The ENIAC Story

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The world's first electronic digital computer was developed by Army Ordnance to compute World War II ballistic firing tables.

"...With the advent of everyday use of elaborate calculations, speed has become paramount to such a high degree that there is no machine on the market today capable of satisfying the full demand of modern computational methods. The most advanced machines have greatly reduced the time required for arriving at solutions to problems which might have required months or days by older procedures. This advance, however, is not adequate for many problems encountered in modern scientific work and the present invention is intended to reduce to seconds such lengthy computations..."

From the ENIAC patent (No. 3,120,606), filed 26 June 1947

As in many other first along the road of technological progress, the stimulus which initiated and sustained the effort that produced the ENIAC (electronic numerical integrator and computer)--the world's first electronic digital computer--was provided by the extraordinary demand of war to find the solution to a task of surpassing importance. To understand this achievement, which literally ushered in an entirely new era in this century of startling scientific accomplishments, it is necessary to go back to 1939.

As the year 1939 dawned on an apprehensive and fearful Europe, soon to realize the worst of its fears with the outbreak of the war on September 1st, the United States continued largely oblivious to the outside world and its impending fate. This obliviousness was in no way better exemplified than in the size and state of unreadiness of the U.S. Army.

Two decades of complete indifference toward military preparedness had witnessed its virtual elimination as a factor of any military consequence in the world. In that fateful year the total strength of the Regular Establishment of the Army was approximately 120,000 officers and men.

The part of this exceedingly small peacetime establishment which provided the principal scientific and logistic support was the Ordnance Department. This Department had the responsibility for the design, development, procurement, storage, and issue of all combat materiel and munitions for the Army. In 1939 it was staffed by a relative handful of officers and career civilian employees.

The only scientific facility then available to the Ordnance Department for carrying out experimentation with weapons was the Aberdeen Proving Ground in Maryland. This facility had been acquired at the beginning of World War I and had been heroically maintained during the disheartening interim period so that at the outbreak of World War II it was able single-handedly to perform the crucial task of testing all combat materiel during the critical period of mobilization of the American war effort.

One of the extraordinarily important tasks which devolved upon the proving ground was the preparation of firing and bombing tables for the Army which at that time, of course, included the Army Air Corps. This responsibility was carried out at the Ballistic Research Laboratory of the Ordnance Department at Aberdeen. Here also were obtained experimental data of high accuracy and precision, necessary to the computation of the firing and bombing tables.

What was the situation at the Ballistic Research Laboratory on the eve of World War II? Its computing group comprised just a handful of civilian employees of the Ordnance Department. These individuals were well trained and highly skilled in the conventional methods of computation of firing and bombing tables. Available to this group at that time was one important calculating device other than standard desk calculators--this was the Bush differential analyzer.

This analogue device, or continuous variable calculator, had been installed at the proving ground about five years previously under the direction of Major James Guion of the Ordnance Department, then head of the ballistic computations section of the proving ground.

The analyzer installed at Aberdeen had ten integrating units and provisions for two input and two output tables as well. But, despite its value as an important mechanical aid to computation, it had several severe limitations. Probably the most severe of these was the mechanical torque amplifier. This element of the analyzer sufficiently amplified the extremely small torque developed by the integrating units so as to permit its transmission and utilization elsewhere in the device to drive other elements including other integrators.

This torque amplifier, although simple in mechanical design, frequently failed toward the end of a long trajectory run with the loss of the preceding computation and an appreciable delay associated with its repair.

The officer in charge of ballistic computations at that time was Lieutenant P. N. Gillon, Ordnance Department, who had just assumed responsibility for ballistic computations at the outbreak of the war in Europe. His immediate recognition of the immensity of the task that would devolve upon the Ordnance Department in the event of America's involvement in the war prompted him to seek both marked improvement in mechanical aids to computation and augmented facilities for their accomplishment.

It was, of course, known that the Moore School of Electrical Engineering of the University of Pennsylvania had a Bush differential analyzer of somewhat larger capacity than the one installed at Aberdeen. As a matter of fact, the one at the Moore School had fourteen integrating units. Therefore one of the first steps taken was the award to the University of Pennsylvania of a contract by the Ordnance Department for the utilization of this device.

Following the award of this contract, Lieutenant Gillon in his capacity as officer in charge of ballistic computations conferred frequently with Dean Harold Pender, Professor J. G. Brainerd, and their associates at the Moore School with a view to effecting proper coordination of the computational work at Philadelphia and Aberdeen.

Fortunately, at this time there was a very talented group at the Moore School under the direction of Professor Brainerd and as a result of Lieutenant Gillon's discussions with the professor and his associates, Assistant Professor Weygand undertook to develop an electronic torque amplifier to replace the mechanical torque amplifiers on the Bush differential analyzers. This work was eminently successful and in a rather brief period of time.

In addition, photoelectric followers were developed by the Moore School group for both the input and output tables of the analyzer. As a result of these accomplishments the productive capacity of the analyzers at both the Moore School and at Aberdeen were enhanced by at least an order of magnitude.

During the same period of time the computational activities at Aberdeen were being expanded greatly, and the increase in staff included both military and civilian personnel. Among the former, shortly after America's entry into the war, one of the very important individuals in the ENIAC story came to duty at the proving ground. This was Lieutenant Herman H. Goldstine, a Reserve officer of the Ordnance Department.

Lieutenant Goldstine had received his doctorate in mathematics at the University of Chicago under Professor Bliss who had, himself, been one of the principal ballisticians at the proving ground during World War I.

Upon reporting to active duty at the proving ground, Lieutenant Goldstine was assigned to the Ballistics Research Laboratory as an assistant to Captain Gillon. In view of the increased importance of the activities in Philadelphia, which by this time included a training responsibility in the mathematics of ballistic computations, Captain Gillon requested that Lieutenant Goldstine be assigned to duty at the University of Pennsylvania as supervisor of the computational and training activities there.

In September 1942, Colonel Gillon was assigned to the Office of the Chief of Ordnance as deputy chief of the Service Branch of the Technical Division with the responsibility for the research activities of the Department, including those at the respective Ordnance facilities. This, of course, included the work performed in the field of ballistic computations.

This responsibility required frequent contact with the activities at the University of Pennsylvania, and as a result thereof in the early part of 1943 Captain Goldstine and Professor Brainerd brought to Colonel Gillon the outline of the technical concepts underlying the development of the ENIAC. This outline had been prepared at Captain Goldstine's request by Dr. John W. Mauchly and J. P. Eckert, Jr.

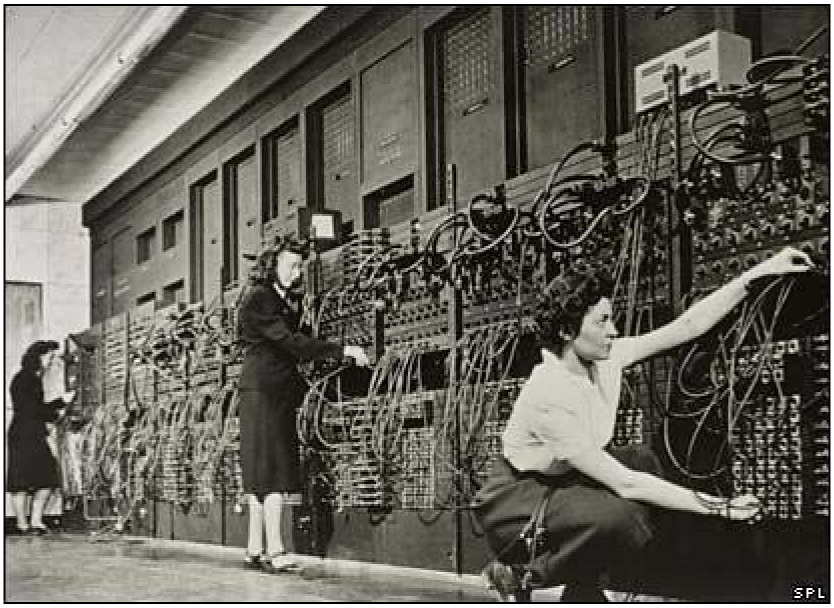
Colonel Gillon fully realized the formidable opposition that probably would be offered to the initiation and prosecution of a development of this sort, especially in view of the highly speculative character of its successful completion. He was convinced, however, of the importance of the need not only to ballistic computations but also to the research activities of the Ordnance Corps as well, and accordingly he undertook to obtain the necessary authorization for its initiation and assumed full responsibility for its support and supervision.

The original agreement between the United States of America and the trustees of the University of Pennsylvania, dated June 5, 1943, called for six months of "research and development of an electronic numerical integrator and computer and delivery of a report thereon." This initial contract committed $61,700 in U.S. Army Ordnance funds.

Nine supplements to this contract extended the work to 1946, increased the amount ultimately to a total of $486,804.22, assigned technical supervision to the Ballistic Research Laboratories, and called for the delivery of a working "pilot model," first to be operable at the University of Pennsylvania and then to be delivered to the Ballistic Research Laboratories at the Aberdeen Proving Ground.

From this point forward, the research staff and faculty of the Moore School under Dr. Pender undertook rigorous prosecution of the development pursuant to the terms of the Ordnance contract. The project was placed under the supervision of Professor Brainerd, with Mr. Eckert as chief engineer and Dr. Mauchly, who provided the original outline for this development, as principal consultant. Captain Goldstine, the resident supervisor for the Ordnance Department, not only exercised extraordinarily detailed and highly competent supervision for the Government but also contributed greatly to the mathematical side of this undertaking. As in all important undertakings which achieve important results, this was the work of many individuals.

The ENIAC was placed in operation at the Moore School, component by component, beginning with the cycling unit and an accumulator in June 1944. This was followed in rapid succession by the initiating unit and function tables in September 1945 and the divider and square-root unit in October 1945. Final assembly took place during the fall of 1945.



By today's standards for electronic computers the ENIAC was a grotesque monster. Its thirty separate units, plus power supply and forced-air cooling, weighed over thirty tons. Its 19,000 vacuum tubes, 1,500 relays, and hundreds of thousands of resistors, capacitors, and inductors consumed almost 200 kilowatts of electrical power.

But ENIAC was the prototype from which most other modern computers evolved. It embodied almost all the components and concepts of today's high- speed, electronic digital computers. Its designers conceived what has now become standard circuitry such as the gate (logical "and" element), buffer (logical "or" element) and used a modified Eccles-Jordan flip-flop as a logical, high-speed storage-and-control device. The machine's counters and accumulators, with more sophisticated innovations, were made up of combinations of these basic elements.

ENIAC could discriminate the sign of a number, compare quantities for equality, add, subtract, multiply, divide, and extract square roots. ENIAC stored a maximum of twenty 10-digit decimal numbers. Its accumulators combined the functions of an adding machine and storage unit. No central memory unit existed, per se. Storage was localized within the functioning units of the computer.

The primary aim of the designers was to achieve speed by making ENIAC as all-electronic as possible. The only mechanical elements in the final product were actually external to the calculator itself. These were an IBM card reader for input, a card punch for output, and the 1,500 associated relays.

Another design objective was to make the electronics simple and reliable. This goal was achieved by utilizing vacuum tubes in a minimum of basic circuit combinations. To ensure reliable operation, circuits were constructed to rigidly tested standard components which were operated at current, voltage, and power levels below their normal ratings.

Accuracy of computation was assured by designing the basic circuits to work independently of the variable tolerances of their components. Numbers were not represented by electrical quantities which could be affected by changes in tolerance but only by the presence or absence of dynamic pulses.

The gate performed the switching or logical "and" function. It consisted of a single pentode which had a control voltage applied to its suppressor grid. Its function was similar to that of a single pole switch in that it "opened" (passed a pulse pattern) when the suppressor grid was positive and "closed" when the suppressor grid was negative.

The buffer contained two or more tubes connected through a common load resistor to form a circuit with the logical properties of the word "or." The grids of the tubes were normally biased at the cut-off point so that a positive input to any tube in the combination produced a negative output.

The flip-flop circuit contained two triodes so connected that only one would conduct at a given time. The bi-stable device had two inputs and two outputs. In the set, or normal position, one side of the output was positive, the other negative. In the reset, or abnormal position, these polarities were reversed. Logically, the flip-flop performed the functions of memory and that of a double-pole, double-throw switch. The state of each flip-flop was indicated by a neon lamp on the front panel of the computer units.

A group of ten flip-flops, (0-9), interconnected to count digit pulses, formed a decade ring counter which was capable of adding and storing numbers. The ring counter possessed the following characteristics: (1) At any one time only one flip-flop could be in the reset state; (2) A pulse to the counter input reset the initial flip-flop in the chain; (3) The circuit could be cleared so that a specific flip-flop was in the reset position while the others remained set.

Each flip-flop of a counter was termed a stage, and reception of a pulse at the input side advanced the counter by one stage. Information was recirculated through the counter; i.e., the last stage was coupled to the first. A variation of the basic counter circuit, the PM counter, controlled the sign of a number in the accumulator. Ten decade ring counters, one per decimal place, plus one PM counter, formed the basic arithmetic and storage unit of ENIAC--the accumulator. The decade ring counters were equipped with ten transmission circuits so that when any ring passed the nine positions, a pulse was passed to the next ring in the series. Input pulses reaching the accumulator added to or subtracted from its contents.

The accumulator was an essential element in all of ENIAC's arithmetic operations. Addition required two accumulators--one transferring its contents to the other. Subtraction, accomplished by a complement-and-add process, also used two accumulators. In normal multiplication, four accumulators stored the multiplier and multiplicand and accumulated the partial products. In division they shifted the remainder and stored the numerator, denominator, and quotient. The function table utilized the accumulators for storage of the argument and accumulation of the function value.

A synchronous system, ENIAC operated under the control of pulses from a cycling unit. The pulses were emitted at 10-microsecond intervals. The overall timing cycle or repetition rate was 200 microseconds, one addition time. Pulses were transmitted to all units continuously and simultaneously, and each computer operation took an integral number of addition times. For checking and trouble-shooting purposes, the cycling unit circuitry included provisions for operation in a one-addition or one-pulse-at-a-time mode.

The ENIAC was not originally designed as an internally programmed computer. The program was set up manually by varying switches and cable connections. However, means for altering the program and repeating its iterative steps were built into the master programmer. Digit trays, long racks of coaxial cables, carried the data from one functioning unit to another. Program trays, similarly, transferred instructions; i.e., programs. In purely repetitive calculations the basic computing sequence was set by hand. The master programmer automatically controlled repetition and changed the sequence as required.

The master programmer contained ten 6-stage counters--each routing incoming program pulses over a field of six output channels. The position of the counters was controlled by either the number of pulses which had been supplied to the output channels or by the number of pulses received at a special input terminal. In this fashion, the number of sequences could be fixed in advance or made contingent on the results of a computation.

Each functioning unit of ENIAC was equipped with local program-control circuits. These circuits contained switches which were set for the function required. When the local program circuit was stimulated by a program pulse, the unit performed the desired operation. After it finished, a program-completion pulse was emitted, via the program tray coaxial line, to the next unit in the operational sequence.

In addition to its cycling unit, twenty accumulators, and master programmer, ENIAC included an initiating unit, a high-speed multiplier, a divider, a square-root unit, and three portable function tables. The initiating unit turned ENIAC on and off, cleared it, and initiated computation.

The high-speed multiplier did its work in much the same fashion as a human would. It contained a built-in multiplication table capable of multiplying up to 9 times 9. Multiplication of the multiplicand by each digit of the multiplier took one addition time. The left- and right-hand figures of each product of a digit of the multiplicand and the multiplier were accumulated separately to form two partial products, which, when combined, formed the final product. The multiplication process for two 10-digit numbers took 2.6 milliseconds.

The divider and square-root unit worked by repeated subtraction and addition, a time-consuming procedure which took an average of 25 milliseconds for a 10-digit number. The divisor was subtracted from the dividend, and the sign of the partial remainder was tested after each step. When the sign became negative, the remainder was shifted up-scale and the divisor was added until the sum became positive. An accumulator serving as a quotient register kept a count of the number of additions and subtractions for the successive decimal places. Extraction of a square root was a similar process.

The principal purpose of the function tables, which actually were banks of switch-controlled resistor matrices, was the storage of the arbitrary functions called for by the problem. The switches selected one of 12 digits and 2 signs for each of the 104 values of an independent variable that were stored in each table. The functional similarity between modern computers and the ENIAC is rather astounding, although the ENIAC was designed almost two decades ago.

The ENIAC was formally dedicated at the Moore School of Electrical Engineering of the University of Pennsylvania on February 15, 1946, and it was accepted by the U.S. Army Ordnance Corps in July, four years after the original suggestion by Dr. Mauchly.

All During 1946 the ENIAC remained at the Moore School, working out numerical solutions to problems in such fields as atomic energy and ballistic trajectories. Dismantling at the Moore School began in the winter, and the first units arrived at Aberdeen Proving Ground in January 1947. The ENIAC became operational again in August 1947.

The ENIAC's first few years at the Aberdeen Proving Ground were difficult ones for the operating and maintenance crews. The computer represented the largest collection of interconnected electronic circuitry then in existence, and its thousands of components had to remain operational simultaneously. The result was a huge preventive-maintenance and testing program, which, in the end, led to some major modifications of the system.

Tubes were life-tested, and statistical data on the failures were compiled. This information led to many improvements in vacuum tubes themselves. Procurement of large quantities of improved, reliable tubes, however, became a difficult problem. Power-line fluctuations and power failures made continuous operation directly off transformer mains an impossibility. The substantial quantity of heat which had to be dissipated into the warm, humid Aberdeen atmosphere created a heat-removal problem of major proportions. Down times were long; error-free running periods were short.

Programming new problems meant weeks of checking and set-up time, for the ENIAC was designed as a general-purpose computer with logical changes provided by plug-and-socket connections between accumulators, function tables, and input-output units. However, the ENIAC's primary area of application was ballistics--mainly the differential equations of motion.

In view of this, the ENIAC was converted into an internally stored fixed-program computer when the late Dr. John von Neumann of the Institute for Advanced Study at Princeton suggested that code selection be made by means of switches so that cable connections could remain fixed for most standard trajectory problems. After that, considerable time was saved when problems were changed.

The ENIAC performed arithmetic and transfer operations simultaneously. Concurrent operation caused programming difficulties. A converter code was devised to enable serial operation. Each function table, as a result of these changes, became available for the storage of 600 two-decimal digit instructions.

Those revolutionary modifications, installed early in 1948, converted ENIAC into a serial instruction execution machine with internal parallel transfer of decimal information. The original pluggable connections came to be regarded as permanent wiring by most BRL personnel.

By February 1949, when the ENIAC completed the computation for Project Chore, an Ordnance Corps contract with the University of Chicago, operating difficulties had been reduced to a minimum. Running times were longer, down times shorter and reduced in number. The Chore contract and others completed during this period proved the ENIAC's worth. Other machines, among them the Bush differential analyzer and the Bell relay calculator, would have required a prohibitive length of time to complete the problems that were assigned to the ENIAC, and the latter was much faster than any digital system then in existence.

For example, a skilled person with a desk calculator could compute a 60- second trajectory in about 20 hours. The analog differential analyzer produced the same result in 15 minutes. ENIAC required 30 seconds--just half the time of the projectile's flight.

The ENIAC led the computer field during the period 1949 through 1952 when it served as the main computation workhorse for the solution of the scientific problems of the Nation. It surpassed all other existing computers put together whenever it came to problems involving a large number of arithmetic operations. It was the major instrument for the computation of all ballistic tables for the U.S. Army and Air Force.

In addition to ballistics, the ENIAC's field of application included weather prediction, atomic-energy calculations, cosmic-ray studies, thermal ignition, random-number studies, wind-tunnel design, and other scientific uses. It is recalled that no electronic computers were being applied to commercial problems until about 1951.

EDVAC and ORDVAC, both faster than ENIAC, began to share the Computing Laboratory's work load with the ENIAC in 1953. It became apparent almost immediately that the ENIAC would have to be modified if it were to remain competitive, economical, and efficient. Modifications, based on new developments in the computer art, were again made on the ENIAC.

In addition to an independent motor-generator set, which eliminated the power troubles, a high-speed electronic shifter, which reduced by 80 percent the time required for numerical shifting and eliminated numerous tubes and program units, was installed early in 1952. Later, in July 1953, a 100-word static magnetic-core memory was added to the system.

The core storage unit, the first operational unit of its kind, was built by the Burroughs Corporation. The Binary coded decimal, excess three, system of number representation was used. It was operated successfully three days after its arrival at BRL and continued in service until the ENIAC was retired.
To provide for the additional memory capacity, the ENIAC was equipped with a new function-table selector, a special memory-address selector, and special pulse-shaping circuits. Three new orders were added to the converter code for use with the new memory.

Despite these modernizations and the fact that trouble-free operating time remained at about 100 hours a week during the last 6 years of the ENIAC's use, its operating costs were far above those of the EDVAC and ORDVAC. The ENIAC was no longer competitive from an economic point of view. The work load gradually was shifted to the other machines, and at 11:45 p.m. on October 2, 1955, the power to ENIAC was removed.

The late Dr. von Neumann suggested that attempts be made to preserve at least some of the ENIAC at the Smithsonian Institution at Washington, DC. So far, efforts at preservation have had several concrete results. An operational ENIAC accumulator unit has been shipped to the United States Military Academy at West Point, NY, for display in the Academy museum. The Smithsonian will display portions of the ENIAC as soon as space becomes available.

The National Science Foundation has several computer exhibits in the United States and Europe, containing portions of the ENIAC. Efforts are being made to have the U.S. Army Office of Military History declare the ENIAC as historical-interest property. It is hoped that this progenitor of a new industry--the key which opened new avenues of approach to solutions of many perplexing scientific problems, the device which pioneered the evolution of high-speed digital computing and automatic data-processing machinery--will be preserved for posterity.

Looking back over the years from 1939 to the fateful evening of October 2, 1955, one can clearly see the life cycle of an enterprise. A need existed for faster computing speeds, and Army Ordnance had made known this need to the Moore School.

Mauchly and Eckert suggested an electronic digital computing design which Gillon believed was worthy of the fullest Ordnance support. Eckert supervised construction. Coders, programmers, and engineers made it run and produced useful results which otherwise would have been unattainable. The rapid progress of computer technology, spurred by the ENIAC itself, soon made the device obsolete.

Thus ended the life of the once glorious pioneer in the field of digital computation. As stated in the June 1958 report of the Operations Research Office of the Johns Hopkins University, entitled "Defense Spending and the U.S. Economy:" "The present electronic computer industry is the direct product of Army-sponsored research...," resulting in the ENIAC, "the first modern electronic computer." It's death was a natural one--it had served its purpose.

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