From Analytical Engine to Electronic Digital Computer: The Contributions of Ludgate, Torres, and Bush

BRIAN RANDELL

This paper, based on an invited lecture given at MIT in March 1980, discusses the little-known work of Percy E. Ludgate (1883-1922), Leonardo Torres y Quevedo (1852-1936), and Vannevar Bush (1890-1974). These three inventors, who apparently were unaware of one another's existence, were all directly influenced by knowledge of Charles Babbage's Analytical Engine, and each played a significant role in the history of the development of program-controlled computers.

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General Terms: Design, Experimentation
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1. Introduction

This paper, based on an invited lecture given at MIT in March 1980, concerns the work of three men, each of whom played a role in the history of the development of the digital computer that deserves much greater recognition than it has so far received. The three individuals, Percy Ludgate, Leonardo Torres y Quevedo, and Vannevar Bush, have not been selected at random. Roughly contemporaneous, working in three different countries (Ireland, Spain, and the United States), and as far as I know unaware of one another's existence, they nevertheless shared one important and, for its time, unusual characteristic: a full appreciation for the significance of Charles Babbage's planned Analytical Engine.

It has been commonly assumed (see Metropolis and Worlton 1980) that Charles Babbage's work on a mechanical digital program-controlled computer, which he started in 1835 and pursued off and on until his death in 1871, had been completely forgotten and was only belatedly recognized as a forerunner to the modern digital computer. Ludgate, Torres y Quevedo, and Bush give the lie to this belief, and all made fascinating contributions that deserve to be better known.

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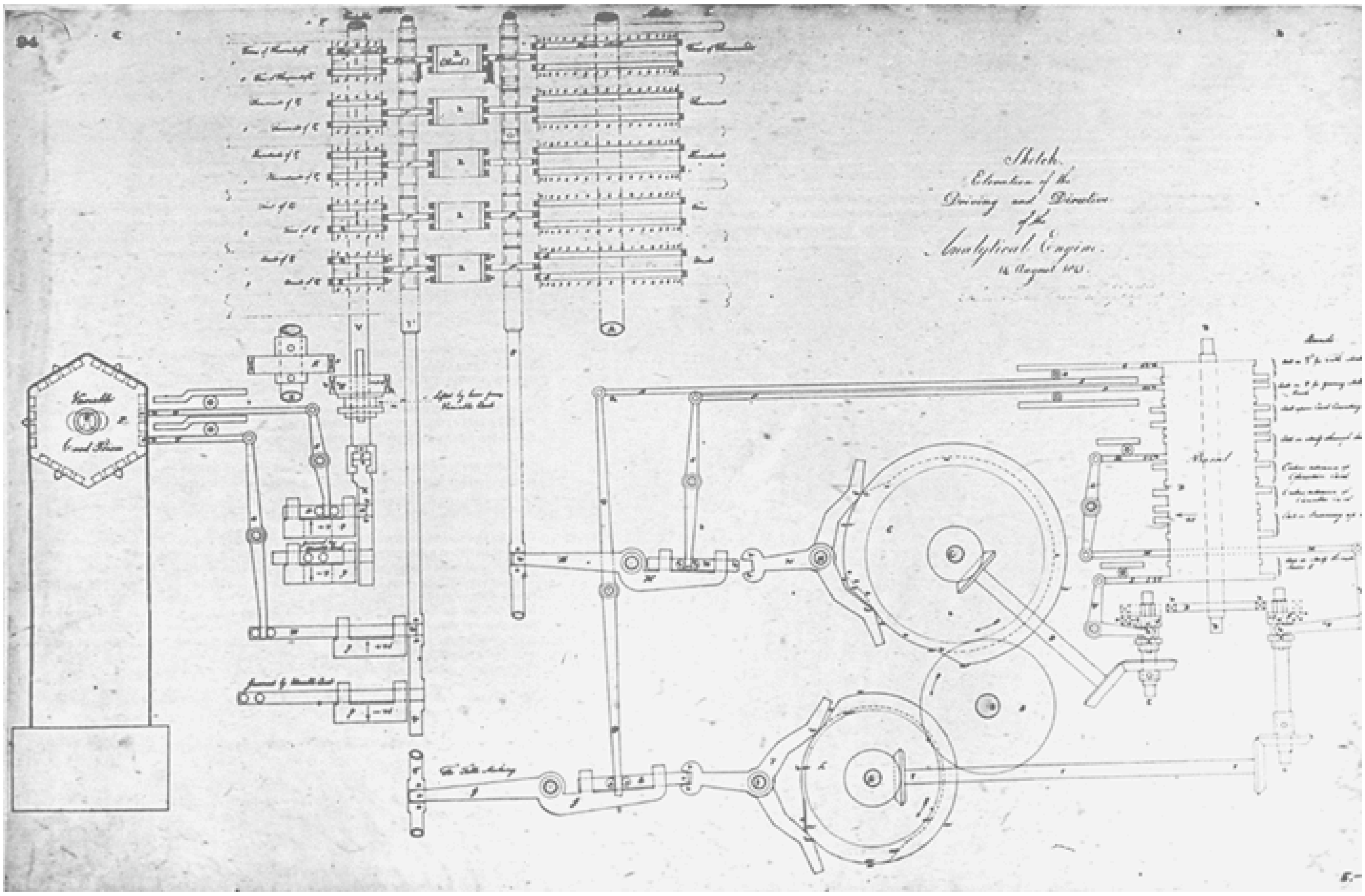

Figure 1. Sketch elevation of the driving and directive of the Analytical Engine, August 14, 1841 (Science Museum, London).

The sequence in which I have listed the three has been chosen deliberately. It corresponds to the sequence in which they did their major work on digital computers, and, as a matter of fact, to the sequence in which I discovered (or perhaps I should say, belatedly became aware of) their achievements. Indeed, I can trace the start of my active interest in the history of computers to my accidental finding of a reference to Ludgate's analytical machine. Moreover, this sequence allows me to end with a brief account of some work that I believe is not at all well known, even at MIT, where it was actually carried out.

Perhaps I should complete these introductory comments by summarizing Babbage's incredible intellectual achievement. In the space of just a few years in the late 1830s he formulated virtually all the basic concepts of, and produced an immensely detailed and sophisticated design for, a general-purpose mechanical digital computer. Figure 1, from the vast collection of his engineering drawings in London's Science Museum, shows the mechanism he envisaged for program control (punched cards, similar to those used for Jacquard looms) and microprogram control (a pegged cylinder, as found in music boxes even to this day). His plans were far too ambitious for his time, of course; he talked of building a machine that would store thousands of numbers-at a time when reliable desk calculators had yet to be marketed-and at his death, after an immensely varied career, only a small portion of an Analytical Engine, comprising an arithmetic unit and a printing device, had been put together.

2. Percy Ludgate

About 10 years ago I came across an article by one Percy E. Ludgate (1914), who wrote mainly about Babbage's Analytical Engine, but also stated that he had himself designed an

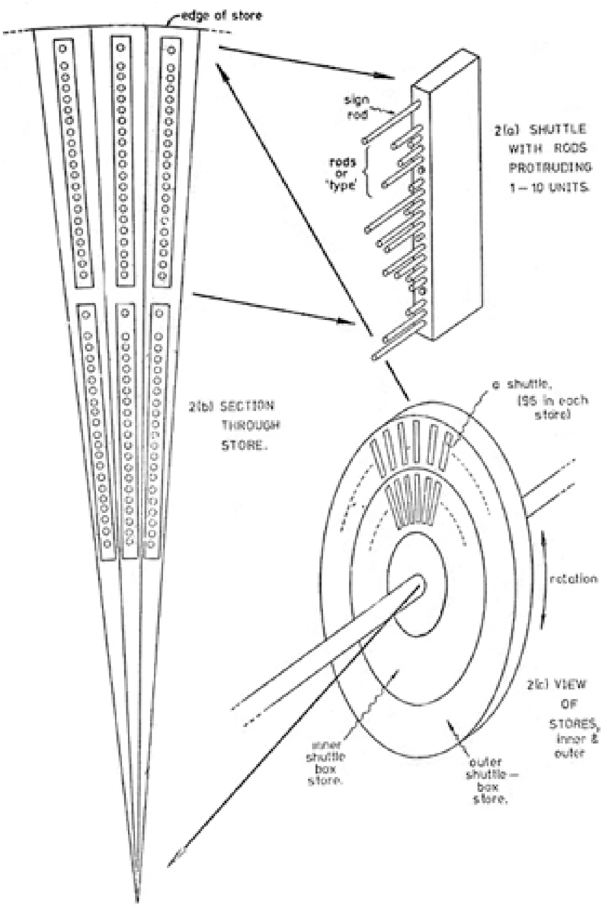

Figure 2. Ludgate's machine–conjectural drawing of store (considered as two separate units, inner and outer) (Riches 1973).

analytical engine some years earlier. A quick foray into our university library produced the paper (Ludgate 1909), which I read with growing amazement. The machine that Ludgate describes in this paper was indeed a general-purpose program-controlled computer, mechanical in operation, although perhaps powered by an electric motor. It was to be capable of storing 192 numbers, each of 20 decimal digits, and would perform all the basic arithmetic operations. It was to work automatically under the control of a perforated tape, or could be controlled manually from a keyboard. What most impressed me was that although Ludgate had, at least during the later stages of his work, known of Babbage's machine, much of his work was clearly entirely original–and indeed with respect to program control, a distinct advance on Babbage's ideas. In fact, all three main components of Ludgate's analytical machine-the store, the arithmetic unit, and the sequencing mechanism–show evidence of considerable ingenuity and originality.

Babbage had planned to use columns of coaxial toothed wheels to represent numbers, with the angular position of each wheel representing the value of a particular digit (the use of toothed wheels for such a purpose was already well established; it went back to at least the seventeenth century and Pascal's calculator). His arrangements for transferring the contents of a particular storage location (i.e., set of wheels) to and from the arithmetic unit involved a wondrous collection of gear wheels and racks. In contrast, Ludgate planned to represent each multidigit number by a set of sliding rods in a shuttle and to arrange such shuttles around a cylindrical shuttle box, which merely had to be rotated to bring the right number to the arithmetic unit. Figure 2 is a conjectural drawing of the mechanism; Ludgate's paper contained no illustrations.

Ludgate's Irish Logarithms

Unit:	0	1	2	3	4	5	6	7	8	9
Simple Index:	50	0	1	7	2	23	8	33	3	14

Compound Index:	0	1	2	3	4	5	6	7	8	...	56	57	58	64	66
Partial Product:	1	2	4	8	16	32	64	3	6	...	35	0	0	0	49

Example: 5 x 7 → '23' + '33' = '56' → 35

Figure 3. Ludgate's Irish logarithms.

Ludgate's planned arithmetic unit was even more novel. Most calculating machines of his day allowed the operator to perform multiplication using repeated addition, although some direct multiplication machines incorporated what was effectively a set of mechanical multiplication tables for single decimal digits. Ludgate, who mayor may not have known of such machines, went for a novel–indeed, as far as I know, unique–scheme for multiplication, based on what a contemporary delightfully termed "Irish Logarithms" (Boys 1904). Multiplication involved converting all the digits of the multiplicand and a single digit of the multiplier to index numbers; the index number

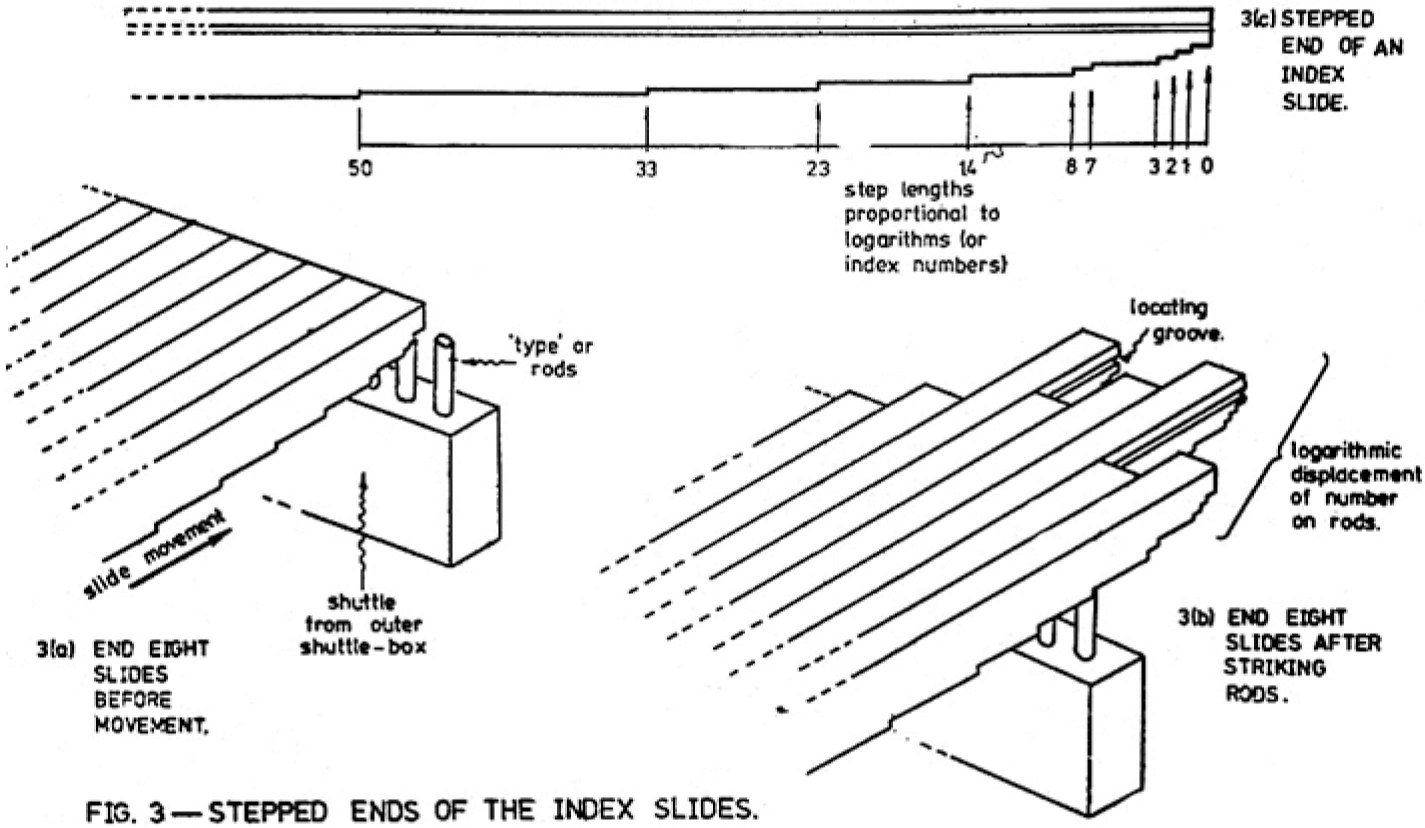

Figure 4. Ludgate's machine-conjectural drawing of arithmetic unit (Riches 1973).

corresponding to the multiplier digit was added to each of the index numbers corresponding to multiplicand digits (by additive linear motion); the results were then converted back to give a set of two-digit partial products. (The required tables are illustrated in Figure 3, and part of the mechanism is illustrated in a second conjectural drawing, Figure 4.) Ludgate's scheme for division was entirely different and equally novel. Instead of using either a conventional trial-and-error scheme of repeated subtraction and shifting, or a logarithmic scheme, he proposed a direct method, based on a series approximation. Moreover, he proposed organizing this as a built-in subroutine, using a form of read-only memory: the perforated surface of a rotating metal cylinder.

This brings me to the final aspect of Ludgate's machine–the method of sequence control, or the means by which a program determined the machine's behavior. Each row of perforations across the control tape (or formula paper, as he called it) specified an instruction consisting of an operation code, two operand addresses, and one or two result addresses. As such, the scheme was a definite advance and simplification of that proposed by Babbage and indeed has more in common with that used nearly 40 years later in the Harvard Mark I. Ludgate obviously agreed with Babbage's assessment of the crucial importance of providing a general means of conditional branching, presumably involving having a number of rows of the formula paper skipped, either forward or backward.

Incidentally, in dramatic contrast to Babbage's Analytical Engine, Ludgate's machine was to be portable, occupying approximately 8 cubic feet. It was to be capable of multiplying two 20-decimal digit numbers in about 6 seconds. Apparently, he had made detailed drawings of the machine, but had not attempted to construct it.

Figure 5. Percy Ludgate.

This, then, is a summary of the information I gleaned from the 1909 paper. But who was Ludgate, what was his environment, and what else had he done? My efforts to obtain answers to these questions soon had what seemed to me nearly all the librarians and archivists in Ireland working on my behalf. One initial report I received from an archivist stated that by all normal criteria, it was clear that Ludgate had never existed. Eventually, however, the heroic efforts of the librarian of the Royal Dublin Society, who telephoned all the Ludgates in the Dublin telephone directory, traced Ludgate's niece, who enabled me to obtain his picture (Figure 5) and to start assembling an account of his life. It turns out that he had been an accountant, who had, it is believed, done all his work on his machines in his spare time, and on his own. Highly respected by his colleagues, he was otherwise little known, and the only other significant achievement that was remembered was the major role he played in helping to organize the national provision of animal food supplies during World War I. He died in 1922 at the age of 39. No trace of his papers and drawings has been found.

The search for Percy Ludgate was immense fun, even though I obtained only about three typewritten pages of facts (see Randell 1971). I still harbor the faint hope that additional material evidence will one day turn up so that we can learn more about the life and work of this little-known inventor. In the meantime, I urge anyone who is at all interested to read Ludgate's original paper. Incidentally, Figures 2 and 4 come from an undergraduate project at University College, Swansea, which involved implementing an electronic version of a Ludgate-type arithmetic unit (Riches 1973). The project was an unexpected and unintended side effect of my historical efforts, but one that I found wholly commendable.

3. Leonardo Torres y Quevedo

I came across the work of Torres y Quevedo (Figure 6) while writing up my Ludgate investigation, a task that involved trying to document the contemporary state of the art. My introductory remarks stressed the similarities between the three inventors who are the subject of this paper. In many ways, however, Torres y Quevedo was the exact opposite of Ludgate–in particular as regards the recognition he achieved during his lifetime. Born in Santa Cruz in the province of Santander in Spain in 1852 and educated as a civil engineer, Torres became director of a major laboratory, president of the Academy of Sciences of Madrid, a member of the French Academy of Sciences, and famous as a prolific and successful inventor. Some of his earliest inventions took the form of mechanical analog calculating devices of impressive originality (see Eames and Eames 1973, pp. 66-68). He was a pioneer of radio control, and in 1906 successfully demonstrated a radio-controlled model boat (Figure 8) operating in Bilbao harbor before an admiring crowd that included the king of Spain. He received similar acclaim for his invention of a semirigid airship that was manufactured in quantity and used by both sets of military forces during World War I

(Figure 9). One of his inventions is still thriving as a tourist attraction at Niagara Falls: the Spanish Aero Car (Figure 10), originally installed in 1916. I want to concentrate, however, on the astonishing variety of digital calculating devices and automata that Torres invented.

Figure 6. Leonardo Torres y Quevedo (Santesmases 1980).

In 1911 he made and successfully demonstrated (Scientific American Suppl. 1915) a chess-playing automaton for the end game of king and rook against king (Figure 7). This chess automaton, believed to have been the world's first (the one earlier apparent chess automaton, exhibited by von Kempelen, turned out to have small human operator hidden inside it; see Chapuis and Droz 1958), was fully automatic, with electrical sensing of the pieces on the board and what was in effect a mechanical arm to move its own pieces. Some years later Torres made a second chess automaton, which used magnets underneath the board to move the pieces. Like a number of his other inventions, this one still exists and is still operational. Figure 11 shows Torres's son Gonzalo demonstrating the automaton to Norbert Wiener.

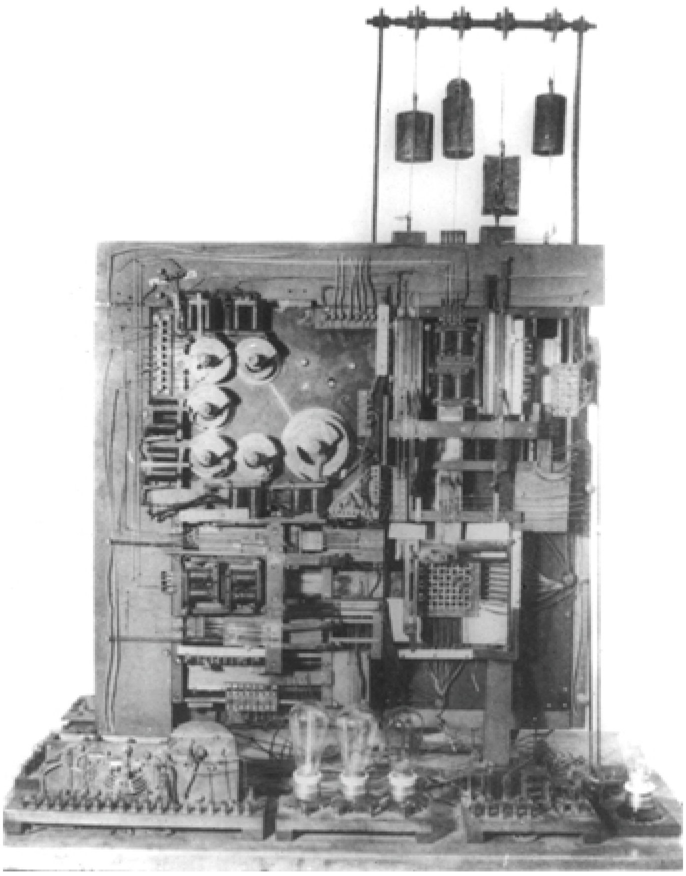

Figure 7. Chess automaton (Santesmases 1980).

Torres y Quevedo's major motivation in all his work appears to have been to exploit, to the full, the new facilities that electromechanical techniques offered, and to challenge accepted thinking as to the limitations of machines. His attitude was well summarized in the Scientific American account (1915) of the first chess automaton.

> There is no claim that [the chess player] will think or accomplish things where thought is necessary, but its inventor claims that the limits within which thought is really necessary need to be better defined, and that an automaton can do many things that are popularly classed with thought. It will do certain things which depend upon certain conditions, and these according to arbitrary rules selected in advance.

Torres's major written work on this subject is the fascinating "Essays on Automatics" (1913), which well repays reading even today. The paper

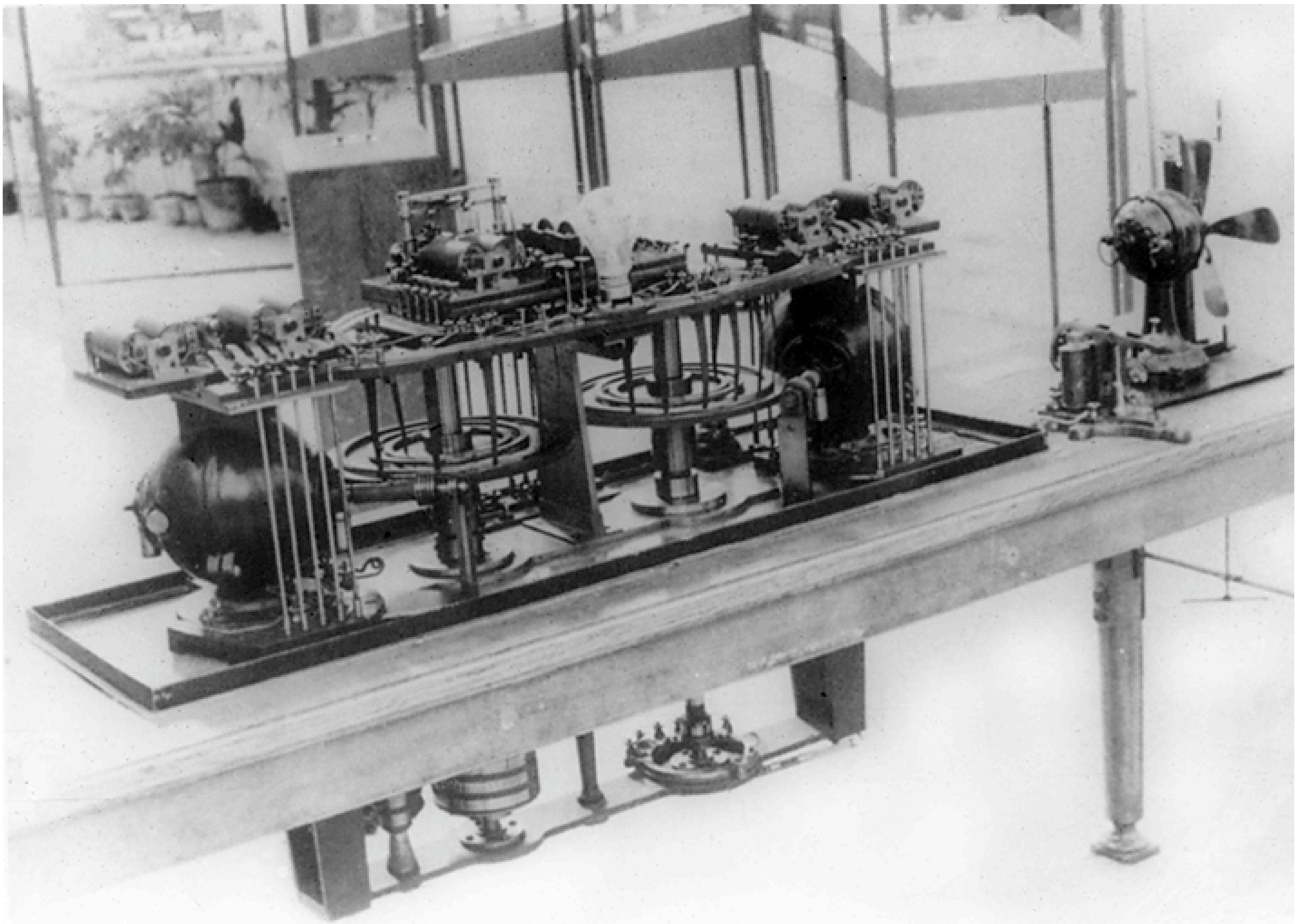

Figure 8. Radio-controlled boat (Santesmases 1980).

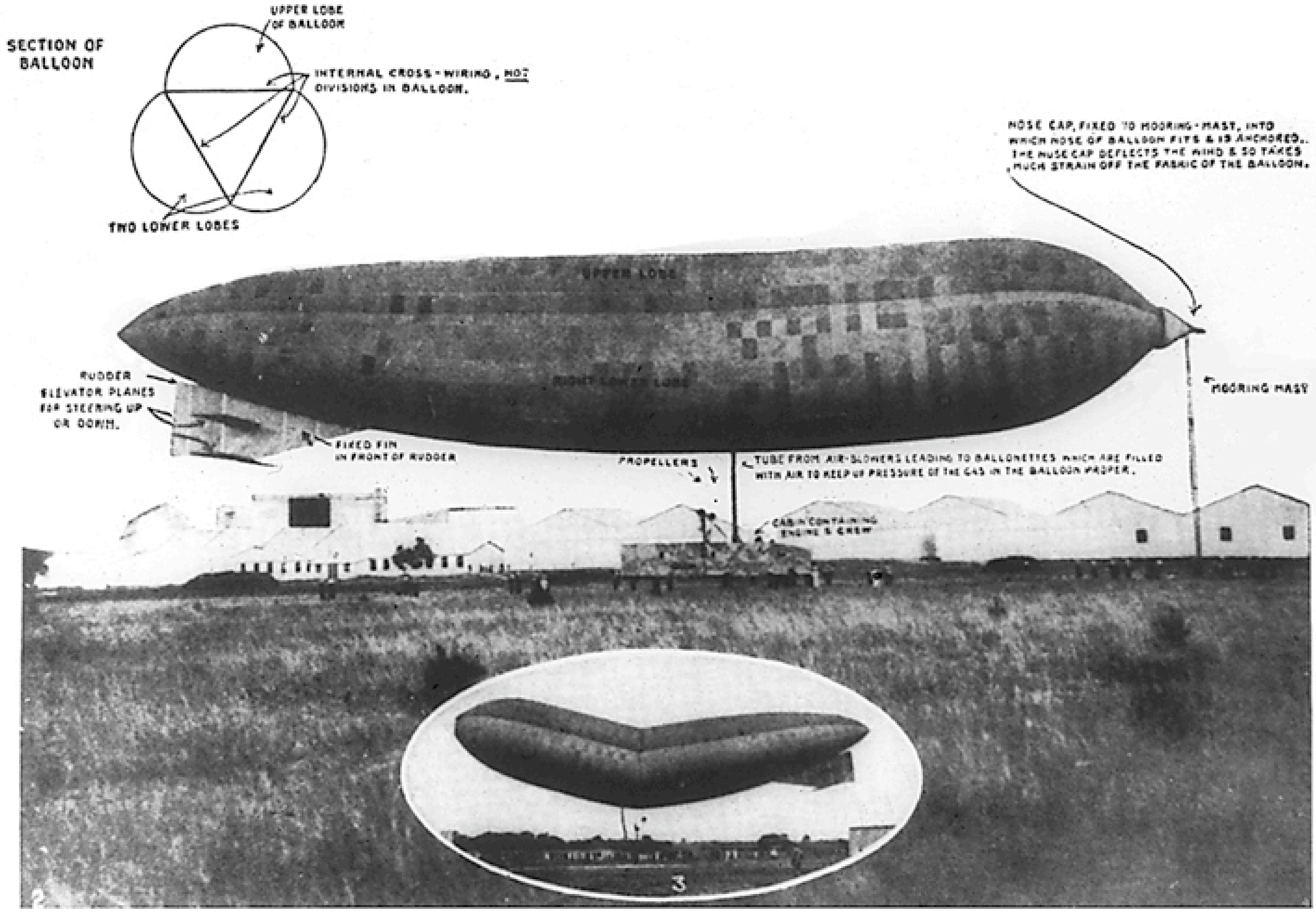

Figure 9. Semi-rigid airship (Santesmases 1980).

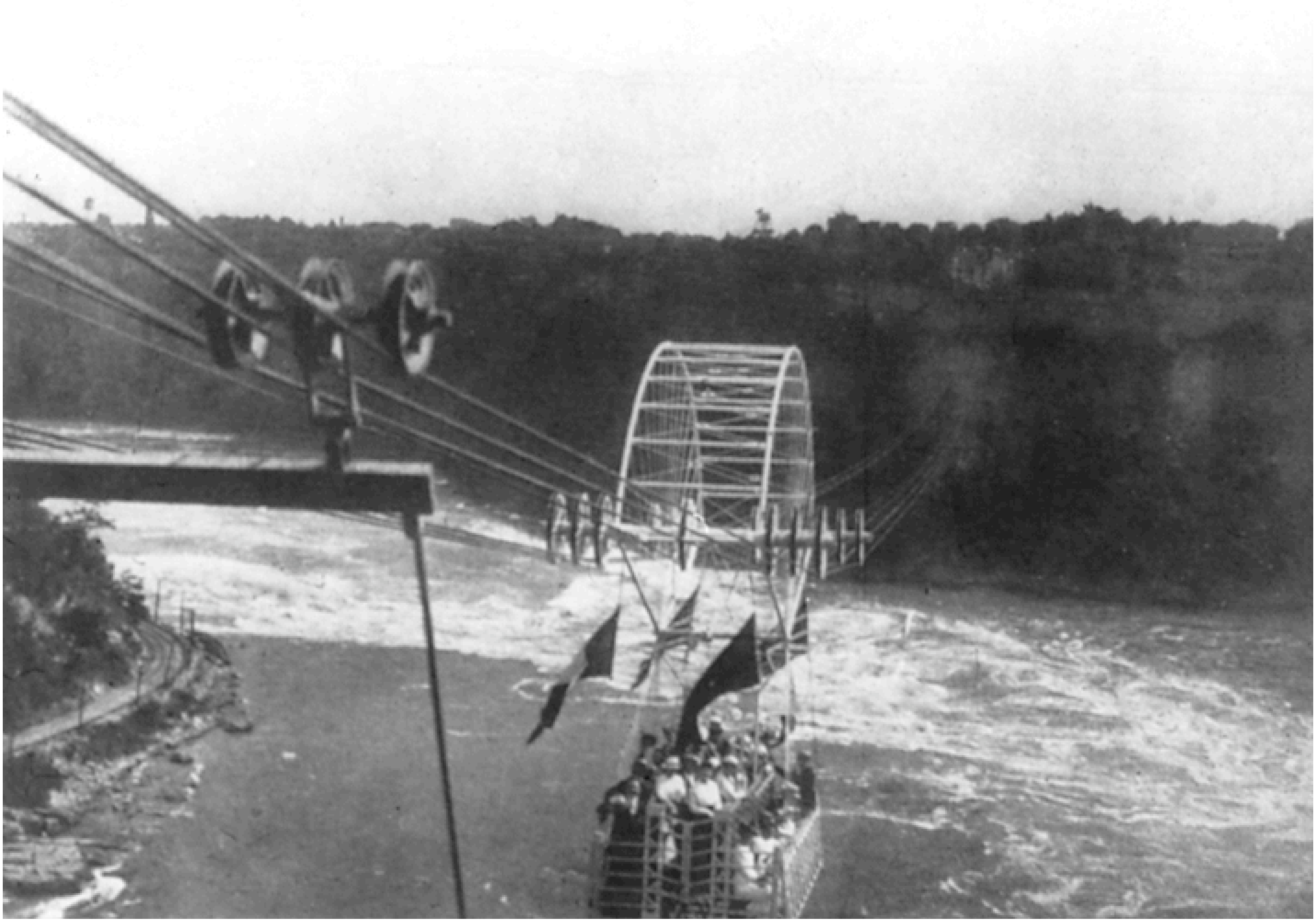

Figure 10. Spanish aero car (Homenaje 1977).

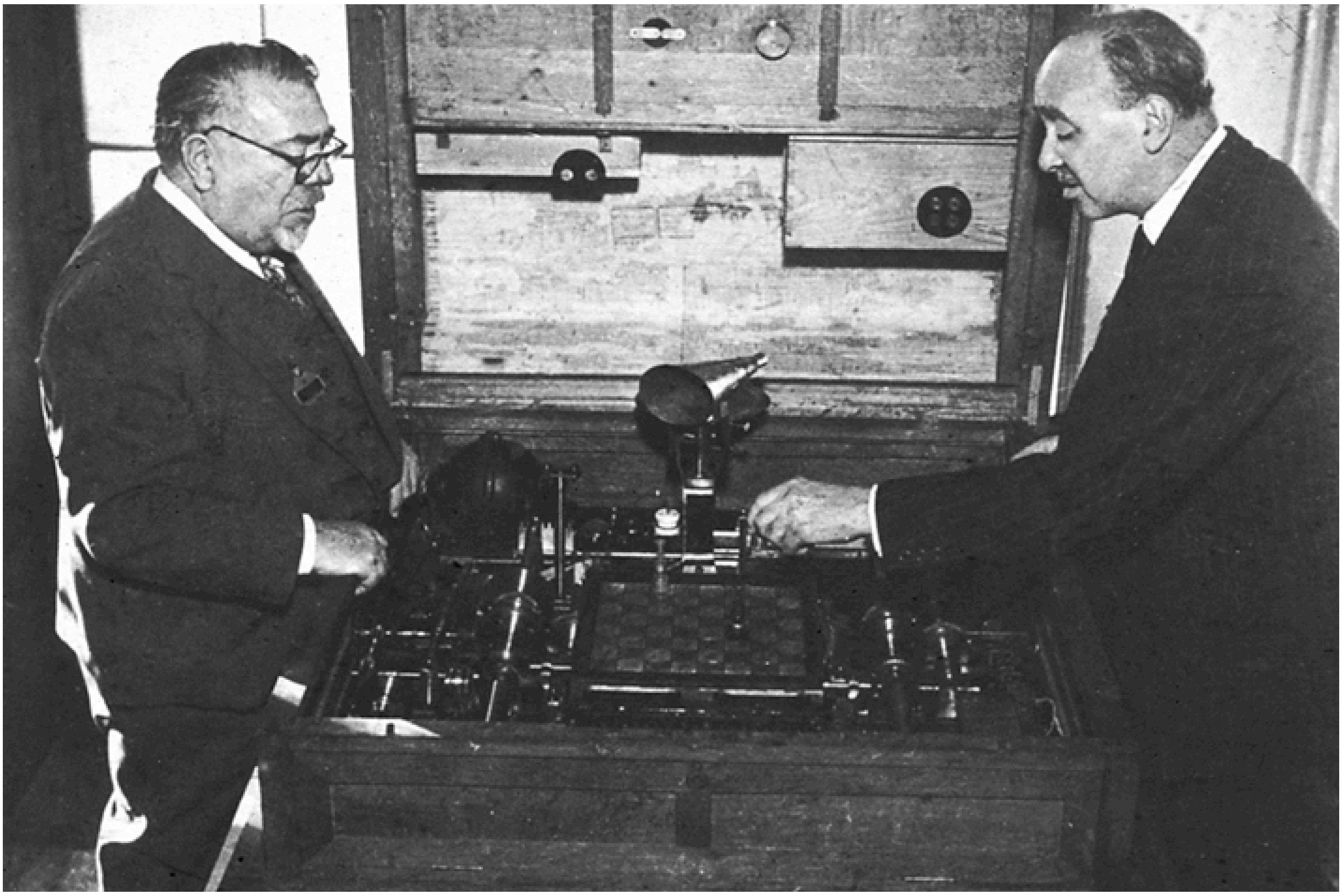

Figure 11. Gonzales Torres y Quevedo demonstrating the chess automaton to Norbert Wiener in 1951 (Eames and Eames 1973).

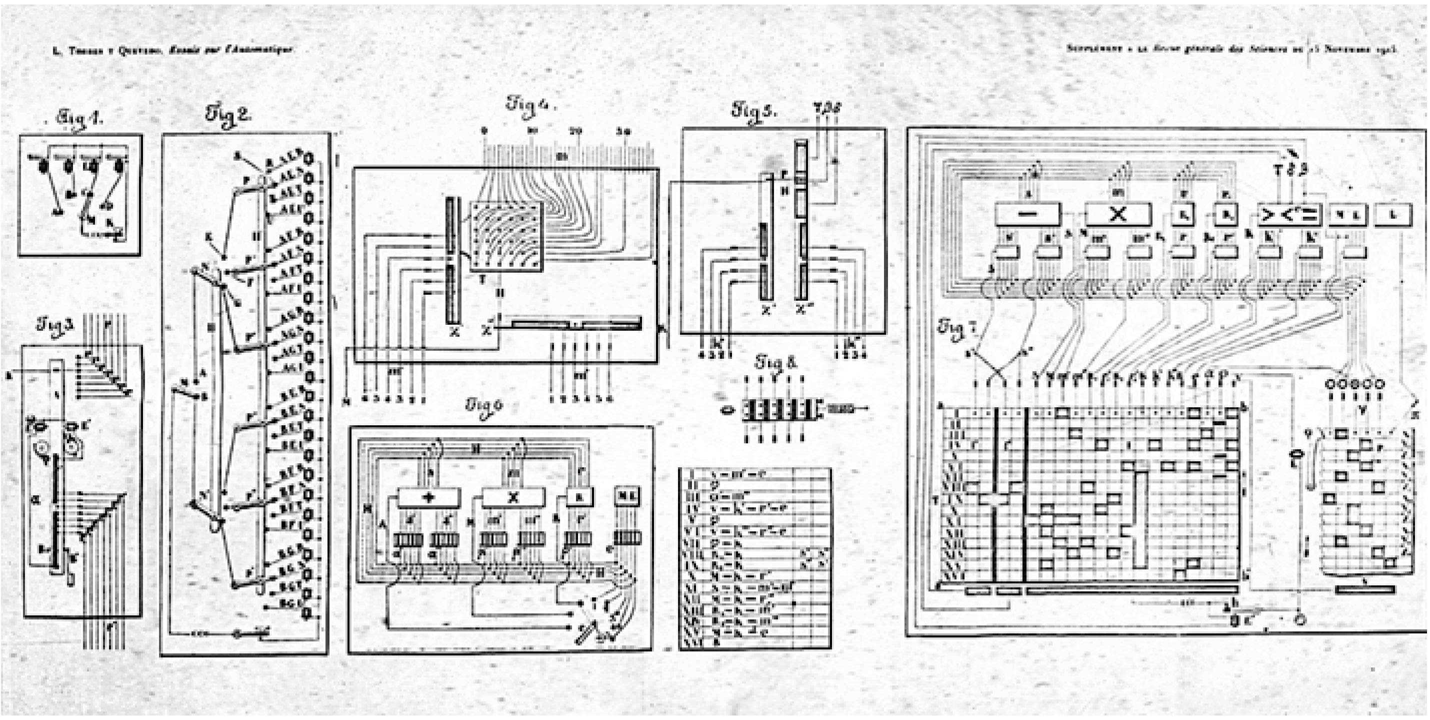

Figure 12. Automaton to calculate $a \times (y - z)^2$.

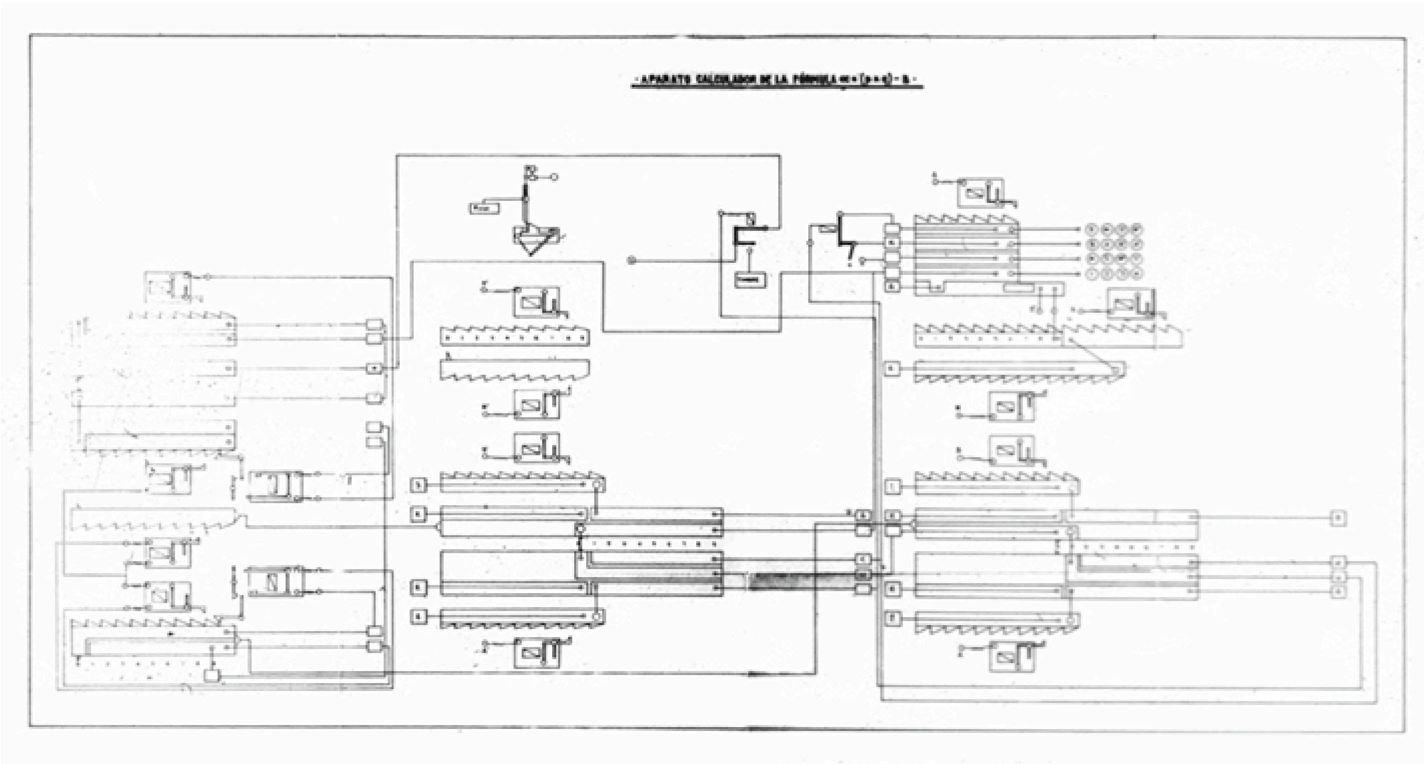

Figure 13. Drawing of 1914 analytical machine (Colegio 1978).

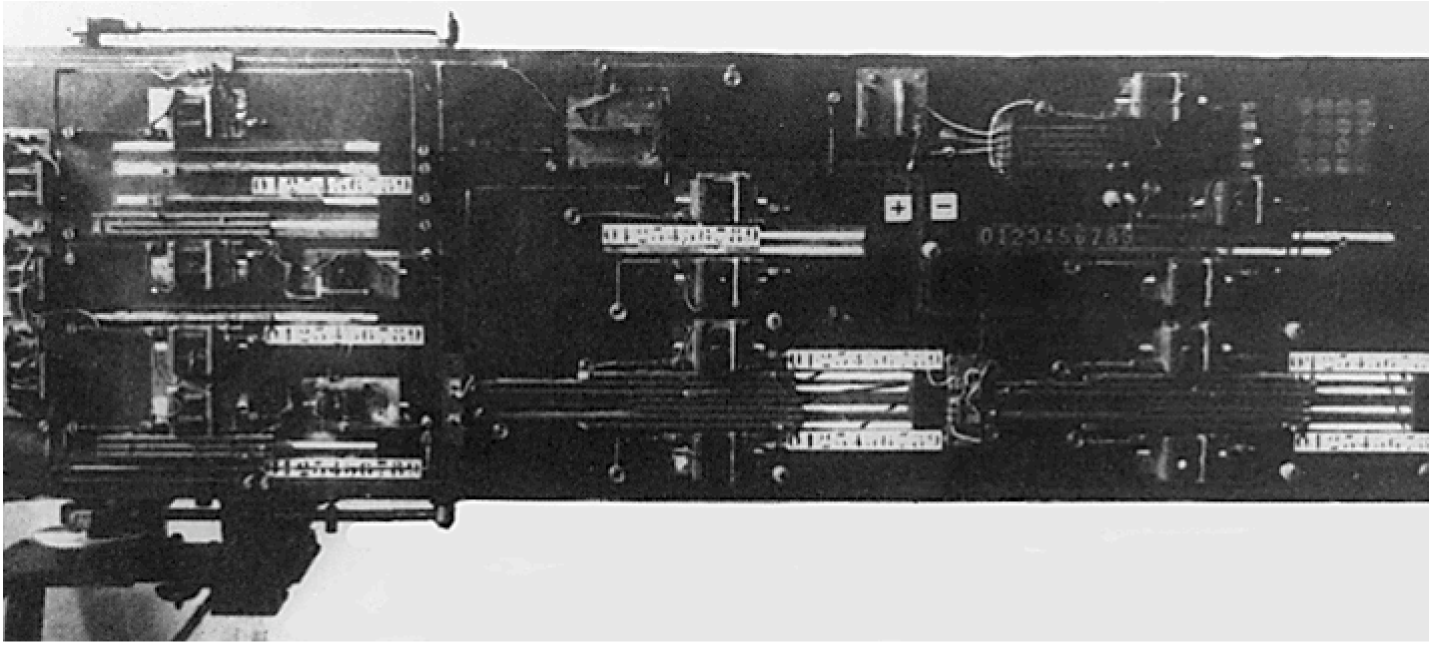

Figure 14. Analytical machine of 1914 (Colegio 1978).

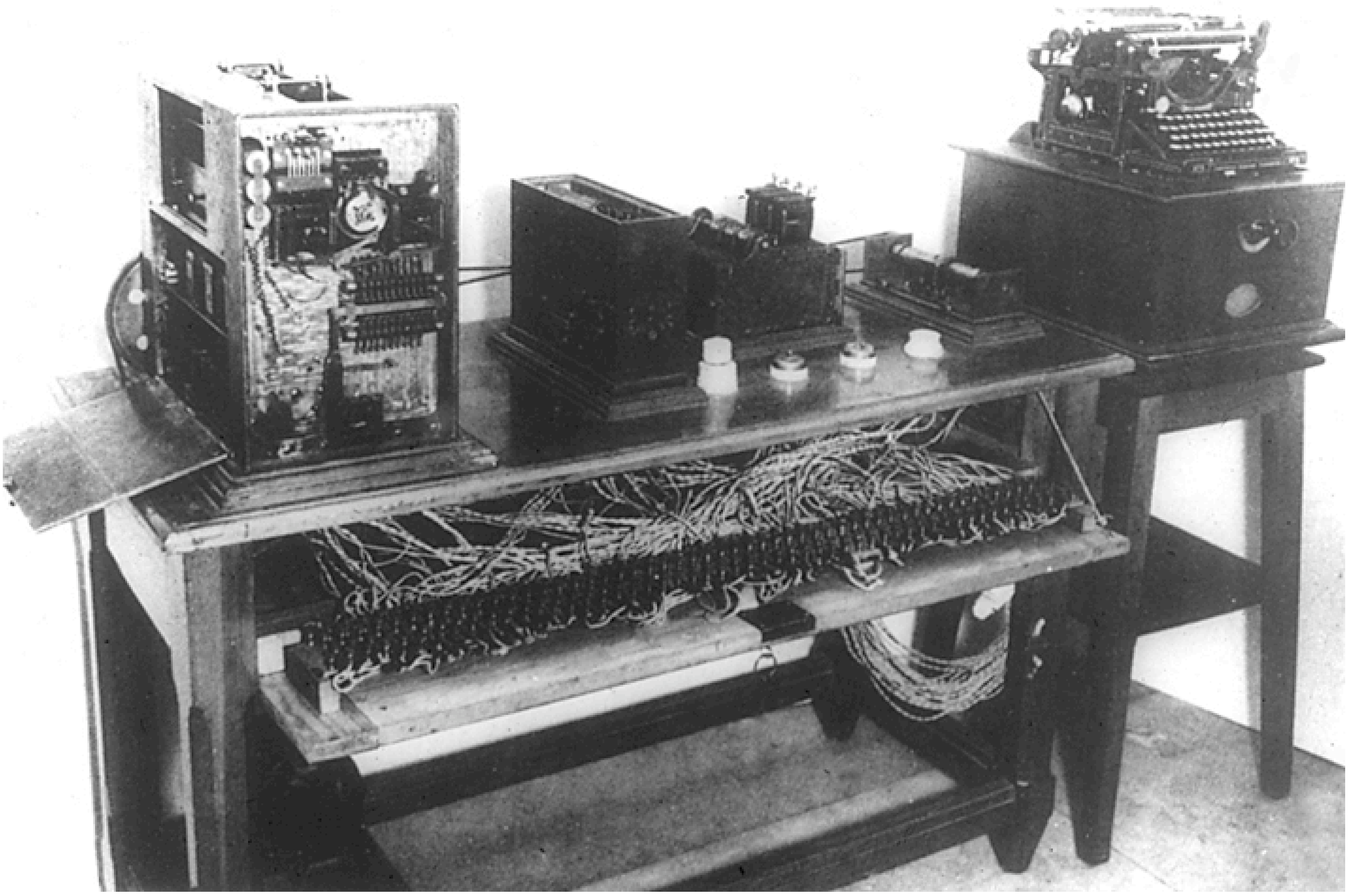

Figure 15. Arithmometer of 1920 (Santesmases 1980).

provides us with the main link between Torres and Babbage. Torres gives a brief history of Babbage's efforts at constructing a mechanical Difference Engine and Analytical Engine. He describes the Analytical Engine as exemplifying his theories as to the potential power of machines, and takes the problem of designing such an engine as a challenge to his skills as an inventor of electromechanical devices. The paper in fact contains a complete design (albeit one that Torres regarded as theoretical rather than practical) for a machine capable of calculating completely automatically the value of the formula $a \times (y - z)^2$, for a sequence of sets of values of the variables involved. It demonstrates cunning electromechanical gadgets for storing decimal digits, for performing arithmetic operations using built-in function tables, and for comparing the values of two quantities. The whole machine was to be controlled from a read-only program (complete with provisions for conditional branching), represented by a pattern of conducting areas mounted around the surface of a rotating cylinder (Figure 12). Incidentally, the paper also contains, almost casually, what I believe to be the first proposal of the idea of floating-point arithmetic!

The paper ends with a comparison of the advantages of electromechanical devices over the sort of mechanical devices that were all that were available to Babbage. It establishes, to my mind at least, that Torres y Quevedo would have been quite capable of building a general-purpose electromechanical computer, more than 20 years ahead of its time, had the practical need, motivation, and financing been present.

This opinion need not rest solely on the fact that Torres documented a plausible theoretical design, however, because it turns out that he went ahead to prove his point with a series of working prototypes. Possibly the first was a demonstration machine, capable of evaluating $p \times q - b$ (Figures 13 and 14). How successful this was in practice we do not know. In 1920 Torres must have removed any uncertainty, because he startled the attendees at a Paris conference, marking the centenary of the invention of the first really practical calculating machine, with a demonstration of his electromechanical arithmometer (Torres y Quevedo 1920). This machine consisted of an arithmetic unit connected to a (possibly remote) typewriter, on which commands could be typed and the results printed automatically (Figure 15). Torres apparently had no thought of making such a machine commercially, viewing it instead as a means of demonstrating his ideas and techniques. Thus we can only speculate on what might have happened if he had gone ahead and made a full-scale computer, or even if his writings had become better known to the English-speaking world. As it turned out, his work had little discernible effect on later developments leading to the modern computer. In all other respects, his career must surely be judged as a very successful one, and one that deserves much wider appreciation outside Spain. His fame rests secure within Spain, where a laboratory has been named after him, books have been written about him (Rodriguez Alcalde 1966; 1974; Santesmases 1980) and a number of his machines, some still in working order, are on exhibition at the Colegio de Ingenieros de Caminos, Canales y Puertos (1978) in Madrid.

4. Vannevar Bush

Torres y Quevedo died in 1936, the year in which the third and final subject of this paper, Vannevar Bush, then aged 46, wrote the paper that first caused me to take an active interest in his career. I should apologetically explain that I have, from the start, made a point of limiting my historical investigations to digital devices and have deliberately ignored the field of analog computers. In this latter field, of course, Vannevar Bush, as inventor in 1930 of the first differential analyzer (Figure 16), is preeminent.

Bush's 1936 paper, entitled "Instrumental Analysis," and given as the American Mathematical Society's Gibbs Lecture that year, was an excellent survey of both analog and digital calculating devices. It included several references to Babbage's work and in particular to the collection of papers published by Babbage's son (1889). The section on digital devices concluded with a discussion of how it might be possible to devise a programmable master controller that would turn a set of existing IBM punched-card machines into, effectively,

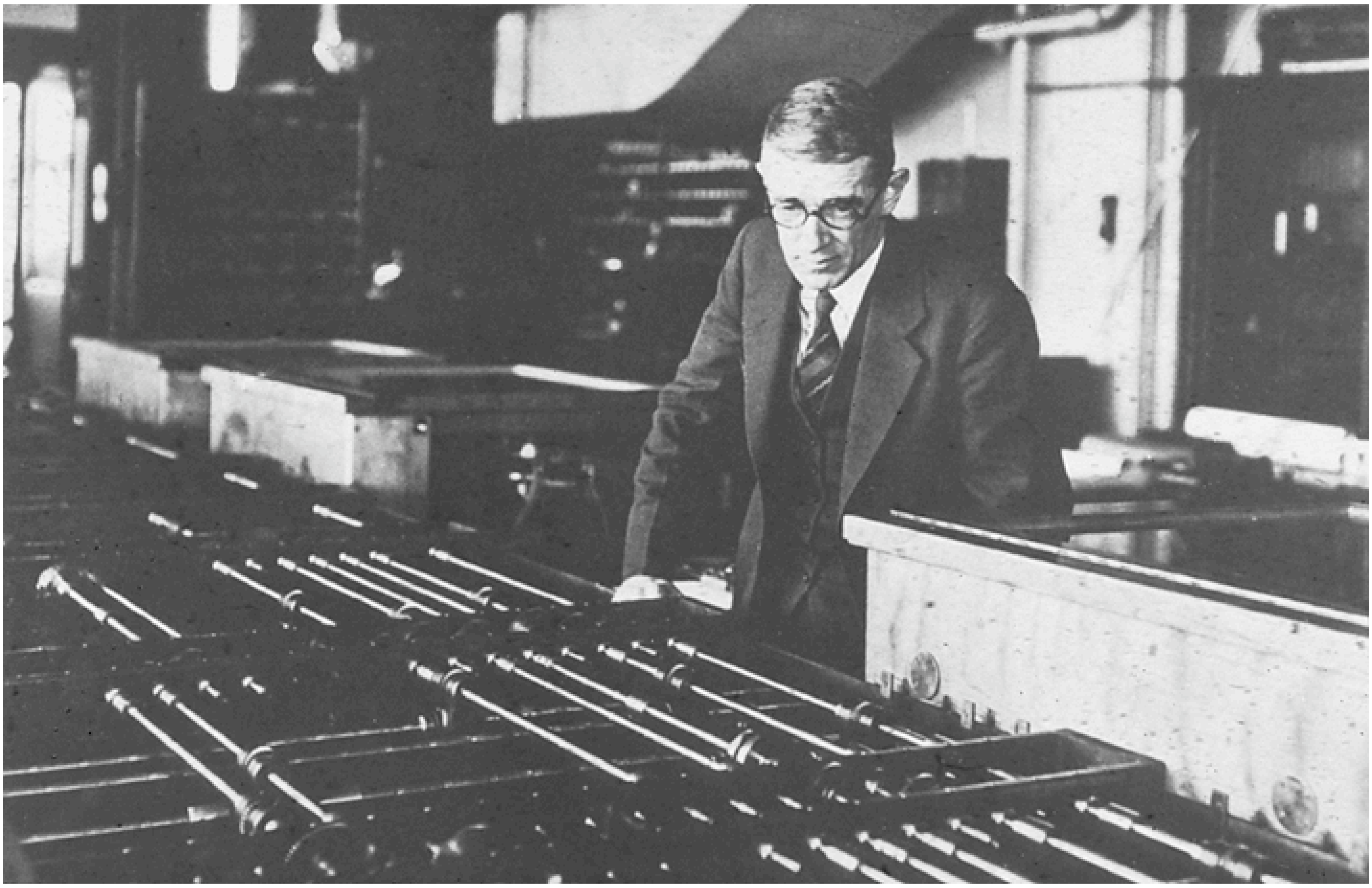

Figure 16. Vannevar Bush and the differential analyzer (Eames and Eames 1973).

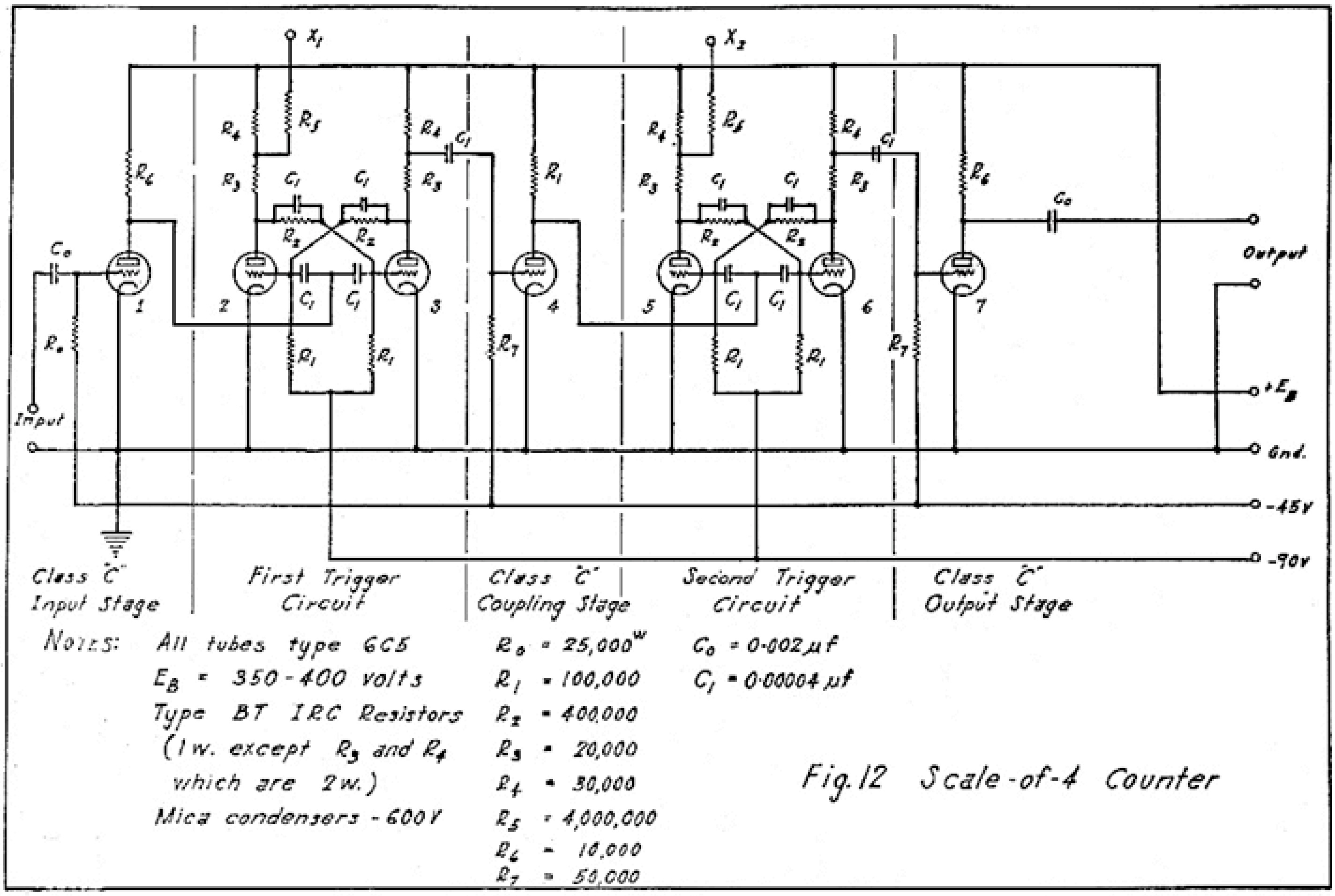

Figure 17. Drawing of scale-of-four counter.

what Bush describes as "a close approach to Babbage's large conception." (In many ways, of course, this is exactly what Aiken, starting in 1937, convinced IBM to do, thus starting a project that led to the successful completion in 1944 of America's first program-controlled calculator, the Harvard Mark I.)

It turns out that Bush did not stop at speculation, but went on to set up a project, the first one in the world as far as I know, to investigate the problems of constructing an electronic digital computer. The very existence of this project, the Rapid Arithmetical Machine, is astonishingly little known. Bush himself in his later years had either forgotten, which seems unlikely, or consciously downplayed the significance of this work. Indeed, in his autobiography, *Pieces of the Action* (1970), he wrote, "Who invented the computer? I can write at once that I did not, in fact I had little to do with that whole development."

When Bush died in 1974, papers such as the *New Yark Times* carried lengthy accounts of his most impressive career (see Reinhold 1974). They detailed his many inventions, his illustrious academic career at MIT and the Carnegie Institute, and, perhaps most important, his vital wartime role as director of the National Defense Research Committee, and later of the Office of Scientific Research and Development.

This office directed the work of some 30,000 scientists and engineers, working on everything from radar, proximity fuses, and amphibious vehicles to the atom bomb.

Bush's work on information retrieval, and in particular his farsighted Memex proposal (1945) for a completely automatic personal information-retrieval machine, is well known–although it is perhaps only now becoming close to being realized via networks of personal computers. (His first actual attempt at construction of an information-retrieval device, the Rapid Selector Machine, which scanned microfilm to select pages carrying relevant index codes, was thought to have been abandoned prior to completion until Bush revealed in his autobiography (1970) that the device had become the basis for a hitherto highly classified project for one of the United States' code-breaking agencies.)

Yet the Rapid Arithmetical Machine project had been forgotten. It was rediscovered during the extensive historical investigations undertaken in connection with the patent litigation between Univac and Honeywell over the validity of the ENIAC patent–litigation that lasted six years and involved testimony by over 150 witnesses and 30,000 pieces of evidence, ranging from a single sheet of paper to a file-cabinet full. Bush's project played only a very small role in the evidence and the testimony, perhaps because none of the MIT people directly involved in the project testified at the trial. Indeed, the Rapid Arithmetical Machine project was not mentioned in the 319-page volume entitled *Findings of Fact, Conclusions of Law and Order for Judgment* (Larson 1973) that was the sole official publication resulting from the litigation. (These findings gave belated recognition and publicity to the work of John V. Atanasoff at Iowa State University and, to a lesser degree, to other early work at NCR, IBM, and Bell Laboratories.) Thus I can perhaps be forgiven for the fact that my book *The Origins of Digital Computers* (Randell 1973) lacks any reference to the project. It was only after the book was published that I learned, in part through the work of Karl L. Wildes, who is preparing a history of the Departments of Electrical Engineering and Computer Science at MIT, of the Rapid Arithmetical Machine project.

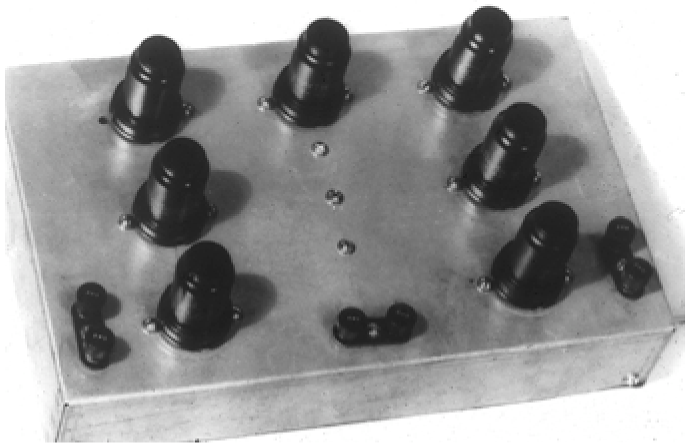

Figure 18. Scale-of-four counter.

Immediately after he delivered his 1936 paper, Vannevar Bush apparently started to work on the design of an electronic digital computer. There is evidence that he documented these ideas in a series of memoranda written during

1937 and 1938 but, despite extensive searches, these have not been found (see my account, "The Case of the Missing Memoranda, " in the *Annals*, Volume 4, Number 1, pp. 66-67). What we know of them comes from later MIT reports by W. H. Radford (1938; 1939) and from some letters and one 1940 memorandum by Bush.

The machine was to be completely automatic, able to read data on perforated paper tape, to store the data in internal registers, to perform any of the four basic arithmetic operations, and to print the results of its calculations. It was to be controlled by a program represented on perforated tape. Each row of holes would consist of several fields that together constituted one instruction. Each field could contain but a single punched hole, whose position indicated directly which operation was to be performed, say, or which storage reservoir was to provide the operand. There was apparently no thought of having numerically coded addresses, nor of providing means of conditional branching.

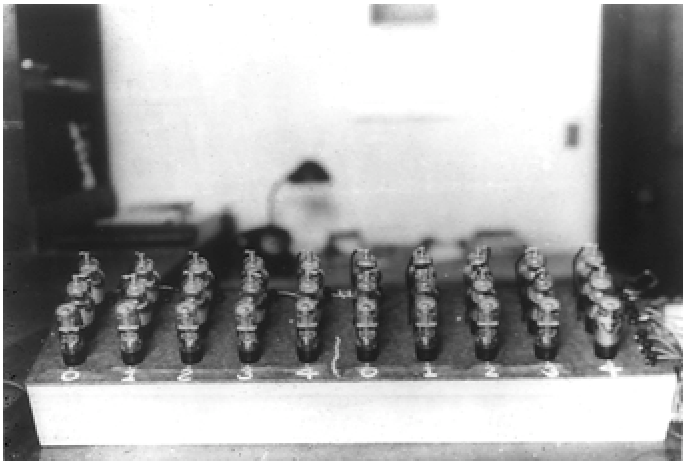

Figure 19. Stepping ring

The machine was in fact to use three perforated tapes: the A (or data) tape, the B (or constant) tape, and the C (or program) tape. Each row of holes on the A tape was expected to contain the set of input data needed for one calculation (comprising the sequence of operations represented by the C tape). Thus the C tape would be read repeatedly, once for each set of input data on the A tape. The B tape was stationary during calculation, with each row being opposite its own reading head. It thus acted as the information in what we would now term a random-access read-only memory. Registers and arithmetic units were to be completely electronic, but relays were to be used in connection with input/output and program control.

Support was obtained from the National Cash Register Company, and later from the National Defense Research Committee, for the full-time employment of first Radford and then W. P. Overbeck on the project. Radford's work concentrated on the design of the basic electronic units. Various units were built and demonstrated successfully, including a scale-of-four counter (Figures 17 and 18) and a stepping ring–the means proposed for storing each decimal digit (Figure 19). Bush's 1940 memorandum reviewing progress to date contains estimates that the machine would be able to multiply two six-decimal digit numbers in about 0.2 second, assuming a basic pulse rate of 10,000 per second.

Overbeck took over in late 1939 and spent the next year or so devising special-purpose tubes in an attempt to reduce the number of vacuum tubes needed. Work on the project came to an abrupt and premature end in early 1942, when Overbeck was claimed for work on the atomic bomb project.

The documents described earlier indicate that by 1939 MIT had a world lead in what turned out later to have been a race to develop the first electronic digital computer. This accolade is normally given to the ENIAC, completed in late 1945 at the University of Pennsylvania's Moore School of Electrical Engineering by a team led by J. Presper Eckert and John W. Mauchly. The ENIAC was in fact preceded by two years by the highly secret, and only recently revealed, Colossus machines–special-purpose electronic digital computers developed in Britain for breaking German ciphers (see Randell 1980). The chief designer of the Colossus was T. H. Flowers (see a future issue of the *Annals* for his story), who kindly reviewed the Bush and Radford reports for me. He concurred with my assessment and stated (1979): "These reports show clearly that by the early 1940s Bush, Caldwell and MIT were on the right lines and amongst the world leaders in the application of electronics to switching and control problems. I have no doubt that their proposals were practical and hardly any doubt that if continued would ultimately have produced something like the ENIAC."

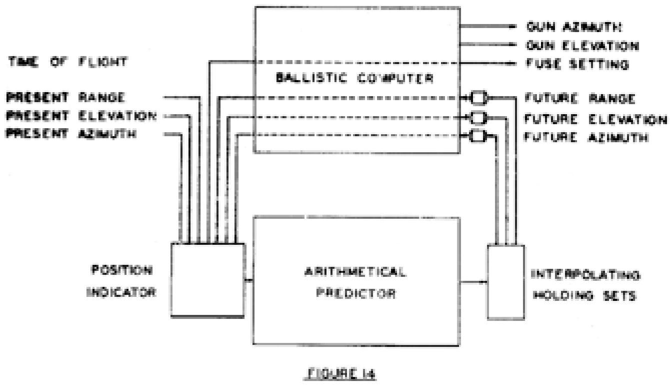

Figure 20. Fire-control system (Crawford 1942).

By 1943, therefore, MIT was temporarily out of the race, and the lead was being assumed by the Moore School. The Rapid Arithmetical Machine project in fact had some influence, however. One of the MIT students who became interested in it, and took its work as a basis for his own M.Sc. research, was Perry Crawford. His thesis (1942) contains a fairly detailed design of a special-purpose electronic digital calculator, intended for on-line prediction of the future position of a moving target, so as to enable automatic control of an antiaircraft gun (Figures 20 and 21). His calculator would have incorporated an electronic multiplier and function generator, as well as a primitive form of magnetic disk memory. Eckert has since stated (1980) that he and Mauchly were prompted by this report to propose the use of a magnetic disk for storing both data and instructions, in what was arguably the first documented proposal for a stored-program computer. More directly, it was Crawford who played a major role in persuading the team at MIT led by Jay W. Forrester, which was working on an analog computer intended for an aircraft simulator, to abandon analog techniques in favor of digital electronics (Redmond and Smith 1980, p. 33). Crawford therefore was pivotal in the development of MIT's Whirlwind computer since this is what Jay Forrester and his team went on to produce. Whirlwind, of course, was one of the most influential of the early American computers, starting a whole generation of real-time and later minicomputer projects, and incidentally reestablishing MIT as a leading center for computer research.

Thus, although Whirlwind obviously also benefited greatly from the work of other pioneers such as Eckert, Mauchly, and John von Neumann, I believe it also owes a debt to Vannevar Bush, the man who claimed to have had nothing to do with the invention of the digital computer. Bush therefore, alone among the three pioneers I have been discussing, can be seen to have done work that was not only splendidly inventive and ahead of its time-worthy, indeed, of their common predecessor and inspiration, Charles Babbage but also that can be argued to have had at least an indirect influence on the course of the development of the modern computer.

5. Concluding Remarks

I do not feel it necessary or appropriate to make a judgment on the relative contributions of these three very worthy successors to Charles Babbage. All three demonstrated great skill, insight, and originality; they were well ahead of their time. In fact, perhaps that was the single most important reason for their work having so little obvious direct impact, and hence being so little known, that I have felt spurred to devote this paper to it.

In 1864 Babbage wrote,

> The great principles on which the Analytical Engine rests have been examined, admitted, recorded and demonstrated. The mechanism itself has now been reduced to unexpected simplicity. Half a century may probably elapse before anyone without those aids which I leave behind me will attempt so unpromising a task. If, unwarned by my example, any man shall undertake and shall succeed in really constructing an engine embodying in itself the whole of the executive department of mathematical analysis upon different principles or by simpler means, I have no fear of leaving my reputation in his charge, for he alone will be fully able to appreciate the nature of my efforts and the value of my results. (Babbage 1864)

Although none of my trio actually completed an analytical engine or, as we would now term it, a general-purpose digital computer, I am sure

Babbage would have shared my enthusiasm for their efforts and would have been delighted to see his reputation in such good hands.

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