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STRAIGHT-THINKING VANNEVAR BUSH AND THE CULTURE OF AMERICAN ENGINEERING

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STRAIGHT-THINKING

VANNEVAR BUSH AND THE CULTURE OF AMERICAN ENGINEERING

Larry Owens

A DISSERTATION
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ABSTRACT

Vannevar Bush was the man chiefly responsible for the mobilization of science and engineering during the Second World War. In the years following, he played an influential role in the creation of the National Science Foundation and the Atomic Energy Commission and in efforts to regularize the provision of scientific advice to the military, becoming a respected spokesman for the importance of science in national life. This dissertation is an exploration of the engineering curriculum in which Bush came of age and of his early career as one of the country's most prominent electrical engineers. It focusses particularly on his development of the differential analyzer, an early analogue computer, finding it both a technical solution to the mathematical problems confronting engineers and an expression of the instrumental rationality that characterized the "culture of engineering" in the early twentieth century.

- Larry Owens

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PREFACE

By any standard, Vannevar Bush was one of the movers of the twentieth century. A prominent engineer who rose through the ranks to become MIT's first vice-president and dean of engineering in 1932, he moved to Washington in 1939 to assume the presidency of the Carnegie Institution. Within a year, however, the threat of war turned his energies in other directions. Capitalizing on friendships within the scientific and engineering establishments built up over the years and strategically situated in the nation's capital, Bush took the initiative in efforts to mobilize science for war. His accomplishments as the head of the National Defense Research Committee and its successor, the Office of Scientific Research and Development, are well known. From the laboratories overseen by these committees came improved radar, the proximity fuse, volume production of penicillin, and, of course, the atomic bomb. Such accomplishments brought fame to Bush and enormous public respect to the country's scientists.

His wartime successes, furthermore, enabled him to play a key part in the debates over the role of science in the postwar world and in the creation of the Atomic Energy Commission in 1947 and the National Science Foundation in 1950. All in all, Bush was as close as any to those events that forged the linking of science, technology, and national defense we have come to take for granted.

Surprisingly, however, we know relatively little about the man who wielded such power. My immediate purpose in the present work, consequently, has been to sketch the outlines of the early career of Vannevar Bush.[1]

* * *

The roots of this man who became the czar of wartime science reached deeply into the soil of New England. He was the descendent of a long line of sea captains who made their home in Provincetown until his father escaped the Cape's declining economy and sectarian controversies in the 1870's to make his home on the outskirts of Boston. There he abandoned the family's traditional Methodism to train for the Universalist ministry at the nearby Tufts College. Over the next decades he became one of the area's well known and well loved pastors. And there Vannevar Bush was born to Richard Perry and Emma Linwood Bush in 1890, one of three children.

For over two decades, Bush was associated with two powerful engineering schools. One was MIT; the earlier and, in some ways, the more formative was Tufts. Established by the Universalists at midcentury, Tufts developed a strong and innovative engineering program under the guidance of Gardner Anthony, a master of drawing and mechanical design. Here Bush discovered a lifelong romance with invention that culminated, in the twenties and thirties, in a series of pioneering analogue computers. Here also he acquired that graphic mathematical approach to things that became a characteristic of his work in engineering. Not least, the ethical environment of Tufts combined with the pastoral commitments of his father to condition Bush's belief that engineering constituted a ministry devoted to social welfare and the public good. He graduated from Tufts in 1913 with both bachelor's and master's degrees.

Between 1913 and 1919, he worked at General Electric, taught mathematics to the women at Tufts, worked as an electrical inspector in the New York Navy Yard, earned his doctorate in electrical engineering at MIT, and returned to Tufts as a young assistant professor, where he divided his time between teaching and consulting for a small company manufacturing radio equipment. From such beginnings came the Raytheon Corporation, eventually one of New England's largest companies and a mainstay of its defense industry. Bush was one of the company's founders in the early twenties.

In 1919, just as the academic market for engineering was turning bullish, Bush joined the faculty at MIT. Starting as an associate professor of electrical power transmission, he rose rapidly through the department, bypassing the chairmanship to become in 1932 the Institute's first vice president and dean of engineering under the new president, Karl Compton. During these years Bush became involved in many of the issues agitating the country's engineers. They ranged over the curricular and conceptual development of electrical engineering, the relationship of the engineer and the government, the characteristics of professionalism, and the larger role of the engineer in American society. In his early years at the Institute, he cooperated with the department's dynamic chairman, Dugald Jackson, in modernizing the curriculum, assumed direction of graduate training, and coordinated the research activities of the department. By the middle thirties, as Compton's right-hand man, Bush had become not only a major figure at the Institute, but a respected spokesman within the country's technical community.

His inventive activity during these years revolved around the notion of mechanical analysis, the development of machine methods for the solution of mathematical problems in engineering. Between 1927 and 1943, Bush developed a series of electromechanical analogue computers that greatly facilitated the solution of complex mathematical problems. In 1936, the Rockefeller Foundation awarded a major grant to MIT which resulted in the famous Rockefeller Differential Analyzer of the Second World War. The Analyzer was quickly superseded by faster digital computers, but in its time it was a significant achievement and clearly revealed the possibilities for machine computation not only in engineering but in more basic fields of science. Moreover, it embodied in a concrete way the culture of engineering in which Bush had come of age. Not only did it express a graphic and mechanical approach to the analysis of the world, but in the fine machining of its planes and lines students found reflected the engineer's claim to "think straight in the midst of complexity." In the decade of Herbert Hoover, the engineer president, this was not the least of the lessons to be learned from Bush's work.

In the calmer times after the war, Bush returned to his responsibilities at the Carnegie Institution. When he retired in 1955, he went home to Cambridge. He took up duties as a member of the boards of directors of Merck and Company, AT&T, the Metals and Controls Corporation, and the MIT Corporation, becoming its honorary chairman in 1959. During the war Bush had became a respected figure on Capitol Hill and he continued to work for various causes after the war, adopting as special concerns the provision of scientific advice to the military and the reform of the country's patent system.

In many ways, Bush was the outstanding example of the expert whose role at the hub of an increasingly complex society captured the imagination of Americans in the early part of the twentieth century. Those were years in which the figure of the engineer became not only a necessary fact of life but a symbol reflecting the contributions of science and technology to human progress. If the consequences of this turning to science and engineering, especially in the light of the nuclear predicaments which followed the war, proved ambiguous blessings, Bush himself never lost faith. The pioneering spirit helped us conquer plains and forest, Bush wrote at the end of his life in his autobiographical Pieces of the Action. Given the chance, it would work its changes once again.

* * *

Although my study was undertaken with biographical concerns in mind and with the thought that it might serve as preparation for an extended treatment of Bush's role during and after the Second World War, it is by no means simply biographical. After all, our subject makes his appearance only after almost a hundred pages and even then he is pursued in the most crabwise manner. There are a number of reasons for this. Bush once confessed to a close friend that he didn't "have much use for biographers." There were, he felt, so few really good ones. Consequently, he always kept his records in such a way that "somebody wild enough to try to write a biography" would have "a pretty rough time." "I hope nobody'll ever write a biography of me, because I think it probably would be terrible."[2] Paradoxically, Bush read "quite a lot" of biographies, enjoying them particularly when they told "the story of a man's involvement with something important." Especially for the years before 1939, after which his growing involvement with the federal government assured that records would endure more securely, Bush himself made it difficult to tell his story in any simple and straightforward way.

In another sense, however, Bush the individual is not the major preoccupation of this dissertation. That attention is reserved for the "something important" with which Bush was involved for over half a century and of which he might be the clearest reflection - what I have come to call "the culture of engineering." The concept of culture, and of engineering culture in particular, is central to my treatment of Bush and engineering and signifies several distinct but connected notions. It refers, in the first place, to the learning that, by the turn of the century, comprised the academic programs of America's schools of engineering. When engineering educators sought to defend technical education against the barbs of humanist pedagogues as an appropriate "culture study," it was largely this meaning they had in mind.

Another, and equally important, sense of "culture" comes very close to the usage familiar to the anthropologist.[3] For the "acculturation" of the young engineer consisted of more than book-learning; indeed, imbedded within the laboratories, shops, classrooms, and public places of the school, crafted from the techniques, tools, and machines that informed shared experience, was a vision of the world. In his ritual passage through the engineering program, the student acquired both the tools of his trade and the the belief that the world was a place suitable to the exercise of those rational, instrumental skills in which he was expert. More interestingly, engineers were quick to conflate descriptive and prescriptive standards, as if right knowing was tantamount to right acting and character equivalent to technical expertise. And for many in the early part of the century, that belief was a large part of engineering's appeal. The student whose ability to "size up the situation," and to "think straight" earned him good grades in Electrical Laboratory, would become the enlightened politician successful in bringing honest and efficient government to the country's corrupt cities. Engineering culture was, most assuredly, "a way of thinking, feeling, and believing," a stock of learned responses to recurrent problems, a web of significance spun by engineers from the materials of laboratory and shop.[4] While engineering educators used "culture" only in the first of these senses, I think they would have found my stress on the second entirely sensible. For of all academics, they were most convinced that culture was more than "book-learning."

Part One of the dissertation articulates the culture of engineering, attending particularly to the engineering curriculum typified by Tufts College. Part Two moves from the general to the specific, sketching in more or less narrative fashion the education of Vannevar Bush. Part Three is a synthesis of Parts One and Two in the form of two case studies - one dealing with the development of the Differential Analyzer, the other with an appearance before the Monopoly Committee of 1939 - that present examples of Bush's mature labors as well as facets of the culture of engineering. The final chapter concludes, appropriately, with Bush's account of the "builder," a parable that neatly combines ideas of invention, expertise, and social calling central to the culture of engineering and recaptures the hopes of engineering educators who met in the shadows of the White City in 1893 to define a mission for a new age.

* * *

In an earlier dissertation concerned with an unknown antibiotic, I noted that the relationships which exist between the members of a laboratory "are forces of a different sort than these physical-chemical ones which are the nominal subjects of our attention." The observation was peripheral to the focus of that study. But it has been my good fortune to go around one more time, and in the present dissertation those "different forces" have occupied center stage. The manifestations of this fortune have been abundant: Gerry Geison transformed a dead-end into a beginning when he told me it made no difference I had tried once and failed; Mike Mahoney lifted my spirits more than once with his enthusiasm for ideas and intellectual curiosity; Dan Rodgers has shown me cultural history at its best; John Servos, whose integrity and critical intelligence have kept me honest, opened doors and set me tasks that gave me new direction; Geoff Sutton, JoAnn Morse, Peter Dear, Pauline Carpenter Dear, David Woolwine, Monica Green, Nina Dayton, Lou Masur, and John Carson helped make my years at Princeton the great adventure of my life; the Institute of Electrical and Electronics Engineers, the Babbage Foundation, and the Whiting Foundation provided encouragement and financial support at a crucial moment. Not the least of fortunes has been my family - tolerant of ill-temper, impatience, discouragement, and sacrifice with hardly a question. I salute you all!

NOTES - PREFACE

1. The secondary account of Bush which best portrays his general importance within the history of American science is contained in Daniel Kevles´ *The Physicists - The History of a Scientific Community in Modern America* (New York: Random House, 1971). The most detailed accounts of his involvement in the legislative battles leading to the creation of the National Science Foundation and the Atomic Energy Commission are J. Merton England, *A Patron for Pure Science. The National Science Foundation´s Formative Years, 1945-57* (Washington, D.C.: National Science Foundation, 1982), and Alice Kimball Smith, *A Peril and a Hope. The Scientists´ Movement in America, 1945-47* (Chicago: The University of Chicago Press, 1965). Nathan Reingold has produced an important new study of Bush in a recent essay titled "Vannevar Bush´s New Deal for Research: or the Triumph of the Old Order," personal copy.

2. The comments are recorded in the typescript(pp.100A-101) of the oral interviews with Bush conducted by Eric Hodgins, June 9, 1964 to August 12, 1964 and located in the MIT Archives.

3. See, especially, Clifford Geertz, *The Interpretation of Cultures* (New York: Basic Books, 1973).

4. Geertz, "Thick Description: Toward an Interpretive Theory of Culture," in *The Interpretation of Cultures*, pp.4-5.

Part One.

The Idioms of Engineering Culture

"All the while
She hums there softly, purring with delight
Because men bring the riches of the earth
To feed her yearning fires. I do her will
And dare not disobey, for her right hand
Is power, her left is terror, and her anger
Is havoc."

- Harriet Munroe, "The Turbine"

CHAPTER ONE:

VIRGINS AND DYNAMOS: THE WHITE CITY(I)

In 1893, the architects of the Columbian Exposition in Chicago confronted the dilemmas of technology and culture and produced the White City. Worried, as were many Americans, over the forces of change quickening as the end of the century approached, these men hoped to celebrate industrial dynamism and progress reconciled within a conservative architectural idiom that spoke of piety, discipline, and character. In retrospect, the juxtaposition of Victorian pieties and aggressive individualism seems tense and awkward, and indeed it was. But while the tensions embodied in the monumental art of the White City seemed threatening, they also expressed an imaginative optimism nothing less than utopian.[1]

Certainly, Henry Van Brunt did not underestimate the challenge he faced. He had been selected to design the building which housed the Department of Electricity, and of all the new manufactures exhibited at the Fair, those of the young electrical industry were most portentous of change. "The fashion of the times," he admitted, was "to stigmatize the marvelous multiplication of mechanical appliances to life in the nineteenth century as degrading to its higher civilization." Nevertheless, it was "the high function of architecture not only to adorn this triumph of materialism, but to condone, explain, and supplement it, so that some elements of ´sweetness and light´ might be brought forward to counterbalance the boastful...."[2] Through ´sweetness and light´ Van Brunt would "condone and explain" the ambiguities implicit in the new technologies of power.

The Electricity Building fronted on its north the central lagoon of the Fair, and on its south the great court which was the ceremonial focus of the Exposition. The exterior of Van Brunt´s building consisted of bays alternating with Corinthian pilasters, with elaborate porches at the centers of each side. The skyline was punctuated by steeples surmounting the columns and by larger towers bordering the four porches. With these vertical elements expressing "playful animation," "brightness," "movement," "energy," "freedom," and the nervousness of movement...suggested by the idea of electricity," Van Brunt sought to temper the low and predominantly horizontal lines of the building which spoke of "dignity," "seriousness," "conformity," and "repose." On the side facing the great court, where it was necessary to make "a concession to that spirit of grandeur and ceremony which should prevail," the "somewhat fantastic movement of the skylines elsewhere" yielded to a "solid elevated attic, forming a severe horizontal outline against the sky." Here the porch was topped by a classic pediment on which were depicted the two reclining female figures representing the lighting and telegraph industries and supporting an escutcheon bearing a likeness of the electromagnet. On a high pedestal in the center of the porch, stood a large statue of Franklin with kite and key, observing the storm clouds.

Van Brunt seems not to have worried over the uncomfortable parallels between Franklin and Prometheus, a transgressor of an earlier natural order. Certainly, he was aware of the need to accommodate the verticalities of electrical ambition with the pieties of the Victorian horizontal. Within the Electrical Building, however, the coherent, if ambiguous, moral lessons of the exterior gave way to the babble and bravado of unrestrained individualism. Among the many, frequently garish, exhibits, the most important were those of General Electric, Westinghouse, and the Fort Wayne Electric Company, and of these the GE exhibit occupied pride of place. Situated at the intersection of vast naves which terminated in the outside porches, an eight-foot tower of light stretched up toward the ceiling, past the second-floor galleries and the clerestory windows. The tower was ivory and gold, covered with thousands of incandescent lamps, an invention, in 1893, only a bit more than a decade old. Atop the tower was a six-foot crystalline lamp, lit from within by a light of two-thousand candlepower. The varicolored exterior lamps were independently controlled and could be flashed off and on in marvelous patterns.

We do not know if Henry Van Brunt thought the boastful verticality of the exhibit properly "condoned and explained" by the decorum of its setting, nor do we know what he thought of the less public "exhibits" concealed within the secret and vital places of the building itself.[3]

> ...difficult of access and uninviting, even threatening in some ways, there is an inspiring impressiveness in the net-work of huge pipes..., the whirr of tons of rapidly-revolving fly-wheels, the clatter of a hundred belts and dizzy spin of the counter-shafts, the measured beat of condenser-pumps and the hiss of steam from an occasional leaky joint, all among the dark shadows of the huge masonry piers which form the engine foundations.

At least one spectator that year found the dynamos of the White City fascinating. It was in Chicago that Henry Adams picked up the electrical scent which led him across the Atlantic and through seven years to the great hall of dynamos in Paris. There, he tells us, confronted by the infinitely mysterious and disquieting power of this modern engine, he had "his historical neck broken by the sudden irruption of forces totally new."[4]

For the less imaginative historians who wrote the official history of the Columbian Exposition, the dynamo appeared less a disturbing symbol of infinity than the agent of Van Brunt's "sweetness and light." After all, did not the light produced by this new power connote illumination, and illumination understanding? And who could measure "the millions who found illumination at the World's Columbian Exposition"? "Only in the infinite hereafter may the educational and moral values of the...Exposition be adequately computed."[5] The modern technology of power, ambiguous and threatening though it might be, could be harnessed by the discipline of culture and education and turned to the service of man.

* * *

Education and culture - these were the crucial instruments in the accommodation of society and the technology reshaping it. Of the varieties of educators who employed the occasion of the Fair to diagnose and prescribe for the ills of their time, it was the engineers who founded, in the midst of the moral pageantry of the White City, the first association devoted to education in the college and university. Meeting as Section E of the World's Engineering Congress, a small band of seventy some engineers established the Society for the Promotion of Engineering Education and published the proceedings of their meeting as the first volume of a new journal. During the following decade, membership grew slowly and steadily to around four hundred. By 1913, the Society had grown to almost thirteen hundred members.

The moment was opportune. At at the onset of the Civil War, there had been four schools providing college-level training in engineering. By 1899, there were eighty-nine, and a hundred and twenty-six by 1917. Up to 1890, these schools had graduated nearly seven thousand engineers, but during the next ten years alone, over ten thousand and in the first decade of the new century twenty-one thousand engineers were graduated. Compared with other professions, the growth of academic engineering was impressive. Enrollment in theology schools increased 87% between

1878 and 1899; in medical schools, 142%; engineering schools expanded 516%.[6]

In a nation that had acquired its technical expertise largely outside of the school, in shop and factory, this dramatic growth of academic engineering provoked serious disputes. One set of issues revolved around the definition of engineering itself and reflected the complexity of the engineering community. Civil, mining, mechanical, electrical, and chemical engineering were only the largest professional varieties at the century's end, and each exhibited a distinct pattern of growth. From the oldest, civil engineering, to the youngest, electrical and chemical engineering, they evolved various relationships to the schools, on the one hand, and to the craft traditions of industry on the other. Their attitudes concerning professional independence, relationship to industry, and sympathy for the traditional mission of the college varied with inherited social role and different requirements for training in science and mathematics. Needless to say, all of these differences found voice in the public councils of the Society.

If the variety of professional self-identities promoted fragmentation within the Society and the community, so did the different institutions created for engineering training. Programs were established as subordinate and less-privileged branches of older colleges; they grew up under the wing of military schools, as did engineering at West Point; and they flourished in private schools specifically established to promote the practical sciences, as at Rensselaer Polytechnic Institute.

They were founded at state universities under the impetus of the Morrill Act of 1863 and at technical institutes modelled on the German technische Hochschule. Towards the end of the century, technical education spread rapidly into the lower schools with the rise of manual training high schools, trade schools, and industrial programs. Justification for these different arrangements ranged from reasons vocationally specific and practical to the need for a "general engineer" grounded in the basic sciences and the humanities.[7]

For good reason, therefore, the Society's debates were vigorous and often divisive. Rhetorical skirmishers engaged in mythopoesis, recounting the heroic feats of pioneering predecessors in order to establish their historical credentials. They celebrated the role of the engineer in the advance of modern civilization. They gathered statistics to quantify their past and they sought to identify as well as distinguish indigenous from traditions European. They debated endlessly the ideal curriculum, argued the relative importance of theory and practice, the extent and nature of mathematical and physical instruction, and the beneficence of specialization. They argued over research and graduate education, and the place of shop and laboratory. And, especially after the turn of the century, they explored the cooperation of school and industry in joint educational programs.[8]

Despite the enormous range of opinion mobilized around most issues, the Society agreed on several fundamental matters. While engineering education required instruction in the principles of science, its fulfillment involved practical experience outside the school. On the other hand, engineering education was more than simply a preparation for industrial service. Engineers formed a proper and increasingly important community within the school in general, a school which, most would have agreed, was undergoing profound changes. Engineers could either redefine the school to meet their needs, or they could attempt to adapt the vocation of engineering to the traditional ends of the college. In fact, they did both.

Because of this determination to make a place for engineering within the college, the Society engaged in serious debates concerning the nature of engineering as culture. "What is culture?", the Dean of Engineering at Kansas asked his audience in 1901. Answer that question and the cultural value of engineering could be determined. "We want living languages and living issues," exclaimed Calvin Woodward, Washington University's Dean of Engineering, in 1903. Disputing the dominance of classical studies, he announced that "we must teach the duties of the american citizen rather than the manner of life of a slave-owner in Athens...."

> It is no longer safe to assume that your engineer or your electrician is an uneducated man, or that he lacks culture. There is more than one kind of culture.

Frederick Hamilton, president of Tufts College, would have agreed that the varieties of culture were manifold. He welcomed engineers to Boston in 1912, telling them:

> I think that teachers of engineering have been of great service to the teaching public, and indeed to the larger public, in broadening the conception of education, in making men realize that education is

> not the small thing which the culturalists have been disposed to believe that it was. ...the time has come now when a man who is a professional railroad engineer... or any other kind of engineer, is recognized by the public at large to be just as much a man of culture, just as much a man of education, just as much a professor in the true sense of the word, as the man who is a professor of Greek or a professor of Latin or a professor of history....
>
> We are enlarging, then, in our schools, our conception of education; we are learning that... whatever field of intellectual endeavor a man enters brings its intellectual results, brings those results in the field of culture, in the field of refinement and in the field of power....(9)

The story of engineering education, then, concerns efforts to establish a niche within the school. Confronted on one side by the guardians of genteel tradition, who decried the inroads of practical training, and on the other by men who argued that the schools should be entirely refashioned to make them useful, the architects of engineering curricula struggled to establish a modus vivendi that respected both the utilitarian demands of industry and the traditional prerogatives of the college - the stewardship of culture and the formation of character. The result of this broadening in the "conception of education" would be, as Hamilton told the members of the Society, an enlarged culture, intellectual and refined but also powerful. The promise of the White City had involved the reconciliation of social order and the power of technology. The manner in which academic engineering sought to fulfill this promise by becoming a culture of power, shall be the aim of this chapter.

* * *

It is a revealing fact that the cultural claims of engineering should have been vigorously promoted by the president of Tufts College. The College was typical of the smaller schools struggling, as the new century approached, to remain competitive in an academic marketplace being reshaped by universities, graduate research, and professional education. Founded in 1854 to serve the needs of the Universalists in Massachusetts, Tufts offered[10]

> to selected young gentlemen the foundations that would enable them to become leaders in church, state, and the professions - notably teaching. The curriculum in general was set by ancient and honorable usage, for all literate men knew that there was a fixed body of knowledge to be transmitted - knowledge that any educated citizen should acquire. It sharpened and furnished the mind, elevated the character, and promoted piety and virtue.

It remained a small institution of some one hundred to two hundred students until the nineties witnessed the establishment of an engineering school, a dental school, a medical school, and the association with a manual training high school. By 1905, in the space of little more than a decade, Tufts was transformed from a small mid-century college into a diversified professional school with a student body grown larger by 700%, 80% of whom were enrolled in the medical, dental, and engineering programs.[11] The engineering program grew by a factor of fifteen in as many years. It established a course in civil engineering early in 1865; it added courses in electrical, mechanical, and chemical engineering in 1883, 1894, and 1898. In the latter year, the trustees and faculty of the College gathered the separate courses into an Engineering School.

Such a dramatic transformation provoked anxious self-reflection. "Notwithstanding the considerable increase in the membership of the different departments of the College during the last few years, we may still be reckoned among the small colleges...." Among the advantages associated with smallness reckoned up by the Annual Report of 1902 was the readier opportunity in more intimate circumstances to cultivate character and habits of study. If the growth of the professional curricula reflected the "composite energy," the "mighty stimulus," of the great community and was appropriate to an "age of aggregation and combination in all the more important enterprises of life," the style of Tufts education remained properly small, personal, and, at least for the president, centered in the values of the three hundred and fifty students who daily assembled in Goddard Chapel. Appropriately, engineers on the Tufts faculty took an active role in the Society. By 1912, Tufts ranked in the top twenty in terms of individual membership out of over one hundred and fifty institutions. It had one less member than Columbia, more members than Harvard, Case, Carnegie, Stevens, Worcester, Michigan, and not quite half as many as MIT. In terms of papers presented at annual meetings, only eight schools were more active in the period 1908 to 1912. In 1913, Gardner Anthony, the Dean of Engineering at Tufts, became the Society's president.[12]

Like many other smaller colleges that remained committed to undergraduate education, Tufts survived the transformation of higher education that occurred towards the end of the century. Given the accepted historiographical view that the older college, reluctant to yield its dependence on classical forms and standards, was repelled by the technical and the utilitarian, it is curious that Tufts should have harnessed its destiny to a school of engineering. That it did so successfully suggests both that these bastions of liberal culture were more innovative than they have been given credit for, and that engineering, as it grew within the schools, was far from indifferent to larger ethical questions beyond the purely technical and drew inspiration from unsuspected springs.

* * *

By any standard, Gardner Anthony was most articulate in interpreting the place of engineering in the school and its relationship with the liberal arts. Four years after he arrived at Tufts as a Professor of Technical Drawing in 1893, Anthony was made dean of the newly-created School of Engineering. Until 1897, the various engineering courses had lacked a coherent administrative identity and teaching had been dispersed among a faculty organized along traditional lines. Burgeoning enrollments, problems of scheduling, and the need to tailor courses to the particular requirements of engineering students, however, convinced the faculty to segregate engineering from liberal arts students. This occurred first in mathematics, later in French and economics; by 1903, even English was being taught to engineers in segregated classes. Carried out largely for administrative convenience, the segregation of the engineering from the liberal arts students touched sensitivities about the legitimacy of engineering as an academic subject and about its relationship to traditional liberal arts.

Anthony addressed these relationships in his 1914 presidential speech to the Society - titled, ironically, "Unity in Education."[13] The growing need for vocational training since the Civil War "has developed an issue between the so-called cultural and vocational courses...largely based on misunderstandings," Anthony explained. The addition of new subject matter, the abandonment of courses "formerly regarded as essential to academic education," and the decline of the lecture system and development of laboratory methods "have forced the higher education out of the cloister and into the market place with its attendant good and evil." Educators have been reluctant to abandon material "which was supposed to possess some inherent cultural value apart from its educational uses."

> This evil has been most noticeable in institutions out of which technical schools have grown and in which not infrequently a conflict between the two ideals has continued for years. It has resulted in a shallowness on the side of letters due to too great freedom in election, and a narrowness on the side of engineering due to too great specialization. [I]t would appear that the educational pendulum has now reached its extreme oscillation toward vocational education and is about returning toward that point which should mark a great unity in the objects of education regardless of the diversity of paths which must ever tend to become more divergent. May not the time be at hand...when we shall think less of educating engineering specialists and more of men, well trained in character as well as mind; when it will not be a question of Greek or thermodynamics but of the vest all-round training for the individual.

Three evils, according to Anthony, had resulted from the rapid growth of technical education. The first was the unfortunate division between the old and the new "resulting from a failure on the part of teachers to appreciate the difference in methods necessary to approach the two classes of mind"; the second attributed undue importance to subject matter alone; the third resulted from the overspecialization of engineering curricula. In his program at Tufts, Anthony sought to combat overspecialization through the formation of a general course for engineers which confined specialized work to the senior year. Closing the breach between engineering and letters proved more difficult. It was insufficient to shorten the arts course "so as to insure the getting of a cultural spray before immersion in a technical bath supposedly free from cultural germs...." The educator must be persuaded to "weave the thread of his specialty into the warp of other courses...," and thereby demonstrate that difference in method need not suppose a conflict of cultures. Anthony beseeched his audience to cooperate with one another and through coordination preserve the unity of higher education.

Anthony's prescription for health seems weaker than his diagnosis, but the deed proved wiser than the word. In one sense, his segregation of the curriculum at Tufts confirmed the deep divisions existing between the older, classically-oriented studies and newer vocational courses. But in another sense, it demonstrated the determination of academic engineers to dispute contemporary definitions of culture, to assert title to a new, enlarged, more relevant notion, still properly within the domain of the school. The boundaries of this new cultural domain were explored by Anthony's colleagues.

Samuel Chandler Earle had hoped to teach Anglo-Saxon to graduate students. The vicissitudes of the job market, however, brought him to Tufts where, by the time that Anthony was completing his curricular segregation, he had assumed responsibility for teaching composition to engineering students. English for engineers had become common in schools by the turn of the century as educators became concerned that their graduates lacked the facility with language adequate for an expanding institutional role. Earle struggled with the difficult task of engaging the interest of his charges who tended to dismiss language skills as the province of poets and dreamy scholars. By the teens, Earle's struggle against this ingrained prejudice had moved Tufts to the forefront of the movement to make engineers articulate.

Earle succeeded by discovering the importance of pedagogy. He agreed with Anthony that it was not enough for English instructors to "condescend" to bring the work of their students "as nearly as possible into line with traditional college teaching.

> To them any radical change in method or purpose is repugnant because they consider English as the last bit of salvage from the arts course remaining in the engineering school and as the only means of true culture in a curriculum otherwise hopelessly practical.(14)

The key to engaging the interest of engineering students consisted in crossing-over from one culture to another. The English instructor could thereby penetrate superficial differences in subject matter and method and act as both translator and interpreter. Earle required his young associates to spend a year as apprentices before entering upon serious teaching responsibilities. During this year, they were in charge of no classes, though they read student papers and held conferences and attended all the classes as "listener and critic." They were expected also to spend as much time as possible

> with the instructors of other departments that they may be in actual contact with engineering work, that they may know exactly what their students are doing in other classes, and that they many have the opportunity of looking on their own subject from other points of view.

Taking advantage of his "cross-cultural" opportunities, the instructor would be able to remedy certain natural deficiencies in the work of his technical students. The first thing he would note after entering the realm of the engineer, Earle tells us, was that much of their thinking was done "by means of visual images and symbols, and not in words." Since thought and language, he argued, are virtually inseparable, the instructor would note that the thought of the engineer - while abounding in the "language" of image and symbol - was inherently incomplete until carried to completion in the form of words. And at this point, the instructor could intervene most effectively. Again, much of the thinking of engineering students was carried on using objects themselves. Often, however, the engineer found himself with objects present only in thought and, once again, the opportunity was presented for the English instructor to assist the effort of translating the language of the object into verbal articulation. Not least, the "cross-cultural" visitation gave students the chance to express themselves to a listener (and interpreter) not privy to the tacit (and thus unspoken) knowledge shared by engineering student and engineering teacher.

Earle's efforts to move across boundaries and between language communities led him to perceptive insights into the manner in which different genres were mixing in schools at the turn of the century. The plurality of cultures encompassed by the technical school could be synthesized, so Anthony argued, only if faculty cooperated and Earle became the epitome of cooperation. It became his practice to discuss the written exercises of engineering students in the shops and drafting rooms. "This helps the students to think of English as a part of their technical training rather than as something which takes them away from engineering buildings." It also situated the interpreter within the "object-language" of the student. Surprising short-circuits could result. Earle told the story of the instructor who

> in talking over a character sketch in which the student has given simply the external appearance, is trying to lead the writer to see for himself other possibilities. The student does not catch the idea, when the instructor in drawing, who has overheard a part of the conference, asks, 'How about the dotted line?' and the student sees at once. Or, circumstances may be reversed. The teacher of drawing, in explaining something to his class, has occasion to pass from the consideration of graphic language to some point of verbal expression, and he immediately calls upon the English instructor for his opinion.(15)

How does one explain the not untypical concern of Gardner Anthony and Samuel Earle with language? Certain reasons seem obvious. Skill in French and German, for example, made accessible a large and rapidly expanding body of foreign literature in science and engineering. Facility in English - in both written and oral forms - was becoming a necessary accompaniment of the modern engineer called upon to transmit and interpret technical reports for corporate managers and a wider public. Moreover, one can still find in engineering journals not infrequent apologies for Greek and Latin as the distinctive marks of the educated gentleman and, therefore, appropriate adornments for the socially rising engineer. Some of this concern with language was frankly defensive in tone and consciously self-serving. It seemed an appropriate response to criticism that technical education was irredeemably materialistic, illiberal, and spiritually degrading.

But there were other reasons as well, not so apparent but equally important. The cross-cultural experiences of Earle and Anthony suggest that engineering educators were, in fact, aware that the artifacts of engineering constituted a form of language with esthetic, ethical, and instructive possibilities every bit as real as those residing in the discourse of more bookish disciplines. Earle's insights into the nature of engineering language have been rediscovered by recent historians, among them Eugene Ferguson and Anthony Wallace. In an important article published in 1977, Ferguson documented the nonverbal nature of engineering throughout most of its history, charging that the recent emphasis on the abstract was cutting engineering off from the roots of its creativity.[16] The thoughts of Anthony Wallace about the "language" of engineering are rooted in his attempt to reconstruct the material culture of the early nineteenth-century mechanics responsible for building the machinery of the textile mills in the Delaware Valley.[17] "The work of the mechanician was," he notes, "in large part, intellectual work."

> This was true in spite of the fact that he dealt with tangible objects and physical processes, not with symbols, and that some of what he did was done with dirty hands. The thinking of the mechanician in designing, building, and repairing tools and machinery had to be primarily visual and tactile, however, and this set it apart from those intellectual traditions that depended upon language, whether written or spoken.

What distinguished the work of the academic from that of the mechanic was not only different media, but different grammars. In highly abstract and symbolic languages, the formal grammar is given _a priori_. For the mechanical "linguist," it is the grammar itself that remains to be constructed.

> To the mechanical thinker, the grammar of the machine ...is the successive transformations of power - in quantity, kind, and direction - as it is transmitted from the power source (such as falling water or expanding steam), through the revolutions of the wheel, along shafts, through gears and belts, into the intricate little moving parts, the rollers and spindles and whirling threads, of the machine itself.

Wallace believed that verbal and mechanical languages were distinguished in other ways as well. More abstract and formalized languages were associated with the school; facility with the mechanical medium was transmitted through the tacit understanding of master and apprentice, created in the workshop and rooted in example and demonstration. Solutions to problems, both traditional and innovative, could be embodied in concrete models that served as archetypes to be multiplied and transmitted.[18]

Nevertheless, the inventors, mechanics, and engineers of the early part of the century, "linguistically" skilled though they might have been, were articulate only in a restricted sense. By the end of the century, the academic engineer, in contrast to his earlier untutored cousin, was becoming multilingual. While he did not abandon the tactile skills of his predecessor, he did accumulate in addition a variety of mathematical and scientific languages which were the province of an academic environment.

* * *

What Wallace and Ferguson have told us recently, Anthony and Earle knew at the turn of the century. Given the precarious position of academic engineering within an evolving school and the sensitivity of engineers to claims of culture, it is not surprising that men like these should have articulated the linguistic qualities of technical expression and promote, thereby, their claims to a new species of culture. After all, had it not been the role of the college in its transmission of culture to promote expertise in esoteric languages and skill in the translation and interpretation of texts? Both the inherent nature of engineering artifacts as well as the institutional pressures felt by professionalizing educators, then, underlie the growth of academic engineering. Anthony was an academic engineer precisely because he could move from one language community to another and use that mobility as an argument for the value of engineering as a practical as well as a "culture study" and liberal art. The Columbian Exposition envisioned the accommodation of culture and the technology of power. Academic engineers like Gardner Anthony bore the responsibility for achieving that accommodation. To appreciate the synthesis they desired, we need to understand how engineering grew articulate in the context of the school, the nature of its primary "texts" and "translations," and their implications for the transmission of engineering knowledge.

The chief architects of the Tufts program were Amos Dolbear and William Hooper, the pioneers of the electrical course, William Ransom, who taught its mathematics, and, of course, Gardner Anthony, who guided the program to national prominence.

NOTES - CHAPTER ONE

1. Alan Tractenberg, *The Incorporation of America* (New York: Hill and Wang, 1982); especially, "The White City."

2. For Van Brunt, see "Architecture at the World´s Columbian Exposition" in the *Selected Essays of Henry Van Brunt* (1969), ed. by William A. Coles. The descriptions of the exhibits are to be found in *A History of the World´s Columbian Exposition* (1895), vol. two, "Department of Electricity."

3. W. S. Munroe, "The Power Plant at the World´s Fair," *Engineering Magazine* 5 (1893): 672.

4. For Henry Adams, see "The Dynamo and the Virgin(1900)" and "Chicago(1893)" in *The Education of Henry Adams*.

5. *A History of the World´s Columbian Exposition* (Chicago: World´s Columbian exposition history co., 1892-). Vol. Four, p.496.

6. Statistical information on engineering has been drawn from a variety of sources: "Report on Engineering Education," *Transactions of the Society for the Promotion of Engineering Education*[SPEE], Vol. 1, 1928-29; C. R. Mann, *Study of Engineering Education* (1918), pp. 6-7, published as *Bulletin #1* of the Carnegie Foundation for the Advancement of Teaching; presidential address by Ira O. Baker, *SPEE* 8 (1900); in general, the transactions of the Society contain much material on its history.

7. For secondary material on the history of engineering, see especially Edwin Layton, *The Revolt of the Engineers* (Cleveland: Case Western Reserve Univ. Press, 1971), Monte Calvert, *The Mechanical Engineer in America, 1830-1910* (Baltimore: Johns Hopkins Univ. Press, 1967), Daniel Calhoun, *The American Civil Engineer* (Cambridge: MIT Press, 1960), Michael McMahon, *The Making of a Profession: A Century of Electrical Engineering in America* (New York, 1984), and David Noble, *America by Design* (New York: Oxford Univ. Press, 1977).

8. For a sense of the issues that preoccupied SPEE members, see the addresses published in the *Transactions*.

9. Frank O. Marvin, SPEE (1901): 15; Calvin Woodward, SPEE (1903): 26,28; F. W. Hamilton, SPEE (1912): 30-31.

10. Russell Miller, *Light on the Hill. A History of Tufts College 1852-1952* (Boston: Beacon Press, 1966): 76.

11. See the enrollment figures in the annual reports of Tufts College.

12. These statistics are based on a survey of papers presented at SPEE meetings and of SPEE membership lists.

13. SPEE 22 (1914).

14. Samuel Earle, "English in the Engineering School at Tufts College," SPEE 19 (1911): 33-47; for biographical information on Earle, see Gardner Anthony, "Samuel Chandler Earle," Tufts College Graduate 15 (1916-17): 187-194.

15. Ibid pp. 43-44.

16. Eugene Ferguson, "The Mind's Eye," Science 197 (1977): 827-836.

17. Anthony Wallace, Rockdale (New York: Norton, 1980), pp. 237-239.

18. For the importance of models in the process of invention, see Brooke Hindle, Emulation and Invention (New York: Norton, 1983).

CHAPTER TWO:

THE IDIOMS OF ENGINEERING AT A SMALL COLLEGE

Some time during 1880-1881, Tufts College received as a gift a small Gramme dynamo and a five-horsepower steam engine to run it. This first dynamo served as the seed crystal around which crystallized the program in electrical science. The following year, William Hooper joined the faculty as assistant professor of physics, Thomas Edison began operation of the world's first central power station on Pearl Street in New York, and the Physics Department announced in the catalogue that

> the facilities which the new electrical machine and engine will furnish render it desirable that a course of study should be arranged in Electrical Engineering for such students as desire to pursue the subject. The demand for competent electricians is much greater at present than for engineers in any other department, and only a few institutions in the country are prepared to give the necessary instruction.(1)

Hooper studied earlier with Amos Dolbear, a pioneer in telephony and the mainstay of the Physics Department, graduating in 1877. He earned his A.M. in a fifth year at the College before becoming principal of Bromfield Academy at Harvard. Upon returning to his alma mater to assume primary responsibility for the electrical course, Hooper faced the daunting challenges that confront any pioneer, bringing to his task enthusiasm and a talent for teaching. His career at Tufts would last thirty-five years.

His immediate requirements were three-fold: space for his program, the accumulation of necessary equipment, and a curriculum. Located first in Ballou Hall, the earliest and, for many years, only academic building on campus, the "electricals" shared the quarters of the physics students. They used the physics lecture room in the northeast corner of the third floor, a laboratory that extended on either side of the lecture room, and a small workshop next to the stairs. Growth forced expansion within a few years into the basement, where Hooper established dynamo and measurement laboratories, and confiscated a small room for a large sixty-cell storage battery purchased second-hand from the Somerville Electric Light Company in 1890. His search for space was so successful that "within a few years Professor Dolbear regretfully announced that he could no longer offer laboratory work in Physics because the electrical engineering students had appropriated all the space."[2] Growth during the next decade was severely restricted by the lack of space, though some relief was provided in 1893 by the establishment of the Bromfield-Pearson School which offered an abbreviated course of technical studies for local students and which took over much of the shopwork and drawing responsibilities of the engineering courses. In 1900, Robinson Hall, the site of engineering for the next thirty-nine years, was constructed with the help of a six-year-old gift come to belated fruition.[3] The electrical course was formally designated a department in 1891 and was organized in 1898, along with the other engineering courses, into the School of Engineering under the leadership of Gardner Anthony.

The character of early engineering instruction was rooted in its workplaces. The original dynamo lab in the basement of Ballou Hall had been lit by a few carbon filament lamps and possibly by one or two gas jets, as gas was the primary source of light throughout the building.[4] An assortment of dynamos was mounted on pine frames and driven from a shaft on the wall which was, in turn, driven by a twenty-five horse power steam engine located elsewhere in the basement. The largest of the dynamos was a three-ton, fifty cycle, single-phase, fifteen kilowatt generator connected directly to the steam engine through a clutch. Smaller generators supplied three-phase current and 110 volt direct current. Two railway motors, supposedly donated by the West End Railway in Boston, could be coupled together for motor-generator tests. Much of the equipment had been built by Hooper himself with the help of student, often in the pursuit of theses.

The shop was, indeed, a crucial facility for the Electrical Department. In those years, the College simply lacked the money to purchase even much less expensive equipment than that required for electrical engineering. What was not donated (often because it was no longer useful to the donor) frequently was built in house. For engineering students, this was a necessity that proved a blessing and gained for them experience in the construction and maintenance of machinery that stood them in good stead after they left school. The shop in Ballou Hall was located on the third floor in a small room that originally housed the Physics Office and contained a variety of lathes, grinders, shapers, and planers, all driven from an over-head shaft.[5]

When the department moved into its new quarters in Robinson Hall in 1900, it acquired an assortment of new machinery, much of it contributed by the General Electric Company. From GE came a new DC-generator to provide power for the Laboratory although, ironically, it was several years before the machine was installed and in the interim the building was lit by gas. Eventually, single-phase alternating current was supplied to the Laboratory from off-campus by the Edison Electric Company. To a large degree, the arrangement of machinery in the new dynamo laboratory was reminiscent of the old. Situated parallel to the wall, the machines were belt-driven from a wall-mounted shaft clutched in the middle to provide some flexibility in the operation of the machines. Unlike the old lab, the machinery in Robinson Hall was driven ultimately not by steam, but by electricity generated by the new GE generator.

Between acquiring and equipping labs for an expanding program, Hooper developed a curriculum. The initial course of study was three years in length, expanded to four in 1892. In its first years, students studied algebra, solid geometry, and trigonometry, shopwork, drawing, surveying, inorganic chemistry, and French. Analytic geometry and calculus were introduced in the second year, and trig continued. In shop, students worked on machine drawing, filing, turning, and screw-cutting; and they began the study of physics and mechanics, spending three hours a week in the physics laboratory. They explored the theory and construction of the steam engine and spent, in the first semester, four hours a week in the study of rhetoric. Calculus continued the third year, and students were introduced to "mathematical electricity" in the lecture room and to electrical measurements, the telephone, telegraph, lighting, plating, and power transmission in the laboratory. In this final year, they sampled natural history including physiology, zoology, and geology, and concluded their course of study with a thesis. Tuition for the program was a hundred dollars a year, and room and board another several hundred dollars. Students were originally granted the degree of Bachelor of Mechanic Arts with the designation "Electrical" on their diplomas. The degree was revised to "Bachelor of Electrical Engineering" when the course was expanded to four years in 1892.[6]

During the next thirty years, Hooper´s curriculum kept pace with the changes affecting the electrical industries generally. The dramatic growth of central power highlighted the importance of alternating current and placed a premium on the more sophisticated mathematical treatment it required. Engineering practice was becoming increasingly fragmented and specialized, and the corporate presence loomed ever larger on the student´s horizon. Pressures increased to include a burgeoning variety of subjects within a curriculum becoming ever tighter, not only new specialties but new concerns such as economics and management. The outlines of the electrical course, nevertheless, remained familiar on through the turn of the century. In particular, while students no longer needed to construct much of their operating equipment, the course retained the emphatically tangible qualities that derived from the key role of the shop and laboratory.

By 1909, students moved more quickly through the prescribed courses in mathematics. The second half of the freshman year was devoted to the elementary calculus; calculus continued through the second year and included an introduction to differential equations. Physics was advanced to the latter half of the first year and extended through the first semester of the junior year, dealing in order with mechanics and sound; electricity, magnetism, and light; and mechanics and heat. During the sophomore year, students spent six hours a week in the Physical Laboratory. Drawing expanded its importance in the curriculum and aimed, in the words of the catalogue,

> to give a broad and exact training in the language of graphics; to teach the principles of its construction, its technique, and the art of expression by this medium. It is designed to give the student such practice as shall enable him to use this language with fluency whenever and wherever it may serve better than a written or spoken language.

The first course in drawing touched on the use and care of drafting instruments, geometrical construction, orthographic projection, and the drawing of simple parts of machines. Sophomores studied the techniques of graphic expression, the transmission of information from drawing to constructor, the application of graphical methods to the problem of mechanical movements, and descriptive geometry. As juniors, electrical students continued the study of mechanisms from a mathematical and graphical standpoint, concluding the year with simpler exercises in design.

Shopwork, begun the first year, was meant to provide not only knowledge of the mechanical processes and materials of construction, but by means of exercises in hand and machine toolwork the formation of "habits of precision and the development of judgement essential to the engineer." Freshmen learned the use of wood-working tools, the lathe, pattern-making, and the principles of foundry practice. The first two years were rounded out with English, French or German, General Chemistry, and physical training.

Juniors studied the mathematical and graphical treatment of the strength of materials throughout the year, in the classroom and the laboratory. They investigated the steam engine (with thermodynamics as an elective), and qualitative chemical analysis. They began intensive work in electrical subjects during the first part of the year with a course in electricity and magnetism accompanied by lab work in measurements. The first courses sponsored by the Electrical Engineering Department were "Electrical Laboratory" and "Dynamo Electric Machinery" offered in the second half of the year. Testing, the calibration of instruments, the study of arc and incandescent lighting, the storage battery, and the magnetic properties of iron occupied lab work and complemented the work of classroom. The senior year culminated in a year-long investigation of the design, construction, and operation of direct and alternating current machinery, supplemented by Hooper's course on their mathematics and physical interpretation. The four years were capped by a semester of hydraulic engineering covering watersheds, canals, water-wheels, and turbines, a course in political economy dealing with the "more important problems of industrial society," and a final thesis project.[7]

If the electrical course changed during the thirty-five years of Hooper's leadership, it also stayed the same. In an enduring fashion, the program pivoted on the artifacts and instruments of power - the machinery and tools designed to generate and control, above all, the dynamo. The shop and laboratory were the context in which students became familiar with these machines, and mathematics, physics, and graphics were the interpretive languages in which the experience of these sites was shared and transmitted. These features will repay our closer attention if we seek to understand the accommodation of power, culture, and school at which Tufts engineers arrived at the end of the century.

* * *

Physics was the first of this trinity of interpretive languages. With physics, electricals acquired the conceptual foundations essential to understanding electrical phenomena and early courses in electrical engineering more often than not developed under the wing of physics departments. The typical physics text guided students through mechanics, sound, heat, magnetism and electricity, and light, utilizing only elementary mathematics and composed very much in the spirit of Faraday and Kelvin. By the second decade of the new century, texts had begun to reflect the revolution in modern physics brought about by relativity, but earlier presentations were still couched in a mechanical idiom that sought "to explain all physical phenomena by means of motions, that would ultimately reduce the whole of heat, electricity and all physics to mechanics."[8] The mechanical view of nature has roots reaching into the seventeenth century but was more recently invigorated by the formulation of the conservation of energy and the success of the kinetic theory of gases in the nineteenth century. Scientifically fruitful, mechanism was a style of natural philosophy very much at home in the Britain of the Industrial Revolution and was famously characterized by Pierre Duhem as abounding with "strings which move around pulleys, which roll around drums, which go through pearl beads, which carry weights;

> and tubes which pump water while others swell and contract; toothed wheels which are geared to one another and engage hooks. We thought we were entering the tranquil and neatly ordered abode of reason, but we find ourselves in a factory.(9)

The British proclivity for mechanism was undoubtedly less crude than Duhem suggested. It did, however, offer a happy style for engineers seeking to understand the behavior of machines.

At Tufts, it was Hooper's teacher Amos Dolbear who set the mold for instruction in physics. Presiding over his department from 1874 to his retirement in 1906, Dolbear was a man of many talents. An undergraduate at Ohio Wesleyan, he received masters in arts and in engineering from Michigan in 1867. Before coming to Tufts, he worked as an assistant professor of natural history at Kentucky, a professor of physics and chemistry at Bethany in West Virginia, and served as the mayor of Bethany in 1873.[10] He achieved fame as an inventor, improving Bell's telephone, and experimenting with wireless telephony in the early eighties before Hertz's experimental discovery of electromagnetic waves. He achieved aerial transmission over short distances by means of an electrostatic device in which the plates of a condenser acted as an antenna.[11]

To Hooper, Dolbear seemed as much philosopher as physicist, with views that were wide-ranging and synthetic. Dolbear, indeed, revived the phrase "natural philosophy" in describing what he did. While he lacked Hooper's feel for detail and his practicality, his cosmic appreciation of the whole of nature excited his students. He compiled an experimental manual for physics, chemistry, and natural history utilizing the "magic lantern"; he wrote treatises entitled Matter, Ether, and Motion. The Factors and Relations of Physical Science and Modes of Motion, Or Mechanical Conceptions of Physical Phenomena; and authored an elementary textbook on natural philosophy. He was, not surprisingly, an ardent admirer of Herbert Spencer. He lectured to the Divinity students on Spencer and taught the conservation of energy to seniors in physics from Spencer's First Principles. He explored the nature of the ether, devised mechanical models for the combining of molecules à la Kelvin and his ring-vortices, and made forays into the realm of the psychical, speculating that thought transference might be due to brain "fields" in resonance.

Mechanism and the conservation of energy were the organizing principles of the physics Dolbear taught his students. While modern science was busily extending Newtonian principles beyond the visible realm to the invisible world of imponderable matter, latent heat, electric fluids, atoms, and molecules - the canons of intelligibility remained constant.

> ...it has become apparent that however different one phenomenon is from another, the factors of both are the same, - matter, ether, and motion; so that all the so-called forces of nature, considered as objective things controlling phenomena, are seen to have no existence; that all phenomena are reducible to nothing more mysterious than a push or a pull.(12)

A complete account of a physical event, then, would consist of the changes of the matter in motion as one followed the process through its thermal, electrical, magnetic, or chemical stages. Within this sequential context, a "machine" was defined as

> a collocation of matter having for its function the transference or the transformation of motion, or both. An atom or a molecule, then are as much machines as a steam-engine or a dynamo; and every molecule in the universe, whether near or remote, is constantly receiving and transforming energy through its individual motions. What the particular phenomenon will be in a given case depends upon the form of the motion received by the mechanism and the new form which the latter has made it to assume.(13)

To account for an event, therefore, was to articulate the underlying "machinery."

One sequence of machines possessed particular paradigmatic importance for Dolbear and for engineering students.

> ...suppose we have a series of active machines. An

> arc lamp, radiating light-waves, gets its energy from the wire which is heated, which in turn gets its energy from the electric current, that from a dynamo, the dynamo from a steam-engine, that from a furnace and the chemical actions going on in it.... The product of the coal is molecular motion called heat in the furnace. The product of the heat is mechanical motion in the engine. The product of the mechanical motion is electricity in the dynamo. The product of the electric current is light-waves in the ether.(14)

For Dolbear's students, this sequence, prominently displayed on the front cover of Modes of Motion, was thoroughly familiar from their work in the dynamo laboratory. In a practical sense, it comprehended the basic vocabulary of the machines and processes in which the young engineer would need to be expert upon leaving school and starting work. It demonstrated the mechanical syntax - the grammar of interconnections - that structured the transformations of energy the engineer was called upon to master. Illustrative of the basic linguistic elements central to the engineer's universe, Dolbear's sequence was paradigmatic for his students in the same way that tables of verb conjugations were paradigmatic for their colleagues in Latin and Greek. To be sure, this rudimentary object-language went little further than the less academic knowledge exercised by Wallace's mechanics. But the academic engineer acquired along with the mechanical paradigm something more - the more formal, abstract language of physics. Not only did the sequence define the practical boundaries of engineering work, it illustrated as well the major areas of late nineteenth century physics. Dolbear thus provided his students with a scheme by which they could translate the object-language of the mechanics into the formal language of physics, and back.

* * *

Dolbear's paradigm of physical science was only one of the languages available to engineering students. Another was drawing or, as Gardner Anthony came to call it, the Graphic Language. Anthony had been a student both at Tufts and at Brown before going to work as a mechanical engineer. At the Brown and Sharpes plant in Providence, he received "as excellent a training as was then available, especially in mechanical drawing and design...."[15] In 1885, he founded the Rhode Island School of Design and, two years later, the Rode Island Technical Drawing School. He came to Tufts in 1893 as Professor of Technical Drawing and Dean of the Bromfield-Pearson School. In 1898, he was made dean of the new School of Engineering. He authored an abundance of texts, including *A Text-Book of Mechanical Drawing*, *Elements of Mechanical Drawing*, *Machine Drawing*, *The Essentials of Gearing*, *Descriptive Geometry*, and *An Introduction to the Graphic Language*.

Technical drawing was inspired by the Industrial Revolution and the growth of engineering. Craftsmen had always needed the capacity to transmit knowledge from person to person and place to place. In the eighteenth and early nineteenth centuries, this transmission was usually accomplished by the movement of skilled persons, instructing students by example, relying for aid upon models and whatever illustrations might be needed.[16] The demands of mass production and the division of labor, concurrent with the rise of the factory system, drove a wedge into the shared experience that made emulation and apprenticeship the dominant vectors in the transmission of technical knowledge.[17] As a result, precision drawings, themselves able to be mass produced after the invention of blue-printing, came to displace the tacit knowledge of design, the know-how, that was passed from master to pupil. Furthermore, as the division of industrial tasks progressed, the relationships between co-workers became less personal and more distant. Thus Anthony could say of the mechanical drawing which marked the mature stages of industrialization: "A drawing should be regarded as a business letter to the mechanic...."[18]

By the century's end, engineers had developed a variety of systems for the depiction in two-dimensions of three-dimensional objects. Descriptive geometry was developed by Gaspard Monge in the 1770's and 1780's. His highly abstract, axiomatic approach formed the basis of technical drawing on the Continent. British engineers preferred the simpler, more practical systems of isometric and orthographic projection developed by Farish, Binns, and Davidson later in the nineteenth century.[19] Americans used all of these systems as well as freehand drawing and a repertoire of techniques developed by architects. Though little has been written of technical drawing in the United States, it appears that academic engineers, especially earlier in the century, preferred drawing à la Monge, a preference probably due to the strong French influence in the early engineering schools; while more practical-minded engineers inclined towards the British systems.

While the nineteenth century witnessed a slow movement towards standard usage, it was a progress not uninterrupted by disputes. Usually highly technical, they revolved around such issues as - Should the engineer first become proficient in the fundamental geometrical axioms of the subject, before considering the object? Or should he work the other way round, acquiring first a workable picture of the object and afterwards considering its projections onto different planes? Their preferences in the matter were determined, in part, by social position and the expectations of their audiences. Mathematicians who taught drawing frequently advocated a solid foundation in descriptive geometry as a prerequisite for practical work, and usually touted the virtues of mental discipline rooted in the geometry of drawing.

Whatever their individual preferences, most drawing teachers in the United States would have agreed that drawing constituted a fundamental human language and it was here that Anthony made his name. His emphasis on "language" allowed him to fashion an approach to mechanical drawing that appealed both to practical engineers concerned with the transmission of information from worker to manager, and to educators committed to engineering as a "culture study." Drawing, as Anthony put it, was a graphic language whose laws the student could study just as he studied the laws that governed French or German. And as a language, it possessed

> ...its orthography, grammar, and literature. Its orthography, consisting of the various types of lines, its grammar being the art of representing objects upon

> planes, and known as orthographic projection; and finally its literature, consisting of the practical application of these principles to the drawings which we are required to read and write.

Moreover, the student's understanding of the graphic language must extend beyond mastery of its basic structural rules, for

> ...in this, as in all languages, we cannot be governed entirely by laws, but must familiarize ourselves with the idioms and conventional methods of our day, remembering always that it is simply a medium for the expression of our thought.(20)

Anthony's 1922 book, An Introduction to the Graphic Language, was based on the introductory lectures which he taught for many years at Tufts. Throughout these lectures, Anthony related technical drawing to the history of the arts and sciences, reminding his listeners that "Leonardo da Vinci was one of the greatest engineers that the world has known...."[21] He first introduced the "reading" of simple pictorial illustrations, perspective, maps, isometric representation, and the different "vocabularies" involved. After discussing the limitations of the simple systems (for instance, the inability to take direct measurements from lines in the drawing), he presented the more complex, and useful, grammars of perspective and orthographic projection, before proceeding to idiomatic graphics, technical sketching, and the graphical interpretation of numerical relationships, noting that

> Any collection of related facts is difficult to grasp when expressed by figures in tabular form, but the same may be seen at a glance when presented by one of the many methods for the graphic representation of these ideas.(22)

Having presented the basic elements of the reading of drawings, assorted vocabularies, and essential grammars, Anthony concluded with the topic of penmanship. He meant not simply lettering, but the wide range of techniques through which an author transcribed ideas onto paper with the help of such instruments as the pencil, foot rule, triangle, compass, T-square, drafting-board, and graph paper.

The emphasis on drawing as a language of utility and beauty, characterized by its instruments, was common among engineering educators. Thomas French, a professor of engineering drawing at Ohio State, spoke in much the same way:

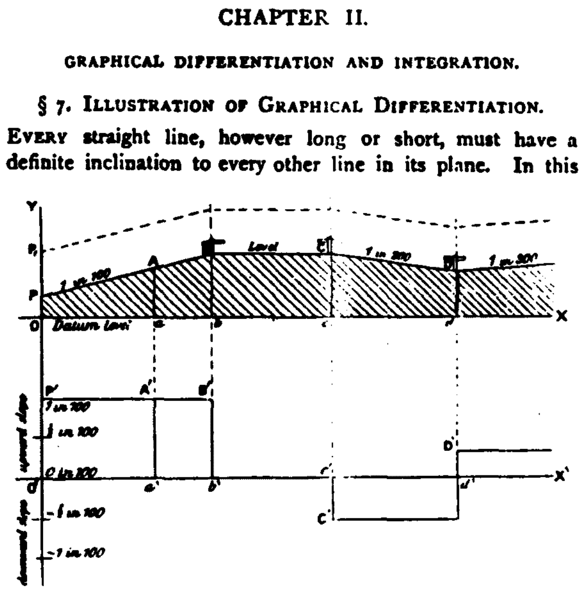
> The analogy between drawing and language is often referred to. I prefer to go farther in saying that drawing, as a mode of thought expression, is a real and complete written language...and that in teaching it we are not only preparing the student in a subject needed in his course but, from the very nature of it, have in our hands an exceptional cultural subject for strengthening the power and habit of exact thinking, that most difficult of all habits to fix, and for training the constructive imagination, the perceptive ability which enables one to think in three dimensions, to visualize quickly and accurately, to build up a clear mental image. ...As one has said it, it is 'the power and habit of observing accurately that marks one of the fundamental differences between the incapable man and the man of power.

Drawing would cultivate not only clear thinking, but through the power it awoke, would become "drawing in relation to life."[23]

Both the drawing they learned from Anthony and the physics they learned from Dolbear were couched in tangible and graphic terms, and focussed on the evocation and control of power. This proclivity for the concrete, graphic, and instrumental was found as well in the mathematics they learned.

* * *

In his 1896 work on the graphical calculus, Arthur Barker of Yorkshire College introduced his subject in the following manner: picture, he suggested, the elevation of a section of railroad consisting of a sequence of linear gradients. Most railroads, Barker noted, indicated the gradient of lines on signs off to the side of the tracks, with the rise or fall (1 in a 100, e.g.) posted on appropriately slanting arms. Beneath the profile of such an elevation, Barker drew a another series of lines expressing the slope of the section of railway immediately above. The lower set he called "the derived curve" of the upper set of lines, with the height of the lower at any point giving the "differential coefficient" of the upper set at the corresponding point.



CHAPTER II.

GRAPHICAL DIFFERENTIATION AND INTEGRATION.

§ 7. ILLUSTRATION OF GRAPHICAL DIFFERENTIATION.

EVERY straight line, however long or short, must have a definite inclination to every other line in its plane. In this

"...the railway companies, by means of boards...really ´differentiate´ the curve of the railway for the information of the engine-drivers."[24] Barker promised the student who mastered this engine-driven calculus little trouble with the remainder of his text.

Such graphic treatment of the calculus would have seemed eminently sensible to another of Anthony´s colleagues. The story is told of William Ransom, the Professor of Mathematics, that he once noticed a spider "taking things in from his point of vantage on the wall." Hurling a textbook "with his usual engineering precision," he killed the spider "dead in his tracks. Turning to his admiring class he said with a smile, ´That is what I call applied mathematics.´"[25]

Ransom graced the Tufts faculty with humor and dedicated teaching for a half-century from 1900 to 1950. His parents had been married by a president of the College and seven members of his family preceded him there as students before he earned his bachelor´s and master´s degrees in 1898. He added a master´s degree in mathematics from Harvard in 1903. Like Dolbear, Ransom´s activities at Tufts were energetic and wide-ranging. While mathematics was his primary responsibility, he also taught physics, astronomy, alternating currents, and navigation to the merchant marine during the Great War. He was not a gifted mathematician, as he himself admitted, but he was an outstanding teacher and eight of his students went on to become heads of departments. He taught Norbert Wiener ("Never again at Tufts," Wiener remembered, "did I have a math course that demanded so much of me.") and Vannevar Bush who believed his courses with Ransom were among the most valuable he ever took. Ransom especially loved to teach mathematics to those who found it mysterious and authored a large number of books for the beginner, among them, Calculus Quickly, Graphical Analysis, Rapid Analytics, Algebra Can Be Fun!, and Pastimes With String and Paper, offering for sale a slide rule - "Easy to Cut and Fold. Full Directions for use. Ten inch scales for multiplication, division, squares and roots, logarithms, and solving right triangles and oblique triangles by the sines. A nickel and a dime for each, ten for a dollar."[26]

Ransom lacked no interest in pure mathematics. Indeed, the course for which Bush remembered him dealt with non-Euclidean geometry and the four-dimensional vector analysis of special relativity. Nevertheless, even his interest in pure mathematics reflected the instrumental and graphical style that pervaded the engineering curriculum. His interest in projective geometry led him to translate Rudolf Böger's 1910 Elements of the Geometry of Position. Of the two advanced dissertations he supervised between 1910 and 1920, one was a translation of Heinrich Liebmann's Nicht-euklidische Geometrie; the other, a study by Llewellyn Perkins entitled The Planar Representation of Spherical Surface Figures. Perkin's dissertation attempted to solve a number of common difficulties in the depiction of three-dimensional objects in texts. His remedy was two-part. The first involved a series of axioms dealing with the construction and projection of such illustrative figures; the second demonstrated several simple devices for accurately drawing figures on paper and blackboard.[27]

If Ransom's research interests embodied a fascination with instruments and representation, so did his mathematical pedagogy. From the first courses in trigonometry and algebra though analytic geometry and calculus, he stressed both the graphical interpretation of functions and the use of mechanical aids in problem solutions. In fact, he claimed to have been the first to introduce the slide rule into freshman mathematics.[28]

He taught calculus from texts he wrote and lithographed himself. In the "Foreword to the Student" from his Early Calculus of 1915, he described calculus as dealing with the variation of quantities. The notions of "rate of increase" and "instantaneous value" should be made clear by an abundance of illustrations drawn from daily life. Problems were not to be solved by the substitution of data into special formulas but "by the application of general principles.

> Each one must be clearly conceived and analyzed in the mind, and usually a diagram must be drawn and dimensioned before one can begin to write the algebraical and numerical parts of the solution.

Having first defined "function," Ransom offered his readers examples of pairs of independent and dependent variables: an angle and its cosine, the time a train has run and the distance travelled, a number in the margin of a table and its correspondent in the body of the table, the 'x' of a point on a curve and its 'y'. He illustrated the derivative of a function with tabular, graphical, and formulaic examples. The derivative was the slope of a curve at a point and the formulas for differentiation were derived by the manipulation of "little zeros."

Ransom's presentation of the calculus should be contrasted with the traditional approach of Isaac Todhunter. Todhunter's *Treatise on the Differential Calculus and the Elements of the Integral Calculus with Numerous Examples* was first published in 1852 and went through ten editions by 1885, with four more posthumous editions by 1923. His text was geared to the Cambridge Examination papers and was, understandably, more rigorous and sophisticated than Ransom's work for the engineering students at Tufts. Though the text precedes Ransom's by some six decades, the treatment is logically sounder and he initially eschews the use of differentials, treating dy/dx as a unitary quantity and not as a fraction. Yet, while more rigorous, there is in Todhunter's treatment little sense of the enormous applied value of the calculus and virtually no examples or problems dealing with concrete situations. He recognized that the student might be "discouraged at the outset because he cannot discover or imagine any *practical application* of the somewhat abstruse points to which his attention is directed." The student must be assured "that the difficulty of which he complains is probably owing, much more to the nature of the subject than to his own want of comprehension," and though applications would come in good time,

> in reading a work on the Differential Calculus, he must be satisfied at first with reflecting upon the meaning of the definitions, and examining whether the deductions drawn by the writer from those definitions are correct.(29)

There was little attempt in Todhunter to encourage the student to interpret the calculus as a tool of everyday life. His text, appropriately, lacked the graphical slant of those meant for engineers. Even geometrical diagrams of the sort a British schoolboy would know by heart were few and far between. The first spare diagram only occurs, in fact, after Todhunter has explained differentiation and illustrates the differential coefficient. What Ransom defined as "acceleration," Todhunter defines as "the degree of rapidity with which the function varies when the variable begins to vary from any assigned value."

Todhunter would have disagreed with his countryman Barker and Ransom both about the pedagogy proper to mathematics and the audience to whom it should be taught. The dispute highlights an important division in turn of the century mathematics and had serious implications for the development of engineering.

* * *

Like physicists and chemists, mathematicians in the United States in the decades following the Civil War saw new opportunities in the transformation of higher education. Daniel Gilman's success in luring J. J. Sylvester to Johns Hopkins in 1876 marked a significant strengthening of the U.S. mathematical community. The founding of the American Journal of Mathematics in 1878 by Sylvester and W.E. Story provided a vehicle for original work as well as a means by which the work of Europeans could be brought to Americans. Additional encouragement for research came when the American Mathematical Society was founded by Thomas Fiske in 1888 and its Bulletin in 1891. Along with this awakened interest in original work, went the emigration of American students to European and especially German schools. By 1900, strong programs in mathematics had been established at Hopkins, Harvard, Yale, Columbia, Clark, and particularly the University of Chicago under the leadership of E.H. Moore and his colleagues Oskar Bolza and Heinrich Maschke.[30]

As the institutional support for mathematics developed, the topics which attracted the interest of mathematicians changed character. Throughout the first three-quarters of the nineteenth century, published work reflected the practical needs of a developing country, concentrating on such matters as algebra and geometry, astronomy, mechanics, and surveying. These were skills which, in the words of two noted historians of U.S. mathematics, depended heavily on "careful observation, accurate computation, and the observance of certain established rules, together with elementary computations."[31] After 1875, the comfortable association of mathematics with astronomy and natural philosophy loosened and the interest of mathematicians shifted to more abstract topics such as analysis, the theory of functions, and more formal algebras and geometry. To be sure, this only parallels a similar growth of disciplinary independence and research in science generally at the end of the century. Nevertheless, the thoroughly pragmatic relationship which had existed between mathematics and the arts and sciences was profoundly altered. Consequently, American mathematicians were growing more isolated just when their colleagues in the natural sciences were feeling the need for more sophisticated mathematical tools. The pendulum of mathematical interest had swung towards application in the seventeenth and eighteenth centuries, reaching "the limit of oscillation in that direction in the first half of the nineteenth century; ...about 1875 it had definitely begun to swing to the side of pure mathematics; and...in the period ending with 1900 it...reached the limit of movement in that direction."[32]

There were forces helping that pendulum reverse its direction. It was engineers who complained first and loudest about the growing abstraction of mathematics and it was in England that the voice of reform was earliest heard. The country first to industrialize, England's early success had depended on the entrepreneurial enterprise of self-taught inventors who thrived in the rough-and-tumble economy of the late eighteenth century. By the middle of the next century, however, Europe had begun to challenge British industrial supremacy, drawing strength from economies more centralized, state-supported, and open to the contributions of technical education.[33]

John Perry was the most aggressive of the British reformers. Perry echoed earlier criticisms that British schools, dominated by the traditional classicism of Oxford and Cambridge, failed the technically-oriented students on whom the nation's industrial strength rested. Also to blame were overly-conservative engineers who believed academic training superfluous, that students could acquire necessary education in the factory and through apprenticeship. British conservatism had begun to crack by midcentury with the stirrings of reform at the two older schools and the founding of the first civic universities.[34] Despite new provisions for technical education, however, mathematical teaching remained in the shadows of the established models. It was here that Perry applied his reforming zeal.

Perry had received his early schooling at Queen´s College in Belfast. Between 1870 and 1873, he taught physics at Clifton College where he claimed to have established the first experimental workshop in England. From 1873 to 1875, he was an assistant to Kelvin in Glasgow before moving to Tokyo to help the Japanese establish a school of engineering. In 1882, Perry joined H.E. Armstrong and W.E. Ayrton at the three-year-old Finsbury Technical College in London to help create a revolutionary program in technical education. There he developed a course in practical mathematics for engineers that included the study of functions on "squared paper." He "encouraged practical methods in mensuration and geometry...all the time keeping close links with science and laboratory work."[35]

Perry appears to have been the first to use "squared," or graph, paper as a teaching aid. Rarely used in schools earlier in the century in part because of its expense, Perry promoted its usefulness as an instrument of mathematical reform. It exemplified his commitment to the teaching of mathematics through concrete examples interpreted by graphical methods. Contradicting the popular opinion that calculus was not a subject easily taught to engineers, Perry insisted that[36]

> there is no useful mathematical tool which an engineer may not learn to use. A man learns to use the Calculus as he learns to use the chisel or the file on actual concrete bits of work, and it is on this idea that I act in teaching the use of the Calculus to engineers.

Perry's efforts helped transform the teaching of mathematics in Britain and by 1908 an observer could note the growing attention paid mathematics "on its experimental and graphical side...exemplified by the use of drawing-boards, improved mathematical instruments, squared-paper," and in "the provision of mathematical laboratories

> ...well-stocked with clay, cardboard, wire, wooden, metal and other models and materials, and apparatus for investigation of form, mensuration and movement....(37)

It is not surprising that engineers took an early part in arguments over the teaching of mathematics. If they disagreed about mathematics, it was not so much over how it might best be taught as whether it had a place at all in the education of the engineer. As academic engineering gathered strength, the dispute was resolved in favor of solid mathematical training. By the century's end, physicists too were complaining that the excessively abstract nature of modern mathematics and its teaching were inhibiting the development of science. Many were sympathetic to the practical and instrumental style of mathematics favored by engineers.

On the Continent, Carl Runge was an outspoken proponent of mathematics in the service of science. Initially, he too had been caught up by the excitement of developments in modern mathematics. A disciple of Weierstrass, he worked in algebra and the theory of functions. But a move to the Technische Hochschule in Hannover and subsequent involvement in the study of atomic structure converted him to applied physics and engineering.[38] In 1911, the International Commission of Teaching of Mathematics asked Runge to conduct a survey of mathematics for students of physics. The countries Runge surveyed included Italy, Austria, Germany, Switzerland, Holland, England, and the United States. He found that the mathematical curriculum for physics students was largely the same everywhere, and included analytic geometry, differential and integral calculus, ordinary differential equation, and dynamics. He also discovered the frequent complaint that mathematics professors often paid little attention to the practical needs of physics students, failing to emphasize useful topics and spending too much time on logical foundations.

Runge's recommendations for the improvement of mathematical teaching stressed the introduction of graphical and numerical methods long the habit, as he said, of engineers. Descriptive geometry, for example, was useful in training the powers of intuition. Furthermore, with the empirical functions physicists often met that were resistant to formal solution, graphical methods could be applied readily. Graphical integration would also remedy the exaggerated importance of differentiation deriving from its relative ease. Generally, Runge sought methods that would permit physicists to escape the analytical straightjacket imposed by the reluctance of mathematicians to attend to practical problems. Engineers and physicists must seek more than existence-theorems, he argued, and if numerical and instrumental techniques existed for the solution of equations, the mathematician should teach them. The slide rule, integraph, planimeter, and calculating machine should all make their appearance in the mathematical lecture. Echoing Perry, Runge felt that practical skill in mathematics should be organized around the "mathematical laboratory," just as were chemistry and physics. "Mathematics cannot be learned by lectures alone, any more than piano playing can be learned by listening to a player."[39]

"Practical mathematics" percolated through the scientific and engineering communities in the United States as well and encouraged debate over the revision of curricula and the publication of texts for a new generation of students. Ironically, the most eloquent proponent of practical mathematics in the U.S. was Eliakim Hastings Moore, the chairman of the mathematics department at the University of Chicago. Though an influential architect of his discipline's newly-won independence, Moore had absorbed the concerns of the great German mathematician, Felix Klein, that the increasing abstraction of mathematics would impoverish science.

Moore presented his case for practical mathematics in his address in 1903 as the retiring president of the American Mathematical Society. The dominant note of mathematics in the nineteenth century had been, he told his audience, the critical examination of the foundations of mathematics. In large part, this critical development proceeded independently of applied problems in the sciences and, consequently, "there has arisen a chasm between pure mathematics and applied mathematics."[40] There had recently been a number of attempts to bridge the chasm and Moore reviewed for his audience the growing number of texts designed to supply the practical mathematics needed by chemists, physicists, and engineers, as well as the invigorating influence of the "Perry movement" in England. The most important suggestion of the English movement was Perry's idea that "by emphasizing steadily the practical sides of mathematics, that is arithmetic computations, mechanical drawing and graphical methods generally, in continuous relation with problems of physics and chemistry and engineering," students could acquire a grasp of the essentials of higher mathematics.

Moore presented to his audience a reformed schedule of mathematical education extending from the primary grades through college, designed to reawaken an interest in mathematics among the constituencies of the schools, to diffuse basic competency, and ultimately to help bridge the gap between pure and applied mathematics. The various topics were to be taught in a "correlated" fashion within the mathematical laboratory. Beginning in kindergarten, the student would learn by doing. Drawing and paper-folding would lead to the study of geometry and the building of models and mechanical drawing to geometrical reasoning.

> The cross-grooved tables of the kindergarten furnish an especially important type of connection [by which the mathematical and the visual are related].... These tables and the similar cross-section blackboards and paper must enter largely into all the mathematics of the grades. The children are taught to represent, according to the usual conventions, various familiar and interesting phenomena and to study the properties of the phenomena in the pictures: to know, for example,

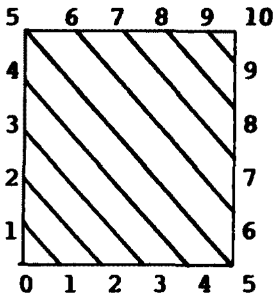
> what concrete meaning attaches to the fact that a graph curve at a certain point is going down or going up or is horizontal.(41)

The attempt to interpret formulaic conventions in terms of the tangible and graphic was to continue on through college. For the details of instruction at the college level in mathematics and physics, the instructor could heed the example of the engineer. "Let the body of material postulated by the engineer serve as the basis of the four years´ course."

Spurred on by a "thoroughgoing laboratory system of instruction," including the use of graph paper, computational and graphical methods in general, colored inks and chalks, and emphasizing cooperation among students, the class would develop "the true spirit of research, and an appreciation, practical as well as theoretic, of the fundamental methods of science." Mathematics taught by the laboratory method would serve as the basis for advanced study in the more abstract realms of mathematical theory. Much of Moore´s program deemphasized the rigor of traditional mathematical instruction and he admitted that many might feel that the interests of mathematics would be irreparably injured. He responded that the familiar use of the tools of mathematics would lead to insight into the nature of the tools themselves. The student "will ultimately have a feeling towards his mathematics extremely different from that which is now met with only too frequently - a feeling that mathematics is indeed itself a fundamental reality of the domain of thought, and not merely a matter of symbols and arbitrary rules and conventions."[42]

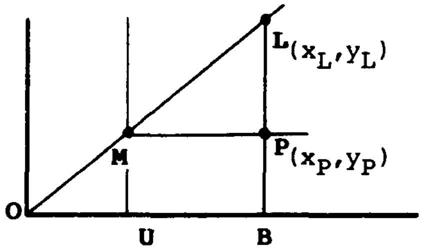
The mathematical "touch" Moore hoped to cultivate in students is suggested in an article he published in the School Review of 1906 dealing with "Cross-section Paper as a Mathematical Instrument." Moore first explained double-entry function tables and demonstrated their isomorphism with corresponding graphical presentation, noting that he was only making mathematical use of notions commonplace, for example, in cartography. For example, if x + y = S, and S is the distance above the base plane, the the graphical representation shown in the figure represents a flat hillside intersecting the horizontal plane at x + y = 0. Through the imaginative use of graph paper,

5	6	7	8	9	10
4	5	6	7	8	9
3	4	5	6	7	8
2	3	4	5	6	7
y: 1	2	3	4	5	6
x:	1	2	3	4	5



Moore hoped to help his students perceive the "rich and suggestive variety of useful functional relations between two or three related variables."[43]

Another technique designed to assist the student acquire an appreciation of the concrete meaning of mathematics employed what Moore called "geometrical linkages." He first explained how to multiply geometrically. In the figure, P is a point whose coordinates are the numbers one wishes to multiply. Construct PM parallel to the x-axis and extend it to its point of intersection



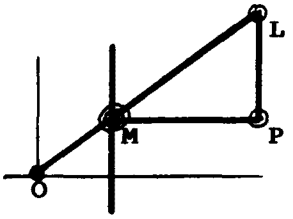
with the line Q parallel to and at unit distance from the y-axis. Construct a line from the origin through M and extend it until it meets the line PL parallel with the y-axis. Since OUM and OBL are similar triangles,

$$OU/OB = UM/BL = BP/BL, \text{ and } 1/x_p = 1/x_1 = y_p/y_1$$

$$y_1 = x_p y_p.$$

The y-coordinate of point L is the desired product.

Geometrical multiplication can be converted into a more general mechanical form by means of the "geometrical linkage." The linkage suitable for performing the illustrated multiplication consisted of bars with slots and pins, pivots, joints, and braces so connected that, while movable in certain ways, other geometrical relationships



were forced to remain constant. Black circles are fixed points, open circles points free to move in the plane, and concentric circles points constrained to move along prescribed paths. In the illustration, M can only move along a path parallel to the y-axis and at unit distance from it. With this arrangement, the y-coordinates of L will equal the product of the coordinates of P. To multiply x and y, one simply placed point P of the device on the point with the required coordinates and read off the product from the y-coordinates of L.[44]

Moore meant to heal the breach between pure and applied mathematics and revitalize the partnership between mathematicians and scientists. Trained in the mathematical laboratory, the student would acquire the skills to move easily between the world of sense and the realm of mathematical ideas, by the mediation of graphical and mechanical idioms. The student would understand pure mathematics when placed into "such a physical and intellectual environment that they learn to see and to think the mathematics for and of themselves."[45]

Moore's hopes were not immediately realized. By 1912, at the same conference at which Runge presented the results of his survey of mathematical instruction, the historian D.E. Smith reported that "graphic methods of one form or another are now found in the course...in all countries, having gradually made their way from engineering, through thermodynamics and general physics, to pure mathematics."[46] Nevertheless, despite the pleas of such men as Perry, Runge, and Moore, applied mathematics failed to take institutional root. In Germany, Runge's program remained an idiosyncratic vision, and the chair of applied mathematics at Göttingen did not find a successor when Runge retired in 1923. In the United States, it was mainly teachers of math and science in the high schools who were encouraged by Moore´s ideas. In the upper reaches of the educational establishment, the new movement seems to have received a cool reception; a national commission on physics, including such eminent figures as Nicholas Murray Butler, G. Stanley Hall, A.A. Michelson, and Robert Millikan, rejected the excessive "mathematizing" of physics.[47] Though schools continued to maintain mathematical laboratories, it was often without the graphical and mechanical emphasis which distinguished the methods of Perry and Moore. The Mathematical Laboratory at the University of Edinburgh had been established in 1913, but by the end of the decade, the graphical methods that had characterized its beginnings, had been abandoned as being less rapid and accurate than newer numerical techniques.[48] It was the engineers who were the earliest and the most enduring of the proponents of practical mathematics.

* * *

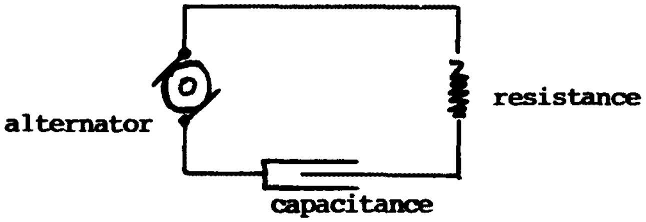
Physics, the Graphical Language, and practical mathematics - together constituted the idioms and formed the family of languages becoming available to the academically trained engineer at the turn of the century. Looking closer into the activity of the Dynamo Laboratory will help appreciate how they all came together. At some point in the electrical course, an advanced student would have confronted a study of AC-generators and their circuits. One afternoon this student would be joined by several of his classmates in the Laboratory to conduct an experiment on the effect of capacitance in alternating current circuits. By this time in the school year, they would have acquired substantial familiarity with the basic instruments and machinery of the lab and at an earlier point would have assembled the generator, circuits, and instrumentation required for the experiment. After a brief discussion of the test to be performed, the instructor would have left the group on their own to begin their study.

The first check was, in effect, a syntactical one. If the fuses blew when the generator was started, then the elements of the "machine" had been assembled in the wrong way. The subsequent write-up of the test contained a description of the equipment and procedures, tables of data, graphs of results, and the discussion and interpretation of results. The interpretive section was of special importance. While the student might rarely be called upon to operate similar machinery, it was essential that he possess the ability to "size up a situation,[49]

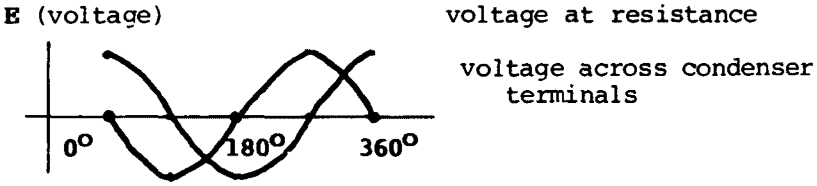
> whether it be one of executive nature or one dealing with equipment. In the latter case all that he will usually have to base his judgment upon will be certain data or curves. Unless he has been trained along such lines of work as to develop his analytical powers he will lack ability which an engineer ought to possess.

Along with sketches of the apparatus, the student would have included a circuit diagram and the curves based on the tables of voltages measured across the terminals of the condenser and the resistance.

The analysis of the curves was two-fold. The first depended on



the application of Kirchhoff's laws and the conservation of energy



to the electrical circuit: in a circuit containing both resistance and capacitance, the total energy imparted to the circuit at any instant of time, **(Ei)dt**, is divided between that lost in the resistance, **Ri^2dt**, and that used to charge the condenser, **$idt\int idt/C$**:

$$(Ei)dt = Ri^2 + (i)dt\int (i)dt/C$$

From this equation the student derived expressions for the current in the circuit and the charge on the condenser as a function of time:

$$i = e^{-t/RC}/R\int (e^{t/RC})\ f'(t)dt + C_1e^{-t/RC}$$

$$-q = e^{-t/RC}/R\int (e^{t/RC})\ f(t)dt + C_2e^{-t/RC}$$

Since the impressed voltage was harmonic and observed the relationships

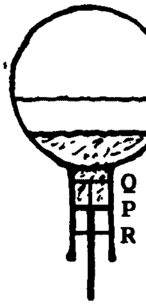
$$E = f(t) = E_0\sin(wt), \quad f'(t) = (E_0 w)\cos(wt),$$

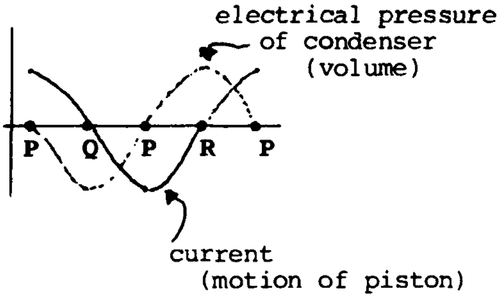
the current and the charge on the condenser could be reexpressed in terms of phase angle:

$$q/C = (I/Cw)\sin(wt + \theta - 90^\circ)$$

$$i = (I)\sin(wt + \theta)$$

These equations expressed what was obvious from the experimental data: that the voltage needed to overcome the charge on the condenser lagged 90° in phase behind the current. Deriving the appropriate equations familiarized the student with the mathematics of electrical circuits. His ability to interpret the circuit in physical terms was bolstered by analogy. In this experiment, the student was offered the following comparison: consider an air chamber partially filled with water, fitted with a piston that alternately compresses and expands the air inside the chamber. The piston moves with a simple harmonic motion in and out, simulating the alternating current in the circuit. The charge on the condenser was represented by the volume of water which entered or left the chamber and was considered to be zero when the piston was at its central position **P**, when the air inside the chamber was at atmospheric pressure. When the piston was at **P**, moving upward at maximum speed, the charge was zero and the current maximum. When the piston arrived at **Q**, the current was zero, and both the charge and the electrical pressure (voltage) of the condenser were at a maximum and opposed to the current. As the piston passed back through the central point **P**, the current was at a negative maximum and the pressure became zero and changed sign.





Laboratory instruction in such a manner provided a variety of resources with which a student could account for the behavior of electrical machinery. The "languages" students acquired ranged from the syntactical facility rooted in the experience of man-handling equipment in the Dynamo Laboratory and getting to work, to the formal language of the mathematics of circuits. Mediating the two were mechanical analogy and the Graphic Language - mechanical drawings and sketches, the graphing of functions, and the more esoteric graphical methods being developed by electrical engineers including the mathematics of the complex plane.

The reliance on analogy reflects the context in which engineering was taught. Not only was mechanical analogy distinctively graphic, but it found conceptual justification in the mechanism of Dolbear´s paradigm. Since the chemical energy of fuel was interchangeable with the heat energy of the boiler, and heat with the mechanical energy of the dynamo and subsequently the electrical energy which lit the lamp, each process could be expressed in terms of the other. To account for the electrical behavior of a circuit in terms of a hydraulic counterpart was thus conceptually and heuristically justified.

The analogical resources were important enough that the text from which the previous experiment has been drawn listed in an appendix a table of the analogical correspondences between the electrical circuit and a mechanical system in either linear or rotatory motion. For instance, given a wheel rotating freely on a shaft, the torque needed to overcome the friction of the shaft and the inertia of the wheel is

$$T = T_R + T' = Rw + (I)dw/dt$$

where **T** is the torque, **R** the friction of the wheel on the shaft, **w** the angular velocity, **I** the moment of inertia, and **dw/dt** the angular acceleration. The table gives as the analogue of this mechanical system, an electrical circuit containing both resistance and self-induction with the corresponding equation:

$$E = E_R + E' = Ri + (L)di/dt$$

were **E** is the electromotive force needed to overcome the resistance of self-induction of the circuit, **R** being the resistance ("friction"), **i** the current ("angular velocity"), **L** the coefficient of induction (the "moment of inertia"), and **di/dt** the "current acceleration."

His facility with mathematics, physics, and graphical method distinguished the graduate of the Dynamo Laboratory from the untutored mechanic of the previous century. To be sure, the student and the mechanic shared their struggle with the weighty, primitive texts of their respective machinery. "To the mechanical thinker, the grammar of the machine...is the successive transformations of power." A good part of the student's time was spent exploring the syntactical possibilities to which the equipment of the Laboratory lent itself. But the scholar had grown articulate in a fashion that set him apart from his forerunner. His was the hard-won ability to move beyond the primitive paradigms of the object-language to find himself, as Samuel Earle put it, "pondering the ways in which other minds work."[50] Cultivating the ability to move back and forth between the language of the machine and the more esoteric dialects of mathematics and physics, never straying far beyond the safe boundaries of mechanical analogy, the student remained conscious of the needs of his audience and of his mediating role in translation and interpretation. Multilingual, the engineering student forged a new niche in America's evolving schools, poised between the intellectually abstract and the materially concrete, between academe and industry. Comfortable among the artifacts of power, the student could read, write, and parse his texts in a fashion not unlike the student of classics.

NOTES - CHAPTER TWO

1. W.R. Ransom, "William Leslie Hooper, 1855-1918," Tufts College Graduate 17 (1918): 6-7; the quote is from Edwin B. Rollins, "An Account of the Department of Electrical Engineering of the Tufts College Engineering School," dated 1946, Tufts University Archives.

2. Rollins, p.56.

3. For the early history of Tufts, see Miller, The Light on the Hill as well as the annual reports.

4. Rollins, p.31.

5. Rollins, p.37.

6. There was a world of contention in the designation of degrees. For the character of the disputes and the desire of academic engineers to invoke special responsibilities, see the proceedings of the Society for the Promotion of Engineering Education.

7. Tufts College Catalogue 1909-1910.

8. George Pegram, "The Attitude of the Newer Physics Toward the Mechanical View of Nature," Educational Review 41 (1911): 290-302.

9. Pierre Duhem, The Aim and Structure of Physical Theory (1906), Part I, Chapter IV, 5. See also, Olson and Kargon for the mechanical proclivities of British natural philosophy.

10. See the starred entry in the 1906 edition of American Men of Science.

11. Science II (1883): 285-287; Albert Stetson, "Lest We Forget. The Story of Professor's Experiments in Telephony," Tufts College Graduate 21 (1923): 143-158; W.L. Hooper, "Amos Emerson Dolbear," Ibid. 8 (1909-1910): 8-17.

12. A.E. Dolbear, Matter, Ether, and Motion. The Factors and Relations of Physical Science (Boston: Lee and Shepard, 1894), pp.vii-viii.

13. Ibid., p.325.

14. A.E. Dolbear, Modes of Motion, Or Mechanical Conceptions of Physical Phenomena (Boston: Lee and Shepard, 1897), pp.104-105.

15. Tufts Weekly, April 26, 1934, pp.1-2.

16. On the importance of models for early inventors, see Brooke Hindle, *Emulation and Invention*.

17. For an account of the struggle to control the workplace that the division of labor provoked in early American factories, see Merritt Roe Smith, *The Harper's Ferry Armory and the New Technology* (Ithaca and London: Cornell University Press, 1977).

18. Gardner C. Anthony, *A Text Book of Mechanical Drawing, Part III, Machine Drawing* (1893), p.14.

19. Peter Jeffrey Booker, *A History of Engineering Drawing* (London: Chatto and Windus, 1963).

20. Anthony, *Op. cit.*, p.14.

21. Anthony, *An Introduction to the Graphic Language; The Vocabulary, Grammatical Construction, Idiomatic Use, and Historical Development With Special Reference to the Reading of Drawings* (D.C. Heath Co., 1922), p.iii.

22. *Ibid.*, p.101.

23. Thomas E. French, "The Educational Side of Engineering Drawing," *Proceedings SPEE* 21 (1913): 99-100; 102; 109.

24. Arthur H. Barker, *Graphical Calculus* (London, New York, and Bombay: Longmans, Green, and Company, 1896), pp.14-15; 12.

25. *The Tufts Weekly*, October 28, 1909, p.2.

26. Material on Ransom can be found in the William Ransom file in the Tufts University Archives. The Bush and Wiener references are in their respective autobiographies, *Pieces of the Action* and *Ex-Prodigy*.

27. A cursory examination of the graduate dissertations on the shelves of the Tufts Library indicates that twenty-five were completed between 1910 and 1925; of the three not dealing with English or history, two were in mathematics, and one (Vannevar Bush) in engineering.

28. On the history of the slide rule, see F. Cajori, "Notes on the History of the Slide Rule," *American Mathematical Monthly* 15(1) (1908): pp.4-5.

29. Isaac Todhunter, *A Treatise on the Differential Calculus* (Cambridge: Macmillan and Co., 1855), pp.11-12. Alexander Russell remembers being asked by Kelvin once to give the meaning of a mathematical expression that had been written on the blackboard. He answered "with much complacency that it was the limiting value of the ratio of the increment of **x** to the increment of **t** when the latter increment was indefinitely diminished. ... His satisfaction was short-lived. Thomson's

comment was, 'That's what Todhunter would say. Does nobody know that it represents a velocity?'" *Lord Kelvin, His Life and Work* (1924), p.27.

30. A substantial history of mathematics in the United States has yet to be written. There is scattered information, for example, in the essays in *The Bicentennial Tribute to American Mathematics 1776-1976*, ed. by Dalton Tarwater and published in 1977 by the Mathematical Association of America (especially articles by Dirk Struik, Judith Grabiner, Garrett Birkhoff, and Mina Rees); in *A History of Mathematics in America Before 1900*, an aging but valuable brief account written in 1934 by D.E. Smith and J. Ginsburg; *A History of Mathematics Education in the United States and Canada*, the 32nd Yearbook of the National Council of Teachers of Mathematics, 1970; and in E.H. Moore's presidential address to the American Mathematica Society in 1903. For a recent account of the consequences of limited mathematical training for the style of American science, see John Servos, "Taking the Measure of Nature: Mathematics and the Education of American Scientists, 1880-1930," personal copy. On "numeracy" in the U.S. in the early eighteenth century, see Patricia Cline Cohen, *A Calculating People. The Spread of Numeracy in Early America* (Chicago and London: University of Chicago Press, 1982).

31. Smith and Ginsburg, *Op. cit.*, p.163.

32. *Ibid.*, p.199; Susan Cannon says of mathematicians that they "began around mid-century that process of segregating themselves, and repudiating demands that their work be useful, which still characterizes some of them today," *Science in Culture*, p.117.

33. See D.S. Cardwell, *The Organization of Science in Great Britain* (London: Heinemann Educational, rev.ed. 1972); Michael Sanderson, *The Universities and British Industry, 1850-1970* (London: Routledge, Kegan and Paul, 1972).

34. See Sanderson especially.

35. William Brock and Michael Price, "Squared Paper in the Nineteenth Century: Instrument of Science and Engineering, and a Symbol of Reform in Mathematical Education," *Educational Studies in Mathematics* 11 (1980): 373; Armstrong's obituary of Perry is in *Nature* 105 (1920): 751-752.

36. John Perry, *Calculus For Engineers* (London, 1897), p.5.

37. Brock and Price, *op. cit.*, p.368.

38. Paul Forman, "Carl Runge," *Dictionary of Scientific Biography*.

39. C. Runge, "The Mathematical Training of the Physicist

in the University," Proceedings of the Fifth International Congress of Mathematicians 2 (1912): 598-607.

40. E.H. Moore, "On the Foundations of Mathematics," Science 17 (1903): 401-416.

41. Ibid., p.409.

42. Ibid., p.408.

43. E.H. Moore, "The Cross-section Paper as a Mathematical Instrument," The School Review 14 (1906): 322.

44. Ibid., p.326.

45. Ibid., p.317.

46. D.E. Smith, "Intuition and Experiment in Mathematical Teaching in the Secondary Schools," Proceedings of the Fifth International Congress of Mathematicians 2 (1912): 622.

47. A History of Mathematics Education in the United States and Canada, pp. 173-177; Solberg E. Sigurdson, "The Development of the Idea of Unified Mathematics in the Secondary School Curriculum, 1890-1930," (Ph.D. dissertation, University of Wisconsin, 1962; cf. note 30.

48. E.T. Whittaker and G. Robinson, The Calculus of Observations (London, 1924), p.vi.

49. This laboratory experiment is reconstructed on the basis of the following sources: E.B. Rollins (cf. note 1); the Tufts College annual reports and catalogues; M.S. Munro, "Electrical Engineering Laboratory Instruction [at Tufts College]," SPEE Bulletin #5 (1914-1915): 51-57, 65-70 from whom the quote was drawn; and two texts that were used at Tufts - E.L. Nichols, A Laboratory Manual of Physics and Applied Electricity, Volume 2, "Senior Courses and Advanced Work" (1894); and Frederich Bedell and Albert Cushing, Alternating Currents, An Analytical and Graphical Treatment for Students and Engineers (1893).

50. S.C. Earle, The Theory and Practice of Technical Writing (New York: Macmillan Co., 1911), p.v.

CHAPTER THREE:

THE CULTURE OF ENGINEERING

Educators were aware that the works of engineering constituted a form of language and defended their program as a "culture study" in a spirit reminiscent of their colleagues in the liberal arts. Though the skills acquired by the engineering student were undeniably utilitarian, they were at the same time intellectually demanding, productive of mental discipline, replete with aesthetic possibilities, and, like traditional studies, opened up a vast reservoir of cultural achievement in the form of the works of the great engineers and artists of the past. To be sure, the "texts" of the engineering student were a far cry from those of the classicist and much of the defense of engineering as a "culture study" revolved around this difference. And it was a difference that mattered, suggesting, to those who had the eyes to see, the utopian possibilities of modern engineering. If traditional academic studies elevated head over hand, the artifacts of power that comprised the "texts" of the engineer demanded their synthesis, a union of the power to know and to do that promised an education suited to the demands of modern industrial society.

* * *

If no man is an island, neither do texts exist cut off from culture and context. The immediate context in which the student exercised his skill and in which his "texts" were imbedded was the laboratory. Familiar with the dynamo and measurements laboratories, he was intimate as well with workshops, drafting rooms, and an assortment of other labs, classrooms, and offices. The sense, then, of "laboratory" was manifold, denoting a complex and differentiated space and a conceptually rich idea. It was a repository of instruments and artifacts, a site for the forging of text and symbol, a studio where the student demonstrated the synthesis of knowledge, power, and virtue that was the ideal of the engineering curriculum. At least three influences added to the weight of meaning born by the engineering laboratory: the nineteenth century revolution in the teaching of science, enthusiastic apologies for manual training, and modern psychologies of education.

"...physics should be studied in the shop rather than in the school...."[1] To many observers at the end of the century, the growth of experimental and laboratory science constituted a major transformation of Western culture. Though the origins of modern science lie in the sixteenth and seventeenth centuries, it was the rise of the teaching laboratory towards the middle of the nineteenth century that signaled the diffusion of scientific enterprise beyond the privileged domain of the self-supporting and into popular education.[2] A benchmark of this movement in the United States was the establishment of Johns Hopkins in 1876 under the guiding hand of Daniel Gilman. "The inhabited world is a great laboratory," he once exclaimed, "in which human society is busy experimenting." And as the world, so was his new university: "The whole establishment becomes a laboratory where everyone is busy, and where enthusiasm in study is the predominant characteristic."[3]

To promote his vision of the school as a laboratory, Gilman created a program which stressed graduate training and fundamental research. In short order, he assembled a faculty of impressive stature and made Hopkins into a leading center of scientific training in the United States. Hopkins was not the first school dedicated to scientific investigation, both the Sheffield School at Yale and Harvard's Lawrence School of Science had preceded it, but its example was timely and proved contagious, and prefigured the tremendous expansion of university science which occurred at the end of the century. The laboratory of the modern university was the necessary instrument of scientific research, and something more as well - a crucible for the forging of character. Trained in the regimen of laboratory life, the modern student would learn to be curious though disciplined, faithful to detail, and observant of rule and procedure, and while individually aggressive in the pursuit of truth, mindful of the cooperative responsibilities natural to the community of inquiry. The laboratory embodied an ideal which quickly spread beyond science proper into other fields - among them, language, literature, and art.[4]

Engineers, too, began speaking of laboratories. Before 1870, there was little in the way laboratory teaching in engineering schools; by the end of the decade, the laboratory method was recognized as key element of the curriculum. The earliest example of a technical school in which the laboratory constituted an important element was probably MIT under its founder William Barton Rogers. In the hands of Eliot and Pickering, laboratory work in the physical sciences had become a reality by 1869. The first engineering laboratory in the United States was that established at the Stevens Institute in 1871 by the mechanical engineer Robert Thurston. Thurston became the leading proponent of the engineering laboratory and after moving to Cornell in 1885, he established its Sibley College as one of the country's foremost engineering schools.[5] By the Great War, the public discussions of educators abounded with descriptions of new laboratory buildings and programs centering around laboratory training.

Engineers agreed that the laboratory formed a key part in the academic domestication of their profession. It distinguished the new engineer from the old and solidified the scientific basis of their discipline. Yet the engineering laboratory was never as "pure" a creation as the scientific laboratory and the arguments on it behalf never as detached or refined. While engineering educators continued to wax eloquent over the laboratory at the end of the century, the tenor of their discussions shifted. While the value of the advancement of knowledge was undisputed, and recognized as the mark that distinguished the academic from the non-academic engineer, the focus of debate moved from such topics as the role of the senior thesis and of graduate training, to more utilitarian matters. The laboratory was important because it introduced elements of practical experience into a curriculum too abstract and isolated from real life, and permitted the student to acquire a foretaste of the conditions he would confront upon leaving school.[6]

Similar arguments were used to justify the place of the shop in the engineering school. Like the laboratory, the shop provided an opportunity to become familiar with materials and procedures of the professions. In terms of provenance, the shop differed greatly from the laboratory. Traditionally, the shop had provided the training required by young men with engineering aspirations and the early schools perforce found themselves in conflict with the engineering elite who had come up through the professional ranks by way of the shop.[7] By the turn of the century, schools had evolved a variety of accommodations between the more formal and academic components of the curriculum and the shop experience which, all agreed, was as essential to the training of the engineer as the laboratory. Some provided shop experience through the on-campus operation of small-scale manufacturing plants which produced goods for sale. Some farmed out students to local industries. A growing number taught shop according to various scientific systems that purported to break shopwork down into its elementary processes employing basic tools and procedures. The latter approach, inspired by Russian models exhibited at the Philadelphia World's Fair in 1876, was first tried by Runkle at MIT and soon became commonplace. In any case, engineers would have agreed that the aim of shopwork was not the production of saleable items, but the provision of those practical skills and standards which formed the bedrock of the engineer's expertise.[8]

By 1900, the shop and laboratory had become the crucial locus of engineering education. Poised between the traditional worlds of school and factory, they served to define the ethos of academic engineering, reflecting the growing prestige of science, the manual competence of the craftsman, and the technical needs of modern industry. To many, this new form of education seemed the best hope for closing the gap between American education and a harsh industrializing society. Even more than the scientist, who embodied the hope that expert knowledge could solve the conundrums of a society turned topsy-turvy, the engineer was seen by many to bridge that enervating disconnection between knowledge and will, the ability to know and to do, that marked the modern malaise.

One such observer was Calvin Woodward. Schooled at Harvard in mathematics and applied mechanics, Woodward was appointed dean of the School of Engineering and Architecture at Washington University in 1871, a position he held with but one interruption for some forty years. In 1879, he helped establish the St. Louis Manual Training School, the first of its kind in the country, designed to offer an alternative to the available high school. In the next several decades, Woodward became a leading voice in the educational affairs of engineers and an outspoken proponent of manual training.

Manual training, Woodward proclaimed, was much more than the teaching of those mechanical skills that facilitated one's entry into industrial employment. The manner in which he caste his defense of manual training tells us something of the optimism that surrounded the growth of engineering. Misrepresented in its early years as a substitute for apprenticeship, and thus the proper concern of the trade school, manual training was much more, essentially and like engineering generally "a culture study." It was a new education that allowed students the chance to become familiar with the tools of their future trades, but as well the opportunity to discover "their inborn capacities and aptitudes, whether in the direction of literature, science, engineering, or the practical arts."[9] While manual training would indeed provide the student with marketable skills, it would do so without the "narrowing, unscholarly atmosphere of the trade school."

It was proposed to "put the whole boy to school, to combine manual with mental training; to put the liberal arts and the mechanic arts into the same curriculum; to deal simultaneously with material forces and appliances and with spiritual forces and appliances." Woodward was speaking of the high school, but he could well have been referring to the engineering school of the turn of the century. The point of manual training was not the construction of artifacts, but the study of tools and their use. It was, as Woodward put it, "'a new art of expression' in the concrete." Just as "scientific study of language begins with declensions and conjugations

> so tool work, drawing, needlework, cooking, etc., begin with fundamental processes with typical appliances upon typical materials. The articles constructed, the figures drawn...are valuable because they involve effort and result in mastery and power. The real end and aim of all education, whether 'manual' or 'spiritual,' is the developed, strengthened, disciplined executive person, regardless of the fate of the exercises or products which were the means of his development.

The new pedagogy and the reformed culture to which it gave rise seemed to its proponents not only a response suited to the times but one which was physiologically sound in a way the older, bookish learning was not. For corroboration, Woodward cited the geologist, educator, and fellow apologist of manual training, C.H. Henderson:

> The brain grows by what it feeds upon. Given perfect health and a wealth of sense impression, especially a wealth of quantitative sense impression...and we have the physical basis for a full intellectual life. Without this large quantitative knowledge and developed brain we live in a world of illusion, a guess world of very imperfect rationality. To cultivate the hand and eye and ear, even the nose and the tongue, is to enlarge the material of thought and the tool of thought.

The efficacy of the manual training was evident in the character of the instructor. Unlike the literary stereotype of the swarthy and untutored artisan, Woodward's teacher was a schooled and scientific generalist who possessed a knowledge of mechanics that differed from that of "the ordinary workman as the mathematical training of a senior wrangler differs from the art of a lightning calculator." He had mastered the principles of a variety of crafts and was "equally at home at every bench." He was draftsman and artist, "ready to sketch an engine or a pump, to find the shade and shadow of a Greek vase." He was a scientist who understood how the principles of the lever and inclined plane underlay all mechanical operations and he had studied the effects of heat upon metals and the dynamics of elastic fluids. And he never said,

> ´I know, but I cannot express it,´ for he can express it, either in words, by drawings, or in the concrete....

Like the multilingual engineering student of Earle and Anthony, the product of manual training developed a sense of language that bridged the abstract and the concrete and practical, and lent his expressiveness the aura of competent power.

> He suits the action to the word and the word to the action. This is an important point, for, like every other teacher in the school, he is a language teacher.

Woodward reminded his audience of all this in his presidential address at the 1903 meeting of the Society for the Promotion of Engineering Education. "There is no necessary divorce between the skilled hand and the cultured mind; both are needed for the highest culture."[10]

> Manual training furnishes many of the elements of culture and discipline which are lacking the the ordinary secondary course of study. Contact with the concrete; clear concepts of materials, forces and instrumentalities; exact knowledge of mechanical processes; analyses of complex operations; the idea of precision; habits of system; or foresight; and of intellectual honesty.

Honest, disciplined, familiar with forces and instrumentalities, adept in the language of power, the product of such schooling would be a mighty savior to a troubled world.

> The world is full of unsolved problems, and the engineers...are to solve them. The earth is ours and the fullness thereof. The arid lands are to be made moist and fertile. The swamp lands are to be made dry and fertile. The wealth of mines and forests is ours. Our mighty engines are the hewers of wood and the drawers of water. We sow and harvest and grind and mix and bake by machinery. We light and heat and travel by machinery; and ours is the noble mission to train the architects and engineers of all these glorious functions. Let us rejoice and magnify our work. Let all the world know that there is nothing nobler or finer than the accomplished, cultivated engineer.

Not all engineers proclaimed the glories of engineering in Biblical periods. Most, however, would have agreed that the setting of engineering education lent itself to character and culture. Indeed, the literature of engineering abounds with metaphors which straddle the worlds of fact and ethic, description and prescription. Working with high voltages and strong currents taught the student, so it was said, "respect for power," while the discipline of the laboratory forced him "to get things straight" and "size up the situation." Mechanical drawing cultivated the imagination by demanding that he "think in 3-D," while the need for accuracy and attention to detain promoted integrity and judgment. The association knowledge and character had always been the prerogative of the school but with the rapid growth of university science and the transformation in pedagogy, the forging of character acquired a distinctive edge even more suited to the laboratory and shop of the new technical schools. On the one hand, especially with their classical colleagues in mind, educators could defend engineering as a "new art of expression in the concrete." But if the laboratory possessed the qualities of a studio and its artifactual products "bookish" characteristics, it also offered the student a medium and a context that enforced a whole range of moral and intellectual virtues.

Technical education, in other words, was seen to be grounded in a way that enhanced and encouraged, as the older learning no longer did, the "natural" links between knowledge, value, and power. This correlation of knowledge and value (at least, as it was recognized within the turn of the century ethical canon), seemed so certain and so intimate that the standards of the laboratory could be used to "gauge" a student's mental and moral characteristics. Gardner Anthony felt that "the experienced teacher of drawing," as an example,

> can see a boy think, for the student leaves the tracks of his mental operations on paper, where it is more clearly interpreted than by any written word.... Slovenliness and inaccuracy in thought are detected instantly in the Mechanic Arts.... When I wish to obtain the most accurate information concerning the mental and moral characteristics of a student, I go to one or both or these departments for details.(11)

The explanations given for the powerful intellectual and moral advantages of the laboratory were various. William Franklin, the author of a physics text used at Tufts and an influential figure in the affairs of the Society, offered an elaborate account couched in the language of mental physiology. "Ideas, like everything else in this world, have to be made out of something," and the only way "to marshall the mind-stuff of a young man for the manufacture of ideas is to introduce the drag net of physical suggestion into every discussion."[12] In this fashion, the student mind could be reorganized and the "idiocy" of conventional, abstract teaching methods avoided. In Franklin's opinion, the advantages of laboratory pedagogy derived from two related factors, both inherent in the organization of laboratory experience: first, was the encouragement of "LOGICAL STRUCTURE, that is to say, a body of mathematical and conceptual theory which is brought to bear upon the immediate materials of sense"; second, was[13]

> MECHANICAL STRUCTURE, that is to say (1) *a carefully planned arrangement of devices*, and (2) *a carefully planned order of operations*.... These two structures - namely, the logical structure and the mechanical of the physical sciences - do indeed constitute a new engine which helps the minds as tools help the hand....

The "new engine" of the laboratory would inculcate clear and organized thought anchored in concrete experience. Appropriately, Franklin defined physics as "the science of taking hold of things and pushing them," to be "studied in the shop rather than in the school...."[14]

Another account of the parallel between the intellectual and material orders of the laboratory was offered by Charles Mann. After a Berlin doctorate, Mann taught physics at the University of Chicago from 1896 to 1914, when he became affiliated with the Carnegie Foundation for the Advancement of Teaching. In 1918 he authored a study of engineering education on behalf of the National Engineering Societies with the Foundation's support.[15] Like Runge, Moore, and Franklin, Mann found in engineering a new pedagogy that promised to heal the breach between the abstract and the concrete, and between intellect and will. Like Franklin, Mann believed that the most important effect of laboratory work was the furnishing of the mind[16]

> with a concrete, ordered basis for abstract, organized thought. The concrete pictures of system, order, and organization, which result from the scientific study of natural phenomena, are necessary to system, order, and organization in the worlds of the intellect and the soul. Were the natural world a physical chaos, the mind would be a mental chaos, and the soul an ethical chaos. The fact that the modern soul is somewhat of an ethical chaos is thus in part the reproach of modern science teaching.

Mann's opinions were encouraged by his sense of the history of engineering. They probably echo as well the philosophical insights of William James and John Dewey, American thinkers whom engineers invoked in those rare moments they turned philosophical. Sensing, it seems, a kindred spirit in the educational rebellion of these American pragmatists, engineering educators agreed that knowledge was more than the reflection of unchanging and eternal verities, that it was rooted in the flux of experience, and the consequence of intervening in the world. As Dewey put it, "We do not live in a medium of universal principles, but by means of adaptations, through concessions and compromises, struggling as best we may to enlarge the range of a concrete here and now."[17] Certainly, they would all have subscribed to the pragmatic man of action who, convinced that ideas are tools that make a difference, was ready and able to undertake the remaking of the modern age.[18]

By the outbreak of the Great War, engineering education had become many things to many people. First and foremost, it provided the technical training that eased the entry of large numbers of young men into the country's expanding factories. It would be a mistake, however, to conclude that, in the struggle of schools like Tufts to adapt old values to new times, no larger lessons were taught. While the majority of graduates left schools with matters of income and status foremost in their mind, it would be nearsighted to presume that none of them took to heart the larger issues that faced their profession and their society. Likewise, it must be admitted that the requirements of industry and management powerfully influenced the training of engineers. Yet to conclude that the logic of the corporation, by itself, adequately accounts for the content and the character of the technical curriculum, oversimplifies the abundant tensions that vexed the souls of engineering educators and underestimates the integrity of the strategies they invested in engineering culture.

For the fact is that engineering education was subjected to forces pulling in a number of directions, with consequences evident in the work of men like Anthony, Earle, Woodward, and Mann. If their apologies for engineering as culture, an expressive "language," and a regimen conducive to ethical behavior seem excessive it is surely because, in large part, engineering is no longer a profession at risk. At the end of the century, however, caught between the hidebound conventions of an older generation of engineers, the changing circumstances of higher education, and the insatiable needs of modern industry for technical expertise, the architects of academic engineering were entirely justified in proclaiming that engineering reoriented culture rather than degraded or abandoned it.

Consequently, it made sense to argue that, just as the student of classics endured the liberating discipline of the ancient languages, so the engineering student was subject to the rigors of his "language" discipline. His texts, however, were written in the studio of the laboratories, workshops, and drafting rooms of the engineering school, in the languages of physics, mathematics, and graphics. Likewise, if the study of "the best that was thought and said in the past" inspired intellectual standards and awoke moral passion, similar claims could be made for engineering. Franklin expected engineering to "rehabilitate" the mind-stuff in a manner fit for modern life. Surrounded by the instruments and engines of power, the student would learn to see clearly, get things straight, and size up the situation. His integrity honed by the discipline of the workshop, he would acquire the skill to move from one audience to another, serving as "the creator of machines and the interpreter of their human significance."[19]

* * *

When Calvin Woodward asked, "Is not the educational army changing front? Is not our new leader an engineer, rather than a philologist or an antiquary?", he touched a crisis of identity in the American school that challenged its sense of mission. And here, too, engineering educators claimed to have reoriented older responsibilities: the duty of the school to serve as a conservator of cultural heritage and fountainhead of ministry.

Engineering's claim to the stewardship of culture derived, in part of course, from its status as "culture study." It depended as well on a lost patrimony rediscovered. In 1922, Gardner Anthony delivered a short talk in which he attempted to summarize the historical development of engineering. Faced with a daunting task, he abbreviated a complex history and focussed on two key dates: the discovery of America in 1492, and the outbreak of Civil War in 1861. The former marked not only the discovery of the New World, but coincided with the revival of learning in the Renaissance exemplified by the career of "one of the greatest engineers of any age, Leonardo da Vinci."[20] A representative of a time when engineering was recognized as an art, Leonardo was joined in Anthony's pantheon by Raphael, Titian, and Michelangelo. 1492, then, symbolized culture as well as discovery. The second of Anthony's dates, 1861, marked for him the midpoint of history's most intense period of engineering development from 1830 to 1890, and the beginnings of engineering education. It was a period of glorious accomplishments for an electrical engineer, witnessing the development of electrical power generation and transmission, and the discovery of the telephone. 1861 signaled, in addition, the onset of the country's most traumatic war - and with the death of an older world, the possibilities of a new. The origins of engineering education in this period suggested to Anthony that his profession was to play an instrumental role in the creation of a new social order on the ruins of the old. Exercising a reawakened cultural power, engineering would facilitate the cooperation of industry and education as its spirit diffused into "almost every phase of human life." Anthony's vision is utopian and even, in its emphasis on new life from old, messianic. Broadly defined, engineering could be interpreted as ministry.

By the first decade of the new century, it was a commonplace notion that religion was in a pronounced decline. Ministers, so it seemed, had lost their moral authority, church attendance appeared to be down, and the enrollment in theology schools was discouraging. Most observers concluded that, underneath it all, the nation was as religious as ever but was engaged in a search for new, more suitable channels for its religious impulses. William Faunce, in the Educational Review's 1905 survey of moral and religious progress, noted "the growing demand for contact with reality in religious, as in intellectual education." And things were changing for the better. The schools of the last quarter of a century had witnessed a movement "from words to things, from symbol to object, from text-book to laboratory, from learning by rote to learning by doing." The religious spirit of the colleges were, in Faunce's opinion, "better adjusted to the conditions about them then ever before." If chapel devotions no longer appealed as they once had, it was because religion on the modern campus was seen more and more "in terms of action and life rather than in terms of formal worship.

> It is translated into ethics, rather than the practice of devotion. Thus, if the student prayer meeting has waned, the interest of the student in missions, and philanthropy, and the service of his generation has steadily increased.(21)

Not everyone agreed with Faunce that the rise of applied Christianity was to be welcomed. Malcolm Taylor, writing, in the Atlantic Monthly in 1910, agreed that the minister had lost influence as well as his audience. But it was a mistake, he felt, to blame this loss on the minister's failure to enter into the daily struggles of his parishioners. "The difficulty with the minister of today is not that he lives too far from the common experiences of other men. Never before was he so close to them." One sees in today's clerical gathering, Taylor noted, "the faces of men of action rather than of thought, types of the engineer or banker, the lawyer or promoter, rather than the mystic or philosopher, or even the teacher." Eager for spiritual leadership, a young minister would find himself distracted by "Boys' Clubs and Friendly Societies, of afternoon calls and church suppers, of playing billiards for the glory of God...."[22] The problem with religion was that the minister was too much in the world. "It is for the church to decide whether she will be guided by prophets or engineers."[23]

Tufts made its choice early, and not in the manner one might have expected. Like most colleges founded by religious sects, it established a school of theology, one that existed for many years in happy cohabitation with the liberal arts and engineering programs. The years around 1900, however, when Tufts was transformed into a predominantly professional school, witnessed a crisis in the school's history. Enrollments dwindled just as those in other programs multiplied. Worries about the relationship of the divinity course to the College's other programs were aggravated by wider debates over the nation's religious well-being and fueled anxious self-searching among the Divinity School faculty. Despite numerous attempts on the part of the faculty and the Tufts administration to rejuvenate the School, largely through emphasizing "applied" Christianity, it remained small and troubled well into the new century.

Despite the troubles of the Divinity School, however, it should not be thought that Tufts repudiated the responsibilities of ministry. Ethical training had never been the sole responsibility of the Divinity School and the commitment to public service in the name of a "larger faith" pervaded Tufts, cutting across schools and curricula. If the crisis of the Divinity Schools suggests anything, it is not repudiation but a shifting emphasis in the standards of devotion from more formal to less formal and traditional forms of ethical commitment. Indeed, devotional practice at Tufts had always been "plastic." While the College had been founded by the Universalists to promote an educated clergy, it had always been aggressively non-sectarian. The formal divinity school was not organized for some fifteen years into the life of the College, four years later than the course in Civil Engineering.

Indeed, Tufts always accommodated comfortably its range of programs, from the traditional liberal arts course, to its professional schools and the School of Divinity. There seem to be a number of reasons for this. Drawn largely from the urban areas of Boston rich in industry and commerce, the College absorbed a practical orientation that was always strong. The College itself had been founded relatively late in the century during a time when college reformers were beginning to loosen the bonds of convention. Furthermore, while inspired by denominationalism, Tufts was remarkably free from doctrinal requirements of all sorts, a fact due in part to the credal freedom of Universalism itself. Not least was the fact that the religious spirit that pervaded Tufts had never been solidly anchored to ceremony and could, for some, be easily transferred to the notion of "profession."

The changing shape of ministry is evident in a small book published in 1915 by Clarence Skinner, the Professor of Applied Christianity at Tufts, titled The Social Implications of Universalism. Skinner repeated the charge that the traditional church was dying but agreed with Faunce that man had not ceased to be religious. He was, indeed, "more religious, and...wants his religion in bigger and more vital terms." Contemporary religion would be founded upon "a twentieth century psychology and theology, a religion which is throbbing with the dynamic of democracy, a spirituality which expresses itself in terms of humanism, rather than in terms of individualism."[24] Confronting new conditions of life created by science, technology, and urbanization, Skinner felt that Universalism and other liberal faiths could make a distinctive contribution "to the larger life of humanity by contributing to it a larger faith." This "larger faith" manifested itself in the "social movement" remaking the new century, in the concerted effort to make available to all, "wealth, health, and fellowship. The democritization of science, industry, politics, education, religion, means their availability to the common life." Within Skinner's liberal theological universe, the ends of religion and the "social movement" were identical, "the one contributes to the enlarging life by an expansive hope and a cosmic faith, the other by making available the resources of science, education and industry."

Skinner's progressive minister, buoyed by his cosmic faith, and Anthony's engineer are cultural heroes cut from the same cloth. The kinship is even closer given a psychology that dissolves boundaries.

> Man cannot be conveniently divided into the material, the social and the religious, for all the apparently diversified interests are but varying functions of a psychic unity. The mental, physical and social are so closely locked, that the stimulus of one wakens a train of stimulated activities in every other sphere of personality.

To illustrate this psychic unity, Skinner invoked Dolbear's image of the conservation of energy and the transformation of power:

> Just as coal is converted into steam, steam into power, and power into light, so the physical is converted into the emotional, the emotional into the ideational, the ideational into activity, and back again in an unbroken circle.(25)

For Dolbear, the management of energy defined the foundations of engineering. So for Skinner did the management and application of that strong current that linked and energized the social, emotional, and intellectual lives define the modern minister as an "engineer" of applied religion. In the moral universe of Tufts College, the modern minister came to assume the style of the engineer, and the engineer the responsibilities of ministry.

It was a convergence that appealed to an age grown antagonistic to the rigidities of doctrinal formulas.

The transformation of ministry was explored by Frederick Hamilton, the Tufts president, who welcomed the engineering educators to Boston for their 1912 meeting. Hamilton had attempted to sort out, in a small book of 1894 entitled The Church and Secular Life, the touchy problem of the contending religious and secular influences in the school. His solution rested on the belief that[26]

> ...the teacher as a teacher is the minister of God.... We do not desire to set up any external relation between God's ministries among men and the school as preparing the way for such ministries. We want to insist sharply and clearly that as education is one of the great means for human improvement, therefore it is in itself a divine ministry.

Further,

> There are many people who are enthusiasts in their chosen work of educating who suppose because they take no interest in creeds and rituals, or even in public worship, ...that they have no part or lot with the Church.... It ought to recognize for itself and impress upon them the fact that their work, in and of itself, without regard to their attitude toward these other things...is a service of God and a divine ministry to men.

"It is for the church to decide whether she will be guided by prophets or engineers," Taylor had complained. Tufts and the Universalists opted for engineers.

* * *

At the end of the academic year in 1913, the senior class gathered for the last time in the Tufts chapel. It had convened to hear William Hooper, Professor of Electrical Engineering and

Acting President, deliver the customary admonishments to the graduating class. If the seniors had been perfunctory in their work, Hooper told them, then they had wasted their time. But if they had "wrestled mightily with new and difficult problems," they could participate in the great developments that marked the modern epoch.[27]

Hooper's talk was thoroughly conventional. But the symbolism of the event transcended the president's prosaic homily. The more important, though tacit, message resided in the juxtaposition of engineering and devotion. Hooper's presence that day, in a chapel wired and lit by his skill as an electrical engineer, illuminates the ethical context and the moral possibilities that colored the engineer's calling. To Henry Adams, in Paris a decade earlier, the dynamo and the cathedral appeared contrary symbols. For the members of Hooper's audience, they were not only compatible but mutually energizing. In the optimism of 1913, educators seemed to have succeeded in synthesizing knowledge and power, and producing a student groomed to play an instrumental role in the making of the modern world. He was Anthony's Renaissance artist, Earle's translator, and the minister of Hamilton and Skinner modulating energy between worlds physical, social, and moral. The historians of the White City had found the promise of utopia in the reconciliation of technology and culture. The engineers of Tufts ventured to fulfill the promise.

* * *

At commencement later that week, the seniors listened to more speeches and witnessed the granting of honorary doctorates to Admiral Peary and George Harwood, an engineer with the New York Central and Hudson River Railroad. They suffered, as well, through brief addresses by fellow seniors, one of whom was a young electrical engineer by the name of Vannevar Bush, who spoke to them on "The Poetry of Mathematics."[28]

NOTES - CHAPTER THREE

1. W.S. Franklin and Barry MacNutt, "The Teaching of Elementary Mechanics," SPEE Proceedings 15 (1907): 316.

2. On science, pedagogy, and the emergence of higher education, see Owen Hannaway, "The German Model of Chemical Education in America: Ira Remsen at Johns Hopkins," Ambix 23 (1976): 145-164; David Hollinger, "William James and the Cult of Inquiry," Michigan Quarterly Review 20 (1981): 264-283, and "Inquiry and Uplift: Late Nineteenth Century American Academics and the Moral Efficacy of Scientific Practice," in Thomas Haskell, ed., The Authority of Experts (Bloomington: Indiana University Press, 1984); Larry Owens, "Pure and Sound Government: Laboratories, Playing Fields, and Gymnasia in the Nineteenth Century Search for Order," Isis 76 (1985): 182-194; and especially, Laurence Veysey, The Emergence of the American University (Chicago and London: University of Chicago Press, 1965).

3. Daniel Gilman, "The Utility of Universities," in University Problems, p.47; The Seventh Annual Report of the President of Johns Hopkins, 1883, p.88; on Johns Hopkins, see Owens, op.cit., and especially, Hugh Hawkins, Pioneer: a History of the Johns Hopkins University, 1874-1899 (Ithaca: Cornell University Press, 1960).

4. See, for example, Louis Franklin Snow, The College Curriculum in the United States (Columbia University Ph.D. dissertation, 1907), p.171.

5. See William Wickenden, "A Comparative Study of Engineering Education in the United States and Europe," Report of the Investigation of Engineering Education (Society for the Promotion of Engineering Education, 1930); on Thurston's role, see Monte Calvert, The Mechanical Engineer in America, 1830-1910 (Baltimore: Johns Hopkins University Press, 1967).

6. There is an obvious shift, for instance, in the emphasis in SPEE discussions of the educational role of the laboratory.

7. Cf. Monte Calvert, op. cit.

8. Joseph Torrey, "Practical Machine-Shop Instruction in Technical Schools," Engineering Magazine 6 (1893-1894): 17-23; Wickenden, op. cit., pp.819-821; C.R. Mann, A Study of Engineering Education, 1918, pp.75-87.

9. Calvin Woodward, "Manual, Industrial, and Technical Education," Report of the Commissioner of Education for the Year 1903, Volume 1, pp.1019-1020; for biographical information, see American Men of Science, 1910 edition.

10. Calvin Woodward, "Presidential Address," *Proceedings SPEE*, (1903): 28; *ibid*., pp.34, 22.

11. Gardner Anthony, "The Best Combination of Academic and Technical Studies in the College Training of an Engineer," *The Tufts College Graduate* 7 (1909): 133-134.

12. W.S. Franklin, Barry MacNutt, and R.C. Charles, "Practical Mathematics," *Proceedings SPEE* 22 (1914): 101.

13. W.S. Franklin, "Physics From the College Point of View," *Educational Review* 41 (1911): 83-84.

14. W.S. Franklin and Barry MacNutt, "The Teaching of Elementary Mechanics," *Proceedings SPEE* 15 (1907): 316-317.

15. C.R. Mann, *A Study of Engineering Education*, 1918; for his career, see *American Men of Science*, 1921 edition.

16. C.R. Mann, "Physics in the College Course," *Educational Review* 39 (1910): 479.

17. John Dewey, "Science as Subject-Matter and Method," *Science* 31 (1910): 123.

18. On American pragmatism, see John E. Smith, *The Spirit of American Philosophy* (New York: Oxford University Press, 1963); for Dewey's influence on education, see Lawrence Cremin, *The Transformation of the School* (New York: Alfred Knopf, 1961).

19. C.R. Mann, *A Study of Engineering Education*, p.113.

20. G. Anthony, "The Rise of Engineering," *Tufts College Graduate* 21 (1922-1923).

21. Faunce, *Educational Review* (April, 1905): 369.

22. Malcolm Taylor, "Prophets or Engineers," *Atlantic Monthly* 106 (1910): 769-774.

23. *Ibid*., p.774.

24. Clarence R. Skinner, *The Social Implications of Universalism*, 1915, pp.1, 5.

25. *Ibid*., p.86-89.

26. Frederick Hamilton, *The Church and Secular Life* (Universalist Press, 1894), pp.40-41.

27. *Universalist Leader*, June 28, 1913, pp.814-816.

28. *Ibid*., p.815.

Part Two.

The Education of Vannevar Bush

"By plumb we are taught to walk uprightly here,
Ever squaring our action by virtue most dear..."

- Perry Bush

CHAPTER FOUR:
A JOURNEY TO BARNSTABLE

Story has it that from the summit of High Point Hill one can see not only the whole of Provincetown but most of the world.[1] This sparse tip of Cape Cod, where stands a monument to the pilgrims, forms one of those magic places that coaxes vision from sight. To Henry Thoreau, pausing in his midcentury journey around the Cape, it seemed a place where the "dry land itself came through and out of the water in its way to the heavens."[2] Here in 1620, having endured the ocean´s fury, the Mayflower´s saints stood in the calm of the Bay and gazed out on a "hideous and desolate wilderness." And here, poised between the sea, a "gulf to separate them from all the civil parts of the world," and the wildness of the new land, they paused to project beyond the small community of their vessel a larger society, "to Covenant and Combine ourselves together into a Civil Body Politic."[3] With the Old World at its back, beyond the ineluctable formlessness of the ocean, with the New World before, yet to be formed, the Cape was a fragile edge where utopia was both possible yet dangerously fragile.

And, it turns out, a breeding ground of ministers and engineers. Indeed, one could find no more suggestive place to begin the search for Vannevar Bush. If his early career were folded into an ellipse, MIT and Tufts College would occupy one focus, Provincetown and the Cape the other. As well as he could remember, both sides of his family had always lived on the Cape. "I am certainly a Cape Cod Yankee," he said, and the family had its share of sea captains and whalers. One of them explored the coast of Africa at the age of twenty-one, another was captain of one of the first ships to trade up the Amazon. Bush's maternal grandfather, Lysander Paine, brought his wife along on the latter voyages and, "as near as I can make out, he ran the ship and she did the business.... She lived with us until I went to college, went blind, nevertheless would not quit, and finally got killed."[4]

One survived in Provincetown by fishing, or by going to sea for souls, for the town bred its share of ministers. One of them was Richard Perry Bush, Vannevar's father, who spent his youth among the sandy dunes of the Cape, sailing at the age of fourteen as a cook on a mackerel fisherman. At the age of twenty, Perry left Provincetown for the suburbs of Boston, the first of his clan to do so. Why we don't know, though several reasons can be surmised. The fishing industry, which had expanded during the earlier part of the century, was in a state of decline and, in all probability, no longer able to sustain a young man's ambitions. More certain were denominational tensions on the Cape. Vannevar Bush remembered his grandfather telling him

> ...how one crowd wanted to build a church and brought the lumber in by ship. Once the competing faiths proceeded to burn up the lumber. They started over again, brought in new lumber, and this time sat over that lumber night and day with shotguns until they got the building framed in.[5]

At any rate, Perry Bush settled near Tufts College, on the outskirts of Boston. He abandoned the Methodist traditions of his family and entered the Tufts Divinity School to train for the Universalist ministry. There he earned his keep by delivering coal to his student subscribers, eventually graduating with a Bachelor's in Divinity in 1879. Upon ordination, he became pastor of the Universalist Church in Everett, moving in 1892 to the First Universalist Church of the Redeemer in Chelsea where he remained for the next thirty years. During his long pastorate, Perry Bush maintained close ties with his alma mater. He earned a doctor's degree in divinity in 1905, and delivered a series of lectures at the Divinity School during the academic year 1909-1910.

In a eulogy delivered in 1926, Lee McCollester, the Dean of the Divinity School at Tufts and a close friend, sought to capture the spirit of this man who had left the ocean-bound confines of Provincetown to seek his career in the suburbs of Boston. "From his home by the sea, he came here to college, and at first some of his professors wondered if he could ever make a successful parson, and whether he had not better keep to the sea and the ships." He did, in fact, make a success of it. Neither, in several senses, did he leave the sea behind. Those were days in which Medford on the Mystic still echoed the glories of earlier days when a quarter of all the state's shipbuilders had worked in its shipyards; those days were past, but the rum that percolated through its social life was a reminder that the river and the docks still linked the town to the Triangular Trade that took Medford rum to Africa, and slaves to the West Indies in exchange for sugar.[6] But the real sense in which Perry Bush "kept to the sea and the ships" was visionary. "[T]he sea was all around him.... It was his inspiration. Something of the moods of the sea were always with him."[7] The sea touched a poetic chord that spoke both of danger and of possibility: "I stand on the edge of the ocean," he wrote in a poem, "And dream as I've oft dreamed before: - In vain I may peer mid the distance, Straining eyes that search for a shore...." The ocean spoke as well of the divine purpose he found in his life:

What the helm is to the vessel,
 As she sails o'er unknown seas;
While the rocks and waves about her,
 While the tempest and the breeze,
All seem ready to engulf her,
 Yet she safely glides along,
Guided by the sturdy rudder,
 Held by hand so skilled and strong,

So to us, on life's broad ocean,
 As we voyage day by day,
Is the Purpose that directs us
 Safely o'er the untried way.
What through storms and trouble gather,
 Bringing sorrow and distress
Safe directed by our Purpose,
 We shall reach the port Success.[8]

He was a cheerful man, a "friend to all sorts and conditions of men." A fisherman from Provincetown and a religious liberal, he was doubly marginal in Boston society, famous for his common touch and ability to mix. This sense of being on the outside of the inner circles of power took root in his son, who reminisced many years later: "...at that time, the center of boy life in the town was the YMCA, and the YMCA...barred liberals from membership, and also Catholics and Jews. As the net result of that, my boyhood friends were the Catholics and the Jews. I was not only not a Boston Brahmin, I acquired a very considerable set of boyhood prejudices against them."[9]

Like the fisherman he had been and the engineer his son would become, Perry Bush had a deep respect for his tools and was not above using the most common of them in "going to sea for souls." Malcom Taylor might have objected that the young minister in these times found himself dismayed by "Boys' Clubs and Friendly Societies, of afternoon calls and church suppers, of playing billiards for the glory of God," but Perry Bush was very good at just these things. Taylor demanded that the Church decide "whether she will be guided by prophets or engineers." Bush happily opted for engineers. He was especially good at "playing billiards for the glory of God." Once he was asked by a mother to intercede with her son who was "sowing wild oats." One evening after dinner, the son

> invited my father down to play a game of pool, with apparently no idea that the minister had ever played the game. They went down to the billiard room...and they set up the balls in the triangle. The minister broke them and knocked them all in. The youngster said, 'I've seen miracles in my time and I'll still see more, no doubt, but I'm perfectly sober and can't

> understand this.´ My father said, ´There isn´t any miracle about it.´ He put them into the triangle again, set them up, again broke them, and put them all in.

There was no talk of good behavior that evening, only pool. The two "got to be good friends, and finally the youngster straightened himself out largely on his own."[10]

The minister´s craft, as exercised by Perry Bush and like the crafts of sailor and engineer, hinged on an intimate relationship between the instrument and the one who wielded it. Here the tool became a symbol of one´s power to deal in a constructive fashion with the world, to trace, sailor-like, meaningful journeys across the chaos of social life or to impose the edges and planes of rationality on the formlessness of brute matter. Unsurprisingly, Perry Bush was deeply involved with the Masons.

"Turn to the past and you will soon discover," he wrote in a poem celebrating the spirit of Masonry[11], that

The _builders_ are they with their genius and art,
  Who by God were selected,
  And duly elected,
In drama of progress to play the chief part.

And again,

By plumb we are taught to walk uprightly here,
Ever squaring our action by virtue most dear,
While our thought from Time´s dreary level oft turns
To that land from whose bourne no traveller returns.

We all who are masons accepted and free,
Twixt the points of the compass clearly can see.

Building, levels, plumbs, squares, and compasses - these are all key ingredients of the symbolic world of the Mason. In certain ways, it is a more straightforward universe than that of the sailor with its eschatological mysteries locked in the precise edges of the builder's tools. Nevertheless, both suggest the utopian possibility that order can be built from the formlessness around one, whether the craft is that of the seaman, the minister, or the engineer.

Perry's eulogist wondered whether his friend should not have kept to the sea and the ships. But in a sense he did just that. In a manner not uncharacteristic of the nineteenth century, Perry Bush found in the sea and the craft of the builder metaphors for life ("Henceforth, I can stand by the ocean:- Atlantic, -grand type of man's life"[12]) and in this sense he was eminently suited to play the influential role in his community which he did. These metaphorical worlds in which Perry Bush was solidly ensconced found strong resonances in the career of his son, Vannevar Bush.

* * *

Van Bush grew up in boats, like his fathers before him. And like them, something of the sea stayed always with him.
In later life, he was notorious for his salty humor and stormy temper which he attributed, maybe in jest, to the Irish grandmother once abducted by an ocean-ranging ancestor. As a teenager and frequent visitor to the Cape, he possessed a motorboat with which he and a cousin went on frequent explorations around the Bay. He preferred sailboats, however, and when a young man owned a ketch, the Caribou, on which he sailed along the Maine coast during the twenties until forced to sell the boat during the Depression. The young Bush was more

than a skilled sailor. He was a boat-builder as well, a craft he seems to have learned from Lysander Paine, who ran a chandlery in Provincetown after retiring from whaling.[13]

In detail we know relatively little of Bush's childhood. Born in 1890 into the Victorian household of an energetic Chelsea pastor, his life was busy and undoubtedly full of normal boyhood activities. He was the second of two children; his sister Edith was five years older, his sister Reba five years younger. Edith was competent and outgoing, a good sailor in her own right, an outdoorsman and fisherman. She preceded her brother through Tufts, graduating in 1903 and becoming a teacher of mathematics first at the high school in Chelsea and then in Provincetown. She returned to the College as a teacher of mathematics, and stayed for thirty-two years, becoming Dean of Women in 1925.

Much of Bush's boyhood was commonplace. He went to school, sang in the choir along with his sisters, and helped his father with whatever miscellaneous pastoral tasks were appropriate. His father once sent him off in horse and buggy to rescue his grandmother during the great Chelsea fire of 1908. He revelled in the sea, fiddled in the attic with a primitive radio set, like many other curious youngsters of the period, and worked in a local bicycle shop. He was knowledgeable in the ways of machines and gadgets. He did well in school, by all accounts, particularly in science and mathematics. In high school, he studied trigonometry with his older sister Edith. If there was a hint of trouble in his youth, it concerned his health. A severe bout of rheumatic fever caused him to fall behind a year in high school and left him with rheumatism which bothered him off and on until it was cured, apparently, by the intense effort of his year of graduate work in 1915. Later, in college, he would lose a semester to appendicitis. The effect of this illness, however, was far from debilitating and, in fact, propelled him to what must have been, at times, frantic efforts to keep up and to excel.

His father left the most lasting mark on the young man. Although Bush never entertained thoughts about following in his father's footsteps and becoming a minister, he did take to heart paternal values and commitments. He adopted, as had his father, a belief in the value of vocation, a calling to some higher purpose devoted to the public good. More practically, Perry Bush demonstrated a remarkable knack for getting along with people, and his son sought to emulate him.[14]

> He was a clergyman, and a good one. He had an interest in all the people about him, and he understood them well. This did not mean just his parishioners, and it did not mean just the upright citizens in the community. He was interested in the chap who kept the saloon down the street, and he understood him too. He had an uncanny sense of how to work with people of all sorts, and I saw him do it. In days when it was hardly ever done, he worked hand in glove with the local Catholic priest...in civic affairs, such as taming saloonkeepers.

He followed in his father's footsteps in many ways. He became caught up in the elaborate ceremony and social activities of the Masons, and while his enthusiasm for the baroque mysteries of this fraternal society waned as he grew older, he long continued to find in Masonry "a quiet haven where men joined in exceedingly simple social and religious association, not, however, devoid of inspiration."[15] Moreover, it seems plain that the substance of Masonic symbolism struck deep chords in both father and son. As one Masonic text put it:[16]

> Force, unregulated or ill-regulated, is not only wasted in the void, like that of gunpowder burned in the open air, and steam unconfined by science.... It is destruction and ruin.... The blind force of the people is a Force that must be economized, and also managed.... It must be regulated by Intellect. Intellect is to the people and the people's Force, what the slender needle of the compass is to the ship - its soul, always counselling the huge mass of wood and iron, and always pointing to the north.

Aligned with the slender needle of the compass, skilled in the use of dividers and the rules of the builder, young Vannevar Bush would seek to measure his success.

* * *

In the fall of 1909, recovered from his bout with rheumatic fever, Van Bush enrolled at Tufts College as a student of electrical engineering. Why he did so, in an explicit sense, we do not know. He was, of course, a son of the sea, a traditional Yankee and offspring of one of the area's beloved pastors. But maybe the fact that this minister's son should choose engineering as a vocation should not surprise us. In truth, he liked to fiddle with things. And like lots of other young men who possessed the mechanical inclinations so common at the turn of the century, engineering was more and more a field of choice. Nevertheless, the growing fascination with engineering was not simply the unthinking response of a mechanical people to greater technical opportunities in a rapidly industrializing society. More than a mere occupation, the new profession of engineering could be seen at colleges like Tufts as a modern calling, an ethical vocation ready to assume many of the qualities and responsibilities of a ministry. If this seems an odd and surprising short circuit of affairs not usually connected, it was nonetheless real at the time and in the right place; not a necessary connection, as the historian likes to seek out cause and effect, but a possible congruence of concerns and energies that made it possible for a young man like Vannevar Bush to carry away from his college years a dedication to engineering as a ministry, to see his profession as a modern-day pastoralism culturally responsible and socially powerful.

Whatever its source, engineering in turn of the century America contained an implicit social imperative which is important to note. Its emphasis on the skills of head and hand, on instrumental rationality, and the strange cross connections with the ministerial ethos all combined to invest engineering with the hopes that here was an effective, fair, and rational device by which Americans could shape the intractable materials of their social, economic, and technological worlds. This would not have been an unreasonable hope for most young men who went into engineering, nor for those industrial managers who sought to promote the training of engineers. Most of these young men were nineteen when they entered college, came from communities near to their schools, and from families native-born for several generations. Comparatively few engineering students were of southern or eastern European descent. 16% of the fathers were professionals (though only 4% were engineers), 17% were farmers, and 42% were in industrial, mercantile, or financial occupations. While less than 3% of the fathers were unskilled and almost a quarter had some experience with college, over half had failed to finish high school. The students themselves felt that, in general, they were in the upper third of their high school classes, and had done well in the sciences as well as in manual training and drawing. Their families, while not wealthy, were well enough off to have allowed the sons to have earned and saved substantial amounts prior to entering college.[17]

Engineering was professionalizing, then, just at that time when cities were being reshaped both by modern industry and by waves of immigration from southern and eastern Europe. While the technical demands of urbanization made a heady market for these newly-made engineers, so did the increasingly alien face of the new urban humanity itself constitute a challenge and an opportunity. As Perry Bush's Masonry put it,[18]

> There are immense Forces in the great caverns of evil beneath society; in the hideous degradation, squalor, wretchedness and destitution, vices and crimes that reek and simmer in the darkness in that populace below the people, of great cities.

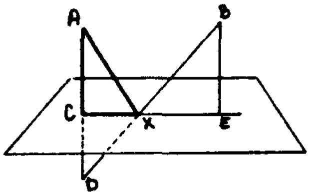
It is an image that foreshadows Fritz Lang's Metropolis, though our engineer would have considered himself part of the solution and not the problem.

Several days after registration, the College community gathered in the gymnasium to celebrate the beginning of another academic year. The audience, including in all likelihood, the young Van Bush, was greeted by President Hamilton, who reminded his listeners that "this college means development of the whole man, and not simply the mastery of a profession." He pointed out the opportunities to enlarge one's acquaintance, "to attend our numerous lectures, to attend chapel, to attend social affairs, and to take part in athletics." Those who were not athletes themselves were encouraged to "help to keep our athletes in good standing in their studies," as in that way they could do more good than by simply rooting for the teams. The President's remarks concluded with the singing of the campus song, and were followed by a brief address by an alumnus who reemphasized the importance of athletics. "Studies come first and athletics second. Naturally one comes to college for an education, but athletics should not be slighted." The President added that he hoped to see college exercises close earlier during the day to give players more time on the field. The Glee Club sang several more songs, and another speaker noted that Tufts as a college was a "corporate organism" and allowed a more intimate education than the larger and more indifferent university. Finally, the Reverend Perry Bush reminisced about his student days and concluded that "the ideal of the College,' despite its dramatic growth, "is always and will always be the same."[19]

Bush took seriously the admonitions he received that evening. In short order, this slightly-built offspring of the Chelsea pastor ("Another minister's son - Shake Van!"[20]) socialized with the men ("Van Bush!! The Boulevard; a song again?", "Say! What did you think of that Freshman Banquet?"), dallied with the women ("In case your hair falls out...place the golden locks in this."), engaged in shenanigans ("O'Neil, fill this jug or suffer the consequences. Signed the Top Floor Rookies."), and turned out for sports ("As a miler, you're good - for nothing!"). Chronic rheumatism and a slight frame (five feet, ten and a half inches, and a hundred and thirty-eight pounds) could not subdue a nervous energy which needed outlets. Too small for football, Bush turned to track. He competed in interclass rivalries, running in the 880, one mile, and two mile races. Never much of an athlete, he thoroughly enjoyed the rough and tumble male camaraderie sports involved. He managed the football team as a senior, arranging a meeting with West Point in which the young Dwight Eisenhower permanently damaged his knee. (I one time told Ike that I managed the team that bent his knee, but I don't think he thought it was funny...."[21]

Social life at the College centered in the clubs and fraternities and Bush lost little time in joining up. At the close of his first semester, he spoke on behalf of the freshmen initiated into Alpha Tau Omega, the engineering fraternity; he was an avid member of the Evening Party Association which staged frequent dances throughout the year; he participated in his class honor societies; and he was elected to Phi Beta Kappa his senior year (He once listened to Hugo Münsterberg present a lecture in the college chapel). He attended recitals, concerts, and plays (One of them was "Doigts de Fee," a comedy depicting the romantic triumph of a poor but beautiful Parisian seamstress in a household turned upside down by the tragic loss of family money. The moral? "...honest labor was no disgrace."). He smoked, drank, and played with an exuberance very much in the spirit of the times. By his junior year, he had become president of his class.

In later years, Bush's religious practice waned, but at Tufts, like everyone else at the College, he attended chapel daily, and just as he was assigned a dorm room, so was he given a seat in chapel. ("The classes sit as follows: Seniors and Sophomores in center aisle on the left and right respectively; Juniors on left aisle; Freshmen on aisle farthest from the entrance, and in the transept."[22]) Students were given tickets indicating their seating assignments, on the back of which they were informed that "You will be required to occupy the above seat through the year, unless otherwise directed. This card must be retained and presented to the usher during the first week of chapel."[23] Needless to say, discipline rarely inspires religious ardor where there is none to begin with, and, at least at certain moments, we know that Bush's thoughts found the opportunity to wander far afield. On the back of his sophomore seating ticket, he scribbled the following geometric diagram:



How often at this Universalist school for engineers, where the icons of science and sentiment were juxtaposed in the manner of Henry Van Brunt, did homily encourage mathematics? Be that as it may, Bush thoroughly enjoyed his father's company and remained active in parish affairs, even attending with him a Universalist convention in New York City.

None of these privileges came free of charge. Bush's bill for his first year came to some $250 (Tuition - $150, room - $80, physical culture - $10, light - $5). He might have saved money by rooming at home, but would the Reverend Bush have tolerated freshmen shenanigans? In any case, scholarships were available for on-campus students, and he seems to have received enough to cover about half of his bill.[24] He made up the difference, as had his father, by working. He first tried washing dishes, but quickly decided, in good engineering fashion, that there were alternatives with a higher ratio of income to effort.[25] Tutoring, however, turned out to be "a really good source of funds." There was an abundance of College athletes needing remedial work and Bush was anxious to help. He was a talented teacher and knew many of charges from his work with the teams ("If you want to know something about Soph. physics, ask Fresh. Bush."). In an enterprising turn, he consolidated his separate tutorials and began teaching en masse. "It paid out pretty well," he remembered.[26]

> I'd have a class in the evening, and everyone who came in would put 50¢ on the barrelhead. Some of these would get the money back at the end of the hour as a rebate. These were the ones that really didn't have the money to pay; their job was to drum up trade. I remember one chap who was a great football star of the day, standing at the front of the chapel among a group of admiring freshmen and telling them, 'Why, you doggone fools, you can't possibly get by that course without taking Bush's tutorial sessions.' So this drove the freshmen into my sessions in good shape.

Our student engineer possessed in full measure the quality of "grit," and it helped keep his charges in line. He once substituted for an absent professor who worried about Bush's ability to control the class. He was reassured in no uncertain terms: "Anyone who raised hot with me might possibly have found himself tossed into the reservoir that night." Between tutoring and his job as an assistant in the math lab, he earned enough to make ends meet. On occasion, he did even better. At the end of one term, he discovered that the College owed him money, confronted the bursar, and demonstrated grit. "...the bursar refused to pay me; said he'd credit it on the next term bill. I told him I needed the money and I wanted it, that he owed it to me and I proposed to get it. He said, 'Well, I can't give it to you, and what are you going to do about it? Why,' he said, 'you wouldn't sue the college, would you?' I said, 'Oh yes I would. That would give me great pleasure, sir.' Whereupon after a bit more argument, he paid me what he owed me."[27]

Bush's pursuits within the classroom were no less energetic than those without. Despite the year lost to illness, he came to college well-prepared. He already had under his belt courses in physics and mechanical drawing, algebra, plane and sold geometry, and trigonometry. During the summer before his matriculation at Tufts, he boned up on French and German at MIT (He did better in French). During his first year, he studied English literature, French, drawing, descriptive geometry, physics, and mathematics through introductory calculus.[28] In the shop, he practiced with bench tools and wood lathes, and studied the use of patternmaking. As a sophomore, Bush worked his way through Shakespeare's romantic comedies, and learned the techniques of Gardner Anthony's Graphic Language, among which was material on the mathematical and graphical approach to gears and other mechanisms. In calculus, he practiced the applications of differentiation and integration; in physics, he surveyed heat and mechanics and worked in lab. He dabbled in Spanish, and learned the fundamentals of surveying. He suffered through chemistry guided by the textbooks of Charles William Eliot and Ira Remsen. His textual authorities were teachers of note; his in vivo example definitely was not. Bush recalled one balmy, spring day when "the breeze was soft through the window, the lecturer droned on, and the class slept, with its eyes still open as required by statutes." The lecturer dropped a flask, the class came awake with a start, and so did a mouse who had been asleep on a pipe, who proceeded to trot home along the pipe overhead. "...this is the only thing I remember from an extensive course in chemistry."[29]

In the latter years, Bush continued his study of mathematics, sampled hydraulic and structural engineering, and investigated the mathematical and graphical approaches to the strength of materials, in the class room and the laboratory. The steam engine was the subject of a three-hour course. In his junior year, he was repulsed by economics, "the old-fashioned stilted economics, which was repulsive and did not really get down to brass tacks on the current scene."[30] The majority of his time in these last several years was devoted to his major in electrical engineering. Here he studied direct and alternating current and the design of AC and DC dynamos.

In all of this, Bush did very well. One of his few setbacks occurred during the latter half of his sophomore year when he suffered what might have been a ruptured appendix. At any rate, his transcript indicates that he suffered a major disaster of some sort; also that by the start of the next year he had recovered sufficiently to accumulate an aggressive number of credits during his first semester. Excluding this one problematic semester, Bush achieved a straight-A record, no mean feat in the engineering schools of the day. To a large extent, the course he pursued during his four years at Tufts was very much like that at other schools. By the time of his graduation, he had become adept in what Anthony, the Dean of the Engineering School, called the Graphic Language; he felt at home in the shop and the drafting rooms; and had become intimate with the engines of power that, in the days before radio and electronics, defined his particular expertise as an electrical engineer. He was able to move comfortably from the crafts of the shop to the esoteric languages of the class room, relying heavily on the graphic idioms in which he had been tutored. In other ways, of course, Bush's schedule was very much his own. He particularly enjoyed mathematics, and it would be a mistake to limit his appreciation to the rudimentary levels suggested by his introductory courses. A look at the mathematics Bush learned beyond the introductory level required of all engineering students will suggest both the sophistication available to an interested student, as well as the general emphasis which carried beyond the elementary even into advanced mathematics.

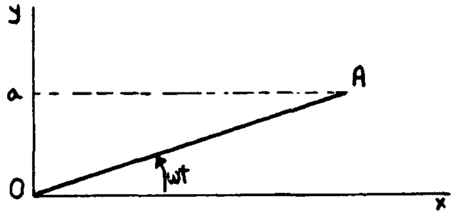
Bush was fascinated by that borderline territory between math and physics in which so little work was being done in American colleges, a lack which had worried E. H. Moore. But Tufts had Billy Ransom who "was not a great mathematician, and knew it, but [who] had a homely art of teaching which was effective, especially with those who found mathematics baffling."[31] During his last two years, Bush took four advanced seminars from Ransom - theoretical mechanics, vector analysis, modern geometry, and the theory of functions. His finest course with Ransom dealt with non-Euclidean geometry. "This was a strange subject for an embryo engineer; it was after Minkowski and before Einstein's general relativity," and after Ransom advertised the course, Bush was the only student registered for it.[32] Enrollment eventually rose to two - Bush and a young instructor in mathematics. What the course lacked in enrollment, it made up for in the opportunity for free and imaginative exploration. While one of the three participants went to the board to demonstrate a theorem - "Let this be a triangle with all of its sides parallel in pairs. We will proceed to find its area." - the other two criticized. "Was this a foolish thing for a young engineer to study? It was one of the most valuable courses I ever took. Here was a subject where one depended completely on careful logical reasoning. If one followed his intuition for just an instant he was inevitably lost. We did it again on the four-dimensional vector analysis of special relativity." At one point, the three went off to read in Scientific American a series of prize-winning essays on the meaning of the fourth-dimension.[33]

As one of their texts, they apparently used a small volume by Paul Carus titled The Foundations of Mathematics, A Contribution to the Philosophy of Geometry. Carus was the German-American philosopher and editor of The Open Court and the Monist who sought to combat through his magazines the relativity and subjectivism that he felt were overtaking the new century. In a flood of books and articles, he elaborated a speculative synthesis of science and religion which found in the attribute of character the expression of the cosmic ethical order, an order in which God was synonymous with the "eternal principle of the laws of existence."[34]

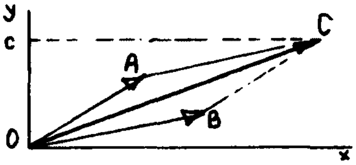
Whatever his limitations as a philosopher, Carus knew his mathematics. Born in Prussia, he had studied math, natural science, classical philology and philosophy at Tübingen, earning his Ph.D. in 1876. In the Foundations Carus surveyed the contemporary crisis in the foundations of mathematics provoked by the discovery of non-Euclidean geometries, and labored to reconcile his belief in the absolutes of space and time with the new worlds of abstract geometry. His solution was straightforward. Disagreeing with Riemann's conclusion that there were many possible spaces, he argued that physical space, as the possibility of motion, was unique, but that mathematical space was a complex construction of "space-measurements." And of these constructed metrics, there were many varieties, including those of Riemann, Lobatchevsky, Bolyai, and Euclid himself.

Whatever our engineers thought about the general problem of the reality of hyperspace (Three of the prize-winning essayists in Scientific American felt that the fourth-dimension was possibly real; one concluded that it was only "metaphysical"), most would have found Carus´ conclusions conveniently familiar and agreeable. The first of these was the notion that geometry was inherently connected to the act of measurement. The second was pedagogical in nature and rooted in Carus´ notion that geometry was the result of constructive activity. "The teaching of mathematics," Carus told his readers in an echo of Moore´s complaints of a decade earlier, was "utterly neglected in the public schools." "Euclid´s method with his pedantic propositions and proofs should be replaced by construction work. Let children begin geometry by doing, not by reasoning.... Lines must be divided, perpendiculars dropped, parallel lines drawn, angles measured and transferred, triangles constructed, unknown quantities determined with the help of proportion.... All instruction should consist in giving *tasks to be performed, not theorems to be proved*...."[35] Carus´ prescriptions echoed both Moore´s earlier call for the redirection of mathematical teaching and the imperatives of the engineering curriculum. Indeed, the engineer became the pivot, the key mediating point, between the abstract prescriptions of intellect (and theoretical science), and the constructive abilities of hand.

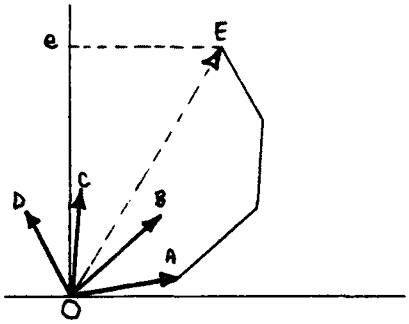
The theory of functions was of interest to our young electrical engineers less for philosophical than practical reasons, and its relevance can be exemplified by the problems confronting engineers in their study of dynamical machinery. In the popular turn of the century text Alternating Currents and Alternating Current Machinery, the brothers Dugald and John Jackson demonstrated the established technique for finding the voltage and current in alternating current circuits. Given that the fluctuation of current was harmonic, it could be represented graphically in the following way:



OA is the maximum current and revolves in a counterclockwise manner about the origin **O** with angle alpha equal to **wt**. The effective value of the current at any time can be determined by projecting **OA** onto the y-axis. Given two superimposed currents acting concurrently, the instantaneous current is determined from the projection of the resultant current produced by the composition of the separate currents.



If **OA** and **OB** are the separate currents at time **t**, and the projection of their resultant **OC**, then the total instantaneous current is **Oc**. Any number of concurrently acting currents could be dealt with in a similar manner through the use of the force polygon, a technique engineers had learned in graphical statics.[36]



The Jacksons' graphical method had the great advantage of "showing directly to the eye the relative phases of the pressures or currents in different parts of the circuit," and avoiding unnecessary formulas which were "fatal to the reader's true progress as they leave him with no true physical conception of the phenomena studied."[37]

However, if the various magnitudes were widely disproportionate, it might prove impossible to obtain results of sufficient precision by measurements taken directly from the graphs. In this case, engineers could use an analytical method introduced by Charles Steinmetz in 1893 which employed complex numbers.[38] In Steinmetz's notation, both the phase and magnitude of the the vector in question could be expressed as $\mathbf{A(\cos\alpha+i\cos\alpha)}$ in polar coordinates or as $\mathbf{t + iu}$ in rectangular coordinates, with **i** (the square root of minus one) signifying counterclockwise rotation through 90°. In some cases, where the fluctuating currents were unusually irregular, these simple graphical methods did not apply, and the Jacksons introduced their readers to the manner in which Fourier analysis could used to approximate irregular curves in terms of a fundamental sinusoid and its higher harmonics. In 1896, they confined their discussion of complex variables to twelve pages and relegated Fourier analysis to a short appendix. Over the next decade or so, as electrical engineers struggled with complex electrical systems, they learned to appreciate the subjects that the Jacksons had earlier relegated to an appendix.

By 1911, then, the theories of functions and of complex variables, which taught the student something about the "good behavior" of the mathematics on which he was coming to depend, were making more common appearance in engineering texts. While few had Bush's talent or persistent interest in more advanced mathematics (he was, after all, the sole engineer in Ransom's seminar), his engagement with mathematics was far from eccentric. Indeed, the pull of practical mathematics was inescapable. It was felt in the case of complex variables; but was present as well in the more exotic reaches of modern geometry and the fourth dimension. Were not engineers, after all, adept in the folding and measuring of space through training in descriptive geometry and mechanical drawing? And did not Carus conclude that modern geometries were the product of the constructive operation of measuring space, that geometry was learned by <u>doing it</u>? Even here in the higher realms of mathematics, the Graphic Language of Gardner Anthony remained a useful idiom for the astute student of engineering.

* * *

On a Wednesday morning towards the end of the summer between his freshman and sophomore years, Bush and a friend set off from Provincetown on a journey by motorboat across the Bay to Barnstable.[39] They set out shortly after six on a fine morning with a light and southerly wind. While his companion slept, Bush fussed with a reluctant motor which insisted on skipping and overheating. He replaced a loose pin and fiddled with the carburetor, but the engine continued to act up. On a course of S by SW, they made only thirteen some miles in three hours. "Pretty rotten!," he thought. The compass as well performed badly, and Bush concluded it needed new gymbals. Another couple of hours had coaxed better behavior from the motor, and shortly before 11:00 Bush sighted "the damn lighthouse" where they stopped to ask directions. A little while later, they arrived at Barnstable and anchored in a creek.

In town, they met some friends and spent the afternoon "doing the fair." They went to the races and watched the ascent of a hot air balloon. Late in the afternoon, Bush returned to the boat, changed clothes, and went off to visit a girl friend. His friend "Bones," meanwhile, went out to "swipe some corn," but finding only "cattle feed" bought some bacon, potatoes, biscuits, and candy to bring back to the boat. Bush returned early in the evening and the two friends settled down for a restless night. At two in the morning, a gang of rowdies went by singing, and an hour later the boat went aground and stuck at an uncomfortable angle until the tide came back in.

The next morning they went into town to buy provisions and supplies to fix the motor. The weather took a turn for the worse, and they decided to stay in Barnstable that day, moving the boat from the creek to the harbor. Thursday and Friday were wet and miserable, but the weather improved towards Friday evening and on Saturday morning (not quite so early!), the two started back to Provincetown, heading into the tide and a light southwesterly wind. Despite the solicitations of two engineering students, the motor behaved worse than ever. It "blew out its packing" some three hours and five miles from Barnstable. In frustration, the two resorted to rigging a cover as a makeshift sail and eventually made it home.

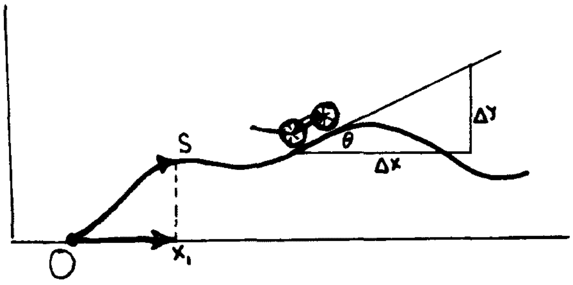
In the diary in which Bush recorded his journey to Barnstable, we find a number of pencil sketches which help us connect this student on vacation to the larger world of engineering and culture. One of them depicts the shortly-to-be-finished Panama Canal stretching across the Isthmus from Colon on the Pacific to Panama on the Atlantic. Elsewhere in his diary can be found the latitudes and longitudes of Cuba and Colon, and the address in Panama of the Pacific Division Engineer.

Was Bush considering heading south at some point to work on the Canal? Probably not, though it wouldn´t have been an inexplicable thought for an ambitious electrical engineer. The construction of the Canal was the greatest engineering feat of its time, and in 1910 it was still four years from completion. Under construction for almost thirty years, it had defeated Ferdinand de Lesseps and its French originators through a combination of hard rock and the ravages of malaria and yellow fever. American efforts had begun in 1904 signaled by gun-boat diplomacy and the creation of a puppet republic which gratefully ceded the new Canal to the United States in perpetuity. The U.S. was to succeed where the French failed for several reasons. Firstly, the project had the staunch political support of the Roosevelt administration which saw the U.S. efforts in Central America as an expression of manifest destiny. Secondly, there was the technological dynamism of the electrical industry which supplied the motive power and the control devices for the canal's locks. Thirdly, the experience of railroad engineers in the problems of large-scale earth removal in difficult places allowed Americans to solve the logistical problems of canal construction. And not least, William Gorgas solved the challenges of malaria and yellow fever. For many in the heady years of Teddy Roosevelt's presidency, success in Panama, in a situation that had baffled the technical genius of the Old World, seemed a celebration of national character and a demonstration of the potency of American science and engineering.[40]

From one point of view, the Panama Canal was a giant exercise in surveying, in tracing a route from one ocean to another. Appropriately, several other sketches in Bush's diary contain the first hints of his Profile Tracer, an ingenious invention designed to simplify the problems of running profiles. In this invention, Bush would be able to combine his feeling for mathematics and the Graphic Language, his familiarity with the shop, and his sense of the subtlety of instruments. While he might have struggled with a reluctant motor on that summer's trip across the Bay, in the Profile Tracer he devised an engine to navigate a steadier landscape.

The running of profiles was a problem in surveying thoroughly familiar to engineering students. They found it not only in its proper texts, but in their calculus books (remember Barker's depiction of **dy/dx**) and their introductions to the graphic idioms of engineering. In general, profiles of elevation over desired routes were obtained by differential leveling. A surveying party comprising three or more men would determine the elevations at a number of different points by the use of rod, chain, and transit. The field notes were later worked up in an office, and the appropriate profile plotted. Bush realized that this cumbersome procedure could be facilitated by devising a portable instrument which would plot the desired profile in a continuous manner as one pushed it along the route. He thought the problem through during his sophomore year and built a crude working model in the summer of 1911.[41]

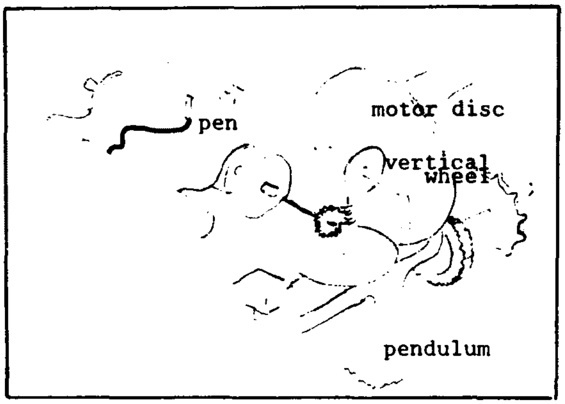
The problem seemed straightforward. The instrument was required to determine and record at every point along the route, the change in both the horizontal and vertical distances as a function of the distance travelled along the path (or the "slope distance"), and to sense its tilt at every point with reference to a horizontal plane tangential to the earth's surface (the "angle of inclination"). On gentle slopes, the slope distance and the distance moved along a horizontal plane approximate closely, and Bush chose to concentrate first on this simpler instance. In this case, the change in vertical distance is equal to the change in horizontal distance (or its approximately equal slope distance) multiplied by the sine of the angle of inclination (see figure 1). Bush accomplished this reduction by the use of a variable friction gear consisting of a motor disc appropriately driven on which rested in the vertical plane a smaller roller wheel and shaft. The motor disc was arranged to swing in the plane of a pendulum by which the machine sensed theta, the angle of inclination. When the Tracer was level, the



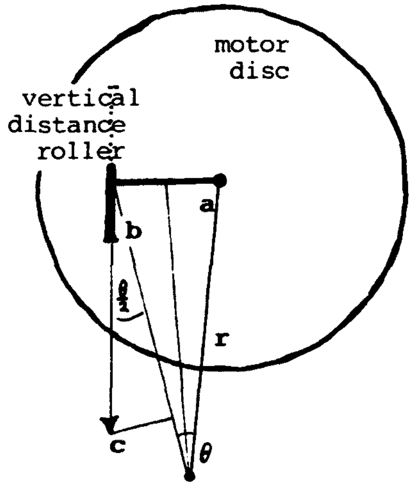
$$dy = dx\ (\sin\theta)$$

figure 1

vertical distance roller rested at the center of the motor disc, and the pen, driven by the roller, traced a level line along chart paper attached to a cylindrical drum driven by the axle of the wheels. When the machine was tilted, and the pendulum deflected, the roller was



displaced from the center of the disc by the angle theta, and then turning with an angular velocity proportional to the angular velocity of the motor disc multiplied by the sine of theta, drove the pen along the vertical axis of the chart. That the motion of the vertical distance roller is proportional to the angular velocity of the motor disc multiplied by the sine of the angle of inclination, can be seen from the diagram:



vector **bc** = velocity at point **b** of the disc

a = the center of the displaced disc

bd = the component of the velocity in the plane of the roller

dc = the velocity component perpendicular to the roller (causing sliding across the disc)

If the angular velocity of the roller is $\mathbf{u}$, then

$$u \alpha (bc)\cos \theta/2.$$

But if the angular velocity of the disc is $\mathbf{v}$, then

$$bc = v(ab), \text{ and}$$

$$u \alpha v(ab)\cos \theta/2.$$

Since $$ab = (2r)\sin \theta/2$$

$$u \alpha (2vr)\sin \theta/2\cos \theta/2 = (vr)\sin\theta, \text{ and}$$

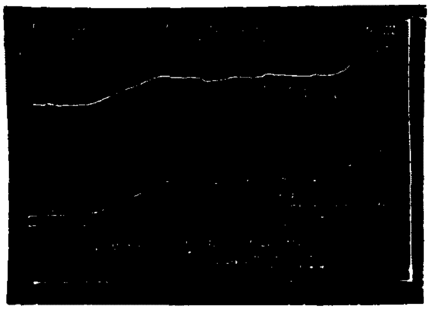
$$u \alpha (v)\sin\theta.$$

Built on the frame of a woman's bicycle, this first crude model worked surprisingly well. Nevertheless, there were a number of bugs. It proved difficult to transmit power from the wheels to the motor disc without introducing torque and interfering with the free swing of the pendulum. A more serious bug concerned the friction drive for the vertical distance roller. It was difficult to transmit enough power by means of friction to drive a pen assembly. At one point, in an attempt to circumvent this difficulty, Bush devised a battery-operated servomechanism which responded to the delicate rotational torque of the roller and supplied the power to drive the pen. This arrangement was discarded because it proved overly complex and the batteries had to be changed frequently.

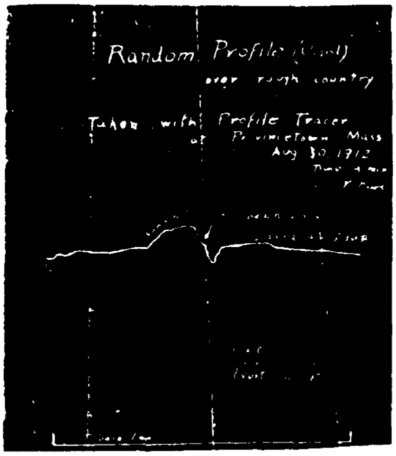
During the winter of his junior year, Bush pondered these various snags and conducted a search of the patent literature for prior inventions. He discovered seven, the first patented in 1857. This model and another patented four years later employed conical friction gears. While they were theoretically correct in their motions, Bush decided for one reason or another that they could never have been built. In 1898 and 1899, two models were patented which utilized discs and wheels as the essential friction element. Again, however, though correct in principle, they appeared impossible to build. In 1910, another disc and wheel model was patented and actually placed on the market for sale. Bush judged this device too heavy and cumbersome to be of practical use, and theoretically unsatisfactory because it made the vertical displacement proportional not to the sine of the angle of displacement but to the angle itself. Having thus surveyed the prior literature, as well as his own problems, he drew up plans for an improved model and applied for a patent.

The following summer, Bush got to work. He borrowed a small workshop in Dedham, spent several weeks putting it in order, and spent the latter part of July and August constructing his Profile Tracer. He used prefabricated gears and did most of the metal and wood work himself. When he finished, he took the Tracer to Provincetown for testing and adjustment. There, mimicking his ancestral sailors plying their ocean paths, he ran his invention up and down the streets of the town and back and forth across the dunes. He practiced on hard ground and soft, backtracking so he could fold the traces back on themselves and test them for reproducibility. He noticed his machine was less disturbed by soft than by rocky ground, and that it was accurate to about one percent.

His Profile Tracer of 1912 embodied the various modifications designed to overcome the drawbacks of the earlier device. He circumvented unwanted torque transmitted from the



wheels to the pendulum through proper gearing and careful attention to the balance point from which the disc and pendulum unit was suspended.



(Illustrations
taken from
Bush's master's
thesis)

The motor disc still drove the pen in basically the same way, but the shaft of the vertical distance roller was threaded and carried the pen on a half nut which rested on the shaft. The roller was held against the motor disc by means of a gentle spring in order to prevent slippage in the friction drive. Furthermore, Bush reduced slope distance, in this improved Tracer, to horizontal distance in a manner similar to that whereby slope distance generated vertical distance. The motor disc was positioned to drive a second roller with a geometry perpendicular to the first so as to move in accordance with the relationship

$$\text{angular velocity} \propto (v)\cos\theta.$$

The shaft of this new roller now drove the chart, no longer directly geared to the axle. Bush solved the problem of slippage in this case by devising a spring mechanism sufficient, on command of the horizontal distance roller, to drive the chart.

Bush thought his Profile Tracer "quite a gadget." His professors did also. When he graduated in 1913, they awarded him a master's degree in addition to his bachelor's. Enthused by his clever success, he had used tutoring income to apply for his patent, and after it was granted had attempted to provoke interest in its commercial manufacture and marketing. When he failed, he "woke up," as he put it, to the economic realities of practical engineering.[42]

> The trouble was that back in 1913 I was densely ignorant. I knew a bit of physics and mathematics. I had graduated in engineering. But I was not an engineer. An engineer has to know a lot about people, the ways they organize and work together, or against one another, the way in which business makes a profit or fails to, especially about how new things become conceived, analyzed, developed, manufactured, put into use. So I charged that invention off to experience - and with no regrets. After all, I got a degree out of it, I had a lot of fun with it, I learned something, and I reoriented my thinking. In fact, for the first time I

resolved to learn about men as well as about things.

* * *

There is irony and not a little humor in the image of this turn of the century engineer struggling with a recalcitrant engine at a magic site in the American landscape, sputtering across the Bay to Barnstable and back again to Provincetown, the home of sea captains, fishers of men, and seekers of utopia. The machines of our technological dreams never work they way they should, not even in the culture of engineering.

CHAPTER FOUR - NOTES

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3. William Bradford, Of Plymouth Plantation (New York: Alfred Knopf, 1952), chapters 9 and 11.

4. Eric Hodgins' interview with Vannevar Bush, June 9 to August 12, 1964, p.1 of the typescript in the possession of the MIT Archives; abbreviated as EH.

5. Vannevar Bush, Pieces of the Action (New York: Morrow, 1970), p.239.

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7. Lee McCollester, "R. Perry Bush," The Christian Leader, May 1, 1926; Universalist Register, 1927, p.52; interview with Richard Bush, December 1983.

8. R. Perry Bush, Poems, copy in the Tufts University Library.

9. EH, p.85A.

10. V. Bush, Pieces, pp.239-240.

11. R. Perry Bush, Poems, pp.108; 94.

12. Ibid., p.22.

13. Richard Bush interview; Molly Gleiser, "Analog Inventor," Datamation, October 1980, pp.141-143; Edna Yost, Modern American Engineers (1952), "Vannevar Bush."*

14. Bush, Pieces, p.238.

15. Ibid., p.240.

16. Albert Pike, Morals and Dogmas of the Ancient and accepted Scottish rite of freemasonry (Charleston, 1871), p.1.

17. Report of the Investigation of Engineering Education, 1923-1929, SPEE, 1930, volume 1, pp.159-192.

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19. The Tufts Weekly, September 23, 1909.

20. The remarks are written in the scrapbook Bush kept while a Tufts undergraduate. Richard Bush was kind enough to lend it to me.

21. EH, p.11.

22. *Ivy Handbook 1909-1910*. This was an informational booklet for Tufts undergraduates.

23. *Ibid*.

24. The receipts are in the Bush scrapbook.

25. EH, pp.7-10.

26. *Ibid*.

27. *Ibid*.

28. Bush transcript.

29. Bush, *Pieces*, p.249.

30. *Ibid*., p.246.

31. EH, p.14; Bush, *Pieces*, p.251; there seem to have been no formal programs in applied mathematics in the United States until the Second World War.

32. Bush, *Pieces*, p.252.

33. Information from a memo book found in the Bush scrapbook; *Scientific American* 101 (1909).

34. Paul Carus, *Foundations of Mathematics: a Contribution to the Philosophy of Geometry* (Chicago: The Open Court Publishing Co., 1908), epilogue; the Carus reference is found in Bush's memo book; on Carus, see Donald Harvey Meyer, "Paul Carus and the Religion of Science," *American Quarterly* 14 (1962): 597-607.

35. Carus, pp.129-130.

36. D.C. Jackson and J.P. Jackson, *Alternating Currents and Alternating Current Machinery* (New York: Macmillan Co., 1896), chapter 4; for the force polygon in statics, see Charles W. Malcolm, *A Text Book on Graphic Statics* (New York: Myron Clark Publishing Co., 1912), p.11.

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38. *Ibid*., pp.208-220; for Steinmetz, see the *Proceedings of the International Electrical Congress Held at Chicago in 1893*.

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40. There are several brochures on the Canal in the Bush scrapbook; for a history of the Canal, see David McCollough, The Path Between the Seas (New York: Simon and Schuster, 1977).

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42. Bush, Pieces, p.157.

Chapter Five:

Bush Goes to General Electric, Or, Elephants and Engineers

In 1913, Gerald Lee wrote to the Atlantic Monthly about a festival he had witnessed in one of the great cities of India. He had found himself in the midst of a large crowd surrounding the King and Queen, a crowd which included a large number of elephants. It was these elephants which drew his attention. He watched those mighty beasts, he said, with their gorgeous trappings, swinging through the crowd, rolling their huge hoodahs, and alongside those beasts, funny little dots of men, silent, moving them invisibly, as by a kind of awful wireless. He found himself asking, Why don't their elephants turn around and chase them? Our elephants chase us, he declared. Who has not seen locomotives come quietly out of their round-houses in New York and begin chasing people; chasing whole towns, tearing along with them, making everybody hurry; speeding up and ordering around the clock great cities, everybody alike, the rich and the poor, the just and the unjust? Any civilization that would be called great, Lee argued, needed to answer certain questions. First, Do the elephants chase the men in it? Second, If as in our own civilization the men have made their own elephants, why should they be chased by them? The future of our country, he said, depended on men who added machines to their souls, like the telephone and wireless telegraph, or to their bodies, like radium and railroads, and who know when and how to use their machines, quietly, powerfully, so as not to be outwitted and unmanned by them. These men, he proclaimed, were the Machine-Trainers.[1]

In these years before the Great War, Gerald Lee was not the only one concerned with the elephants of technology running amok in the gardens of American society. This apprehension pervaded the initial meeting of engineering educators in Chicago in 1893 and influenced educational programs developed in the following years. But academic engineers were not the only ones who sought to tame the elephants of technology and divert their strength to useful purpose. Industrialists, also, were exercised by the dilemmas of technology and unsettled by the spectre of social disruption evoked by dynamic industrial expansion. Far from being unrepentant adherents of laissez-faire, many of the latter turned to the corporation and new forms of social cooperation to frame solutions academic engineers found within the academy. In each case, educators and industrialists forged roles for the engineer that reflected differing institutional prerogatives and allegiances. Gardner Anthony's scholar-engineer was an instrument of culture, ministering to the needs of a new technological order. For industrial spokesmen, technology was handmaiden to the modern corporation and the engineer a company man. Shaped to industrial ends, technology would help the company alleviate human suffering, rationalize the competitive chaos of the marketplace, and remake American society in the corporate image.[2]

* * *

George Perkins exemplifies the expansive vision which drove these corporate apologists. The son of a Chicago insurance salesman, Perkins left school at the age of fifteen and worked his way up through the ranks of the New York Life Insurance Company to earn fame and fortune, starting out as an office boy and becoming a vice-president at the age of forty-one. In 1901, he quit the world of insurance to go to work for J. P. Morgan as a personal financier and organizer, helping to establish both International Harvester and U.S. Steel. He became an important political advisor to Teddy Roosevelt and helped found the Progressive Party in 1912, serving as the chairman of its national executive committee.[3]

For Gardner Anthony, the domestication of technology hinged on skill and culture - the ministry of engineering. For Perkins, the answer lay in organization - and the most suitable organization was the modern corporation. Indeed, the corporation was not a human artifact at all, but the product of natural evolutionary forces which were remaking not only the biological world but the social and business worlds as well. The archetypal "corporation" was none other than the Universe itself, established in the act of Creation, that initial and greatest of all incorporations. "...in the very beginning of things, the universe was organized - and all that man has done in society, in the Church, in business, and all that he ever can do in the centuries to come, can never bring to pass so complete a form of organization, so vast a trust, so centralized a form of control, as passes before our eyes in each twenty-four hour of our lives as we contemplate that all-including system of perfect organization called the Universe." Organization was "the all-pervading principle of the universe," and led Perkins in properly Spencerian fashion to envision the natural complexification of industry and exchange. "Business was originally done by individuals trading with one another; then by a firm of two or more individuals; then by a company; then by a corporation, and latterly by a giant corporation...."[4] The competitive individualism of early business might have been appropriate for the nineteenth century. But the new conditions of the twentieth century required a higher form of organization, cooperative in its economic policies, humane in the treatment of its growing labor force, and responsible to the public as a trust established in its interest.

In part, Perkins's search for "higher forms" was conditioned by changes in contemporary economy - largely, the establishment of a national market and the development of the technical means for its exploitation. In an attempt to moderate destructive competition and to facilitate management, in short, to rationalize the marketplace, industrial leaders experimented with various forms of consolidation, among them the pool, the trust, and the holding company. The largest and most dynamic of these companies - Du Pont, General Motors, Standard Oil, General Electric, and Sears, Roebuck - embarked upon a strategy of vertical integration which secured their markets through the acquisition of essential resources and raw materials.[5]

Not least important of essential resources, especially to industries caught up in the throes of technological change, was invention itself. George Perkins felt that each great change in social organization had been occasioned by a discovery of the mind. The ox-team and hoe had established trade between individuals, the sailing ship and the stagecoach had encouraged exchange between firms. The locomotive, the steamboat, the reaper, and the telegraph provoked the corporation. "[W]ith the birth of the larger corporation we had the express train, the Atlantic cable, the ocean liner, the local telephone, the seeder, the reaper and the binder; with the giant corporation came the Twentieth Century Limited, the crossing of the ocean in five days, the long-distance telephone, wireless telegraphy, and a great extension of machinery into agricultural work."[6] The key, therefore, to the management of progress was the control of the knowledge on which invention depended.

Practically speaking, there were a number of ways in which the corporation could appropriate technical knowledge. The rights to inventions could be purchased outright; for that matter, the inventor himself could be "purchased" as a hedge against future production. More interesting were strategies directed at the production of knowledge itself. The development of necessary work skills could be secured through vocational education and the establishment of in-house training and apprenticeship programs.[7] Likewise, industries could establish indoctrination programs for recent engineering graduates designed to familiarize them with the details of manufacturing and to introduce them to the customs and mores of company life. Moreover, companies could go beyond the adaptation of knowledge and invention. The beginning of the century saw a number of industries dependent on technical knowledge create in-house research and engineering laboratories designed to harness the production of knowledge to corporate purpose. By all of these means, the modern corporation attempted to secure the availability of the skills, inventions, and knowledge on which its competitive survival was coming to depend.

Charles Steinmetz and Willis Whitney were major strategists in the campaign to incorporate knowledge and both, not surprisingly, were employees of one of the most technologically sophisticated of modern corporations - the General Electric Company. Steinmetz, arriving from Europe bearing the radical credentials of a German socialist, was soon acquired by GE for the sake of his unparalleled understanding of electrical equipment. He found a comfortable niche at GE and went on to play a major role in its technical maturation as chief consulting engineer. That he could remain at the same time a dedicated socialist, active in community politics and as president of the local school board during the socialist administration of mayor George Lunn, suggests the flexibility of the cooperative vision that pervaded much of big business.[8]

Steinmetz believed that the cooperation of socialism and American business was suited to the times. Once capitalism had collapsed along with the individualism that was its driving force, it would be replaced in proper evolutionary order by the collectivist community of Perkins´ corporation. Speaking from the vantage point of a company grown large through its electrical successes, Steinmetz confidently declared the passing of the old order:

> Industrial competition of everybody for himself and against everybody else - and the devil take the hindmost - has failed and is disappearing, is indeed practically dead. But there is growing up in the industrial organization a competition to further the common end, the welfare and advance of the organization; a rivalry as to who can accomplish most for the benefit of the corporation; and the reward is in power, in reputation, and also in money. It is this competition in cooperation which the change of the industrial system is introducing....(9)

Like Perkins, Steinmetz saw in the changes of his times evidence of a fundamental transformation in the nature of the political economy. The chaos of individualistic competition was rapidly passing; cooperative, and orderly, competition modulated by corporate allegiance was on its way in. And competitive cooperation depended as much on the domestication of invention and knowledge production as on the consolidation of smaller rivals. The solitary inventor doggedly pursuing an eccentric vision might have been appropriate in the economically and technologically simpler economy of the previous century. But the new age, Steinmetz felt, called for something else. Thus prodded by their resident electrical socialist and worried by the challenges of rivals to their dominance of the electrical market, the executives of General Electric established in 1900 the first industrial research laboratory.[10]

For John Broderick these events had special significance. A longtime employee and one of the company's earliest historians, Broderick saw in General Electric and the new laboratory the realization of Francis Bacon's New Atlantis. New Atlantis had its Salomon's House; GE had its laboratory. And both were meant to serve as the moral and intellectual centers of utopian societies.

> [I]f the author of New Atlantis were to return to life, after his sleep of three hundred years, he would be much less bewildered than was Rip Van Winkle, back from the mountain after his nap of twenty. Visiting Schenectady, he would find the research laboratory there very much to his liking; he would see carried on diligently and systematically in its huge buildings the search, only imagined by him, for 'a knowledge of causes and the secret motions of things'; he would have the pleasure of mingling with groups of trained men zealously doing sundry chores like the ones which had been assigned to the 'fellows' of Salomon's House; and presently he would be made agreeably muzzy by a veritable feast of the 'fruits' of which he had written with a seer's enthusiasm.(11)

Where Anthony looked backed to Leonardo and Renaissance individualism, Broderick celebrated the rebirth of Bacon's utopian communitarianism. There was more to this factory, it seems, than met the eye.

If GE appeared as a model of the enlightened technological community in the mythic fancies of men like Broderick, it came to earth in the accounts of Willis Whitney. An MIT graduate in chemistry with training in Leipzig, Whitney was lured into industry by Edwin Rice with the offer to become the new laboratory's first director. Somewhat to the consternation of our company historian, Whitney described himself as "a plodder of the garden variety - reasonably happy, to be sure, in my humdrum way, yet nothing more than a plodder."[12] Yet Whitney was destined to become powerful in the American scientific establishment, for he brought to his job not the creative enthusiasms of genius or the vision of the seer, but the more ordinary talents of the manager of men who brought to the search for knowledge the instincts of an accountant. In a talk on the organization of industrial research delivered at Clark University in 1909, Whitney followed Broderick in apostrophizing the great Bacon. But what drew Whitney's attention were Bacon's strictures against ambition. Like the unmediated individualism which characterized earlier times, the ambitiousness to which it gave rise was "vulgar and degenerate." While patriotism, ambition in the service of one's country, was "more dignified, but not less covetous," the only legitimate ambition concerned the struggle to increase control over nature.[13] And where better to manage the ambition for knowledge than within the confines of the corporate community.

Whitney's account of the Research Laboratory illustrates how corporate allegiance domesticated the pursuit of knowledge and invention. The organization of the laboratory was divided into two parts: the first dealt with personal and mental factors, the second with material organization. These could be abbreviated, he said, as the "mind and matter organizations." On the face of it, Whitney considers the personal qualities which characterize the mental dimension of his lab to be paramount. More important to the successful "operator" than the necessary knowledge were the qualities of character - a sense of fair play and, above all, an active optimism before which all problems dissolved. Nothing was more detrimental to the success of the laboratory than a sophisticated knowledge quick to sense the grounds of failure. "Research needs more aviators," Whitney told his Clark audience, demonstrating that industrial workers could be adventurers as well as employees. An atmosphere of optimism in a laboratory community governed by the sense of fair play would allow its members "to cultivate a flying spirit" and mobilize the imagination needed to discover innovative solutions to the often difficult problems they were given to solve.

Whitney's use of the image of flight is somewhat ironic. On the one hand, it suggests the freedom and excitement of exploration at the frontiers of knowledge. On the other hand, it reminds one that flight as often as not is escape, a breaking lose from the confines of one's earthbound existence. And, truth to tell, Whitney's aviator was, on most days, grounded, confined to the hangars of the corporation while its managers argued the profitability of routes and flight plans. To be sure, fundamental knowledge had newly acquired importance for American business, but it was knowledge as property more than knowledge as discovery that solidified the support of industry for in-house research. All the inventions resulting from the work of the laboratory were the property of General Electric, Whitney informed his audience. Not only was that the only equitable and practical resolution of the difficult problem of assigning individual credit for communal labors, but, more significantly, the problem itself which established the context of the inventive activity of the lab was "an asset of the organization." Moreover, Whitney continued, "both the risks and the equipment belong to the organization. The accumulated experience of the force as a whole is its property. Finally, the privilege of directing the work of operators along the lines where no direct financial benefit (or an immeasurable one) to the company could ever be determined, must belong to it."

To authenticate ownership, proper documentation was essential. Operators were required to keep good notes which would eventually find their way into company files. Weekly typewritten reports, frequently including photographs of experimental data, apparatus, and of the laboratory itself in order to record "standing conditions," read and endorsed by witnesses, were also regularly filed away. Furthermore, the spirit of aviation did not entail the freedom to chose one´s own problem, to file one´s own flight plan, so to speak. The laboratory was as much subject to the division of labor as were the manufacturing elements of GE. Efficiency soon demanded it. "Thus, any large industrial research laboratory is soon . . . systematized into organized clusters of people, working along distinct and different lines. This permits . . . of the combined use, to maximum efficiency, of the delicate hands of young women, the strength and skill of trained mechanics, the mind of the useful dreamer, the precision and knowledge of the skillful chemist, and the data of the accurate electrical engineer."[14] Above all else, Whitney was a successful manager responsible for coordinating the diverse specialized functions of the laboratory.

The Research Laboratory proved a successful investment. In the years following its creation, it presented the company with the ductile tungsten filament and the gas-filled lamp which enabled General Electric to maintain its competitive edge. It offered a persuasive model for the establishment of research laboratories in other companies, and demonstrated that good fundamental science was compatible with company loyalty, a point confirmed in 1932 when the lab's most famous "operator," Irving Langmuir, received the Nobel Prize for his earlier work on surface chemistry.[15] It demonstrated as well that good research was compatible with good accounting and that research was an investment with good financial return. Not least it corroborated the belief of men like Perkins, Steinmetz, Broderick, and Whitney that the modern corporation was the device best suited to modulate the divisive ambitiousness and uncontrolled invention that marked the previous century.

Whitney's Laboratory illustrates the manner in which General Electric "tamed" the process of invention. While Whitney's Atlanteans shaped new and borrowed knowledge to commercial purpose, the company's Test Course worked an equivalent change in men. Based as it was on the command of science, the electrical industry recognized earlier than most the need for steady supplies of well-trained engineering talent to serve at all levels of the company hierarchy, from manufacturing, quality control, and design, to sales, marketing, and management. Thomson-Houston, one of General Electric´s parent companies, hired its first college-trained engineers in 1884. By the next year, Edwin Rice, at that time the company´s manager of engineers, expected applicants to spend from four to six months in a tour of "apprenticeships" in various departments.[16] By 1892 when Thomson-Houston merged with Edison General Electric, the "Experts´ Course," which would come to be known as "the Test," enrolled forty student engineers; by 1907, the number had risen to 500.

Once accepted into "the Test," the recent graduate would arrive at the plant to start work in one of the Testing Departments devoted to the quality control of the company´s various products. At GE´s Schenectady plant, he could have found himself in any of thirteen buildings engaged in the testing of motors, generators, steam turbines, and a variety of control devices. Working in a crew of student engineers bossed by a permanent employee of the Test Department, and responsible for the department´s testing, the new addition quickly gained familiarity with the equipment manufactured in each of the company´s departments.[17] After a sufficient period of apprenticeship, the trainee would negotiate a transfer to a new department. At each of his departmental way stations, the student would be evaluated by the head of the section with regard to technical ability, industry, neatness, accuracy, the "ability to push things," and personality, for only the personable man could expect advancement. After a period of at least six months, the trainee might have been offered the opportunity for a trial in the department of choice. This work of the trainees in the departments was supplemented at the end of the day by courses of lectures presented by prominent engineers and managers on a wide variety of topics of general interest. Life outside the factory centered, for the Test men, on the Edison Club. Intended to promote the "spirit of comradeship" which had "contributed largely to the rapid development of the electrical industry," the Club provided reading rooms, a kitchen, bowling alleys, and an assembly hall. Pervaded by the "University Spirit" and the camaraderie of young engineers being initiated into the company, the Club helped make "the life of the test man in Schenectady not only wholesome but happy." By the time the test man finished his course of training, he would have "got fully into the swing of <u>life in a large manufacturing plant</u>" and would have "´run the gauntlet´ - mentally, physically, morally, and industrially."[18]

The Test Course proved a reliable source of engineering talent. By 1919, 54% of its graduates had taken positions at General Electric in engineering or management. Those who left the company went on to positions in other firms, in railroads, in mining, communications, or in public utilities and government. Moreover, this assured pool of engineering talent was elastic, providing the company with a ready supply of workers in boom times, but without committing it to an oversupply in slack times.

Above all, the Test Course was a kind of gate, a locus on the boundary between two cultures, the academic and the corporate. And it was not a gate which allowed free passage. Designed, as George Wise notes, to initiate, indoctrinate, and select future staff, the Test Course transformed the raw material of the schools into a product capable of being worked by the company.

> Is the college man handicapped by his college training? The consensus of opinion seems to be that the first year out of college must be spent in living down many of the things which have been held up to him as ideals - liberal thinking, poise, individuality, enthusiasm and self-confidence, and he must instead become a very insignificant part of a large general scheme....
>
> But is there not some way of utilizing to excellent advantage in the modern corporation these self-same characteristics? Modify but do not destroy them. Direct these energies so that they may become the greatest factors in the development of modern industrial efficiency. This is the chief function of the training of graduates by a modern corporation, to maintain in the college man the traits which four years of study have developed, to study his personality, to find out the things for which he is best suited, to gradually get him accustomed to company discipline, and to fit him into that particular niche in the organization for which he is best fitted.(19)

Many academic engineers in the mold of Gardner Anthony worked to acculturate technology - to craft a curriculum which would be of use to industry while remaining true to the traditional mission of the college. Spokesmen for the corporation, in their efforts to reconcile social order with the imperatives of commercial progress, did not focus so much on the individual and his cultural mission as on the organization of a new cooperative community in which knowledge and invention played key roles. Endowed with a Spencerian pedigree which placed it at the summit of social progress, the corporation of Perkins, Broderick, and Whitney would calm the madness of economic individualism, tame technology and harness it to social service, and provide the industrial laborer a new and dignified role, as Broderick suggested in 1922 in a book entitled Pulling Together which reflected the Twenty's rosy enthusiasm for welfare capitalism. This orgy of cooperative rhetoric peaked in the decade after the Great War, and was soon overwhelmed by the agonies of the Depression. But for the moment, industrial leaders could argue that the country should turn to the modern corporation for a progressive model of the rational society.[20]

Gardner Anthony and George Perkins should not be seen as irreconcilable opposites. On most of the great questions facing early twentieth-century America, indeed, they would have been in enthusiastic agreement. Both would have affirmed the beneficence of power, and the relevance of character in the man who wielded it. Both would have seen advancing technology as the key to social well-being, and both would have invested the engineer with a pivotal role in its working out. And both would have granted a major role to engineering education. But in other ways, the spokesmen of industry and of the school looked in different directions. For most engineering educators of the sort that made Tufts a small but powerful engineering school at the end of the nineteenth century, engineering education worked its most potent changes in the realm of character and in the nature of the intelligence its curriculum cultivated. In moving across the boundary dividing the school and the factory, the young graduate did not so much lose these qualities as find them foreshortened.

While educators and corporate managers might have focussed on the same utopian ideals, vaguely perceived on the far horizon, their perceptions of the foreground were markedly different. To stress the cooperative community and the primacy of the industrial community, as the managers did, is to make a claim about allegiance. For all of the men we have seen, allegiance to the cooperative corporate community would purge the destructive ambitions of nineteenth-century individualism and thereby permit the rational and orderly development of the new technologies which underpinned the modern age. For the men who chose to stand with the schools, the relation between social progress and the new instruments of power seems a much more individual and personal one. It is for men such as this that the vision of the engineering profession as a ministry would have proved inspiring. In this vision, the future rested on the competent skills of the well-schooled engineer, and that mission was above all a personal and moral one. For the manager, the pivot was not the individual but the organization. Thus the problem confronting industry was not just one of making practical the abstract and general training of the schools, it was a matter of the realignment of loyalties.

David Noble suggests that the industrial system was dissolving the boundaries between the laboratory and the workshop, the university and the factory. That might be the case, although the merging of identities occurred earlier with the establishment of the first engineering schools, and certainly was not simply a response to an initiative coming from the side of modern industry. In any case, it might be more apt to describe the increasing dominance of large industry in modern technological matters as the consequence not of the dissolving of old boundaries, but as the laying down of new ones with their new sets of attendant allegiances. Vertical integration brought within its organizational imperative knowledge and invention along with other essential resources. And in this new synthesis, many saw the same optimistic promise which Edwin Rice sensed so strongly at General Electric: "We may all join in the satisfying thought that the world has been made happier, better and richer, in every sense, because of the "Life" which we have spent in our great electrical workshop."[21]

Gerald Lee felt that our civilization would be chased by its technological elephants until men could be found with machines in their bodies and souls. What he left out of his prescription was the modern corporation which had learned to animate both men and machines through the soul of a new allegiance.

* * *

Bush remembered the day that a General Electric agent came to Tufts in the search for young talent. The scout informed his audience that, as test men, they could earn $11.20 a week, and that their eleven dollars would be sufficient to cover room, board, and so on. "A chap in the rear popped up and asked what he was supposed to do with the twenty cents."[22] Whatever the answer, Bush must have been satisfied, for, shortly after graduation, he went off to Schenectady to earn his $11.20 "on test," resolved, we can guess, to learn about men as well as machines.

We know little of the year Bush spent with GE, though it is likely that he was in the audience that listened to E. W. Rice, the company's president, deliver the opening address of the 1913-1914 season of the Schenectady Section of the AIEE, a speech in which he celebrated both the role of the electrical engineering in the advance of civilization and dedicated new quarters for the company's Edison Club. Some thirty-three years ago, Rice noted, he too had been "on the test." In fact, in the early 1880s when he wound, assembled, tested, and installed the first arc-light dynamo for the Thomson-Houston Company, he was "the test." There was no "electric club house" in those days, and little was known about electricity. That soon changed, for the technical sophistication of the industry blossomed and the ranks of the test men swelled to over five hundred. No one should consider the company's investment in the Club as philanthropy, Rice cautioned. Indeed, it was a wise business investment whose returns would come not as money, but in the roles played by future engineers whose careers were nurtured in the environment of the Club. The men of the Club were to be the Company's and the industry's leaders, scientific and engineering optimists, ready to grasp their opportunities and play key parts in the "competition in cooperation" which characterized America's new corporate society. History, Rice told his listeners, would be made in this room.[23]

History, then, began "on the test," and while details are scarce, it is probable that in many ways Bush's year was much like that spent eleven years later by his sometime student, colleague, and friend, Harold Hazen, later to be the Dean of the Graduate School at MIT. It was August when Hazen arrived in town to begin work.[24] This was 1924 and Schenectady's involvement with heavy industry was readily apparent in the large plants of the General Electric Company and American Locomotive. Hazen was nevertheless impressed with the beauty of the setting, which seems to have retained, whether real or imagined, some of that pastoral quality apparent in late nineteenth century descriptions. Its beauty had been noted in 1888 when a writer for the Electrical World had arrived in Schenectady to "spend a day with Edison."[25] The town was hemmed in by the placid banks of the Mohawk and girdled by the uprolling mountains, where the air hung "drowsily. . .over the quaint homesteads built by the ancestors and offspring of sundry Rip Van Winkles." But as one drew near the town, one's attention "was arrested by a huge range of factory buildings.... Massive and handsome, lifting themselves boldly up from the level meadows of the Mohawk Valley, their appearance, as one after another of the roofs swings into the line of vision, arouses curiosity, for it is easily seen that the place is the home of an industrial enterprise of no mean order." This factory in a garden was the seat of "the manufacture of dynamo-electric machines, electric motors and kindred apparatus in establishment over which floats the name of Edison," and it was "astir with the sharp outburst of steam and smoke and athrob with the pulsation of machinery."

With four other new test men, Hazen took over the second floor of a two-family house located on the edge of a park near the center of town. He started out as a "flunkie" or "wop" on the crew testing radio receivers, a task not available during Bush's earlier sojourn. Two months later, he moved to another building and the testing of small direct-current motors. His boss was Pete Mulvey, who did not think much of MIT grads, it seems, though Hazen held his tongue and got along well. "Pete was in no sense a learned man - quite the opposite - but he had a good feel for people and a native intelligence backed by long and perceptive experience."[26] It is not unlikely that Bush met up with Mulvey and, like Hazen, appreciated his natural feeling for men and machines and quickly worked out a modus vivendi. Just before Christmas, Hazen was given the choice to move again - to the Maintenance Department for layout and design work, to Building 16 and the testing of GE's largest machinery, or to Pittsfield for work on transformers. Maintenance had no appeal for Hazen, and Building 16, while it was the plum of the Test Course, involved the inconveniences of the night shift. So off he went to Pittsfield.

There Hazen labored over the impressively large transformers (twenty-five feet from base to tip) which had become a vital part of long-distance power transmission. These were high-voltage machines, some of them designed to drop from 100,000 to 13,000 volts, and the Test station was enclosed by an electrically screened cage and located next to the large pit holding the transformer to be tested. It was work both dirty and dangerous, and Hazen remembered his denim overalls becoming saturated with the oil used to cool the transformers and encrusted with the asphalt dissolved off the power cables. Routine work with high voltages and large currents demanded attention to safety, but with the insouciance typical of engineers, Hazen was not above circumventing rules. "...I recall once using a moderately heavy twisted-pair green flexible cord for bringing a test voltage of 10,000 volts (!) from the transformer into the back of my test cage. It hissed a little with corona when I put the voltage on but it worked satisfactorily. The electric code, of course, permits such a cord to be used only for 120 or at most for 240 volts. On Test, however, improvisation was the rule, and the sole "code" for us was whether it worked."[27] Hazen finished his tour at Pittsfield in April and looked forward to getting back to Building 16. As it was, he never made it, for he was diverted from the Test Course by an attractive offer to work in the office of Robert Doherty who had succeeded Charles Steinmetz as the company's Chief Consulting Engineer. Doherty's office was the "elite engineering group of the whole company," and Hazen spent the next five months working on the stability of power systems. Hazen was sorely tempted by the excitement and the challenges of his work to remain at GE. But it was the very difficulty of the problems created by these new systems which convinced him that there was valuable high-level work to be done at a first-rate engineering school, so at the end of the summer, he headed back to MIT to take up graduate study.

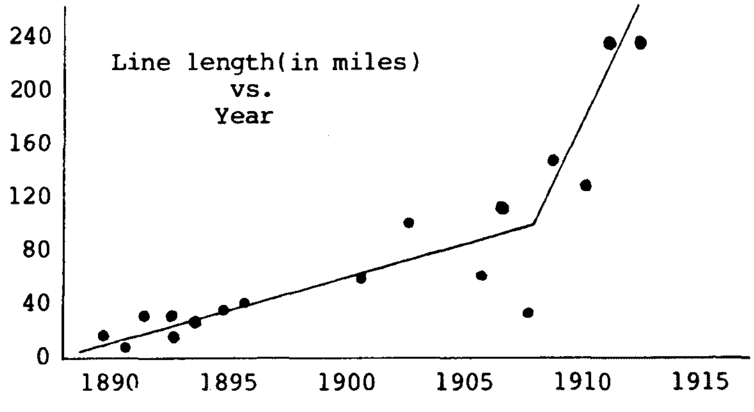
Unlike Hazen, Bush started his stint with an advantage. The company soon discovered he owned a master's degree, upped his salary to $14.00 a week, made up the back pay, and jumped to the conclusion that, since he was earning a higher salary, he must have been at work not for three but fifteen months, and therefore promoted him to foreman. His financial windfall was soon consumed at the local beer hall when his fellow test men discovered his good fortune. The opportunity, however, was put to constructive use and Bush gained experience supervising some twenty men in the testing of valuable machinery. At Schenectady, Bush worked with the large rotating machinery which GE manufactured there. Partway through his year, he transferred, as did Hazen later, to Pittsfield and high-voltage transformers. And he, too, seems to have cherished his attempts to flout authority and circumvent rules. "One safety precaution was a gate between the switchboard and the transformer.... Opening the gate shut off the power, and this was pointed out to visitors as a fine safety precaution. But the test men could readily use the adjacent gate and often did, bypassing the built-in safeguard."[28] Dumb, and not very effective, Bush might have thought. He certainly, as he remembered later, learned "how not to run a company" during the year he spent with GE. We don't know what he meant, though it is hard to imagine this blunt and aggressive young engineer feeling comfortable with an overabundance of rules.

* * *

What might Bush have learned doing his sojourn in the workshops of General Electric? Some of his lessons, whether conducted on his own, in his ambitious perusal of the various electrical journals, in the diversity of educational opportunities which both the Company and the environs offered, or in the discussion which would have arisen among the test men grooming themselves to play leading roles in their profession, would have concerned the technical problems which abounded at the cutting edge of electrical engineering. Other lessons, if less exact, were nonetheless important and reflected the larger ambitions of engineers in American culture around the time of the Great War. First, there are the more straightforward lessons.

Prior to 1890, the industry had largely concerned itself with the establishment of central station service in the larger urban centers. The early stations of what might be called the Edisonian Period dealt primarily with the provision of direct current for incandescent lighting and, to a lesser extent, factory power and traction in high density areas with radii not much more than a few miles. The gradual integration of originally isolated and independent markets through the development of aggressive marketing strategies and control technologies, pioneered largely by Samuel Insull in Chicago between 1892 and 1914, and the consequent growth of large networks utilizing alternating-current allowed the industry to dramatically increase the distances over which power was transmitted.[29] In 1890 the Willamette Falls Electric Company used water power to transmit electricity at 4000 volts thirteen miles to Portland for the purposes of lighting. The next year the Telluride Power Company transmitted 3000 volts some three miles to operate a one-hundred horsepower synchronous motor. The possibilities of AC power transmission were dramatically demonstrated to the world at the Frankfort Exhibition in Germany with the experimental transmission of power at 30,000 volts over a hundred miles. By 1893, in California, there were systems which transmitted electricity at voltages of some 5000 volts over significant distances.

The difficulties attending these enlarging systems, the reverse salients as Hughes would have it, were numerous. The refractory starting and behavior of single-phase motors prompted the three-phase machine and inspired the development of the induction motor. As transmission lines lengthened and the corresponding voltages increased, engineers found their knowledge of insulation stretched to its limit. They explored the design and composition of the insulators which separated the power lines from the support towers and turned their attention to the towers themselves. The invention of the steel tower, first used by the Guanajuato Power and Electric Company in Mexico, and the



[Argensinger, GE Review 18 (1915): 454-459] suspension insulator broke a technical barrier and transmission lines of voltages dramatically higher than 60,000 volts soon followed.[30] Along with problems of insulation and protection against lightning, lines of 100,000 volts or more required new designs for transformers capable of working at these high voltages. Both Bush and Hazen appropriately found themselves working with these monster transformers in the time they spent "on test."

If the machinery of power transmission exercised the talents of electrical engineers, so did adequate scientific accounts of its behavior. These were not unimportant matters, as Steinmetz himself noted, for "on their understanding depends our success in the economic use" of electrical energy.[31] Engineers tended to look upon electrical currents as examples of wave motion along conductors. If the limits of the conductor were a small fraction of the wave length, as in the case of power transmission where frequencies of 25 to 60 cycles per second produced waves thousands of miles long, then the energy radiated as a necessary consequence of the fluctuating current was negligible. In the case of wireless telegraphy, the dimensions of the conductor (in this instance, the antenna) and the high frequencies of current, from a 100,000 to a million cycles per second, produced a primary loss of power through radiation through space.

While the steady state condition in power transmission was fairly straightforward, the system became susceptible to higher-order, higher frequency disturbances as both its size and its interconnections increased. And it was this higher-order behavior which produced a generation of technical problems which occupied electrical engineers for several decades after the turn of the century.

> Just as in a pail of water even a gale will not cause an appreciable disturbance, or, as a small pond is usually quiet while the ocean is never at rest, but continually traversed by undulations from small ripples to big waves, so in a small isolated plant high voltage disturbances are practically unknown; are rare in smaller central stations; while in the huge modern systems waves continuously traverse the circuits, from minute high frequency ripples of negligible energy to occasional high power surges of destructive energy.(32)

These higher-order, wave-like disturbances, or transients as they came to be known, exhibited a variety of forms and causes. "Oscillations appear as waves which start suddenly and gradually die out, like the waves produced by throwing a stone in water; such are the disturbances caused by switching, synchronizing, etc." There were transients in the form of travelling waves, produced by arcing grounds and lightning, and other oscillations that, like the resonance of a tuning fork, gradually built up in intensity until they wreaked destruction.

For these very practical reasons, it was incumbent upon electrical engineers to understand the physical behavior of power lines. The theory of travelling waves, as it was known, was given its first form by William Thompson, Lord Kelvin, in 1854 when he was asked to study the feasibility of the transatlantic cable. Earlier underwater cables had surprised engineers by producing noticeably attenuated and retarded signals, and some felt that these effects would prohibit transatlantic telegraphy. Developing equations for the "flow" of electrical current along a wire analogous to those derived by Ohm for the diffusion of heat along a conductor, Kelvin demonstrated that the proposed cable was practical although the transmission of the peak of the telegraphic signal was indeed retarded by distance, in proportion to its square. James Clerk Maxwell laid the foundations for understanding electrical phenomena in the space surrounding the conductor with his work on electromagnetic theory in 1873, and Oliver Heaviside extended the theory over the next fifteen years to the problems of telegraphy. He described the manner in which a sudden application of a voltage to one end of a long line produced a travelling wave which reflected back and forth from the ends of the line until it gradually died away. Heaviside, as well, derived equations which took into account the full range of circuit characteristics - not just resistance and capacitance, but leakance and inductance.[33]

Between the turn of the century and the Great War, American engineers elaborated the mathematical physics of large systems. Arthur Kennelly and Steinmetz developed the mathematics of the complex plane and extended the laws of the direct current circuit pioneered by Ohm and Kirchhoff to the more complex case of alternating current. The work of Steinmetz, in particular, helped engineers understand the "irregular" behavior of lines when subjected to switching and lightning strikes and at those points in the circuit where constants changed abruptly, as at junctions and at points where overhead and underground cables joined. John Carson, an engineer at AT&T, applied Heaviside´s operational calculus to the differential equations arising from the study of long lines. Michael Pupin and George Campbell studied the influence of "loading," and Pupin constructed an early artificial line, a device which duplicated, on a miniature scale, the behavior of large grids.[33] These sophisticated efforts were complemented by the more intuitive practical mathematics of reformers like John Perry and W.S. Franklin. Perry's Mathematics for Engineers was used in 1913 as the basis for an A.I.E.E. sponsored math class for young engineers at GE's Pittsfield works. Franklin showed his audience at the Washington meeting of the A.I.E.E. in 1914 how to "picture" the dangerous power surges that threatened transmission lines.[34]

These, then, were the technical problems that a young electrical engineer would have found at the cutting edge of his profession in 1913: first, the design of components of the new high-voltage power networks that were beginning to radiate out from populated centers - ranging from the building of new kinds of towers and the insulators suspended from them, to efficient switches capable of working at high voltages, and monster machines of a new generation of the electrical age, from enormous transformers to steam-driven turbogenerators capable of delivering 14,000 kilowatts; second, the acute problems deriving from the need to understand the higher-order behavior of electrical circuits and to solve in practical fashion the equations generated by contemporary circuit theory.

Bush would have encountered these problems at every point in his year at General Electric. He would have sensed other sorts of problems as well, problems related to the larger role of the engineer in American society, vigorously debated in the meetings and publications of professional societies like the American Institute of Electrical Engineers. The nation was struggling to accommodate the forces unleashed by industrialization and two of the chief protagonists were the technical school and industry. While both cooperated in the establishment of a new order, their centers of gravity were profoundly different. The schools taught the ways of machines, forged character, and expanded the definition of culture. The inventive genius of industry expressed itself through organization and the creation of new forms of social relations. The product of the school was a steward of culture. The industrial engineer was a company man who subordinated individual ambition to the cooperative vision of the corporation. To put the matter differently, while the cultural world of the academic engineer was defined by the sacred "texts" of his profession, that of the industrial worker focussed on boundaries and property, on the manufacture and ownership of knowledge. These diverse worlds were not necessarily contradictory or opposed and most engineering graduates schools hurried enthusiastically into industrial careers. But the tensions, while latent, were there nevertheless, and corporations expended great effort in helping new employees cross the boundaries between the world of the college and the world of the corporation. Engineers, likewise, expended great energy in crafting an independent identity, one that looked to the culture of the school for its intellectual and moral equipment, to the ideals of the profession for definition, and to the traditions of

American individualism for its mythology. The opportunities and risks that confronted engineers were apparent in the presidential addresses of the A.I.E.E.

In 1913 and 1915, the presidents Ralph Mershon and Paul Lincoln delivered relatively straightforward surveys: "The Trend of Electrical Development" and "Some Aspects of Institute Affairs." The other presidential addresses, by Dugald Jackson in 1911, by Gano Dunn in 1912, and by Cyprien Mailloux in 1914, bear closer attention. Mailloux, who helped found the Institute in 1884, took the occasion of the Institute's thirtieth anniversary to recapitulate its history and the character of its membership. The electrical engineer had indeed played a key role in the transformation of modern life, Mailloux reminded his audience, directing electrical invention "in the direction of higher civilization and greater benefits for mankind in general, through a more general and better utilization of the sources of energy which nature has in reserve."[35] "I think that we are entitled to say that the electrical engineer has been and that he is still a prophet as well as a minister of the world's progress." However, engineering was threatened by its very success. Propelled by the growing complexity of modern life, engineering was becoming increasingly specialized and, indeed, fragmented. New specialties and new societies sprang up overnight, in some cases warranted, in others not. To a degree, the president claimed, the Institute had moderated the invidious tendencies of specialization by adopting a "federated" structure which allowed electrical engineers great flexibility in pursuing their specific interests without sacrificing the general cohesiveness of the society.

The greatest danger in overspecialization, however, rested in its truncation of the evolution of the engineer. The most serious message Mailloux left with his audience that day was that, as appealing as that vast "technological workshop" that constituted the engineering world was, it did not give adequate scope to the full development of engineering talent. Indeed, the increase of technical knowledge, the development of engineering methods, was not the summum bonum of engineering life. That lay in the promotion of a "guild-spirit," an esprit de corps, that would propel engineers to take up their proper role in the "outer world," as the doctor, lawyer, clergyman, and teacher had already done with less aptitude than the engineer. Despite his catalytic role in the material transformation of modern life, the engineer was saddled by what the public believed to be his untutored artisanal origins. Moreover, he had been simply too busy keeping the machines of a new age working to purse his higher and deserved place.

The frustrated evolution of engineering threatened more than its social status. Indeed, Mailloux perceived American society at the turn of the century to be convulsed by an endemic crisis of authority. What seem to be, in the light of liberal historiography, bulwarks of popular democracy in the Progressive Era, such as demands for direct legislation, were interpreted by men like Mailloux as an insane democratization run amok. Every opinion was to be expressed, and all were of equal value. The dilemma for these men was to reconcile the growth of popular democracy and the establishment of legitimate checks on vested interests, with the need for the authoritative expertise demanded by a technologically complex culture. For Mailloux, it was the engineer who was to mediate the conflicting claims of democracy and expertise, but only if the public adequately understood his training and his true capacities.

> ...just as engineering has helped materially to improve physical conditions, so the engineering class can help materially to improve civic, ethical, economic and even moral conditions, in modern life. The education, the training and the experience of the engineer fit him especially for such a mission. He has to deal less with fiction and more with facts than most men of other intellectual classes. He learns early to understand and appreciate the value and the utility of scientific method and precision in his habits of thought and expression as well as in his work. He also learns early to distinguish between the classes of subjects with which he is competent to deal, and on which he may presume to speak authoritatively.... The man who has been taught and trained to exercise such discrimination and discretion is qualified for sane, sound, rational, logical thinking; he is apt to be more careful and accurate in his statements; he usually says what he means and means what he says; and his opinions are bound to carry weight and receive consideration.(36)

The embodiment of mental balance and intellectual precision, the engineer was the exemplar of the responsible expert whose civic role would leaven the community and bring him public respect.

Dugald Jackson had broached the subject of professionalism three years earlier in his 1911 presidential address, "Electrical Engineers and the Public." As Mailloux would later, Jackson detailed the growing responsibility of engineers in the formation of the modern technological age. And like Mailloux, he urged them to expand their horizons, to take part in the social and economic readjustments which their inventions necessitated.

"Theologians and physicians can practice their professions aloof from the ordinary affairs of the world, but the engineers associated with industrial events cannot."[37] To be sure, this exposed engineers, more than other professions, to the temptations of commercialism. What allowed the engineer to navigate the narrow straits between the Scylla of worldly temptation and the Charybdis of academic isolation, was his disinterested dedication to public service, a trait he shared, Jackson informed his listeners, with Martin Luther, Gladstone, and Lincoln.

If Mailloux saw the crisis of authority as the engineer's immediate challenge, for Jackson it was the corporation. Like George Perkins, Jackson believed the modern corporation to be the product of Spencerian evolution, the consequence of the one-man business and the simple partnership subjected to natural law, "by successive differentiations and integrations producing development from the homogeneous to definite, coherent heterogeneity." One might have hoped that Spencerian philosophy would have collapsed into coherent simplicity refracted through this precise, and clear-thinking engineering mind. But his message was straightforward: the corporation could not be undone, despite the undoubted excesses brought to light by the work of muckraking journalists. Nor should it be undone, for, like Perkins, Jackson felt that the evolution of the corporation was correlative with technological progress. It could, however, be "adjusted" and its excesses moderated. And the key to its adjustment lay in upright individualism.

Criticism that indicted the corporation itself for its abuses of power was misguided, Jackson felt. "We must return to the old and approved recognition that a misdeed is a personal thing, and remember that responsibility for it cannot be shifted from the personality of the man in responsibility to an impersonal aggregation entitled a corporation which he manages."[38] To Jackson's mind, and most engineers, indeed most Americans, would have agreed, the modern corporation was not interpreted within the dynamics of class conflict. The consolidation of economic power it embodied did not so much represent class interest as it did the dynamics of organizational evolution and technological progress. And if it was men who were to be held responsible for the corporation's misdeeds, likewise it was men who were best suited to assist the corporation and the public in reconciling their conflicting interests. Particularly, engineers would play the central role. "...engineers have a special duty, as professional men who are trained and experienced in straight thinking, to use their influence for the establishment and support of right and reason in the dealings between the public and the public service corporations."

Mailloux's engineer was balanced, sane, and precise in his habits of thought. Jackson's engineer is a straight thinker. The solution of the social and economic problems they confronted rested in these qualities of mind and in the parameters of character. This combination of disinterested skill and upright individualism enabled the engineer to responsibly mediate between the public and the corporation. Jackson's beliefs, indeed, had been honed in the heat of battle. As one of the period's most famous consulting engineers, Jackson had played a key role in many of the controversial disputes between the private utilities and liberal minded, progressive reformers like Morris Cooke over the setting of fair rates and the fundamental question of public versus private ownership.[39] The worst solutions, to a man like Jackson, looked to government legislation and to public ownership, for "our inexpert and shifting governmental bodies" lacked the competence and the public lacked the incentives that led individuals to risk their livelihoods in the expectation of financial rewards. "The public, misled or annoyed by the reluctance of some honest but overcautious managements to make frank public statements of financial results . . . , enraged by the acts of a few adventurers who from time to time have secured a speculative hold in the public service field, and enticed by the arguments of individuals with ulterior motives, are likely to follow the radical leadership of demagogues or of honest but false empirics." The alternative to demagogues and empirics, of course, was the "exertions of fair-minded and right-thinking men" - the engineers. Fair-mindedness, balance, sanity, honesty, and, most often, straight-thinking captured in idiom the essential qualities of the engineering mind.

Gano Dunn would have agreed. In his 1912 presidential address, "The Relation of Electrical Engineering to Other Professions," Dunn asked how the newer profession of engineering was unlike its older counterparts. The law, the ministry, medicine, and teaching had changed relatively little in long periods, he felt, while engineering was young and dynamically changing. In fact, it was changing and diversifying so rapidly that it was difficult to define in any easy and inclusive fashion. While the Encyclopedia Britannica recognized only military engineers before 1750, current engineers recorded twenty-seven varieties, "ranging from Civil through Mechanical, Electrical, Mining, Illuminating and Chemical, to Metallurgical, Refrigerating, Industrial, Agricultural and Aeronautical."[40] There were also "efficiency engineers," "social engineers," and even "human engineers," which seemed to suggest that engineering was expanding beyond the world of the workshop into civilized life generally. Large parts of university and college courses were being devoted to engineering, (even classics, Dunn claimed, was borrowing parts of the technical curriculum), the man and woman "in the street" were increasingly sophisticated in technological matters, and even the common metaphors of everyday speech were drawn more and more from engineering. What was it that accounted for this dynamic growth, that explained both the multiplication of specialties and the diffusion of the engineering mentality beyond the school and workshop into the wider community?

Simply put, it was this: while the traditional professions were defined more by what they did than how they did it, engineering was, in essence, a method. More than just scientific method, however, engineering carried the search for knowledge beyond fundamental experiment to its "practical and utilitarian ends." In one sense, it was applied science, first investigated and then scorned by the Greeks, kept alive by the Arabs, rediscovered by Renaissance Europe, and brought to fruition only in the modern world. Or, more accurately, it was that method which underlay applied science. "In the material world . . . which is at once the workshop and the throne, the glory and the limitation of the engineer, marvel has followed marvel and shall be followed by more marvels, for we are beginning to catch the tools' true play, beginning to see the vision of our dominion over the earth."

With this unusual phrase, Dunn captured the secret of engineering self-confidence. For it was here, in the instrumentalities of power, in the tools, the techniques, and the machines, which defined the nature of their work experience, that engineers sought the paradigms of thought and character which formed their self-identity. As Dunn put it, engineering's methods "merely apply 'straight thinking to material problems for useful purposes.'" And if those whose became adept at the "tools' true play" became "straight thinkers," they also peopled their metaphysics with the standard units of the engineering profession.

> But there is a philosophic debt that we electrical engineers owe our units. They school our minds. The ability to measure with precision difficult and complicated quantities enables clear thinking on them and renders reasoning about them possible that otherwise could not be attempted. To name a thing is to know it.

If engineers cut their methodical teeth on the instruments of their trade, they also found in them comfortable models by which to interpret the world.

> The wonderful electrical units are a fluent language that gives the widest opportunity to thought. By their character they educate our faculties of definition and of relation. They typify all quantitative thinking, not merely electrical. They are, indeed, the epitome, the last word of the great minds of our age, as to what the scientific method of thought is.

Dunn found "the electrical method of thinking" in unusual places: "...I even find myself thinking of the crowds passing in the streets in terms of amperes and volts, and of the fluctuations of the stock market in terms of current, inductance, capacity, resistance and resonance." "The forms of thought" which characterized electrical engineering, exemplified by its standardized units, Dunn found "so comprehensive, so rigid, so rich in detail, and so illuminating that engineering does not bound them. They may be called the manifestation of Science in civilization...." Once others learned, as had engineers, that "That which can impose form upon our thought enables us successfully to think of any kind of thing," the electrical method of thinking would become universal. And this led to Dunn's most interesting conclusion. For once everyone learned the value of straight thinking, a large part of a what his audience recognized as the profession of engineering would disappear. Or, put in another way, they would all become engineers.

Who were these men who spoke for their colleagues in the years immediately preceding the Great War? Aside from Mailloux, who at the age of fifty-seven was somewhat of an elder statesman, they were all between forty-two and forty-six years old, in the prime of their careers.[41] A more revealing factor, especially in the light of the rampant specialization at work in contemporary engineering, is the common pattern of cross-society membership. In short, these were men at the peak of their careers and at the top of the professional pyramid. Aware of the necessary diversification inherent in growth and specialization, these men were nevertheless fearful of professional fragmentation and refused to yield to it. They firmly believed that there was a common core to engineering that transcended its diverse occupational applications, a method, an "electrical way of thinking," that entailed, somewhat surprisingly, both an epistemology and a metaphysics. Schooled in the instrumentalities of power, straight-thinking and clear-sighted, they brought order from chaos by imposing the hard edges and decisive lines of engineering on the social, political, and economic worlds.

Moreover, without exception their careers express a profoundly conservative individualism. At home in industry as well as academia, they were most comfortable standing on their own two feet and many found appealing the vocation of consulting. Neither impotent scholar nor hired hand of the corporation, theirs, they supposed, was the disinterested voice of the independent expert, whose electrical way of thinking rose above conflict of interest and spoke to the public good. For the most part, they are neither corporate apologists nor liberal reformers, but men in between, _for_ modern business, on the one hand, but not _of_ it, and reluctant, on the other, to yield the privileges and the risks of the individual to government. Ironically, these engineers were probably more deeply conservative, more profoundly committed to individualism in political and moral economy than the businessman of economic myth. If the technological dilemmas of the age were to be solved, the answers lay not with organization but with character and quality of mind.

* * *

Bush condensed the experience of his year "on test" into very few anecdotes. His father once stopped off in Schenectady to visit his son on the way back from a trip to Canada. When the young Bush passed through the gates on his way to meet the train, the guard asked where he was going. He answered he was going across the street to get a beer. As it was, the minister surprised his son by emerging from the train attired in the uniform of the Ancient and Honorable Company of Artillery, and when they passed back through the gates into the plant, the guard saluted. "He may have thought my companion was on the Board of Directors," Bush thought.[42] Another time he found himself in the midst of a strike. For the workplace at General Electric was far from being a tranquil utopia and there were visions at stake other than those of George Perkins and John Broderick. "Around twenty thousand men were out, crowds milled about the gates, and test men were allowed through the lines to keep essential facilities running. My sympathies were entirely with the strikers. So I readily took on the task of exploring the works for them, to see whether strike breakers were being smuggled in and the like. This fact greatly facilitated my going through picket lines manned by some thousands of husky and irritated strikers."[43]

Bush's account, sparse though it is, suggests some of the traits that distinguished contemporary engineers. First and foremost, he was unabashedly ambitious, quick to take advantage of opportunities and anxious to make his mark. Joined with an impatient intelligence was a certain skepticism towards bureaucratic authority. Beyond these traits of character, however, lies an implicit concern with rules and boundaries. And here we have a clue to the imaginative life of one engineer that is worth pondering. For boundaries, like rules, separate the legitimate from the illegitimate, the public from the private, the self from the other. Thus, boundaries define and limit identity, power, and authority; either directly or tacitly, they demand a distinctive allegiance. Yet the boundaries of the stories are characteristically flouted, as though the young Bush were uncertain of his loyalities. Eventually, like many other engineers, he came to see himself as a man whose talent, indeed responsibility, was this crossing of boundaries. A talented electrical engineer, he would become as well a mediator whose allegiance was first and foremost to the country at large and was grounded in professional independence rather than the circumstances of employment. Bush and like-minded engineers were men in-between the great sectors of American society; given the corporation's power to shape modern work patterns, this was a position increasingly precarious as the century progressed.

* * *

As it turned out, Bush's stay at Pittsfield, and his sojourn through the Test Course, was cut short by another mishap. A fire destroyed the power cables to the transformer test area, and the next morning the company "fired all the test men, or rather laid them off for a few weeks without pay, which was the same thing. I went to my rooming house where my landlady said, 'What are you here for?' 'Fired,' said I. 'You owe me three dollars,' she said. So I gave her the money and took the train."[44]

NOTES - CHAPTER FIVE

1. *Atlantic Monthly* 111 (1913): 198-199.

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34. "Notes from the Pittsfield Section, AIEE," General Electric Review 16 (1913): 140; W.S. Franklin, "Some Simple Examples of Transmission Line Surges," Transactions of the American Institute of Electrical Engineers [AIEE] 33(1) (1914): 545-559.

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CHAPTER SIX:

BUSH GOES TO MIT: THE WHITE CITY(II)

"An engineer has to know a lot about people, the ways they organize and work together, or against one another, the ways in which business makes a profit or fails to, especially about how new things become conceived, analyzed, developed, manufactured, put into use." With this in mind, Bush had gone off to GE and signed up "on Test," resolved to "learn about men as well as about things." If his year at GE was not entirely successful, he had at least been blooded in the world of work. He had as well, by chance or purpose, escaped the strong current that was sweeping the great majority of young engineers from the schools into the factories.

* * *

And so it was that he found himself out of work and low on money, on the train back to Medford Hillside and Tufts College.[1]

> I remember that I walked into the office of Dean Wren [sometime in the middle of October] and told him I wanted a job. He said he didn't have any job I'd want, and I asked him, "When do I report?" He repeated, "I haven't got any kind of job you'd want." I asked, "Would it be alright if I go to work Tuesday morning?" After quite a bit of this he finally said, "Okay, okay, you asked for it." (2)

Wren might not have been as reluctant as Bush remembers, for he soon found himself teaching trigonometry to a roomful of young women who had chased off their thin-skinned former instructor. No stranger to classroom antics ("All right, girls, my fun comes later."), Bush set out to bring life to what all agreed was a pretty lifeless subject. He succeeded well enough, for Wren wrote to President Bumpus in February that "Mr. Bush has proved himself so valuable that his services should be retained at least for the remainder of the year," and recommended a salary increase for the second term from $300 to $400.[3] Bush was already looking elsewhere, for that very month Bumpus wrote to G. Stanley Hall, the president of Clark University, that "we have a very excellent man, Vannevar Bush, an Instructor in Mathematics, who shows signs of having qualifications which will lead to excellence in his chosen field. I think it would be very good thing for Clark, and also for Bush, if he could take graduate work in Worcester...."[4]

That summer found him at work for the government in the New York Navy Yard, waiting word from Clark on the possibility of financial support. His duties as an electrical inspector were not onerous, but the inspector's blue slip granted him a general access of which he took advantage to explore the ships and submarines docked at the Yard. He was struck by the abundance of resources, often wasted, the storage battery that was never used but rated a worker whose sole job was to look after it, the assistants "to do everything," Bush recalled, he "was supposed to do in the first place," but who only responded if he shouted loudly for them - "Hickey!" Bush's aggressive ambitiousness did not make him friends among his fellow inspectors. When the head of his section fell ill, unbidden he took over that job in addition to his own, and when the head inspector left town, those duties as well. "With these three jobs, I was reasonably busy for a while." Bush remembered the man in charge once coming into the office:

> "Where's Huey?" I said, "He's out on the West Coast." "Where's so-and-so?," meaning the head of my section. I said, "He's sick." "Oh," he said, and walked out, and that was that. He never inquired as to how I happened to be sitting in Huey's office.

This self-promotion permitted Bush to join his higher-ups in small talk and in smoking his pipe with his feet on the desk in flagrant disregard of no-smoking signs, while the other inspectors had to go outside to smoke.[5]

Bush resigned his position at the end of the summer, reporting to the Yard's engineering officer that he felt the job lacked the "opportunity for rapid advancement, and not because of any dissatisfaction with the work." To his patron Bumpus, he wrote, "From certain viewpoints, financially for instance, I could well continue in this work for a while; but I am convinced that there is an opportunity for larger things in Worcester [at Clark], and that a year from now will see me much nearer where I want to be because of the present sacrifice."[6] And so, with the promise of a $1500 scholarship in his pocket, Bush went off to

Clark to study mathematical physics with Arthur Gordon Webster.[7]

Webster was a figure of some note in 1915. A Harvard graduate, he had earned his PhD in 1890 under the great Helmholtz in Berlin and had been at Clark ever since. There he established himself as a leading figure in the modest community of American mathematical physicists, helping found the American Physical Society in 1899 and becoming its president in 1903 and a member of the National Academy of Sciences in the same year. A talented teacher and ingenious experimentalist, Webster's strengths as a physicist lay in the classical fields of heat, light, and sound. He was particularly interested in acoustics. Finding new developments in atomistics and in quantum and relativity theories somewhat befuddling, he once remarked that "being an old fogy, I sometimes feel that there are too many electrons about,

> and that one of the wonderful fly-traps that you read so much about in the papers ought to be devised to catch them. I remember (dimly) that when I was a boy in college I had a great aversion to molecules. I had never seen one, and didn't like them. And now I have the same queer feeling about electrons. But perhaps I shall see one some day. (8)

As it turned out, Bush's stay at Clark was brief indeed. Webster insisted that Bush concentrate on acoustics which was, after all, his strength but one in which Bush seems to have had little interest. Moreover, Bush might have felt a bit out of place at the country's only school devoted solely to graduate research. He summarized his abrupt departure from Clark in the following words:

> I was standing in the corner with two or three other

> students, when along came a chap whose name I've now fortunately forgotten. He had hair about six inches long, and as he walked down the corridor, it flopped on his shoulders. I asked the other students, 'For Pete's sake, what's that?' And they said, 'That's Professor Blank.' Well, I was scheduled to take a mathematics course under Professor Blank, and this was just too much. So I went back to my boarding house, checked out, took the train for Boston and resigned my fellowship by mail. (9)

Bush was always ready to frame an anecdote. Even in the youth of my wisdom, he seems to say, I was the no-nonsense engineer, thoroughly masculine in approach, quick to size up a situation, and instantly decisive, even at the cost of self-sacrifice. There were, of course, other reasons for Bush's departure, as well as for his initial attraction, and it is important to speculate about them, for the Clark episode offers a glimpse of an alternate future that once beckoned, one he spoke little of in later life.[10] Bush had acquired "enormous admiration" for Webster, in part through his popular and highly regarded lectures to Clark students on mathematical physics published under the title The Theory of Electricity and Magnetism. For one who entertained hopes of making a name as a mathematical physicist or, at least, as one adept in the mathematical "handling of things in engineering," Webster and Clark were sensible choices.[11]

Webster's approach to physics was conditioned by a keen sense of the limitations of American science. Addressing the combined audiences of the American Physical and the Mathematical Societies in 1904, he asked what it was that was responsible for the "painfully small" contributions of American science. His list of responsible causes anticipated the best insights of later historians of science: the consuming preoccupation with the conquest of a new continent, the more palpable temptations of commercial success, recent material prosperity and a consequent loss of the "ideality" required for the pursuit of speculative knowledge, the isolation of physicists from one another and from their European counterparts - all of these factors inhibited the development of that theoretical faculty necessary for the discovery of fundamental truths. In addition, he stressed "the insufficient equipment which American physicists have generally possessed in mathematics."[12] When university presidents could imagine that it was possible, in the manner of a Faraday, to do physics without mathematics, and when a physicist as prestigious as Henry Rowland could warn his listeners against the lure of mathematics with the caution that "we never get out more from it than we put in," then much of the great work of the nineteenth century would remain "a closed book" and American science would remain in the second rank.[13] While much had been done to promote American strength in pure mathematics, especially since the founding of Johns Hopkins and the work of J.J. Sylvester, both mathematics and physics, as well as engineering, remained handicapped by the absence of mutual interests. Only mathematical enlightenment would repair the weakness of American science, and only a curious appreciation on the part of mathematicians for the real-world problems of physicists and engineers would inspire great advances in "pure" mathematics.

Webster proposed to remedy the plight of disadvantaged Americans by reforming the mathematical curriculum. And in this, he invoked both E.H. Moore and John Perry. Mathematical teaching was a disaster and would be reinvigorated only when the teaching of pure and applied mathematics went hand-in-hand; when teachers realized that, for the greater part of their students, mathematics was a tool, "to be mastered because one can do something with it." Citing John Perry, who highlighted "the useful and interesting rather than...the formal or strictly logical," Webster stressed the use within the mathematical curriculum of diagrams, ruler and compass, squared paper, and the drawing board.[14]

It isn't surprising, then, that Webster should have appealed to an ambitious young engineer with a pronounced bent for mathematics, attuned to the instrumentalities of the engineering workshop and eager to make a name for himself at a crucial interface within American science. Less certain are the reasons for Bush's abrupt departure from Clark, despite the ingenuous frankness of his autobiographical accounting. Certainly there is a hint in his ready dismissal of Professor Blank, the mathematical longhair, of a lack of sympathy with the local environment of Clark, more in tune with Henry Rowland's highbrow refuge of academic idealism than with the rough-and-ready training he had encountered in the engineering curriculum at Tufts, or among the transformers and dynamos at GE and the fighting ships of the New York Navy Yard. Moreover, Bush might very well have calculated that the financial prospects of training in physics under Webster were none too good. He was once needled in later life when a friend expressed surprise at his accomplishments "because after all you're not a profound individual."

> 'When you started in at first, you showed some signs of getting the profundity that goes with real scientific accomplishment, but you didn't pursue it. Well, my answer to him was that when I started on my professional career, I was broke, I was married, and I doggone well had to earn some money. While doing that, I didn't have time for a lot of other things I'd liked to have done.(15)

When Bush arrived at Clark and learned through the grapevine that Webster was not easy to work with and that his set task would be acoustics, it became clear that life in Worcester was not for him. Once again he found himself at loose ends, back in Chelsea, and, as he put it, "in quite a spot." $1500 was no small sum.

* * *

MIT's school year began at the end of September, on a Monday. The previous Saturday Bush completed his application for admission to the graduate program in engineering. Failing to mention his aborted career at Clark or the sore subject of $1500, he listed his experience at General Electric, his summer in the Machinery Division of the New York Navy Yard, and his year of teaching at Tufts. He hoped, he said, to do advanced work in electrical engineering in the subjects of transmission lines and transients, alternating current machinery, hydraulics and structures, and in the minors areas of physics and mathematics, especially in differential equations. Some of his work in the minor fields would be done at Harvard, with whom the Institute had recently agreed to conduct joint programs in engineering. By the end of October, Bush had been accepted into the doctoral program and, with the help of Bumpus, had been awarded the Harvard Eveleth scholarship of $200.[16]

By 1915, MIT had established itself as the country's premier school of technology, both in the overall quality of its special programs and in its sense of cultural mission. Indeed, the Institute was something of a crossroads from which its students could observe the intellectual traffic crisscrossing the landscape of a modernizing, industrial America. In the first few weeks of class, students would have read in The Tech that enrollment had reached an alltime high of 1855, that Willis Whitney, class of '90 and the famous director of the GE Research Laboratory, had agreed to serve on Thomas Edison's Naval Consulting Board, and that Herbert Hoover had appealed to the American people for emergency wartime relief on behalf of his Committee for the Relief of Belgium. They would have noted that the electricals had taken their first field trip to the Edison "L" Street station in Boston, had held their first smoker ("Fall in line with hundreds of thousands of red-blooded smokers of the good old U.S.A. Smoke the cigarette tobacco that's been an American institution for three generations - "Bull" Durham. The rich, relishy, star-spangled taste of "Bull" Durham puts the national spirit of get-up-and-hustle into your hand-rolled cigarette."), and that the Wireless Society had heard Professor Arthur Kennelly expand on the future of radio telephony. The present war in Europe, they would have read, was a "war of men skilled in handling machinery," and they would have noted the address by Frank Gilbreth, the famous mechanical engineer and proponent of scientific management, on a "Motion Study for Crippled Soldiers." "'Character First' Verdict of American Engineers" announced the October 25 edition in reporting a survey by the Carnegie Foundation. Also announced in an early edition was the freshman reception sponsored by the Technology Christian Association, a function which "no first year man can well afford to miss," even if they had missed the first TCA sponsored talk of the previous day. At that event, the pastor of the Park Street Congregational Church had told the story of the Scottish politician who had risen to power on the strength of his wife's speech-writing skills. He jilted her for another woman, of different talents, lost his powers in a moment of parliamentary crisis, and was rescued by his faithful wife. The moral of this story, if it wasn't plain to the audience, was that without the aid of a power greater than ourselves "we are as helpless as the workman at his machine before he has geared it into the main shafting above. Men cannot become supermen until they have geared themselves with the Main Shafting which extends through the Universe."[17]

The Institute's rise to preeminence was paced by the Department of Electrical Engineering. Established in 1882 as an optional course within the Physics program, electrical engineering grew rapidly under the care of the physicist Charles R. Cross. In 1885 when the Institute granted its first degrees in EE, the department had a class of 30 undergraduates; by 1915, there were 217 undergraduates and 9 graduate students taught by a staff of 34. While graduate study had been discussed as early as 1888, it wasn't formalized until 1902 with the completion of the Lowell Laboratory of Engineering Research and the establishment of the Graduate School of Engineering Research. Even then, graduate work in the department remained relatively insignificant until after the First World War. The department granted its first two masters degrees in 1904 and the Institute's first doctorate in electrical engineering was granted in 1910; by the beginning of the 1915 school year, four doctorates had been awarded. The lack of a strong graduate program did not, however, prevent the department from serving, in the years right after the turn of the century, as an important breeding ground for engineers who went on to occupy positions of authority both within the schools and without. A census of the department's graduates conducted in 1930 lists some 105 (of an estimated 780 students graduated since 1885) who had worked themselves into the presidencies of various companies, among them General Electric, General Motors, Bell Laboratories, and the influential Boston engineering firm of Stone and Webster; another 67 who had become vice presidents in, among other companies, International General Electric, Commonwealth Edison, Westinghouse, General Electric, General Motors, Bell Laboratories, and the First National Bank of Boston; 17 who had become deans of engineering or heads of departments. All together, the department produced a large number of the technically competent personnel demanded by the nation's utilities, electrical manufacturers, and schools.

As befits its mixed parentage, the electrical engineering curriculum combined the mechanical engineer's concern with engines of power generation and the preoccupation with electricity and magnetism characteristic of the physicist. Its characteristic concerns in the early decades through the First World War, as reflected in the choice of undergraduate thesis topics, centered on electrical machinery, the measurement of electrical phenomena, and the operation of power plants. Its curriculum pivoted around electrical machinery set in a program of study that combined lecture and laboratory work in physics and mathematics with the shop work of the mechanical engineer. Electrical engineering was the most interdisciplinary of the engineering fields at MIT. In 1910, for example, students spent 30% of their time on topics narrowly defined as "electrical," in contrast with the 50% and 41% that marked the narrowly technical courses in the civil and mechanical curricula. Approximately 9% of their time was devoted to mathematics; 22% to physics and applied mechanics; 4% on drawing and mechanic arts; some 14% to english, history, and language; and 25% to mechanical and civil engineering subjects. In 1932, the proportion of time devoted to EE subjects was still no more than 30%; physics, mechanics, thermodynamics, and hydraulics occupied some 26% of the curriculum; mathematics a little over 10%; drawing and mechanic arts had risen to 7%. Drawing and the required 9% devoted to English were categorized together as "modes of expression."[18]

The early development of the department was overseen by the physicist Charles Cross. It was Dugald Jackson who was the architect of its twentieth century persona. The son of a professor of mathematics, Jackson earned his degree in civil engineering from Penn State in 1885. It was there that he took advantage of summertime work with the inventor William Stanley to earn an expense-paid trip to the 1884 International Electrical Exhibition held in New York City, where he met Frank Sprague and discovered, in peering over the balcony at Edison's famous Jumbo generator, his longstanding interest in the design of electrical machinery. After graduation and several years at Cornell, he helped found the Western Engineering Company, serving as vice president and chief engineer. Between 1889 and 1891, he worked with the Sprague Electric Railway Company and as chief engineer of the Central District of the Edison General Electric Company, taking charge of the installation of new electrical equipment in the Middle West. In the latter year, he moved to the University of Wisconsin to take charge of the organization of its new department of electrical engineering, in all probability, the nation's first. It was at Wisconsin that he coauthored with his brother his important series of textbooks on electricity, magnetism, and electrical machinery. In 1905, he was elected president of the Society for the Promotion of Engineering Education, in 1910 of the American Institute of Electrical Engineers. In 1907, he moved to MIT.[19]

Jackson brought to his new post in Boston a deep knowledge of the nation's electrical utilities, a profound belief in the scientific basis of engineering, and a firm commitment to the role of the professional engineer in the progress of Western civilization. His experience with electrical power brought him a lucrative consulting business; it led, furthermore, at least once, to a collision with Morris Cooke, the reform-minded mechanical engineer and vigorous proponent of scientific management, over the setting of "just rates" in public utilities.[20] Despite the bitter struggle that occurred between these two men, Jackson was no corporate lackey. Both men agreed that the engineer had to play a central role in the ordering of modern civilization and in the taming of its powerful economic engines; but whereas Cooke saw capitalism as badly flawed and the engineer as a radical political force counterpoised to the greed of big business, Jackson forged a more sympathetic role, basing the engineer's authority on the moral and technical integrity of an independent stance, within the professional society, within the role of the private consultant, and, most importantly, within the culture of the engineering school.

Jackson set his priorities at MIT to reflect these concerns. He stressed the economic connections of engineering, established a longstanding course on "the organization and administration of public service companies," that drew upon his experience as an independent consultant, and devised over the next several decades cooperative programs with General Electric, the Edison Electric Illuminating Company of Boston, the Boston Elevated Railway Company, and the consulting firm of Stone and Webster. He was even more concerned, however, with building a strong and independent academic base for engineering.[21] He consequently stressed the importance of training in the basic

A SKETCH OF THE AGENDA AND INCOME OF THE DIVISION OF ELECTRICAL ENGINEERING RESEARCH/1913-1915

-Study of Terminal Freight Handling encouraged by Edgar, president of the Edison Electric Illuminating Company of Boston; over two years contributed	7500
Study also supported by the Boston and Maine, and the New York, New Haven, and Hartford Railroads	2500

[It was the success of these studies that was largely responsible for the establishment of the research laboratory.]

-"The Subdivision of the Nickel" How far can a streetcar passenger be profitably carried for a nickel? An anonymous donor contributed for a period of 5 years	25000
-Grant from AT&T (Pres. Vail was a member of the Institute Corporation) For a period of 5 years, a sum not to exceed $10,000/yr	50000
-The Dering Electrical Library Donated by Vail and AT&T; valued at	100000
-Maintenance of the Dering Library For a period of 5 years	25000

AGENDA:

-Core losses in electrical machinery
-The characteristics of speech transmitted by telephone, including the forced and free vibrations of receiver diaphragms and the phase relations of harmonics in sound waves
-The "skin effects" and transient phenomena in long-line power transmission

[*Technology Review* 15 (1913): 554-557; 16 (1914): 427-429.]

sciences in his long tenure at MIT, cultivated laboratory and shop work, and vigorously promoted the cause of departmental research and graduate training. While the Institute had inaugurated graduate research in engineering in 1902, in 1905 there were no candidates for advanced degrees; there were, in fact, no students even registered in the Graduate School for Engineering Research. "It was still a matter of argument with the faculty," as Jackson put it, "as to whether engineering was a research field and therefore should be admitted into the group for which Doctor's degrees should be provided."[22]

Nevertheless, Jackson's arrival coincided with a new interest in research that was sweeping through the Institute. When he arrived, the total budget of the Institute was somewhere between $800,000 and $900,000 and there was virtually no graduate work of a formal kind. Over the next several decades, Jackson designed a program which moved laboratory work to the center of the curriculum. He established the Division of Electrical Engineering Research with a departmental budget of $30,000 in 1916 alone. He supervised a program which by 1931 had produced 561 master's degrees and 20 doctorates, over half of all the advanced degrees in electrical engineering awarded in the United States.[23] "The life of the teaching of electrical engineering subjects to undergraduates is rooted in the laboratory," he noted in his annual report to the president in 1908; in 1914 he reported that "the close association of undergraduate instruction, graduate instruction and research in the electrical engineering sciences which we aim to accomplish is of much practical pedagogic importance." It had often proved hard, Jackson remembered, to coax money for research on the basis of projections, however persuasive. He had learned to "extemporize" needed apparatus, starting small and letting success speak for itself. "After all extemporization is one of the primary things in carrying on research. In my early days here an Instructor whom I found from time to time sitting in a corner of the laboratory trying to find out some facts regarding which his curiosity had been aroused was a God-sent encouragement. Gradually our staff has come to be mostly composed of such men, the conventional type having mostly disappeared; but it has all come to pass by gradual and constant effort without demanding large appropriations or changes of the Department in the old and poverty-stricken days during which time we made the best of such opportunities and facilities as we had."[24]

Jackson turned, as well, to strengthening the connections between engineering and mathematics. He had discovered at Wisconsin that the mathematicians had usually been uninterested in problems of "interpretation" and in the use of equations to express physical facts, preferring to treat mathematics as a "philosophy." Since this "cramped the influence of the Mathematics Department on the engineering students," it was arranged for C.S. Slichter to become Professor of Applied Mathematics, charged with the responsibility of developing mathematics as an instrument and exploring the "utilization of equations to represent physical facts, and also the problem of suitable interpretation of an equation that has been secured by transformations of one kind or another." When Jackson arrived at MIT, he found "the usual antagonisms and jealousies [existing] between the engineering staff and the Departments of Mathematics" and was urged by his new colleagues to shift the responsibility for teaching the mathematics and physics required by engineering students to the engineering staff itself. Jackson preferred, however, as he had done at Wisconsin, to encourage the development within the Math and Physics Departments of interest in the "real-world" problems of engineers. Mathematics for the engineer was a logical tool and an instrument of power, and over the next several decades Jackson laid the foundations for what became at MIT powerful programs in applied mathematics and physics.[25]

Bush passed through Jackson's department like a meteor through the atmosphere, quickly, with much heat, and no little turbulence. His graduate committee, indeed, seems to have worried that he would incinerate; but he was, in the jargon of the day, a man of gumption and grit with little time and less money to waste. Jackson, of course, was his major advisor and Jackson, as Bush remembers it, had the reputation of an ogre, which isn't surprising when one remembers that in 1915 Jackson was caught up in his struggle with Cooke and was certainly not in the best of moods. "We used to say that, if one wished to visit him in his office, it was well to toss one's hat in first and then, if it stayed in, to follow it. He worked well only with those who traded him blow for blow," which was just fine with

Bush, thanks, as he liked to say, "to a small trace of Irish in my blood."[26] F.S. Woods and H.M. Goodwin were his advisors in mathematics and in physics, and Arthur Kennelly was his research advisor. Bush set out a course of study that concentrated on electrical power generation and transmission, strongly bolstered by minors in mathematics and physics. The program included the mandatory graduate seminar which, for 1915-16, focussed on the study of engineering history and for which Bush apparently came to grips with Leonardo da Vinci and Michelangelo. With characteristic brass, he proposed to complete this program within the year.

Kennelly, however, was appalled that Bush meant to finish the PhD in a single year, considered him "a heretic, and intended to stop what he thought was an end run," and Kennelly was a key member of the committee.[27] A mathematically-minded professor of engineering, Kennelly had been given charge of the department's research efforts and had initiated a broad range of studies including the resistance of road-surfaces to electric trucks (with funds from Edison and the Gould Storage Battery Company) and the mechanical properties of telephone receivers (with the financial help of the AT&T Company). His international stature surely played some part in turning Bush's sights to Cambridge after his debacle at Clark, for Kennelly was a Harvard professor whose availability to Bush and other MIT students was a consequence of a cooperative institutional program in engineering recently established by presidents Lowell and Maclaurin. Our upwardly-mobile engineer from Chelsea was certainly not unmindful of the Harvard connection for he began corresponding on Harvard letterhead and took to referring to his work "at Harvard."[28] With Jackson's support, however, he revised the original plan of study in which he had proposed to do some of his work at Harvard and managed to complete his requirements within the year.

> Once during the year Jackson, who knew my plan, called me in and told me he feared I would wreck my health if I persisted, advised me to take a second year, and told me that, if I did, he would try to find funds for me. I told him I would make a deal, that I would visit him occasionally so that he could look me over, that if he concluded I was in real danger and told me to quit, I would quit. So once in a while I would meet him in the corridor and say, "How do I look?" He would back off, look me over, and say, "All right, go to it, but do not kill yourself."

As a matter of fact, hard work proved therapeutic, and rid him of the rheumatism that had dogged him from childhood.[29]

While Bush scoffed at the administrative Kennelly, Kennelly the electrical engineer had a marked influence on the young graduate student, both in his choice of research interests and in the style in which he approached them. Kennelly's strength lay in the mathematical analysis of electrical circuits and it was in that field that Bush would establish his technical reputation. Kennelly was the son a British navyman who had become harbormaster at Bombay when his son was born. When he was twelve, he was turned towards electrical engineering by a public lecture on submarine telegraphy by Latimer Clark. He left school at fourteen and went to work as an office boy in the London office of the Society of Telegraph Engineers. A year later he enlisted with the Eastern Telegraph Company and during the next eleven years became thoroughly familiar with the laying, operation, and repair of the submarine telegraph cables which formed the nervous system of the British Empire. In 1887, he came to the United States, joining the staff of Thomas Edison's new laboratory in Menlo Park. Between 1893 and 1901 he did electrical consulting, and in 1902 was appointed professor of electrical engineering at Harvard. Kennelly did important work on electrical standardization; he successfully explained in 1902 Marconi's surprising success in transmitting radio signals across the Atlantic the previous year by hypothesizing, independently of Oliver Heaviside, the reflection of radio waves off an ionized layer of the upper atmosphere - the Kennelly-Heaviside layer as it came to be known. His most important contributions to electrical science, however, concerned electrical circuit theory.[30]

The expansion of the electrical industry in the half century around 1900 is coincidental with the struggle of engineers to deal with the description of ever more complex circuits, generally with little help from mathematicians. It was Kennelly, in fact, who took an important early step beyond the simple algebra of direct-current problems when he demonstrated in 1893 that Ohm's Law could be extended to the alternating-current circuit through the redefinition of resistance as "impedance" and by using the mathematics of vectors in the complex plane. He hoped to show, he said, that "the working theory of alternating currents can be made as simple as the working theory of continuous currents."[31] Some months later, Steinmetz delivered his famous Chicago address on the importance of complex numbers for the analysis of electrical circuits and showed that Kirchhoff's Law, like Ohm's, had its AC equivalent.[??] By the following year, Kennelly had adopted the use of hyperbolic functions to the complex plane as especially suited to the analysis of exponentially-decreasing currents.

Eventually, Kennelly's attention turned to the yet more difficult treatment of oscillating current and it is this work that, in all likelihood, provided the immediate background for Bush's choice of dissertation topics. The influence of this context was two-fold and illustrates the intimate connection between mathematics, electrical circuits, and mechanical systems which characterized the problem-universe of early electrical engineers. By 1915, Kennelly had carried some distance a study of the behavior of telephone diaphragms begun in 1908.[32] By determining such characteristic constants as the pull exerted by the electromagnet, the stiffness of the diaphragm, its resistance to motion, and its equivalent mass, one

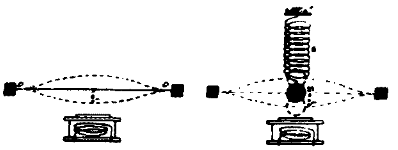


Fig. 6. Fig. 7.

DIAGRAMS ILLUSTRATING A TELEPHONE-RECEIVER DIAPHRAGM VIBRATORY SYSTEM CONSIDERED AS REPLACED BY ITS EQUIVALENT SIMPLE VIBRATOR

(From Kennelly; see note 32)

could write an impedance equation which completely defined the mechanical behavior of the receiver.

Kennelly based his analysis of the diaphragm on an "elementary theory of simple vibration" that pictured the motion of a particle moving against retarding forces around a central force. The mathematical expression describing the resulting spiral path,

$$x = x_o e^{-\Delta} + x_o e^{jw't}$$

($\mathbf{x}$ is the positional vector **OP**, $\mathbf{w}'$ the angular velocity, and Δ a damping factor which is a function of the forces retarding the motion of the particle) was, not surprisingly, equivalent to the equation Kennelly obtained for the vibratory behavior of the diagphragm. More interesting was the fact that

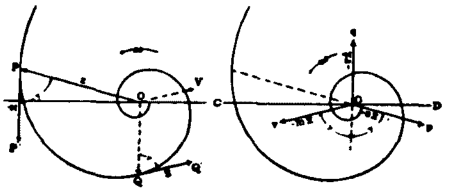


Fig. 30. Fig 31

Locus of Damped Oscillatory Displacement, Velocity and Acceleration Force

(From Kennelly: see note32)

that the behavior of electrical circuits, acted upon by periodically-varying forces, was also entirely equivalent, both with the mechanical system of the receiver and the particle model on which he based his treatment. As Kennelly realized, "all of the preceding theory is immediately applicable to the case of a simple alternating-current circuit, containing resistance, inductance, and capacitance in simple series...."(33) Telephone diaphragms, particles moving under the influence of central forces, electrical circuits - all, it turns out, behaved like chimes which, when struck, gave forth sounds that gradually died away.

Meanwhile, Kennelly had been extending his work on circuits. In November of 1915, he presented to a meeting of radio engineers in New York results dealing with the impedances and angular velocities of oscillating-current circuits.[34] He had shown in 1893 that, if resistance was replaced by impedance, Ohm's Law would work for circuits governed by alternating current, circuits in which the periodic oscillations were sustained by an impressed force. In his 1915 address, he claimed to have discovered that, for unsustained, and thus decreasing, oscillations, or transients, the impedance along a closed circuit was zero. The principle, it turns out, was not new, having been stated in 1884 by Heaviside, as Arthur Webster and others were quick to point out.[35] Kennelly's work did, however, provide the starting point for Bush's dissertation.

In particular, Kennelly worked through the application of his newly "discovered" law to various types of circuits - circuits containing the elements of resistance, capacitance, and inductance interconnected in a variety of simple ways. He concluded his discussion with a more complex case - the inductively-coupled circuit. Like two strings that vibrate in harmony when one of them is plucked, so two electrical circuits will resonate in mutually-interacting ways when one of them is "plucked." The solution of this case, however, was not easy. After noting for his audience "the close analogy which exists between the arithmetics of electric oscillations in oscillatory-current circuits, and of small mechanical oscillations in mechanically vibrating systems," Kennelly concluded with the caution that the coupled circuit required the solution of a fourth degree equation with two pairs of conjugate complex roots which was, "in general, very tedious."[36]

This is the point at which Bush took up the problem. Having listened carefully, apparently, to the abundant criticisms provoked by Kennelly's talk, he dipped deeply into the works of Heaviside and discovered an engineer whose mathematical techniques helped him progress beyond his advisor. The problem in analyzing the behavior of circuits, in brief, was to find equations that contained in accessible form both the frequencies characteristic of the "plucked" circuits and the amplitudes of those vibrations, a more difficult problem with which Kennelly seems to have made little headway. Bush knew that, in general, the equation for the current in a coupled circuit would be of the form:

$$Ae^{n_1 t} + Be^{n_2 t} + \ldots + We^{n_k t}$$

where **A, B,..., W** are the amplitudes of the oscillations, **t** is the time from the moment the circuit is closed, and the **n**'s are the roots of the equation for the generalized impedance (Z=0) and represent the generalized angular velocities of the circuit. Kennelly had shown how to find **n** (a "tedious" problem when the circuit exhibited more than a single frequency of oscillation); what Bush discovered in Heaviside was a theorem which related the coefficients of this equation to the generalized impedance of the circuit in a form which made the calculation of the sought-after amplitudes relatively straightforward.

Bush derived the Heaviside Expansion theorem in the following manner: he first expanded the generalized impedance by means of Taylor's Theorem, giving

$$Z = f(n) = f(n_0) + (n-n_0)dZ/dn + ---$$

Ignoring higher-order terms and recognizing that $f(n_0) = 0$, Bush argued that the current times the generalized impedance balanced the voltage for any current term at the moment of closing the circuit. He could therefore write

$$E = n_0(dZ/dn)_{n=n_0} A_1 e^{n_0 t}$$

At $t = 0$,

$$A_1 = E/ (ndZ/dn)_{n=n}0$$

and the current

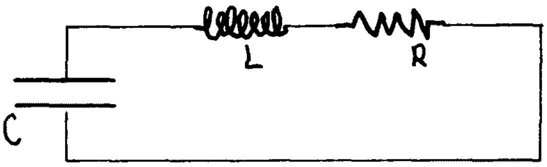
$$i = [E/ (ndZ/dn)_{n=n}0]\ e^{n_0 t}$$

If one consider all the terms of $Z=f(n)$, the equation took the form

$$i = \sum_{n=n_1}^{n=n_k} [E/ ndZ/dn]\ e^{nt} \qquad (1)$$

where n_1, $n_2, \ldots, n_k$ are the roots of $Z=0$. Bush's derivation of Heaviside's theorem was far from rigorous, as he himself recognized; but neither, in fact, was Heaviside's.[37] And it did give Bush a convenient way to derive the coefficients of the terms of the current equation for any circuit for which he could easily differentiate $Z = f(n) = 0$.

An example was the circuit



In this case,

$$Z = R + Ln + 1/Cn \qquad (2)$$

Or,

$$Z(n) = 0 = LCn^2 + RCn + 1.$$

To form the expression for the current, one need only differentiate **Z** with respect to **n**:

$$dZ/dn = L - 1/Cn^2,$$

$$n(dZ/dn) = Ln - 1/Cn.$$

From (1),

$$i = E/[Ln_1 - 1/Cn_1]e^{n_1 t} + E/[Ln_2 - 1/Cn_2]e^{n_2 t} \qquad (3)$$

where the roots n_1 and n_2 are obtained from (2):

$$n = -R/2L \pm j[1/LC - (R/2L)^2]^{1/2}.$$

For the particular values R = 200 ohms, L = 0.1 henry, and C = 4×10^{-6} farad,

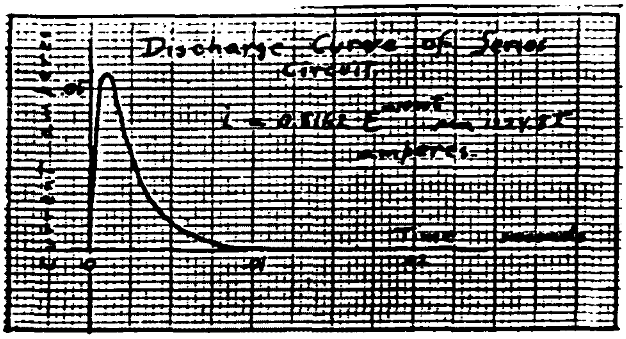
$$n_1 = -1000 + j1224.8$$

$$n_2 = -1000 - j1224.8.$$

If the condenser was initially charged to 100 volts, then

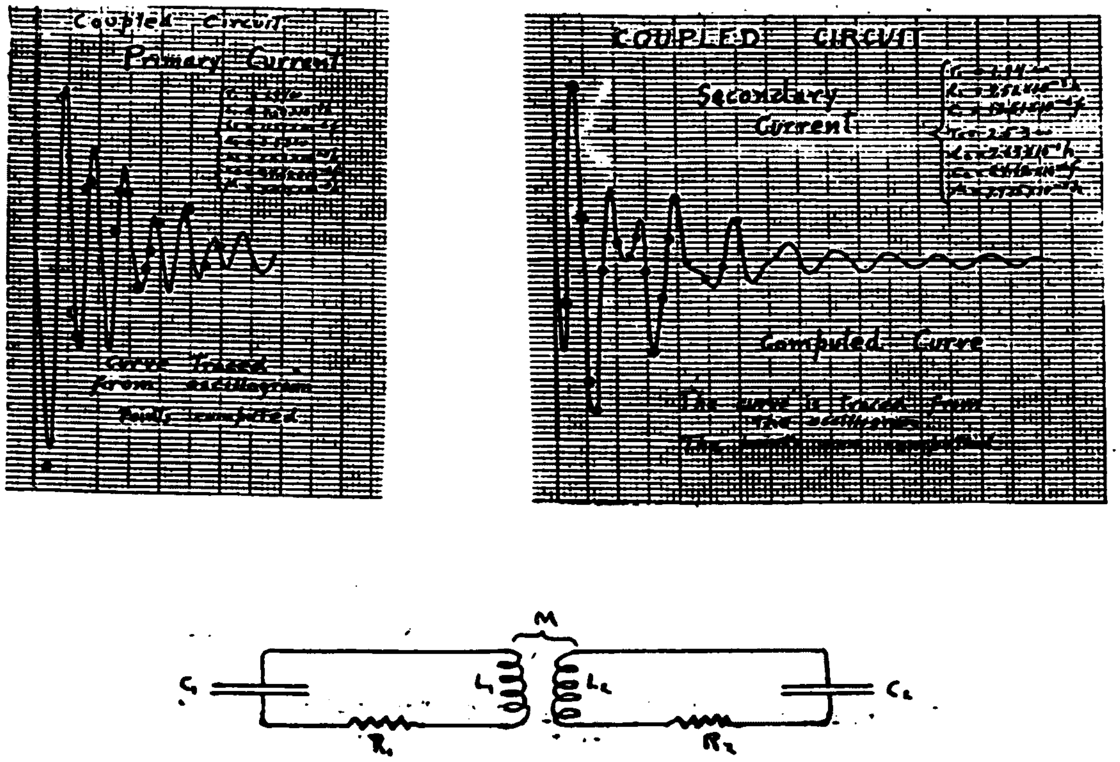
$$i = 0.8162e^{-1000t} \sin(1224.8t) \text{ amps.}$$

This current thus consists of a sinusoidal term of amplitude 0.8162 amperes and angular velocity of 1224.8 radians/sec, combined with the exponentially decreasing term e^{-1000}. Bush's plot of the discharge curve for this circuit is shown below.



The treatment of the coupled circuit was now straightforward. Bush proceeded to solve the current equations by two methods: first, the traditional method using differential equations, and second, the method of generalized angular velocities. The former method led to a fourth degree equation and a fourth order determinant "with the greater part of its elements complex. This is hardly a method to appeal to an engineer for daily use."[38] The latter method likewise led to a fourth degree equation - but one that could be solved algebraically. Its solution was still, needless to say, tedious and protracted. To check his methods, Bush constructed a test circuit, recorded its electrical behavior with an oscillograph, and compared actual with computed results. As a further example, Bush illustrated how the method of generalized angular velocities might be application to the study of long-distance transmission lines. Once again, he checked his results - in this instance by taking advantage of the artificial line with lumped parameters which Kennelly had built at Harvard.[39]

Bush concluded his thesis by pointing out problems for future study: techniques should be adapted to the study of long lines with the electrical parameters of inductance, capacitance, and resistance distributed rather than lumped; more complex circuits subject to forced oscillations should be treated; and, not least, an effort should be made to reduce theory to practice - "It is one thing to have a theory capable of attacking a given problem and an entirely different thing to apply it practically. Before many of the problems now before the engineering world can be solved, it will be necessary to develop theoretical methods of attack into such a form that they can be efficiently used by the men who understand the practical side of the problem at hand."[40] A problem unmentioned but ubiquitous in the thesis was the thoroughly trying struggle that faced engineers attempting to come to grips with the mathematics of circuits, a struggle in



The coupled circuit results from Bush's dissertation.

which they received scant help from pure mathematicians and formal methods. This struggle to forge practical mathematical methods would remain with Bush throughout much of his later career.

With his research complete and Kennelly's objections overcome, Bush scheduled four oral examinations within the space of a month. All in all, they gave him little trouble. In the middle of March, he was examined in mathematics. Two factors helped here. Bush knew that the department head, Harry Tyler, was "a hound on the history of mathematics." So "I got a set of cards and put a whole lot of useless information into my head about which mathematician did what. Sure enough he landed on that and questioned me on history for quite a long while."[41] In addition, Bush was something of a "fish out of water," as he remembered, in his predilection for applied mathematics. Despite Jackson's concern with cross-fertilization between mathematics and engineering, no one in the Mathematics Department knew their way around the problems of engineers, and no one among the electricals understood the mathematical work of Heaviside that Bush drew upon for his dissertation. Almost. E.B. Wilson, who had joined the Mathematics Department in 1907, shared Jackson's commitment to applied mathematics. "With the large necessities of the physicist and the growing requirements of the engineer, it is inevitable that the great majority of our students of calculus should need to use their mathematics rapidly and vigorously rather than with hesitation and rigor."[42] And it was Wilson to whom Bush turned for help with Heaviside. When the examiners got down to "serious questioning," Wilson "proceeded to ask me a couple of questions about the mathematics of the stuff we'd been working on -- Heaviside's approach to 'circuit theory.' Of course it was just the sort of thing that he and I'd talked about, so that I could readily answer the questions and show that, although it was non-rigorous, it was very powerful. He did this, without doubt, to help me out; he knew that the other fellows sitting around the room knew practically nothing about that particular aspect of Heaviside's work."[43]

During his physics oral, presided over by Professor Cross, Bush was asked the question "What is the nature of 'White Light'?" He proceeded to deliver a lecture on the classical theory of light, concluding "'Now gentlemen, that is the classic theory. I'll now proceed with an outline of the present quantum theory.' And somebody said, 'Well I guess that's enough....'" Bush did suffer a momentary loss of confidence during his major examination on electrical engineering. Jackson opened up with a question on the theory of long lines, "And I flubbed it! I couldn't think. I was completely off my trolley. Jackson said, 'Now wait a minute here. I know perfectly well that you know all about that subject.' Then he paused for a minute and he said, "Look, you go take a walk around the block for an hour and we'll reconvene then.' I did exactly that and when I came back my head was clear and I went through the examination all right."[44]

Bush completed his major examination on Monday, June fifth; on Tuesday the thirteenth, he graduated. It is uncertain whether Bush attended commencement, though it seems probable. It is certainly worthwile pausing to consider the events of that last week, for they were momentous and, in their own way, as much a part of the American culture of engineering as the oscillations of electrical circuits and the transient behavior of long-distance power lines.

* * *

In the early evening hours of graduation day, Mother Technology crossed the river Charles into the New World. It was a journey routed through interconnected worlds of fact and symbol and captured the larger hopes of American engineering. Because ours is a more skeptical, jaundiced age, we must go along and let the magic of that journey reawaken the vision that made engineering a matter of such importance in the years around the Great War.

The journey was, also, a metamorphosis, first and literally, a molting in the life of a school at the moment of its Golden Jubilee. In 1870, five years after MIT admitted its first class, only one in nine of the some 7300 practicing engineers listed in the census had graduated from technical schools; by the time Bush earned his doctor of engineering, one in two of the country's 55,000 engineers had graduated from schools.[45] As if to mark this coming of age of engineering education, the faculty and students of "Boston Tech" could, throughout 1915 and early 1916, peer across the Charles from Boston to a new site in Cambridge and watch, not just "a huddled lot of factory-like buildings or skyscrapers," as President Maclaurin put it, but "a great White

City" wrenched from the earth by sheer engineering will, rising on piles from the waters of Back Bay. Made possible by the benefactions of the mysterious Mr. "Smith" and others, the new campus would allow the Institute to escape the urban confines of Boylston Street and assume a proud new location, still fronting Boston but a partner now and equal of its rival Harvard at the intellectual heart of the country.[46]

Faculty, students, and alumni said goodbye to "the battered and outgrown homestead" of the old Rogers Building on a rainy Monday. Graduation Tuesday was swept clean by a sunny, windy afternoon that gave way to a cool, clear evening.[47] In the early twilight on the steps of Rogers, James Phinney Munroe, the Corporation's secretary, took up a small golden casket containing the Institute seal, and wound his way to the dock at the foot of Chestnut Street, in the company of faculty, students dressed as halberdiers and Venetian sailors, and the Institute charter and archives born aloft in a great chest. There they boarded a great white barge modelled after the Venetian state barge, with, above the prow, "a great seated figure in white, a strong woman with a lifted torch, Mother Technology enlightening the World." The Institute flag flew from the poop and the class flags lined the bulwarks. Henry Morss, class of '93, was costumed as Columbus, and guided the barge out into the Basin to the strains of Grieg's "Land Discovery" played by the student orchestra.[48]

On the Cambridge side of the Charles, the barge was awaited by the governor, the mayors of Boston and Cambridge, and ten thousand spectators arranged along the sides of the Great Court.

Below the governor and the mayors on the steps of the main colonnade stood Ralph Adams Cram, MIT´s senior professor of architecture and the pageant´s marshal, dressed as an ancient, white-haired Merlin in robes of black and gray. As it grew dark, searchlights found the barge nearing the shore and it was greeted by music, the cheering of the crowd, and a barrage of fireworks. Cram led the debarking voyagers across the Court where the seal and charter were placed on an altar below the governor. Then, as Cram returned to the center of the Court, the lights went out. He struck the ground with his staff, and the "Masque of Power" was underway.

Lights brightened, revealing at the Court´s center a circular area surrounded by seven thrones. While the orchestra blared the music of "Chaos," the circle filled with leaping scarlet figures waving smoking torches. As the smoke cleared, one could make out the Spirit of Time on his throne brooding on the six "Elements of Chaos" - Earth, Air, Fire, Water, Steam, and Electricity - as each performed their characteristic dance. Suddenly, the Elements shrank back before a "huddled, crouching, sinister group" called from the dark by the Time Spirit to conquer nature - Primitive Man, "brawny, brown men-things, their matted black hair falling over bestial faces." Men and Elements struggled until Prometheus snatched the torch of Fire. Eventually, Will and Wisdom come to man´s aid, at the head of a procession of heroes representing all the ages of civilization. The heroes vanquish the Elements and assume the vacant thrones as the Time Spirit dances "the quick arrogant dance of the Pride of

Civilized Man." But the victory proves hollow. Once again the lights dimmed, the orchestra blared, and "out from the dark behind the Time Spirit's throne dash four great figures on horseback, War, in full panoply, Greed, with the boar's head, Vainglory, with the cockscomb, and Selfishness" followed by hordes of bronzed and scarlet minions. With Chaos victorious, the lights go out.

When the lights came back on, they illuminated three standing figures - Will and Wisdom now joined by "a tall, beautiful woman, crowned with the Cross - Righteousness. Civilization lifts its head and adores her." Searchlights shifted to the Basin's edge where they found Merlin accompanied by the tall, white figure of Mother Technology and the Seven Liberal Arts. Mother Technology receives the homage of Will, Wisdom, and the Time Spirit as she and her companions take their seats on the steps below the governor and the mayors. In a grand triumphal procession led by Merlin, the ages of civilization, including the Nineteenth Century "bearing the banners of the fifteen departments of the Institute" and vanquished War, circled the Court and gathered before Mother Technology where they presented the Elements "chained now and mastered." The pageant ended with the chorus singing "Mother Tech" and the Star Spangled Banner. Searchlights, first crossing with the lights from the Rogers Building which then died out, pointed straight up into the sky. MIT had arrived in the New World.

Who could have thought that engineering could be choreographed![49] But the culture of engineering had a variety of dimensions and what might seem to us bizarre and superficial was taken to heart in 1916. As the historian of the pageant put it, "It was, to the minds of some of us, the perfect symbol of what has been happening all these years. The necessity for concentration on the purely utilitarian has passed.... With the tradition of the pageant in mind Technology can safely work toward that larger education which is the marriage of usefulness and beauty. For the men who could do the pageant can do anything."[50]

"We are here to dedicate a noble group of buildings to a noble purpose," Maclaurin told his audience the next afternoon. Of those purposes, some were explicit and some not. Boswell´s classical architecture certainly spoke of the continuity of past and engineering present. "The center of intellectual achievements in the world has passed in turn from Egypt and Babylonia, to Greece, to Alexandria, to Constantinople and to Western Europe. Is it to cross the Atlantic? If this be so, the intellectual leadership must accord with the genius of our people for practical affairs."[51] It was a lesson pressed home by the previous day´s pageant in which the seal of the Institute had been conducted across the Atlantic of the Charles by the representatives of the Old World. Moreover, the character of that leadership had taken on the genius of the American people for practicality and usefulness. If the classicism of the new buildings signified the unity of past and present, the centrality of the laboratory indicated that philosophy had been joined solidly to the rational instruments of science and engineering.

The laboratory at MIT was, indeed, joined solidly to its larger context so plainly revealed by the pageant and the Masque of Power: it is Will and Wisdom, after all, in the company of Righteousness that do homage to Mother Technology. The lesson was struck when Munroe, in his farewell to Rogers, cited the twofold obligation to interpret Nature and to fashion "from plastic youth the solid fabric of true men." Its science would be of no avail if the Institute failed to teach its students "that the man of science must be honest in everything, at all times effectively industrious, a seeker of the public rather than of his private good, a server from his first day to his last of that civilization which has endowed him with all the accumulated treasures of the centuries, and which demands, be it small or be it large, his social and civic contribution in return."[52]

The last lesson of that week was the grimmest. While the Masque of Power led to peace and order, it was a progression that turned on conflict, from the primeval struggle of man and nature to the eventual triumph of Will and Wisdom, bolstered by Righteousness, over the minions of war. There is, indeed, a strange numerology marking the Institute's history: from the Civil War to the Great War, an even half century; from the Great War to Pearl Harbor, a quarter century. And at the joining, the Golden Jubilee. The connection did not pass unnoticed. Munroe, speaking in the Rogers Building: "There is probably sound basis for the belief that men and women born in times of exceptional moral conflict, -at such epochs, for example, as that now shaking the foundations of the world, -go through life with soberer minds and keener emotions than those given to the rest of us. Perhaps that is one of the reasons why this Building, conceived in the period of the Civil War, has had upon those passing within its influence an effect so unusual and so profound."[53]

The war in Europe was never far from the proceedings of that week. Charles Winslow, class of '98, had once presented the bust of the great Civil War general and Institute president, Francis Amasa Walker, that stood in the Rogers Building. He spoke again at dedication ceremonies in 1916. "In his allusion to the struggle in Europe, Professor Winslow pointed out as a task for the future, 'the control of those forces of confusion in human society which are stronger than steel and more complex than the organic molecule.'"[54] At the concluding banquet on Wednesday evening, Coleman du Pont, one of MIT's most generous donors, delivered "a ringing plea for Preparedness": "We should work out plans at once for such an efficient, energetic, effective engineering mobilization as the world has never seen; then, should the moment ever come when the country calls for the support and help of its engineering heads and hands, we would be ready."[55] Engineers, it was commonly assumed, would play a central role in the European conflict for, as it was put by the Tufts president, "The conduct of this War is not merely a military procedure. It is not an affair of arms; It is not a conflict between armies. It is a huge business proposition. It is a great engineering undertaking."[56]

Patriotic participation was not the sole attraction of war.

A deeper temptation concerned the unique responsibility felt by engineers to shape the emerging order. Maclaurin was clearest about that at Wednesday's dedication. "[O]ur look must be ever ahead. The opportunity before us is alluring in the extreme. The greatest war in history will inevitably mark the end of one era and the beginning of a new," and in that new age engineers would play a crucial part. "In that era no half measures will avail. We must get it into the minds of the rising generation that for success nothing must be done haphazard or by 'rule of thumb.' All must be orderly and logically planned, resting ever on the solid ground of fact...."[57] Newton Baker, Woodrow Wilson's Secretary of War, would be blunt a year later: "We have just emerged into the twentieth century, and it seems there are just a few 'hang-over' impossibilities from the nineteenth century that will have to be eradicated before the plane of life will be possible of elevation...."

> Nobody knows what the world is going to be like when this war is over. No imagination has yet been able, I think, even faintly to picture the sort of civilization which will exist in Europe after this fearful conflict is over. Nobody knows how long the conflict is going to last. ... But we do know that when this war is over the rehabilitation of a stricken, if not paralyzed civilization is going to be a long-drawn-out and uphill task, and there will be need on every hand for trained minds, for trained and skilled bodies; that the day of the engineer will then be the big day. ...he must be there in great numbers to rebuild the world.(58)

Engineers would rebuild the world. Building on the ruins of "the pretensions of dynasties and houses and the prestige and contentions of autocracy," they were determined that it would be an American world.

Celebrations concluded on Wednesday with an evening of feasting, speeches, and festivities for 1500 alumni and guests in Boston's Symphony Hall - all transmitted telephonically to alumni in thirty-four cities around the country. All the classes from '68 to '16 were arranged along the floor of the hall; the head table stretched across the stage and behind it hung a large portrait of Old Rogers. At the head table sat Charles Stone, of Stone and Webster, the president of the Alumni Association. To his right sat Maclaurin and to his left J.J. Carty, chief engineer of AT&T and the man responsible for the telephonic linkup. Thomas Edison and Theodore Vail couldn't speak that night, though the audience might have heard Edison, if he had come and had spoken, tell them what he had already said of their school: "If every State in the Union had such a technical school as the Massachusetts Institute of Technology, it would be a great thing for the county."[59] They did hear Alexander Graham Bell, the inventor of the telephone, who gave tribute to Professor Cross, and they listened to Orville Wright, "the shyest man in America," who said a few words, "wishing good luck to the Institute in its career." His speech "wasn't long, but it was appreciated." At the evening's end, after a final address by former president H.S. Pritchett - who reminded his listeners that "Rogers was the prophet of preparedness. Today the whole nation demands it." - President Maclaurin wished each of the clubs from around the country a good night:

"Good-night, Seattle."

> "This is Seattle. Seattle sends its heartiest congratulations and best wishes. Good-night, Dr. Maclaurin."
>
> "Thank you. Good-night, Spokane..."
>
> And so on down through the list, bidding each one good-night....
>
> Finally, the alumni of Technology heard the "Star Spangled Banner" sung from Washington. As the second verse died away Major Henry Lee Higginson asked if all the cities couldn't sing the song together. Mr. Drake, after a hurried, continent-wide consultation, said he thought they could. So after a false start by Boston's too-zealous band, everyone joined in, and those singing in Boston could hear their brethren from the east coast to the west, from the Canadian border to the Gulf singing the same song of the flag.(60)

* * *

Earlier in that frenetic year, Bush's own plans for the immediate future were much less cosmic. They were, in fact, still up in the air. During a midyear meeting with William Hooper, his old electrical teacher from Tufts, he intimated that he meant to leave at the end of the year with the hope of completing his dissertation some time later. "I undertook to pump him without his realizing that he was being pumped," Hooper wrote to Bumpus. "You are of course aware that I regard Mr. Bush as a young man of very unusual ability in mathematical physics and expect to see him establish a high reputation in the not distant future." If Bush could be lured back to Tufts, the future of the electrical engineering department would be secure. Hooper had been a pioneer, he wrote Bumpus, but his day was passing. The "future demands a man of different type. Theoretical Electrical Engineering has come to demand an accomplished mathematician...."[61] Bush might have gone elsewhere. Western Electric had offered him work "right in my line," starting at $1500 or better with generous annual raises. But he wrote to Bumpus that he had told his contact at Western Electric "that I was much inclined to go with my old college, because of the advantage of living in Boston, and the unusual opportunity which I believed ahead of the Tufts Engineering School."[62]

There was another reason that inclined Bush towards Tufts. He hoped to get married that fall. While neither prospective income seemed to him large enough to begin married life on, the Tufts job had extra possibilities: "I took the job at Tufts, and I did it, I think, primarily because I thought I could supplement my income. So it turned out. I immediately went to work on doing a bit of consulting and the first outfit I ran into was Amrad. I remember the joy with which I picked up something I could do in my spare time, and earn twenty-five dollars a day at - which was pretty good money at that time."[63] And so with his dissertation complete and his orals passed, Bush headed back, yet again, to Tufts, this time as a young assistant professor with a growing reputation.

NOTES - CHAPTER SIX

1. Bush, Pieces of the Action[PA], pp.157, 244.

2. Hodgins, Oral History[OH], pp.1-20; Bush, PA, p.244.

3. Tufts College Catalogue 1914-15; Frank Wren to H.C. Bumpus, February 17, 1915, Tufts University Archives.

4. Bumpus to Hall, February 23, 1915, Tufts University Archives.

5. OH, pp.21-23A.

6. The resignation is in the Federal Archives and Records Center, GSA, Archives Branch, Building 22 MOT - Bayonne, Bayonne, New Jersey 07002; Bush to Bumpus, September 7, 1915, Tufts University Archives.

7. OH, pp.554A-555.

8. Science 34 (September 8, 1911): 3-5; on Webster, see Joseph Ames, "Arthur Gordon Webster," Biographical Memoirs of the National Academy of Sciences 18 (1938): 337-347.

9. OH, pp.25-26.

10. OH, pp.94A-95.

11. OH, pp.24-26.

12. Webster, "Some Practical Aspects of the Relations Between Physics and Mathematics," Physical Review 18 (1904): 297-318.

13. On science, engineering, and mathematics, see Chapter Two and, especially, John Servos, op.cit.

14. Webster, op.cit., pp.314-315.

15. OH, pp.94A-95.

16. Bush's application and his letter of acceptance were shown to me by Karl Wildes at MIT; Bush to Bumpus, November 24, 1915, Tufts University Archives.

17. The Tech, October 1, 1915.

18. The statistical information on the Electrical Engineering Department is taken from the MIT President's Reports, the Catalogues, and, most importantly, the massive compilation of statistical and historical information prepared for the department's semicentennial celebration in 1935; for the latter,

see the Jackson Papers, Box Three, Folder 245, MIT Archives. The recent history of the department by Karl Wildes and Nilo Lindgren, *A Century of Electrical Engineering and Computer Science at MIT, 1882-1982*, is a good general survey.

19. "Dugald Caleb Jackson," in the Jackson Papers, Box Three, Folder 242; Bush, "A Tribute to Dugald C. Jackson," *Electrical Engineering* 70 (1951): 1063-1064; Jackson, "The Evolution of Electrical Engineering," *Electrical Engineering* 53 (1934): 770-776.

20. See Edwin Layton, *The Revolt of the Engineers*, pp.160-163, and David Noble, *American by Design*, pp.137-140, for two accounts of Jackson.

21. On Jackson's use of cooperative programs to expand the influence of the department, see W. Bernard Carlson, "Electrical Engineering Education and the Needs of Industry: The Case of the MIT-GE Cooperative Engineering Course, 1907-1923," personal copy.

22. Jackson to D.C. Jackson, Jr., March 7, 1932, Jackson Papers, Box Three, Folder 185, MIT Archives.

23. *Ibid*. Jackson had the efforts of A.A. Noyes and W. Walker on which to model the Division; see John Servos, "The Industrial Relations of Science," *Isis* 71 (1980): 531-549.

24. *Ibid*.

25. Jackson to E.E. Dreese, May 7, 1934, Jackson Papers, Box Three, Folder 187.

26. Bush, PA, pp.252-253.

27. *Ibid*., p.253.

28. See, for instance, W. Hooper to Bumpus, January 28, 1916, Tufts University Archives.

29. V. Bush, "Application for Candidacy for an Advanced Degree, September 25, 1915," and "Petition for Change of Proposed Course, February 9, 1916," in the possession of Karl Wildes; Bush, PA, p.253.

30. V. Bush, "Arthur Edwin Kennelly," *Biographical Memoirs of the National Academy of Sciences* 22 (1943).

31. Arthur Kennelly, "Impedance," *Transactions of the American Institute of Electrical Engineers* 10 (1893): 212; "The Impedances, Angular Velocities and Frequencies of Oscillating-Current Circuits," *Proceedings of the Institute of Radio Engineers* 4(1) (1916): 47-94.

32. Kennelly and H.A. Affel, "The Mechanics of Telephone-

Receiver Diaphragms, as Derived from their Motional-Impedance Circles," *Proceedings of the American Academy of Arts and Sciences* 51 (1915-16): 422-482.

33. *Ibid.*, p.472.

34. Kennelly, "The Impedances, Angular Velocities...," *op.cit.*, pp.47-78.

35. See the responses included after Kennelly's paper; Webster, pp.83-85. Peeved, Webster points out that few of the discoveries engineers were announcing were new.

36. *Ibid.*, pp.72-73.

37. V. Bush, *Oscillating-current Circuits. An Extension of the Theory of Generalized Angular Velocities, with Applications to the Coupled Circuit and the Artificial Transmission Line*, MIT, April 1916.

38. *Ibid.*, p.53.

39. A. Kennelly and Tabossi, "Artificial Power Transmission Line," *Electrical World* (February, 1912).

40. Bush, *op.cit.*, p.155.

41. OH, p.383.

42. E.B. Wilson, Preface to *Advanced Calculus* (Boston: Ginn and Company, 1912), cited in W.E. Byerly, "Wilson's Advanced Calculus," *Bulletin of the American Mathematical Society* 19 (1913): 362.

43. OH, p.382.

44. OH, pp.383-384.

45. Statistics from Charles Riborg Mann, *A Study of Engineering Education Prepared for the Joint Committee on Engineering Education of the National Engineering Societies* (New York, 1918); appeared as Bulletin #11 of the Carnegie Foundation for the Advancement of Teaching.

46. On the early history of MIT, see Samuel Prescott, *When MIT was 'Boston Tech' 1861-1916* (Cambridge: Technology Press, 1954); for Maclaurin's quote, see *Technology Review* 15 (November 1913): 544.

47. The phrase is James Phinney Munroe's; see *Technology Review* 18(7) (July 1916): 479.

48. My account of the semicentennial celebrations follows closely the lengthy report by R.E. Rogers in the above volume of

the Technology Review.

49. My appreciation for the Masque and the move across the Charles into new buildings has been heightened by a delightful talk delivered by Bruce Sinclair at the American Philosophical Society in 1984 and by the reading of a typescript of a presentation at MIT by Kathleen Marquis and Helen Samuels, "Technology Moves to Cambridge."

50. Rogers, p.466.

51. Rogers, p.530.

52. Rogers, pp.470, 478.

53. Rogers, p.471.

54. Rogers, p.481.

55. Rogers, p.551.

56. H.C. Bumpus, "Address at the Manufacturers' Dinner Conference, February 28, 1918," Bumpus file, Tufts University Archives; for provocative insights into the relationship of American engineers and the war, see David Kennedy, Over Here. The First World War and American Society (New York: Oxford University Press, 1980).

57. Rogers, p.530.

58. Newton Baker, "The Engineer in the War," SPEE 25 (1917): 32-33.

59. Technology Review 14 (1912): 49.

60. Rogers, pp.547-555.

61. William Hooper to President Bumpus, January 28, 1916, Bumpus file, Tufts University Archives.

62. Bush to H.C. Bumpus, March 11, 1916, Bumpus file, Tufts University Archives.

63. OH, p.557A.

Part Three.

Straight Thinking in the Culture of Engineering

"The fact is that Mr. Waite behaves admirably in character; he is precisely what he has always been - a man with the technical training of an engineer..."

- Henry Waite, MIT ´90, and City Manager of Dayton, Ohio

CHAPTER SEVEN:

THE TEXT AND CONTEXT OF AN EARLY COMPUTER

> Everything has its language, and the power of feeling what a thing means, by the way it looks, is a matter of experience - of learning the language.
>
> - Gerald Stanley Lee, The Voice of the Machines (p. 67)

One day in 1943, the Rockefeller Differential Analyzer was dedicated to winning the war. For the next several years this large mathematical machine, the centerpiece of MIT's Center of Analysis, labored over the calculation of firing tables and the profiles of radar antennas.[1] Weighing almost a hundred tons and comprising some two thousand vacuum tubes, several thousand relays, a hundred and fifty motors, and automated input units, the Analyzer was the most important computer in existence in the United States at the end of the war.[2] Wartime security prohibited its public announcement until 1945 when it was hailed by the press as a great electromechanical brain ready to tackle the problems of peace and to advance science by freeing it from the pick-and-shovel work of mathematics.[3]

The development of the Analyzer had occupied Vannevar Bush and his colleagues at MIT for almost twenty years. In 1927, an early model made the front page of the New York Times: "'Thinking Machine' Does Higher Mathematics; Solves Equations That Take Humans Months." In 1930, the group constructed a model which proved so successful that it inspired imitation around the world. In the United States, General Electric, Aberdeen Proving Ground, and the universities of Pennsylvania, California, and Texas all built Analyzers. More were constructed abroad, in England at Manchester and Cambridge, and in Ireland, Germany, Norway, and Russia.[4] Bush's success prompted him to plan an analyzer more capacious, quicker in calculation, and more flexible in application, which would establish MIT as an international center for the study of machine computation. He persuaded the Rockefeller Foundation in 1935 to finance the new machine, and in 1939 the Carnegie Corporation contributed money to help establish and maintain a center to serve as a site for the study of machine analysis. At the time, Bush's program seemed an adumbration of future technology. Harold Hazen, the head of the Electrical Engineering Department in 1940 and a long-time colleague, predicted that the Analyzer would "mark the start of a new era in mechanized calculus," and Karl Compton, MIT's president, declared in 1941 that the new machine would be "one of the great scientific instruments of modern times."[5]

Within five years of its announcement, however, the early enthusiasm which had marked the development of the Analyzer had died, and the Center of Analysis had collapsed as a vital site for the study of computation.[6] In the early spring of 1950, Samuel Caldwell, the Center's director and another of Bush's close colleagues in the development of the Analyzer, came to the home of Warren Weaver to discuss the status of the machine and the program it had inspired. Weaver was the director of the Natural Sciences Division of the Rockefeller Foundation and a respected mathematician, and had been intimately involved with the MIT project from its beginnings in the thirties. The long meeting between the two men turned into an autopsy of the program begun fifteen years earlier with Rockefeller support. No one had expected in 1936, they admitted, that the whole field of "computer science" would so quickly overtake Bush's project. But things had indeed changed, and Caldwell confessed to Weaver that the Analyzer was "essentially obsolete" and the whole program had "become a real burden on MIT."[7]

What happened? Why did a twenty-year effort to create a computer fail when it did? The reasons, of course, are manifold. In the first place, the war released an unprecedented flood of federal money and spawned a multitude of laboratories at MIT, disrupting the simpler institutional environment in which the Analyzer was conceived and nurtured. But if the war brought new public monies which overwhelmed the older tradition of private philanthropy which had sustained the Analyzer, it also ushered in a variety of computational tasks, in the fields of large-volume data analysis and real-time operation, which were beyond the capacity of the Rockefeller Analyzer. The years around the war's end were marked by intense competition in computer development, and Bush's machine was quickly challenged by more capable computers incorporating radically different designs - by Eckert and Mauchly's ENIAC at the University of Pennsylvania, and by Jay Forrester's Whirlwind at MIT itself.[8] These new computers were electronic and digital, rather than electromechanical, and to them belonged the future of computer technology. In brief, the Rockefeller Analyzer succumbed to technical obsolescence.

But there are other reasons as well. In a letter to Caldwell some days after their post mortem, Weaver wrote:[9]

> [I]t seems rather a pity not to have around such a place as MIT a really impressive Analogue computer; for there is vividness and directness of meaning of the electrical and mechanical processes involved... which can hardly fail, I would think, to have a very considerable educational value. A Digital Electronic computer is bound to be a somewhat abstract affair, in which the actual computational processes are fairly deeply submerged.

Weaver's insight can help us understand that the Rockefeller Analyzer was not so much an aborted beginning, as the culmination of a series of inventions stretching back, in fact, to Bush's undergraduate years at Tufts College. Furthermore, Weaver's reference to its vividness of meaning and educational value suggests that Bush's machines could be read as weighty "texts" embodying a variety of idioms - technical, intellectual, and ethical - ingredient in the culture of engineering in which he came of age. In the context of the early twentieth century engineering school, the analyzers were not only tools but paradigms, and they taught mathematics, method, and modeled the character of engineering.

* * *

In the decade following the First World War, electrical engineers came up against severe mathematical difficulties in their studies of vacuum tubes, telephone lines, and especially long-distance power transmission lines. Given the large financial risks which accompanied the construction of power networks, it was imperative that engineers be able to predict the operating characteristics of proposed systems.[10] Consequently, in 1920, a year after Bush joined joined the faculty of Jackson's department, the Research Laboratory undertook a major assault on the mathematical problems involved in the study of long-distance lines. The attack was two-pronged and dealt, on the one hand, with the construction of artificial lines designed to reproduce on a laboratory scale the behavior of power networks, and, on the other, with the search for methods to handle the refractory equations generated by these networks.[11]

While the pertinent mathematics had been developed by electrical engineers, the practical solution of the equations for specific cases was far from simple. Of particular importance to MIT engineers studying line stability was the so-called Carson equation, whose solution demanded the use of standard tables, the tedious plotting and replotting by hand of component functions, and the determination of integral areas by the use of the planimeter.[12] Early in 1925 Bush suggested to his graduate student Herbert Stewart that he devise a machine to facilitate the recording of the areas needed for the calculation of the Carson equation. In the course of his work, Stewart apparently discovered the series of papers which William and James Thomson had published in 1876 describing the disc-globe-and-cylinder integrator and its application to harmonic analysis. William Thomson explained the use of the integrator for calculating the integral

$$\int_{0}^{x} f(x)\phi(x)dx.$$

Stewart was properly intrigued, for the general form of the Carson equation was of the same type:

$$y(t) = F_1(t)\int_{0}^{t} f(\xi)\phi(t)d\xi.$$

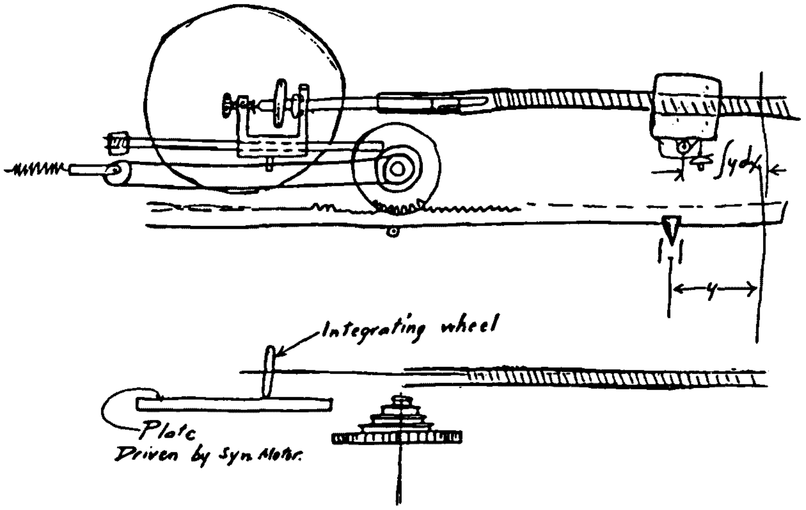
However, since this use of the Thomson integrator required knowledge of the integral

$$\int_{0}^{x} f(x)dx,$$

Stewart dismissed the device as unsuitable for his project, feeling that **f(x)** might not, in the general case, be easily integrated. His dismissal of the Thomson integrator is ironic, for he might have found in the Thomson papers(which had been collected as Appendix B′ in Thomson and Tait's 1879 *Treatise on Natural Philosophy*) the essential insights which Bush would bring to fruition in the development of the mechanical integrator for which he had set Stewart searching.[13]

A Stewart colleague, F. D. Gage, suggested that he interpret the equation electrically rather than mechanically. He then realized that the integration of the functional product could be performed with an ordinary watt-hour meter. Stewart intended to read the meter at appropriate time intervals, but Bush recommended linking the meter to a pen driven by a servomotor which would permit the integral's continuous recording. To generate the second-level product, Stewart turned again to the watt-hour meter until Bush pointed out that it could be accomplished more simply by an elementary mechanical linkage. Stewart received his master's degree in September, 1925 for his work on this first Product Integraph.

Two more Bush students became involved with the Product Integraph. King Gould used the machine to study the temperature gradient along the heated filament of a vacuum tube.[14] Harold Hazen began the study of vacuum tube circuits, and soon realized that he could treat more complicated circuits if he had two levels of integration with which to work instead of one. He sketched out a second element for the Integraph employing a wheel-and-disc integrator(a close cousin of the Thomson device), and showed his idea to Bush who quickly recognized the generality of his innovation and generated a twenty-page memo outlining a new machine.[15] After all, although first-order differential equations were encountered frequently in science, "it was once said that physics revolved about the second-order differential equation, and while recent developments have somewhat obscured



3-23-26
HLH

Hazen's sketch of a second integrating element for the new model Product Integraph. (The sketch and Bush's response are found in the Hazen Papers, MIT Archives.)

this importance there is still much of physics thus described."[16] Under Bush's guidance, Hazen built a two-element machine capable of solving most second-order equations to an accuracy of several percent. In May 1928 the Franklin Institute awarded Bush its Levy Medal for his work on mechanical computation with honorable mentions to Stewart, Gage, and Hazen.

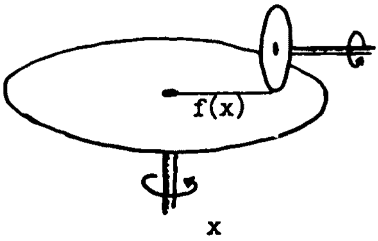
The new model Product Integraph was applied to the study of vacuum tube circuits, transmission lines, mechanical oscillations in synchronous motors, and electron orbitals.[17] Yet despite its successful applications, no one was satisfied with the new Integraph. A hybrid machine that employed both an electrical and a mechanical device to perform the same function of integration, it suffered from the limitations of the former while failing to maximize the advantages of the latter. The watt-hour meter was physically more complex and inherently less precise in its operation than a well-engineered mechanical integrator. Moreover, the meter was a more complex logical device in that it integrated the product of two functions, while the mechanical integrator, as will be seen, simply integrated **f(x)dx**. The combination of mathematical elegance and mechanical simplicity appealed to Bush, and by the fall of 1928 he had secured funds from the administration at MIT to build a new machine that would take advantage of the simple virtues of the wheel-and-disc integrator.[18]

The Differential Analyzer fulfilled Bush's expectations.[19] The new machine consisted of a long table-like framework criss-crossed by interconnectible shafts. Along one side were arrayed a series of drawing boards and along the other six disc integrators. Pens on some of the boards were driven by shafts so as to trace out curves on properly positioned graph paper. Other boards were designed to permit an operator, who could cause a pen to follow a curve positioned on a board, to give to a particular shaft any desired rotation. In essence, the Analyzer was a device cleverly contrived to convert the rotations of shafts one into another in a variety of ways. By associating the change of variables in an equation with the rotations of shafts, and by employing an assortment of gearings, the operator could cause the calculator to add, subtract, multiply, divide, and integrate.

The disc integrator, the heart of the Analyzer and the means by which it performed the operation of integration, is a variable friction-gear that consists of a disc resting on a wheel at a variable distance from its center. The geometry of the integrator forces its constituent shafts to turn in accordance with the relationship

$$y = \int_a^b f(x)dx.$$

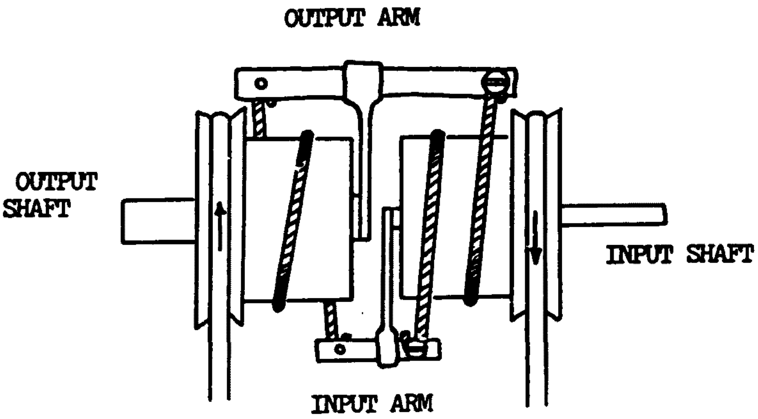
The precision of the disc-integrator depends on eliminating slippage between the wheel and the disc when the wheel turns under load. In the Product Integraph Bush had reduced the load carried by the wheel shaft by the use of a servomotor which followed its rotations. In the Differential Analyzer, he accomplished the same end, and continued his replacement of electrical by mechanical elements, by incorporating another Hazen idea - the torque amplifier designed by C. W. Nieman of the



$$y = f(x)\Delta x \qquad y = \int_a^b f(x)dx$$

a)

The Disc Integrator



b)

The Torque Amplifier

The Torque Amplifier and the Disc Integrator

Bethlehem Steel Corporation.[20] Nieman's torque amplifier was a purely mechanical device for the amplification of motion that depended on the winch principle. By its use Bush was able to eliminate most of the torque load carried by the wheel shaft of the integrator, and to supply the power needed to drive his calculating engine.

The use of the Analyzer can be illustrated by an example based on one of Bush's own. Consider the equation of a falling body when the gravitational force **g** varies with the distance **x**:

$$d^2x/dt^2 + (k)dx/dt + g(x) = 0$$

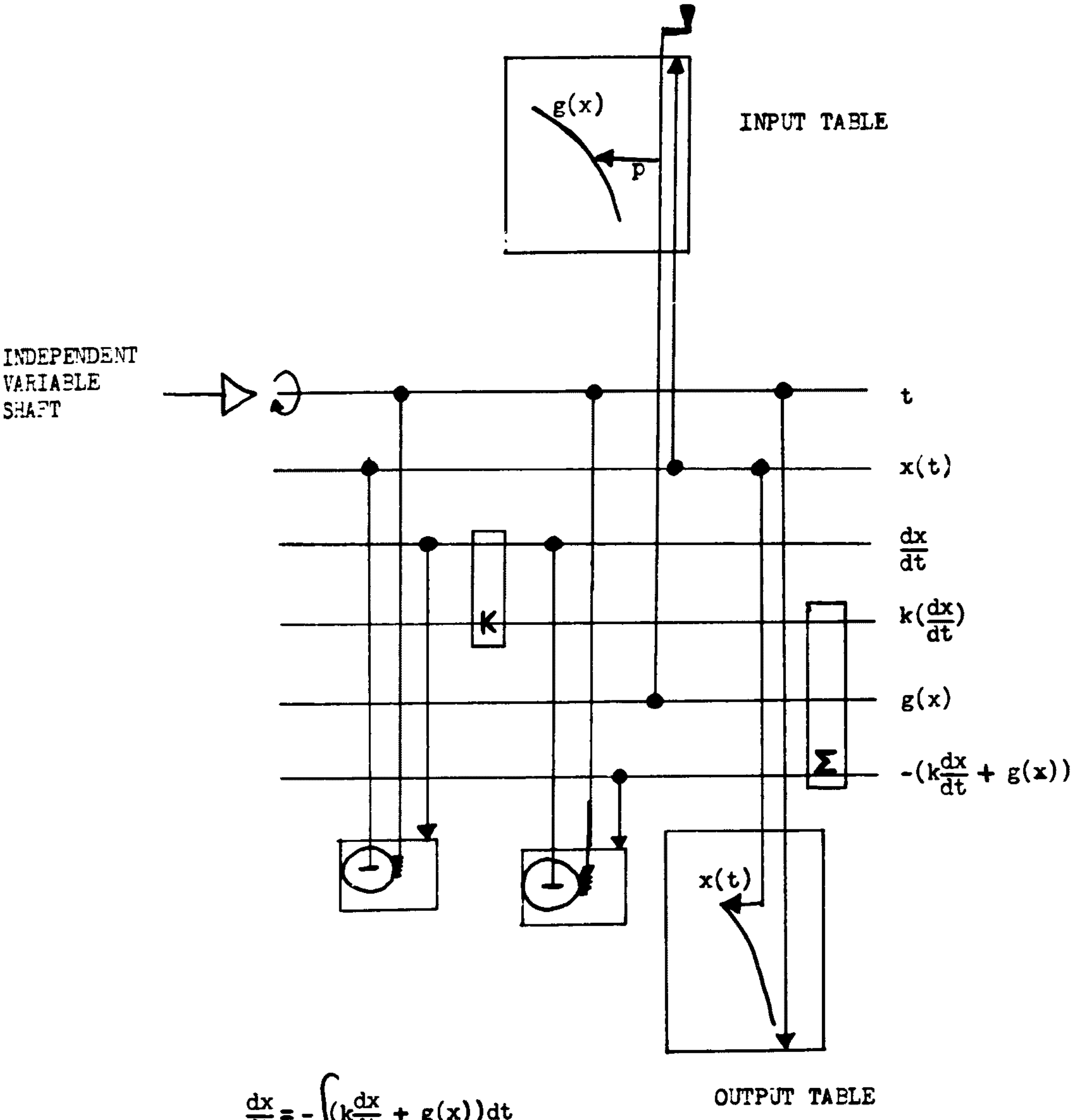
or,

$$dx/dt = -\int[(k)dx/dt + g(x)]dt.$$

In Bush's words,

> A bus shaft is assigned to each significant quantity appearing in the equation. The several relations existing between these are then set up by means of connections to the operating units: a functional relationship by connecting the two corresponding shafts to an input table, a sum by placing an adder in position, an integral relationship by an integrator, and so on. When all the relationships which are involved have been thus represented a final connection is made which represents the equality expressed in the equation. In the example above this connection is through an integrating unit.... When this has been done the machine is locked, and the rotation of the independent-variable shaft will drive everything else, thus forcing the machine to move in accordance with the expressed relationship....(21)

A schematic of the Analyzer connected to solve the equation of the falling body is illustrated in the figure. The horizontal lines represent bus shafts, **K** and **Σ** multiplying and adding gears, and the integrators are represented by the indicated symbol. The



$$\frac{dx}{dt} = -\int\left(k\frac{dx}{dt} + g(x)\right)dt$$

terms of the equation associated with the rotations of particular bus shafts are noted at the side of the diagram. **G(x)** would have been plotted earlier and an operator stationed at the input table to keep the pointer **p** on the curve as the Analyzer worked through the equation. The function **x(t)**, which expresses distance with respect to time, would be traced automatically on the output table.

The Differential Analyzer did more, obviously, than compute **x(t)**. Through his elaboration of the mathematical possibilities inherent in the disc-integrator, and by the elimination of extraneous non-mechanical elements, Bush invented an elegant, dynamical, mechanical model of the differential equation. Articulated in a particular pattern, its shafts, gear-boxes, integrators, pens and drawing boards set in motion, the Differential Analyzer did not so much compute as kinetically act out the mathematical equation.

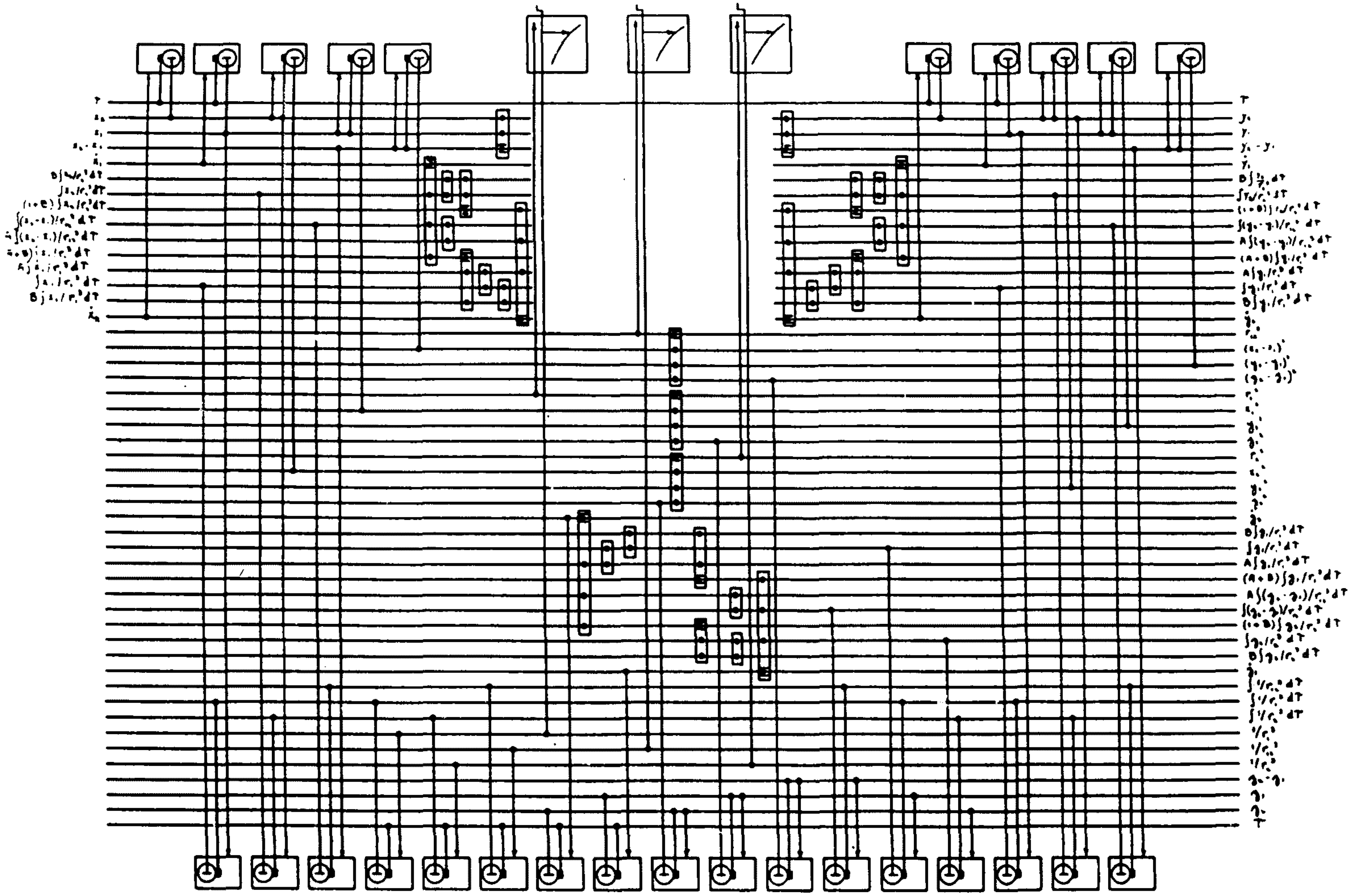
Between 1926 and 1935 the development and application of the analyzers generated four bachelor's theses, twenty-eight master's theses, and four doctoral dissertations.[22] Among the students who worked on the analyzer project were a number destined to become influential figures at MIT - Harold Hazen, Sam Caldwell, Gordon Brown, and Harold Edgerton. Most of the problems studied with the help of the analyzers were drawn from the field of electrical engineering - but not all. By 1935 applications reflected the frontiers of scientific investigation and included studies in atomic physics, astrophysics, cosmic rays, and seismology. As early as 1932 Bush's colleague in the Physics Department, Philip Morse, used the Analyzer to help thread his way through the computational thicket created by the quantum revolution of the twenties.[23] The Englishman Douglas Hartree, a pioneer in the development of wave mechanics, visited Bush during the summer of 1933 to become familiar with the Analyzer and used it for his calculation of the atomic field of mercury. Back at the University of Manchester, he constructed several analyzers modeled on the MIT machine, one of them from standard Meccano parts for a cost of some twenty pounds.[24]

Experience, mathematical skill, and sometimes days were required to translate difficult problems into forms which could be attacked by the calculator and then to connect the machine to perform the desired calculations. When Lemaitre and Vallarta calculated the trajectories of cosmic rays under the influence of the earth's magnetic field, it took five staff members and eighteen students thirty weeks to obtain the solutions.[25] Nevertheless, the Analyzer found an eager audience of scientists and engineers frustrated by impossibly difficult calculations. For these, the not inconsiderable labors involved in work with the Analyzer were inconveniences to be born lightly.

Success prompted Bush to plan yet another analyzer, one more precise in its calculations, convenient to operate, and with a larger universe of mathematical possibilities. The opportunity to pursue his plan presented itself in the person of Warren Weaver, who in the autumn of 1931 had become the director of the Natural Sciences Division of the Rockefeller Foundation. Weaver

FIGURE

Schematic diagram of the Differential Analyzer set up to solve the Vallarta-Lemaitre cosmic ray problem. (Bush to Weaver, April 15, 1933, in the Rockefeller Archives, RF1.1/767D/2/20.)


T
x_2
x_1
$x_2 - x_1$
$\dot{x}_1$
$\int x_2/r_2^3 dT$
$(1+B)\int x_2/r_2^3 dT$
$\int (x_2 - x_1)/r_{12}^3 dT$
$A\int (x_2 - x_1)/r_{12}^3 dT$
$A\int x_1/r_1^3 dT$
$\int x_1/r_1^3 dT$
$B\int x_1/r_1^3 dT$
$\dot{x}_2$
T
y_2
y_1
$y_2 - y_1$
$\dot{y}_1$
$\int y_2/r_2^3 dT$
$(1+B)\int y_2/r_2^3 dT$
$\int (y_2 - y_1)/r_{12}^3 dT$
$A\int (y_2 - y_1)/r_{12}^3 dT$
$(A+B)\int y_1/r_1^3 dT$
$A\int y_1/r_1^3 dT$
$\int y_1/r_1^3 dT$
$B\int y_1/r_1^3 dT$
$\dot{y}_2$
$(x_2 - x_1)^2$
$(y_2 - y_1)^2$
$(z_2 - z_1)^2$
$B\int z_2/r_2^3 dT$
$\int z_2/r_2^3 dT$
$A\int z_1/r_1^3 dT$
$(A+B)\int z_1/r_1^3 dT$
$A\int (z_2 - z_1)/r_{12}^3 dT$
$\int (z_2 - z_1)/r_{12}^3 dT$
$(1+B)\int z_2/r_2^3 dT$
$\int z_1/r_1^3 dT$
$B\int z_1/r_1^3 dT$
$\dot{z}_1$
$\int 1/r_{12}^3 dT$
$\int 1/r_2^3 dT$
$\int 1/r_1^3 dT$
$1/r_1^3$
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had first heard of the Analyzer at a meeting in Paris with Sven Rosseland in 1932. Making plans for his new Institute of Theoretical Physics at the University of Oslo, Rosseland was interested in acquiring an analyzer with Rockefeller money to facilitate astrophysical calculations.[26] Weaver visited Bush in November to see the machine for himself, and he was "very much impressed." An applied mathematician, Weaver was undoubtedly intrigued by the Analyzer's practical applications, as well as Bush's claim that a machine only twice as big could solve the three-body problem.[27] He came away from this first meeting with the feeling that it was "a matter of first-rate scientific importance for the Foundation to aid in disseminating knowledge concerning this new and extremely effective scientific device."[28]

Always ready to seize the moment, Bush began an active campaign to persuade Weaver that the Analyzer project deserved large-scale support. "To dream in rather a definite way" was characteristic of Bush, and he made a point of keeping Weaver up-to-date on the progress of the three-body problem.[29] He shared as well his ideas concerning an improved computer, and reported that it was "going to become possible to produce something quite startling." Foremost was the possibility of enabling the Analyzer to switch rapidly from one problem to another in the manner of the automatic telephone exchange.[30] He also shared with Weaver the prospect of unwelcome competition. The interest of men like Hartree and Rosseland provoked Bush to write that "with all modesty, I think that this radical development should be in my own hands," and Foundation support would assure that.

"It is rather hard...to appreciate the extent of the struggle which is necessary to overcome even simple mechanical difficulties in a device of this sort."[31]

The Depression discouraged the Foundation from responding to Bush's overtures until the spring of 1935 when it awarded MIT a preliminary grant of $10,000 to complete their study of the improved Analyzer.[32] Within the year Bush reported that the new machine was easily in reach, and would incorporate three improvements: the automatic electrical interconnection of machine elements, increased precision in the working of the integrators, and a "function unit" designed to translate digitally coded mathematical functions into continuous electrical signals. The new machine seemed just over the horizon and he looked forward to the time when the Institute, as he wrote to Weaver, would "become a center of analysis of a certain important type, to which research workers everywhere will turn for their solutions of their equations."[33] In March 1936 the Foundation awarded MIT $85,000 for three years to build the Rockefeller Differential Analyzer.

The next few years were enthusiastic but frustrating. Bush's enthusiasm for invention was contagious, and the crew working on the new machine thoroughly enjoyed its work under him.[34] Yet his predictions proved overly optimistic. More precise integrators were developed with little difficulty, as were the servomechanisms needed to create the electrical connections between elements. But other problems with which the group had less experience proved more difficult. The function unit, as it turned out, was not complete even by the end of the war. The most frustrating problem involved automatic control. Intended to work on multiple problems simultaneously, the Analyzer needed to be able to assign computing elements to different problems quickly, efficiently, and automatically, even as one problem finished and another began. The matter introduced "extraordinarily complicated difficulties" into the design of the machine.[35] In essence the earlier devices had been dedicated machines, assembled anew each time an equation was to be solved. The automatic control of the new machine posed, in fact, a software problem and it is not surprising that Bush and his team should have found it unsettling. Moreover, Bush had been MIT's vice-president and dean of engineering since 1932 and his duties were attracting more of his energies. In Bush's absence responsibility for the project fell on the shoulders of Sam Caldwell. Still, the project was in good hands and Weaver felt that "things were going exceptionally well."[36] When Bush announced he would leave MIT to become president of the Carnegie Institution of Washington, the project was dealt a serious blow.

Before he left for Washington, however, he brought to fruition his plans for a center of analysis. Along with James Conant, Frank Jewett, and Irvin Stewart, Bush was a member of the National Research Council's Committee on Scientific Aids to Learning. In February, Bush had received from Stewart a letter suggesting the publication of a catalogue of important scientific instruments available to investigators. He informed Stewart of MIT's work on machine analysis, writing[37]

> There should be created in this country a center of mechanical analysis amply manned and equipped for such work, to turn out tables and solve actual problems for research workers everywhere. We have the ambition to create such a center.... To do this we will need support, but I can think of no place where support could be given to a program that would have more general benefit upon research programs in almost every branch of science throughout the country.

The Committee(which apparently received a portion of its funds from the Carnegie Corporation) submitted a proposal to the Corporation on Bush's behalf. His maneuvers were successful and in January, 1939 the Corporation awarded MIT $45,000 for two years to establish a Center of Analysis with Sam Caldwell as its director. The Center would house and coordinate the battery of computational devices developed at MIT over the years, with its centerpiece being the new Rockefeller Analyzer, undoubtedly the largest aid to learning the Committee ever supported. The Center was to provide assistance with problems of computation, and foster research into computational and analytical tools.[38]

With Bush gone and development plaguing the engineers, progress on the new calculator slowed. While the older Differential Analyzer carried the growing load of the Center's computations, Caldwell and his staff found the time to pursue other projects. In fact, by February 1941 work on a Rapid Arithmetical Computing Machine had come to occupy the major part of the Center's research.[39] Bush had initiated study of an arithmetical machine at the end of 1936 in conjunction with cryptographic work for the government. Unlike the analyzers, this device was meant to deal with large volumes of arithmetic calculations at high speed. The design of the computer included a keyboard for entering data, an input unit for inserting numbers at appropriate moments in the process of computation, a control unit to automatically coordinate machine operations, an output unit, a storage unit for holding numbers temporarily during computation, and the computing unit. Bush attacked the problem of the high-speed computing element first with the help of a grant from the National Cash Register Company. By the fall of 1939, Bush, Sam Caldwell, Mark Radford, and others had devised a number of high-speed devices including vacuum tube counting rings and a matrix switch which would utilize, in one of its forms, the magnetic properties of molybdenum or chrome permalloy.[40]

By the time the first demonstration of the Rockefeller Analyzer was held on December 13, 1941, the project was two and a half years behind schedule. Convinced that Caldwell's staff was being distracted by other work and facing the imminent cessation of outside financing for the Center, Karl Compton delivered an ultimatum: Make the Analyzer self-supporting by October or the Institute would suspend the project.[41] The President's concerns were undoubtedly aggravated by outside events. Six days before Caldwell's demonstration, the Japanese bombed Pearl Harbor.

When Caldwell returned to peace time work at the end of the war, he faced the challenge of revitalizing the Center's programs. Given the transformations wrought by the war at MIT, this proved an impossible task. In the first instance, the war accelerated a generational change in the Institute's staff. With both Caldwell and Hazen preoccupied with the affairs of the

National Defense Research Committee, supervision of the Center fell to Richard Taylor, the young assistant who had worked on the function unit and automatic control. When Caldwell tried to regain control after the war, he found that Taylor enjoyed running the Center and felt he ought to go on doing so.[42] These shifts in personal relationships were complemented by institutional changes. After the war, when Caldwell found his colleague Gordon Brown promoted "over his head," he began to doubt the extent of administrative support for the Center.[43] Be that as it may, Brown's success certainly had cause. He had served as the war time director of the Servomechanisms Laboratory established in 1940 as an outgrowth of a training program for naval fire control officers. By the war's end the Laboratory had a staff of almost a hundred and had developed considerable expertise in the field of fire control systems. Since these involved computing devices, the Lab inevitably encroached upon territory once occupied solely by the Center and the Differential Analyzer. The Servomechanisms Lab is only one example of the massive institutional adjustments provoked at MIT by the war's demand for mission-oriented research and the consequent influx of federal defense money.[44]

Nevertheless, Caldwell worked hard to reinvigorate the Center of Analysis. His strategy was to turn, once again, to the Rockefeller Foundation. Spurred on by developments in digital computing at the University of Pennsylvania and at the Institute for Advanced Study in Princeton, Caldwell created a plan designed to reassert MIT's leadership in the field of computing. Aware that the Center was no longer the sole repository of necessary skills, he proposed cooperation between the Center, the Mathematics Department, and the Research Laboratory of Electronics established at the end of the war with the dissolution of the Radiation Lab. The Center would be responsible for the design and construction of a new computer, the Research Lab for the basic electronic components, and the Math Department for the applied mathematics which was assuming greater importance in the design and construction of computers. In short order Rockefeller awarded Caldwell and the Institute $100,000 to study computer design and the possibilities of the new electronic machines.[45]

Within these revised plans for the Center, it is clear that Caldwell intended the Rockefeller Analyzer to play a continuing role. Indeed, in their 1945 account of the new machine he and Bush had promised a series of future publications detailing innovations for which the present issue had lacked space. But for Taylor, the Center and the science of computing had outgrown their dependence on mechanical analysis, despite Hazen's 1941 claim that the Analyzer marked the start of a new era in mechanized calculus. As Taylor ironically noted in a memorandum outlining the new program, one of the Analyzer's drawbacks reflected the sophisticated mathematics with which it dealt. Well-suited to differential equations, the Analyzer bumbled arithmetic. Furthermore, the mechanical inertia of its operating parts limited its speed and accuracy.[46]

As it turned out, Caldwell's cooperative program failed to materialize. The Research Laboratory had its hands full with contract work funded by the military, and the mathematician central to Caldwell's plan, Norbert Wiener, proved a reluctant and irascible partner.[47] For Warren Weaver, who appreciated the need for first-rate mathematical help if MIT was to compete with such high-powered teams as von Neumann, RCA, and the Institute for Advanced Study, the "time for mathematical thinking [was] fast slipping away."[48] Yet Caldwell's Center would probably have been in trouble in any event. No longer occupying a privileged position in the study of computing and with government support readily and generally available at other sites, the Center could make only a token contribution to the vigorous and competitive boom in post-war computing. Not only was it ill-prepared to compete with ENIAC and the Princeton IAS computer, but it faced a fatal challenge within MIT itself.

In the winter of 1944, the Institute and the Navy had agreed to develop an Airplane Stability and Control Analyzer to serve as a universal flight simulator for the design of military aircraft. The mission fell within the province of the Servomechanisms Lab, and Gordon Brown assigned the project to Jay Forrester, a young research assistant from Nebraska. The original plans called for a cockpit with flight controls, an engineering station, and computing equipment. Forrester had first intended to use an Analyzer as the computing element but soon realized, as had Taylor, that the mechanical principle of Bush's computer severely restricted its speed. The allure of computer building soon swept away the other elements of the plan, and Forrester and his team in the Servomechanisms Lab set out to develop a reliable, ultra-high-speed machine capable of operating in real-time. The funding provided by the Navy was generous. Whereas the Rockefeller Foundation had granted the Center of Analysis $100,000 for its computer study, in 1945/46 alone the Navy alloted Forrester $875,000. In 1949 Forrester was spending the Navy's money at the rate of $100,000 a month. By 1951 he had succeeded in constructing Whirlwind, the first real-time electronic digital computer.[49]

The Whirlwind project accentuated the inadequacies of the Center of Analysis and of the Differential Analyzer as significant influences in the study of computing. In the spring of 1946, only half-way through the Center's two-year study, Compton returned to the Foundation the $50,000 which the Institute had so far spent. The Whirlwind project, he said, was fulfilling the objectives of the Rockefeller grant with such "vigor" and on such a substantially larger scale, that the expenditure of Foundation money for the same purpose was not only unjustified but "foolish."[50]

* * *

How does one tell the story of a machine? On what categories should the analysis rest, within what interpretive framework should one search for the meaning of engineering artifacts? However the historian chooses to answer these questions, utility must certainly play a role. Bush's analyzers were successful, to a large extent, because they were able to alleviate computational frustrations within electrical engineering and in scientific fields where theoretical advances had outrun the stratagems of applied mathematicians. When faster machines based on a radically different technology became available after the war, in part as a consequence of new sources of funding, those who needed machine aids in computation could turn elsewhere. But there are other categories than utility, or, rather, broader sorts of utility than so far invoked in our account. Machines exist not only as tools, but also as symbols, as John Kasson has shown us in Amusing the Million and Civilizing the Machine. Bush's analyzers did indeed do more than simply compute **x** as a function of **t**.

Weaver was right when he reminded Caldwell that the Analyzer had "a very considerable educational value." In 1928 Bush had attempted to justify the considerable expense of the Product Integraph in the course of an article for the Tech Engineering News: the Integraph, he said, enabled its users to cope with difficult mathematical equations. But it also provided "the man who studies it a grasp of the innate meaning of the differential equation." For this man, "one part at least of formal mathematics will become a live thing."[51] Years later, Bush recounted an anecdote that made the same point. When the Army wanted to build their own analyzer at the Aberdeen Proving Ground, he loaned them a mechanic who had been hired as an inexperienced draftsman to help with the construction of the MIT calculator. The Army wanted to pay the man machinist's wages; Bush insisted he be hired as a consultant with appropriate pay.[52]

> I never consciously taught this man any part of the subject of differential equations; but in building that machine, managing it, he learned what differential equations were himself. He got to the point where when some professor was using the machine and got stuck...he could discuss the problem with the user and very often find out what was wrong. It was very interesting to discuss this subject with him because he had learned the calculus in mechanical terms - a strange approach, and yet he understood it. That is, he did not understand it in any formal sense, but he understood the fundamentals; he had it under his skin.

Studying the analyzers might help get the calculus under one's skin, but it taught something more as well. Continuing his justification of the Integraph for his Tech audience in 1928, Bush invoked virtues that echoed both his New England ancestry and turn of the century engineering:[53]

> Before a man can build with his hands a seaworthy boat he must patiently learn to saw to a line and plane to an accurate surface.... The study of engineering mathematics becomes soul-satisfying only when one begins to grasp the power that lies in the ability to think straight in the midst of complexity, and visualizes the relationship between such reasoning and that engineering accomplishment which is useful and admirable, seaworthy and a thing of beauty.

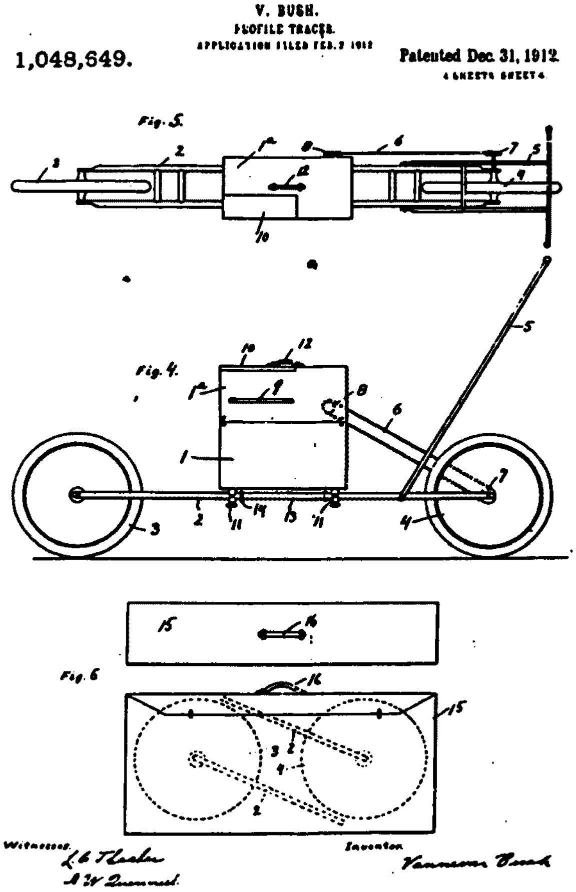
"To think straight in the midst of complexity." For young engineers coming of age in the glory years of Herbert Hoover, this was not the least of the lessons taught by the Differential Analyzer. Bush's expectations were not his alone. They were, in fact, constitutive of engineering culture.

The virtues associated with the analyzers - the idioms they constituted and the culture they reflected - had been crafted in the class rooms, laboratories, and shops of the engineering school. Especially in the matter of mathematical pedagogy and in notions of graphic language do we discover precedents for Bush's claims regarding his computers. Recall the conversation between Earle's English instructor and the engineering student that took place at Tufts just a few years before Bush's arrival as an undergraduate in 1909. The instructor was having difficulty explaining how the student's essay failed to capture any but the most superficial qualities of its subject when the drawing instructor, who was listening in, interrupted: "How about the dotted line?" The student, Earle tells us, saw the point at once.[54] Familiar with the use of dotted lines in mechanical drawings to depict features hidden from view, Earle's student was able to apply his knowledge of a more familiar language to one less familiar.

Composed in the studio of shop and laboratory, the works of engineering were indeed, as we have seen, appreciated as examples of language. The benefits of this approach had been promoted by Gardner Anthony through his notion of a Graphic Language that possessed its vocabulary, grammar, idioms, and transcriptive instruments; it possessed relevance for the practical mathematics touted by men like John Perry and E.H. Moore; and its moral potency was trumpeted by educators like Thomas French: strengthening the constructive imagination and fixing "the power and habit of exact thinking," it distinguished "the incapable man and the man of power."[55] When Bush claimed that the study of the Differential Analyzer, constructed from the material of the shop, laboratory, and drafting room, promoted the ability to think straight in the midst of complexity, he was echoing an established tradition.

If we find in the early engineering school, then, that repository of idioms that found expression in the Differential Analyzer, we can discover there as well the first edition, so to speak, of the text that Bush and his colleagues would revise more than once, before producing the most successful of their editions, the analyzer of 1931. During the course of his lectures on the Graphic Language, Anthony dwelt for a while on the vocabulary of topographical maps, illustrating for his students contour lines and profiles of elevation. It is in a setting such as this that the young Bush might have been introduced to the problems faced by surveyors and the instruments they had at their disposal. Profiles were commonly obtained by running levels, and required several men, careful fieldwork, and tedious data reduction afterwards. Bush set himself the task of mechanizing this job as an exercise for his master's thesis. His invention comprised an instrument box slung between bicycle wheels, and as it was pushed along the path for which one desired a profile, a device within the box continuously recorded the required elevation onto a revolving drum.

"It was quite a gadget," Bush admitted, and it earned him his degree. He patented the invention, which he called a Profile Tracer, and attempted to interest several companies in its manufacture. However, his entrepreneurial attempts flopped and he sagely charged the invention to experience. But if this first calculator failed in the commercial market, it had a happier future. What Bush had in fact invented was an arrangement of



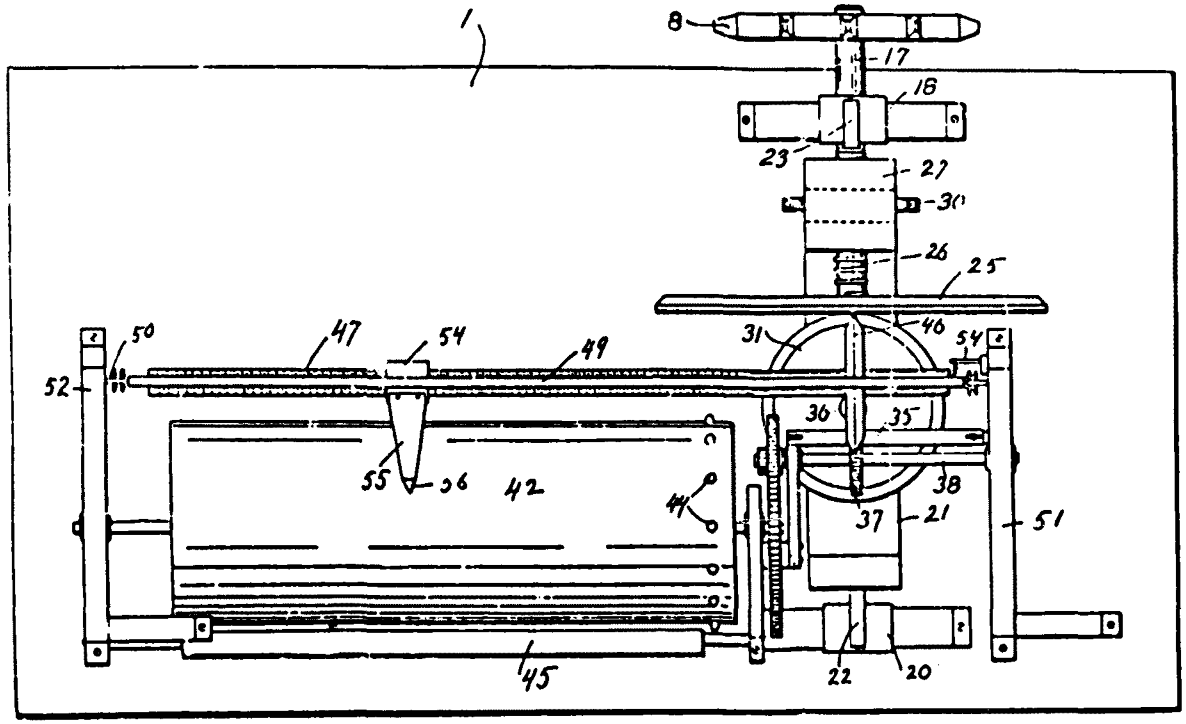
The Profile Tracer.
(from the patent application of 1912)

gears, shafts, and servo-driven pens which translated mechanical motion into graphical mathematics. And the key mechanism was a disc-integrator with which he would "have quite a lot to do."[56]

In 1919, after a year with General Electric and several more teaching at Tufts, Bush joined the staff of MIT's Department of Electrical Engineering. In many ways the Institute he joined was like the College he left. The curriculum stressed mechanical skill, work in shop and laboratory, and mathematics and physics couched in the graphic idiom. The calculus was introduced to freshmen in a manner which emphasized graphical presentation and intuition over abstract rigor. In Joseph Lipka's Mathematical Laboratory, students could hone their problem-solving talents with graphical methods and mechanical methods of various kinds - slide rules, planimeters, a plethora of nomographic charts, and instruments for the mechanical integration of areas under curves.[57] All in all, the program at MIT still carried about it "the odor of the shop," a description Calvin Woodward had once applied to early electrical engineering.[58]

But in other ways MIT was very different, and a variety of forces were converging to transform the environment and enlarge opportunities when Bush arrived. First, the decade between the Great War and the Depression was a bull market for engineering. Enrollment in the Electrical Engineering Department almost doubled in this period. Furthermore, the decade witnessed the rapid expansion of graduate programs, especially in electrical engineering, which had been insignificant before the war.[59] Second, as we have seen the development of electrical technology and the growing complexity of systems and circuits propelled the growth of circuit analysis and the aggressive search for methods of solution of mathematical equations beyond the scope of formal techniques. Third, the interwar years found corporate and philanthropic donors more willing to fund research and development within the university. All of these factors, as well as a diffuse public appreciation for the expert skills of the engineer which peaked in the twenties, worked to Bush's advantage at MIT. The Profile Tracer might have flopped in the commercial market, but within the bull market of the engineering school where inventions, in addition to being useful, could be read as books, Bush's mathematical practice-texts were a great success.

At this point our story becomes familiar. The technical success of the analyzers, the opportunities they provided for graduate research, the possibilities of new applications on the frontiers of science, and the availability of support from private foundations encouraged Bush to produce a bigger and better version of his popular 1931 computer. Ringed round by tantalizing problems in atomic structure and cosmic radiation, he and his colleagues labored to develop a new machine which would in a flash rearrange itself to tackle new and more difficult problems. But what is most significant about the Rockefeller Differential Analyzer is what remained the same. Electrically or not, automatically or not, the newest edition of Bush's analyzer still interpreted mathematics in terms of mechanical rotations,



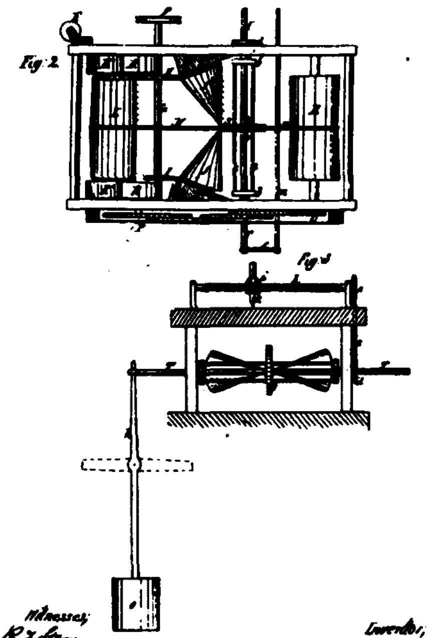
A detail drawing of the Profile Tracer drive mechanism from the patent application

No. 32,969.

PATENTED JULY 30, 1861.

O. H. BOGARDUS.
GRADE DELINEATOR.

2 SHEETS—SHEET 2.



Witnesses;

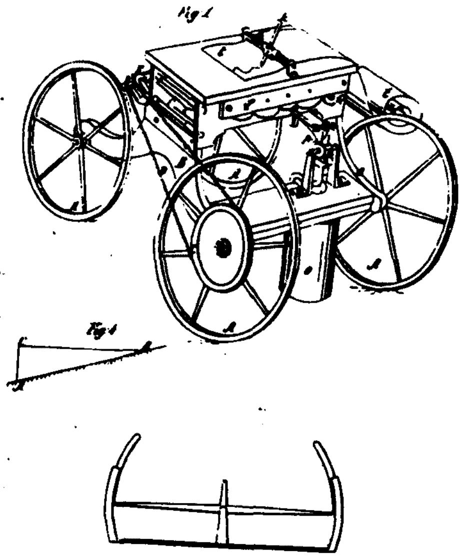
Inventor;
O. H. Bogardus

No. 32,969.

PATENTED JULY 30, 1861.

O. H. BOGARDUS.
GRADE DELINEATOR.

2 SHEETS—SHEET 1.



Witnesses;

Inventor;
O. H. Bogardus

Examples of the prior art from the Profile Tracer patent application still depended on expertly machined wheel-and-disc integrators, and still drew its answers as curves. Very much in the manner of the Profile Tracer, Bush's computers traced contours through the landscape of mathematics.

* * *

How does one tell the story of a machine? If nothing else, the evolution of the analyzers teaches us that there is more to machines than has met our eyes. Like all expensive investments, these machines were sensitive to the demands of utility, and when Weaver and Caldwell admitted in 1950 that the Analyzer project had been overtaken by the whole new field of computer science, they conceded that such demands could be decisive. But Bush's machines inhabited another world as well where utility had a distinctively bookish aspect. Here, in the market place of the school, the analyzers were exercises in the language of early twentieth century engineering. The student could find in these machine texts a catalogue of his technical universe, lessons on the nature of mathematics and its instruments, and even expressions of the ethos which pervaded engineering education. Variations on the theme of mechanical analysis, the analyzers embodied an engineering culture belonging to the first decades of our century. When engineers and their new corporate and federal supporters turned to the problems of computation at the end of the Second World War, they discovered the need for new texts in a more modern idiom, composed by a younger generation of inventive authors.

NOTES - CHAPTER SEVEN

Much of this chapter appeared previously in Technology and Culture 27(1) (1986): 63-95, with the title "Vannevar Bush and the Differential Analyzer: The Text and Context of an Early Computer."

1. The first demonstration of the still incomplete Analyzer was held on December 13, 1941. By March 1943, when the staff and facilities of the Center had been converted entirely to war work, about half of the Analyzer was in operation. S. H. Caldwell to Warren Weaver, December 14, 1941. The letter is in the Rockefeller Archive Center, in RF1.1/224/2/25. See also Caldwell to Bush, April 19, 1943, located in the Bush Papers, the Library of Congress.

2. The small band of digital pioneers would argue this claim. But ENIAC did not become operational until some months after the war, and while the Harvard-IBM Mark I was completed in mid-1944, both it and the Bell relay machine proved significantly slower than the Analyzer for the computation of trajectories. The development of digital computers, especially as logic machines, seems to have been further along in Great Britain largely due to Alan Turing. For their history, see H. H. Goldstine, The Computer From Pascal to Von Neumann (Princeton, 1972); Nancy Stern, From ENIAC to UNIVAC (Bedford, Mass., 1981); N. Metropolis, J. Howlett, and G. Rota, ed., A History of Computing in the Twentieth Century (New York, 1980); and Paul Ceruzzi, Reckoners: The Prehistory of the Digital Computer, From Relays to the Stored Program Concept, 1935-1945 (Greenwood, 1983). For Turing and his interest in computing machines as a response to the crisis in the foundations of mathematics, see William Aspray, From Mathematical Constructivity to Computer Science: Alan Turing, John von Neumann, and the Origins of Computer Science in Mathematical Logic; and Alan Hodges, Alan Turing: The Enigma (New York, 1983).

3. See Life (January 14, 1946); also, Popular Science Monthly 148 (1946).

4. For a valuable bibliography of analyzer literature, see the notes to Chapter 5 of E. C. Berkeley, Giant Brains, Or Machines That Think (New York, 1949).

5. MIT President's Reports for 1940, p. 101; and 1941, p. 28.

6. The Analyzer and machines of a similar type did not, of course, disappear overnight. The Rockefeller calculator was not dismantled until 1954(personal communication from Frank Verzuh, 6/4/82). Descendents of Bush's analyzers still constitute a modest weapon in the armory of engineers, as can be surmised by a glance at the current texts on library shelves.

7. See Warren Weaver's project diaries for March 17, 1950. The diaries Weaver kept as a Foundation officer are preserved at the Rockefeller Archive Center.

8. See Nancy Stern on ENIAC; for Whirlwind, see Kent Redmond and Thomas Smith, *Project Whirlwind, The History of a Pioneer Computer* (Bedford, Mass., 1980).

9. Weaver to Caldwell, March 27, 1950, in RF1.1/224/2/26.

10. The concern with such problems is obvious in the pages of the Journal of the American Institute of Electrical Engineers. In general, see Thomas Hughes, *Networks of Power* (Baltimore, 1983). In particular, see for example V. Bush and R. D. Booth, "Power System Transients," *Journal of the American Institute of Electrical Engineers* 44 (1925): 229-240.

11. See the MIT *President's Reports* for the period; also, Herbert R. Stewart, *A New Recording Product Integraph and Multiplier*, MIT Masters thesis, 1925; and Karl Wildes and Nilo Lindgren, *A Century in Electrical Engineering and Computer Science at MIT, 1882-1982* (Cambridge, 1985).

12. Stewart, *op. cit.*; John Carson, *A Mathematical Discussion of the Building-up of Sinusoidal Currents in Loaded Lines* (Bell Telephone Laboratories, 1925); C. P. Steinmetz, *Theory and Calculation of Transient Electric Phenomena and Oscillations* (New York, 1911).

13. During 1924-25, the development of the Product Integraph was the majority activity in the Research Division of the Electrical Engineering Department. For a description of the first Product Integraph, see V. Bush, F. D. Gage, and H. R. Stewart, "A Continuous Recording Integraph," *Journal of the Franklin Institute* 212 (1927): 63-84. My account of the origins of the Integraph is based on materials in the MIT Archives and on discussions with Karl Wildes, April 12 and 13, 1984. It might be that Stewart never closely studied the Thomson papers. When Bush first suggested the project, he directed Stewart to Fred Dellenbaugh's 1921 masters thesis as a fairly complete collection of "mechanical calculating contrivances which had been developed in the past," and in which he would have found a condensed description and diagrams of the Thomson integrator emphasizing its use in harmonic analysis, that is with equations of the form

$$\int f(x)g(x)dx.$$

[Stewart to Bush, May 4, 1926, Hazen Papers, MIT Archives; Frederick Dellenbaugh, *Harmonic Analysis, A Critical Compendium of Methods and Devices for the Analysis of Complex Alternating Current Waves with Suggestions for Improvements and Discussion of the Requirements of Such Devices*, MIT masters thesis, 1921.] E. C. Berkeley and L. Wainwright, in *Computers, Their Operation and*

Application (New York, 1956), claim that Wainwright invented a "virtual prototype of the differential analyzer" in 1923 and communicated it to Bush in 1924. They cite his response to a later query: "I have become quite familiar with the literature of this subject, and as far as I know you(Wainwright) were the first person after Kelvin to proceed in study along these lines and the first to suggest a machine elaborated in detail for the handling of ballistic equations," pp. 114-115. Obviously, the analyzers incorporated the work of many people. As will become clear, however, their deeper origins lie not with Wainwright, Kelvin, Bush´s colleagues, or even with Bush himself. They reflect a common universe of technical discourse that reaches back to the turn of the century and beyond.

14. V. Bush and K. Gould, "Temperature Distribution Along a Filament," Physical Review 29 (1927): 337-345.

15. Wildes, op.cit.; Gordon Brown, "Eloge: Harold Locke Hazen, 1901-1980," Annals of the History of Computing 3(1) (1981): 4-12; the sketch and Bush´s memo are in the Hazen Papers, MIT Archives.

16. V. Bush and H. L. Hazen, "Integraph Solution of Differential Equations," Journal of the Franklin Institute 204 (1927): 577.

17. For a list of topics, see note 6 in V. Bush, "The Differential Analyzer," Journal of the Franklin Institute 212 (1931): 447-488.

18. Wildes, op.cit.

19. Waldo Lyon, a departmental colleague, contributed the new name, apparently in response to the following: "We need some new names! The so-called product integraph was much more than an integraph. It was a machine for solving differential equations. ... In token of appreciation to one who suggests a name which is accepted, the following procedure is proposed: The new machine will be set up to solve a differential equation, and the recording pencil will in this manner be caused to draw on the recording platen the name of the successful contestant. this will be accompanied by all due and proper ceremony." MIT Archives, AC13, Box 3, Folder 69. Dugald Jackson informs us that the Differential Analyzer cost MIT approximately $25,000. Jackson to Jackson, Jr., March 17, 1932. Jackson Papers, MIT Archives, Box 3, Folder 185.

20. Brown, op.cit.; C. W. Nieman, "Torque Amplifier," American Machinist 66 (1927): 895-897.

21. Journal of the Franklin Institute 212 (1931): 459.

22. See the "List of Problems Studied with the Aid of the Differential Analyzer," attached to material sent by Bush to

Warren Weaver, April 22, 1935, RF1.1/224/2/22.

23. P. M. Morse and W. P. Allis, "The Effect of Exchange on the Scattering of Slow Electrons from Atoms," Physical Review 44 (1933): 269.

24. D. R. Hartree, "Approximate Wave Functions and Atomic Field for Mercury," Physical Review 46 (1934): 738-743; also the Hartree citations in the Berkeley bibliography(note 4).

25. See George Gray's draft, "A Roomful of Brains," returned by Caldwell to Weaver, December 17, 1937, in RF1.1/224/2/23. For the study, see Vallarta and Lemaitre, "On the Geomagnetic Analysis of Cosmic Radiation," Physical Review 49 (1936): 719-726.

26. "Memorandum of Professor L. R. Jones' talk with Professor Sven Rosseland, Paris, July 6, 1932," in RF1.1/767D/2/19.

27. Weaver's diaries, November 21, 1932.

28. Weaver to Lauder Jones, December 6, 1932, in RF1.1/767D/2/19.

29. Bush to Weaver, January 6, 1933, RF1.1/767D/2/20; the phrase is Bush's.

30. Bush to Weaver, April 15, 1933, in RF1.1/767D/2/20.

31. Bush to Weaver, July 7, 1933, in RF1.1/224/2/22.

32. See the grant history in the Rockefeller files on the MIT Differential Analyzer Project.

33. Bush to Weaver, March 17, 1936, in RF1.1/224/2/23.

34. "To V. Bush, GREETINGS! 'To Doc' would perhaps be a better salutation for this note of farewell and Godspeed, for among ourselves we have always called Doc as the title most appropriately expressing the affection and respect we have felt in working with you.

We would not have you leave without saying that it has been fun to build a Differential Analyzer with you. We think that you will agree that it has been fun, but we are not going to ask you to agree with some other feelings of ours, for of those we are better judges than you. We know, for example, the many ways in which we have felt your influence: in your generous praise for our successes, in your sympathetic analyses of our failures, in the enlivening breezes you have brought to our develo;mental doldrums.... The Differential Analyzer Staff." In RF1.1/224/2.

35. Weaver diaries, January 10, 1939.

36. Ibid.

37. Bush to Stewart, February 28, 1938, in the file on the "Support of a Center of Analysis at MIT" in the records of the Carnegie Corporation of New York.

38. Bush to Stewart, June 13, 1938; Stewart to Frederick Keppel, July 15, 1938, both in the Carnegie Corporation files.

39. Samuel Caldwell, "Report on Center of Analysis, July 1, 1939 - February 1, 1941," in the Carnegie Corporation files.

40. W. H. Radford, "Research on A RAPID COMPUTING MACHINE," October 1939; copy from Perry Crawford, May 1982. Bush informed Weaver in October, 1938 that equipment for carrying out arithmetical calculations at "almost unbelievably high rates" had already been constructed by the government and by the National Cash Register Company. Weaver diaries, October 28, 1938.

41. Weaver diaries, March 12, 1942; Caldwell to Weaver, March 13, 1942; Karl Compton to Weaver, March 14, 1942. In the event MIT, encouraged by Weaver's offer of another $25,000, did not terminate the project. The letters are in RF1.1/224/2.

42. Weaver's diaries, April 11, 1946.

43. Ibid.

44. John Burchard, Q.E.D., MIT in World War Two; Kent Redmond and Thomas Smith, Project Whirlwind, The History of a Pioneer Computer (New York, 1948).

45. Excerpt, Caldwell to Weaver, January 16, 1946; grant history, both in RF1.1/224/4/31.

46. Richard Taylor, "Memorandum, Electronic Calculating Machine, 4/9/46," in RF1.1/224/4/31.

47. "Division 14, NDRC, MIT Research Laboratory in Electronics: Interim Progress Report, 3/15/46," in RF1.1/224/4/31; Weaver to Hazen, March 4, 1947; Hazen to Weaver, March 12, 1947; both in RF1.1/ 224/4/32.

48. Weaver to Hazen, March 4, 1947, in RF1.1/224/4/32.

49. Redmond and Smith, op.cit.

50. Compton to Weaver, June 26, 1947, in RF1.1/224/4/32.

51. V. Bush, "Mechanical Solutions of Engineering Problems," Tech Engineering News 9 (1928).

52. V. Bush, Pieces of the Action (New York, 1970): 262.

53. Bush, "Mechanical Solution."

54. Samuel Earle, "English in the Engineering School at Tufts College," Proceedings of the Society for the Promotion of Engineering Education 19 (1911): 44.

55. Thomas French, "The Educational Side of Engineering Drawing," ibid. 21 (1913).

56. Bush, Pieces of the Action, pp. 155-157; see Bush's masters thesis, "An automatic instrument for recording terrestrial profiles," Tufts College, January 1913. Bush might not have known of the disc integrator when he devised the Profile Tracer. However, variable friction gears much like the one he designed for the Profile Tracer were well known to engineers. See, for example, the illustration of the deal-frame in Knight's American Mechanical Dictionary, Volume One, 1876.

57. L. M. Passano, Calculus and Graphs (New York, 1921); Joseph Lipka, Graphical and Mechanical Computation (New York, 1918).

58. C. M. Woodward, "Report of the Committee on Technological Education - The Relation of Technical to Liberal Education," in Addresses and Proceedings of the National Educational Association (1894): 613.

59. See the MIT President's Reports for the period.

CHAPTER EIGHT:

ENGINEERING AND THE FRONTIERS OF INVENTION: THE WHITE CITY(III)

In 1939, as Depression was shading into war, Vannevar Bush was called to testify before the famous Monopoly Committee. Bush, an engineer, onetime MIT administrator, and recently selected president of the Carnegie Institution of Washington, provoked exchanges that offer a glimpse of the forces remaking the political economy of the twentieth century. His testimony reveals, as well, the cultural symbolism through which an important figure sought to understand and control those forces. Bush was fated to wield enormous influence during the period of the Second World War, when he presided in ironic fashion over a consolidation of science and federal power that deeply worried him in an earlier decade. But at the moment of the hearings, it was Bush the inventor speaking, a man who began and ended his career in the workshop, who took his stand on the frontier of invention and found in the moral autonomy of expertise a solid foundation on which to build the modern social order.

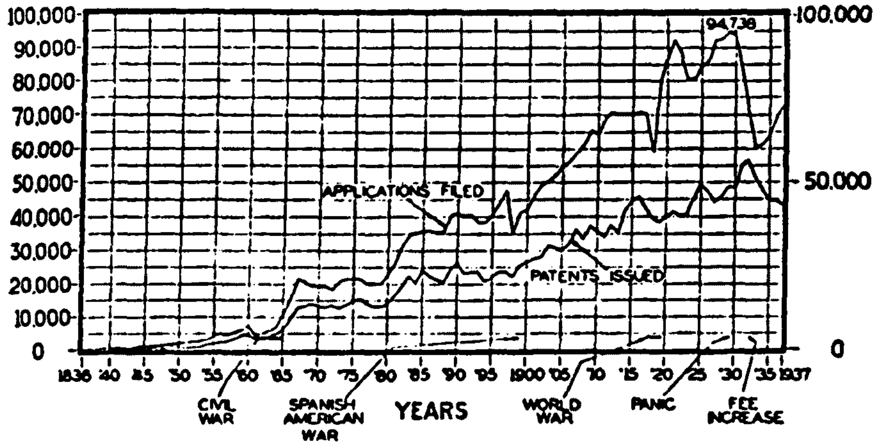
* * *

During the thirties, the corporate utopia of Perkins and Broderick foundered on the rocky shoals of Depression. After a number of unsuccessful attempts to rehabilitate the nation's economy, the Roosevelt administration convened in the summer of 1938 the Temporary National Economic Committee to study the country's ills. Over the next months, the Monopoly Committee as it came to be known, investigated a variety of industries and heard from a large number of witnesses including corporate executives, directors of research laboratories, and, not least, inventors.[1] In fact, it turned its attention first to the problem of the patent system. It wasn't surprising that it did so, for patents are a function of invention and it was acknowledged that modern industry rested on invention. In addressing the patent question, the committee opened up a number of issues that proved to be central to its study - among them the corporate abuse of the patent system, fears about the declining importance of the individual in the modern economy, and the role of the expert in a democratic society.

The first witness was Conway Coe, Commissioner of Patents since 1934.[2] Coe reviewed the history of the system, reminded the committee of its origin in the constitutional grant of power to Congress "to promote the progress of science and useful arts by securing for limited times to authors and inventors the exclusive right to their respective writings and discoveries," and emphasized its contribution to the nation's progress. The cotton gin, reaper, tractor, telegraph, celluloid, and bakelite, were only a few of the innovations dependent on patent protection for their successful introduction into American markets. All was not well, however, and Coe struck a worried note that would reverberate throughout the hearings. In the previous century, the annual number of patent applications received by his Office had risen from a small number in the years before the Civil War to almost 90,000; by 1937, the Office had granted over two million patents. Such numbers caused Coe to wonder aloud, "What manner of men are our inventors?"; "What becomes of their inventions?" Coe turned to his charts to make his point. Plots correlating patents to population suggested that the inventiveness of the people had peaked in the 1870s and had subsequently leveled off or even declined. Where, then, were the large numbers of patents going? Other charts revealed the answer. As late as 1921, 72% of patents awarded went to individuals; by 1938, the majority were going to corporations.

In part the change was due to the growing importance of industrial research, in part to weaknesses in the patent system itself - some legal, some administrative - which allowed, Coe believed, well-heeled corporations to dominate the machinery to the disadvantage of the independent inventor and the small businesses to which he gave rise. Coe's statistics corroborated widespread convictions that the American people were in the midst of an inventive, as well as an economic, crisis and that the blame lay at the door of the corporation. "My conviction is that

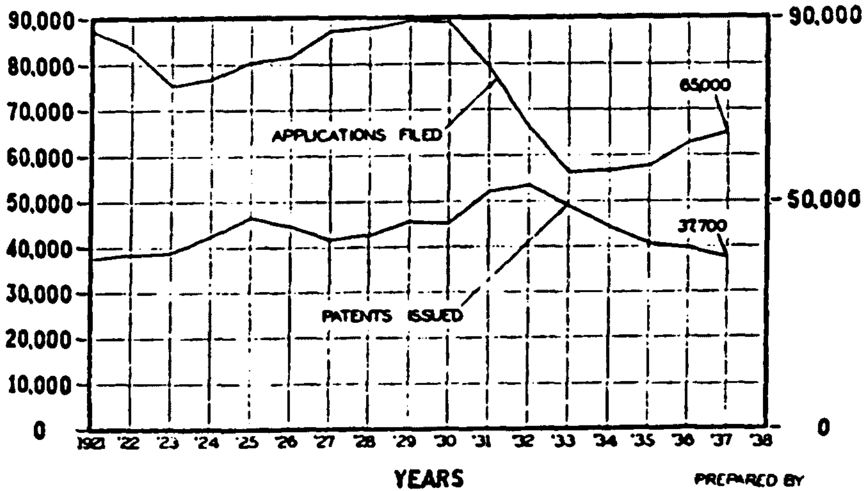
Exhibit No. 179



APPLICATIONS AND PATENTS
INCLUDING DESIGNS AND REISSUES
1836 TO 1937

PREPARED BY
U.S. PATENT OFFICE

Exhibit No. 180



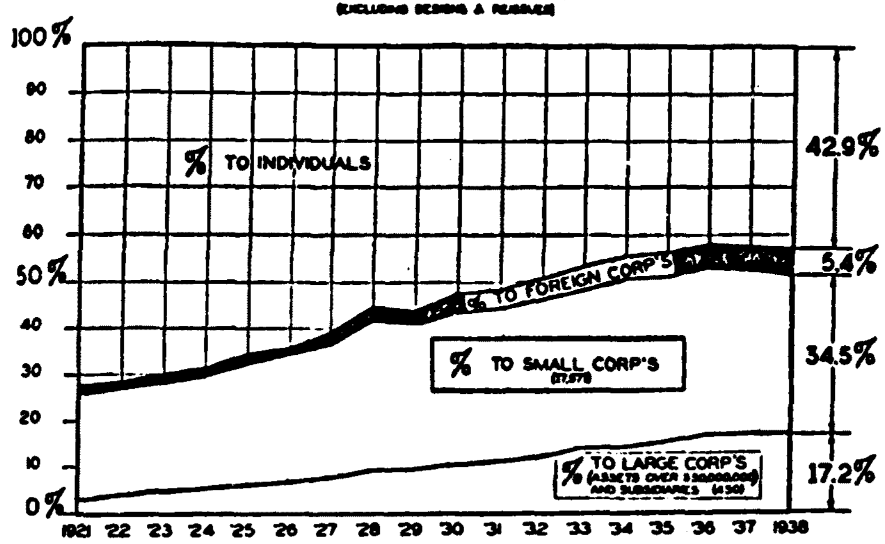
APPLICATIONS AND PATENTS
1921 TO 1938
(EXCLUDING DESIGNS & REISSUES)

PREPARED BY
U.S. PATENT OFFICE

(From Coe's testimony before the Monopoly Committee)

Exhibit No. 187

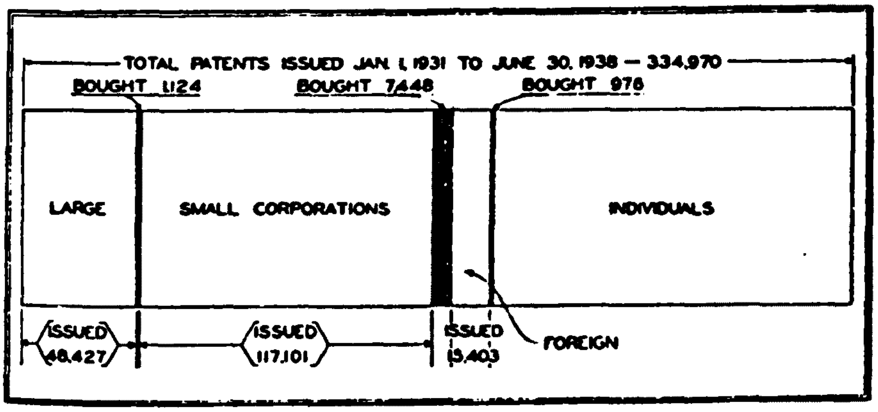
DISTRIBUTION OF PATENTS AS ISSUED
(EXCLUDING DESIGNS & REISSUES)



PREPARED BY
U.S. PATENT OFFICE

Exhibit No. 188

PATENTS ACQUIRED BY CORPORATIONS



PREPARED BY
U. S. PATENT OFFICE

the poor inventor, and through him the public, suffer injustice precisely for the reason and to the extent that the monopoly...purportedly bestowed on him is not now fully safeguarded. ...Genuine protection in that form would be the last surviving bulwark standing between the inventor and the onslaught of mighty corporations."[3]

Coe's worries about American inventiveness were shared by many. As early as 1922, the economists Ogburn and Thomas had posed a series of questions that sought to clarify the causal forces behind the making of important inventions. "Are inventions inevitable? If the various inventors had died in infancy, would not the inventions have been made and cultural progress gone on without much delay? Are inventions independent of mental ability? Is not the determinism in inventions a matter of cultural preparation?" Remarking on the frequent occurrence of simultaneous discoveries in a survey stretching back several centuries, they concluded that the cultural environment was the essential factor in evoking inventions at any particular period in history.[4] More recently, the sociologist and marine historian S.G. Gilfillan had reached even more radical conclusions. Discovery was a function of culture and the individual inventor merely the instrument of his times, the tool of large social forces that, in both occurrence and conception, shaped the progress of invention. "The popular belief in individual, single, great inventors for things has been grotesquely developed by the same process as that which built all the classic mythologies to account for the origins of this and that...." With a fine insight into the corporate mind, Gilfillan observed that this "mythology of heroes" well served the need of corporate groups for symbols and cults promoting common identity and company loyalty. It was also a valuable financial asset. "The American popular belief that McCormick invented the reaper may be worth millions to the International Harvester Co., the fame of Bell certainly is to the telephone company, Fulton is the hero of the Hudson River Day Line, Edison and Marconi of various companies, and the Wright Brothers of the Wright Aero Corporation, while the rival Curtiss interests set dead Langley on an airplane, like the Cid on his horse again, to fight their battle."[5]

Underneath the grotesquerie of the American mythology of inventor-heroes, Gilfillan perceived a fundamental distortion: "...<u>by attempting to make make private property of a set of ideas</u>(an invention), a thing inherently most difficult to define, name the author of, and protect, we call forth multifarious and prodigal struggles over the ownership of ideas...." And it was naive to invoke the rights of the inventor. "For natural rights have no existence, according to the Philosophy and Sociology of today. They are a figment of 18th-century imagination, embalmed in our sacred Declaration of Independence." If inventions could not be conceived as property, neither, it seems, should they be naively reified. In the most fascinating section of what is, by all rights, a fascinating book, Gilfillan attempted to demonstrate that even the recognition of discovery and invention was a function of language and rested on the ability to frame definitions.[6]

Since the social consequences of invention were too important to be left to the vagaries of the free market, Gilfillan proposed that the ownership of patents be invested in those groups most immediately concerned - the trade associations. With the sanction of the federal government, the trade associations could manage invention, freely dispensing patent rights and rewarding inventors in order to encourage those devices most socially desirable.[7]

Coe's criticisms of the patent system were comparatively tame and his recommendations for reform much less radical. Despite the inequities that had crept in over the years, Coe felt that the system was fundamentally sound. He recommended a number of changes in the machinery of the patent process designed to restore the balance between small inventors and businesses and the large corporation. He further suggested that the jurisdictional chaos that complicated the appeals process and lent itself to the larger resources of corporations could be rectified by the establishment of a single court of patent appeals. In any case, he warned, it would be a mistake to judge the patent system solely in economic terms, for it possessed a significance as much spiritual as economic. Indeed the system had developed in the people "a creative faculty that has served other ends than the evolvement of things purely mechanical. That faculty, I believe, has proved signally useful in solving some of the great problems that have arisen in our task of preserving and perpetuating our democratic form of government."[8]

The committee turned next to Vannevar Bush. Bush was an appropriate witness, for by 1939 he had acquired a worldwide reputation as a mathematically-minded electrical engineer who had presided over the development of a generation of pioneering calculators. He was a respected industrial consultant and a hard-nosed administrator, onetime vice president and dean of engineering at MIT and the recently chosen president of the Carnegie Institution. Moreover, he was a talented inventor who had earned his spurs in the boom-and-bust decade of the twenties, had been the chief architect of MIT's patent policy, and was the author of an important study of the patent system conducted by the Science Advisory Board at the request of the Department of Commerce. These earlier experiences, considered in the light of Coe's caution that the patent system be judged in more than narrow economic terms, will help make sense of the inventive issues that troubled Commissioner Coe, Bush, and the Monopoly Committeemen in 1939.

* * *

In 1916, with his doctorate in electrical engineering fresh in hand, Bush considered going to work for Western Electric.[9] At Tufts, however, he had deeply impressed his teachers as a promising mathematical physicist and they succeeded in luring him back as an assistant professor and heir apparent of the soon-to-retire head of the electrical engineering department. The position left Bush time to consult at a newly-established radio company on the edge of the Tufts campus - the American Radio and Research Corporation; it was there that he became familiar with the highly-competitive and always precarious world of the small, innovative, science-based firms which were quickening industrial life in the years after the world war.

Amrad was the brainchild of Harold Power, a Tufts student and president of its Wireless Society who, like many other scientifically inclined young men of the time, had cultivated an early interest in radio. At the age of fourteen he had worked as a wireless operator on steamers that plied the New York-Boston route. Summers at Tufts were similarly spent with John Jacob Astor and, after graduation in 1914, with J. P. Morgan on his yacht Corsair. Power convinced Morgan to finance a new radio company headquartered in a small, two-story, stucco building with a machine shop in the basement, experimental labs above, and a three-hundred foot radio tower outside, and in this hillside workshop, Power began to manufacture radios and other electrical equipment.[10]

Amrad spent some months fiddling with the design of transmitters and experimenting with broadcasting. The company's business began to boom when the Signal Corps placed an order for eight "cart sets," portable transmitter/receivers mounted on gun carriages. When the United States entered the war in 1917, Amrad found its hands full. With a work force that had grown to some seventy-five and a large new Morgan-financed addition to cope with government orders, Amrad began to turn out "motor boat" and "battleship" sets for the Navy, and "trench transmitters" for the Signal Corps. Buoyed by continuing military contracts and the opening up of a new market for ham radio equipment, the company survived a postwar slump, doubled its work force, and moved into a new manufacturing plant in 1921.[11]

While Power concentrated on moving the company into the peacetime market for civilian radio, Bush, as head of the company's small research laboratory, was busy exploring the behavior of electrons. In 1919, Bush hired a young Ph.D. graduate from Harvard by the name of C. G. Smith who had studied the spectral behavior of ionized helium with Theodore Lyman. Over the next several years, Smith, with help from Bush, developed a series of radio tubes that rectified alternating to direct current, permitting transmitters to operate off line current. The "S-tube" proved a boon for amateur radio enthusiasts by replacing the bulky and expensive batteries or gasoline generators previously necessary.[12]

While Smith and Bush were improving the S-tube, Power proceeded to go broke. In the decade following the war, the radio field was highly volatile, intensely competitive, and not a little cutthroat, with numerous companies large and small struggling to occupy space in market which had opened out beyond its original specialized and military applications to include the fields of broadcasting and amateur radio.[13] While Amrad possessed a valuable resource in its laboratory and in the inventive talents of Bush and Smith, Power failed to play to his strength. ("[He] did not know much about business management; there was no reason to expect he would. More unfortunately, he thought he did."[14]) Relying heavily on designs evolved during the war, Power proved unable to keep up with the rapidly improving technology of radio circuitry, and when he tried, he found his way blocked by competing patents. After his military contracts dried up in 1925, Morgan sold the company to Powell Crosley who kept it going until the Depression forced it to close in 1930.[15]

Bush had long since abandoned ship. Al Spencer, the mechanic who headed Amrad's model shop, had created, on his own time, a concave, bimetallic disk that snapped when it was heated. Bush realized that Spencer's device constituted a reliable, quick-acting thermostat for home appliances like electric irons. In 1921, he and Spencer, along with Laurence K. Marshall, an aggressive young entrepreneur who had roomed with Bush at Tufts, joined a group of Boston businessmen and established the Spencer Thermostat Company. Eventually, the device was licensed to Westinghouse who succeeded in marketing Spencer's invention as the "Million Dollar Thermostat."[16]

But Bush had other irons in the fire as well. At one point, Smith invented a refrigerator that Marshall felt would sell. It didn't, but did provide an excuse for Bush and Marshall to establish the American Appliance Company in the summer of 1922, backed by the same Boston businessmen who had financed Spencer Thermostat. When the refrigerator design eventually proved unworkable, Bush's thoughts turned to the radio tubes he and

Smith had worked on at Amrad. Marshall was intrigued, and in late 1924, convinced J.P. Morgan, who owned the patents and probably felt by then that Amrad was a losing proposition, to sell the S-tube patents to American Appliance for $50,000 - $10,000 in cash, and $40,000 in company stock.[17]

Amateur radio and the armed forces offered limited markets for radio equipment, but with the unexpected and dramatic growth of public broadcasting after the war, the market boomed. Despite the fact that GE, Westinghouse, AT&T, and RCA had cornered key radio patents through a series of cross-licensing agreements, small, independent companies blossomed and grew overnight, to some 200 receiver makers in 1922 and some eighty independent tube-makers by 1925. "It has been suggested some of these operations were on such a small scale that in the event of threatened legal action the operators could move the entire plant under the cover of darkness and set it up elsewhere under a new name by the following day!" Cutthroat competition and RCA's dominance shrank their number to fifteen by 1930 and even further during the decade of the Depression.[18]

Raytheon - the name American Appliance adopted in 1925 - was an independent that survived. It did so by utilizing the managerial talents of Marshall and the inventive abilities of its small laboratory to exploit a modest corner of the market - the production of custom-designed power packs employing the S-tube (technically a gaseous conduction rather than a vacuum tube and therefore unaffected by many of the patents owned by the dominant corporations). Even so, the company's position was precarious.

When Westinghouse decided to market a product that infringed the S-tube, Bush confronted Charles Neave, the company's patent attorney. As Bush remembered it, "the encounter was a bit dramatic. He showed me a Westinghouse tube. The glass was coated so that one could not see inside, but he told me Westinghouse did not use the short path idea and hence did not infringe. I said, "Crack it." He looked at me a moment and then cracked the tube open over the edge of his wastebasket; and here was the short path clearly used. So he smiled and said he would advise the Westinghouse Company to keep off the grass."[19] Bush concluded that Neave was an honorable man, for Westinghouse might well have drawn Raytheon into an exhausting legal battle, whatever the legitimacy of its patent rights. He added, it should be noted, that juries were in the habit of awarding generous settlements to small companies thwarted by large ones.

Once more, however, Raytheon found itself set upon by the radio "club." In an attempt to consolidate their control of the market, RCA declared that manufacturers of radios who didn't buy all their tubes from the club couldn't get any. Raytheon quickly found orders for its tubes cancelled. In retaliation, the company "started making thermionic tubes, infringing every patent in sight, and selling them on the black market, Since it paid no royalties, it did not do badly. Of course it was sued in return, but, matters being a bit complicated, no cease and desist order issued from the court." Eventually, threatened by public opinion and possible antitrust action by the Federal Trade Commission, RCA softened its position. In 1929, Raytheon and RCA reached an out-of-court settlement. Raytheon allowed RCA to use the S-tube patents and others it might develop while Raytheon could manufacture tubes whose patents were owned by the club.[20]

Amrad and Raytheon provided Bush experience in the risky world of the small, science-based firm where imaginative research and development and entrepreneurial grit, bolstered by the protection of the patents system, were crucial to survival. Later, as an administrator, he coped with the challenge of devising patent policy for MIT.

In 1920, as part of a campaign to woo the support of industry, MIT established the Division of Industrial Cooperation and Research. Touted as the symbol of a new age of academic and industrial cooperation in the support of applied science and industrial progress, the Division's mission was to cultivate the Institute's industrially-sponsored research as well as to manage the new program known as the Technology Plan. Under the terms of the Plan, participating companies would be entitled, for a standard fee, to information on the employment qualifications of its graduates as well as consulting on matters of research. For an added fee, the Institute would contract to do research itself.[21]

Despite the initial hoopla, however, the history of the Institute's industrial relations over the next fifteen years was troubled.[22] Corporate sponsors were frustrated by the Institute's dislike for narrowly-focussed projects with promise of immediate, practical applications. Independent consultants objected to fees which undercut standard rates. And the Institute's associations with particular companies exacerbated industrial rivalries. On the other hand, to many at the Institute, the Plan threatened to transform the Institute into an industrial consulting lab and endangered the independence and quality of its research activities. While the Plan had gathered some four million dollars in contracts for its first five-year period, contracts dropped to about $250,000 in the second five years, and to $30,000 in the third period.[23] After a decade during which the Institute had vigorously promoted cooperative research and consulting, the appointment of the Princeton physicist, Karl Compton, signaled a revaluation of its ties to industry.

For the proliferation of outside arrangements did indeed, in the eyes of the new president, threaten the Institute's mission to promote technological advance from a strong base of fundamental science. It injected "a strong financial or economic element into the choice of a line of activity," when selection should depend solely on its intrinsic scientific worth. It created an invidious financial distinction between those on the staff who consulted and those who didn't. It tended to inhibit more fragile academic work, reduced the responsibility on the part of the administration to maintain adequate salaries, and undercut the fees charged by commercial consulting firms. An overemphasis on industrial work, especially of the confidential commercial variety, was "a real danger to be guarded against." At a time when professors earning annual salaries of $5000 were being tempted by offers from industry of seven times as much, Compton´s efforts to place his house in order were far from easy.[24]

In 1932, Bush was made MIT´s first vice-president and dean of engineering and, over the next several years, he acted as President Compton´s strong right arm in efforts to reorganize the Institute´s industrial relations. They formed the Division of Industrial Cooperation and Research, strengthened the authority of deans and department heads to oversee outside consulting, and formulated a personnel policy which emphasized loyalty to the Institute. Under the new plan, intended to discourage, as Compton put it, low-grade consulting of the "pot-boiling type," fifty percent of outside fees would be collected by the bursar to form a "Professor´s Fund" while base salaries would be raised in compensation.[25] In addition, they formulated an Institute patent policy.

Before 1930, few schools worried about patent policy, an attitude of benign neglect encouraged by the general belief among academics that concern with such matters was inappropriately commercial and might endanger non-profit, tax-free privileges. Such reluctance was overcome both by the growing need for industrial research and by the financial benefits contributed by successful patents to schools strapped for funds during the Depression.[26] Neither Bush nor Compton objected to their staff consulting with industry or profiting from inventive activities. Indeed, MIT´s influence as the country´s primary school of technology rested firmly on such abilities. They did, however, object when proliferating and unmanaged arrangements threatened the school's primary commitment to education and research. MIT's patent policy was devised by Bush and Compton to ensure the harmony of private and institutional ends.

The policy was relatively straightforward. Inventions made by staff members in the course of Institute research belonged to the Institute. Inventions to which the Institute contributed neither funds nor facilities belonged to the individual or, in the case of consulting research, to the contracting firm. Cases in doubt were decided by the Patent Committee chaired by Bush.[27] The real problem, as it turned out, was what to do with the patents once acquired. There were a number of precedents to guide the MIT administrators in deciding this matter. In 1921, the University of Toronto established a special university committee to manage the Insulin patent which brought in $500,000 in 1924 alone. The University of Wisconsin chose a different mechanism to oversee its Vitamin D patents. In 1925, the University assigned its rights to the Wisconsin Alumni Research Foundation, a non-profit organization founded by alumni and concerned with ensuring quality control in the manufacture and distribution of the vitamin.[28] Both arrangements had their difficulties, attributable, in part, to the demands placed on the university to act the part of a commercial enterprise. MIT chose a third alternative - the Research Corporation.

In 1905, while a physical chemist on the faculty of the University of California, Frederick Cottrell invented a method for the electrostatic precipitation of particulate matter from industrial flue gases. Cottrell established a successful business based on his invention, and when the University refused his offer to assign them his patent, formed the Research Corporation in 1912. Organized as a non-profit corporation, it had two aims: to commercialize Cottrell's precipitation patents and to devote profits from these and other patents it might acquire to the support of scientific research. Cottrell's company seemed tailored to the Institute's needs. Worried that managing its own patents would commercialize its educational mission, alienate its friends in the business community who possessed competing interests, endanger its tax-exempt status, and overburden the administration, the Institute decided to employ the Corporation to handle its patents.[29] In this way, the Institute was able to reap the benefits of staff inventiveness while remaining somewhat insulated from their commercial exploitation. It was an arrangement that would bring MIT into conflict with federal authority over the question of the public good.

"It is the business of government," as Hoover put it in 1924, "to provide an open road for the exercise of the individual initiative of its citizens, not to substitute its own activities for that initiative; to see that free opportunity is given for the economic production of wealth, not to produce wealth itself." While the dramatic growth of industries like the electrical utilities impinged on the public interest and demanded state involvement, it was nevertheless the part of government "to regulate and control, not to manage or operate." "In the transformation in the whole super-organization of our economic life, we are passing from a period of extreme individualistic action into a period of associational activities." And in this growth of enlightened associationalism, the professional engineer played a key role.[30] The establishment of the Tennessee Valley Authority in 1933 dealt a dramatic blow to these conservative notions of political economy.

The TVA was rooted in the New Deal perception that business had failed to police its own house and, indeed, lacked the will to do so. As David Lilienthal, the TVA's director and general counsel, put it to a Philadelphia audience, America's industrial prowess was due to the pioneers who constructed the railroads, erected the factories, and electrified the country. The rise of the corporation, however, overwhelmed the free play of the market, and pioneers turned into bureaucrats. "[And] bureaucracy is much the same wherever you find it. Log-rolling, mutual back-scratching and nepotism are common manifestations in the administration of large business under the new regime. In the hands of business bureaucrats industry grew complacent and fearful of innovations.... Industry had an opportunity to lead in bringing order out of chaos in which the depression plunged us, but it refused to seize its opportunity, or even to recognize it."[31] Mandated to develop and manage the commercial resources of the Tennessee Valley, the TVA represented a significant federal intrusion into the marketplace, one that would stimulate local industry, so its proponents hoped, and provide a yardstick with which to measure the "fairness" of private utilities .

Part of the Authority's mission hinged on the production and transmission of electrical power. And here MIT spied an opportunity to contribute to the technology of this innovative enterprise while earning for itself Depression-scarce funds for the conduct of research. Although alternating-current technology had made long-distance transmission possible some half-century earlier, technical problems limited the distance over which electricity could be transmitted to some three hundred miles. The solution to this limitation appeared to lie in the use of high-voltage direct current. In the summer of 1933, Compton proposed to Morgan that MIT and the TVA cooperate in developing a new system of power transmission utilizing the very high voltage direct current made possible by the recent invention of Van de Graaff's electrostatic generator.[32] Van de Graaff had followed Compton from Princeton's Physics Department to MIT, and had established there a vigorous and financially hungry research program in high-voltage physics. With $250,000 from the TVA, MIT would design the system and build a trial installation.[33]

Within a matter of weeks, Dugald Jackson, the chairman of MIT's Electrical Engineering Department, had shifted project planning into high gear - there would be a supervisory board (including Jackson, Van de Graaff, Edward Bowles, Compton, and Bush as chairman), project supervisor, assistant superintendent, a secretary in charge of accounting and patent affairs, and research divisions concerned with vacuum chambers and conduits, generators and motors, conductors, switches, cables, operating characteristics, and construction estimates. Both sides were enthusiastic about the cooperative project, yet despite almost striking a deal in September negotiations proved difficult and protracted. Finally, a year and a half later, Arthur Morgan, the TVA's chairman, backed out.[34]

In part what seemed simple in principle, proved difficult in practice. The DC current technology was untested and raised serious questions among the MIT staff.[35] As Compton put it to a benefactor unconnected with the power project, "Although we have been unable to discover any flaw in these ideas, they are so revolutionary that the chances are probably against their success. Yet the stakes are very high, and the work will be well worth doing even if it is only partly successful."[36] Furthermore, the negotiations necessary to launch the project were complex, involving a federal agency, a private university, and an independent firm, the Research Corporation, whose job was to commercialize patents. And it was the issue of patents and their proper disposition that proved the fatal snag.

Things began well enough. In only a few weeks, Compton had drafted a press release. Yet already there were hints of uneasiness among the TVA negotiators. Concerned that the Van de Graaff system, if it were to prove commercially valuable, be used in the public interest and not to strengthen monopoly, the Board of the Authority hoped that the government would be given free use of the patents. Compton rejected that proposal, but suggested that he might be willing to grant free use to the TVA. Furthermore, Compton proposed that a Board of Arbitration be established to determine appropriate shares in commercial rights once the system was perfected, for Princeton University, MIT, the National Research Council, and the Research Corporation had all had a hand in the matter. Sounding a theme that would come to embody an important philosophical difference between the engineers on the one hand, and the government on the other, Morgan told his fellow board members that it would undoubtedly prove difficult to compose a contractual provision that would satisfactorily cover possible developments. Their best guarantee of just treatment rested in the "high character and common sense of Dr. Compton."[37]

Over the next seven months, while the Institute continued to work on the electrostatic generator and associated components, Bush and the TVA's legal staff attempted to draft an adequate contract. William Sutherland, the Authority's general solicitor, was dismayed by the complexity of the emerging agreement. If the TVA and the Research Corporation both retained the rights , for instance, to freely license manufacturers, how could the Authority be adequately protected from being charged exorbitant prices by manufacturers independently licensed by the Research Corporation? Sutherland remarked to a colleague that the arbitration provisions, obviously crucial, were "rather sketchily drawn, and it may be that they should be enlarged upon, and in any event they should be made as uniform as reasonably possible."[38] Bush, on the contrary, felt that contractual arrangements could be greatly simplified by depending on the good judgement of the parties involved. Consequently, he proposed a greatly simplified draft in which each of the parties would contribute what they did best. The TVA would contribute the initial funds for development, MIT would conduct research "to the best of its ability," and its best judgment, and the Research Corporation would have "complete control of all business aspects of the matter...." "Now you will note that I have omitted several points which we have considered recently, in the attempt to simplify, and also because the best way to provide against contingencies is to give broad discretion to a capable organization operated for the public benefit. ... The special provision for preventing discrimination against T.V.A. by manufacturers is omitted on the basis that Research Corporation will prevent any unjust discrimination whatever. If we cannot depend upon it to take care of such matters...we cannot produce the desirable result by complicating the document. I have great confidence in Research Corporation. If there were a more ideal organization for the purpose we might turn to it, but there is not. Hence I believe we must simply decide that they are intelligent and reliable, and give them full authority."[39]

The project foundered on that disagreement. Irritated that MIT would not guarantee to the agency rights to dispose freely whatever developed out of the experimental research - "After all, the money is of the whole people and, in my judgment, the policy should be that any results should be available to the whole people" - Lilienthal turned thumbs down.[40] Compton tried to salvage an agreement. Protesting to Morgan that the Institute could be "trusted not to handle any technical development in any manner which would put personal or institutional benefits ahead of the best interests of the public," and believing the project presented an opportunity to clarify "what should be the proper relation between an inventor, a public institution and the government," Compton attempted to extend negotiations. It made no difference. The TVA was entirely too suspicious to commit the government to contracts based on trust and claims to expertise - issuing from MIT or the Research Corporation.[41] The MIT people, on the other hand, were fearful that a unrestricted grant of royalty-free rights "would place in the hands of the Government, a powerful tool for combating private public-utility interests throughout the country and we refused to become a party to such practice."[42] Morgan finally closed the file on the project eighteen months after Compton drafted his press release.

The inability of the TVA to strike a deal with MIT and the Research Corporation acted out on a smaller stage disagreements that were echoing through the public places of Depression America. In a Christmas address to the American Association for the Advancement of Science in Boston in 1933, the New Deal Democrat Henry Wallace chided the scientific community for ignoring the problem of social justice. "...I would like to suggest that the very training which made possible the enormous material expansion of the past century may to some extent have made impossible the building of a just social system for the prompter and more uniform distribution of the wealth produced by the system. Most of the scientists and engineers were trained in laissez-faire, classical economics and in natural science based on the doctrine of the struggle for existence. They felt that competition was inherent in the very order of things, that 'dog eat dog' was almost a divine command."[43] For Vannevar Bush, the problems of social justice were not to be solved by political mandate, but were best left to the private forces that had made the country strong. Writing in 1935, at a moment when economic conditions seemed to be improving, Bush noted that "We are still in trouble in this country and serious trouble. The next Congress will probably pass a bonus and aid to farmers is running wild. Just how long the national credit can stand this sort of thing is anyone's guess." Bush sensed change in the wind. "Straw votes ...show a considerable turning away from the New Deal. This country being what it is, a swing of that sort once started is likely to go very far. ... The forces of recovery are powerful things, and they operate to a considerable extent independently of political affairs, in the absence of wars or actual destruction of financial systems by foolish manipulation. Hence I feel sure that we are on the way out and rapidly so, provided the political tinkering can be held down."[44] Given such profoundly divergent beliefs, is it surprising that MIT and the TVA failed to reach agreement?

* * *

MR. DIENNER. Then we might summarize your qualifications briefly as a man who as a graduate engineer has done practical work, an educator, and inventor, a director of research, an author, businessman, and a public servant.

DR. BUSH. I think I qualify for all of those. I have

> about 20 or 30 patents in my own name.(45)

Coe's earlier testimony had done little to dissuade the committee that corporate power was indeed throttling the independent inventor and distorting the original purposes of the patent system. John Dienner, a patent lawyer and special counsel to the committee, went immediately to the matter of invention.

> MR. DIENNER. Under modern conditions in industry, how do new ideas come forward? I mean by that, consider the individual, consider the corporation, or other forms under which enterprise is conducted. How do these ideas come forward? What produces them?

Bush's response was characteristic. "First, they result oftentimes from the long program of research, careful and meticulous analysis of the situation by a group of men, through large industrial research laboratories or scientific institutions.... In addition, there is the independent inventor, whose day is not past by any means...."[46] An ambivalent response the committee must have thought, and, in any case, not the black and white answer that made for easy conclusions.

> Mr. DIENNER. Do you consider that the patent system, even with the advent of research organizations, can retain its democratic character?
>
> Dr. BUSH. The patent system is a decidedly democratic affair, for it offers the same opportunity to any individual of this country, no matter where he may be placed. He has the same status before the Patent Office. He appears there as an individual and from that standpoint it is an exceedingly democratic thing which, of course, I think is a very important aspect of it. I think there is no threat to that situation due to the existence of the great research laboratories.

Bush's reassurances notwithstanding, the committee chairman pressed the point.

> The CHAIRMAN. ... We have a system developing of collective action, so that the individual now is one of a group, so it is important for us to know, in studying patent questions, whether or not this research of which you speak redounds to the benefit and liberation of the individual or of a collective group.
>
> Dr. BUSH. And if we can make progress in that direction I will be very happy in having been of aid, for I, too, have wondered whether, as we have our recent trends today, the individual is disappearing. Personally I don't think he is. Certainly in pure science he is not. In pure science today the individual can map his own path and make his own recognition as an individual.
>
> The CHAIRMAN. All the testimony which has been presented this committee thus far with respect to research laboratories rather indicates that these are instrumentalities of large groups and that the individual inventor subordinates himself to the rule of the laboratory, and whatever he invents, whatever he discovers, he contributes to the group activity....
>
> Dr. BUSH. And as I tried to bring out, that is one phase of the production of new ideas, a very new and I think beneficent phase, a group phase, but the individual phase has not disappeared....(47)

Ambiguity and circumlocution were not habitual with this straightforward engineer. But Bush's position was a difficult one for a number of reasons. In part, his discomfort is due to the fact that he is the Hooverian Daniel in the lions' den of the New Deal. Bush certainly agreed with the committee that excessive concentration threatened individualism, however that term was defined; he was, in fact, apprehensive throughout his life of the "great trend that there is toward aggregation and centralization" and of the dangers it posed to democratic traditions. Nevertheless, he was too much the Hooverian to welcome the use of federal power as an instrument of social and economic change. Cooperative research, at any rate, was thoroughly beneficial and was here to stay.[48]

Certainly the patent system had lost its edge, blunted by the remaking of the modern economy, for it was an instrument devised in an age when industrial research was non-existent and technologies simpler and rarely science-based. But radical change was a recipe for disaster. The patent system could be restored to order, Bush agreed with Coe, by revising antiquated procedures abused by affluent corporations. The application process could be made less Byzantine and interference procedures simplified. Was Bush aware, he was asked, that large firms acquired patents to suppress inventions and protect their markets? No, he replied, for the suppression of patents representing genuine improvements would be dangerously counterproductive for the firm involved. Furthermore, legislating compulsory licensing to prevent suspected suppression would endanger the very foundation of the patent system itself - the profit motive with its financial rewards attendant upon invention. Indeed, compulsory licensing would favor those large research laboratories with ends more comprehensive than the production of patentable inventions.[49]

Did not large corporations control the market through the pooling of patents? Bush responded that there were good pools and bad pools. The complexity of modern technology and the economic structures necessary to control it demanded cross-licensing and the formation of pools, for no single company could by itself market the best product without relying on patents owned by competitors. Closed pools, on the other hand, that exchanged royalty-free patent rights (thereby circumventing the profit motive) and that excluded from the pool newcomers who had come into possession of potentially valuable patents, constituted undesirable monopolies and should be dealt with by anti-trust legislation.[50]

The proper role of government in this technologically-sophisticated political economy was to act the referee, to oversee the rules of the competitive game and to guarantee the proper balance between large and small, collective versus individual innovation. Beyond that regulatory role, the government had no business. The companies that he had helped organize some years ago, Bush informed the commissioners, would not have been possible under current conditions. "Only men of large means can properly take the long shot that is involved, and men of large means today, with the taxation system that we have, are not inclined to take long risks...." Furthermore, the bureaucratic red tape created by new regulations controlling the issuance of securities was strangling the financing of new business.[51] "There has been a powerful trend toward stronger Government control of large industry in recent years," Bush had written in 1934. "Unfortunately this has resulted in many measures which have borne heavily and which have added artificial hazards to those naturally in the path of new ventures."[52]

Yet the agreement between Bush and the committee that individual opportunity should be preserved and excessive concentration curbed masked profound differences in their appreciation of the inventive problems confronting the nation in 1939. Five years earlier, Bush had written a report on the reform of the patent system as the chairman of a subcommittee of the Science Advisory Board, a report the committee had read carefully.

> The CHAIRMAN. I glanced over this report by the Science Advisory Board, and I found on page 29 this statement ...: "The frontiers have disappeared. No longer may a citizen break new ground beyond the horizon." You refer there to a citizen being, I take it, the natural person. "But the opportunity for pioneering in the application of science to human need remains and calls for the same virtues of courage, independence, and perseverance. It still is possible to enter uncharted regions in industry and it is still hazardous to thus open new territory for the national welfare." Now let me ask you there: Is it as easy for a citizen, a natural person, to penetrate these frontiers of science as it was for Daniel Boone and the geographical pioneers of our history to penetrate the geographical frontiers?
>
> Dr. BUSH. I think the risks are quite comparable.
>
> The CHAIRMAN. Is that your answer, taking into consideration also the accumulation of capital resources by large groups of individuals operating as groups?
>
> Dr. BUSH. ...I think the courage and resourcefulness called for today in a man who would break new ground in the industrial field, produce new companies, new products, for the benefit of the public, and the risks he takes, are as great as the risks of any pioneer; and his reward ought to be commensurate....
>
> The CHAIRMAN. Yes; but I have not made my question clear. You described to us this morning a system which is followed by the Massachusetts Institute of Technology. [ie. its patent policy] As I understood it, you described the collective effort of a staff of an institution of learning. Now, my own feeling is that staff working together can probably produce better results than the individuals working separately.
>
> Dr. BUSH. Oh, yes; in certain fields very much better.
>
> The CHAIRMAN. So that illustrates what has been developing through our society in the last 50 years, namely, collective effort in science and economics, so the question proposes itself, as it were: Is the individual who operates outside of a collective group protected in our present system sufficiently?
>
> Dr. BUSH. In my opinion he is not, and I think the day of the individual inventor is not past, for as fine

> as these cooperative groups may be and necessary as they are to our general progress in this country, they do not cover the entire field.(53)

The hint of misunderstanding in this exchange suggests that Bush and O´Mahoney, in one sense, were not talking about the same things at all. They both invoked the totemic landmarks that set the boundaries of acceptable political discourse - the pioneer, the frontier, and, implicitly, invention. And both agreed that the individual was important, and that individual invention was, to some extent, threatened by corporate dominance of the patent process. But while the Senator´s invocation of the frontier constitutes an oblique indictment of an economic fact - the inequity of economic organization, for Bush the frontier was more a matter of virtue. What marked the pioneer of invention was quality of character - courage, perseverance, resourcefulness, and independence. To understand the manner in which this notion of character framed Bush´s vision of invention and laid the foundations of his trust in expert authority demands that the historian consider not only political economy, but the ethics of straight-thinking that girded engineering culture.

* * *

Gilfillan might have balked at the American mythology of invention, but for many engineers it went to the heart of the matter. Further, the pioneer and the inventor were cut from the same heroic cloth of individual effort. It is a formula that appears early in Bush´s work, as in his description of research at Amrad: "In the laboratory of the present we dream the life of the future. These dreams are not the colorful, indefinite flights of fancy, where logic and physical laws are forgotten. They are careful dreams, often painstaking and plodding, the serious dreams of the pioneer who is always interested in what lies beyond the next range of mountains."[54] It is ensconced, as has been intimated, in the heart of the Science Advisory Board's Patent Committee report over which Bush presided in 1935: "The frontiers have disappeared. No longer may a citizen break new ground beyond the horizon. But the opportunity for pioneering in the application of science to human needs remains, and calls for the same virtues of courage, independence, and perseverance. It still is possible to enter uncharted regions in industry, and it is still hazardous to thus open new territory for the national welfare."[55] And, of course, it pervaded Bush's famous 1945 report on post-war science policy, Science - The Endless Frontier: "The pioneer spirit is still vigorous within this nation. Science offers a largely unexplored hinterland for the pioneer who has the tools for his task. The rewards of such exploration both for the Nation and the individual are great."[56] The frontier is a cultural trope of extraordinarily common occurrence, of course, a reassuring talisman, as it were, whose power derived from widespread perceptions that the modern age was being radically transformed in profound and disconcerting ways. If Bush's report to the President invoked the frontier, it should be remembered that Roosevelt had first used the image in his original letter to Bush.

Bush's pioneer draws strength, in part, from Herbert Hoover. In his popular American Individualism of 1922, Hoover had redefined the frontier for a post-Turnerian people. "Individualism has been the primary force of American civilization for three centuries," Hoover said. And "the American pioneer is the epic expression of that individualism, and the pioneer spirit is the response to the challenge of opportunity, to the challenge of nature, to the challenge of life, to the call of the frontier. That spirit need never die for lack of something for it to achieve." A response to the challenge of geography, American individualism sowed fields, built roads, and bridges, and cities, and created governments. But if the geographical frontiers had vanished, other frontiers remained to challenge the pioneer. "There are continents of human welfare of which we have penetrated only the coastal plain. The great continent of science is as yet explored only on its borders, and it is only the pioneer who will penetrate the frontier in the quest for new worlds to conquer."[57] The engineer was the pioneer of the new frontier.

Bush's engineering pioneer resonates, however, far beyond Hoover's small book. Indeed, the symbolic weight born by engineering derived from converging streams of American experience: the republican ideology that promoted the public good above self-interest, the deep-seated though diffuse religious underpinnings of much American life, and the struggle of many technical schools at the turn of the century to craft for themselves and their graduates a cultural role suited to an industrializing society. Here especially, in the laboratories and workshops of the schools, did educators believe that the talents of their students were honed to a mental and moral edge. As the engineering educator Calvin Woodward put it in 1903: "Manual training furnishes many of the elements of culture and discipline which are lacking in the ordinary secondary course of study. Contact with the concrete; clear concepts of materials, forces and instrumentalities...; analyses of complex operations; the idea of precision; habits of system; or foresight; and of intellectual honesty." "[T]he world is full of unsolved problems, and the engineers...are to solve them."[58]

Bush sounded a similar note when, in a 1928 article describing his mechanical computer, he claimed that its use would cultivate the ability "to think straight in the midst of variability and complexity."[59] The idioms of engineering rooted in the workshop and laboratory were replete with metaphors straddling description and prescription, the "is" and the "ought." The engineering curriculum in which Bush came of age taught the student "respect for power," how "to get things straight," and the need "to size up the situation." It was schooling which transmitted skill and knowledge, and forged character as well. This "ethics of straight-thinking" is evident in a letter Bush wrote in 1933 to a colleague in which he referred indirectly to the difficulties of Depression America. "If there is one thing that the study of science should emphasize, it is absolute mental honesty. I know from long experience that, even in an assistant in a laboratory, a failure to strictly abide by evidence is fatal to usefulness and progress. The matter goes much further than this however. In our society generally at the present time there is a tendency to 'get away' with almost anything. This is exemplified in our general disregard for law, and fully as seriously in the tendency toward erratic and ill-constituted thinking."[60]

The consequences of straight-thinking for political reform are evident in the tale of the MIT engineer Henry Waite who became the city manager of Dayton, Ohio. Dayton, it seems, was once a city like any American city, corrupt and inefficient.[61] But in the spring of 1913, flood waters rushed down the Miami Valley like a Biblical deluge, sweeping away the old order and bringing in the new. In the flood's aftermath, the city's hard-nosed businessmen turned to General Goethals, the builder of the Panama Canal. Rebuffed by Goethals, they went to a close second-best, Henry Waite who, after graduating from MIT, had worked his way up through the railroads, becoming ultimately vice-president and chief engineer for the Clinchfield Coal Corporation. Waite took over as city manager and, with the straight-thinking and intellectual integrity honed in the laboratory, rebuilt Dayton's government. He lowered the death rate and the infant mortality rate, pasteurized the milk, cleaned the streets, and closed the red light district. He cut the weeds on the vacant lots, drove out the loan sharks, and established a new department to oversee the welfare of the city's burgeoning work force. On the newly cleared lots, he constructed baseball diamonds and "placed the full force of the city government behind the amateur baseball league." The city's now sanitized entertainments included a municipal dance-hall, where "Mr. and Mrs. Waite may sometimes be detected two-stepping with the proletariat."

As important as what Waite *did*, was the style in which he did it. And here we should pay close attention to the impression the new city manager made on the journalist who came to Dayton to hear his story. The manager's door, we are told, "was always open," "and Mr. Waite is always completely within view." No skulking in dark, mysterious corners here. His garb was appropriate to his work, shirt-sleeves in the summer, or an "easy-fitting business suit,"; certainly not the "frock coat and the white necktie that usually distinguish urban statesmanship in this country." Trim and smooth-shaven (not even a beard to hide behind), "his steady poise, his quietly resting body, the gray eyes that calmly gaze at his callers through eye-glasses indicate not only assurance, but extreme self-command. He does not greet his callers with effervescence; neither does he treat them with disdain. While talking with them he does not glance at the ceiling and nervously finger his mail; neither does he encourage protracted interviews. There is a feeling that Mr. Waite has all the time necessary for the details of the business in hand; yet it is equally apparent that he has no time for ordinary small talk or extraneous matters. He listens attentively, asks questions quickly, smiles pleasantly at the right moment.... The fact is that Mr. Waite behaves admirably in character; he is precisely what he has always been - a man with the technical training of an engineer, experienced in the problems of public works, accustomed to dealing with figures and facts, and having none of the talents that make the great American politician." He is the pioneer of a post-diluvian world, the contriver of a well-oiled political machine, and the inventor of a new order.

Very much in the spirit of Henry Waite, Bush worried about the role of the engineer in a world that, in 1937, appeared headed for a "grand crash." What would become, Bush seemed to ask, of a democracy befuddled by technology? The answer to that question rested not with enlarged government, but with the mobilization of disinterested expertise. And what made a man a member of such a community? Not special knowledge alone, for "the skilled machinist possesses special knowledge, as does indeed the man who owns and manages a machine shop; yet neither thereby is constituted a professional man." Nor did source of income, place of employment, or academic degree. Industry had been often grasped the importance of the professional man, but too often in conditions that conflicted with "the maintenance of true professional status...." Indeed, the "true criterion" of the professional - and the engineer - was independence. "Completely free from prejudice as to class or race, laboring for the ultimate good of society at large as he envisages it, above passion, secure in the possession of special knowledge which the world needs and hence independent of the whims of individuals and groups, the true professional man is and should be a figure apart, wherever he may be placed."[62] Bush would not have had engineers become politicians, not, at any rate, if politics constituted the manipulation of special interests characteristic of early Dayton. But if by "political" one meant a concern with the res publica, then the larger commitments of engineers were pre-eminently political.

The ethics of straight-thinking characterized a refurbished patent system as much as the politics of reform. In this vein, Coe and Bush both found in disinterested expertise the solution to the judicial tangle that undermined the validity, and consequently the efficacy, of patents. By the 1930's, patent litigation was commonplace. If an applicant disagreed with the decision of the examiner as to the validity of the patent, he could appeal first to a Board within the Office. If that decision was unfavorable, he could appeal again, either to the Court of Customs and Patent Appeals or, at his choice, to a federal district court. If need be, an appeal could be lodged yet again, this time in one of the ten circuit courts of appeals. Even at this level, however, decisions were limited in jurisdiction, and contrary judgments could easily be obtained in other circuits. The course of hearings in disputed cases was thus expensive and time-consuming and presented a heavy burden for smaller plaintiffs.

Bush had proposed in his 1934 Science Advisory Board report that circuit courts be replaced, in the matter of patent appeals, by a single court located in Washington. In order to deal competently with the technical issues of patent litigation, judges would be chosen on the basis of their legal and scientific training. For lower courts, juries of experts would be established to provide judges technical advice independent of expertise called upon by defense and prosecution. These permanent juries of experts would be drawn from "men of the highest type, both from the standpoint of their professional attainments in the sciences and their applications, and from the standpoint of their trustworthiness and public spirit."[63] Bush´s proposal was not new and it would resurface in the future. But it is a notion very much in the spirit of the culture of engineering. It echoes C.O. Mailloux´s 1914 address to electrical engineers that foretold a crisis for democracy unless engineers take their appropriate place at "the helm in public affairs." Remarking on the confusion of rights of expression and the authority of opinions, one a matter of law, the other of knowledge, Mailloux chided partisans of direct legislation for requiring the individual to pass on questions beyond his competence. "How can enlightened thought and opinion and rational action be realized under such circumstances?" The answer, of course, was to enlist the engineer to help improve the "civic, ethical, economic and even moral conditions" of modern life.[64]

At least one member of the committee, however, Senator William King of Utah, expressed reservations:

> Senator KING. May I ask one question? Who would select the supposedly nonpartisan adviser, technical advisers, to the judge who acts in the first instance?
>
> Dr. BUSH. The court itself, sir, in my judgment should select its own advisers. There is no lack in this country of properly qualified scientific and tech-

> nical men who are utterly nonpartisan, who have no connection in industry whatever in some cases, who would be available if called upon in a dignified way by the court.

The response did not satisfy King, however, who lacked Bush´s calm assurance in the unanimity, if not the impartiality, of scientific opinion. He had seen experts disagree in court and when it had been suggested that the court turn to independent experts to sort out the truth of the matter, "there was a conflict as to who should guide the court in selecting the expert to advise him." By what expertise does one chose between experts? Would not Bush´s proposal be subject to the same difficulty?

> Dr. BUSH. I would personally be quite content to see the court select its own advisers, and I feel quite sure that that would be done in such a way that perfectly adequate and impartial advice would be obtained in order to aid the judge in the determination of facts in a field of science, which by its very nature is one that he cannot know intimately and cannot learn in the brief space of a trial.(65)

The single court proposal never, in fact, overcame the objections of those who resisted its elitist implications. Typical were the remarks of the district court judge Simon Rifkind some years later: "The highly industrialized society in which we live has a great appetite for ´know-how". Such a society elevates and aggrandizes the position of the expert. His is the voice with the ready answer. His opinions become the facts upon which lesser mortals - laymen - risk life and fortune." Once the law came to depend on the specialized knowledge of a small and exclusive group of experts, isolated from broader opinions, it risked the creation of a "primitive priesthood," signaling "decadence and decay." It was the role of the law, not of technical expertise, to mediate conflicting interests in a democratic society, and the law could only serve that responsibility if it resisted the demands of overspecialization.[66]

Bush admitted neither that facts could not be settled, nor that objective and impartial expertise could not be easily found. Impartial and expert mediation, based on the facts of the matter, was too deeply imbedded in his training and experience and he would have agreed wholeheartedly with Mailloux that, if all were entitled to opinions, not all opinions were of equal weight. The commitment to disinterested expertise - the ethics of straight-thinking - was a lens of metaphysical power, molded in the culture of American engineering. Once shattered, questions about expertise could not even be phrased. Engineers might be politicians, but only if politics were redefined as something other than the arbitrary juggling of special interests. Likewise, an engineer might act the judge, but only if the public recognized that some opinions were more authoritative than others. And, above all, straight-thinking was rooted in the primacy of character.

With its implicit emphasis on the moral primacy of character, the ethics of straight-thinking clashed with current social and psychological accounts of human behavior. Only on occasion did the "social psychology" of engineering came clear.

During the spring semester of 1934, the Electrical Engineering Department at MIT organized a series of orientation lectures designed to introduce sophomores to the curriculum. The series opened with a lecture by Karl Wildes on "The Intellectual Qualities of the Engineer" that was followed in subsequent weeks by talks by Dean Bush and President Compton on "The Pursuit of an Objective" and "The Spirit of Inquiry." Over the semester, students were told about the relationships between teacher and student, the sorting of students by "mental speed," course requirements and opportunities for research, safety, the importance of physics and applied mathematics for engineering, the necessity of effective english, and the linkages of the curriculum (basic science, rigorous thinking, and "modes of expression").[67]

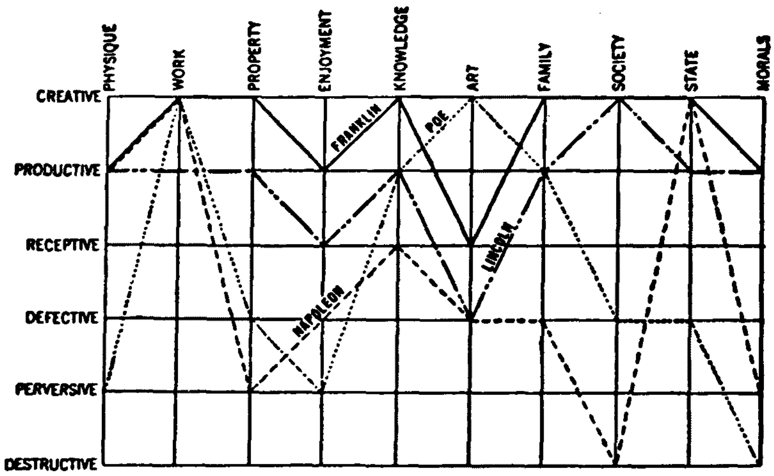
For Karl Wildes, personal and intellectual qualities were key to engineering success. Particularly important, Wildes emphasized to his sophomore audience, were integrity and "soundness of character," scholarship, cooperation, initiative ("self-starting"), thoroughness, responsibility, industry, and judgment. And "How does a student develop this quality?," Wildes asked his listeners. By observing others, through solving problems requiring judgment, and "by testing his own judgment by laboratory check."[68] In the course of his talk, Wildes discussed the forms used by the department and by prospective employers to rank students. The first form, apparently used within the department, rated students in terms of the aforementioned traits, along an axis both quantitative and descriptive. The scale of "industry," for instance, extended from 50% and "Needs Urging" through 70% and "Steady" to 85% and "Energetic." The scale of "personality" stretched for "poor" at 50% to "pleasing" at 85%. Wildes also shared with his audience another form such as might be used by an employer to rank a candidate after an interview. Was his approach "cold," "shy," "bold," or "cordial"? Was his walk listless, or energetic and determined? Were his facial expressions blank or friendly? Did he scowl, or did muscles twitch? Were his eyes shifty, inflamed, and dull, or clear and expressive? Did he have a repelling voice, or was it pleasing? Were his manners extreme? That is, was he either crude or over-polite? Was his poise nervous and uneasy, or did it command attention? And what of the candidate's mental characteristics? Was he a slow thinker or keen? And what of enthusiasm? Did he change moods easily or did he show grit? Open mindedness? Did he seem stubborn or liberal?[69]

We might, of course, ask what the function of such interviews was and whose interests were imbedded in this taxonomy of candidates. But that is not at issue at the moment. Our interest lies elsewhere. For Wildes' lecture allows us a glimpse of that calculus of traits by which engineers sorted out the facts of character and personality. And engineers knew that character and personality, alloyed with technical knowledge, were the essential ingredients of success. When Charles Mann had polled practising engineers on the essential qualities of the successful engineer, character had received a ranking of 41%, technical knowledge only 13%.[70] Character and personality are the theme which underly the lectures on the "foundations for human engineering" delivered by Charles Gow as part of MIT's course in "humanics." Emphasizing the primacy of character, Gow lectured on honesty, loyalty, discretion, courtesy, friendliness, judgment, and initiative, qualities all of which would help the engineer up the company ladder and lend weight to his technical judgments. Gow prefaced his discussion of particular qualities with the "ladder of success." "The business world of today is like a peculiar-shaped ladder, broad at the base and tapering toward the top. Around the foot there is a tremendous crowd, through which one must force his way if he is to reach the bottom rungs and attempt the the ascent. Because of the great effort necessary, most of the crowd is more or less indifferent to the opportunity afforded for climbing. The masses are vaguely hopeful that someone will clear a path and push them heavenward without too much exertion on their own part." Some waste their time looking for the "escalator" to propel them effortlessly towards success. Others attempt to pull down those who have found the ladder and have begun to struggle upwards. "By virtue of their outstanding qualities," a few manage to leave behind "the maelstrom of purposeless humanity" and reach the higher rungs of the ladder. "Near the very top stand a select group who, by their superior ability and persistence, have outdistanced all of their contemporaries. So few in numbers and so overwhelmed with responsibilities are they, that they are constantly urging those below them to hurry to their assistance, and to share with them in the rewards." Happiness must be earned, Gow taught his students, and the higher the ladder, the greater the strength of body, mind, and character was necessary "to hold your position."[71]

Gow illustrated the calculus of personality by adopting a scheme invented by William de Witt Hyde in 1908. Plotting temperament along the ordinate and human activity along the abscissa (see figure), depicted the personality profiles of Franklin, Lincoln, Poe, and Napoleon. Napoleon, not surprisingly, does not fare very well in this scheme, for while he was a hard worker and creative, he was also nervous (remember the twitching), ostentatious, selfish, and blasphemous. The key to the personality for Gow was balance. "Personality is the integral of the many traits which go to make up a man. It is not the gear train, or the pendulum, or the case; it is the whole clock. Outstanding personality is a harmonized well-balanced combination of all the desirable elements of human character." "There are a great many wheels in a clock, but unless they all function in perfect synchrony, the clock is useless. It is thus with a human being. He has a great many motivating influences, and they are working all the time, but the result is only satisfactory when there is a harmonious and synchronized relationship between them."[72]

It was balance that was the keynote of a book published in 1943 by Bush's friend and MIT colleague F.A. Magoun. In the Balanced Personality, How to Solve the Conflict Between Desire and Conscience, Magoun depicted the human personality as the dynamic product of the "'I wants' of Desire" contending with the reflected in a man's reaction to work, family, and the rest.

Using these six strata as ordinates and the ten groupings as abscissae, a table has been drawn up by which to make such an analysis as Dr. Hyde had in mind. In using the table, remember that it is not what a man has,



but only what he contributes to civilization, that counts. For example, as Emperor of France, Napoleon enjoyed luxury and wealth, but in the property group he must be rated as perversive because he exploited rather than created.

Men do not follow one line consistently straight across. Even the outstanding figures of history touch the top line in comparatively few places. Rare indeed is he who touches it along more than fifty per cent of its points as does Benjamin Franklin. Such inventions as bifocal lenses and the Franklin stove entitle him to the highest rating in the second group. He created property in the establishment of the *Saturday Evening Post*, the

(From Charles Gow, Foundations of Human Engineering [New York: Macmillan Co., 1931])

"´Thou shalt nots´ of Conscience" mediated by a discriminating Wisdom. Magoun´s argument that behavior was the consequence of deep-seated forces in conflict reflected a fashionable Freudianism to which Bush objected. In fact, in a letter to his friend, Bush took a swipe not only at the Freudians, but at psychologists who would explain human behavior either as the result of hormonal chemistry or in the terms of Watson´s behaviorism. To one who did not know him well, Bush chided, Magoun seemed to portray people as "90% behaviorists, oscillating somewhat wildly and ineffectively under the pressure of their environment and generally a rather disagreeably conditioned group...." How would his friend deal with the maternal instinct, Bush asked, "which is an enormous force in the world and quite diametrically opposed to ´desire´, although I know that some of the Freudian devotees would take everything of the sort and explain it away by some transformation of sexual desires, and others would point out that it is controlled by a hormone and hence must be utterly mechanical."[73]

With other elements of his friend´s account, however, Bush would have been in complete sympathy. In a series of illustrations scattered throughout the book, the artist depicted the personality, in proper engineering fashion, as a balanced beam with two young women at either end and a masculine figure astride the fulcrum. The young woman at the near end, immodestly posed with her short skirt hitched alluringly above her left knee, represents Desire; at the distant end, modest in her long skirts and high-buttoned shoes, sits, somewhat stiffly, the prim figure of Conscience. At the center of the beam, stands the masculine figure of Wisdom, the only figure of the three, the caption notes, solidly in contact with the ground of reality, and, please note, laden with the paraphernalia of the engineer. By means of chart and transit, our wise engineer views reality with vision and proportion and reconciles the conflicts between desire and conscience; without his mediating influence, the personality would oscillate wildly and neurotically. Though couched in terms psychological, Magoun's vision of the balanced personality really tells us much more. For the wise engineer is more than the balance wheel in the human personality; down from the balance beam of the personality, he strides purposively across the landscape of industrial America, reenacting the mediating accomplishments of Henry Waite and forestalling that "grand crash" that Bush had feared in 1937.

Granted, much of this is pop psychology. But Bush, like many engineers, knew what he liked and what he didn't. And he didn't like psychologies that sought the explanation of human behavior in impersonal causes - whether Freudian, behavioral, or hormonal. Such doctrines undermined the belief that the individual bore ultimate, and irreducible, moral responsibility for his actions, a responsibility that was imbedded in character, just as Henry Waite's responsible expertise was plainly etched in the lines of his face. This notion that the individual is the origin, rather than the consequence, of productive forces, accounts for Bush's predilection to think in terms of instincts. Unlike psychologies that sought to interpret behavior as a

Balanced Personality is possible only when the "I wants" of Desire and the "Thou shalt nots" of Conscience are harmoniously integrated—as distinct from being merely reconciled—to the point of freedom from inner conflict. This can only be done by the discriminating judgments of a Wisdom that stands solidly on reality.

BALANCED
PERSONALITY

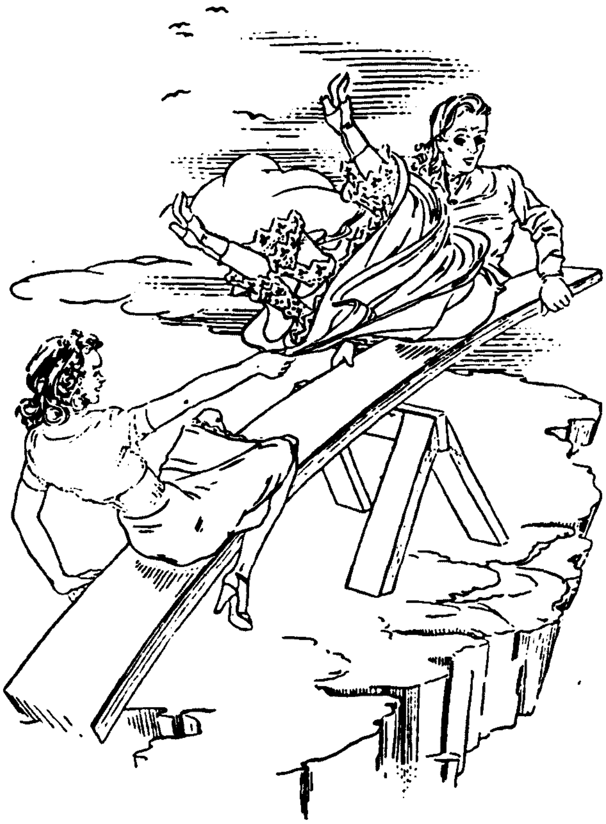
How to Solve the Conflict between Desire and Conscience

F. ALEXANDER MAGOUN

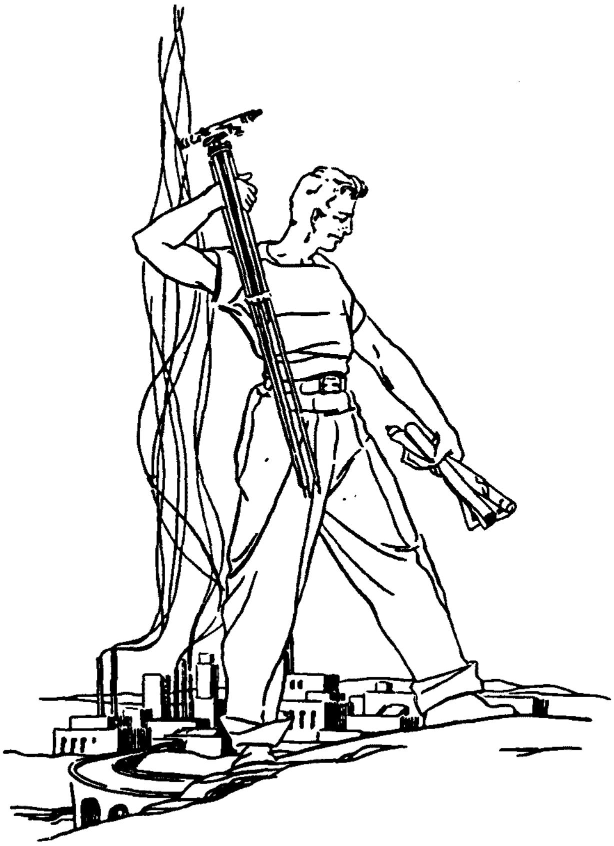
Associate Professor of Human Relations,
Massachusetts Institute of Technology

With Illustrations by
GOULD K. HULSE, Jr.

HARPER & BROTHERS PUBLISHERS
NEW YORK AND LONDON



Where there is no Wisdom, Conscience and Desire become involved in an inner conflict which leads to solution by force. Desire will proceed without regard for the consequences of her acts, whereas Conscience may become over-apprehensive.



Wisdom is seeing reality with vision and a sense of proportion. It rests solidly on the facts, and by the use of good method sees them—and the emotional background from which they stem—as a whole, in detail, thought through to the end without distortion. Only through Wisdom is it possible to keep the future present *in* the present.

dependent variable, instincts seemed independent variables in the equation of human behavior, in some way passed on from biological generation to generation and susceptible to the moral influence of good teaching, but otherwise points of origination and, it turns out, key ingredients in the moral economy of expertise.

The language of instinct goes back, of course, to Darwin, though more immediate sources for American psychologists were William James and Thorstein Veblen. Both Veblen and James compiled catalogues of human instincts that read like checklists of Victorian moral proprieties - sociability and shyness, modesty, imitation, cleanliness, play, sympathy, curiosity, acquisitiveness, constructiveness, and, of course, the maternal instinct were among the lists generated by early twentieth century psychologists. All of them transparent ingredients of the human makeup. A key instinct for our engineer was constructiveness, in Veblen's terms the instinct of workmanship, which, as James put it, was "as genuine and irresistible an instinct in man as in the bee or the beaver. Whatever things are plastic to his hands, those things he must remodel into shapes of his own, and the result of the remodelling, however useless it may be, gives him more pleasure than the original thing. [C]lothes, weapons, tools, habitations, and works of art are the result of the discoveries to which the plastic instinct leads...."[74] Invention, in other words, was an elemental urge, neither the cooperative consequence of the large industrial laboratory, nor the impersonal product of the broad forces of culture, though it could be cultivated within the laboratory and encouraged by the social environment.

Reminiscing in old age over his inventive career, Bush mused "an invention has some of the characteristics of a poem. Standing alone, by itself, it has no value; that is, no value of a financial sort. This does not mean that inventions - or poems - have no value. It is said that a poet may derive real joy out of making a poem, even if it is never published, even if he does not recite it to his friends, even if it is not a very good poem. [I]n the same way an inventor can derive real satisfaction out of making an invention, even if he never expects to make a nickel out of it, even if he knows it is a bit foolish, provided he feels it involves ingenuity and insight. An inventor invents because he cannot help it...."[75]

The psychology of instincts waned rapidly during the twenties and was replaced both professionally and in the popular arena by various newer psychologies, more or less faddism, which ranged from Watson's behaviorism, the glandular psychologies of men like the New York internist Lewis Berman, to the Freudianism Bush detected in the work of his colleague F.A. Magoun.[76] What the "new psychologies" had in common was the denial that behavior was best accounted for in terms of mental life and purposive action. Behavior, that is, was not transparent; it was, rather, to be explained as the consequence of various impersonal forces, whether the result of glandular disorders, subconscious sexual drives, or environmental stimuli that produced behavioral responses without the necessary mediation of conscious moral purpose. The affinity apparent in an engineer like Bush for an older psychology couched in the language of instinct and purpose lies in just this fact - that the individual was preserved as an irreducible moral actor, the origin of significant intervention and not its consequence. Moreover, certain instinctive impulses stressed by James, Veblen, and others, seemed particularly important for self-conscious engineers. The instinct variously named workmanship, constructiveness, contrivance, or, for that matter, invention, suggested that engineering with its stress on instrumentality and effective action had some special kinship with an essential element of the human identity. If engineers were pop psychologists, it was an affection that fed on their fascination with the primacy of character and efficiencies of behavior. In all of these ways, the engineer seems the distilled product of Victorian America, where instincts could be seen as innate predispositions to behave in certain ways, ways which found expressions in an effective amalgam of character, virtue, and skill that would tame the technological wildness of an industrializing society.

If invention and engineering could be seen as the offshoots of the urge for contrivance, so could economic behavior. In 1915, in a book entitled Inventors and Money-Makers, the Harvard economist F.A. Taussig complained that contemporary economic theory was crippled by its one-dimensional portrait of human nature. Committed to an outdated utilitarian calculus of pleasure, modern economists hoped to ape the mathematical sciences and, physics-like, unify their discipline around a single force - the unmoderated pursuit of profit. In such a view, the man of business could be nothing but an unrelieved force of disruption, bent on warping public goods to private ends.

But businessmen, like all of us, were complex mixtures of instincts and moral sentiments including the instinct of contrivance, which found its expression in business in the manager's delight in well-wrought plans. Moved by sympathy, devotion, play, and altruism, as well as by acquisitiveness and competition, Taussig's economic man was a genteel being very different from the rapacious animal of orthodox economics. And in an age of enlarging social sympathies, one could hope to find, Taussig felt, the "spirit of devotion" and "spontaneous approbation for public-spirited action...even in ordinary pecuniary operations. Business will not necessarily remain solely business."[77] Just as politics in Dayton, one should add, in the efficient and contriving hands of Henry Waite, would not remain simply politics.

Businessmen, then, were not necessarily economic predators but natural contrivers akin to the straight-thinkers of politics and engineering, disinterested experts inventing arrangements for the public good. And as with engineers, the touchstone of their authority was not just special knowledge but the prerogatives of character. Once again Bush found himself befuddled by the questions of the Monopoly. Not infrequently, the patent system was used to control the introduction and distribution of inventions for the benefit of the public. The quality of pharmaceuticals, for instance, and indirectly the safety of the public, could be guarded by restricting licenses for manufacture to approved companies. This placed enormous responsibility on the shoulders of those organizations designed to manage patents. This question of control provoked the curiosity of the panel. At MIT, Bush informed the committee, staff inventions were assigned to the Research Corporation, which had the responsibility for managing and commercializing them. Income from the inventions was divided between the inventory, MIT, and the Research Corporation to be reinvested in financial support for further research. As non-profit organizations, the Institute and the Corporation were "bound to utilize their funds for the benefit of the public."

> The CHAIRMAN. And who in the Research Corporation has the authority to determine what the public interest is?
> Dr. BUSH. The board of directors and the board of trustees of that organization.
> The CHAIRMAN. How are they selected?
> Dr. BUSH. It is a self-perpetuating organization formed in the same way that the board of trustees of an educational institution is usually formed.
> The CHAIRMAN. So that the proper functioning of this board rests, of course, in the last analysis upon the good faith and the intelligence of the members of the board who perpetuate themselves.
> Dr. BUSH. That is right, sir, and if we did not have at the Massachusetts Institute of Technology great confidence in their intelligence and integrity in the public interest we would not recommend the individual going with them. They are a distinguished group and have shown great intelligence.

That might or might not have satisfied Senator O'Mahoney. It left questions in the minds of others.

> Senator KING. Are they selected from various institutions of learning?
> Dr. BUSH. No, sir; they are self-perpetuating; they select their own successors....
> Mr. PATTERSON. I think the committee has in mind what qualifications are necessary for membership on that board. When a man resigns and a successor is elected, are there any particular qualifications?
> Dr. BUSH. I don't know offhand whether there are any particular qualifications laid down or not.
> Mr. PATTERSON. Beyond the matter of intelligence and public interest, are there any?
> Dr. BUSH. I don't know, sir. There may be in their by-laws, but I don't recall.
> Senator KING. By and large would you say that the public has been benefited by the operations and activities of this organization to which you have just referred?
> Dr. BUSH. I think it has been benefited very greatly indeed in many ways.(78)

Genuinely puzzled by the committee's readiness to anticipate abuse of power, his response was evasive. His discomfort suggests the gap that separates, over the matter of authority, the engineer and a committee generally suspicious of the self-interest of big business. For Bush, the authority of expert contrivers, whether in business or elsewhere, is the starting point of social action; for his audience, it is the problem to be explained, and private power is frequently abused. It is a revealing incommensurability characteristic of his appearance before the monopoly committee. More than simple disagreement over the facts of the matter, and more than mere evasiveness, Bush and the committee occupy mismatched worlds. Whereas Bush moves within the moral economy of expertise, a meritocratic order based on the moral authority superior knowledge, his questioners inhabit a world imbalanced by the maldistribution of social and economic power. What seems for one a matter of moral economy, appears to the other a puzzle of political economy.

Politicians, businessmen, inventors, were, at their best, all engineers, for all exemplified the instinct of contrivance. Moreover, the various alloys of traits and instincts which distinguished one public actor from another and formed the instruments of expert knowledge were rooted in the primacy of character. The art of contrivance, expert knowledge, the centrality and irreducibility of character - these constituted the moral economy of expertise, and engineering was its paradigmatic embodiment.

These were beliefs deeply imbedded in Bush's world-view. In his disputes with the TVA over the role of the government in the disposition of publically-supported research, in his disagreement with the monopoly committee that the technical expert should have a central judicial role in the settlement of patent cases, in his belief that ill-constituted thinking was a root cause of the Depression, in his antipathy to the efforts of psychologists and social thinkers to reduce behavior to social forces - all these instances reflected his commitment to the primacy of expert knowledge anchored in the solid ground of character, character not to be diluted or explained away as the product of the environment, but the moral starting point from which to bring order and shape to a malleable world. Bush was above all a contriver in the public interest, an engineer who saw his technical skills forming an instrument of professional ministry. In this view, the art of contrivance was a sacred calling.

* * *

It is a striking fact that the patent system has endured for a century and a half substantially unchanged, despite mounting criticism that it has lost its relevance for a world in which the nature and context of invention have been dramatically transformed.[79] At the end of the Second World War, in a forum in American Scholar, the merits of the patent system were debated once again. The Washington lawyer Walter Hamilton declared that "an institution, like a human soul, may go astray." The creature of the age of reason, the system had fallen victim to the changing conditions of invention and the independent inventor, now "wearing the livery of his corporate master," had been "superseded by a corps of technicians, working for a corporation in a laboratory." Casper Ooms, patent advisor to the AEC and onetime commissioner of patents, disagreed. Granted abuses that plagued it, the system "still measures up to the duties for which it was designed. 'The progress of science and the useful arts' has maintained an ever-increasing pace, and the industrial economy has been immeasurably enriched. Had this progress been impeded by the patent system, evidences of this failure would be at every hand."[80] Bush himself reentered the lists with a 1956 report to the Senate Subcommittee on Patents, Trademarks, and Copyrights in which he repeated many of the reforms he had called for in his 1939 appearance before the monopoly committee.[81] Very little, in fact, had changed.

Now this endurance is a puzzle. Why has the patent system endured for a century and a half substantially intact, in spite of mounting criticism that it has lost its relevance for a world in which the context of invention has been radically transformed. Endured in its insistence that invention demands that uniquely individual "flash of insight" to be patentable, and that invention should be thought of as the rightful property of individuals even in an age when most inventions are the result of cooperative effort. What, then, are the advantages of a system built on the fantasy of an individualism that seems no longer relevant?[82] I suggest that it has done so, in part, because the symbols of invention - the pioneer and the frontier among them - have served the interests of a variety of groups for whom the patent system has become contested ground. Far from being fixed in meaning, these symbols have proved highly plastic, capable of being flexibly interpreted according to the needs of diverse social, economic, or political "locations." The system of symbols that has clustered around the patent system constitutes, in other words, a hegemonic mythology that embodies, not consensus, but muted conflict bounded by a shared universe of discourse. Jackson Lears has recently remarked on Antonio Gramsci and the notion of cultural hegemony: "People indeed create their own symbolic universes...to make life understandable and tolerable, and those symbolic universes do come to have an apparently 'objective' validity, particularly over generations as they spread from scattered individuals to broad social groups. But a given symbolic universe, if it becomes hegemonic, can serve the interests of some groups better than others."[83]

Consider the purposes these ideas have served. For the individual inventor, the system appears to be a bulwark against the unfortunate tendencies of an organizing age, and if the system has proved an instrument of corporate domination, it nevertheless extends important hopes that things will come right. For Bush, I have tried to argue, the ideas of the pioneer, the frontier, and invention imbedded in the patent system invoked a moral economy that sanctified the social role of the expert contriver. But the corporation, as well, made use of these ideas. Maurice Holland's Industrial Explorers of 1929 is only one example of a multiplying breed. In a series of wondrous essays that run the gamut of industrial research from the legendary electrical innovations of GE and Bell Telephone to MIT and Samuel Prescott's $30,000 cup of coffee, Holland tells the tale of the "explorers of the twentieth century...whose work is carried on behind the walls of quiet laboratories, in corners of great industrial plants, and in institutions dedicated to the pursuit of knowledge." "Industrial explorers are the research workers on the frontier of industry. Impelled by the spirit of research to push beyond the borders of the unknown, these explorers open up new territory with the tools of science, stake out claims to their discoveries, and consolidate with practical application the new position in the advance. They are, too, trail blazers on the path of progress; and their pioneer work builds the foundation of the road which connects the outposts of industry with the main highways of commerce."[84] The advantages to the corporation in such stuff are manifold, not least, because it envelopes its fictive personage with the comfortable virtues of an earlier age, suggesting that, despite appearances, things have not really changed. So frequently was the metaphor invoked that, when Bush referred to the pioneering experience still available on the frontiers of technology, he provoked O´Mahoney to reply: "that is a very common statement which is being made on every hand these days...."[85] Nevertheless, when the director of the GE Research Laboratory, William Coolidge, followed Bush to the stand and was asked whether the day of the single inventor was at an end, he broke into what was obviously a well-worn metaphor - and elicited a frustrated response from the chairman:

> Dr. COOLIDGE. This tree of knowledge is always growing, it is always putting on new branches, so that the frontiers, instead of being reduced, as you may say the geographical frontiers are being greatly reduced - it seems to me the frontiers of scientific knowledge are always being extended.
>
> The CHAIRMAN. Oh, I quite agree with you on that. I didn´t mean to imply anything else. I evidently didn´t make myself clear. I am asking whether or not in the conditions which you have described the future of invention, the future of discovery, is not being occupied by the collective efforts which are represented by your organization to the disadvantage of the individual enterprise of the individual person.(86)

Not all those who invoked the frontiers of invention were set in the conservative mold of Vannevar Bush. No less a New Dealer and social reformer than Henry Wallace suggested the liberal interpretative possibilities in his 1934 New Frontier. "´Be up and coming. Work hard. Look out for yourself. Fear God and take your own part. Let´s go. Up and at ´em.´" These "energetic individualistic traits" had been cultivated, Wallace said, by the presence of the geographical frontier. But its disappearance, and associated social and economic changes had turned the American vision on its head and put millions out of work. Consequently, the frontier Wallace imagined faced not to the past, but the future. The younger generation, he urged, must build "seaworthy vessels in which to reach a new world...." And they would embark on a journey "toward frontiers quite different from any we have known in the United States," a new frontier that would be marked by social invention, as the old frontier had been distinguished by mechanical invention and the "competitive seizure of opportunities for wealth."[87]

The frontiers of invention, obviously, meant many things to many people. Disagreements over political economy, the relation of the federal and the private powers, the place of corporate monopoly, the changing contexts of invention - all these arose at one time or another over the course of the Monopoly Committee´s investigation. But Conway Coe, the Commissioner of Patents, had it right at the very beginning when he cautioned the committee not to confine its study of invention to its economic dimensions. When as thoroughly earthbound a bureaucrat as the Commissioner of Patents can look at the thousands of patents flooding his office and see symbols, then something´s up. Pointedly, then, the last chart Coe shared with the committee abandoned the use of statistics. Exhibit No. 205-A was a page from the patent granted Abraham Lincoln in 1849 for a lifeboat "designed to carry its burden...safely over dangerous shoals."[88] A patent, yes, but a metaphor also for a ship of state, as Coe put it, and a later and tragic storm. Only by taking Coe's lesson seriously do we understand the full range of issues that faced the Monopoly Committee when it turned its attention to the matter of invention.

* * *

At the end of the Second World War, Bush wrote an allegory entitled "The Builders" that captured the essential qualities of the culture of engineering. Human knowledge is like an edifice under construction. Some labor in the quarry. "There are those who are quite content, given a few tools, to dig away unearthing odd blocks, piling them up in the view of fellow workers, and apparently not caring whether they fit anywhere or not." Others kibitzed. "Some groups do not dig at all, but spend all their time arguing as to the exact arrangement of a cornice or an abutment." Others simply watched. "Some, indeed, neither dig nor argue, but go along with the crowd, scratch here and there, and enjoy the scenery. Some sit by and give advice, and some just sit." In the midst of this democratic confusion, however, there were others who sensed the secret laws and hidden forms. These were the men "of rare vision who can grasp well in advance just the block that is needed for rapid advance on a section of the edifice to be possible, who can tell by some subtle sense where it will be found, and who have an uncanny skill in cleaning away dross and bringing it surely into the light. These are the master workmen. For each of them there can well be many of lesser stature who chip and delve, industriously, but with little grasp of what it is all about, who nevertheless make the great steps possible.

> There are those who give the structure meaning, who can trace its evolution from early times, and describe the glories that are to be, in ways that inspire those who work and those who enjoy. They bring the inspiration that not all is mere building of monotonous walls, and that there is architecture even though the architect is not seen to guide and order.
>
> There are those who labor to make the utility of the structure real, to cause it to give shelter to the multitude that they may be better protected, and that they may derive health and well-being because of its presence.(89)

Bush tells us his allegory is about the growth of scientific knowledge. It is, of course, about more that that. Just as his appearance before the Monopoly Committee, ostensibly about invention and the patent system, is about more than that. It is about the White City in 1893 and hopes that engineering education might bring about a reconciliation of technology and culture. It is about Tufts College in the years before the Great War and the belief that technical learning and devotion are not only compatible but essential to that ministry demanded by a society troubled by industrialization. It is about MIT in 1916, anticipating the contributions of engineering to the New World that would rise from the ashes of the Old. And it is about the role of the inventor and expert contriver in the modern economy. If democracy is to survive, it must learn to listen to its master builders, those brought up within the moral economy of engineering, for whom technique was king and character a badge. For those on the Monopoly Committee, or in American society in general, who did not or could not trust the moral responsibility of the nation's experts, political economy and moral economy could never overlap, despite the totems that staked the boundaries of their shared discourse.

NOTES - CHAPTER EIGHT

1. For an account of the Monopoly Committee and New Deal efforts to deal with the problems of the Depression economy, see Ellis Hawley, The New Deal and the Problem of Monopoly (Princeton University Press, 1986).

2. See the hearings before the Temporary National Economic Committee, Seventy-Sixth Congress, First Session, Part 3 [TNEC], pp.838-867;1123-1137.

3. TNEC, p.856.

4. William F. Ogburn and Dorothy Thomas, "Are Inventions Inevitable? A Note on Social Evolution.," Political Science Quarterly 37 (1922): 83-98.

5. S.C. Gilfillan, The Sociology of Invention (Cambridge: MIT Press, 1970 reprint of 1930 edition), pp.77-78.

6. Ibid., pp.21-32.

7. Ibid., pp.119-130; Gilfillan, "A New System for Encouraging Invention," Journal of the Patent Office Society 17(12) (1935): 966-970.

8. Coe, TNEC, p.863.

9. William Hooper to President Bumpus, January 28, 1916, Bumpus File, Tufts University Archives.

10. Boston Sunday Herald, January 2, 1916.

11. On Amrad, see the nine-part history by Alan Douglas in Radio Age, June 1981 to April 1982.

12. John W. Stokes, 70 Years of Radio Tubes and Valves (New York: The Vestal Press Ltd., 1982).

13. For the history of radio, see W. Rupert Maclaurin, Invention and Innovation in the Radio Industry (1949); Gleason Archer, History of Radio to 1926 (1938) and Big Business and Radio (1939); and especially Hugh G. J. Aitken, The Continuous Wave. Technology and American Radio, 1900-1930 (Princeton: Princeton University Press, 1985). On the role of patents in the struggle to control markets, see Leonard Reich, "Research, Patents, and the Struggle to Control Radio: A Study of Big Business and the Uses of Industrial Research," Business History Review 51 (1977): 208-235.

14. V. Bush, Pieces, p.162.

15. Alan Douglas, Part Nine.

16. Otto Scott, The Creative Ordeal. The Story of Raytheon (New York: Atheneum, 1974), p.22; James L. Jenks, Jr., Evading the Law (Wakefield, MA: Wakefield Item Press, 1983), p.51.

17. Scott, p.28.

18. Stokes, op.cit., p.29; Aitken, op.cit., p.500.

19. Bush, Pieces, p.198.

20. Scott, p.49; Bush, p.199.

21. David Noble, America By Design (New York: Oxford University Press, 1977), pp. 142-144; John Servos, "The Industrial Relations of Science: Chemical Engineering at MIT, 1900-1939," Isis 71 (1980): 531-549.

22. Servos, op.cit.

23. "Industrial Cooperation and Research File," MIT Archives, Compton Papers, Box 217, Folder 3.

24. "Memorandum of Conversation with Prof. Jackson, September 11, 1930," Compton Papers, Box 217, Folder 2; "New Plan of Faculty Appointments, 1-22-31," Tyler Papers, MC 91, Box 1, Folder 9; "Conference with Professors Lewis and Ryan, V.B., March 18, 1932," Compton Papers, Box 217, Folder 4; for the quote, see "Meeting of Corporation Visiting Committee and Staff of the DICR, 3-10-32," Compton Papers, Box 216, Folder 14.

25. "New Plan of Faculty Appointments"; but see "Memo. to Dr. Compton, March 13, 1934," AC4, Committee on Patents/Office of the President, and Bush to Dellenbaugh, 9-14-34, Tyler Papers MC 91, Box 1, Folder 12. The administration apparently backed away from its insistence on fixed cuts, settling for a statement of "Principles Concerning the Obligations of Full-Time Members of the Staff." See "Meeting of Visiting Committee...," op.cit.

26. Vincent McKusick, "A Study of Patent Policies in Educational Institutions, giving Specific Attention to the M.I.T.," Journal of the Franklin Institute 245 (March, 1948): 193-225, and (April, 1948): 271-293.

27. "Institute Policy Regarding Patents," AC 4, Committee on Patents, Box 242, Folder 60; "Institute Procedure for Handling Inventions, Memo. for Executive Committee, 12-1-34," MIT Executive Committee Records, Volume 7.

28. McKusick, op.cit., Chapter II; "The Patenting of Institute Inventions," Technology Review 39 (June, 1937).

29. By 1948, the Research Corporation was managing a large number of patents for many universities; among them, in addition

to MIT, were Columbia, Princeton, University of California, and the University of Arizona. See McKusick; also, "Institute Procedure for Handling Inventions."

30. Herbert Hoover, *Prosperity Through Power Development, A Compilation of Papers Presented at the First World Power Conference Held at London, England, July, 1924.* (New York: NELA, 1925), p.44; on associationalism, see Ellis Hawley, *The Great War and the Search for Order*.

31. David E. Lilienthal, "Business and Government in the Tennessee Valley," paper read before the American Academy of Political and Social Science, Philadelphia, January 5, 1934; found in *Lilienthal - Selected Speeches*, Volume 1, in the Firestone Library at Princeton University.

32. Compton to Morgan, August 3, 1933, David Lilienthal Papers, Correspondence 1938, Box 88, MIT folder, Seeley Mudd Library, Princeton University.

33. W.A. Sutherland to John Snyder, March 2, 1934, *Ibid*.

34. Jackson to Vannevar Bush, August 15, 1933, Jackson Papers, MC 5, Box 3, Folder 186, MIT Archives; see also the MIT folder in the Lilienthal Papers.

35. Jackson to Bush, August 16, 1933; Bush to Jackson, August 19, 1933, Jackson Papers.

36. Compton to Colonel E.H.R. Green, December 1, 1933, Compton Papers, Box 252, Folder 53, MIT Archives.

37. "Re: Massachusetts Tech (M.I.T.) Transmission Line, August 28, 1933," MIT folder, Lilienthal Papers.

38. Sutherland to John I. Snyder, March 2, 1934, *Ibid*.

39. Bush to Sutherland, June 12, 1934, *Ibid*.

40. Lilienthal to Board of Directors, May 29, 1934, *Ibid*.

41. Compton to Morgan, July 3, 1934 and October 25, 1934, *Ibid*.

42. "The Round Hill High Voltage - Nuclear Disintegration Project," June 21, 1935, Compton Papers, Box 252, Folder 56, MIT Archives.

43. Henry Wallace, "The Social Advantages and Disadvantages of the Engineering-Scientific Approach to Civilization," *Science* 79 (January 5, 1934): 1-5.

44. Bush to Norbert Wiener, October 30, 1935, Wiener Papers, MC 22, Box 1, Folder 43, MIT Archives.

45. TNEC, p.871.

46. TNEC, p.871.

47. TNEC, p.873.

48. Bush to William H. Davis, March 25, 1947, Bush Papers, Patent Survey Committee (1946-1947) Folder, Library of Congress.

49. TNEC, pp.880-892.

50. TNEC, pp.887-890.

51. TNEC, pp.898, 900-901.

52. TNEC, p.900.

53. TNEC, pp.899-900.

54. Bush, "Research on the Side Hill," *The Tufts College Graduate* (1923?): 140.

55. The SAB report is reproduced in full in TNEC, part 3, pp.1139-1148; pp.1147-1148.

56. Bush, *Science - The Endless Frontier*, July, 1945, Government Printing Office, p.vi; Roosevelt: "New frontiers are before us...," p.viii.

57. Herbert Hoover, *American Individualism* (Garden City, New York: Doubleday, Page, and Co., 1922), pp.63-64.

58. Calvin Woodward, "Manual, Industrial, and Technical Education," *Report of the Commissioner of Education for the Year 1903*, Volume 1 pp.1019-1020.

59. V. Bush, "Mechanical Solution of Engineering Problems," *The Tech Engineering News*, March, 1928, p.66.

60. "Memo. to Professor Magoun, February 14, 1933," Office of the Vice President, Records, 1932-1938, Acc.# 77-9, Box 1, Folder M-N, MIT Archives.

61. For the story of Henry Waite, see *Technology Review* 20 (1918): 384-392.

62. Bush, "The Engineer and His Relation to Government," *Electrical Engineering* (August, 1937): 928-936.

63. SAB Report, TNEC, part 3, p.1139.

64. C.O. Mailloux, "The Evolution of the Institute and of Its Members," *Transactions of the American Institute of*

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66. Simon Rifkind, "A Special Court for Patent Litigation? The Danger of a Special Judiciary,"*American Bar Association Journal* 37 (June, 1951): 425-426.

67. "Sophomore Orientation Lectures for 1934," Jackson Papers, Box 3, Folder 236, MIT Archives.

68. The outline of Wildes´ lecture is found in the above.

69. The forms likewise.

70. Mann´s figures are cited by Magoun in his introduction to Charles Gow, *Foundations of Human Engineering* (New York: The Macmillan Company, 1931).

71. Gow, pp.28-29.

72. Gow, pp.167-169.

73. Bush to Magoun, December 8, 1943, Bush Papers, F. Alexander Magoun Folder, Library of Congress.

74. William James, *The Principles of Psychology* (New York: Dover Publications, 1950; originally published in 1890), Volume 2, p.426.

75. Bush, *Pieces*, p.150.

76. J.C. Burnham, "The New Psychology: From Narcissism to Social Control," in *Changes and Continuity in Twentieth-Century America* (1968), ed. John Braeman, John Branner, and David Brody.

77. F.W. Taussig, *Inventors and Money-Makers* (New York: The Macmillan Co., 1915), p.134; Bush cites Taussig in his 1956 report - see note 81.

78. TNEC, pp.877-878.

79. See David Noble, *American by Design*, chapter 6, for a survey of patent reform efforts.

80. *American Scholar* 17 (1947-1948): 470-475; see readers´ replies in 18 (1948-1949): 106-112; 128.

81. "Proposals for Improving the Patent System," Senate Document no.21, 85th Congress, First Session (GPO, Washington, 1957).

82. Remember Gilfillan, note 5, p.119.

83. T.J. Jackson Lears, "The Concept of Cultural Hegemony: Problems and Possibilities," American Historical Review 90(3) (1985): 567-593.

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87. Henry A. Wallace, New Frontiers (New York: Reynal and Hitchcock, 1934), pp.3-7; 274-.

88. TNEC, p.863.

89. Bush, "The Builders," in The Endless Horizons (Washington, D.C.: Public Affairs Press, 1946).