ON BEYOND BABBAGE

The Rise of Automatic Digital Computers

BY JANET RALOFF

Nineteen twenty-two. In two years Thomas Watson Sr. will reorganize the Computing-Tabulating-Recording Co. as International Business Machines (IBM). Transistors won't be invented for 25 years. The birth of the first Univac, for which Sperry Univac was named, is 29 years away. Still farther off is the unveiling of the world's first integrated circuit: Jack Kilby's manually wired "Solid Circuits" will be announced by Texas Instruments in 37 years—and priced at $450 each.

But computerization's roots extend back well before the 20th century. Though most people conventionally date computers from the advent of digital, automatic versions around World War II, manual ancestral forms trace back millenia to the abacus. Together with a whole family of more complicated European and American calculating engines, these manual and semiautomatic machines have paved the way for the sophisticated progeny that define much of modern society.

Increasing the output of human beings by thousands-fold was not possible until computers meshed with electronics. "Without the speed made possible only by electronics, our modern computerized society would have been impossible: Machines that can do as much as 10 or 20 or 30 or even a hundred humans are very important but do not revolutionize modern society," says Herman H. Goldstine, a major participant in the digital computer's development and author of *The Computer—from Pascal to von Neumann* (Princeton Univ. Press, 1972).

Perhaps that explains why the Pascaline got so little notice. Developed around 1643 by 20-year-old Blaise Pascal, the machine added successive numbers dialed onto its wheels. Once a 10-cogged wheel had rotated a full turn, representing 10, it tripped the wheel to its left, advancing that 10-cogged wheel one step, to "carry 10." An adjustment to let it run backward was necessary when subtracting. Gottfried Leibniz developed a more universal machine around 1673. Not only could it add and subtract fully automatically, but also multiply and divide.

Then, along came Charles Babbage. With funds from the British Chancellor of the Exchequer, his Differential Engine was launched in 1823. Its function was specialized, to solve sixth-degree polynomials—$a + bN + cN^2 + dN^3 + eN^4 + fN^5 + gN^6$ — by calculating successive differences between sets of numbers. Though Babbage had trouble executing a working prototype and eventually scuttled his project, Pehr Georg Scheutz of Sweden built two improved Babbage-design Difference Engines—with Babbage's help.

In 1833 Babbage turned his attention to developing a more general-purpose machine, which he worked on until his death in 1871. The Analytical Engine would have been the world's first programmable digital computer, complete with a memory and printer. Again, it was never finished. Mechanical parts then available were a constant headache to Babbage. Small imperfections in the machining of rods, wheels, ratchets and gears for his device would compound as the components were assembled into parts that heaved and threatened locking seizures.

By the 1920s, analog (or measuring) computers were on the rise. In early 1927, Vannevar Bush and colleagues at the Massachusetts Institute of Technology announced they had a device that could evaluate integrals and solve "problems in connection with electrical circuits . . . and certain problems involving integral equations." This was the continuous integraph. Its basic integrating component was a modified watt meter, as designed by Elihu Thomson (and used today in homes to measure electrical power consumption). Current and voltage readings were replaced by arbitrary time functions (introduced as voltages proportional to heights of curves to be integrated). The machine was also capable of multiplying mathematical functions — $F(x)=f_1(x)f_2(x)$ — with a mechanical linkage, but only first-order equations.

While both of its inputs were electrical, its output was a mechanical rotation. Goldstine notes in his book that "it was at that time technologically impossible or extremely difficult to convert this rotation into an electrical signal." So later that same year Bush and Harold Hazen (also at MIT) unveiled a modified version that used the mechanical output of the last machine as an input for a James Thomson integrator. An inelegant machine, it offered use in solving certain second-order equations.

By 1931 Bush had seized on a third scheme — the elegant and more versatile differential analyzer. Totally mechanical (the watt meter eliminated), all inputs and outputs were rotational — movements of shafts and gears. Though these Bush-variety analog computers proliferated, differential analyzers marked the practical climax to the domination of analog machines in computing. Even as firms and governments scurried to get their own Bush-type device, digital computers were ascending to their present position of seemingly unassailable dominance.

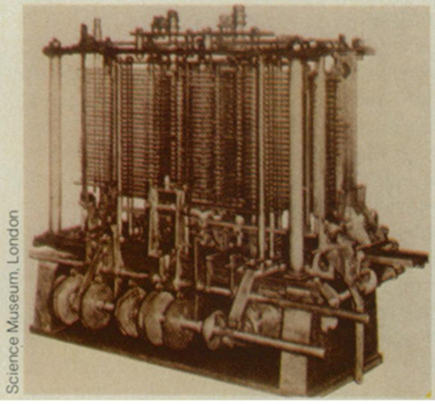
Analog computers process data in the form of continuously variable quantities, such as rotations of a shaft and continuous readings of voltage or temperature. In contrast, digital machines, often called counting computers, perform arithmetic and logic operations on discrete, discontinuous numbers.

The advantage of the new digital machines was that unlike analog computers, accuracy was not limited by the engineering properties of electromechanical components. All too often, the faster an analog computer was run, the less accurately it depicted the mathematical situation sought. "So it was with the differential analyzer," notes Goldstine. "If it was run slowly, its accuracy was considerably better than when it was run fast." The digital machine was also simpler, imitating the human method of calculation by counting and then logically building up variations on the theme — subtraction, multiplication, division, and so on. The primary reason analog devices reigned over the first half of the 20th century was their relative speed. But electronics changed all that.

Computing circuits can be constructed as easily from relays as from vacuum tubes. But electromechanical relays proved significantly slower than vacuum tubes and transistors. Because of the inertia of their mechanical parts, relays require between one and 10 thousandths of a second to physically open or close a circuit. But in vacuum tubes and transistors, "The elements being moved are electrons, and they have masses of 9×10^{-28} grams as compared to relay contacts whose masses are probably about one gram. Thus there is essentially no inertia to be overcome, and a vacuum tube can be said to operate almost instantaneously," Goldstine says. In fact, electronic circuits should easily run a thousand times faster than electromechanical counterparts.

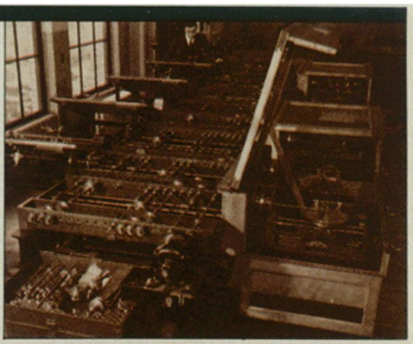
Enter the war years. The American military needed ballistics-trajectory tables to handle every combination of gun, shell and fuse that could be assembled from the American armory. Initially the army tried to compile these tables by human computers—a battery of women wielding calculators. But the task proved superhuman. A single trajectory—and a table generally used 3,000 — took roughly 12 hours to solve and record numerous nonlinear differential equations in several variables. "In 1943, even though it was using all its available machinery [including a differential analyzer], the Ballistics Research Laboratory (BRL) was falling far behind in providing firing tables for new artillery," says

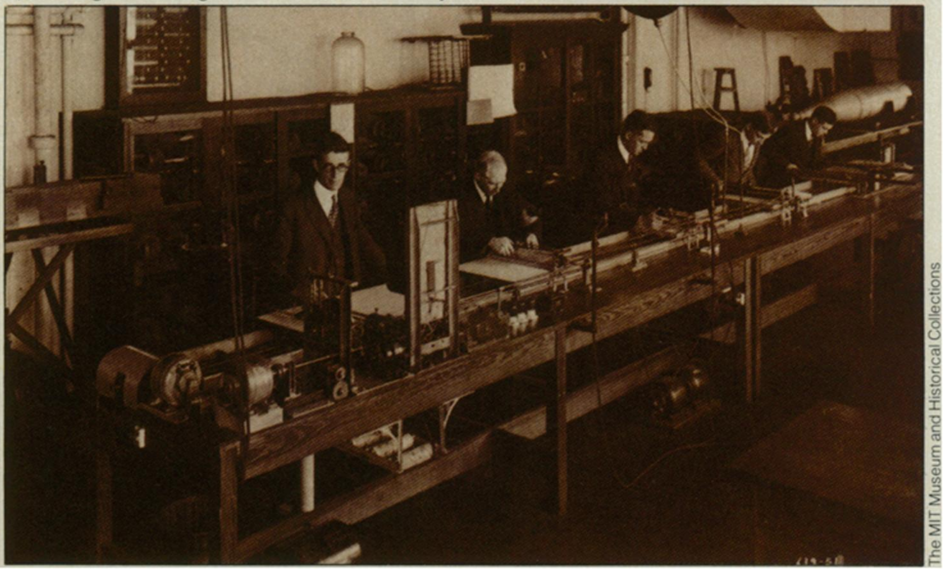
Small part of the calculating unit and printer for Charles Babbage's Analytical Engine (below)—the only part completed prior to his death. Considered the world's first conceptualization of a general-purpose computer, the device, Babbage believed, would be capable of performing any mathematical operation with the proper programming. Steam powered, it would have used Jacquard-loom-type punched cards not only to program sequences of arithmetic operations but also to program the operations themselves.



Science Museum, London

(Below) Vannevar Bush, far left, and co-workers at the Product Integraph in 1927, an early step in the development of analog computers. Bush's differential analyzer (at right) marked the next advance. More elegant and versatile than Bush's earlier computers, it consisted of six Thomson integrators (one is shown open in right foreground) and a few other devices linked by interconnecting shafts whose rotations were proportional to variables. Several were built in the U.S., and by 1940, at least seven large machines were operating, including in Russia and Germany.





The MIT Museum and Historical Collections

ENIAC (right) was the first and most primitive general-purpose digital electronic computer. Several hundred times faster than the best relay machines, it was the first to fully exploit vacuum-tube technology. In fact, the huge device contained roughly 18,000 vacuum tubes and 1,500 relays. However, unlike Eckert and Mauchly's subsequent machines, it had no memory or capability of storing computer programs, a design sacrifice to wartime expediency. Dedicated formally at the Moore School in February 1946, ENIAC was designed to perform ballistics-trajectory calculations. It eventually was also used in weather prediction, cosmic-ray and random-number studies, and nuclear-energy research.

Moore School, Univ. of Pa.

Because the Manchester University Mark I (right) ran its first program in 1948, it's generally credited as the world's first alterable stored-program computer. What also made this British machine notable was a new system for direct-access memory—the Williams tube. The U.S. had its own Mark I. A collaborative effort between Harvard's Howard H. Aiken and a team of IBM engineers headed by Clair Lake, this electromechanical digital computer was completed in 1944. Each multiplication took 6 seconds—slow by ENIAC's standards.

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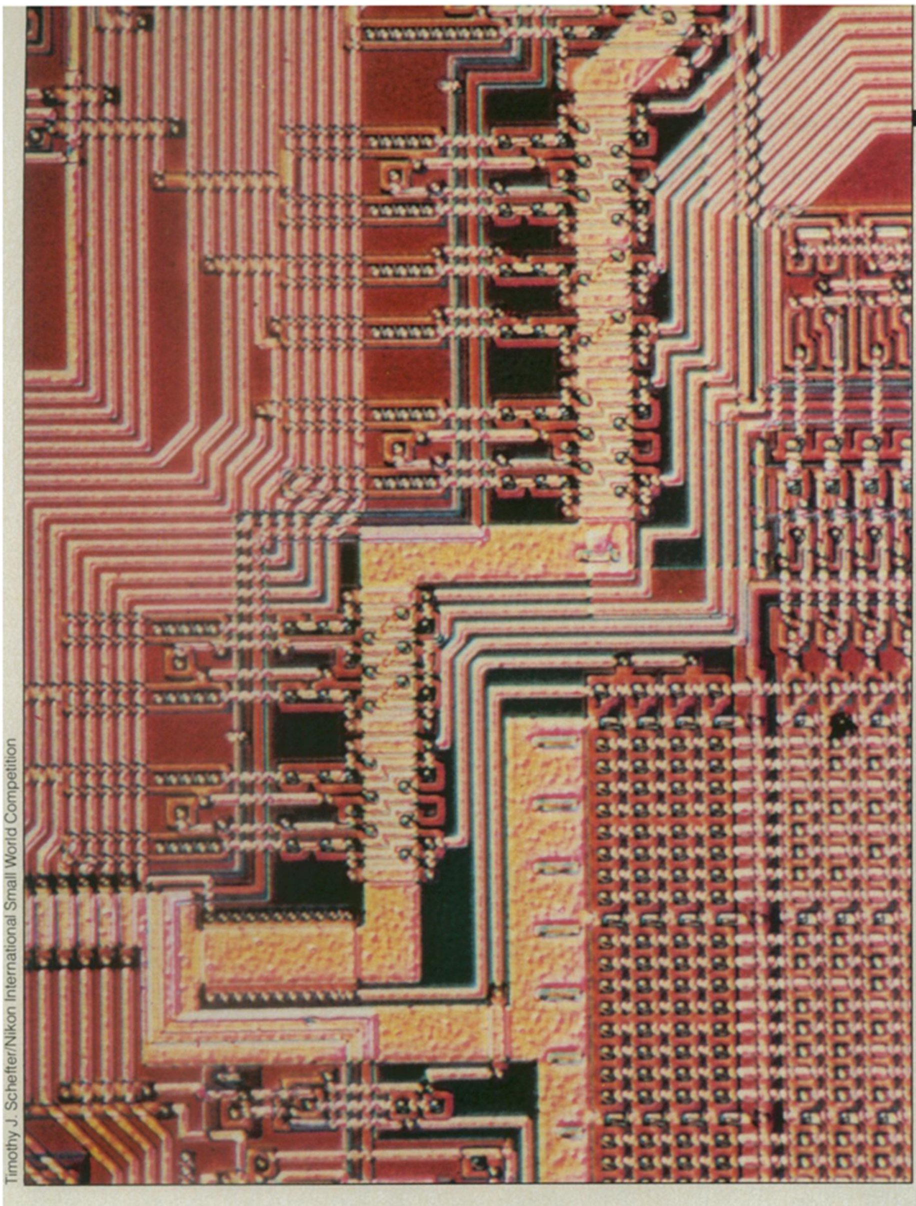

Timothy J. Scheffer/Nikon International Small World Competition

Digital computers have shelved vacuum tubes for miniature transistors built into integrated-circuit chips.

Nancy Stern, the computer historian who authored *From ENIAC to UNIVAC* (Digital Equipment Corp., 1981). "The government needed faster and more suitable computational equipment," she says, something that "became the single most important impetus to technological development in the field of electronic digital computers."

When first proposed in August 1942, John Mauchly's plan to build a high-speed vacuum-tube computer was ignored. But the proposal was resurrected in 1943 and the army suddenly waxed enthusiastic. Along with Goldstine, Mauchly worked at the University of Pennsylvania's Moore School, which had collaborated with BRL on designing its differential analyzer. Goldstine ultimately convinced government officials that Mauchly's computer was not only feasible, Stern says, but also that it might prove invaluable to the war effort. On June 5, 1943, a contract was signed to develop the Electronic Numerical Integrator and Computer — ENIAC. Mauchly was the principal consultant, and John Presper Eckert Jr. its chief engineer.

The machine made its initial test run in November 1945. It was there that mathematician John von Neumann entered the picture, suggesting the computations to test ENIAC's mettle: calculations to determine the feasibility of a new thermonuclear weapon named Super. So admirably did ENIAC perform that von Neumann took consuming interest in the Moore School's activities. In fact, as a result of interest in its next planned computer — the Electronic Discrete Variable Calculator, or EDVAC — he wrote the first widely circulated report on the modern electronic digital computer. It was the first description of a logic framework for stored-program computers and for programming concepts.

In 1946 Eckert and Mauchly left the Moore School to form their own firm. Their first commercial venture was production of an EDVAC-like machine called BINAC. Almost simultaneously they began to work on the Universal Automatic Computer — UNIVAC — which would seal their fame and eventually serve to name the computer division of the Sperry Corp.

Meanwhile, turned on to computers, von Neumann decided to seek his own computer project at the Institute for Advanced Study at Princeton. Goldstine followed in March of 1946 to begin work on what would prove a competitor to EDVAC. Writes Goldstine, the IAS "and the Moore School projects represented complementary schools of thought." Their primary difference was the way each machine added. The IAS device added all corresponding pairs of digits simultaneously — called parallel processing — whereas EDVAC added pairs serially, one after another. "As it happens," Goldstine recalls in his book, "both were successful, but the Institute system, because of its parallel mode, was much faster" and would serve as a model for future generations of computers.

The rest, as they say, is history. Aided in large part by the 1947 invention of the transistor, digital computers got faster, their components smaller and less costly. According to IBM's Lewis M. Branscomb in the Feb. 12 Science, "The price of small, general purpose computers of comparable power, in dollars per instruction executed per second, has been dropping at an annual compound rate of about 25 percent per year since the early 1950s."

Recent advances in building silicon wafers, the base substrate for integrated circuits, and for etching electronic features onto them, have made it possible to place more than 500,000 logic circuits on a single wafer. And this molecular-level, subminiaturization of working, interconnected components is the primary reason, Branscomb says, that "circuits are 10,000 times more reliable today than they were 25 years ago."

Less clear is the cost forecast for programming. "It has been speculated that as much at $100 billion has been spent in the field of programming during the past 30 years," Branscomb says, "about the same as the cost of all the computers installed around the world." And while the ratio of hardware costs to programming costs used to be four-to-one "in the early days," it is now "probably closer to one-to-four or more," observes Joel Birnbaum, director of the Computer Research Center at the Hewlett-Packard Laboratories research center in Palo Alto, Calif.

What is on the horizon? Sperry Univac's self-styled futurist, Earl Joseph, speculates on billionth-of-a-meter scale circuitry. Writing in the Jan. 11 "Computerworld," Joseph envisions development of switchable organic molecules — the equivalent of a transistor — "by genetically engineering DNA amino acid sequences to produce specifiable proteins as templates for the self-construction of larger molecules — to grow computer and memory molecules."

Digital computing has come a long way since 1922. Where it will end is anybody's guess, but Science News will continue to chart its progress. ☐