Introduction to "The ENIAC"

ARTHUR W. BURKS AND EDWARD S. DAVIDSON, FELLOW, IEEE

Invited Paper

This introduction to the 1948 Classic Paper "The ENIAC," by Brainerd and Sharpless, seeks to avoid redundancy with the republication of the 1947 Burks paper and its introduction by Schneck in the July 1997 issue of this PROCEEDINGS. Consequently, we limit ourselves to a few personal reflections.

Keywords—*Computers, electronic, ENIAC, history.*

I. FOREWORD[1]

It is an honor to join in writing this introduction with Electronic Numerical Integrator and Computer (ENIAC) engineer and computer pioneer Arthur Burks, Professor Emeritus of Philosophy and of Electrical Engineering and Computer Science (EECS). Burks is living proof that the entire computer age, from its inception with the ENIAC to today, spans but less than one active professional lifetime (only a bit more than twice the age of an undergraduate student). My own connection with the ENIAC is one-level indirect. While an M.S. student in communication science in 1962, I learned of the ENIAC and of logic and automata in general in the philosophy course that Burks offered. (There were no computer science or computer engineering majors or departments then; the Communication Science Program, which Burks co-founded, eventually became the Department of Computer and Communication Sciences and merged with Electrical and Computer Engineering in 1984 to form EECS at the University of Michigan.) The next year, I began work as a Logic Designer on Honeywell's H-200 development team led by another ENIAC engineer, J. C. Chu, who is also listed (along with Burks) in the Acknowledgment of the Brainerd and Sharpless Classic Paper (Fig. 1). Chu had just left RCA and was about to make Honeywell ever so briefly the second largest computer manufacturer, although well behind the then indomitable IBM shortly before IBM's introduction of System 360, the first instruction set architecture to run on a family of computers—a mere 20 years after the ENIAC.

Fig. 1. John G. Brainerd as the 1975 IEEE Founders Medal Recipient.

A portion of the ENIAC was reclaimed in 1965 by Burks and removed from its long warehoused sleep. It was taken in pieces to a car wash for steam cleaning and sand blasted to remove the green oxide that coated its connections, re-enameled and baked, reassembled, powered up and it ran, a feat that today's supercomputers would not likely withstand 40 years hence. That ENIAC portion has stood proudly in our EECS Building atrium since 1989.

Today, Intel microprocessors are the market-dominating processor technology, and supercomputers (always whatever is the largest, most powerful, and most expensive computer system of its day) are now vast internetworked collections of such microprocessors, whether geographically close or far flung—and once again, as with the ENIAC, computation rate is not the performance-limiting factor, rather it is still the communication, the I/O, the setup for the computation. It seems that communication science may be at the heart of the problem after all.

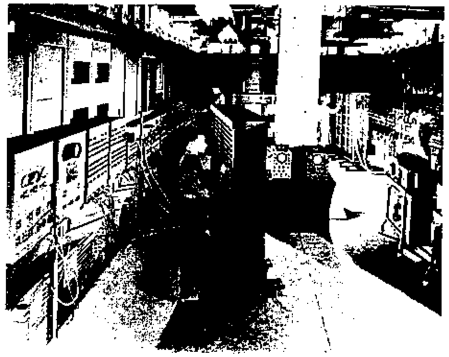

Fig. 2. The ENIAC shown in development at the University of Pennsylvania's Moore School of Electrical Engineering in 1946.

II. REFLECTIONS[2]

On February 15, 1946, the 18 000-vacuum-tube ENIAC (Fig. 2) was publicly dedicated at the University of Pennsylvania's Moore School of Electrical Engineering. In its demonstration at that time, the digital ENIAC solved the trajectory of an artillery shell in only 25 s, whereas the shell itself took 30 s to reach its target. This marked the first time that a complicated nonlinear real-time process had been calculated in less than real time. Moreover, the electronic portion of the calculation took up only 5 s—the other 20 were consumed by the IBM punched-card I/O of data.

The Army officers and their scientific advisors to this Army-sponsored project felt that their money (ultimately $500 000) was well spent. The ENIAC, operating reliably at 100 000 pulses per second, was 5000 times as fast as a human computer using a desk calculator and 60 times as fast as the most powerful (electrically driven) mechanical computer, the analog differential analyzer, of which only two were available to the Army. The ENIAC was physically about 20 times as large as the largest radio transmitters, and designing, building, and testing it was a tremendous—and revolutionary—undertaking.

Fig. 3. John William Mauchly (courtesy of IEEE Press).

Fig. 4. J. Presper Eckert (courtesy of the IEEE History Center).

The original ENIAC proposal had come from J. W. Mauchly (Fig. 3) in 1942, and a more complete draft was prepared by him and J. P. Eckert (Fig. 4) in early 1943 at the request of Lieutenant H. H. Goldstine. (Mauchly had joined the Moore School faculty as an Instructor in 1941, Eckert as a Research Associate and Instructor. Goldstine, stationed at Aberdeen Proving Ground, MD, was serving as Army Liaison Officer to the Moore School.) Goldstine and Brainerd (Director of Wartime Research at the Moore School) proceeded to secure funding for this proposal from Aberdeen's Ballistic Research Laboratory.

Eckert was named Director of the ENIAC Project, which began on May 30, 1943, and Mauchly became Eckert's chief consultant. Eckert had already gained a reputation

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[1] Section I is by E. S. Davidson.

[2] Section II is by A. W. Burks.

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as an electronics expert. He had been advising Mauchly as to what could be expected from electronic circuitry in computational tasks, and now it was he who established the reliability criteria for the whole system; for example, every circuit should be designed to do its job in half the time allowed by the clock cycle. Mauchly consulted with Eckert on a continuing basis.

There were about ten engineers, including T. K. Sharpless, co-author of this 1948 article. Of this group, Sharpless, R. F. Shaw, and I contributed to many of the design decisions; we three also had the responsibility, toward the end, of checking all the drawings for logic and electronics—and so for the correctness and reliability of the entire machine. There were many wire people, mostly women for this wartime project, and there was a very busy shop.

At that time, there were two electrical engineering professional organizations. The American Institute of Electrical Engineers (AIEE) was the older, beginning with low-frequency power and light engineering. After DeForest invented the vacuum tube and high frequencies entered the picture, the Institute of Radio Engineers (IRE) was formed. Most of the Moore School engineers belonged to both organizations. (Later, of course, the two were merged into the IEEE.)

For this reason, there were two articles on the ENIAC soon after it was completed: my 1947 article in the PROCEEDINGS OF THE IRE and the 1948 Brainerd and Sharpless article in the AIEE journal *Electrical Engineering*. The former was republished in the July 1997 issue of this PROCEEDINGS with an introduction by Schneck, and now we have this republication of the Brainerd and Sharpless article. They are, as it happens, quite different in their approaches and content.

Brainerd went on to become Director of the Moore School and was the recipient of many honors. He died in 1988 at age 83. At the conclusion of the ENIAC Project, Sharpless was put in charge of designing and building that computer's immediate successor, the Electronic Discrete Variable Computer (EDVAC) under Director of Research I. Travis. The EDVAC had a memory of 32 acoustic (mercury) delay-line tanks, each holding 32 words of 32 bits each. Its team suffered considerable turnover, and Sharpless himself left before the project ended. He and a former fellow student formed a computer business called Technitrol. Among other things, it manufactured and sold mercury delay lines, including those used in the EDVAC-type MIDAC built for the U.S. Government at the Willow Run Research Laboratories of the University of Michigan.

Unfortunately, Sharpless died prematurely of Hodgkins disease in 1965, but not before Technitrol had proven to be very successful, enabling him to give a new building to his *alma mater*, Haverford College.

Arthur W. Burks received the B.A. degree in mathematics and physics in 1936 from DePauw University, Greencastle, IN, and the Ph.D. degree in philosophy in 1941 from the University of Michigan, Ann Arbor, where he specialized in symbolic logic and the logic of Charles Sanders Peirce.

He became an Instructor at the Moore School of Electrical Engineering, University of Pennsylvania, Philadelphia, in the fall of 1941. During World War II, he worked on war research projects with J. W. Mauchly and J. P. Eckert. He was one of the principal designers of the ENIAC, receiving his assignments directly from Eckert. He gave the public demonstrations of the ENIAC when it was unveiled in February 1946. He had also participated, along with Eckert, Mauchly, von Neumann, and Goldstine, in the planning of the EDVAC in a series of meetings at the Moore School in 1945. After the ENIAC dedication, he joined von Neumann and Goldstine at the Institute for Advanced Study. In September 1946, Burks joined the Philosophy Department of the University of Michigan, where he continued to work in computer science as well as in philosophy. In 1957, he started the Graduate Program in Communication Science. He then served as the first Chairman of the Department that ensued and became a Professor of Electrical Engineering and Computer Science when the LSA and the Engineering Departments merged. He is now Professor Emeritus of Philosophy and EECS. He is also Adjunct Professor of Philosophy at Indiana University/Purdue University, Indianapolis, as Executive Consultant to the Peirce Edition Project. He has published numerous articles in both philosophy and computer science and has published or edited six books.

Dr. Burks has received an honorary Dr. Sc. degree from DePauw University, and he has been named a Russel Lecturer by the University of Michigan. He received a Computer Pioneer Award from the IEEE Computer Society and the George Stibitz Computing Pioneer Award from Montana State University and the American Computer Museum at Bozeman.

Edward S. Davidson (Fellow, IEEE) received the B.A. degree in mathematics from Harvard University, Cambridge, in 1961, the M.S. degree in communication science from University of Michigan, Ann Arbor, in 1962, and the Ph.D. degree in electrical engineering from University of Illinois, Urbana, in 1968.

After working at Honeywell from 1962 to 1965, and on the faculties of Stanford University and the University of Illinois from 1968 to 1973 and from 1973 to 1987, respectively, he joined the University of Michigan as Professor of Electrical Engineering and Computer Science (EECS), served as its Chair through 1990, and as Chair of Computer Science and Engineering since fall 1997. He managed the hardware design of the Cedar parallel supercomputer at the Center for Supercomputing Research and Development from 1984 to 1987 and directed Michigan's Center for Parallel Computing from 1994 to 1997. His research interests include computer architecture, supercomputing, parallel and pipeline processing, performance modeling, application code assessment and tuning, and intelligent caches. With his graduate students, he developed the reservation table approach to optimum design and cyclic scheduling of pipelines, designed and implemented an eight microprocessor symmetric multiprocessor (SMP) system in 1976, and developed a variety of systematic methods for computer performance evaluation. His current research focuses on extending such techniques to evaluate and improve the performance of application codes on parallel, vector, and workstation architectures, and on intelligent cache design and management. He has supervised 44 Ph.D. and 38 M.S. students.

Dr. Davidson was elected Fellow of the IEEE in 1984 for "contributions to the use of pipeline structures in computer architecture" and served as Chair of ACM-SIGARCH from 1979 to 1983. He received the IEEE Computer Society's Harry M. Goode Memorial Award in 1992 and its Taylor L. Booth Education Award in 1996.

The ENIAC

J. G. BRAINERD, FELLOW, AIEE, AND T. K. SHARPLESS, ASSOCIATE, AIEE

Classic Paper

The ENIAC is the only electronic large-scale general-purpose digital computing device now in operation. Its speed of operation compares favorably with other electric and mechanical computers. Developed under wartime pressure, it has been of value not only in producing results but in pointing the way toward improvements for future designs.

The ENIAC (electronic numerical integrator and computer) is a large-scale device, adapted to problems requiring a large amount of work for their solutions, and particularly to problems which involve the repetition of a large number of similar types of computations to achieve a result. The ENIAC does not reach a point of practical usefulness until applied to a problem which is such that a large amount of repetitious computation is necessary to obtain numerical answers. Such problems often involve the solution of differential equations, the evaluation of series, or the preparation of mathematical tables. For example, the equation

$$\frac{d^2y}{dt^2} + \epsilon(1 + k \cos t)y = 0$$

(where ϵ and k are parameters) is one which arises in several electrical problems, and has extensive use elsewhere. To solve it for values of $\epsilon = 1, 2, 3, \ldots 10$ and $k = 0.1, 0.2, \ldots 1.0$ requires 100 results, each of which is a table of y versus t. Each separate complete solution applies to one value of ϵ and one of k. To get this, the equation is solved by a corresponding difference equation, and if $\Delta t = 0.0004$, then about 7850 "lines" are called for in the range $0 < t < \pi$. In carrying out each line of work, approximately 10 multiplications and many more additions and subtractions were needed. Thus, in one solution of the equation for the given values of ϵ and k and for the range $0 < t < \pi$, there were 78 500 multiplications and many more additions or subtractions. Multiplying these by 100 (as this number of complete solutions was desired), there resulted 7 850 000 multiplications and many more additions and subtractions. The work of obtaining two separate solutions for y in each instance, corresponding to two different sets of initial conditions, required 15 continuous hours of ENIAC operating time. This included making a test run after every 5 regular runs, thus increasing the work outlined by 20 percent. Ten digit numbers were used throughout, (the reason for using such "large" numbers is discussed briefly later) and each result was recorded for $t = 0.0, 0.1, 0.2, \ldots$ up to $t = 3.14$ after which the values for $t = 3.1408, 3.1412, 3.1416, 3.1420$, and 3.1424 were added to enable values of the results at π to be obtained accurately by interpolation. This brief summary of machine operations and time used in solving an actual problem indicates the orders of magnitudes of these two items as they are related to the ENIAC.

Electrical engineers in the United States have had a major interest in the development of large-scale computing devices. Probably the most extensively used such instrument in the world is the ac calculating board, but although this is a large scale device it is hardly a general purpose computer even though it has been used by Kron of the General Electric Company in such problems as solving certain partial differential equations.

Another large-scale device is the differential analyzer, which originated in the electrical engineering department of Massachusetts Institute of Technology. Of the five now in the United States, two are at Massachusetts Institute of Technology, one at the Moore school of electrical engineering of the University of Pennsylvania, and one at the General Electric Company.[*] Differential analyzers have been used extensively in connection with machinery, stability, and similar problems, as well as in many fields outside electrical engineering, and all the analyzers now in the United States are in almost continuous use. The primary purpose of differential analyzers is to solve sets of ordinary differential equations, and, although they have been put to numerous other uses, this remains their prime objective.

Among other large scale computing devices are the Bell Telephone Laboratories relay computer and the International Business Machines automatic sequence controlled calculator at Harvard University [1]. Particular note should be made of these machines, because in some respects it

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[*] The fifth is substantially a duplicate of the one at the Moore school, and is in the Ballistic Research Laboratory of the Army Ordnance Department, Aberdeen Proving Ground, Md.

may be said that operations carried out by the ENIAC by electronic methods are performed in them by mechanical means. (The converse is not necessarily true, as will be explained subsequently.)

Another, and important, large-scale general-purpose computing "unit" is a group of business machines such as those of the International Business Machines Corporation. These devices can be used for addition, subtraction, multiplication, recording, and so forth, and by transferring punched cards from one to another, the sundry numbers in a problem can be operated on as desired. The Watson computing laboratory at Columbia University contains such a unit, as do numerous other places. Engineers might be interested to know there are units at the General Electric Company and in engineering departments of the Massachusetts Institute of Technology and University of Pennsylvania.

TERMS

A discussion of some terms used in connection with computing devices will simplify a description of the ENIAC.

Large-Scale: Although the afore-mentioned large-scale devices all require a moderately large room to contain them, size is not necessarily an accompaniment of large scale. Indeed, one of the purposes behind new electronic machines now under development is to reduce physical size and complexity. Large-scale refers rather to the magnitude of the problems which may be placed on a device so labeled. A desk calculator of any of the common types is a small-scale device; the ENIAC (and others) which without human intervention may perform thousands of additions, multiplications, and so forth in the proper sequence and with numbers evolved in the operations as the work proceeds, is a large-scale device.

General Purpose: A general purpose machine is one which will handle many types of problems, in contrast with specialized devices. A desk calculator is a general-purpose small-scale machine; an ac calculating board is a special-purpose large-scale calculator.

Continuous (Analogue) Versus Digital: A continuous variable or analogue type of computer is one such as a differential analyzer, where the angular displacements of rotating shafts or other devices give direct measures or analogues of results at each instant. The continuous motions of the shafts are to be contrasted with a desk calculator where continuous variation is impossible because adjacent keys in a column differ by a unit, and it is not possible to go between the values given by unit change in the right-hand column. The distinction between analogue and digital devices does not imply that they are to be applied to separate fields. A large-scale general-purpose digital device such as the ENIAC and others for most practical purposes can differentiate and integrate by using extremely small intervals of the independent variable ($\Delta t = 0.0004$ was cited in a foregoing example). It is true that the independent variable will not change uniformly, but rather in steps; nevertheless, the steps may be taken so small as to make over-all errors small. AC calculating boards, differential analyzers, slide rules, and so forth, are continuous variable devices; most development now under way on large-scale computers is confined to digital types. The reason for this is that higher accuracy is obtainable with the digital device. For example, the ENIAC can handle numerical quantities of 10 significant figures and with a minor change can handle 20 significant figures. On the other hand, differential analyzers or other analogue machines yield at best 4 or 5 significant figures, and to increase this would require complete and revolutionary design changes.

Electronic Versus Mechanical: By an electronic computing device is meant one in which the arithmetic and control procedures are performed in the machine by electronic circuits. The ENIAC is the only electronic large-scale general-purpose computer now in operation. In contrast, mechanical means such as relays are used in other existing large-scale digital instruments, and the basic arithmetic device in all differential analyzers is the mechanical integrator. AC calculating boards are electric devices; the word electronic is used because the new electric computers (ENIAC and those under development) use electron tube circuits extensively.

Amplitude Versus Step Mechanisms: The distinction to be attempted here between amplitude and step mechanisms has to do with the internal operation of calculators and not with the question of continuous (analogue) versus digital machines. An amplitude mechanism is one in which a result is indicated by the amplitude of some quantity, as, for example, the voltage on a capacitor. The voltage may be read as closely as possible, or the device might be used in a digital system in which any voltage from 7.5 to 8.5 indicated the number 8. A step mechanism is, like a relay, one characterized by an on-off or an open-closed state. If ten relays are arranged in a column and labeled 0, 1, 2, ... 9, then if all are open except that labeled 8, the number 8 is indicated. The definiteness of on-off or open-closed devices like relays and certain tube circuits has led to their use almost exclusively in large-scale digital computers. A basic elementary circuit in the ENIAC is a pair of tubes (trigger circuit) so arranged that when one (number 1) is conducting the other (number 2) is not. If, for any cause, number 2 becomes conducting and number 1 not, a reversal has occurred. This reversal can be made to correspond to the change from open to closed or conversely of a relay, or, in more general terms, from a normal to an abnormal state.

Synchronous Versus Sequential: If as soon as one operation such as a multiplication is completed a signal is given which initiates immediately the following operation, a calculator is said to have sequential operation. An individual operating a desk calculator would work on a sequential basis. If on the other hand no operation can begin except at an integer multiple of some fixed time interval after a previous operation has begun, the calculator is said to work synchronously. The ENIAC is of the latter type, its operation being controlled by a group of pulses which are repeated every 200 microseconds. A new operation can start only at the beginning of one of these 200-microsecond intervals.

Series Versus Parallel Operation: A large-scale digital calculator is said to have parallel operation if two or more arithmetic operations (two additions, or an addition and a multiplication can be carried out simultaneously). It has series operation so no two arithmetic processes can be carried out at the same time. The ENIAC has a limited amount of parallel operation, but because of the high speed of the electronic machines the tendency in new development is toward series operation wherever the mode reduces complexity.

Decimal Versus Binary: This heading lists two of the large number of possible number codes which can be used in connection with a digital machine. In the ENIAC numbers appear in the usual way they are used, and this representation is called a decimal one. On the other hand, the open–closed or on–off characteristic of relays, certain tube circuits, and the like, has led to extensive consideration of the use of the binary, or base two, system. In this case a number would be "translated" from its common expression in the decimal system to its expression in the binary system of numbers. It would be retained in this latter system, and most or all operations would be performed on it in this system, until a desired result is achieved, in which instance it would be translated from the binary to the decimal system either before or after recording. Other number systems besides the binary may be considered—the choice of a system to use internally is determined by saving in equipment, simplification in circuits, magnitude and complexity of translation equipment, weight given to simplicity of understanding for maintenance men and other nontechnical personnel, and so forth. As the ENIAC uses the decimal system, no further discussion of this topic will be included here, except to note that other systems such as the binary and the biquintic are in use.

MACHINE COMPONENTS

Most large-scale computing devices can be broken down into several components. Despite the fact that in the ENIAC these components are mixed almost inextricably with one another, it is convenient to use them for a brief functional outline.

1) *The Arithmetic Component* consists of 20 accumulators for addition or subtraction, one multiplier, one divider square rooter, and three function tables on each of which can be set values of a known function to be called up in the course of the solution. (The calling up is arithmetic; the settings are memory as next described.)
2) *The Memory Component* consists of the same 20 accumulators, any one of which can be used to "hold" or "store" a number so long as that accumulator is not used for other purposes, the same three function tables which are memory devices yet at the same time arithmetic, and finally an unlimited memory obtained by sending numbers to be remembered to the output device, and having them available for recall through the input device.
3) *The Control Component* may be considered to consist of two parts: control of basic operations without regard to the problem on the machine, and control of the sequence of operations for a particular problem. The latter usually is known as programming and is achieved on the ENIAC by external connections inserted by hand between the panels of the various arithmetic and other devices. In order to carry out such processes as to have a cycle of operations repeated, another cycle begun and repeated, and then the first one again carried out a certain number of times, and to do many other programming jobs, there is a master programmer available for control. Other large-scale general-purpose digital machines now in operation have programming done automatically, and the electronic computers now under development likewise will have this feature. The control of basic operations, independent of the particular problem on the machine, is obtained in the ENIAC (disregarding power supply and auxiliary equipment controls and control of the numerous direct voltages for tubes) by a series of pulses generated at the cycling unit and repeated every 200 microseconds. Fig. 1 shows the group of pulses so required in each 200-microsecond interval. Some idea of the uses of the pulses will be contained in the description of the operation of an accumulator.
4) *Input and Output Devices.* The questions of how data, such as initial values of variables, values of parameters, are supplied to a device such as the ENIAC, and how results are to be taken out of the machine, are to a large extent independent of the computing device. Thus, data may be recorded originally on a punch tape, on a magnetic tape, on punch cards such as are used in business machines, or otherwise, and an appropriate mechanism devised to insert into the computing machine the electric or other type of signals needed to inform the machine of the numbers being supplied to it. Likewise, a result which it is desired to record many appear somewhere in the machine, and this result may be brought out to a mechanism which will translate the machine result (given by indications in certain circuits in the case of the ENIAC) to a punch tape, a magnetic tape, an electric typewriter, a punch card, an indication on a film, or other medium. It is interesting to note that the speed at which input and output devices operate may be so low, relatively, that, on occasion, they may be the limiting factor in determining the over-all time in which a problem can be done. This limitation is particularly evident in the case of a high-speed electronic computer such as the ENIAC, and might be illustrated by reference to the problem cited previously. The equation there given was solved on the machine 100 times, and in each instance it was solved for some 7850 values of t, differing in steps of 0.0004 from zero to π. If each one of these results for a given set of values of ϵ and k were

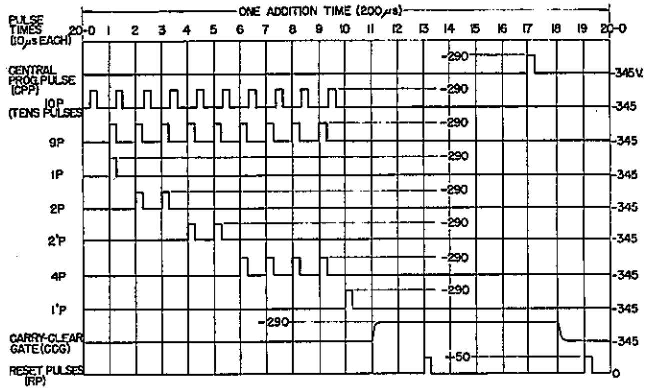

Fig. 1. Pulses used in the operation of the ENIAC.

tabulated, the machine would obtain the solution and then wait until the slow-speed recording of the previous solution was completed. Actually, every hundredth result was recorded, and thus the machine ran through 100 lines while the output device was recording the final result of the previous 100 lines. In this way the machine had plenty of work to do during the time required for recording.

In the ENIAC, input and output are by International Business Machines punch cards, and there are other input methods as well. Consider, for example, the case in which it is desired to record a result in the machine. This result, appearing in electrical form, is translated to a set of mechanical relays which, in turn, cause an International Business Machine card punch (usually called the "printer") to punch on a card the result. This is a relatively long-time procedure, but meanwhile the ENIAC is proceeding without interruption, unless it should happen that it produces a new result for recording before recording of the first one is completed, in which instance the ENIAC pauses in its work until it receives an appropriate signal from the card punch.

Current developments in large-scale general-purpose digital computing devices are devoted to a considerable extent to obtaining speedier input and output mechanisms. It may be noticed that the function tables mentioned in "Memory" may be used to insert arbitrary data into the ENIAC at high speed, and in addition there are built-in facilities of limited extent in the ENIAC (in the unit called "constant transmitter") for inserting at high speed numbers (such as π) which frequently may be used in a particular problem.

BASIC CHARACTERISTICS

Large-scale computing devices often are compared on the bases of flexibility, accuracy, speed, reliability, and capacity. These characteristics are so intertwined with one another that no absolute clean-cut distinction between factors affecting each can be maintained, but in a broad way they serve as an introduction to the comparison and evaluation of the large-scale machines.

Fundamentally the desideratum is to solve a given problem to the accuracy desired in the least possible time and at minimum cost. "Time of solution" is a term which has been used in numerous ways; it may include all the time from first tackling the problem with pencil and paper to final tabulation of results obtained on the computing device. But often "time of solution" means machine time (interval the machine is devoted to the problem). It also has been used to denote operating time which is the time the machine actually operates in solving the problem and excludes setup time, if any, close-down time, and time for major maintenance work, if any. However, with regard to the basic objective it is over-all time—a useful but not precise interval—which is of interest.

Flexibility: In a digital machine flexibility means that the device or devices for carrying out arithmetic processes may be interconnected in arbitrary fashion, or ordered to perform operations in arbitrary sequence, so that there would be no limitation on the operation to be performed next on a given number in the machine. This flexibility is to be contrasted with a machine permanently "wired" so that it is restricted to variations of one problem.

In a more general sense flexibility denotes the existence in a machine of a device or devices for carrying out the usual arithmetic processes: addition, subtraction, multiplication, division, differentiation, and integration, as well as it denotes flexibility of potential arrangements. Digital machines such as the ENIAC are described as general purpose machines because they are both flexible as to arrangement, and have devices for all the arithmetic processes, including differentiation and integration, which are carried out by approximate methods so accurately that they suffice for most purposes.

Virtually all practical problems requiring numerical solutions come within the scope, but not necessarily the capacity, of the general purpose digital computers. There is a lower limit of complexity or quantity below which it does not pay to use a *large-scale* general-purpose computer, but this practical limitation should not be allowed to shadow the fundamental fact of the preceding sentence: virtually all practical problems requiring numerical solutions come within the scope, but not necessarily the capacity, of the general purpose computers.

Computers such as ac calculating boards and differential analyzers are not general purpose devices, and despite the extension of their application to problems not originally contemplated when they first were devised, they remain substantially specialized and not flexible in the sense that term is used here.

Accuracy: Most continuous variable or analogue computers give results which may be accurate to three or four figures; the accuracy depends on the problem under solution, the part of the solution considered, and other factors, as well as on the device. Many results from differential analyzers are obtained in the form of curves. AC calculating boards yield answers obtained by instrument readings. In contrast, numerical solutions accurate to five or more figures sometimes are required in practice. It is desirable that new tables of mathematical quantities be given to several significant figures beyond current use to allow for future needs which usually are more exacting than existing ones. Computations which involve many differences of nearly equal numbers require many more significant figures in the numbers than will be obtained in the result. Numerous other examples of the desirability of high accuracy may be cited. For these reasons, and the added fact that to help justify its existence a large-scale general purpose computing device like the ENIAC definitely should increase accuracy over such "old-time" (in the era of large-scale computers) devices as the differential analyzers, most large-scale general-purpose digital computers deal with numbers which may seem outsize to engineers, but which actually are not. In the ENIAC, provision is made for using 10-digit numbers (as in the case of simple 10-column desk calculators) in almost all parts of the machine. This figure was chosen after a rough study of a particular differential equation which had to be solved many thousands of times during the war, and the choice was made to insure that 5-figure accuracy was found in the results. There are definite reasons why the accuracy of the solution of a differential equation (or other mathematical form) may decrease radically when handled by digital methods; a simple example not associated with any computing device or with a differential equation would be a column of 1000 numbers to be added (it will be recalled that in the ENIAC many thousands of operations may take place in obtaining a solution). If each number is given to 11 significant figures, and the decimal point is at the same position in all of them, then disregarding the 11th figure in each case and carrying out the addition would result in an error of the order of magnitude of 500, the 5 appearing in the eighth digit position. While such an error in simple addition might not appear directly in the ENIAC because provision for round-off is made, nevertheless, problems such as differential equations can involve processes which result in decreased accuracy (assuming the machine operates correctly) because of the way the machine solves the problem.

Table 1
ENIAC OPERATING SPEED

Operation	Time Required, Microseconds	Speed, Operations Per Second
Addition or subtraction	200	5,000
Multiplication of two 10-digit numbers	2,800	360
Calling up of the value of a function (from function table)	1,000	1,000

The "floating decimal point" which may improve accuracy for a fixed size of number to be used in a machine or, conversely, may decrease the size of number required for a given accuracy is a feature not included in the ENIAC.

Speed: Setup time is the time required to arrange the interconnections for the particular problem at hand. In machines with automatic programming this is done by instructions given by the input device as the problem proceeds. In the ENIAC, interconnections (not including those which are the same for all problems and are built in) are made by hand, small patch cords being inserted at appropriate points in the machine and in the trunk system which extends around the front of the machine. The time required for this depends on the problem and the experience of the operator. It ranges from 30 minutes to a full day, and in this time the machine is not in operation, hence setup time is wasted so far as use of the machine is concerned.

The speed with which arithmetic operations are carried out is given by Table 1, which shows the times required. This is an extremely important item, for it shows the great speed with which the ENIAC works in solving a problem. Take, for example, the time required to multiply two 10-digit numbers: it is approximately 3 milliseconds, or the speed is approximately 300 such multiplications per second. Now consider a problem requiring 1 000 000 multiplications. If there were no delays such as might be caused by slow-speed input and output equipment, this might be accomplished in an hour. Allowing 100 percent leeway for all other operations except input and output (note that addition and subtraction are much faster than multiplication), this means that the problem might be solved in 2 hours, plus the time delay resulting from waiting for the input and output devices to complete their operations—if the latter operated very few times this would be negligible; if the problem required frequency operation of these devices this might amount to hours.

In connection with development work now under way on electronic large-scale general-purpose computing devices, increase in speed of arithmetic operation is not considered of major importance, although new machines may have speeds greater than those of the ENIAC by factors from slightly more than one to approximately ten.

It is interesting to note that the high speed of operation of the ENIAC makes less important the mathematical work which is often an intensive part of the preparation of a problem for solution. If the problem, for example, is to be hand-computed by a computing pool, it is often desirable and sometimes essential, that the solution be obtained by the most efficient method—quickly converging series, a special method of solution, maximum interval consistent with accuracy so that arithmetic work is minimized, and so forth. If this same problem were to be solved on the ENIAC, a savings of 50 percent in solution time well might be negligible and the many days' work by high-quality personnel which often is put into such problems before any arithmetic work is done possibly might be cut down.

Reliability: There is no point in saying that a problem involving one million multiplications of 10 digit numbers can be carried out in two hours if the machine will have a breakdown before the problem is completed (although storage of results at regular intervals may save work up to the end of the interval preceding the trouble). The ENIAC was in numerous respects a pioneering device. Although several thousands of vacuum tubes have been used in a single network previously (this excludes systems such as the telephone system which uses many more tubes but in which a tube failure does not render the entire system inoperative) it is probable that no single device has had the 18 000 tubes which appear in the ENIAC. Since first use of the ENIAC much experience has been gained in operation and maintenance, and much of this bears directly on the question of reliability.

For 11 months the machine was in active use by Army Ordnance Ballistics Research Laboratory personnel at the Moore school. During this time a log book was kept listing all shutdowns and troubles encountered in the course of running problems. In this period of time the removal rate for tubes was one per 20 hours. In other words, 400 out of 18000, or somewhat less than two percent, of the tubes caused trouble during the course of the 8000 hours of the study. It should be pointed out that the ENIAC was put into action immediately upon completion because of the urgency of some of the problems awaiting its operation. As a result there was no opportunity for a real "run in" period. This fact accounts for a rather high incidence of intermittent troubles resulting from bad soldered joints. There are some 500 000 soldered joints in the machine. (Besides its electronic circuits ENIAC includes a number of mechanical and electromechanical parts such as ventilating fans, protective relays, input and output relays and punch card reader and punch. This equipment totals about ten percent of the total components of the complete machine.) After the first few weeks of operation the practice of keeping power supplied continuously to the heaters of the vacuum tubes was followed as it was discovered that each shutdown resulted in two or three tubes failing. Power failures cannot be prevented entirely and several occurred during the 11 months.

The method used for checking the results of a problem was generally as follows. Before and after each run of a problem test problems were run. In addition, many problems were checked within themselves, that is, certain terms or parts of these problems always must equal some constant such as one. Thus a check operation may be programmed comparing this part to one. The machine may be stopped automatically if this comparison is not right or the results may be printed for the operator to examine. Besides these precautions, each problem usually was run twice and the results compared.

Of the time that the ENIAC might have been actually computing, about 50 percent was unproductive. Approximately half of this time was used for setting up the problem—connecting patch cords, setting switches, and checking these operations. This time is longer than is the rule now since operators and coders of problems were unfamiliar with the job and also because the problems solved initially were of extremely complex nature. The other half of this unused machine time was spent in maintenance and repairs.

A brief summary of the classes of failures requiring repairs follows.

1) Vacuum tube and electronic circuit component failure. These accounted for 20 percent of the repair and maintenance time.
2) Circuit failures of mechanical nature such as bad solder joints, broken wires, short circuits. This accounted for 40 percent of repair time.
3) Failures of the electromechanical input and output equipment accounting for 20 percent of the repair time.
4) Failures of dc power supply including rectifier tubes. Ten percent of the repair time was used for these failures.
5) Failures of ventilating equipment and protective devices which accounted for the final ten percent of the time.

It should be noted that these times include the time to find and repair the failure. In addition it can be said that the frequency of failures falling in category 2) was reduced greatly as time passed.

Capacity: The question of capacity of a large-scale machine, that is, the maximum "size" of problem it will handle, is essentially one of programming and memory in the case of the digital devices. With a machine such as a differential analyzer or an ac board, it is a question of the amount of equipment (for example, the number of integrators or input tables in the differential analyzer). Restricting discussion to the large-scale general-purpose digital machines where automatic programming is incorporated, as in many of the new machines, but not in the ENIAC, the question reduces substantially to memory capacity.

To illustrate, in the ENIAC interconnections of the various units for a particular problem are by external connections, and when all of the places where a connection of a given type can be made are occupied, no further connections can be made to that unit. In contrast, a machine with automatic programming is arranged so that various units performing arithmetic operations can be called into use and after completing an operation can be freed so as to be available whenever next needed. This effectively eliminates the restriction on capacity resulting from programming. However it should not be thought that the ENIAC is limited unduly in this respect. The omission of automatic programming was for the sake of simplicity, but the extensive provision for interconnections has resulted in programming not being a serious limit on capacity.

For an appreciation of the reason that memory capacity is important, some consideration should be given to modern problems. To take one particular class, consider problems in electromagnetic field theory, hydrodynamics, or elasticity, which are expressed in terms of partial differential equations. Speaking broadly, these cannot be handled by differential analyzers which are intended primarily for ordinary differential equations. It was mentioned that Kron had used the General Electric Company's ac board to solve some problems involving partial equations in each of these fields, but although this represented a distinct advance the method is quite limited. It is possible to solve a partial differential equation by a method similar to that used to solve an ordinary differential equation on a digital machine, that is, by replacing the "infinitesimal" differentials such as dt by finite but very small differences Δt. For partial equations the process is not so simple as there is more than one independent variable. In place of a "line" of computations followed by another using the results of the first line, and so on, a grid of results must be obtained, and these must be remembered in computing other results. Estimates by persons working in the fields usually place the desirable capacity of numbers to be remembered at between 1000 and 5000 (each number would have a certain number of digits—for example, 10 in the case of the ENIAC).

Present large-scale general-purpose digital machines could do this, but in the case of the ENIAC, for example, it would be necessary to record most of the 1000 to 5000 intermediate results by using the output device, and then to sort and reinsert each of these results at the right time by means of the input device. As previously mentioned, the input and output devices are slow-speed affairs, and the process would consume a great deal of time. Consequently it is reasonable to consider the capacity of the ENIAC limited in this respect. New development work in the field of the large-scale general-purpose electronic digital computers is devoted to a large extent to achieving adequate memory of the order of 1000 to 5000 10-digit numbers.

GENERAL DESCRIPTION OF THE ENIAC

In light of the preceding discussion the following characteristics of the ENIAC may be listed:

1) large-scale;
2) general purpose;
3) digital;
4) electronic;
5) uses 10-digit numbers;
6) uses decimal system;
7) high speed;
8) synchronous operation;
9) some parallel operation possible;
10) complete flexibility within limits of programming capacity.

In addition, it may be noted that the ENIAC consists of 40 panels erected along a U-shaped contour, plus dc supplies for tube voltages, and so forth (Fig. 2). The ENIAC has been housed in a room 30 by 50 feet. It contains approximately 18 000 vacuum tubes, and uses about 130 kw.

AN ACCUMULATOR

To describe in any detail all the sundry units in the ENIAC would require considerable space; in lieu of this the operation of one unit only—an accumulator—will be outlined, without going into circuit details.

Broadly speaking, the purpose of an accumulator is to perform additions and subtractions, to store a number, or transmit a number when called on, and to receive numbers for addition or subtraction or for storage. An electric device consisting of ten similar basic units of which all units except one were "off" or "normal" or otherwise distinguished, and one unit was "on" or in an "abnormal" state or otherwise oppositely distinguished would serve to form one column. Ten of these devices alongside one another could form the ten columns necessary to permit indication of a 10-digit number. The accumulators of the ENIAC use a "ring counter" for each column. The basic unit of the ring counter is a trigger circuit so arranged that nine of the trigger circuits are in a normal state and one in an abnormal state. Fig. 3 shows a decade counter and Fig. 4 a block diagram. The electric circuit includes a pulse-shaping circuit for assuring good wave form of the pulse and also includes carry-over circuits. Carry-over is required because after a counter reaches 9 the next pulse received by it should return it to 0 and add 1 in the next digit position. (Because the counter goes from 0, 1, 2, ... 9, and then back to 0, it is called a ring counter.) Carry-overs are of two types—when there is not already a 9 in the next digit position, in which instance one carry-over completes the work, and when the opposite is true. In the latter instance a further carry-over is required, and provision is made for this.

To eliminate the need for the counters to work in two directions, that is, from 0, 1, 2, ... to 9, and from 9, 8, 7, ... to 0, as would be required in ordinary addition and subtraction, the complements of negative numbers (with respect to 10^{10}) are used, and subtraction thus becomes a process in addition. However, as it is necessary to know whether a number is a simple positive number or a complement of a negative number, electrical means are provided for having an appropriate signal travel with the representative of a negative number. If P and M are used to denote respectively plus and minus quantities, then $P\,0\,000\,342\,789$ is the number $+342\,789$ whereas $M\,9\,999\,452\,111$ represents $-547\,889$ which is obtained by

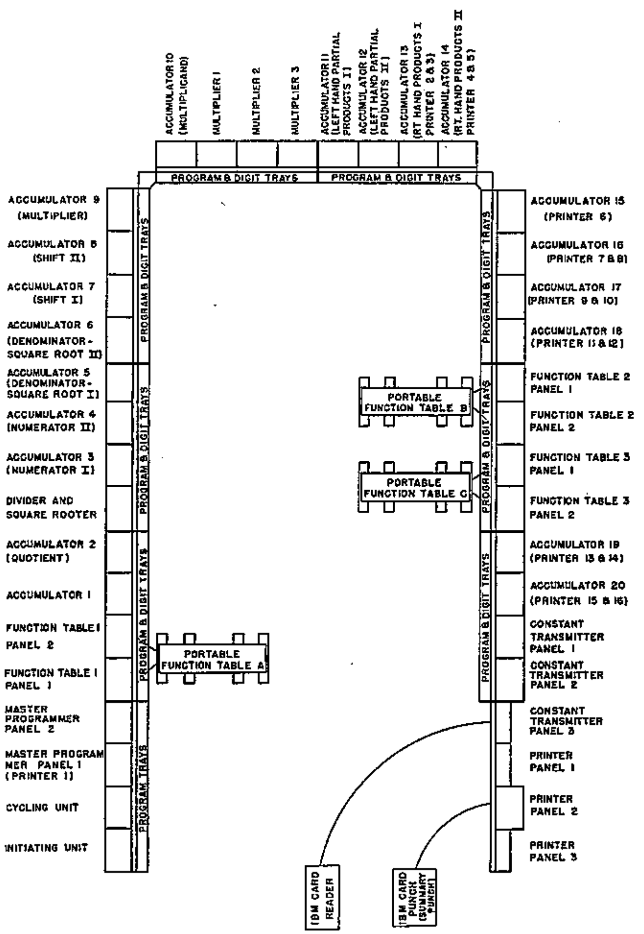

Fig. 2. ENIAC floor layout. Initiating unit—Controls for power, operation controls. Cycling unit—Source of pulses used in operation of ENIAC; name is derived from cycle of pulses shown in Fig. 1 and does not refer to cycles of arithmetic operations. Master programmer—Controls the cycles of arithmetic operations and performs other programming functions. Function table panels—Used in conjunction with function table to call up at high speed numbers "set" in function table. Accumulator—Performs additions and subtractions, stores results, and so forth. Divider—Performs divisions and also can be used to take square roots. Multiplier—Performs multiplications. Constant transmitter—Receives at low speed information from the input device (an International Business Machines card reader, as indicated) or other device, and supplies this information at high speed when called for (note that the input device is at what appears to be the next to the last position rather than at the "beginning" of the ENIAC; this is of no significance). The constant transmitter also has a limited capacity for storing numbers set on switches on its front panel. Printer—Receives at high speed results to be recorded and transmits them to the relatively slow-speed output device (an International Business Machines card punch as indicated). Digit trunks—Special transmission lines into which connection can be made to transmit numbers from one part of the ENIAC to another. Program trunks—Special transmission lines into which connection can be made to transmit program orders (electric pulses) from one part of the ENIAC to another. Trunk from cycling unit—Permanently connected to other units to which is supplies the group of pulses shown in Fig. 1 every 200 microseconds when ENIAC is in continuous operation.

Fig. 3. A decade counter.

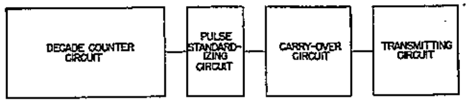

Fig. 4. Block diagram of decade unit.

subtracting 9 999 452 111 from 10^{10}. If now the number +342 789 is in an accumulator, and the number −547 889 is sent to that accumulator to be combined with the former, the accumulator actually will receive the complement of the latter, and the operation will be

$$\begin{array}{ll} P\ 0000342789 & \text{(in accumulator)} \\ M\ 9999452111 & \text{(sent to accumulator)} \\ \hline M\ 9999794900 & \text{(result in accumulator).} \end{array}$$

There is a *PM* indicator in the accumulator which will indicate *M* for the result; this means that the answer is negative and that 9 999 794 900 is its complement. The true answer therefore is obtained by subtracting the latter from 10^{10} and is −205 100. Complements are obtained easily in the ENIAC, and the process of using them in place of negative numbers does not involve any great complexity.

An accumulator is not a counter, although each accumulator contains ten decade ring counters. A counter as its name implies "counts," and to get to any number such as 342 789 would go through the indications of all integers from 1 to that number. This would be a very long process. An accumulator, like a desk calculator, adds in all columns at the same time, and thus requires for its operation only the time for its counter unit (one in each digit position) to count from 0 to 9, plus time for causing carry-over, plus time for certain other processes. In the ENIAC the ring counters in each digit position are advanced by the reception of pulses. These pulses are 2 microseconds in duration, and follow one another at 10-microsecond intervals. Nine pulses are required to carry out additions and subtractions before carry-over, and 110 microseconds are needed for carry-over and other necessities. Thus one addition or subtraction requires 200 microseconds, which is the basic "addition time," and is the interval covered by the chart in Fig. 1.

Fig. 5 shows the front of an accumulator, and Fig. 6 gives a drawing of the front control panel appearing approximately in the center of Fig. 5. As the diagram of Fig. 2 shows, there are 20 accumulators in the ENIAC. The external operation of an accumulator can be explained by noting the various uses of the parts appearing in Fig. 6.

In the upper left-hand corner are receptacles marked interconnecting plus I_{L1} and I_{L2}. These are for interconnection to another accumulator to enable the pair of

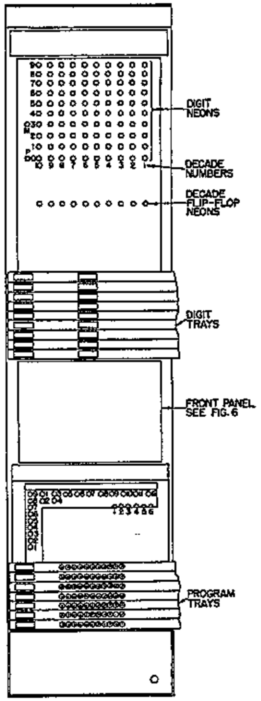

Fig. 5. Front view of an accumulator.

accumulators to handle a 20-digit number. Likewise at the upper right are receptacles I_{R1} and I_{R2} used for a similar purpose.

The digit input terminals are receptacles for numbers coming to the accumulator. The lettering α, β, γ, δ, ϵ, indicates five separate receptacles, any one of which can be connected to any other unit of the machine by means of the digit trunks (transmission lines) which may be plugged into at each panel. There are 11 wires in each connection, ten to carry pulses corresponding respectively to the ten digits of a 10-digit number, and the 11th to carry the *P* or *M* indication. The α, β, γ, δ, ϵ receptacles allow five incoming interconnections, so that at different times during the solution of a problem the accumulator can receive numbers from the various other units to which connections are made.

The digit output terminals are the terminals through which the number in the accumulator at a given time may be sent out (*A* is for add output and through it goes the number in the accumulator, *S* is for subtract output and through it goes the complement of the number in the accumulator). Only one output receptacle is necessary, as this may be connected to as many digit trunks for transmission to other parts of the machine as required. This does not mean that

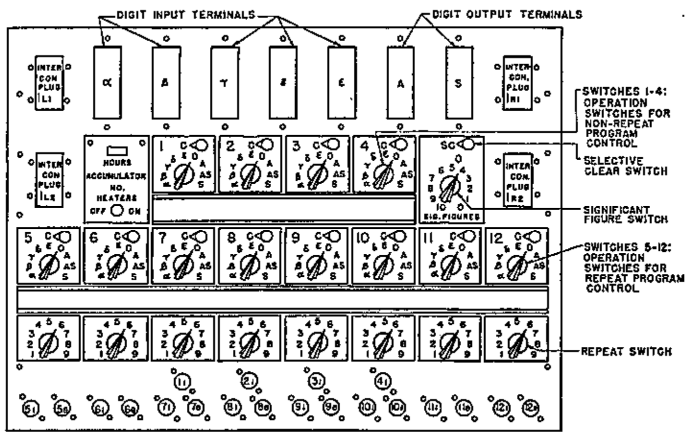

Fig. 6. Accumulator front control panel. Terminals $1i, 2i, \ldots 12i$—Program input terminals. Terminals $5\theta, 6\theta, \ldots 12\theta$—Program pulse output terminals.

these other units will receive all outputs of the accumulator under review. The pulses arrive at all these other units, but only in those which have received a program signal to accept them will the pulses (numbers) enter.

The panel marker which has the accumulator number has the on-off switch for accumulator tube filament heaters, and shows the number of hours of operation of the tube heaters. This is desirable for maintenance. In the corresponding position on the right-hand side is the significant figure switch, which, by proper setting, results in the accumulator "clearing," that is, eliminating the number in it and indicating 0 000 000 000, except that a five is put in whatever digit position desired, if any. This is a common mathematical trick for rounding off numbers, and explains why certain simple round-off errors such as that given with an example of numerical addition earlier need not appear in the ENIAC. It does not do away however with round-off errors in general, and these are often of major importance. The selective clear switch, when in a proper position, enables the accumulator (and others with switches so set) to be cleared by a signal sent out to all from the initiating unit.

Omitting switches 1 to 4 for a moment, consider any one of the switches 5 to 12. Immediately beneath operation switch 5 for example is a repeat switch, and beneath this are shown terminals $5i$ and 5θ (i for input, θ instead of O for output because O resembles zero) all of which go with the operation switch 5. If operation switch 5 is set to α, and terminal $5i$ receives an appropriate program signal from elsewhere in the machine, then the accumulator will admit the number being sent to it on the α digit input terminal at the top of the panel, and this number will be added to whatever is then in the accumulator, or if nothing (0 000 000 000) is present the incoming number (and its sign indication P or M) will be stored. If the repeat switch is set to any value such as six, the number will be received six times provided it is sent out from elsewhere in the machine at least six consecutive times. If it is sent out more than six times, the accumulator here under discussion will receive it only six times. This is a simple method of multiplying by small numbers, namely, adding the numbers together the appropriate number of times.

Consider now another switch, say operation switch 6. If it is set to A, its repeat switch to nine, and the program terminals 6θ connected to another unit of the machine (or to any of the i terminals of this accumulator) then the following will take place: The number in the machine will be sent out over the A digit output terminals (top right of figure) when an appropriate signal is received on $6i$; this will be repeated eight more times (total of nine times) because of the setting of the repeat switch; after this is done a program signal will be sent from 6θ to another unit to start operations there; if the clear correct switch is set to C the number in the accumulator will be cleared out of the accumulator in accordance with the setting of the significant figure switch but if the clear correct switch is set to 0, the number in the accumulator will be retained there.

Operation switches 1–4 are similar to those of 5 to 12, but have no associated repeat switches and no program output (θ) terminals.

This brief description of the external operation of an accumulator will tend to give an idea of the external operation of the other ENIAC units, and of the interconnections between units and the programming (except for use of the master programmer) which must be set up for a particular problem.

A common example of the use of accumulators as the only arithmetic units in a problem is that of generating the squares of all integers from 1 to 10 000 correct to 10 significant figures. Write

$$(n+1)^2 = n^2 + 2n + 1$$

which says that the square of an integer plus twice that number plus one is the square of the next higher integer. The work can be carried out thus: set the constant transmitter to supply the number one, and connect it to accumulators 1 and 2 using one of the α, β, γ, δ, or ϵ digital input terminals in each. Connect the A digit output terminal of number 1 to one of the unused α, β, γ, δ, or ϵ terminals of number 2; program so that number 1 transmits twice to number 2 and number 2 receives twice, and thereafter the constant transmitter supplies one to each accumulator. The machine then proceeds as follows, assuming the numbers one and one appear initially in both accumulators: number 1 transmits twice and number 2 receives, so that one is sent twice from number 1 to number 2, resulting in three appearing in number 2 and one in number 1; thereafter the constant transmitter sends one to each accumulator so that number 1 contains two, and number 2 contains four. This is the end of the first line, and if suitable programming were arranged the result could be recorded, and the second line started.

Number 1 now sends two twice to number 2, which brings the number in the latter up to eight. The constant transmitter now adds one to each accumulator's number, so that number 1 has three and number 2 has nine. This ends the second line. This process then is continued. It is so fast that if no time is taken out for recording it can compute in six seconds the squares of all integers from 1 to 10 000 correct to ten significant figures. (Actually the process can continue beyond 10 000 to the integer whose square last falls within 10^{10}, and could go farther if accumulators were connected for 20-digit operation.)

BRIEF HISTORY

While the ENIAC exists independent of its history, it is interesting to note that it was actual pressure of computing work that led to its inception. During the war the differential analyzer of the Moore school of electrical engineering of the University of Pennsylvania was used intensively for ballistic computations; the ballistic research laboratory of the Army Ordnance Department maintained a computing center of approximately 100 trained persons (college graduates) on the Pennsylvania campus in cooperation with the University, and under separate contracts the Moore school maintained other computing groups. In addition several hundred persons (Army employees) were given intensive 3-months' training courses in mathematics, plus approximately 100 specially selected members of the Women's Army Corps. The Ordnance Department had virtually duplicate facilities at Aberdeen, Md., both as to differential analyzer and number of computers. The total computing center was probably one of the largest, if not the largest, in the world.

Despite all this it was soon evident that if the work were to continue at its then rate of growth, and if personnel could not be obtained more easily than was possible in the early years of the war, the work would outrun the capacity of the computing center. It was in this atmosphere of pressure that development of the ENIAC was undertaken, and it was because of this pressure that there are deficiencies and omissions now apparent in the machine, which nevertheless retains its position as the first electronic (high-speed) large-scale general-purpose digital machine, and which is the forerunner of numerous others now under development. Although the ENIAC is a general purpose machine, its name (electronic numerical integrator and computer) reflects the preoccupation with numerical integration of differential equations which was such an important part of war computing work.

ACKNOWLEDGMENT

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