Trailblazers in Electromechanical Computing

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Massimo Guarnieri

Over the last six decades, electronic computing has been thoroughly integrated into the field of science and technology to become a fundamental tool for study, research, and design. Developing into vacuum tube, transistor, integrated circuit, and microprocessor technologies, electronics has boosted an amazing growth in computing power [1]. The commissioning in 2016 of the all-Chinese Sunway TaihuLight with a computing power of 93 PFLOPS (10^{15} floating point operations per second), two and a half times larger than the previous top world supercomputer, the Chinese Tianhe-2 of 2013 powered with Intel processors, suggests that the evolution is still far from saturation. It is intriguing to wonder what automatic computing was like before electronics enabled this boost in computing power. Indeed, the search for mechanical tools aimed at relieving the burden of computing reaches far back in the past, at least to ancient times when the abacus was built. However, with electricity this possibility took a major leap forward.

The son of a German immigrant, Herman Hollerith (1860–1929) graduated with a degree in mining engineering in 1879 and joined the Massachusetts Institute of Technology (MIT) in Cambridge in 1882, where he taught mechanical engineering while researching on automated data recording and processing. He encoded data by means of holes punched in specific positions of a card. Similar cards had already been used in Charles Babbage's uncompleted mechanical "Analytical Engine" of 1837, which were inspired by the Jacquard loom technology of 1801. Hollerith's new idea was to use conductive needles that, passing through the holes, touched the underlying plate, thus closing electrical circuits that advanced the electromagnetic pointers in dial indicators (Figure 1). In this way, data reading and recording were greatly accelerated [2]. Hollerith patented the tabulator in 1889. The late 19th century experienced a surge of immigration in the United States, and the Federal Census Bureau was required to do a huge amount of work every ten years. The manual counting of 1880 had required almost eight years to complete, and in the meantime the population experienced strong growth, banishing the helpfulness of the census results. The use of Hollerith's tabulator dramatically reduced the time needed for the 1890 computation. Hollerith founded the Tabulating Machine Company in 1896 and sold its machines in several countries worldwide. In 1901, he patented the first automatic keypuncher to speed up operations. In 1911, the company and three other firms were consolidated into the Computing-Tabulating-Recording Company, which became International Business Machines (IBM) in 1924. In 1928, astronomer Leslie John Comrie (1893–1950) first used IBM punched-card equipment in scientific research for computing astronomical tables by means of the finite differences method. Soon after, IBM modified its tabulators to facilitate this kind of computation.

FIGURE 1 – The counter dials of the Hollerith tabulator first used for U.S. census data processing, 1890. (Photo courtesy of Wikimedia Commons.)

Hollerith's tabulator of 1890, the first successful electric computing machine, used digital binary logic (hole/full), naturally suited to manage discrete census data (e.g., male/female, single/married, number of children, and so on). Forty years later, Vannevar Bush (1890–1973) adopted a different approach for different problems, building on the pioneering work of other researchers (e.g., Lord Kelvin's brother James Thomson and Ernesto Pascal). Electrical networks were then expanding and interconnecting to get smoother generation demand and to provide better supply quality [3], but they remained prone to frequent blackouts. The study of efficient countermeasures called for complex network analyses, which could hardly be solved by hand, also resorting to reduced-order methods such as nodal and mesh analyses.

In 1927, Bush directed the construction of a machine capable of solving systems of 18 ordinary differential equations, as encountered in such problems. It was an analog mechanical computer based on interconnected integrators, in which the quantities to be calculated were represented through physical quantities (distances and angular positions) with analogous behavior, rather than in digital form. It was followed in 1931 by an upgraded electromechanical model, dubbed the *differential analyzer*, which gained remarkable success and was replicated in other research centers [4] (Figure 2). A full electric version was developed before World War II and was used in wartime for computing the U.S. Navy artillery firing tables.

Bush was one of the most eminent U.S. technologists of the 20th century. He joined MIT in 1919, becoming its vice president in 1932 and honorary president in 1962. He founded the defense contractor Raytheon in 1922, was a U.S. presidential advisor from 1934 to 1951, chairman of the National Defense Research Committee, and director of the Office for Scientific Research and Development from 1941 to 1947. In these positions, he promoted the development of U.S. radar, submarine devices, amphibious vehicles, and the atomic bomb under the Manhattan Project.

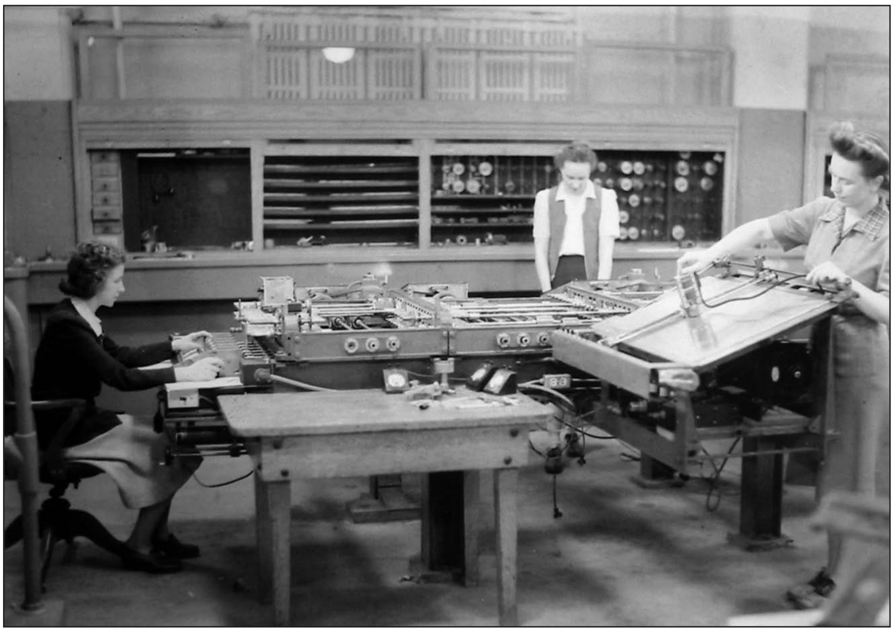

FIGURE 2 — A differential analyzer at the Moore School of Electrical Engineering, University of Pennsylvania, Philadelphia, circa 1942–1945. (Photo courtesy of Wikimedia Commons.)

Electromechanical relays have played a pivotal role in electrical telecommunications since their invention. From the 1830s, they were used by Davy, Morse, and others for telegraph signal regeneration, a kind of digital amplification against long-distance attenuation, thus allowing transmission as far as was wanted. Telephone networks, namely, analog communication, made use of relays in automatic telephone exchanges from 1892. In the 1930s, they were widely diffused in such devices and hardly replaceable to the eyes of most technologists.

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In 1937, George Robert Stibitz (1904–1995), then a researcher at Bell Lab, the leading U.S. communication research center, located in New York City, took home from work some spare electromechanical relays and other components and built a crude digital adder calculator dubbed *Model K* (with the letter *K* standing for kitchen, the room in which he was standing when he constructed it) [6]. Exploiting the relay's two states (open/closed) it operated in binary digital logic and proved that such circuits could handle the binary math introduced by Juan Caramuel y Lobkowitz in 1670 and described by Gottfried Wilhelm von Leibniz in 1679. Bell Labs authorized Stibitz to start a research program with Samuel Williams that resulted in the Complex Number Computer (later Model I Relay Calculator) in 1939. It was capable of computing on complex numbers, as its name suggests, but it was also structurally complex. In fact, it included 3,000 relays and 800 km of cables. The following year, Stibitz demonstrated the machine from 360 km away via a telegraph line, thus establishing the first remote connection. It was Stibitz who proposed in 1942 the term *digital,* with the meaning now commonly used.

In 1937, mathematician Howard Hathaway Aiken (1900–1973) of Harvard University, Cambridge, Massachusetts, inspired by Babbage's analytical engine of 1837, conceived an electromechanical digital computer originally named the *Automatic Sequence Controlled Calculator*. It was built with the financial and technical support of IBM and became operative in 1944 [7]. Renamed *Harvard Mark I*, it was 16-m long, 4.5 tons in weight, and consisted of 765,000 electrical and mechanical components, including switches,

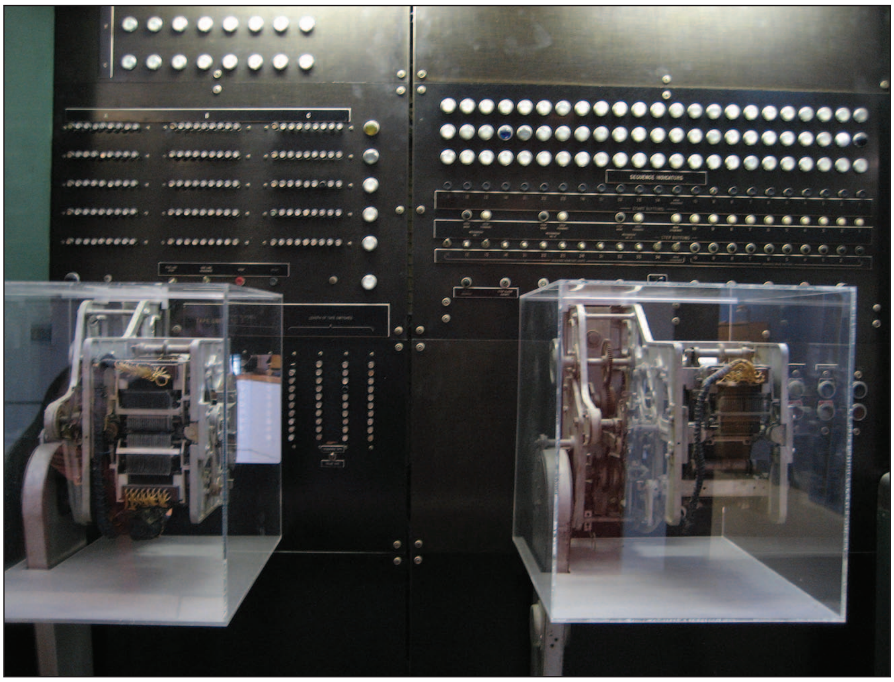

FIGURE 3 — A close-up of input/output and control readers of Aiken's Harvard Mark I, 1944. (Photo courtesy of Wikimedia Commons.)

relays, rotating shafts, clutches, gears, and ten-position wheels representing the ten digits, as it used decimal logic (Figure 3). It was programmable, the program being stored on a punched paper strip (the first U.S. stored-program machine), and used IBM punched cards for data entry. It could handle every mathematical and scientific problem, store 72 23-digit numbers, and compute a multiplication in 6 s and a division in 15.3 s. It was used by the U.S. Navy to perform ballistic calculations for firing tables, described by linear differential equations. Mathematician John von Neumann used it in the calculations of fissile material implosion for the Manhattan Project. Mark I was followed by Mark II (also an electromechanical machine, 1947), Mark III (partially electronic, 1949), and Mark IV (all electronic, 1952).

In the 1930s and 1940s, the exploitation of electromechanics in numerical analyses was not only an American achievement. In 1938, Polish cryptologist Marian Adam Rejewski (1905–1980) and coworkers built a machine dubbed *Bomba* for breaking the messages encrypted by the German electromechanical machine Enigma, whose three 26-position rotors with their six sequences combined with a six-plug selector allowed 100 million encoding options. Five weeks before the war broke out, they passed their achievement to French and British agents [8], and, in 1942, eventually fled to the United Kingdom and joined the British Government Code and Cypher School at Bletchley Park. Here, the Polish Bomba concept had already been seminal to develop a more advanced machine.

Designed by mathematician and information pioneer Alan Turing (1912–1954) in 1939, the British Bombe was more powerful than the Polish forerunner in breaking the codes generated by Enigma, which, in the meantime, had become far more complicated with the addition of two or three rotors, thus obtaining between 1.5 and 18 trillion combinations [9]. The Bombe was provided with 108 drums for emulating more Enigma machines at the same time and was designed to discover which rotors were daily in use and their initial positions, together with one plugboard wiring. It actually excluded most of the possible combinations, reducing further decoding operations to a manageable number (Figure 4). However, being electromechanical, the Bombe was not so fast: 20 min were needed for running through all 17,576 possible positions of a single rotor order. Decoding did not occur as quickly as was wanted. All these machines were mechanical and electrically driven, with rotors and drums put in rotation according to the coding and breaking logics. It was a battle between electromagnets, motors, and gears that played a major role in the outcome of World War II. The contribution of Turing to automatic computing went well beyond the construction of codebreaker machines. He had developed fundamental studies on computable functions at the age of 22 and had conceived the working principle of an ideal machine in 1936, the Turing machine, capable of performing this computation. After the war, in 1950, he devised the Turing test, now commonly used in artificial intelligence, for identifying intelligent machines, capable of a behavior indistinguishable from a human's.

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On the German side, other outstanding developments in automatic computing were explored by young engineer Konrad Zuse (1910–1995). To avoid the tedious manual calculations required by his work in aeronautical design, he undertook in total autonomy the construction of a mechanical binary programmable computer, later known as *Z1*, which he completed in 1938, almost simultaneously to Stibitz's early work [10]. It had a keyboard for data entry, a processing unit, a storage unit, and a control unit that used punched cards.

Dissatisfied with its performance, Zuse, supported by government funding, made a second machine in 1940, *Z2*, based on relays and thus electromechanical. In 1941, he completed a more advanced version, *Z3*, programmable, operating with floating point (and Turing complete, although Zuse was unaware of the computational theories of Alan Turing, Figure 5). *Z3* was the first fully operational programmable computer. Because his machines had been destroyed in a war bombing, Zuse in 1942 started the construction of an even more advanced version, *Z4*, which was completed after the war. In 1943–1945, Zuse invented the first high-level programming language, Plankalkül, to operate *Z4*. The machine was sold to the Swiss Federal Institute of Technology in Zürich in 1950, becoming the first computer to be marketed. Compact, efficient, and conceptually very advanced, Zuse's machines were well beyond the contemporary American electromechanical machines. Years later, he admitted that at that time he had considered using electronics in computing to be absurd. He did not grasp the tremendous increase in computation speed that electronics could provide. Nevertheless, something was already moving in that direction, on different sides. Most of the developments described previously were preceded by the work, little known at that time, of a young scientist from Iowa State College, Ames, which, at that time, was not one of the major U.S. research centers. John Vincent Atanasoff (1903–1995) conceived a binary computer in 1937 to alleviate his computational toil. After getting the funds, with the assistance of Clifford E. Berry (1918–1963), he made a full-scale machine that was put into preliminary operation in 1942 [11]. Later dubbed the *Atanasoff–Berry computer*, it featured electromechanical parts and drums but also, for the first time, 300 electronic valves and a 1,600-capacitor regenerative memory capable of 50 30-b numbers, elements that distinguish it as the first electronic computer, although it was also an electromechanical one. It was not programmable, being specifically made for solving systems of linear partial differential equations. Data entry resorted to IBM punched cards, and the maximum-capacity 29 equations were solved in 15 days. It passed almost unnoticed to the scientific community and was relinquished and then dismantled after Atanasoff was called to wartime active service.

The gigantic Selective Sequence Electronic Calculator, the heir of Aiken's machines completed by IBM in February 1948, was also partly electronic and partly electromechanical. Placed in Madison Avenue, New York City, it was

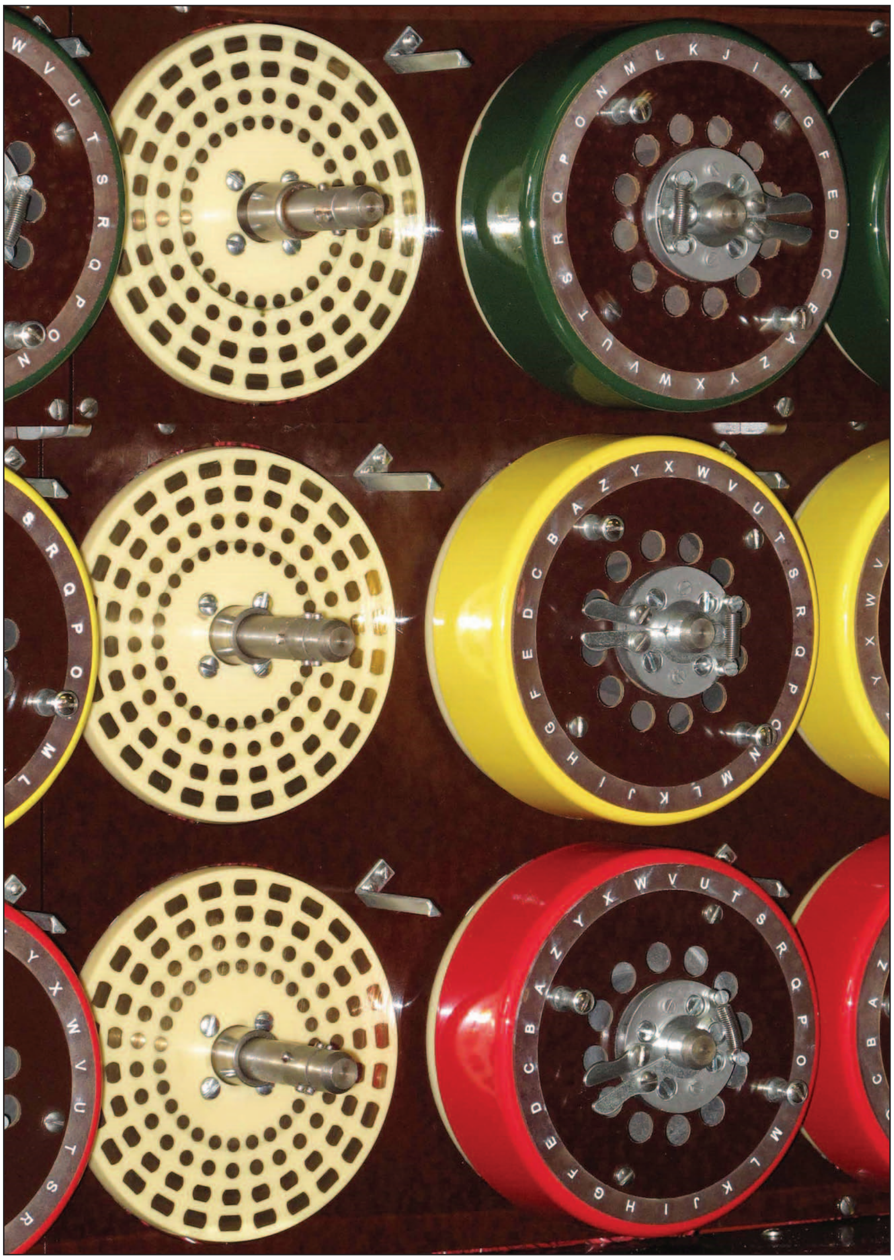
FIGURE 4 — A close-up of drums on a rebuilt Bombe. The machine was operative in 1939. (Photo courtesy of Wikimedia Commons.)


FIGURE 5 — A replica of Zuse's Z3. The machine was operative in 1941. (Photo courtesy of Wikimedia Commons.)

mostly used for demonstration and promotion purposes. It was the last large electromechanical computer.

Some years earlier, something new was happening, promoted by wartime needs. Colossus, the first fully electronic computer, was put into operation at Bletchley Park, United Kingdom, in 1943 as a very fast codebreaker computer, based on the visionary idea of Tommy Flowers (1905–1998) of using vacuum-tube (i.e., electronic) switches in place of relays. Consequently, Colossus was much faster than every electromechanical computer. It was kept secret for years, but details were passed to the United States as part of war cooperation. The Electronic Numerical Integrator and Computer, the first fully electronic and fully programmable digital electronic computer, began operations at the Moore School of Electrical Engineering of the University of Pennsylvania, Philadelphia, in 1945, under U.S. Army control [12]. Neither of these machines were of the stored-program type, already explored in Aiken's and Zuse's electromechanical computers. Nevertheless, another story was secretly unfolding. The times were ripening in preparation for a great leap forward to present-day technology.

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