Dr. Atanasoff's Computer

The men who for decades were credited with inventing the first electronic digital computers were not, in fact, first. That honor belongs to a once forgotten physicist named John V. Atanasoff

by Allan R. Mackintosh

History is finally catching up with John V. Atanasoff. After decades in obscurity this 84-year-old retired physics professor is now gaining recognition from computer scientists for something he accomplished almost half a century ago: the invention of the first electronic digital computer. Until very recently, standard histories of the computer routinely credited his feat to others.

Those histories recognized that the computers we know today had their origin in the 1930's and early 1940's, when many complementary and competing attempts were made to automate, accelerate and otherwise eliminate the drudgery of large-scale calculations. In 1932, for instance, Vannevar Bush of the Massachusetts Institute of Technology completed a mechanical computer called the differential analyzer, which did calculus by rotating gears and shafts. Late in the 1930's Konrad Zuse of Germany, George R. Stibitz of the Bell Telephone Laboratories and Howard H. Aiken of Harvard University (in collaboration with the International Business Machines Corporation) independently developed "electromechanical" computers, in which a series of electrically controlled devices known as relays represented numbers. The "on" and "off" positions of the relays stood for the digits 0 and 1 in the binary, or base-2, system. (Unlike the standard decimal, or base-10, system, which represents numbers in terms of the digits 0 through 9, the binary system represents numbers in terms of 0's and 1's.)

The histories would go on to say that the first electronic computers were invented in the mid-1940's. In contrast to mechanical or electromechanical computers, electronic computers operate primarily by means of such electron devices as vacuum tubes, transistors or, now, microchips; electrons, rather than computer parts, do most of the moving. The first such machine was generally agreed to be the Colossus, which was built by the mathematicians Alan M. Turing and M. H. A. Newman and their colleagues at the Bletchley Research Establishment in England and was operational by 1943. The Colossus helped to decipher the German Enigma code and so decisively affected the course of World War II. The second machine was thought to be the Electronic Numerical Integrator and Computer, or ENIAC, which was built by John W. Mauchly and J. Presper Eckert and their colleagues at the University of Pennsylvania and was operational by 1945.

In reality, between 1937 and 1942—well before either of these impressive and important machines was conceived—Atanasoff had designed and built two smaller electronic computers. The first was a prototype for the larger machine that has come to be known as the Atanasoff-Berry Computer, or ABC. Berry was the late Clifford E. Berry, a graduate student of Atanasoff's and a close collaborator from 1939 to 1942.

The belated recognition of Atanasoff's achievement is not the product of scholarly investigation. Instead it is the incidental result of a lawsuit initiated in 1967 between the Sperry Rand Corporation and Honeywell, Inc. Sperry had bought the patent to the ENIAC and was charging royalties to other manufacturers of electronic computers. Honeywell refused to pay, and so Sperry sued Honeywell; meanwhile Honeywell sued Sperry for violating antitrust regulations and for attempting to enforce an invalid patent.

Honeywell contended that the patent was invalid because in preparing to fight Sperry the company's lawyers had come across a mention of Atanasoff. When they tracked him down, Atanasoff, who had not been privy to the workings of ENIAC, was able to compare that machine with his own. He realized that parts of the ENIAC patent (which covered essentially all aspects of electronic computing) were derived from the ABC and from information he had shared with Mauchly in the early 1940's.

Much impressed by Atanasoff's testimony, Judge Earl R. Larson of the U.S. District Court in Minneapolis concluded on October 19, 1973, that the ENIAC patent was invalid. Mauchly and Eckert, he found, "did not themselves first invent the automatic electronic digital computer, but instead derived that subject matter from one Dr. John Vincent Atanasoff." Both during the trial and after, Mauchly refused to acknowledge that he had learned anything of significance from Atanasoff. Mauchly's widow, Eckert and others also take this view, but in my opinion the court testimony clearly contradicts Mauchly's position.

Larson's decision, which Sperry accepted without appeal, did not immediately bring fame to Atanasoff, in part because the U.S. media were preoccupied with the Watergate scandal that led to the resignation of President Richard M. Nixon. Nevertheless, awareness of Atanasoff's contributions has slowly percolated through the scientific community, and the fact that Atanasoff was the first to design and construct an electronic digital computer is now generally accepted. Much of the credit for that recognition goes to Arthur W. Burks, who was involved in the development of the ENIAC, and to his wife, Alice. The Burkses, respectively professor and a research associ-

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ate in the department of electrical engineering and computer science at the University of Michigan, have investigated Atanasoff's work on the ABC thoroughly and have described it—and the patent trial—in an influential article and a recent book.

The path that led to the Atanasoff-Berry Computer essentially began when Atanasoff was working on his doctorate in theoretical physics at the University of Wisconsin at Madison in the late 1920's. His thesis on the electronic structure of helium involved many weeks of laborious computation with a desk calculator and made him long for a more automatic method of computing. Atanasoff's preoccupation with the idea persisted after he earned his degree in 1930 and became an instructor at Iowa State College (later University).

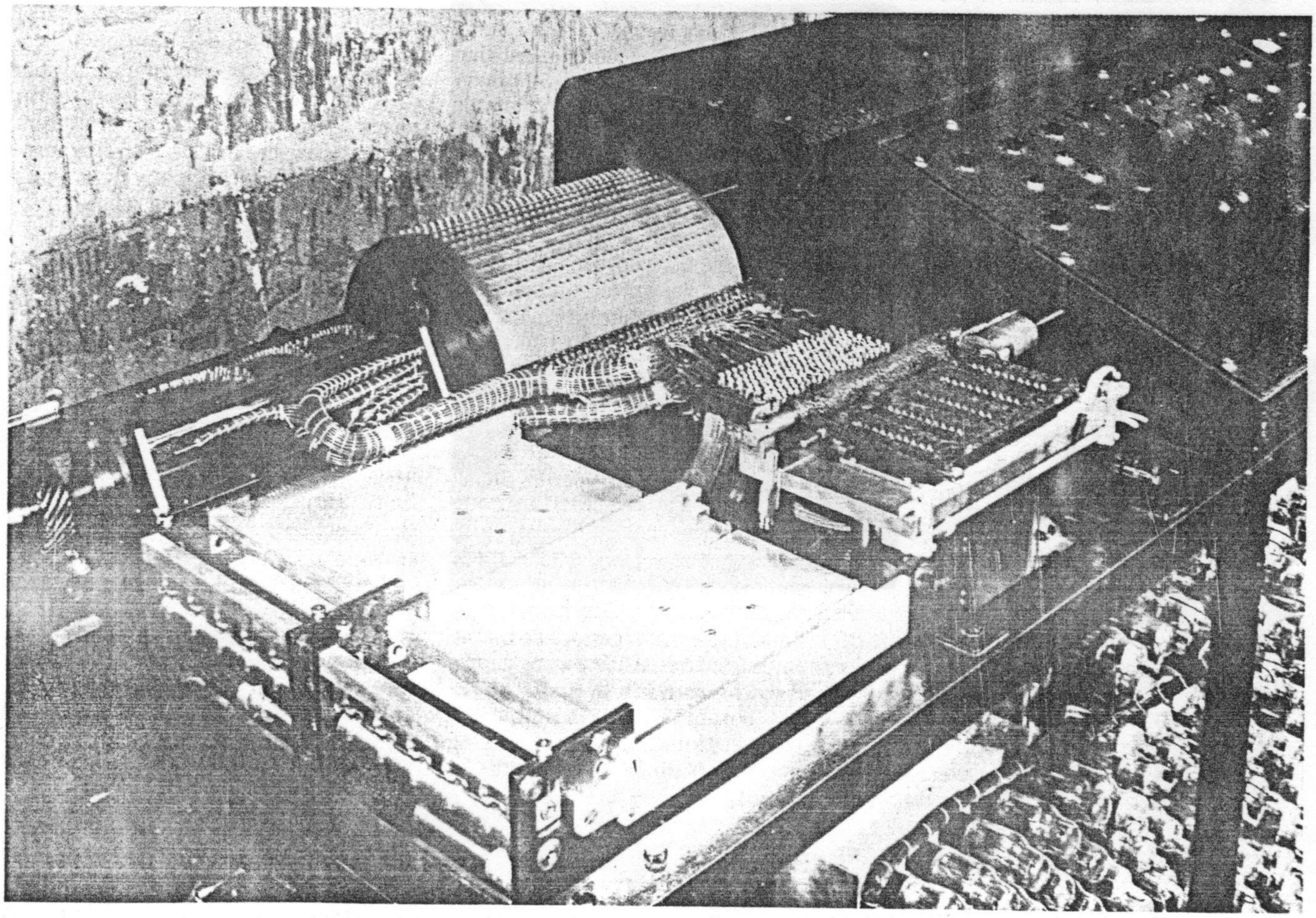
At Iowa he pondered the way to achieve such automation for several years. By the winter of 1937 he had decided on a few general principles. For example, he had determined that the memory function—the storage of data—should be separated from the computational function and that the method of computation should be digital rather than analog: the machine would express numbers as digits rather than by analogy to some physical quantity, such as a distance along the axis of a slide rule. Atanasoff had also toyed with the idea of calculating in terms of bases other than base 10. Nevertheless, his ideas did not seem to "jell," as he put it, and he grew more and more distressed. Then one night of that bleak winter he made several decisive breakthroughs.

The evening had not begun with particular promise. It had, in fact, been so frustrating that he left his laboratory, got into his car and began driving eastward from the college at Ames at high speed, concentrating on his driving to take his mind off his troubles. After several hours he ended up some 200 miles away in the state of Illinois, where he stopped at a brightly lit roadhouse for a drink.

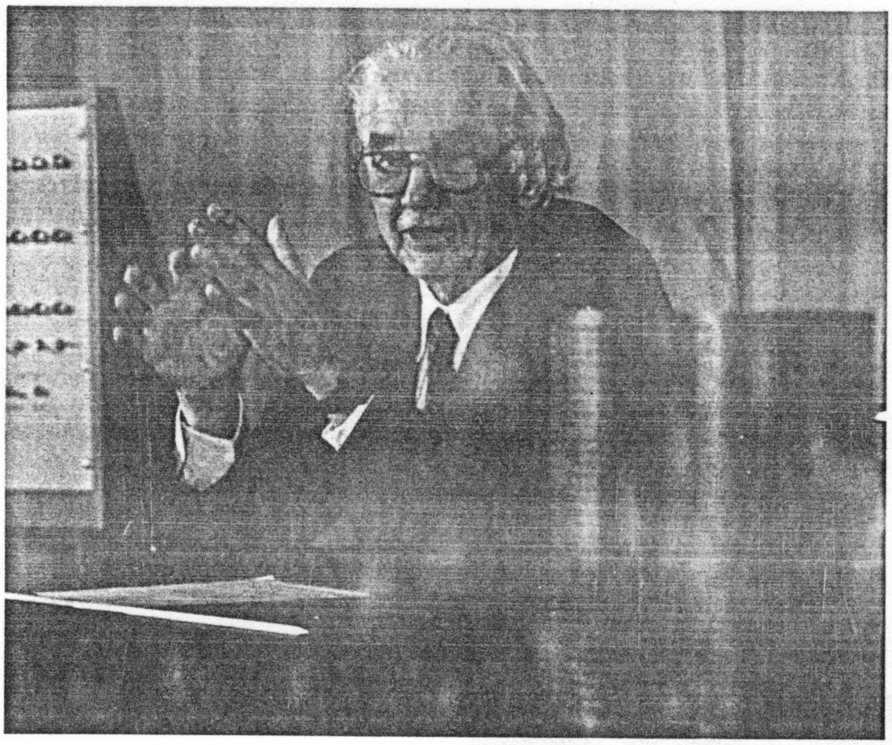
"It was extremely cold and I took off my overcoat," he recalled in trial testimony. "I had a very heavy coat, and hung it up, and sat down and ordered a drink, and as the delivery of the drink was made, I realized I was no longer so nervous and my thoughts turned again to computing machines.

"Now, I don't know why my mind worked then when it had not worked previously, but things seemed to be good and cool and quiet.... I would suspect that I drank two drinks perhaps, and then I realized that thoughts were coming good and I had some positive results."

Positive indeed. Atanasoff resolved to rely on electronic switches (electronic devices that direct the flow of electrical signals), rather than me-



ATANASOFF-BERRY COMPUTER was built between 1937 and 1942 by Atanasoff, then a physics professor at Iowa State College (now Iowa State University), with the help of Clifford E. Berry, a graduate student. The ABC was not the first digital computer ever devised; several earlier machines also manipulated numbers directly instead of representing them as physical quantities, such as the rotation of a pointer. The ABC was, however, the first computer to employ electronics—in the form of vacuum tubes—to carry out computer operations and digital arithmetic; some tubes can be seen at the bottom right. The ABC was also unusual in that the memory and computational elements were separate. The memory consisted of capacitors (devices that store charge) attached to the large drums at the back. The trays at the left are punch-card readers.



ATANASOFF is seen during a celebration of his 80th birthday in 1983 at Iowa State. In the foreground is a memory drum from the ABC, the only major component that survives. Each ring of capacitors on the drum stored one number of up to 50 binary digits, or bits. The drum stored 1,500 bits. Today the total memory in even a simple calculator watch, such as the one on Atanasoff's wrist, can be 10 times that amount.

chanics, to carry out the computer's control and arithmetic functions. In this he was a pioneer. No machine designed for solving complex mathematical problems had been based on electronics before.

He also decided that his digital machine would manipulate binary numbers and would act on those numbers by following rules of logic instead of by direct counting [*see illustration on page 96*]. That same evening Atanasoff also solved a specific problem related to storing numbers in base 2. He had earlier considered employing capacitors, devices that store charge, for the computer's memory. A positive charge on one end of a capacitor could, for instance, represent the number 1, and no charge on that end could stand for 0. The problem was that capacitors have a tendency to lose their charge. Relaxing in the tavern, Atanasoff came up with the idea of regenerating the memory, a process he called jogging. He would restore the charge in a capacitor so that if the capacitor was in, say, the plus state, it would remain that way; it would not change with time or decay to 0.

Having made these decisions, Atanasoff recalled, "sometime late in the evening I got in my car and drove home at a slower rate."

Because modern computers continue to manipulate stored binary digits electronically according to rules of logic and to separate computation and (regenerative) memory, Atanasoff's early decisions are worth examining in more detail. Why, for example, is a digital machine preferable to an analog type for calculation?

Atanasoff's wisdom on that point can best be appreciated by comparing the ABC with Bush's differential analyzer, which was the most advanced scientific computer of the time. In addition to being essentially mechanical, the analyzer was an analog computer: the results were represented by the rotation of a shaft.

Analog computers are suitable for many applications, but in measuring analogous quantities instead of operating on numbers they are subject to an inevitable loss of precision. Atanasoff's digital computer easily attained an accuracy that was 1,000 times greater than was possible with the differential analyzer. Moreover, the precision could readily be increased even further if needed by adding more digits. With analog computers, adding precision is both difficult and extremely expensive. For instance, in order to increase the accuracy of a slide rule by a factor of 10, one would have to increase the length of the rule by the same factor.

Digital computing today is based on the binary system. Clearly Atanasoff was not the only person thinking along these lines—electromechanical computers were often binary—but he was the first to hit on an electronic means of manipulating the binary digits. What does a base-2 number look like? In base 10 each digit in a number represents, from right to left, a given number of 1's, 10's, 100's, 1,000's and so on. Hence the number 237 actually stands for 2 times 10^2, plus 3 times 10^1, plus 7 times 10^0 (any number to the zero power is equal to 1). In base 2 each binary digit, or bit, stands for some number of 1's, 2's (2^1), 4's (2^2), 8's (2^3), 16's (2^4) and so on. Hence the base-10 number 237 would be represented in base 2 as 11101101; counting now from left to right, the number "contains" one unit each of 2^7 (128 in the decimal system), 2^6 (64), 2^5 (32), 2^3 (8), 2^2 (4) and 2^0 (1), and no units of 2^4 or 2^1.

The base-2 system would obviously be impractical for normal use, but because all numbers are represented in terms of 1's and 0's, the system offers the decisive benefit of enabling programmers to represent any number as a series of elements in one of two modes, such as the charged and uncharged states of Atanasoff's capacitors or the "up" and "down" magnetization of regions in a magnetic disk.

Atanasoff decided to store his binary digits in capacitors after considering several alternatives, such as vacuum tubes and ferromagnetic materials (in which the orientations of small magnets can be altered by a magnetic field). He chose capacitors because they were reasonably inexpensive and could send signals to the computational unit without their having to be amplified. This choice, like his solution for recharging the memory devices, continues to influence contemporary computing. Today capacitors are crucial parts of the microchips that form the dynamic memories of modern computers, and Atanasoff's "jogging" is of vital importance to the memory's operation.

Finding a way to preserve memory in capacitors was certainly important, but Atanasoff's greatest achievement was probably the development of a complex electronic switch known as a logic circuit. While he was at the Illinois roadhouse, he had envisioned two memory units, which he called abaci. Then he visualized, as he put it, a "black box"—the logic circuit—into which would pass the numbers held in memory; on the basis of hard-wired logical rules, the black box would then yield the correct results of an addition or subtraction of the numbers at output terminals.

He decided to build the black box out of vacuum tubes. These would receive signals from the capacitors in the memories, which he named the keyboard abacus and the counter abacus, in analogy respectively to the keys and the movable carriage—the counter—of the mechanical desk calculators popular at the time. The tubes would also receive signals from other capacitors that stored carry-over digits (in the case of addition) or borrowed digits (in the case of subtraction). "Having been taught by a man with a soldering iron," the logic circuit would then select the right answer and replace whatever was in the counter with the result. The tubes would operate on the information so rapidly that they could be enlisted repeatedly to add or subtract the various digits of any two numbers in the abaci. Logic circuits today are stored in tiny chips, which are much faster than vacuum tubes but perform essentially the same functions envisioned by Atanasoff.

What has become of Atanasoff's other major decision, namely to separate memory from processing? His legacy lives here as well. In modern computers, such as the desktop microcomputer, there are three distinct elements: the input-output system, consisting primarily of the keyboard, screen and printer (he decided to have the input and output punched into cards that already existed for use in calculators); the central processing unit, in which the control and processing operations are carried out, and the memory, which has internal and external (disk) components.

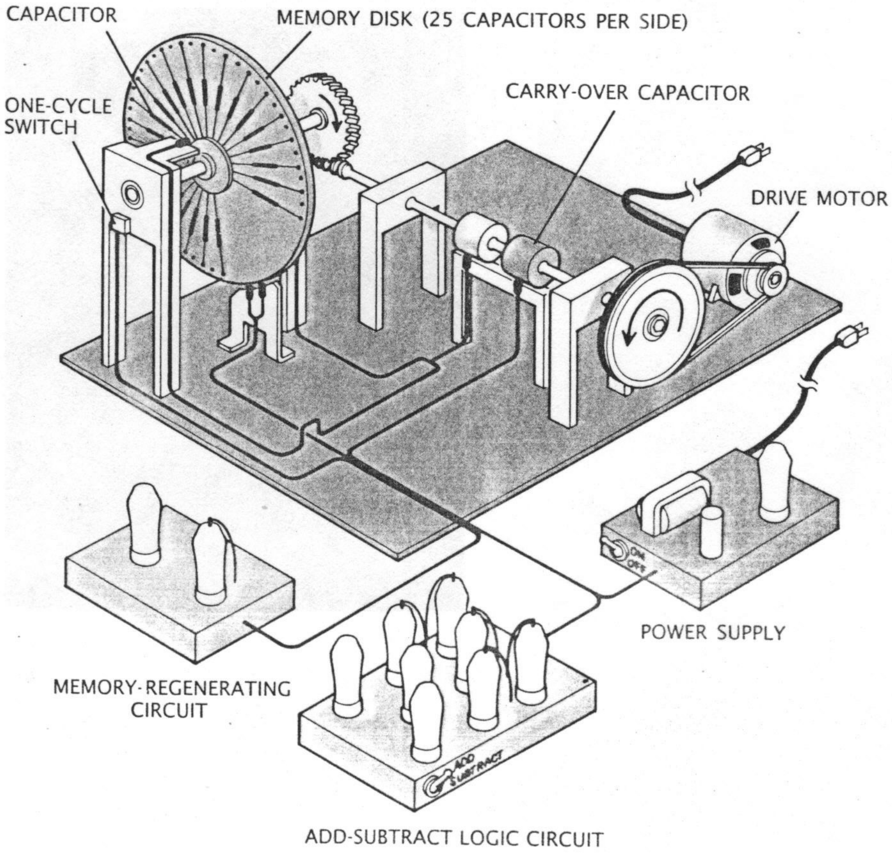
Although Atanasoff was convinced he had found the right principles for electronic computation, he knew that translating these principles into practice would require a prodigious effort. In that effort he received vital assistance from Berry, who was as obsessed as Atanasoff by electronic computing. Atanasoff later recalled that both men were busy, and yet "I do not remember a single instance in which either of us did not have time for the computer; our hearts were really in this adventure."

Their first step was to construct a small prototype to test the essentials of Atanasoff's conception: the electronic logic circuit and the regenerative binary memory. This they did with remarkable speed. The prototype was operational by October, 1939.

It had two memory abaci, mounted on the opposite sides of a plastic (Bakelite) disk. Each abacus consisted of 25 capacitors and hence was able to hold a 25-digit binary number, the equivalent of an eight-digit decimal number. Atanasoff and Berry entered the binary numbers into the abaci by manually charging the capacitors that represented the number 1 and leaving uncharged the capacitors that corresponded to 0. When they pressed a switch, the disk rotated once. As it did so, the electronic logic circuit, which consisted of eight vacuum tubes, read the numbers from the abaci. With the help of a capacitor that held carry-over digits, the circuit then added the numbers and placed the answer in the abacus designated as the counter, for manual reading. At the same time the number in the keyboard abacus was jogged by a regenerating circuit.

The prototype was not a very impressive computer, to be sure: old-fashioned pencil-and-paper computation worked faster. Yet it bears the same relation to electronic computing as, for example, the Wright brothers' airplane bears to aeronautics. By demonstrating the viability of Atanasoff's principles, the prototype opened the path that led to the modern computer.

Atanasoff was now ready to build the ABC proper, which he did between 1939 and 1942. It was designed to do a specific, large-scale computing task that is common in engineering and physics: solving simultaneous linear equations. An example of two such equations is the pair $2x+5y=9$ and



PROTOTYPE for the ABC was built in 1939 to test two basic ideas. Atanasoff planned to constantly recharge, or regenerate, the memory capacitors so that they would not lose charge unpredictably. He also planned to calculate by means of logic circuits: sets of vacuum tubes that would add or subtract binary numbers according to logical rules instead of by counting. The prototype was a success. A rotation of the memory disk (*pink wheel*), whose capacitors stored one 25-digit binary number on each side, caused the single logic circuit (*bottom center*) to add or subtract the number on one side of the disk to or from the number on the other side. As the circuit calculated (in the process storing and retrieving carried-over or borrowed digits from one carry-over capacitor), the regenerating circuit (*bottom left*) refreshed the memory.

$x + 2y = 4$, where x and y are the variables, or unknowns. Let us call the first equation a and the second one b.

As anyone who has studied high school algebra may remember, sets of equations with the same variables can be solved readily by a methodical approach called Gaussian elimination: the addition or subtraction of one equation to or from the other until one coefficient of one variable is equal to 0 and so drops out. In the example here, subtracting b from a twice reduces the coefficient 2 in $2x$ to 0 and thus results in the equation $y = 1$. When 1 is substituted for y in the original equation a, the result is $x = 2$. Note that the process of subtracting b from a twice amounts to multiplying b by 2 and then subtracting it from a once; multiplication, after all, is merely multiple additions.

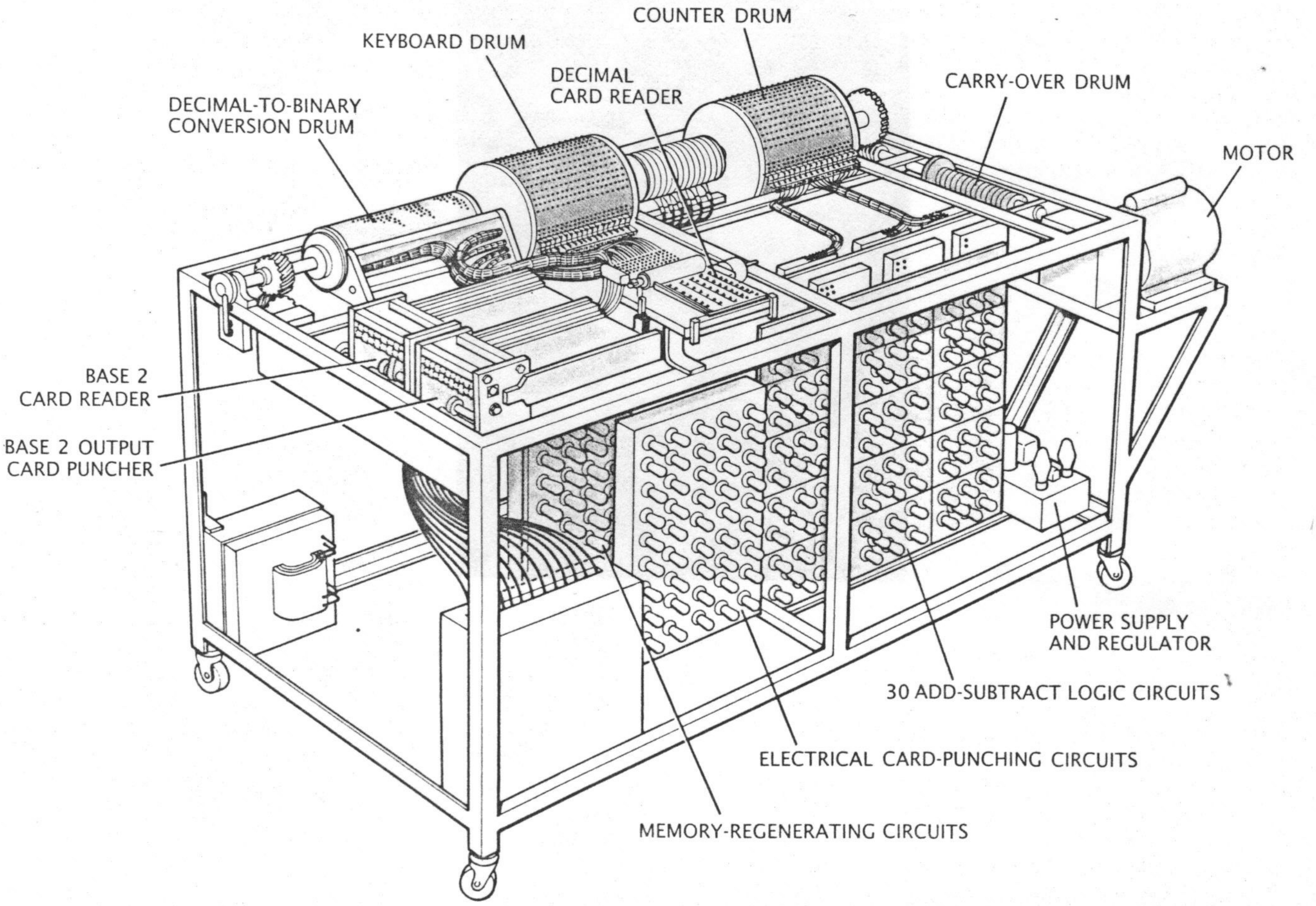
Atanasoff had his sights set on a more complex problem, of course: he wanted to solve n equations with n unknowns—specifically 29 equations with 29 unknowns, x_1 through x_{29}. The solution of such sets of equations follows the example above. As before, one takes two equations—for example $2x_1 + 5x_2 - 3x_3 + 7x_4 + \ldots + 6x_{29} = 9$ and $x_1 + 2x_2 + 4x_3 - 2x_4 + \ldots + 8x_{29} = 4$—and subtracts a multiple of one from the other so that one of the unknowns is eliminated. In order to eliminate x_1, for instance, one would multiply the second equation by 2 and subtract it from the first to produce the result, called the eliminant: $x_2 - 11x_3 + 11x_4 + \ldots - 10x_{29} = 1$.

By repeating this process with different pairs of equations, one can generate 28 equations from which the variable x_1 has been eliminated. Repetition of the procedure with these 28 equations yields 27 equations from which both x_1 and x_2 are missing, and so on until there is only one equation with one unknown. It is then simple to work one's way back up the hierarchy of equations to determine the value of all the variables.

The method is straightforward but clearly involves an enormous amount of arithmetic. Atanasoff estimated, quite realistically, that solving a set of 29 equations with an old-fashioned desk calculator would take about 10 weeks of mind-numbing toil; he estimated that his computer would manage the task in a week or two.

In order to realize his goal of solving many simultaneous equations, Atanasoff placed the keyboard and counter abaci of the ABC on large drums rather than on a disk. Each drum could hold 30 binary numbers that were each specified by up to 50 digits.

The ABC carried out Gaussian elimi-



COMPONENTS OF ABC were designed to enable the machine to solve 29 simultaneous equations, each having 29 variables, x_1 through x_{29}. Such equations can be solved by repeatedly adding one equation to (or subtracting it from) another equation until one variable in the second equation is eliminated. This process is repeated many times to produce the solution: the values of all the variables. To perform such calculations the ABC read the coefficients of the variables (such as the 2 in the term $2x_1$) from prepunched cards, converted them into base 2 and loaded the numbers in one equation into the "keyboard" memory drum and the numbers in the other equation into the "counter" drum. For every rotation of the drums, each of the logic circuits (seven vacuum tubes per circuit) added or subtracted one pair of coefficients, entering the result in the counter. At the same time the memory-regenerating circuits recharged the keyboard capacitors. When the ABC eliminated a designated variable, the machine stored the remaining numbers in the equation on punch cards for later use.

nation for two equations at a time. Their coefficients, which had earlier been punched on cards in decimal form, were converted into base 2 by a specially designed conversion drum and stored in the memory. The coefficients for one equation were loaded onto the counter drum and the coefficients for the second equation went to the keyboard. With each rotation of the drums, which took one second, the logic circuits performed one addition or subtraction on the two sets of coefficients. Specifically, one logic circuit, now consisting of seven tubes, added or subtracted the coefficient of, say, x_1 in the keyboard to or from the coefficient of x_1 in the counter, leaving the sum or difference in the counter. At the same time the other circuits processed the other pairs of coefficients in the same way. (This process, by which a number of identical operations are performed in parallel, is called a vector operation, and a computer carrying out such operations is a vector processor.) Meanwhile still other circuits jogged the keyboard abacus, refreshing the memory.

Later, after multiple subtractions and additions had been performed and a designated coefficient was eliminated, the ABC punched the set of remaining coefficients (the eliminant) on cards in binary form. The cards were then stored until needed in a later step, at which time a binary-card reader transferred the information into the memory. When all the variables had been obtained in binary form, the decimal-card reader operated in reverse to translate the binary data into ordinary numbers.

The punch-card input-output system worked well in preliminary tests, but when it was incorporated into the ABC, an error occurred about once in every 10,000 punching and reading operations. This meant that large systems of equations could not be handled satisfactorily—that is, without extensive recalculation and checking—although small systems could be solved readily. Atanasoff and Berry were still trying to solve this relatively trivial problem when World War II forced them to abandon work on their computer. Berry took a draft-deferred position and Atanasoff joined the U.S. Naval Ordnance Laboratory.

Today the computer they left behind is frequently described as an uncompleted machine. It would be more accurate to characterize it as a functioning but fallible computer, in which the electronic-computing part—the logic circuitry—was a brilliant success. Considering the remarkable speed with which the ABC was designed and constructed, it is safe to assume that the problem with the binary card system would have been solved quickly. Indeed, an input-output system developed decades before by IBM would have been suitable for the purpose (and was later incorporated into the ENIAC). Moreover, by demonstrating the power of his computer, Atanasoff could certainly have obtained financial support to complete the project.

If Atanasoff and Berry had been able to continue, there is little doubt that the ABC would have been fully operational by 1943. Instead it suffered the fate of most aging equipment: it was cannibalized and finally dismantled without Atanasoff's knowledge.

If the ABC was forgotten for so long, how is it that Atanasoff's ideas have influenced modern computing? The answer, of course, lies with Mauchly and his inclusion of Atanasoff's innovations in the ENIAC.

The ENIAC was very different from the ABC. It was the first general-purpose electronic computer, whereas the ABC was designed to be a special-purpose machine. (The ENIAC could be programmed for different problems by altering the configuration of wires plugged into a control panel.) Mauchly and Eckert's machine was much larger than Atanasoff's, with thousands rather than hundreds of vacuum tubes, and it was much faster because its memory was electronic and did not rely on rotating drums. Moreover, the ENIAC calculated by direct counting rather than by logic, and it did so in base 10.

Nevertheless, it is clear that Mauchly and Eckert incorporated Atanasoff's basic elements of electronic digital computing into the ENIAC and a later computer, the EDVAC. Most obviously, the ENIAC and the EDVAC employed electronic switching to control the operation of the computer; the EDVAC also employed logic circuits for arithmetic operations, which were done in base 2, and it made use of regenerative memory. Mauchly also got from Atanasoff the idea that digital electronics would make it possible to build a machine that could do calculus with greater precision and speed than Bush's differential analyzer.

Atanasoff, who by May of 1941 "knew we could build a machine that could do almost anything in the way of computing," decided the ABC could be converted into a digital, electronic differential analyzer after a colleague from M.I.T. told him that workers there were considering incorporating electronics into a new analog version of the analyzer. Atanasoff wrote of the possibility to Mauchly, and the two men discussed it extensively when Mauchly visited Atanasoff for the better part of a week in June, 1941. During that visit Atanasoff also demonstrated the ABC, which was then almost ready to run. Four years later the ENIAC realized Atanasoff's vision.

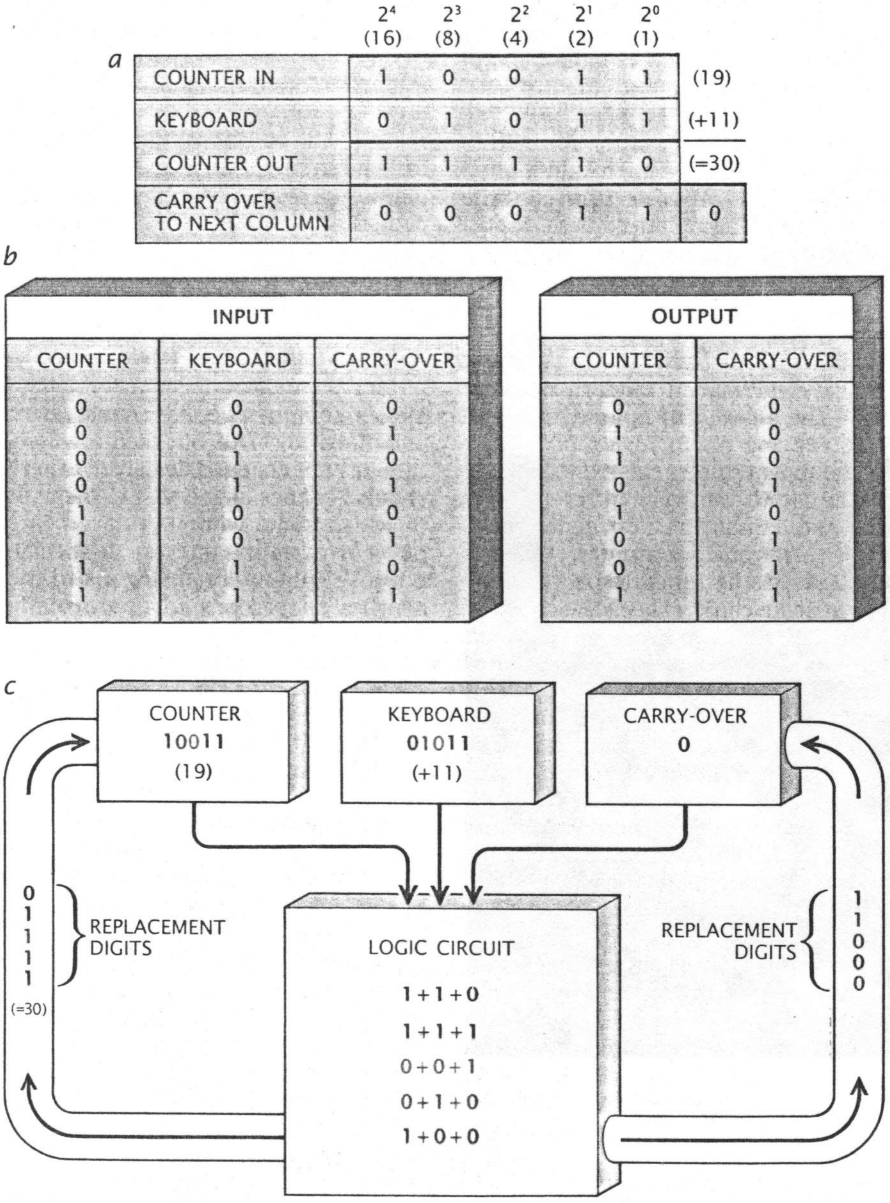
The ENIAC and the Colossus, which was also programmable, paved the way for the next step in the development of the electronic computer: the incorporation of a program into the memory. This advance in general-purpose devices not only made programming easier and more flexible but also enabled the program to operate differently depending on the results of intermediate steps.

Since the first stored-program computers were introduced in the late 1940's, computers have become faster and more powerful, but their architecture has not changed decisively. There are also echoes of the past in the uses to which some computers are being put. For example, interest in special-purpose computers analogous to the ABC has revived recently, particularly among scientists who have specific problems to solve. In fact, the ABC and a modern vector processor for solving linear equations are astonishingly similar (although the newer machines are enormously faster).

Atanasoff would surely have received earlier recognition for his contributions if he had obtained a patent for his work. As the Burkses point out, he could have laid claim to the concept of electronic digital computation as well as to electronic switching in computers, circuits for logical addition and subtraction, the separation of processing from memory, capacitor-drum memories, memory regeneration, use of the binary number system in electronic computing, modular units, vector processing and clocked control of electronic operations, among other innovations.

It is an understatement to assert that this would have been one of the most important patents ever issued. Unfortunately, because of the confusion created by the war and the ineffectiveness of the people entrusted with the task of obtaining a patent, no patent application for any of Atanasoff's innovations was ever made. For his part, Atanasoff did not take up the patent effort after the war because he was led to believe the ENIAC operated on very different principles from the ABC and that it would be the model for future computers, rendering valueless any patent for the concepts and devices embodied in the ABC. He was also heavily involved in other projects and, later, in founding his own engineering-research company.

In addition to shedding light on a major achievement in technology, Atanasoff's story provokes a few thoughts about the scientific enterprise. For one thing, the lot of the inventor is not always easy. In spite of much effort, Atanasoff was able to raise only $6,000 for the ABC—whereas half a million dollars was provided to fund the ENIAC because of its military value (among other functions, it churned out firing tables for artillery).



	2^4 (16)	2^3 (8)	2^2 (4)	2^1 (2)	2^0 (1)	
COUNTER IN	1	0	0	1	1	(19)
KEYBOARD	0	1	0	1	1	(+11)
COUNTER OUT	1	1	1	1	0	(=30)
CARRY OVER TO NEXT COLUMN	0	0	0	1	1	0

INPUT			OUTPUT	
COUNTER	KEYBOARD	CARRY-OVER	COUNTER	CARRY-OVER
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

EACH LOGIC CIRCUIT in the ABC added two numbers at a time, such as the ones in the example here (*a*), according to rules laid down in a table (*b*). Assume that the equivalent of the decimal number 19 in the counter and the equivalent of the decimal number 11 in the keyboard had to be added. After the numbers were converted into base 2, which expresses numbers in terms of powers of 2 (such as 2^0, 2^1, 2^2, 2^3, or 1, 2, 4, 8), they would be written as 10011 (16 + 0 + 0 + 2 + 1) and 01011 (0 + 8 + 0 + 2 + 1). The logic circuit would operate on these numbers by first adding the digits in the right-hand column (2^0). To do so it would determine that the configuration of the digits in the counter, keyboard and carry-over memories—1, 1, 0—matched the second-to-last line of the "input" section of the table. (The initial carry-over digit is always 0.) On the basis of the corresponding "output" section, the circuit would then (*c*) send a 0 (*black*) to the counter (where results were registered), replacing the 1 that was there originally. A 1 (*red*) would also be sent to the carry-over memory. The procedure is equivalent to determining by counting that 1 plus 1 equals 2 and that the number 2 in base 2 is written as 10. The circuit would add the digits in successive columns in the same way until the final result was reached.

Another thought has to do with the creativity of scientists. Atanasoff's breakthrough on that winter night in 1937 illuminates the creative process with remarkable clarity. He embarked on his project by immersing himself in all aspects of automatic computation. For a long time he grappled with his problem, suffering much frustration and making little obvious progress, but his mind continued to absorb information and to work on it, largely subconsciously. Then, when he was engaged in a completely different activity, the solution came to him.

To the uninitiated Atanasoff's 200-mile drive to the roadhouse might seem to be a particularly inefficient way to get a drink, but he knew perfectly well what he was doing. He appreciated that the mind needs variety and relaxation in order to perform creatively. Having conceived of some fundamental principles, he then allowed "a kind of cognition" to come into play. Such a reliance on intuition may not be in accord with the common perception of scientific investigation as a strictly rational activity, but it is nonetheless an approach followed by many research scientists.

Finally, it is no coincidence that many major advances in technology have been made by scientists: the research endeavor often requires the invention of new tools, and investigators who are deeply absorbed in solving scientific problems are uniquely motivated to rise to the challenge. This connection between science and technology should be understood by anyone who thinks the support of basic research can be restricted without slowing technological progress.

FURTHER READING

THE ENIAC: FIRST GENERAL-PURPOSE ELECTRONIC COMPUTER. Arthur W. Burks and Alice R. Burks in *Annals of the History of Computing*, Vol. 3, No. 4, pages 310-399; October, 1981.

ADVENT OF ELECTRONIC DIGITAL COMPUTING. John Vincent Atanasoff in *Annals of the History of Computing*, Vol. 6, No. 3, pages 229-282; July, 1984.

THE FIRST ELECTRONIC COMPUTER: THE ATANASOFF STORY. Alice R. Burks and Arthur W. Burks. University of Michigan Press, 1988.

ATANASOFF: FORGOTTEN FATHER OF THE COMPUTER. Clark R. Mollenhoff. Iowa State University Press, 1988.

THE FIRST ELECTRONIC COMPUTER. Allan R. Mackintosh in *Physics Today*, Vol. 40, No. 3, pages 25-32; March, 1988.