Vannevar Bush and the Differential Analyzer: The Text and Context of an Early Computer

LARRY OWENS

One day in 1942, 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] (See fig. 1.) Wartime security prohibited its public announcement until

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[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, Bush Papers, 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 because of Alan Turing. For their history, see H. H. Goldstine, *The Computer from Pascal to von Neumann* (Princeton, 1972); Nancy Stern, *From ENIAC to UNIVAC: An Appraisal of the Eckert-Mauchly Computers* (Bedford, Mass., 1981); N. Metrop-

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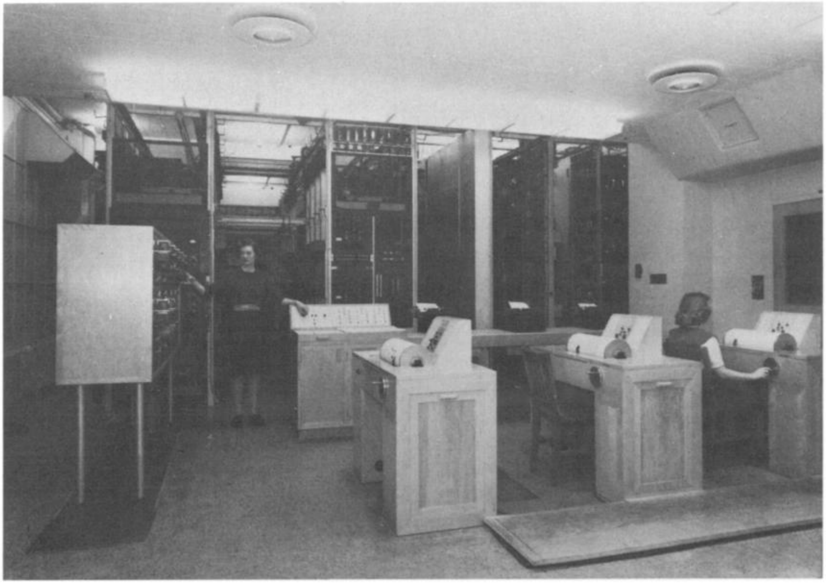

FIG. 1.—The Rockefeller Differential Analyzer. (Courtesy of the MIT Museum.)

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

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olis, J. Howlett, and G. Rota, eds., *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* (Westport, Conn., 1983). For Turing and his interest in computing machines as a response to the crisis in the foundations of mathematics, see William F. Aspray, Jr., "From Mathematical Constructivity to Computer Science: Alan Turing, John von Neumann, and the Origins of Computer Science in Mathematical Logic" (Ph.D. diss., Univ. of Wisconsin, Madison, 1980); and Alan Hodges, *Alan Turing: The Enigma* (New York, 1983).

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

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

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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 he had been intimately involved with the MIT project from its beginnings in the 1930s. 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 that had sustained

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[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, June 4, 1982). Descendants 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.

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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 instrument. 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 are these suggestions of failure the most interesting features of this twenty-year project? In our rush to write the history of the most glamorous of modern technologies, we must be careful lest we find in older artifacts only anticipations of future developments, and overlook dimensions of meaning that open windows on the past. Warren Weaver indicated this extra dimension in the case of the analyzer when he remarked in a letter to Caldwell some days after their postmortem:

> [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.[9]

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 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 20th-century engineering school, the analyzers were not only tools but paradigms, and they taught mathematics and method and modeled the character of engineering.

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In the decade following the First World War, electrical engineers came up against severe mathematical difficulties in their studies of

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[8] See Nancy Stern (n. 2 above) 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.

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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, between 1920 and 1925 the Research Laboratory of MIT's Electrical Engineering Department 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]

Much of the mathematics of long-distance lines had been developed by General Electric's Charles Steinmetz and the Bell Telephone engineer John Carson, but, while the derivation of the appropriate equations proved to be relatively straightforward, their solution was not. Of particular importance to MIT engineers worried about the stability of lines was the equation derived by Carson:

$$I = A(t)(E)\sin\theta + Ep\cos(pt + \theta)\int_0^t \cos p\delta A \cdot (\delta)\,d\delta$$
$$+ Ep\sin(pt + \theta)\int_0^t \sin p\delta \cdot A(\delta)\,d\delta,$$

where I is the entering current, and $E\sin(pt+\theta)$ the voltage suddenly applied to the sending end of an initially unenergized transmission line. Normal procedure for the solution of this equation involved, first, the calculation of the products under the integral signs from tables of functions and their plotting by hand in graphic form, then the determination of the areas under the curves (and thus the integrals) with the use of an Amsler planimeter, and finally the necessary multiplication and addition of curves to give, in graphic form, I versus t.[12]

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[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: Electrification in Western Society, 1880–1930* (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 master's thesis, 1925; and Karl Wildes and Nilo Lindgren, *A Century of Electrical Engineering and Computer Science at MIT, 1882–1982* (Cambridge, Mass., 1985).

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

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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 that 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:

$$y(t)=F_1(t)\int_0^t f(\delta)\phi(\delta)d\delta.$$

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 that Bush would bring to fruition in the development of the mechanical integrator for which he had set Stewart searching.[13]

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[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 master's 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 Discus-

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A colleague, F. D. Gage, suggested that Stewart 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 that 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] (See fig. 2.) 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 this importance there is still much of physics thus described."[16] Under Bush's guidance, Hazen built a two-element

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sion of the Requirements of Such Devices," MIT master's 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. 114–15. 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): 337–45.

[15] Wildes (n. 13 above); Gordon Brown, "Eloge: Harold Locke Hazen, 1901–1980," *Annals of the History of Computing* 3 (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.

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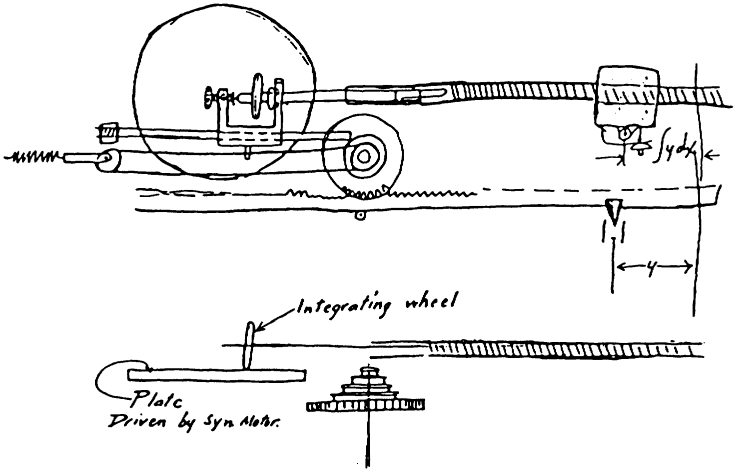

FIG. 2.—The sketch by Harold Hazen of a second integrating element. (Hazen Papers, MIT Archives; facsimile by author.)

machine capable of solving most second-order equations to an accuracy of several percent (fig. 3). 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]

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[17] For a list of topics, see n. 6 in V. Bush, "The Differential Analyzer," *Journal of the Franklin Institute* 212 (1931): 447–88.

[18] Wildes (n. 13 above).

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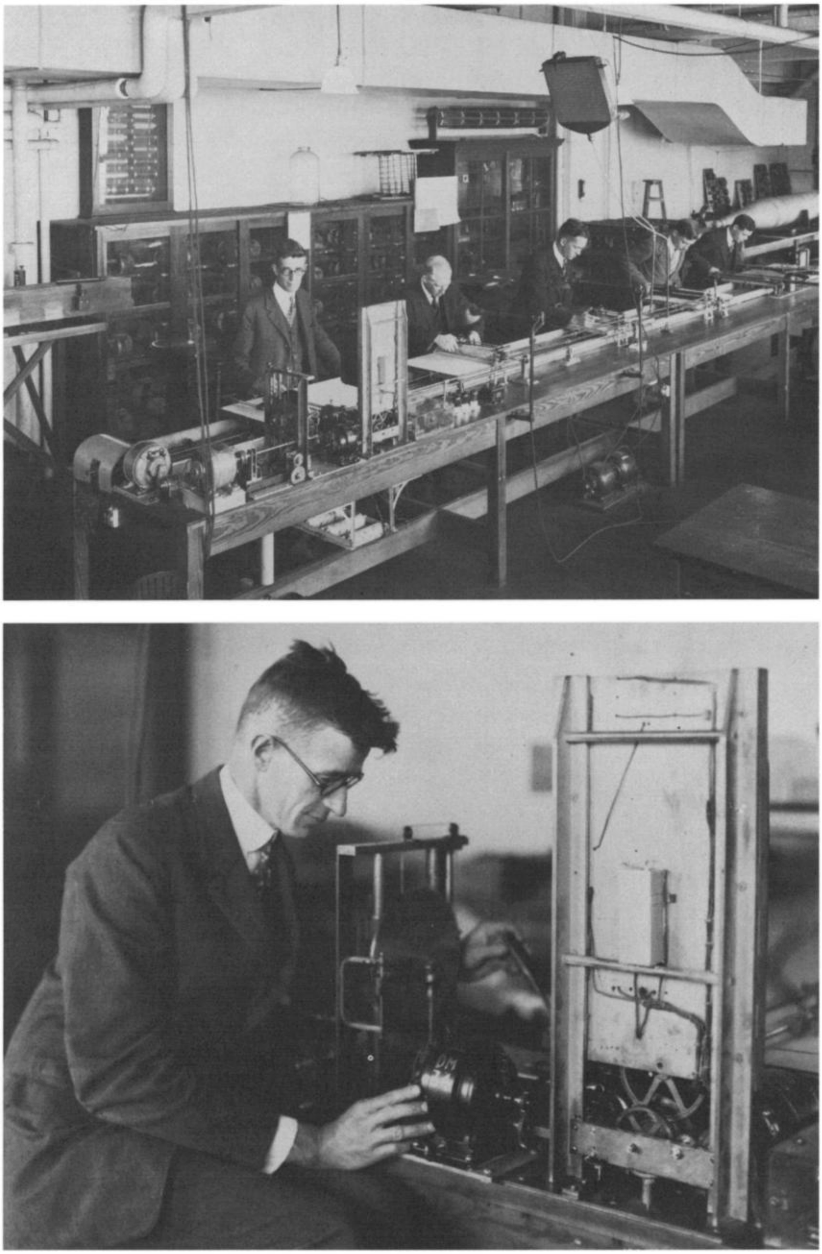

FIG. 3.—(top) The revised Product Integraph with Bush at the near end and, leading away, F. G. Kear, Harold Hazen, and F. D. Gage; (bottom) Bush seated at the output end of the integraph with the disc integrator in front of him and the watt-hour meter, seen from the rear, to its right. (Courtesy of the MIT Museum.)

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The Differential Analyzer fulfilled Bush's expectations.[19] The new machine consisted of a long table-like framework crisscrossed by interconnectible shafts (fig. 4). 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.

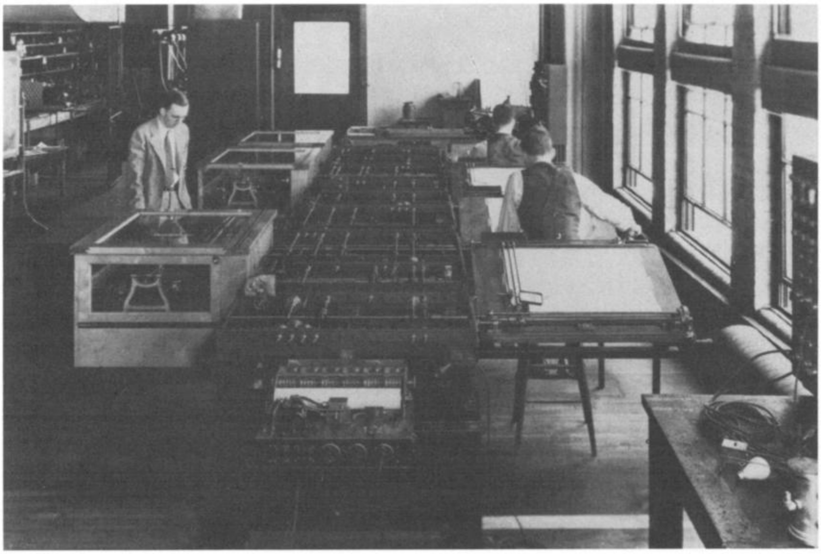

FIG. 4.—The 1931 Differential Analyzer. Sam Caldwell can be seen at the left. (Courtesy of the MIT Museum.)

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[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.

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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 (fig. 5*a*). 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 Bethlehem Steel Corporation.[20] This was a purely mechanical device for the amplification of motion that depended on the winch principle (fig. 5*b*). 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:

$$\frac{d^2x}{dt^2} + k\frac{dx}{dt} + g(x) = 0,$$

or,

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

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

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[20] Brown (n. 15 above); C. W. Nieman, "Torque Amplifier," *American Machinist* 66 (1927): 895–97.

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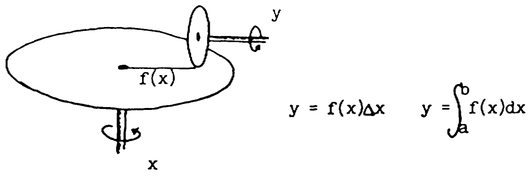
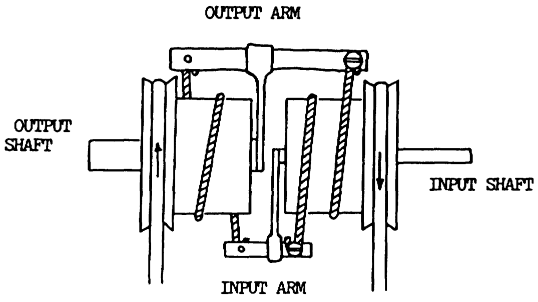


a)
The Disc Integrator



b)
The Torque Amplifier

FIG. 5.—A schematic diagram of the disc integrator and the torque amplifier.

> 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 diagram of the analyzer connected to solve the equation of the falling body is shown in figure 6. The horizontal lines represent bus shafts, *K* and Σ multiplying and adding gears, and the integrators are represented by the indicated symbol. The 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

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[21] "The Differential Analyzer" (n. 17 above), p. 459.

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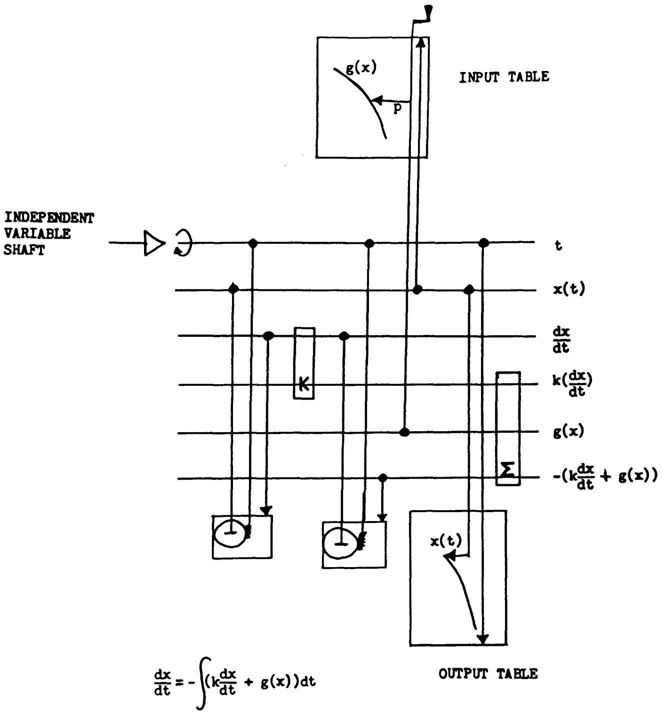

FIG. 6.—A diagram of the Differential Analyzer set up to solve the falling-body equation.

analyzer worked through the equation. The function *x(t)*, which expresses distance with respect to time, would be traced automatically on the output table. (See fig. 7.)

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 nonmechanical elements, Bush invented an elegant, dynamical, mechanical model of the differential equation. Articulated in a particular pattern, its shafts, gearboxes, integrators, pens, and drawing boards set in motion, the Differential Analyzer did not so much compute as kinetically act out the mathematical equation.

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Between 1926 and 1935 the development and application of the analyzers generated four bachelors' theses, twenty-eight masters'

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FIG. 7.—Bush and Caldwell standing at the output board of the Differential Analyzer inspecting a family of curves produced during the solution of an equation. (Courtesy of the MIT Museum.)

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 1920s.[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 Manches-

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[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.

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ter, 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 that 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] (See fig. 8.) 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

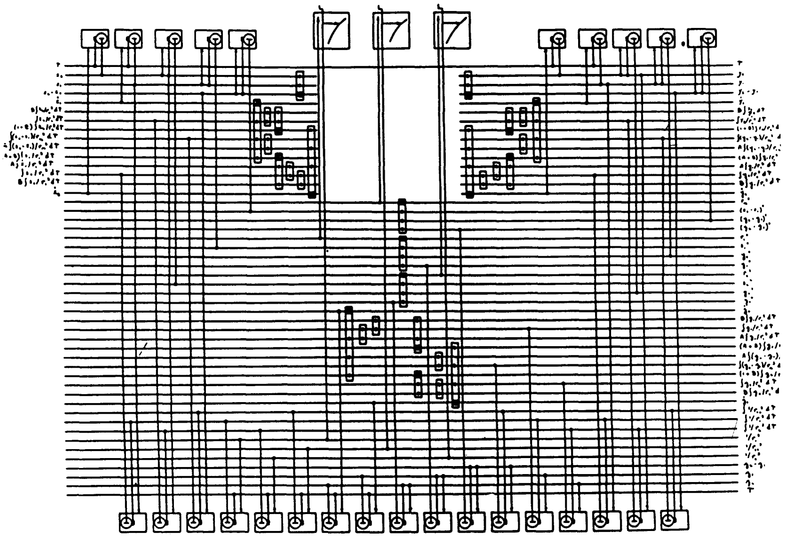

FIG. 8.—Diagram of the Differential Analyzer set up to solve the Vallarta-Lemaitre cosmic ray problem. (Bush to Weaver, April 15, 1933, Rockefeller Archives.)

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[24] D. R. Hartree, "Approximate Wave Functions and Atomic Field for Mercury," *Physical Review* 46 (1934): 738–43; also the Hartree citations in the Berkeley bibliography (n. 4 above).

[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): 719–26.

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autumn of 1931 had become the director of the Natural Sciences Division of the Rockefeller Foundation. Weaver 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 the 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 auto-

[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.

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matic 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

[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 you 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 developmental doldrums .... The Differential Analyzer Staff." In RF1.1/224/2.

[35] Weaver diaries, January 10, 1939.

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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 catalog of important scientific instruments available to investigators. He informed Stewart of MIT's work on machine analysis, writing:

> 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.[37]

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

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[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.

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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 coordinate machine operations automatically, 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 that would utilize, in one of its forms, the magnetic properties of molybdenum or chrome permalloy rings.[40] (See fig. 9.)

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 had bombed Pearl Harbor.

* * *

When Caldwell returned to peacetime work at the end of the war, he faced the challenge of revitalizing the center's programs. Given the transformations wrought at MIT by the war, 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

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[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.

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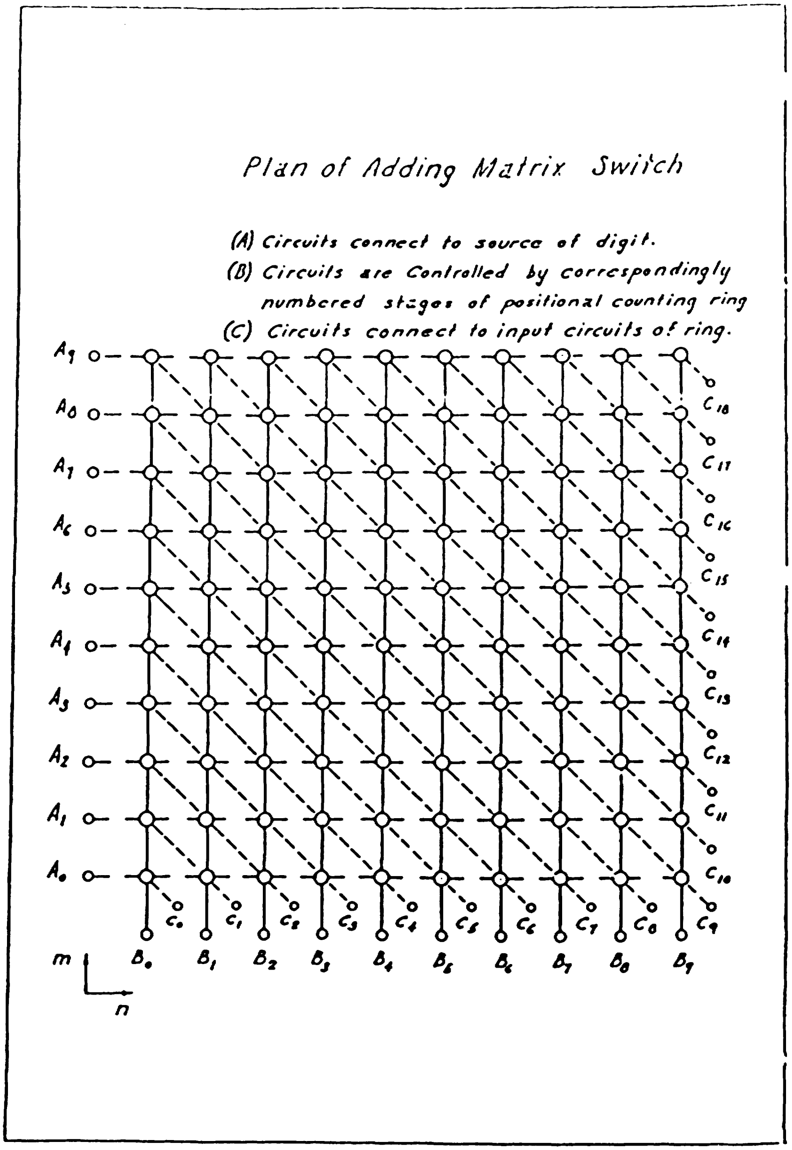

FIG. 9.—Diagram of the matrix switch for the Rapid Arithmetical Computing Machine. (From the report prepared by W. H. Radford, "Research on A RAPID COMPUTING MACHINE," October 1939; courtesy of Perry Crawford.)

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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 wartime 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 on 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 that 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 pres-

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

[43] Ibid.

[44] John Burchard, *Q.E.D., M.I.T. in World War II* (New York, 1948); Redmond and Smith (n. 8 above).

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

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ent 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 John 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 postwar 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 fund-

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[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.

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ing 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 halfway 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 surpassed 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, maybe, broader sorts of utility than so far invoked in our account. As John Kasson has shown us in *Amusing the Million* and *Civilizing the Machine*, machines exist not only as tools, but also as symbols. Bush's analyzers did indeed do more than simply compute $x(t)$. To flesh out our story of this particular machine, we must discover what this something else was.

Weaver was right when he reminded Caldwell that the analyzer had "a very considerable educational value." In 1928 Bush had attempted to justify the 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

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[49] Redmond and Smith (n. 8 above).

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

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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 machine at the Aberdeen Proving Ground, he lent 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:

> 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.[52]

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 of 1928, Bush struggled to put into words other tacit qualities expressed by the calculator:

> 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.[53]

"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 the early 20th-century culture of engineering.

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

[52] V. Bush, *Pieces of the Action* (New York, 1970), p. 262.

[53] Bush, "Mechanical Solutions."

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The intellectual and ethical idioms embedded in the analyzers arose out of the classrooms, laboratories, and shops of the turn-of-the-century 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. The historian can insinuate himself into the somewhat alien frame of mind of that early environment by listening in on a conversation which took place at Tufts College between Samuel Earle and a student just a few years before Bush arrived as an undergraduate in 1909. Earle had been entrusted with the daunting task of teaching English composition to engineers, a new project at the time, and had established the practice of meeting his students in the shop or drafting room to discuss their writing exercises. One day he found himself having difficulty explaining to a student how his essay, in its attempt to portray the character of a man, had failed to convey any but his most superficial qualities. The drawing instructor, who had overheard the conversation, at some point interrupted with the question, "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 invisible features and catalyzed by the remark of his drawing teacher, Earle's student was able to apply his knowledge of a more familiar language to one less familiar.

This anecdote suggests that the artifacts of engineering, particularly in the context of the school, can be interpreted as exercises in language. It suggests also that in the particular context of the turn-of-the-century engineering school the student was expected to move with facility between a number of different language communities serving as translator and interpreter; that the primary language on which the others, such as physics and mathematics, depended derived from the visual, tangible elements of the shop and laboratory. In such a setting the Graphic Language was a fundamental skill for the student engineer.

Gardner Anthony, for many years the dean of engineering at Tufts College, was an acknowledged master of mechanical drawing and graphics in the engineering curriculum. In 1922 in a small book with a long title, *An Introduction to the Graphic Language; the Vocabulary, Grammatical Construction, Idiomatic Use, and Historical Development with Special Reference to the Reading of Drawings*, Anthony summarized ideas he had been developing for over three decades and which formed the basis for the course he taught at Tufts. Drawing, he felt, was a universal lan-

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

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guage and possessed, like other languages, its own vocabulary, orthography, grammar, and literature. He first introduced his students to the vocabulary and idioms of simple pictorial graphics, continued to the more complex grammatical conventions of perspective drawing and descriptive geometry, and concluded his course with the topic of penmanship.

Anthony meant by penmanship not simply lettering, but the whole range of techniques by which ideas were transcribed from mind to paper with the help of such instruments as pencils, triangles, T-squares, compasses, graph paper, and drafting boards. Orthography, in fact, was an exercise in writing straight and in thinking straight. In the Graphic Language Anthony and fellow engineering educators found what they believed was "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 . . . to visualize quickly and accurately . . . ." "[I]t is the power and habit of observing accurately that marks one of the fundamental differences between the incapable man and the man of power." Ultimately drawing would promote not only clear thinking, but with the constructive power it evoked it would also become "drawing in relation to life."[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 the virtues of Gardner Anthony's Graphic Language.

The penchant of engineers for the graphic idiom pervaded their notions of mathematical pedagogy. And here engineers found themselves in a dilemma which reflected the course of development of 19th-century mathematics. In the United States the community of mathematicians had acquired by the end of the century the rudiments of professional identity and were becoming noticed for activity in pure mathematics for the first time by European observers. Ironically, however, this maturation of the mathematical community threatened the traditional relationship between mathematics and the arts and sciences. Consequently, just when numerous recently established technical schools were discovering the need to teach their students more sophisticated mathematics like the calculus, many mathematicians were unable or unwilling to meet their practical demands.[56] While the

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[55] Thomas French, "The Educational Side of Engineering Drawing," ibid., vol. 21 (1913): 109.

[56] For an aging but valuable account of the history of mathematics in the United States, see: D. E. Smith and J. Ginsburg, *A History of Mathematics in America before 1900* (Chicago, 1934); the articles by Struik, Grabner, and Birkhoff in *The Bicentennial Tribute to American Mathematics, 1776–1976* (Washington, D.C., 1977), ed. J. Dalton Tarwater; *A History of*

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disciplinary status of mathematics and engineering differed in Europe, there too the abstraction of modern mathematics frustrated the needs of engineers and experimentalists for adequate analytical tools.

The years around the turn of the century thus witnessed the growth of a movement to reform the teaching of mathematics. The movement was largely spearheaded by engineers and first took definite shape in Britain with the work of the mechanical engineer and educator John Perry. His most important work was done at Finsbury Technical College in London after 1882, when he pioneered a course in practical mathematics for engineers that emphasized practical examples, the use of graph paper for the presentation of problems (a Perry innovation, apparently), and mechanical devices for measurement and computation. Contradicting the common opinion that calculus, given its essential formal rigor, was not a subject easily taught to engineers, Perry insisted that "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."[57] Perry's efforts helped modernize the teaching of mathematics in Britain, and by 1908 an observer could note the growing attention paid to mathematics "on its experimental and graphical side . . . exemplified by the use of drawing-boards, improved mathematical instruments, squared-paper," and the provision of mathematical laboratories "well-stocked with clay, cardboard, wire, wooden, metal and other models

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Mathematics Education in the United States and Canada, the 32nd Yearbook of the National Council of Teachers of Mathematics, 1970; and E. H. Moore's presidential address to the American Mathematical Society in 1903. For a new look at the way that limited mathematical training influenced the development of American science, see John Servos, "Taking the Measure of Nature: Mathematics and the Education of American Scientists, 1880–1930," paper read at the 1983 meeting of the History of Science Society in Norwalk, Conn. Complaints about the scarcity of mathematicians willing to take an interest in applications could be heard as late as 1941: "Though the United States holds a position of outstanding leadership in pure mathematics, there is no school which provides an adequate mathematical training for the student who wishes to use the subject in the field of industrial applications rather than to cultivate it as an end in itself. Both science generally, and its industrial application in particular, would be advanced if a group of suitable teachers were brought together in an institution where there was also a strong interest in the basic sciences and in engineering." Thornton Fry, "Industrial Mathematics," *American Mathematical Monthly* 48 (1941): 1–39. Most of the mathematicians working in industry, Fry noted, had been trained as physicists or as electrical or mechanical engineers.

[57] John Perry, *Calculus for Engineers* (London, 1897), p. 5. For more on Perry, see 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*, vol. 11 (1980).

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and materials, and apparatus for investigation of form, mensuration and movement . . . ."[58]

The "Perry Movement" percolated through the mathematics and engineering communities in the United States as well, encouraging the revision of curricula and the writing of new texts. The most eloquent proponent of practical mathematics in this country was E. H. Moore, the chairman of the mathematics department at the University of Chicago and a major figure in the American mathematical establishment. One of the architects of his discipline's new professionalism, Moore had nevertheless absorbed the concern of the great German mathematician Felix Klein that the increasing abstraction of modern mathematics threatened to impoverish the teaching of mathematics and its applications to science and engineering. In his presidential address to the American Mathematical Society in 1903, Moore proposed a program designed to revitalize mathematical pedagogy for students at all levels. Based on the methods of Perry and incorporating the approach of engineering educators, Moore's new curriculum centered around "arithmetic computations, mechanical drawing and graphical methods generally, in continuous relation with problems of physics and chemistry and engineering," and pursued in the mathematical laboratory. Educated in this tangible environment, the student would acquire "a feeling towards his mathematics extremely different from that which is 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."[59] By 1910 the teaching of mathematics in most engineering schools thoroughly reflected the precepts of Anthony, Perry, and Moore. Practical mathematics and the Graphic Language complemented the practical demands of the schools and helped cultivate students whose thoughts about the world were composed of the symbols of shop and laboratory. This was an engineering curriculum which separated "the incapable man and the man of power" and discovered in the discipline of orthography the habit of thinking straight in the midst of complexity.

The early engineering school, then, was a repository of idioms which found expression in the Differential Analyzer. Looking closer, we can discover not only the idioms but also 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.

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[58] Brock and Price, p. 368.

[59] E. H. Moore (n. 56 above).

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During the course of his lectures on the Graphic Language, Anthony dwelt for a while on the vocabulary of topograpical 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 afterward. Bush set himself the task of mechanizing this job as an exercise for his master's thesis. His invention was an instrument box slung between bicycle wheels; 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 (figs. 10, 11, and 12).

"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 gears, shafts, and servo-driven pens which translated mechanical motion into graphical mathematics. And the key mecha-

FIG. 10.—Bush testing the Profile Tracer near the reservoir at Tufts College. (Courtesy of the MIT Museum and Charles Eames, Venice, California. The photo is from Bush's 1913 master's thesis, "An Automatic Instrument for Recording Terrestrial Profiles.")

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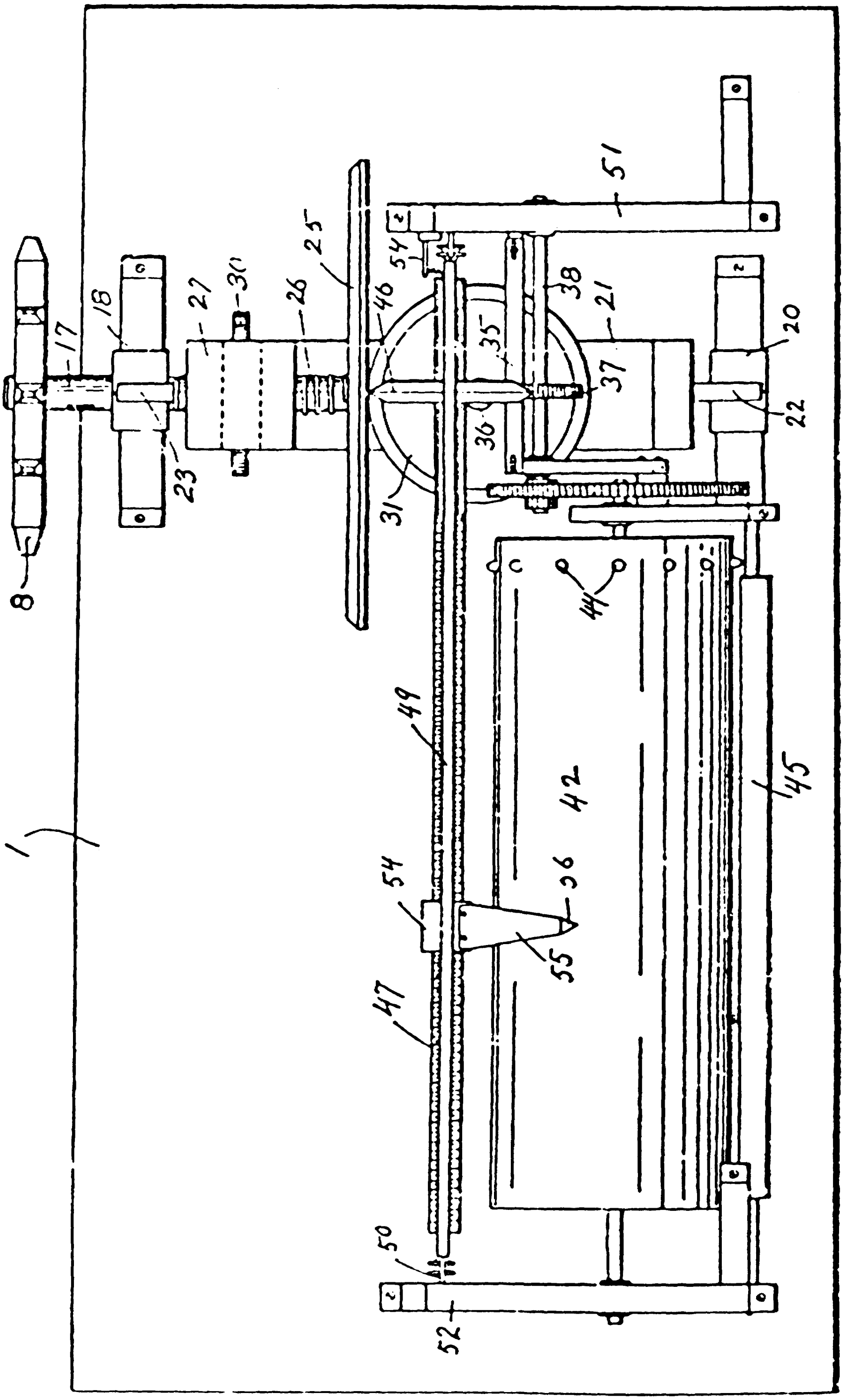

FIG. 11.—A drawing from Bush's patent application illustrating the inner mechanism of the Profile Tracer

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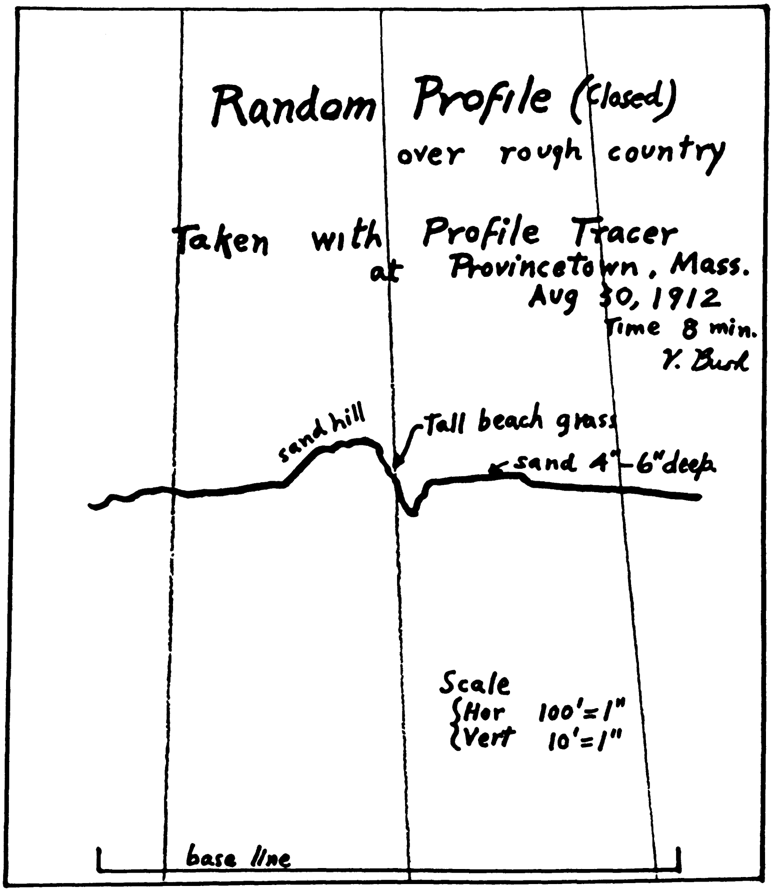

FIG. 12.—A reproduction of a typical tracing found in Bush's master's thesis.

nism was a disc integrator with which he would "have quite a lot to do."[60]

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

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[60] Bush, *Pieces of the Action*, pp. 155–57; see Bush's master's 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, e. g., the illustration of the deal-frame in *Knight's American Mechanical Dictionary*, vol. 1, 1876.

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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.[61] 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.[62]

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.[63] 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 1920s, 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 Differen-

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

[62] 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), p. 613.

[63] See the MIT *President's Reports* for the period.

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tial 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, still depended on expertly machined wheel-and-disc integrators, and still drew its answers as curves. Differential equations and contours of elevation—Bush's computers were very much the offspring of the early Profile Tracer.

* * *

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, one where utility had a distinctively bookish aspect. Here, in the marketplace of the school, the analyzers were exercises in the language of early 20th-century engineering. Forged in the machine shop, the analyzers spoke the Graphic Language while they drew profiles through the landscape of mathematics. The student could find in these machine texts a catalog 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.

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