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SWAC

National Bureau of Standards Western Automatic Computer

recent developments and operating experience

SWAC—the National Bureau of Standards Western Automatic Computer—is now being operated 24 hours a day, 5 days a week to solve a wide range of complex problems in physics, engineering, mathematics, statistics, and meteorology. At present over 70 percent of this time is devoted to problem solution, the remainder being reserved for maintenance, engineering development, and testing of new equipment.

SWAC is a general-purpose digital computer constructed by NBS in 1950 under the sponsorship of the Wright Air Development Center. The first of the high-speed electronic computers to be completed with the very fast Williams-tube (cathode-ray tube) memory, SWAC operates at a rate of 16,000 additions or 2,600 multiplications per second.

Recently the scope and complexity of the problems that the machine can handle have been greatly extended through the installation and successful operation of a magnetic-drum auxiliary memory. Based on the principle of the magnetic-tape recorder, the new memory holds 16 times as much mathematical information as the cathode-ray–tube memory, with which it will be used to increase the overall memory capacity of the machine. The magnetic drum will also act as a storehouse for a library of numerical methods or routines of instructions which, when obeyed by the machine, can facilitate the solution of a large class of problems.

SWAC was designed and built at the NBS Institute for Numerical Analysis in Los Angeles to provide a rapid, powerful computational tool on the West Coast and to aid in the Institute's program for the further development and increased utilization of the art of machine computation. The ultra-high-speed machine has been used by NBS principally to solve aircraft problems originating with the Air Force and its contractors, other problems in science and engineering submitted by Government agencies, and mathematical problems arising in connection with the Bureau's work on computation methods and computing machine development.

SWAC's high-speed results from its special Williams-tube memory and its parallel mode of operation. The memory unit consists of a bank of cathode-ray tubes that store information as bright spots of charge. The unit is operated in parallel, that is, all the digits of a number are transferred in or out of the memory simultaneously, thus greatly reducing the time required for transfer of information. In serial machines, such as

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those using acoustic-delay-line memories, numbers and instructions are represented by trains of electrical pulses. But in SWAC parallel circuits transfer numbers and instructions almost instantly, within the time of a single pulse (about one tenth of a microsecond). Arithmetic operations are also carried out in parallel, with a consequent increase in speed of computation. In its parallel method of operation SWAC differs from SEAC (National Bureau of Standards Eastern Automatic Computer), a serial machine constructed by NBS at its Washington (D. C.) laboratories

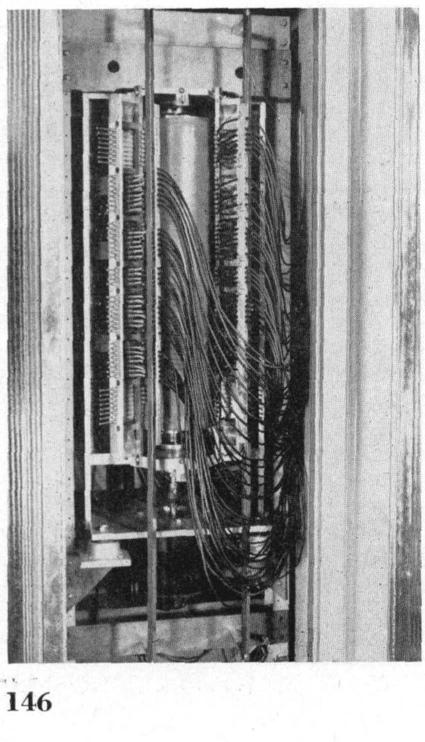
Magnetic-Drum Memory

While the cathode-ray-tube type of memory delivers information at a very rapid rate, its capacity is limited by the number of digits that can be stored on the face of a single cathode-ray tube. To provide greater flexibility and computing power, a magnetic drum external memory was developed by R. Thorensen and associates of the NBS staff. With the drum memory, many complicated types of problems can be handled by transmitting information out of the computer for storage and then feeding the information back into the computer at a later stage of the problem.

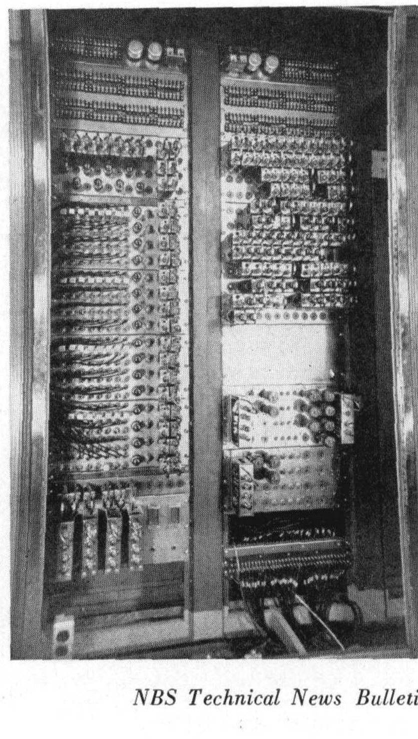
SWAC's drum memory, like those developed elsewhere, is a revolving metal drum that retains numbers and instructions on its surface in the form of magnetic pulses like those used in tape recording. At intervals, blocks of magnetic pulses are removed from the drum by a magnetic head and are taken into the computer to be transformed electronically into spots of charge in the Williams-tube memory, where they remain until called for by the control unit.

SWAC stores and processes information in units called words, each word consisting of 37 binary digits, the equivalent of 11 decimal digits. (The binary number system is analogous to the decimal system, but its base is 2 rather than 10.) The magnetic drum has a capacity of 4,096 words of 37 binary digits each, in contrast with the 256-word capacity of the cathode-ray–tube memory. This high-capacity memory makes possible the solution of very large sets of simultaneous equations, such as arise in logistics; certain types of partial differential equations that occur frequently in aeronautical research, in heat-transfer problems, in electromagnetic theory, and in other fields; and combinatorial problems, applications of which have recently engaged the attention of scientists. Instruction routines stored on the drum will handle, among other things, the conversion of information from a decimal representation into the binary representation used by the machine, as well as the final conversion back to decimal form when it is required to print out results.

In the construction of the magnetic drum, primary consideration was given to simplicity of design and maximal efficiency in the transfer of information between it and the cathode-ray-tube memory. A drum memory ordinarily has a much larger capacity than a Williams-tube memory, but access to a drum memory is generally slow. In particular, if information is required from some specific location on the drum, the computer may have to wait up to a maximum of one drum revolution before receiving any information. However, in the magnetic-drum memory developed for SWAC, access time is shortened in two ways: (1) Numbers are transferred in sizable blocks from the magnetic drum memory to the cathode-ray tube memory, thus

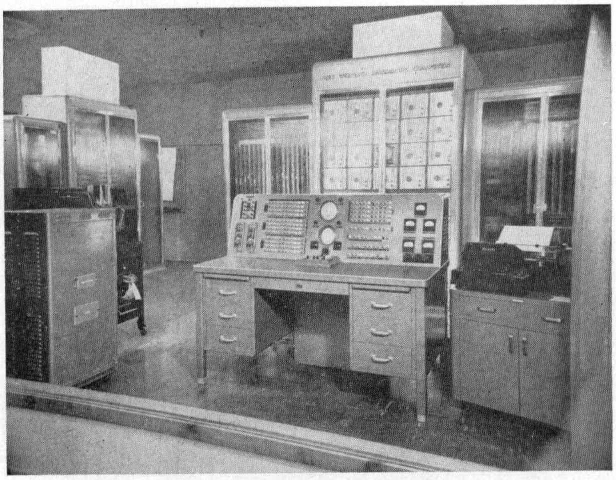


Magnetic drum auxiliary memory recently added to SWAC to increase its problem solving capacity. The revolving metal drum retains numbers and instructions on its surface as magnetic pulses. Blocks of magnetic pulses are removed from the drum by a magnetic head and taken into the computer to be transformed electronically into spots of charge in the Williams tube memory.



Control circuitry for this memory. The high storage capacity of the drum memory makes possible the solution of very large sets of simultaneous equations, such as arise in logistics; certain types of partial differential equations which occur frequently in aeronautical research, heat transfer problems, electromagnetic theory, etc.; and combinatorial problems.

General view of SWAC, showing Williams memory behind operating console (center foreground), cabinets containing control unit on either side of memory, other cabinets in left background containing magnetic-drum auxiliary memory and its control circuitry, punched-card input-output system in front of magnetic-drum memory, and paper-tape input unit on right of console.



minimizing the total number of times the drum memory must be consulted. (2) The numbers in each of these blocks are stored sequentially around the cirmumference of the drum so that one block forms a band or channel completely encircling the drum. When a transfer to or from the drum memory is made, the whole channel is handled at one time. Transfer of information starts immediately after the proper channel has been selected and continues for exactly one drum revolution, thus eliminating all waiting time. In this way the access time per word is reduced to 500 microseconds—about $1/30$ of the normal access time of a magnetic drum memory.

Information is stored serially on the drum in 40-binary digit words. The first 36 digits represent numerical information, the 37th digit gives the algebraic sign, while the remaining three digit positions are empty. Thirty-two words are stored in each channel and constitute a basic transfer block. As the drum rotates at 3,600 revolutions per minute, 32 words are transferred in approximately 17 thousandths of a second.

The drum contains 128 information channels plus 4 timing channels. The timing channels feed a timing generator, which generates a pulse for each digit space, a pulse for each word space, and a reference pulse for each revolution of the drum. The pulses marking each word space go to an address counter, which counts from 0 through 31. This counter continuously keeps track of the word spaces as they pass under the magnetic read-write heads. The reference pulse is used to initially synchronize this counter with the drum.

The cathode-ray–tube memory operates in parallel with the serial magnetic-drum memory, and the two are not in synchronism. Direct communication between the memories is therefore not possible. Information from the drum must first be played back into a vacuum-tube shifting register and then transferred in parallel to the cathode-ray–tube memory. Each digit takes 13 microseconds to play back, so the 3 empty digit spaces in each word give a total delay of 39 microseconds between words. This delay is more than adequate for transferring a number from the register to the cathode-ray–tube memory and for clearing the register to receive new information.

The entire drum-memory system consists of less than a dozen different types of basic single-tube plug-in units that are developed to a high degree of stability under the variety of conditions of loading and aging. Only about 250 vacuum tubes are used.

In addition to the drum memory, plans call for a slow-speed auxiliary memory consisting of a magnetic-tape unit. It will have a much larger capacity than the other two memories, holding approximately 4,000,000 binary digits, but its average access time will be quite long—about 3½ minutes.

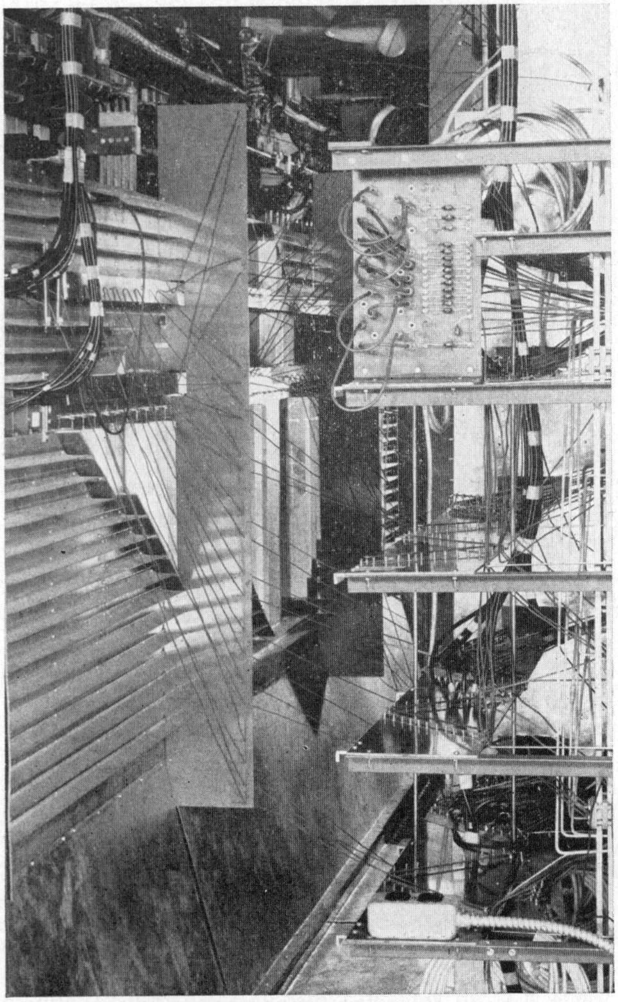
Description of SWAC

SWAC is automatically sequenced, that is, it automatically performs all of the logical and arithmetical operations required to solve a particular problem once it is supplied with coded instructions and numerical data. The computer stores in its high-speed memory not only the numbers involved in the computation but also the instructions necessary to perform the computation. This makes it possible for the calculator to use fully the speed of the Williams-tube memory, doing complete arithmetic operations in a few microseconds.

The computer proper is housed in a single console approximately 12 ft wide, 5 ft deep, and 8 ft high. It consists of three major parts: An arithmetic unit, a memory unit, and a control unit. Four other parts complete the computer system; they are the magnetic-drum memory, the input-output units, the operating console, and the power supply.

The arithmetic unit performs the arithmetic operations of addition, subtraction, and both rounded-off and exact multiplication. It also performs the logical operations of comparison and extract. Comparison involves changing the course of the computation depending on the relative sizes of two numbers. Extract divides numbers up into parts that the computer can handle in different ways. The arithmetic unit receives information from the memory in the form of numbers to be operated upon and instructions as to the nature of the operation. Having acted upon such instructions and completed the operation, the arithmetic unit returns the answer to the memory.

The memory feeds its information to the arithmetic unit in accordance with instructions it receives from the control unit. The control unit consists of electronic circuits from which control the operations of the computer proper. This unit takes information from the input unit, directs it to the memory, tells the memory when to send information to the arithmetic unit, tells



Interior view of SWAC. Arithmetic unit is at left, and at right is control circuitry on inner side of console.

the arithmetic unit when and where to return answers to the memory, and controls the feeding out of completed solutions to the output unit.

SWAC uses both a punch-card input-output system and a paper-tape system. For card input, the coded problem is punched on a standard IBM card, and the answer is received in the same way. In the paper-tape input-output system, a coded problem punched in paper tape is fed into the machine, and answers are automatically given in typed form by an electric typewriter.

The operating console, an office desk with specially built panels mounted on its top surface, permits the human operator to control the operations of the machine and to watch the machine as it operates. The console is provided with control switches and neon lights that indicate what is taking place inside the machine. Oscilloscope screens make it possible for the operator to view the memory pattern of any given unit of the Williams tube memory.

SWAC is supplied with electrical power, carefully regulated in voltage, by means of a motor-generator set and related equipment, largely electronic in nature. The computer is thus isolated from line voltage fluctuations that might affect its operation. About 30 kilowatts are consumed when the machine is operating.

Williams-Tube Memory

The Williams-tube memory consists of a bank of 37 cathode-ray tubes. each of which can store 256 digits on its face in a matrix pattern of dots and dashes. The dots represent "0" while the dashes represent "1". As SWAC is a binary machine, all decimal numbers and instructions are fed into it in a code which utilizes only the digits 0 and 1.

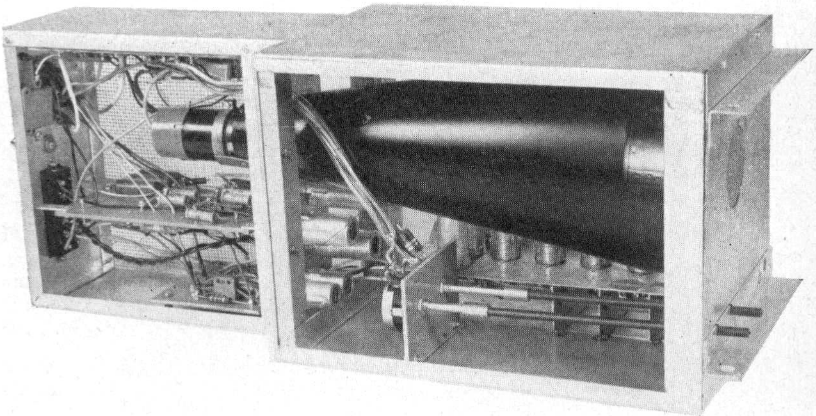
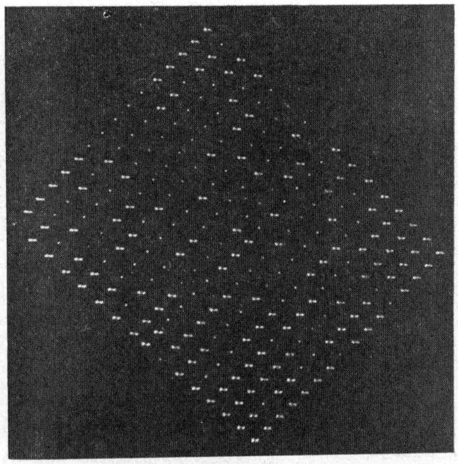
The number of digits that can be stored on the face of one cathode-ray tube determines the number of words that can be stored in the memory. That is, the *n*th cathode-ray tube stores the *n*th digit of each word. Thus, a given word has one digit stored in the same relative position in each of the tubes. This makes it possible to position all of the electron beams at a given location, or address, in the memory and thus to transfer all of the digits of a word simultaneously. As a result, the time required to transfer a word to or from the memory is only 16 microseconds.

To produce either a dot or a dash at a given spot on the face of a Williams-tube unit, the electron beam is turned on to produce a spot of charge on the screen. If the beam is left on only long enough to establish equilibrium and is then turned off, a dot is produced. If the beam is left on longer and is deflected from the dot position by the superposition of a small sawtooth voltage on the positioning voltages, a dash is produced. The dots and dashes are read off by an amplifier, which picks up the signal from the tube screen, amplifies and reshapes it, and causes the electron beam inside the tube to place a signal back on the face of the tube.

Unless this type of storage is continually renewed or regenerated, the original charge pattern tends to disappear over a period of time as the charged spots gradually collect stray electrons. Thus, to provide continuous storage, an electron beam is made to inspect successively each point of charge and to energize electronic circuits that, when necessary, restore the charge to its initial value. The regeneration process takes place during short intervals that alternate with the reading-in or reading-out of information in the memory. In this renewal process the machine spends only 8 microseconds on each point of charge on the face of the tube, and complete regeneration occurs 250 times a second. Such a continuous regeneration process makes it possible to store information indefinitely. A crystal-controlled oscillator regulates both the rate of regeneration of the memory and the operations of the arithmetic unit.

Operating Experience

SWAC contains about 2,600 tubes and 3,700 crystal diodes. The average tube life is between 8,000 and 10,000 hours. To date, very few tubes have been lost on account of heater failure. The largest percentage

Left: **One of the 37 cathode-ray tubes that make up SWAC's Williams-tube memory.** ***Right:*** **Memory pattern of dots and dashes from the face of one of these tube units.**

of tube failures have resulted from low emission and intermittent shorts.

All electronic components in the computer proper are mounted on removable plug-in chassis, so that faulty operation can usually be corrected by replacing a bad chassis with a good spare. The faulty chassis can then be repaired in the laboratory without loss of computer time. The majority of the plug-in chassis contain an average of 10 tubes each; however, the magnetic-drum circuits are built of much smaller units, usually consisting of a single tube.

One of the difficulties encountered with the cathode-ray–tube type of memory is "spillover," or redistribution of charge, which limits the number of times the spots adjacent to a particular spot may be read before the spot in question must be regenerated. To mitigate this difficulty, circuits have been installed that eliminate most of the drift in the patterns on the face of the tubes. A substantial improvement in operating time has resulted.

Other improvements have been achieved by rebuilding certain parts of the circuitry that have shown a high out-of-order maintenance time. A substantial improvement in operating time occurred when an air-conditioning unit was installed to maintain the incoming air in the ventilation system at a constant temperature. This minimized the temperature cycling of crystal diodes and substantially decreased their failure.

General operating efficiency has also been increased by the addition of a loudspeaker and buffer tube with a plug-in arrangement allowing the operator to "listen" to any of the commands in a problem. For example, an alternate succession of add and subtract commands produces an 8-kilocycle note.

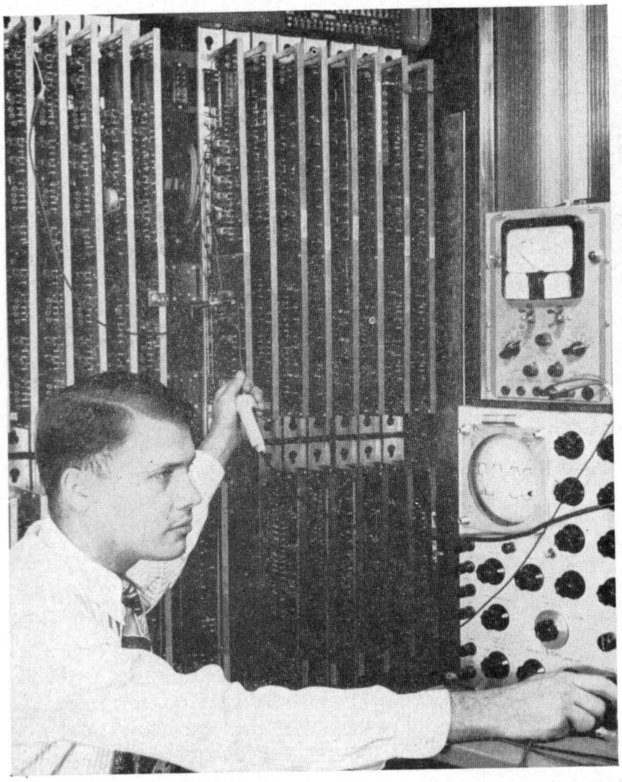
Recently, by the addition of one tube and a few crystals, a converting output command was obtained. This command, effective only with the output typewriter and tape punch, converts fractional binary numbers to octal, decimal, or any other base up to 16.

Problems Solved

During the 8-month period ending June 1, 1953, SWAC spent an average of 53.2 hours a week in actual computing. The remainder of the operating time was spent in code checking, memory adjustment, maintenance, testing of components, and development of improved facilities. More than 50 problems were handled in the past year, ranging from minutes to hundreds of hours in running time. During this period the punched-card input-output systems was operative, but the magnetic drum had not yet been installed.

Problems in least squares, reduction of data, heat transfers, stress analysis, and a tremendous variety of other physical phenomena can be described by systems of linear equations. However, most of the methods now in common use for solving such equations are variations of the elimination method developed by Gauss. These methods all tend to yield answers of low significance when the matrix of the coefficients is almost unity. Using SWAC for extensive numerical trials, M. R. Hestenes and E. Stiefel of the NBS staff recently developed a new approach, known as the conjugate gradient method, which appears to have broad utility for the solution of problems arising in applied physics and engineering. SWAC has now solved many systems of equations of order 10 to 15. Codes have been prepared for the solution of systems of any order up to 45, but no system of that high order has as yet been solved. However, the characteristic values and their associated vectors have been found to nine significant decimal digits for a 45th order system, as well as for systems of order 10 to 20.

In the field of differential equations, a large amount of computing time has been devoted to the study of associated Legendre functions, $p_n^m(x)$, which are important in mathematical analysis of radiation fields from antennae. The specific problem was the determination of the nonintegral values of the order (n) which, for fixed values of degree (m) and argument



Checking the operation of a part of SWAC's control circuitry.

(x), would make the value of the function zero. For each combination of m and x, an infinite set of discrete values of n will satisfy the requirements. SWAC found the first 30 values of n corresponding to 1 value of x and 3 values of m.

With the aid of SWAC, NBS has carried on research in the application of the so-called "Monte Carlo" method to the solution of complicated differential equations and of previously unsolved statistical problems in nuclear physics. The Monte Carlo method, developed by J. von Neumann of the Institute for Advanced Study at Princeton and S. Ulam of Los Alamos Scientific Laboratory, is a new mathematical technique that solves a physical or mathematical problem by creating an artificial statistical model of the physical or mathematical process involved. It applies the same techniques that are used in analyzing games of chance to the analysis of physical problems where the events are random and are governed by the laws of probability. Large-scale computers such as SWAC provide an excellent means for the solution of problems of this kind because they are able to create conditions that imitate the statistical behavior of the given problem. Thus, the randomness of the event can be taken care of by putting into the extended memory of the machine a set of random numbers which are first tested for their random quality. SWAC has been used to compile large groups of random digits, to explore their statistical behavior, and to investigate their utility for solving partial differential equations by random walk processes. Recently problems concerning nuclear forces have been attacked by means of the Monte Carlo method.

Problems in the evaluation of definite integrals have arisen from studies in probability and statistics. One such problem, the computation of a table of survival probabilities for biological experiments, required the evaluation of 12,500 double integrals with each variable ranging from plus to minus infinity. This table was computed in 177 hours. A second table, for biological experiments in which the exact level of a radiation dose is unknown, required the evaluation of 7,500 single integrals, this time with an infinite lower limit and a finite upper limit.

Many applied problems have dealt with the reduction of large blocks of data. A study of the large-scale circulation patterns in the earth's atmosphere was typical. Some 750,000 pieces of data, each 5 decimal digits in length, were processed to yield about the same number of answers. SWAC spent 325 hours on this problem.

SWAC has also been applied to several combinatorial problems. In some it has exhaustively searched through all possible combinations of the variables. One such problem was that of finding different sets, that is, a set of n numbers such that all $n\ (n-1)$ nonzero differences give distinct remainders when divided by n^2-n-1. Another problem, involving permutations, dealt with the optimal assignment of duties in an organization.

SWAC has proved an effective tool for the analysis of Fourier synthesis of X-ray diffraction patterns of crystals. Such analyses, at present being carried on by members of the Chemistry Department of the University of California at Los Angeles, lead to the determination of the arrangement of molecules inside the crystals.

In the field of pure mathematics, SWAC has been used to study the primality of Mersenne numbers, that is, numbers of the form 2^p-1, where p is a prime. These numbers, when prime, are related to the "perfect numbers" of the Greeks, which are the sum of all their integral divisors excluding themselves. The present list of values of p that yield prime numbers is as follows:

2, 3, 5, 7, 13, 17, 19, 31, 61, 89, 107, 521, 607, 1,279, 2,203, and 2,281.

The last five values were added to the list by SWAC as a result of the systematic testing of all prime numbers up to 2,297.

Mathematical research directed toward more effective utilization of electronic digital computers is continuing at the NBS Institute for Numerical Analysis. Further progress in this program should materially increase the scope of the problems that SWAC and other high-speed computers can handle and should also make possible additional savings in actual computing time.

For further technical details, see The SWAC—design features and operating experience, *by H. D. Huskey, R. Thorensen, B. F. Ambrosio, and E. C. Yowell, Proc. IRE (October, 1953). For details about SEAC, see* SEAC, *NBS Technical News Bulletin* **34,** *121 (Sept. 1950).*