SUPER ELECTRONIC COMPUTING MACHINE

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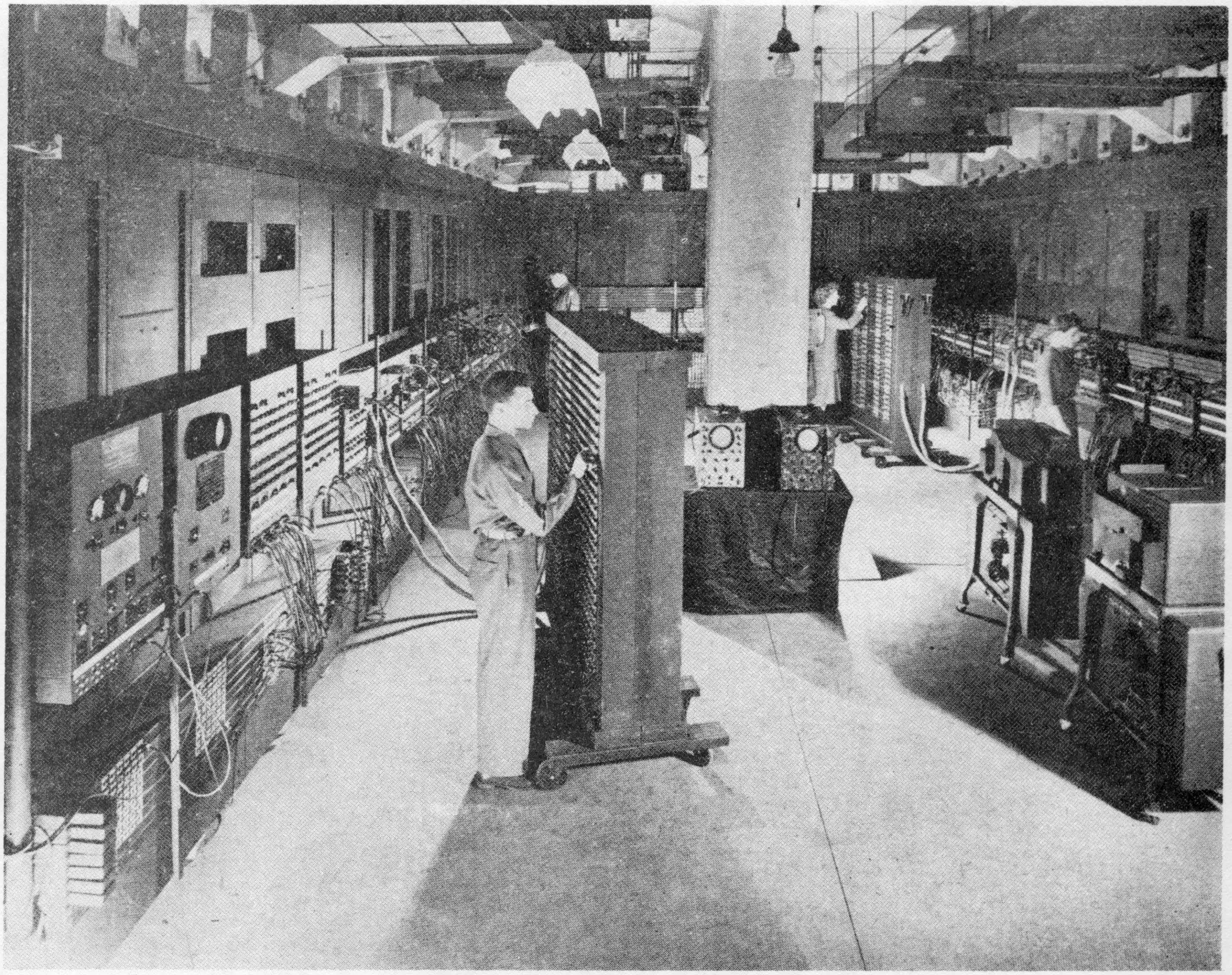
ENIAC, requiring 18,000 vacuum tubes, was developed at the request of the Ordnance Dept. to perform 5,000 computations a second



General view of the Electronic Numerical Integrator and Computing machine in process of being prepared to solve a hydrodynamical problem

The ENIAC (Electronic Numerical Integrator and Computer) is the first all electronic computing machine to be built. While other computing devices use electronic equipment, the actual computing in these machines is done mechanically or electro-mechanically, not electronically. It is the purpose of this article to explain how the ENIAC solves mathematical problems electronically.

● As the name, ENIAC, implies, this machine is capable of integrating (and also of differentiating) electronically. Though electronic circuits which integrate and differentiate (such as RC and RL circuits) are known, the ENIAC does not make use of them. Rather, it integrates and differentiates by reducing these processes to numerical computations, that is, to a series of the elementary arithmetic operations of addition, subtraction, multiplication, division, square-rooting, and the looking up of values of the various functions required.

Thus the ENIAC consists of twenty adders (called Accumulators because they both store and add numbers), a high-speed multiplier, a divider and square-rooter, and three function tables, in addition to control units for directing the arithmetical operations (cycling unit, initiating unit, and master programmer) and units for getting numbers into and out of the machine (constant transmitter and printer); see Fig. 1 for a plan view of the machine. Though one of the

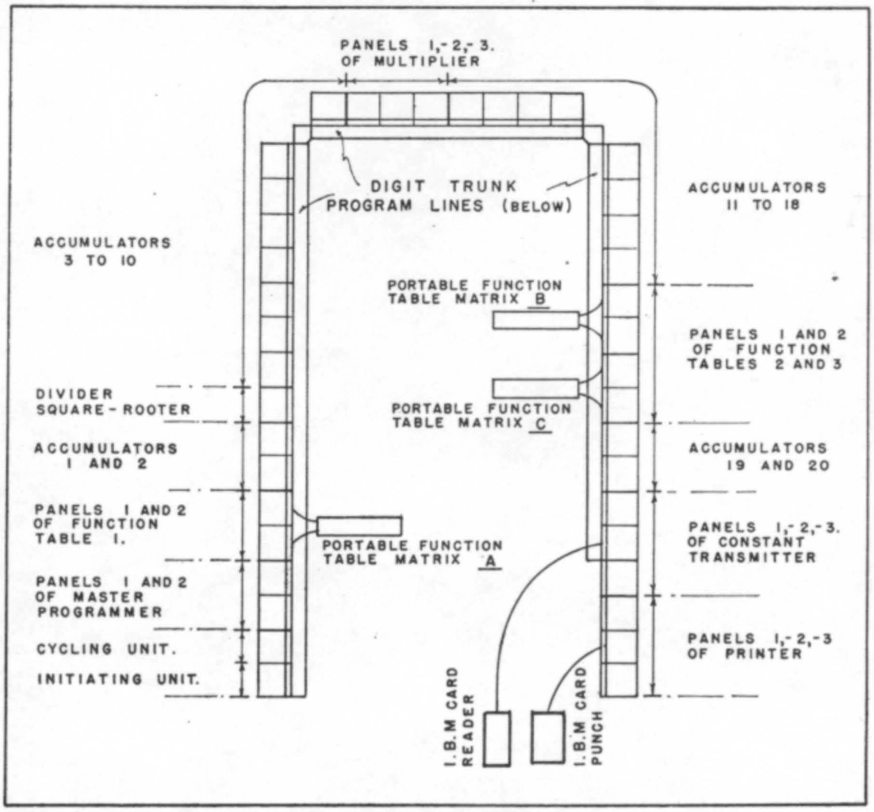


Fig. 1—Layout of the various parts of the ENIAC from initiating unit to printer as in general view

primary tasks of the ENIAC is to solve differential equations, the fact that it does this by computing makes it a much more general and versatile device than a machine which does only that one job (such as a differential analyzer).

It is an important feature of the ENIAC that amplitude-sensitive circuits are not the electronic means of achieving these arithmetic and control operations. Numbers are not represented by the magnitudes of voltages, but by the presence or absence of electrical signals on wires or by vacuum tubes being either off or on. Similarly, numbers are not added in circuits which add voltages, but are added by means of electronic counters which count pulses representing the numbers.

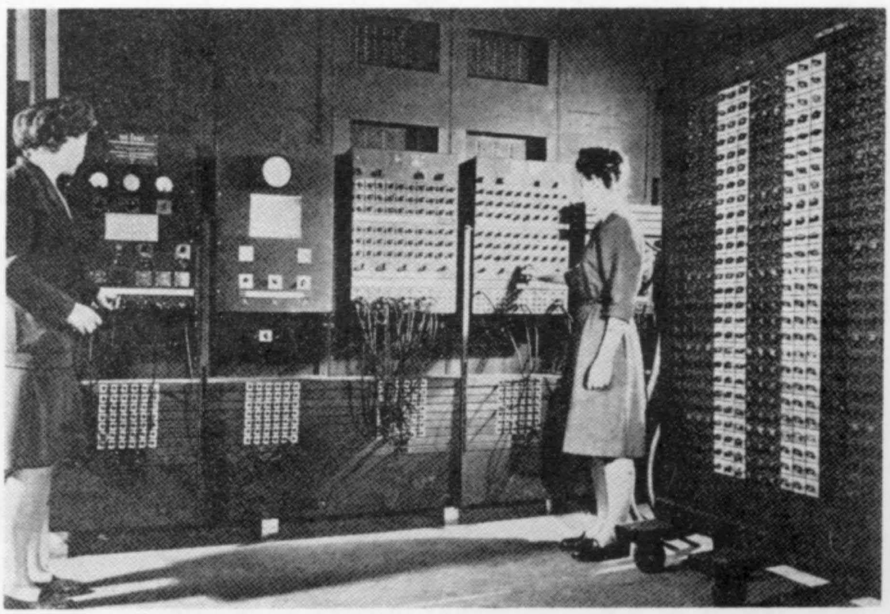
All tubes in the ENIAC are operated as switches (i.e., either "on" or "off") and hence the effects of the variation of resistors, changes in tube currents, etc., do not affect the accuracy of the computations, provided, of course, that these variations are kept within certain broad limits. The accuracy of ENIAC computations is not limited by the accuracy of the circuit components, but only by the fact that the numbers it can handle must not exceed twenty digits.

Thus the ENIAC is a digital or discrete-variable computer in contrast to a continuous-variable machine such as the differential analyzer (in which quantities are represented by the positions of continuously varying shafts). That large-scale computations by other than electronic means will soon be out of date is shown by the fact that the ENIAC is 1000 times faster than any other existing digital machine!

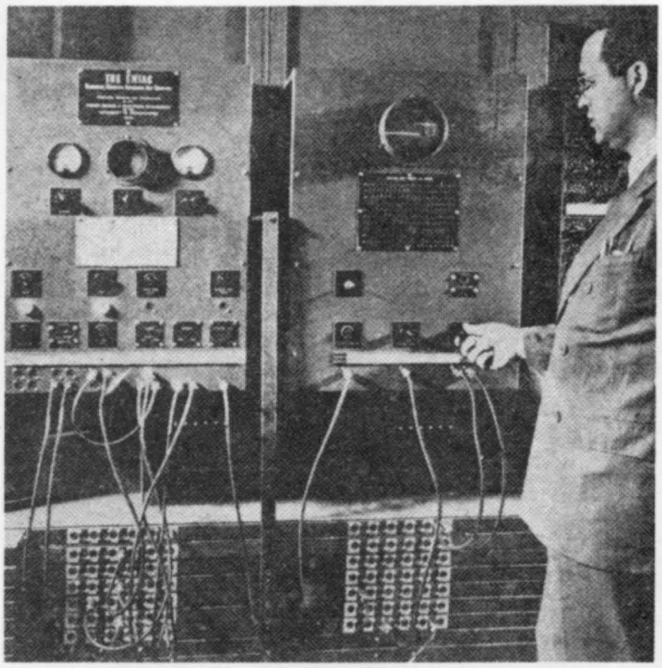
It is impossible in this article to describe in detail a machine with 18,000 vacuum tubes, 6,000 switches, 5,000 terminals, using 80 dc voltages, etc. On the other hand, a general description of the machine will not explain how the computation is done electronically. So let us take a very simple differential equation ($\frac{dy}{dx} = y$), show how it can be solved by a series of additions, multiplications, etc., set it up on the ENIAC (see Fig. 3, which shows only the ENIAC equipment used in the problem), and describe how some typical operations are performed electronically (see Fig. 7).

The solution to $\frac{dy}{dx} = y$ is, of course, $y = K e^x$. But the ENIAC, even though it is an "electronic brain," cannot give an answer in this form. What it can do is compute a numerical solution for any given set of initial conditions. Thus if it is told that when x is zero y is

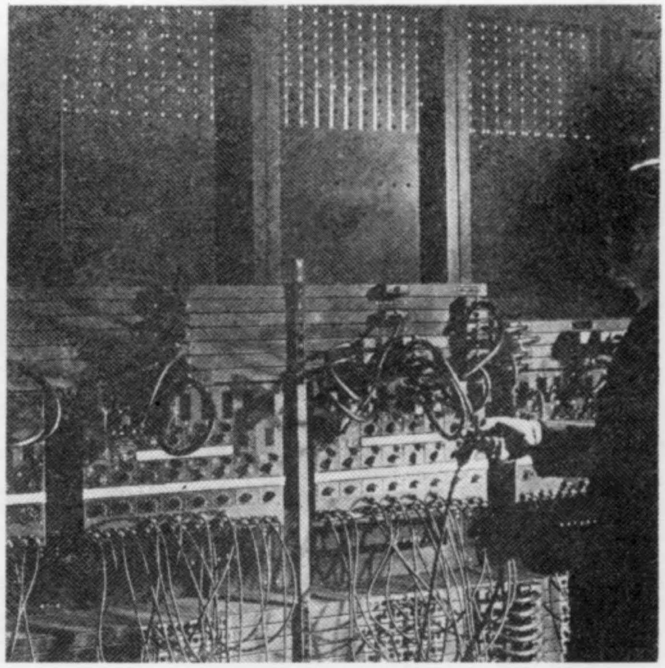
Two Ordnance Department technicians arranging program settings on the Master Programmer



[1]The ENIAC was designed and built at the Moore School of Electrical Engineering for the Ordnance Department of the United States Army. Major H. H. Goldstine was the Ordnance Department representative; Dr. J. G. Brainerd was the administrative supervisor; Mr. J. P. Eckert was the chief engineer; and Dr. J. W. Mauchly was consulting engineer.



Initiating and cycling units of ENIAC. 'scope screen shows one of the fundamental electrical signals transmitted to all units. Neons above the 'scope correspond to the 20 different parts of addition. Each of these parts represents 1/100,000 of a second



Close-up of two accumulators showing the operation of addition taking place. The unit on the left is storing the number plus 1203762893 as indicated by the lighted neons. The next accumulator, which will transmit its number, is storing 30333311112

one ($x_0 = 0$, $y_0 = 1$), it can compute the values of y for various values of x (for example, for $x = .01, .02, \ldots, .99, 1.00$). It always gives numerical answers to mathematical problems. This is, however, the form in which they are useful to engineering and empirical science.

To solve a differential equation numerically, we first replace the derivative ($\frac{dy}{dx}$) by the ratio of increments ($\frac{\Delta y}{\Delta x}$). This gives $\frac{\Delta y}{\Delta x} = y$, or $\Delta y = y \Delta x$, which tells us how to compute the increase in y for a given change in x. Calling the initial values x_0 and y_0 and the next values x_1 and y_1, we have

$x_1 = x_0 + \Delta x \quad (x_1 = 0 + .01 = .01)$

and

$\Delta y_0 = y_0 \Delta x \quad (\Delta y_0 = 1 \times .01 = .01)$

and hence

$$y_1 = y_0 + \Delta y_0 = y_0 + y_0 \Delta x$$
$$(y_1 = 1 + .01 = 1.01).$$

By means of the same formulas the next values (x_2 and y_2) can be computed from x_1 and y_1:

$x_2 = x_1 + \Delta x \quad (x_2 = .01 + .01 = .02)$

$$y_2 = y_1 + \Delta y_1 = y_1 + y_1 \Delta x$$
$$(y_2 = 1.01 + 1.01 \times .01 = 1.0201).$$

See Fig. 2. This process can be repeated indefinitely (after ten steps we have $x_{10} = 0.1$, $y_{10} = 1.1046$, or $e^{0.1} = 1.1046$). The computation of 100 values of y and x ($x = .01, .02, \ldots, .99, 1.00$) would give a table of e^x such as is found in the *Handbook of Chemistry and Physics* and would take the ENIAC 0.06 seconds (not counting the time for printing the answer).

Three accumulators are required for this computation. An accumulator is both an electronic storage or memory device and an electronic adder. It can store a ten-digit number with sign and can be combined with another accumulator so that the pair can hold a twenty-digit number with sign. It can transmit the number held in the form of groups of pulses or receive groups of pulses representing a number and add that number to its contents in 1/5000 second. Counter circuits are used for the electronic storage and addition.

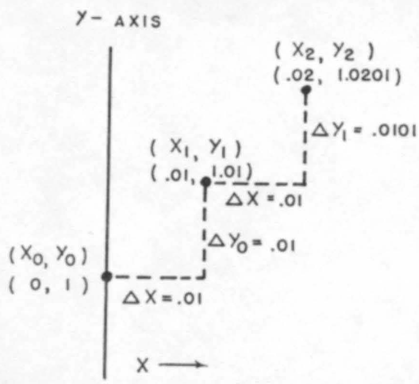


Fig. 2—Steps in numerical solution of a differential equation

Each accumulator contains ten decade counters (one for each digit). A decade counter is made up of ten flip-flops or Eccles-Jordan trigger circuits. Fig. 4 shows a flip-flop in one of its two states, called the "reset" state, i.e., with tube #1 on and tube #2 off. When a negative pulse is received on the "set" input, tube #1 will cease conducting and cause tube #2 to go on. Thus the flip-flop "remembers" that it has received a pulse on the "set" input and indicates this fact by raising the voltage on the static output line. A negative pulse on the "reset" input will send it back to its original state and cause the static output voltage to drop.

The ten flip-flops of a decade counter are so inter-connected that at any given time one flip-flop is in the "set" state and all others are in the "reset" state, and so arranged that when a pulse is received on a common input that flip-flop will "reset" and cause the next one to be "set." Thus if the #3 flip-flop is "set" the counter registers the digit three. When a pulse is received on the counter input, the #3 flip-flop will be "reset" and in so doing will "set" the #4 flip-flop so that the counter registers four (that is, $3 + 1 = 4$).

The ten static output wires of the flip-flops of a counter indicate the number held. These wires are used to operate neon bulbs mounted on the front of the accumulator which enable one to read the number held and to transmit numbers statically to the high-speed multiplier and the printer.

The transmission of a number from one accumulator to another is

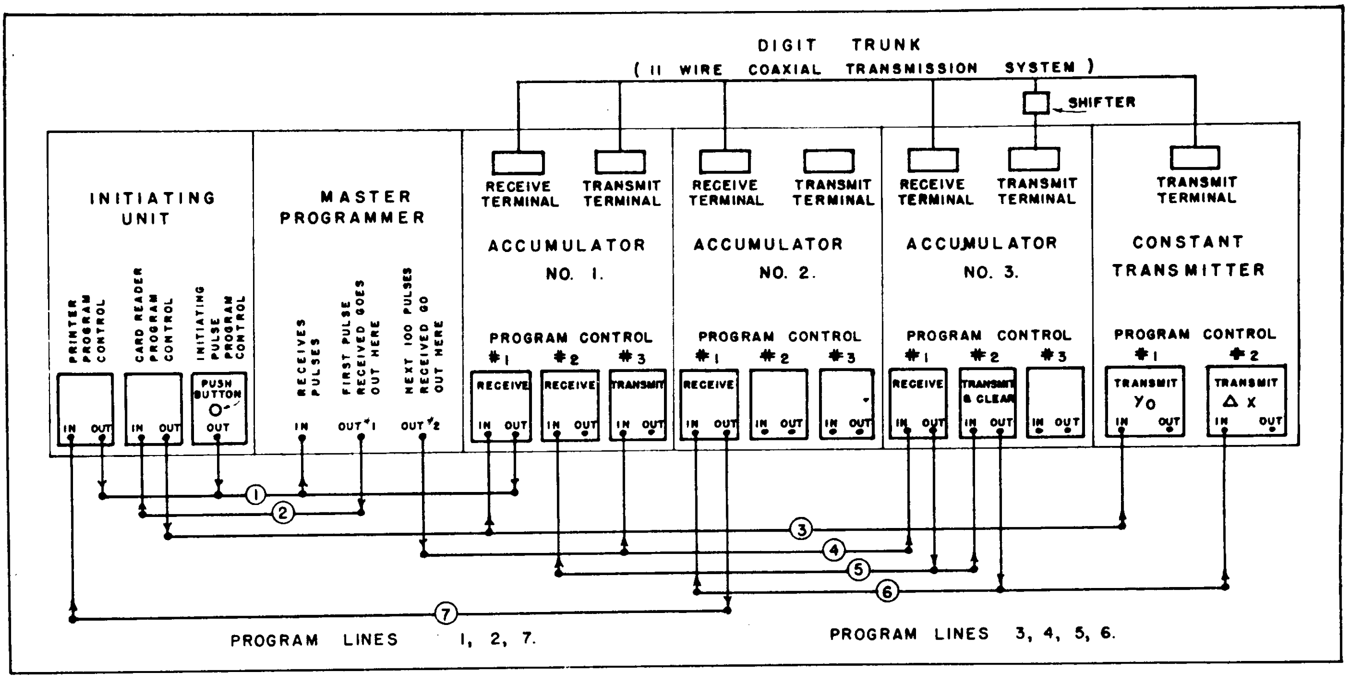


Fig. 3—Interconnection of units required to solve the differential equation $\frac{dy}{dx} = y$. This uses only a very small part of the ENIAC

done dynamically, that is, by means of groups of pulses. If accumulators 1 and [illegible] hold y_1 (1.0100 00000), one can produce y_2 (1.0201 00000) in accumulator 1 by causing accumulator 3 to transmit to it, shifting its number over two places to the right (so as to multiply by $\Delta x = .01$). This multiplication is done by a shifter which shifts the wires coming out of accumulator 3 over two places before connecting them to the digit trunk. Both accumulators are instructed to operate at the same time.

Since accumulator 3 is told to transmit, it will produce groups of electrical pulses (each pulse lasting about two microseconds) to represent each of the digits and the sign held in its counters. These groups of pulses will come out of the transmit terminal and go over the eleven-wire digit trunk to the receive terminal of accumulator 1. The exact method by means of which the static representation of a number in a counter is converted to pulse form is too complicated to be described here. Suffice it to say that the pulses are derived from a central source (called the cycling unit) which supplies standard timed signals to all ENIAC units.

The pulses for each digit go over a separate wire; this enables all the digits of a number to be transmitted simultaneously, accounting for the rapid addition of two numbers in the ENIAC. Since the number transmitted (after shifting) is 0.0101 00000, one pulse will go over the third wire from the left and one pulse over the fifth wire from the left ("0" being represented by no pulses). These pulses will go to the receive terminals of all the accumulators; but since only accumulator 1 has been instructed to receive, they will be passed into the decade counters of only this accumulator. The third counter from the left holds one; it will receive one pulse and change to two. The fifth counter from the left holds zero; it will receive one pulse and change to one.

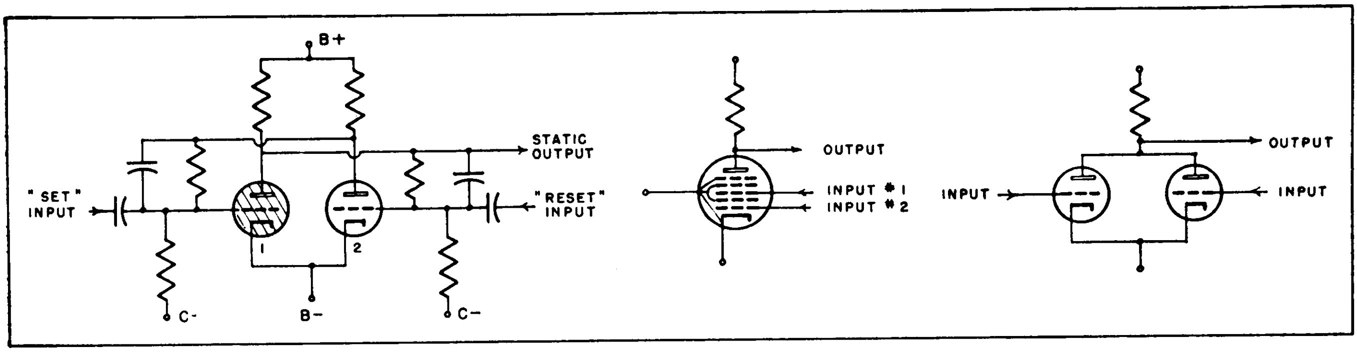
When two numbers are added together there will, in general, be some carry-overs. Since all digits are transmitted simultaneously, these must be remembered until all possible pulses have been received. This is done by means of a flip-flop which is "set" when the counter goes from nine to zero. At the proper time the cycling unit sends out signals which cause the carry-over to take place.

The necessity to allow time for carry-overs and also for circuits to be set up at various other places is the reason why twenty pulse times are required for a complete addition to take place, even though nine pulses are sufficient to represent the largest decimal digit. The cycling unit gives out pulses at a basic rate of 100,000 per second; hence an addition time is 200 microseconds, or 1/5000 second. Subtraction is accomplished in the same length of time by means of a system of complements.

The accumulator circuits which we have been describing handle the numbers in a problem and hence are called numerical circuits. Other circuits are needed to tell the numerical circuits when to operate and what operations to perform (transmission, reception, etc.). These are called programming or control circuits. In Fig. 3 the program controls of the various units are represented by boxes, with the terminals for receiving and transmitting pulses shown, and with the instructions for the operation (which are actually set up on switches) written in.

The programming of the operation described above (adding the contents of accumulator 3 to those of accumulator 1 and clearing accumulator 3) is controlled by the #2 program control of each accumulator. When it is time for this operation to be performed, an electrical "program" pulse is sent to the input terminal of each program control (over program line 5). Each program control then directs its accumulator to do the operations set up on the switches of the program control; the manner in which it does this will be described later.

After the operation is completed, a program pulse is emitted from the output terminal. Since the operations of both accumulators are synchronized by means of the electrical signals from the cycling unit, these output pulses come at the same time; hence only one need be used to inaugurate the next operation of the sequence. In this case, it goes via program line 6 to cause Δx to be added to x.



Figs. 4, 5 and 6—Show, at left, the basic Eccles-Jordan flip-flop trigger circuit, a one tube switching circuit representing the word "and" and a two tube buffing circuit having the properties of the word "or"

We shall next describe how the initial conditions ($x_0 = 0$, $y_0 = 1$) and other data ($\Delta x = .01$) are fed to the machine and how the answers are taken out. Numerical data are supplied to the ENIAC by means of an I.B.M. card reader operating in conjunction with the constant transmitter. A card is prepared with holes in it to represent the numbers to be fed to the ENIAC and placed in the card reader. Each card holds eight ten-digit numbers. Whenever a program pulse is sent to the card reader program control, it causes this card to be passed under electrical contacts and the information to be transferred to relays in the constant transmitter, an operation requiring about one-half second.

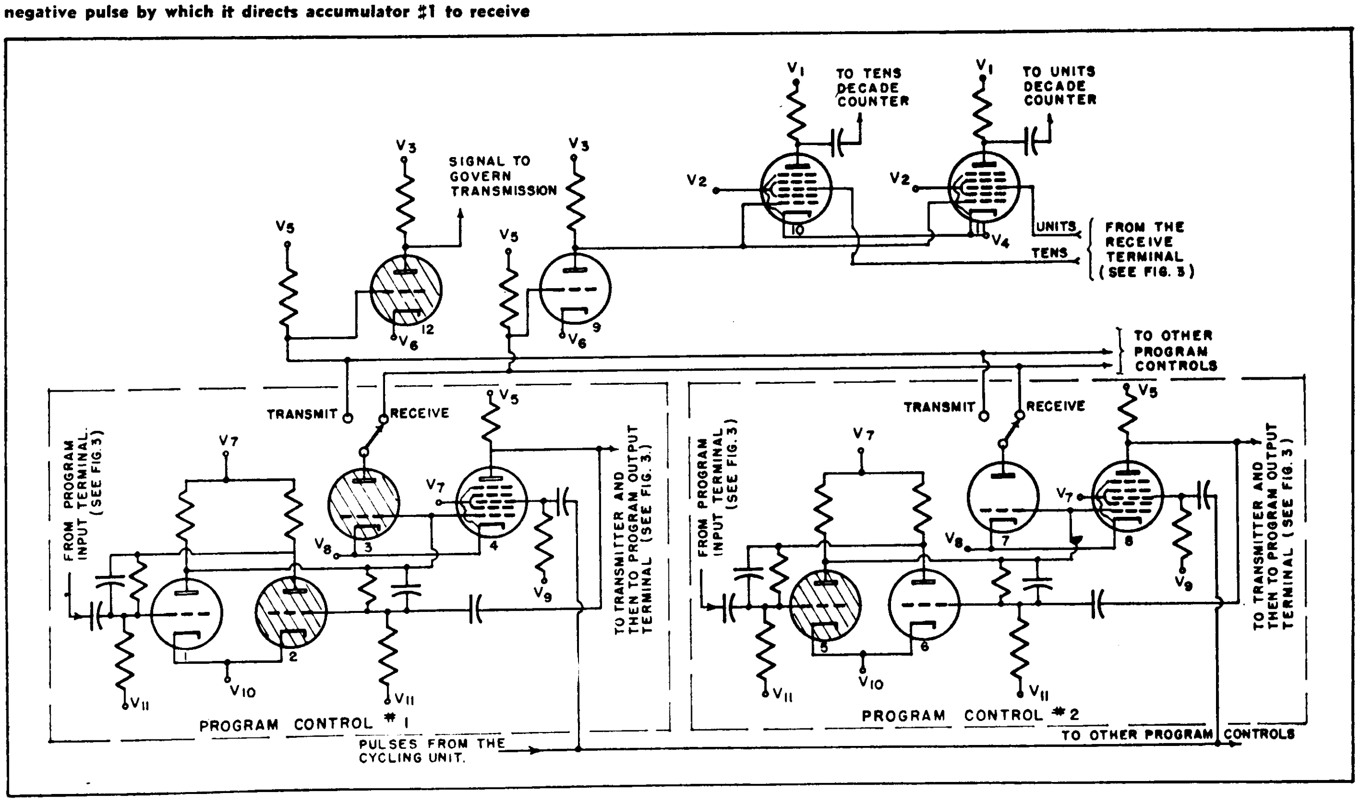
These relays in turn activate switching tubes (See Fig. 5) which are supplied with approporate sets of pulses from the cycling unit. Whenever one of these numbers is needed, a program pulse is sent to a constant transmitter program control which has its switches set to direct the transmission of the given number, and the pulses from the cycling unit are electronically switched onto the digit trunk.

This method of feeding numbers to the ENIAC is, of course, electro-mechanical rather than electronic. The ENIAC is nevertheless a completely electronic computer, since the computation is done exclusively by electronic means. Human beings express numbers by mechanical motions, so there must be some connection to the mechanical world in any computer. The ENIAC printer is likewise electro-mechanical. It operates in conjunction with an I.B.M. card punch.

Whenever it is desired to punch on cards the numbers held in accumulators, computation is stopped and a program pulse is transmitted to the printer program control. The static outputs from the decade counters of eight accumulators go to the printer, where vacuum tubes set up relays which in turn cause the card to be punched with the numbers held in the accumulators. This is a relatively slow operation, requiring about 0.6 seconds. After the cards are punched, they are placed in another machine which prints the answers on paper.

We are now able to see what is involved in the solution of $\frac{dy}{dx} = y$ for one hundred values of x (x =

Fig. 7—A typical ENIAC circuit illustrating the action of program controls #1 and #2 of accumulator #1. Program control #1 has just received a negative pulse by which it directs accumulator #1 to receive



.01, .02, ..., .99, 1.00). The ENIAC must first read a card (containing $y_0 = 1$, $\Delta x = .01$) and transmit y_0 to accumulator 1. It must then transmit y_0 to accumulator 3 and back to accumulator 1, shifting it over two places so as to multiply by Δx; transmit Δx from the constant transmitter to accumulator 2; and finally tell the printer to punch a card with the numbers in accumulators 1 and 2 (y_1 and x_1). This last sequence is to be repeated 100 times and then the machine is to stop.

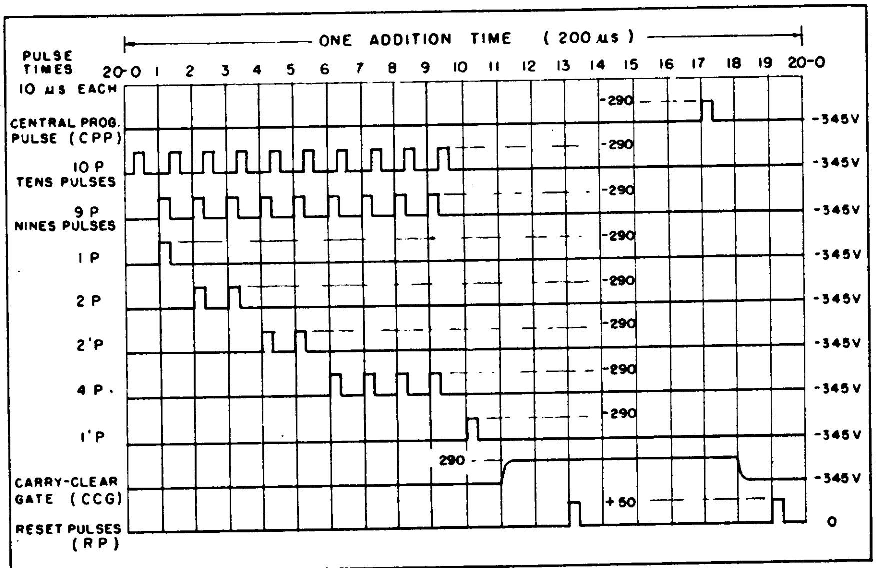


Fig. 8—Sequence of pulses sent out by the cycling unit to control the operation of the ENIAC

The problem is started when the operator pushes the button on the initiating pulse program control. A pulse is then given out which goes to the master programmer which handles the overall control of the sequences of operations set up on program controls. The master programmer is here arranged to transmit the first pulse it receives over line 2 to cause the initial conditions to be read from the punched card and transmitted to accumulator 1. After this sequence of two operations is finished, a pulse is transmitted from program control 1 of accumulator 1 back over program line 1 to the master programmer. This time it is sent out of output 2 to program line 4, causing the ENIAC to compute x_1 and y_1 from x_0 and y_0 and to print them.

When this is finished, a program pulse is transmitted from the output of the printer program control back to the master programmer over line 1. Again the master programmer sends it out of output 2 so that x_2 and y_2 will be computed and printed. This process is repeated 100 times and then the ENIAC stops. Thus the ENIAC is an automatically sequenced computer; once it is set up to do a problem and started, it will do the complete job without further direction.

Let us now consider how the ENIAC does these automatically sequenced computing operations electronically. The circuits of the ENIAC are for the most part compounded out of five kinds of circuits, each of which is quite simple. These are: (1) flip-flops, used for electronic storage; (2) counters, used for electronic storage and adding; (3) switching circuits, used for electronic switching; (4) buffing circuits, used for electronic isolation of channels in one direction but not the other; and (5) inverting circuits, employing normally conducting tubes merely to reverse polarity.

A switching circuit (Fig. 5) uses a multi-grid tube (6L7's, 6SA7's, etc.) with two inputs and one output; it will give out a negative plate signal only when it receives positive signals on both input #1 and input #2 (and is thus an electronic representation of the word "and").

A buffing circuit (Fig. 6) uses two or more tubes (6SN7's, 6L6's, 6V6's, etc.) connected together with a common load resistor to form a circuit with the properties of the word "or." The grids of all tubes are normally biased to cut-off, so a positive input signal to any tube will produce a negative output signal (which will not, because of the buffing action, affect any of the other inputs).

Fig. 7 shows how a typical ENIAC circuit is compounded out of these basic circuits. It illustrates the action of program controls 1 and 2 of accumulator 1, both of which direct the accumulator to receive (but at different times). The circuit is shown after program control 1 has received a negative program pulse telling it to direct accumulator 1 to receive. The fact that it has received the program pulse is remembered by the flip-flop which stays in the "set" position during the time the number is being received. This flip-flop turns on the buffer (tube #3) which turns off the inverter (tube #9). The action of a buffer is required here because the same circuit of tubes #9, 10, and 11 is used when program control 2 is directing the reception of a number. That is, control 1, or control 2, or any other control with a switch set to "receive" must be able to direct the accumulator to receive a number, and each at a different time. Tube #9 turns on the switches (tubes #10, 11) which connect two lines of the digit trunk to the decade counters. It is in this way that accumulator 1 is programmed to received y_0 from the constant transmitter.

After the operation has been completed, the program control must emit a program pulse which will go to direct the next operation in the problem. When the flip-flop is set, it switches on tube #4, which receives a pulse from the cycling unit at the end of every addition time. This pulse then passes through tube #4, "resets" the flip-flop, and goes out the program output terminal to stimulate the next operation. Later on in the problem, program control 2 is used in the same way to cause accumulator 1 to receive a number from accumulator 3.

We have now completed our description of how the ENIAC solves $\frac{dy}{dx} = y$. The actual setup of the problem is accomplished by manually interconnecting the program controls and digit terminals as shown in Fig. 3 and setting the switches according to the information written in the boxes. It should be remembered, however, that this problem uses so little of the total ENIAC equipment that it is, in actual fact, too simple for the ENIAC to bother with. It does not use, for instance, two of the important arithmetic units of the ENIAC: the high-speed multiplier and the function table.

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ENIAC

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The function table is an important unit of the ENIAC for the reason that most problems put on the machine involve the use of a mathematical function which has no simple analytical expression. Thus the computation of the trajectory of a shell [redacted] is done by solving the differential equations of a moving body, taking into account the ballistic drag function, that is, the resistance of the air to the shell as a function of the velocity of the shell. This is the problem the Ordnance Department must solve in order to produce a firing table.

The ENIAC was designed to handle this problem, being provided with three function tables for setting up the ballistic drag function.

$$(a^2 - u^2)\frac{\partial u}{\partial x} - uv\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) + (a^2 - v^2)\frac{\partial v}{\partial y} + \frac{a^2 v}{y} = 0,$$

$$\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = 0$$

Fig. 9—Equation for the motion of air as a sharply pointed projectile moves through it

The actual numbers are set on switches located on the portable function table matrix (see Fig. 1), which can hold the value of the function for 100 arguments (from 0 to 99) by means of resistors connected to various wires by the switches. When the ENIAC needs the value of a function, such as f(67), pulses representing 67 are sent to the function table, and in 1/1000 of a second it will look in the portable function table matrix for f(67) and transmit pulses representing that value of the function.

The high-speed multiplier is at the heart of most ENIAC computing, because the solution of most complicated problems involves a good deal of multiplication. Furthermore, multiplication, being more complicated than addition, requires a longer time. Multiplication by successive additions of two ten-digit numbers would require (at a maximum) nine additions for each digit of the multiplier, and hence ninety addition times.

Since in a typical ENIAC problem, there is one multiplication for every four additions, it is clear that a more rapid method of multiplication is desirable. This is accomplished by the high-speed multiplier, which (by using an electronic multiplication table) multiplies two ten-digit numbers in thirteen addition times, or about 1/400 seconds!

Because of its speed, the ENIAC is capable of solving problems hitherto beyond the scope of man, and this will have repercussions in both engineering and theoretical science. The great speed is the result of the application of electronic technics to computation. Thus it is that the ENIAC, the first electronic computing machine, inaugurates a new era of scientific progress.

IRE-URSI CONVENE

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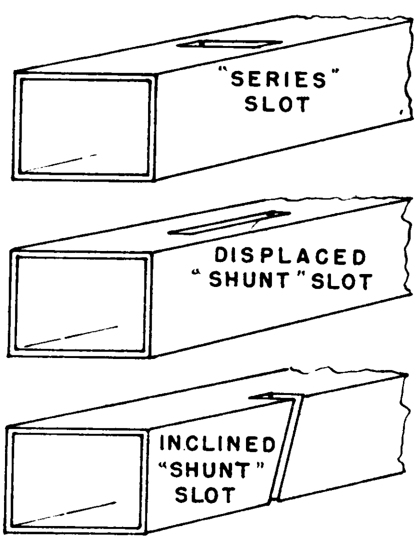
decibel change in input signal level over a frequency range of 25 to 20,000 cycles per second.

A description of the temperature-sensitive resistors used in radiosonde equipment was given by G. L. Davies and Charles B. Pear, Jr., (Washington Institute of Technology). These resistors were made from a semi-conducting ceramic material and have a high negative temperature coefficient. Their characteristics are such that they approximately follow the relation:

$$\frac{R_T}{R_{303}} = \frac{Ce^{\frac{B}{T}}}{T^S}$$

with empirical constants C = 0.17 10^6, B = 1306. and S = 2.86.

A method of exciting cylindrical reflectors in the microwave region



Common wave guide coupling methods. (Bell and Bruton.)

directly from rectangular waveguides was discussed by R. E. Bell and D. C. Brunton (National Research Council, Canada). The coupling between the waveguide and the means for radiating a beam was obtained by the use of arrays of slots in the guide. Methods whereby two waveguide systems could be coupled to each other were also discussed. Some of the arrangements used for couplings from waveguides are shown in the sketch.

A paper on parabolic antenna design for microwaves by C. C. Cutler (BTL) gave the fundamental relations for parabolic radiators at microwave frequencies. This paper took up the relation between phase for polarization and the effect of the size of the primary radiator within the parabola.

WIDE READING

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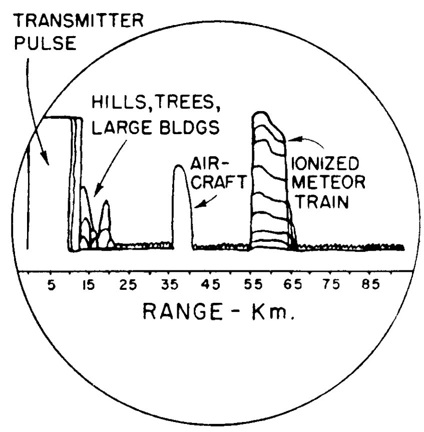
density "D" and "E" region clouds ionized by high velocity meteoric impact.

That the limiting or critical scattering frequency lies above 100 megacycles per second, was substantiated when "echo-returns" coincident with the appearance of bright meteor trains were observed on radar units operating in India.



In the figure, the sharp leading edge of the echoes from the airplane and from the ionized layer indicate reflection from well-defined boundaries. The numerous peaks within the echo envelope prove multi-returns from the meteor train. At approximately 105 megacycles per second, echoes were received lasting from ½ to 3 seconds on half-path lengths of 30 to 125 km.

The observation of meteoric impact ionization and the radio effects associated therewith will be greatly aided by the employment of a high-angle radial pattern radar unit operating on frequencies of about 50 megacycles per second. Undoubtedly valuable quantitative information on masses, velocities, and numbers of meteors may be obtained in this fashion.