920, however, firm foundations for real change began to be laid in American engineering schools by a number of European engineers. Even at the time, their efforts were recognized. In his famous 1920s study on engineering education, William Wickenden reported that "Technical research has depended in large measure on men of European training or upon men trained in pure science. These conditions are gradually being corrected, but American engineering is still far from being self-sufficient on its higher intellectual levels."[42] Later, Solomon Hollister of Cornell noted that the first European degree was about equal to an American master's degree. "With such training, they stand out in our engineering staffs and have made significant contributions."[43] In fact, these Europeans brought engineering science to the U.S. They approached engineering with a belief in the utility of applied mathematics and greater interest in developing theoretical bases for engineering.

One of the most important European engineers was Stephen Timoshenko, a Russian immigrant who arrived in 1922.[44–46] Working at Westinghouse Electric in Pittsburgh, he sharply criticized the poor education of American engineers:

> "I was amazed at the complete divorce of strength-of-materials theory from experimental research. Most of my students had done no work whatever in mechanical testing of materials with measurements of their elastic properties. The newer methods of calculating beam deflection and investigating flexure in statically indeterminate cases had not been taught them at all ... In the face of so feeble a background [I offered a course given for sophomores in Russia]."[47]

A further remedy was an informal evening seminar Timoshenko introduced at Westinghouse in Pittsburgh shortly thereafter.[48] After he joined the engineering faculty of the University of Michigan in 1927, Timoshenko was even better positioned to address shortcomings in student understanding of the physical properties of building materials, allowable stresses, and fatigue in metals. He began transforming American approaches to the strength of materials, structural mechanics, and dynamics (especially vibration), by placing this work on a mathematical footing. An important step in this direction was an enormously influential summer school in mechanics he directed at Michigan from 1929 into the mid-1930s. The program brought together like-minded European-trained faculty and young American engineering teachers and graduate students interested in learning this mathematically-oriented approach to engineering. Finally, after he moved to Stanford in 1936, Timoshenko began writing his highly acclaimed textbooks.[49–54]

Clearly, Timoshenko approached engineering differently than traditional Americans. Only one American engineering school was even beginning to think this way in the 1920s—the California Institute of Technology. Physicists George Ellery Hale and Robert Millikan, the guiding spirit and first president of Caltech respectively, envisioned a school that would make "engineering grow out of physics and chemistry."[55] To that end, they persuaded the "strongly theoretical" Theodore von Kármán to come to Caltech and build a scientific and mathematical approach to aeronautical engineering.[56–58] The payoff was immediate, as von Kármán introduced Ludwig Prandtl's work in fluid dynamics, especially boundary layer theory, and trained a generation of American aeronautical engineers to work his way.[59–61]

At other American engineering schools, changes in direction also followed the arrival of European engineers or their students. Harald Westergaard played a less visible but no less important role in civil engineering.[62–66] He had studied with Prandtl at Göttingen and August Föppl at the Technische Hochschule in Münich before arriving at the University of Illinois in 1914. Westergaard earned the first Ph.D. in theoretical and applied mechanics granted by the University of Illinois, and stayed to teach structural theory and the theory of elasticity. He became an U.S. citizen in 1920; climbed the academic ranks at Illinois, becoming a full professor in 1927; and married his mentor's daughter.

Westergaard pursued two main research interests—the design of reinforced concrete paving slabs and the analysis of stress related to dams. Both involved elasticity, the reaction of structural materials to loads and strains. During the 1920s, he developed the first mathematical analyses of concrete pavements for roads and bridges as a consultant to the Bureau of Public Roads. He also analyzed dams for the Bureau of Reclamation, serving for a time as senior mathematician for the Hoover Dam project. After completing the preliminary studies, Westergaard remained as a consulting engineer, calculating the stresses that the water in the new Lake Mead would create on the ground behind the dam.

Through this research and his teaching, Westergaard introduced Americans to European approaches to engineering. He seemed a thoroughly absent-minded European professor who was known on campus as "The Great Dane."[67] But his biographer thought Westergaard should be remembered for more important things. "Early in his career, Westergaard came under the influence of engineers who based their theories on the application of mathematical research to engineering, and in America he was an early proponent of the school which regarded engineering problems as problems in classical physics."[68] A brilliant graduate instructor, he demanded precision and style from his students, as well as knowledge of engineering fundamentals expressed in mathematical terms. Westergaard spread this European approach as a participant in Timoshenko's engineering summer school at the University of Michigan in 1931, 1932, 1934, and 1936; indeed Michigan offered him Timoshenko's position in 1936. But Westergaard accepted instead an offer from Harvard, where he replaced Comfort Adams as Gordon McKay Professor of Engineering. He wrote to Harvard president James B. Conant that he intended to move the engineering school, "along the lines of the science of engineering…."[69] Westergaard, Timoshenko, von Kármán, and others clearly approached engineering quite differently than had Burr and Adams.* Most obviously, the Europeans were more accomplished in mathematics. Von Kármán later commented in an autobiography that his training had not differed radically from Einstein's. As a result, the Europeans approached engineering problems as general cases in physics or exercises in applied mathematics. Yet, these Europeans were not mere theoreticians, for they shared the engineer's commitment to solving real-world problems. All of them spent time as consultants. Westergaard, for example, studied reinforced concrete structures for the U.S. Shipping Board's Emergency Fleet Corporation in 1918, dams and pavement slabs for federal government agencies in the 1920s and 1930s, and airport runways for the Air Force in the 1940s. Like other European engineers, he believed he had at his disposal more powerful problem-solving tools than practical American engineers who relied on design experience and rules of thumb. Or as von Kármán put it, "nature was inherently mathematical," and he spent his career "searching for mathematical solutions in areas where practical men saw only insurmountable chaos."[75] Slowly, this European approach found adherents in American engineering schools during the 1930s. Only after World War II did their approach become widely accepted.

IV. ENGINEERING SCIENCE ENTERS THE ACADEMY: HOLLISTER, TERMAN, AND WALKER

Large-scale adjustments in American engineering education began because the war created new possibilities for academic engineering research; these opportunities in turn triggered a further sequence of changes in American engineering colleges after World War II. Within a decade, the entire educational enterprise had been transformed.[39] First, an avalanche of federal money, primarily from the military and the Atomic Energy Commission, displaced the smaller industrial research projects that had been conducted by a few engineering colleges before 1940. Trade associations had been the key research supporters in the 1930s, and a few thousand dollars a year constituted a large project. After 1945, however, federal grants worth hundreds of thousands or even millions of dollars a year supported not just researchers but entire graduate programs with marvelous new facilities and expensive equipment.

Moreover, these federal agencies posed entirely different research queries than had prewar research sponsors. The military was concerned with cutting edge technologies, such as computers and electronics, nuclear power, jet propulsion and rockets, and exotic materials. With little known about the technologies, both scientists and engineers were funded to ask basic questions, not conduct tests.[76–79] Engineering scientists were much better equipped to conduct such projects than many practically-trained engineers and received priority in funding. Both the volume of government support and this new research focus were justified by the lessons of the 1940s, for as the assistant secretary of the Navy noted at the dedication of a navy laboratory at Penn State in 1949: "The last war proved conclusively that it is not possible to conduct basic research during hostilities and to convert knowledge gained thereby into weapons soon enough to have a decisive effect."[80] The military embarked upon a massive permanent research program to be prepared for the next war, and engineering science assumed much greater importance in American engineering colleges.

Engineering educators were able to respond to these shifts in direction in large part because of the preparatory work of European engineers like Timoshenko and Westergaard. American engineers schooled in the European approach now began to alter undergraduate curricula and expectations about graduate work. First, they made more time for science and math courses. In part, status worries were involved. Frederick Terman, an electrical engineer who had specialized in radio and spent the war at the Radiation Laboratory at MIT, was not the only engineer irritated that physicists received most of the credit for wartime research accomplishments. But he also recognized that many engineers had been ignorant of the science underlying electronics and atomic weapons. As dean of engineering at Stanford immediately after the war, Terman was determined engineers would not play second fiddle in the future.[81–84] Stanford and other American engineering schools began replacing machine shop, surveying, and drawing classes with science and mathematics courses, and hiring faculty who could win research grants. At the same time, graduate programs expanded quickly, especially at the doctoral level. Before the war, most engineering faculty held Masters degrees, but doctorates were rare because experience in industry counted almost as much as formal schooling. This outlook changed after the war. In part, some engineers pressed for doctoral programs that emulated programs in university science departments. Others noted that the specialized knowledge required to solve some engineering problems required longer periods of study. Finally, engineering schools wanted doctoral students to help conduct the projects funded by large federal grants. Graduate work in engineering grew steadily in importance during the 1950s, with the strongest emphasis placed on engineering science.

These changes in research and curriculum moved engineering science into the mainstream of American engineering education. For the first time, the vision of Robert Thurston was supported throughout engineering education. Solomon Cady Hollister of Cornell, Eric Walker at Penn State, and others joined Terman as influential leaders who encouraged the widespread introduction of this scientific style of engineering.* Yet the final results were not exactly what they had envisioned.

One of the most important engineering educators after the war was Solomon Cady Hollister at Cornell.[85–88] He earned his bachelor's degree at the University of Wisconsin in 1916 and became a consulting structural engineer with a special interest in reinforced concrete and bridges. He helped build the first practical concrete ships during World War I, and later worked on the penstocks for Hoover Dam in the 1930s, probably crossing paths with Comfort

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*Among the European engineers who also contributed to change in the U.S. were Karl Terzaghi, a Hungarian who developed soil mechanics; Max Jakob brought the theory of heat transfer from Germany to the Armour Research Institute in 1937; Boris Bakhmeteff; Max Munk; A. L. Nádai; and Richard von Mises. Americans who studied in Europe and brought ideas home included Berkeley's Morrough P. O'Brien and L.M.K. Boelter, a specialist in heat transfer. See references 70–74.

*Many other individuals, of course, helped to reform American engineering education after the war, including H.P. Hammond, Dean of Engineering at Penn State and William L. Everitt at the University of Illinois. My identification of Hollister, Walker, and Terman as key individuals is not meant to diminish the contributions of other engineering educators.

Adams. He accepted a teaching and research post at Purdue in 1930, then became Director of the School of Civil Engineering at Cornell in 1934. In 1937, Hollister became the first non-mechanical engineer to serve as dean of engineering at Cornell.

That school had slipped from its position at the top of American engineering schools, and Hollister addressed this situation by promoting the newer approach to engineering. His Wisconsin education, he believed, provided a good preparation. Among his professors had been Edward R. Maurer, who began teaching mechanics in 1892. Maurer published several textbooks and, like William Burr, developed an appreciation for theory connected to problem solving. This approach showed in Maurer's work as associate editor of the *American Civil Engineer's Pocket Book* and in a 1908 volume for the American School of Correspondence, *Strength of Materials: A Practical Manual of Scientific Methods of Locating and Determining Stresses and Calculating the Required Strength and Dimensions of Building Materials*.[89,90] Hollister later remembered:

"I was trained in the theory of structures—the German theory, the Swiss theory and Austrian theory. These fields I knew thoroughly and I knew the English practice theory and the English practice didn't go anywhere near as far as the Germanic groups went ... I'd take a course—an undergraduate advanced course—in ... roof structures. And instead of doing a Fink truss, which was the thing to do, I did a three-hinged arch span for a major railroad terminal ... I did domes and the theory of the dome is a complicated thing ... I was using as a text Emperger's *Handbuch für Eisenbetonbau*."[91]*

Hollister felt comfortable in the worlds of theory and practice, and insisted his students should as well. Like the Europeans of this era, Hollister assumed mathematics and engineering science were crucial problem-solving tools. In 1938, for example, he created a course on differential equations for engineering students after finding no one taught applications. "I asked a simple question [of the math department], 'Do you teach the physical significance of a differential equation?' No, that was not their responsibility." So he got his new course. Similarly, Hollister scoffed at mechanics textbooks that claimed, " 'This is a book you can read without the use of the calculus.' If you're going to take the calculus out of engineering, you are going to destroy engineering."[92]

Hollister was not the only American engineering talking like a European as the war ended. Eric Walker, for example, had quite similar views. He was two decades younger, earning his Harvard Ph.D. in 1935. His was a highly theoretical education, for Harvard had several European-born engineers on its faculty in the 1930s. "They taught us elegant theory: vector diagrams for rotating machinery, hyperbolic functions for transmission lines and even triple integrals," he later wrote.[93] They left him best prepared for research, he discovered after a discouraging interview with an industrial firm, so Walker remained in academia and in 1938 became head of the electrical engineering department at Tufts. During the war, he served at the Navy's Underwater Sound Lab at Harvard, and moved with that facility to Penn State in 1944 as head of electrical engineering and director of the Navy laboratory. He became Penn State's dean of engineering in 1950 and its president in 1956.

Like Terman, Walker's wartime experiences convinced him that engineers needed to know about and be able to apply the newest scientific knowledge and understandings. Therefore, after 1945, Hollister, Terman, and Walker joined other engineering faculty in seeking ways to better prepare engineering students. A spate of articles were appearing in engineering journals, calling for more math and science classes, for more attention to engineering science fundamentals, and for less work on specific technologies. For one example, see reference 94. James Kip Finch, dean of engineering at Columbia, wrote that a transition was underway from "a highly practical and effective program of study, which has emphasized technical methods of use and application, to new plans which must have far greater emphasis to the development of basic theory, to more thorough scientific education, and to research and education for research."[95] In short, the style of education endorsed by Europeans like Timoshenko now found very wide support. However, less agreement existed on how to move that way. Under Hollister, Cornell adopted a five-year undergraduate curriculum to provide more time for those additional courses. Terman simply adjusted course content and hired new faculty. Walker, in a state university overwhelmed by returning veterans, moved more slowly. Everyone, however, recognized that while all engineering students needed more exposure to science, those working in certain areas needed MUCH more science. To provide this exposure, new undergraduate programs or majors appeared, built strictly on engineering science. The University of Illinois, whose physics department was in the College of Engineering, offered a degree in engineering physics in the early 1940s. Hollister and Terman adopted this idea in 1946. Cornell started an engineering physics program, while Stanford may have offered the first B.S. in Engineering Science. Ironically, Terman initially could not get that program accredited, for the first team of outside reviewers found too little engineering application in it.[96,97] But he pressed ahead and other schools soon followed suit. Penn State created an honors course in engineering science in 1953–54, and by 1959, at least three additional schools offered such curricula, while seven schools offered engineering physics.[98]

A feature common to all these programs was their selective nature, with admission limited to the brightest students. At Cornell, those students had a choice of such specialties as atomic physics, crystal structures, optics, electronics, wave propagation, properties of materials, aerodynamics, or stress and elasticity. Perhaps the most intriguing feature of these initiatives was their sponsors' assumptions that the primary beneficiary would be industry. Terman and Walker's experiences in wartime R&D convinced them that corporations, as much as the U.S. military, needed to embrace engineering science. Stanford's Terman sought to build bridges to the electronics industry, while Cornell made its links to industry more explicit: "The new division is designed to meet industry's demand for men with broad training in these fields to engage in the increasingly important work of industrial research and development."*

This effort to link engineering science and to practice in industry simply continued the long-standing assumption that ties between industry and American engineering schools were natural. Thus, Terman began building bridges to early electronics researchers that culminated in the Stanford Research Park and the Silicon Valley phenomenon.[79,83,100] At MIT, C. Richard Soderberg

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*Hollister was referring to a multi-volume work by Fritz Emperger, *Handbuch für Eisenbetonbau*, W. Ernst & Sohn, Berlin, 1907; 2 ed. 1910.

*Appropriately, the head of Cornell's program had degrees in both physics and engineering and had been associate director of RCA's research lab before the war. He remained a consultant to that company after the war. See reference 99.

came to assume a prominent role, in part because of his embodiment of this same combination of engineering science and practice.

Soderberg came to the United States from Sweden in 1920 to study naval architecture at MIT, and remembered his disappointment at the intellectual atmosphere in Cambridge.[101–104] He joined Westinghouse in 1922, where he participated comfortably in Timoshenko's training program and soon oversaw the design of large electric motors and other moving machinery. Eventually he was appointed chief design engineer for large steam turbines at the company's South Philadelphia plant. In 1938, he returned to MIT, in part because he believed Westinghouse was losing interest in the European style of engineering. Soberberg's arrival in Cambridge also coincided with the Institute's decision to copy Caltech's more theoretical and scientific approach to engineering.[105] Soderberg was a marvelous teacher of theoretical mechanics. He stressed the fundamentals, including the strength of materials, vibration, and the dynamic behavior of machinery, but always tied the subject to problem-solving in the real world. He drew upon his experience in ship design and heavy electrical equipment, and extensive consulting work on generators with Swedish electrical firms and later on jet engines with Pratt & Whitney. In other words, Soderberg perfectly embodied the new style of engineering being advocated in the late 1940s. Fittingly, he held several key administrative roles at MIT after the war. He was Jerome Hunsacker's successor as head of the mechanical and aeronautical engineering departments in 1947, and was charged with restoring their reputation, meaning he strengthened engineering science. He served on the so-called Lewis Committee that produced a planning report which reshaped MIT, calling for the Institute to provide a better blend of theory and practice and more work in the humanities, to strengthen graduate programs, and to develop interdisciplinary work. The report was a blueprint for postwar engineering education everywhere, and from 1954–59, Soderberg pursued it as MIT's dean of engineering.

Yet even as Soderberg assumed the dean's responsibilities at MIT, the desire to pursue engineering science in American engineering schools was leading to a different pathway than that envisioned by Walker, Terman, and Soderberg, and others. Indications of divergence became apparent in the preparation of a study of engineering education by the American Society for Engineering Education (ASEE) in the early 1950s. Hollister, ASEE president in 1951–52, set the study in motion after the Engineers' Council for Professional Development (forerunner to the Accreditation Board for Engineering and Technology), worried that engineering curricula were not "breaching the gap between the fundamental sciences and engineering instruction."* The first draft of the so-called Grinter Report stressed the need for more science in engineering curricula and then, more controversially, proposed two tiers of engineering instruction.* The committee thought most students would be served by a professional-general program that provided solid training in fundamental science for jobs in industry. Only a few engineering schools needed to develop advanced undergraduate and graduate programs in fundamental engineering science (professional-scientific) to prepare students for government and industrial research programs. Readers of the report disagreed sharply, however, and the final version of the Grinter Report settled for a strong endorsement of the need for more science in engineering schools.[104]

Why the protest? The key, again, was military research funding. What engineering school would voluntarily cut itself off from military research dollars, the key to building academic engineering programs? Certainly Hollister, Walker, and Terman all understood the linkage. Penn State and Stanford had not been strong research centers before the war, but government funding provided Penn State with the Navy Ordnance Research Lab, with a circulating water tunnel for advanced hydrodynamics studies, and a research nuclear reactor, among other facilities. And thanks in part to a variety of military contracts and grants, which he leveraged with corporate support and start-up companies, Terman built Stanford into an engineering powerhouse, with special strength in aeronautical engineering, materials, and electronics.[79,80,84]

By the late 1950s, engineering deans had learned this equation for growth. Schools seeking to grow had to develop graduate programs to support fundamental research programs, and emphasize engineering science. But the goal was not to serve industry, rather to attract federal research funds. About 70 percent of all research money came from the federal government through the 1950s, making this source far more important—and lucrative—than corporate funding. Government-sponsored research eclipsed industrial support with hardly a complaint on many campuses. At Georgia Tech, for example, a chemistry professor who was bothered (perhaps because his department had no government contracts) complained to the school's president about tainted military funds. But the president was not concerned, replying that the only problem with this money was "there t'aint enough of it."[105]

In 1965, Eric Walker was ASEE president and used the office as an opportunity to launch another study of engineering education. This report found that engineering education had been largely transformed since 1945. Engineering science had moved to the very center of every engineering school that planned to grow. But little talk was heard of seeking support from industry; the only patron that mattered was government. And nearly every engineering school with ambitious leaders had developed a professional-scientific curriculum, not a professional-general program. Thus engineering science came to dominate American engineering schools.[106]

V. THE BALANCE OF THEORY AND PRACTICE

The impact of the transformation of engineering curricula was evident almost immediately. A comment from a history of engineering at Purdue perfectly symbolized the changes, as the author plaintively noted that by 1960, "The tendency [of research] seemed to be toward such far-out matters as 'a theoretical study of the scattering of electrical waves by perfectly reflecting bodies …'" He added, "when … the engineering editor tried to get pictures to illustrate reports on research in progress, he was sometimes told there was nothing to photograph unless he was willing to photograph an equation."[107]

The Purdue editor was not the only person bothered by change. In his history of the AIChE, for example, Terry Reynolds notes that practicing engineers working on real problems were soon complaining about the gulf between their interests and those of faculty.

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*These words came from a report by the Engineers' Council for Professional Development, which Hollister had chaired. See reference 102.

*Information on the process of developing the report can be found in reference 103.

Other professional societies witnessed similar debates after 1960, and letters to the editor lamenting this situation were not unusual. Many writers complained that engineering journals contained little material of practical use, and some engineers even dropped their professional memberships.[108–110] Most intriguingly, educators and reformers such as Eric Walker and Solomon Hollister were not pleased about how things turned out. By the 1970s, Hollister was bemused that engineering had so completely turned away from industry. Theodore von Kármán also expressed dismay, noting that while he had received an education heavy in mathematics and science, one should never confuse a scientist and an engineer! For him, as for Timoshenko, math and engineering science were merely tools, not ends in themselves. Eric Walker agreed, and was even more outspoken in denouncing engineering faculty who had forgotten this point. In his autobiography, Walker criticized European-born Harvard professors of the 1930s because "Their sacred cow was 'engineering science'—meaning theoretical analysis regardless of whether it could be applied … As for applications, the general attitude among these European superstars was 'That's not our department.'"[111] By the 1970s, Walker felt this description fit too many engineering faculty. Frustrated at the "overemphasis on science for its own sake" among engineering educators, Walker argued that "The danger for engineers … is that they can become too enamored of research for its own sake. A good engineer … must strike a balance between knowing and doing."[112]

This is the historical context, then, for recent discussions about the place of design and engineering science within engineering curricula. To many practicing engineers and engineering faculty alike, parts of this history are quite familiar, because they lived through it. But if the basic style of engineering education that has dominated American universities for the past three decades was put in place quickly in the years after World War II, those changes rested upon a foundation well prepared by European engineers after 1920. More importantly, the final shape of the educational system based on engineering science that actually was developed in those years swerved away from the vision of its founders, largely under the impetus of enormous federal research expenditures. It created a gulf between engineering schools and industrial practice, and perhaps even an imbalance of theory and practice in the colleges. It is this legacy that advocates of change are seeking to undo in the 1990s. Almost forty years after Hollister, Walker, and others first proposed the idea, engineering educators are again attempting to harness more effectively engineering science to questions of practice and the problems of industry. [For example, see reference 113.] The world of engineering and technology is very different in 1997, to be sure. But maybe the result will be a style of engineering education that more closely resembles what Hollister, Walker, and his European colleagues envisioned after World War II, a system that balances theory and practice.

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