Conclusion

The arithmetic element of the IBM Type 701 Computer makes use of a new electronic storage circuit, the microsecond delay unit, whose output may be either of two dc levels, yet uses dynamic pulse storage techniques. Through the use of this device, in conjunction with dc coupled diode adding circuits, important simplifications are realized in shifting registers, and in the execution of division and testing for zero in the accumulator.

Acknowledgment

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The SWAC-Design Features and Operating Experience*

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Summary—**The SWAC is an ultra-high-speed digital computer utilizing a Williams tube memory, an auxiliary magnetic drum memory and a punched card input-output system. A general description of the functional organization of the computer is given together with a brief discussion of the various commands and how they are executed.**

Some of the special engineering features of the computer are described, in particular those relating to the electrostatic and magnetic drum memories.

Finally a short survey of the types of problems solved by the computer during the last year is presented.

Introduction

THE NATIONAL BUREAU OF STANDARDS Western Automatic Computer (SWAC), located in Los Angeles at the Institute for Numerical Analysis of the National Bureau of Standards, is a digital computer utilizing a Williams tube memory,[1] an auxiliary memory in the form of a magnetic drum,[2,3] and a punched card input-output system. A primary feature of the SWAC is its high speed, which, for handling the binary equivalent of eleven decimal digit numbers, is greater than that of any other computer now in operation.

The SWAC stores in its high-speed memory the numbers involved in the computation and also all the instructions necessary to perform the calculation. This makes it possible for the calculator to utilize fully the speed of the Williams tube memory, doing complete arithmetic operations in a few microseconds. Instead of handling numbers as a train of pulses, there are parallel circuits in the SWAC which transfer numbers almost instantly (actually the transfer takes place in the width of a pulse which in some cases is one-tenth μsec). This transferring of numbers in parallel makes it possible to do computations at many times the speed of serial computers (for example, acoustic delay-line machines) without having excessively high pulse rates on the lines of the computer.

The SWAC is the first of the Williams tube computers to be completed in this country. At present it is producing useful results during seventy per cent of the time that its power is turned on.

Brief Description of the SWAC

The Williams tube memory in the SWAC stores 256 words (numbers or instructions). The various digits of a particular number are stored in corresponding positions on each of 37 cathode-ray tubes. A word in SWAC is 37 binary digits long, which is the equivalent of about 11 decimal digits. A Williams tube memory requires regeneration. To accomplish this, time is divided into 8-μsec intervals. During one of these intervals a particular number in the memory may be regenerated, read out into the arithmetic unit, or replaced with a new number. The regeneration takes place during alternate 8-μsec intervals with the whole memory being regenerated once each 4,096 μsec. The other 8-μsec periods are called action intervals, and it is during these periods that numbers may be transferred between the memory and the arithmetic unit.

The SWAC uses eight basic commands: add, subtract, multiply (rounded-off answer), product (two word answer), compare, extract, input, and output. The compare command has a variation which compares absolute values. There is a special form of input used for initially

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1 F. C. Williams, and T. Kilburn, "A storage system for use with binary digital computing machines," *Proc. IEE*, Part III, pp. 81–100; March, 1949.

2 R. Thorensen, "Design Features of a Magnetic Drum Memory for the National Bureau of Standards Western Automatic Computer (SWAC)," *Proc. Electronic Computer Symposium;* April 30, May 1–2, 1952, Los Angeles, Calif.

3 A. A. Cohen, "Magnetic Drum Storage for Digital Information Processing Systems," Mathematical Tables and Other Aids to Computation, vol. IV, No. 29, pp. 31–39; January, 1950.

inserting the information into the computer. Normally the source of the next command is an address in the memory which is specified by the command counter in the control circuits, but three of the commands—add, subtract, and multiply—have variations consisting of special four address forms wherein the source of the next command is specified by the fourth address. In normal add and subtract commands, the fourth address specifies the source of the next command only if the operation overflows. The command system used in the SWAC is called a modified four address system.

The execution of each command involves (except in the case of input and output) at least four references to the memory. Since one reference can be made during each action period, it is seen that the minimum time for the execution of a command is 64 μsec, and in fact, the computer executes any arbitrary sequence of addition, subtraction, and compare commands at the rate of about 16,000 complete operations per second.

To see what happens in the 64 μsec that are required to execute one of these commands, consider an addition command. In the *first* action period, the first operand is found in the memory and transferred to the arithmetic register where it is complemented with respect to 2^{37} if it is negative. During the *second* action period, the second operand is found, complemented if negative, added to the number in the arithmetic register, and if the result is negative it is complemented, so that, in the *third* action period the answer can be placed back in the memory. In the *fourth* action period, the next command is found in the memory and transferred to the command register in preparation for the next following step in the computation.

The only event that takes a substantial amount of time in the above operation is the actual addition process. Here time must be allowed for the carry to propagate through the thirty-seven binary positions of the numbers. This carry (and the no-carry which may occur after a complementation) propagates in approximately 3 μsec, but for safety, a time of 5 μsec is allowed.

The multiply command which produces a rounded-off answer also requires four accesses to the memory. The actual multiplication is performed as thirty-six shifts and possible additions, each taking a total of 8 μsec per addition and shift. Thus, a multiply command actually needs a minimum of 64 plus 288 μsec. However, for purposes of simplicity in the control circuitry, each command must take a multiple of 64 μsec, making a multiply command require 384 μsec. A product command produces a double-length answer, and thus requires five accesses to the memory, but it, too, takes only 384 μsec.

The so-called extract command is actually a combination of two processes: (a) the selection of any specified set of the 36 binary digits of a number, and (b) the shifting of the result a specified amount to the right or the left. This command has many logical applications and is used, for example, to store two or more numbers in one memory location, to increase the effective capacity of the memory, or to operate in a "floating point" number system. The execution time for this command depends upon the amount of shift involved and takes from 128 to 384 μsec.

The simple compare command is a special sort of subtraction command in which the sign of the difference determines whether the SWAC shall proceed to the next command or shall obey another specified command instead. This useful command is executed in 64 μsec.

The input and output commands control the transfer of information between the high-speed memory and the input and output typewriters, the tape reader and tape punch (Flexowriter), the punched-card reader (collator) and the card punch (summary punch), and the magnetic drum. The typewriters and tape equipment accept and transmit data one base-sixteen digit at a time, operating at about eight characters per second.

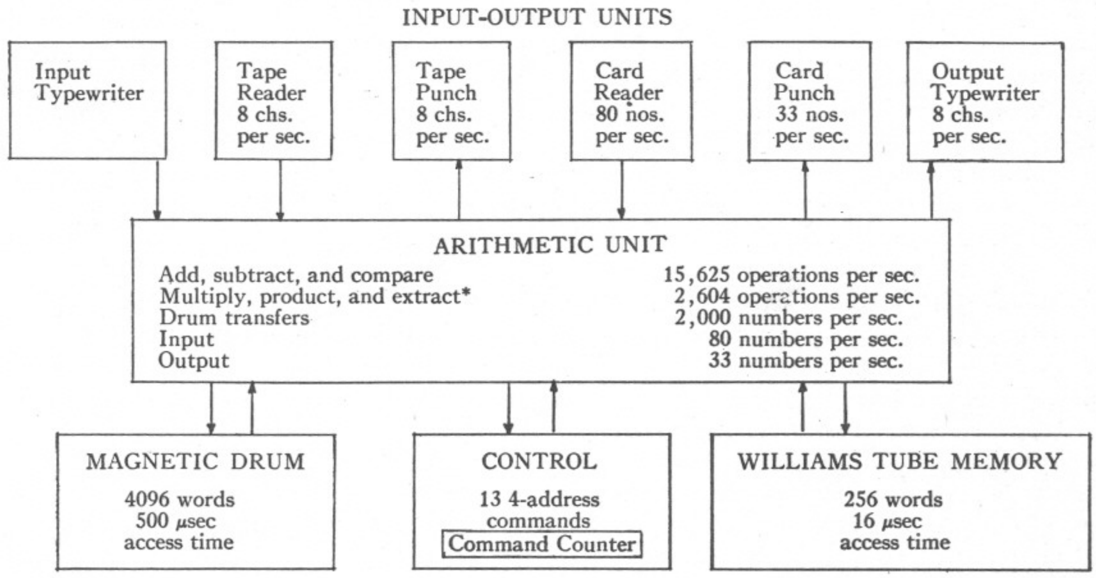
For card input, twenty numbers may be placed on a standard eighty column card as binary punches with two numbers on each row of the card. This still leaves room for a serial or problem number on the cards for identification purposes. One command places the two numbers from one row on the card in any two addresses in the high-speed memory. In a similar fashion, one command can cause two numbers to be punched on one row of a card in the card punch. Once a card is started in either the collator or the punch, all ten rows must be handled in order. However, several milliseconds elapse between any two rows on the card so that actual computing (like binary-to-decimal conversion) may be done in the interim.

The transfers to and from the drum are most efficiently handled in blocks of thirty-two words, which is precisely the number of words on any one track of the drum. A word in position P of track T on the drum is transferred into address $A+P$ in the high-speed memory where A and T are specified in the command. This makes it possible to begin the transfer with the first number that becomes available, and to know that the transfer persists for precisely one revolution time of the drum. The drum rotates at 3,600 revolutions per minute; so thirty-two words are transferred in approximately 17,000 μsec. Since there is no wait time, the access time per word on the drum (when handled in blocks of thirty-two words) is about 500 μsec.

Under some circumstances it may be desirable to transfer less than thirty-two words at a time, to or from the magnetic-drum memory. The drum-transfer command has therefore been made flexible enough to allow also for block transfers of sixteen words and eight words. In these cases the specific portion of the track to be transferred is also specified in the command. The time required, however, for a block transfer of 8 words is the same as that required for a block transfer of 32 words, or just one revolution of the drum. Therefore whenever possible, a block transfer of thirty-two words is used.

Thus, the SWAC has a 256 word high-speed memory with an access time of 16 μsec, and an auxiliary 4,096 word memory with an access time of 500 μsec.

The chart gives a summary of SWAC characteristics: Crystal diode gating is used extensively in the arithmetic unit, and 6AS6 vacuum tube gates with crystal mixing are used elsewhere. The more recent drum circuits use 7AK7 gates.



* Note: Up to 5,208 extract operations per second.

Special Engineering Features

The SWAC proper occupies a floor space of about 4 by 12 feet. The drum occupies a space of 2 by 7 feet. Figs. 1, 2 and 3 illustrate various units of the SWAC and associated equipment. There is an operating console on a standard office desk in addition to punched card and paper tape input-output units. All of the above units are located in a room 20 by 30 feet. The power-supply equipment comprises a regulated alternator, a set of selenium rectifier dc power supplies, and a control cabinet housing regulators, heater transformers and high-voltage power supplies. The power equipment occupies a total space of about 60 square feet.

A blower system moves about 4,800 cubic feet per minute of outside air through an air conditioner heat exchanger, through the computer, and back outside. The air conditioner cools the air to 40 degrees F., and reheats it to 60 degrees to control the humidity. The exhaust air is approximately 90 degrees F.

All the electronic components of the computer proper are mounted on removable plug-in chassis. As there are spares for almost all types of chassis used in the SWAC, it is rare that a fault cannot be cured by replacing a bad chassis with a good spare. Laboratory test equipment has been constructed so that faulty chassis can be repaired in the laboratory without use of computer time. The majority of the pluggable chassis carry, on the average, ten tubes each; however, the magnetic-drum circuits are built of much smaller units, usually of one tube each.

There are high- and low-speed flip-flops in the computer. The high-speed ones are based on circuitry developed at the Massachusetts Institute of Technology. In all, there are about 2,600 tubes and 3,700 crystals in the SWAC system, and the power consumption is about 30 kw.

The SWAC is designed to work in a synchronous manner. That is, regeneration of the memory proceeds at a fixed rate determined by a crystal-controlled oscillator. The operations in the arithmetic unit derive their timing from the same source so that this unit works in step with the memory and every command takes a fixed length of time. The timing pulses for the various commands are derived from so-called period pulses coming at 8-μsec intervals corresponding to 8-μsec periods of the memory system. Timing arrangements inside these intervals are derived by the use of electrical delay lines.

In the Williams tube memory system, a time of 8 μsec is allowed for the operations at each cell in the memory. During these 8 μsec, about $2\frac{1}{2}$ μsec are allowed for the beam deflection circuits to stabilize. The beam is then turned on for about 1 μsec. If the position checked is found to store a zero (a dot in the dot-dash system), the beam is turned off for the rest of the period. If the position is found to store a one (dash), the beam is held on for another $3\frac{1}{2}$ μsec, while a sawtooth signal is applied to both deflection voltages (this restores the one, or dash, charge distribution on the face of the cr tube). The beam is turned off shortly before the end of the 8-μsec period so that it is safely off before the deflection voltages start to change.

Of interest, because of its novelty, is the method of eliminating the wait time when reading numbers from the drum or transferring information to the drum. The drum has 128 tracks with 32 words per track. Thus, each word arrives from the drum as a serial pulse train.

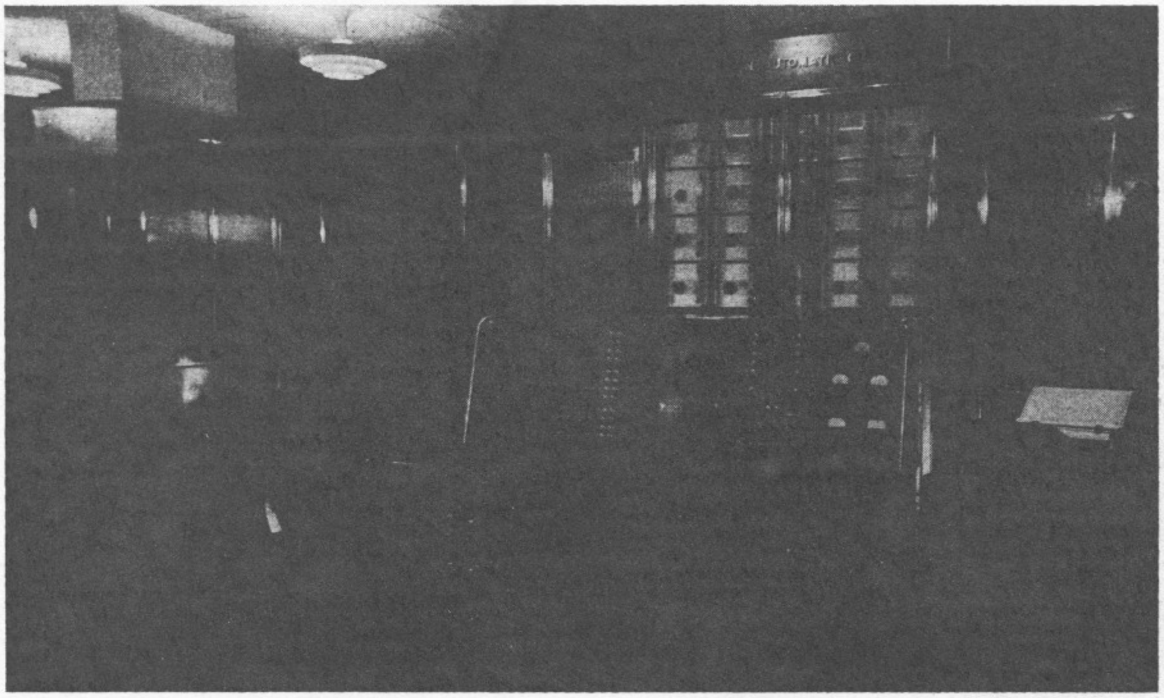


Fig. 1—The SWAC system. The SWAC computer and console, center right; IBM input equipment and magnetic drum memory unit, extreme left.

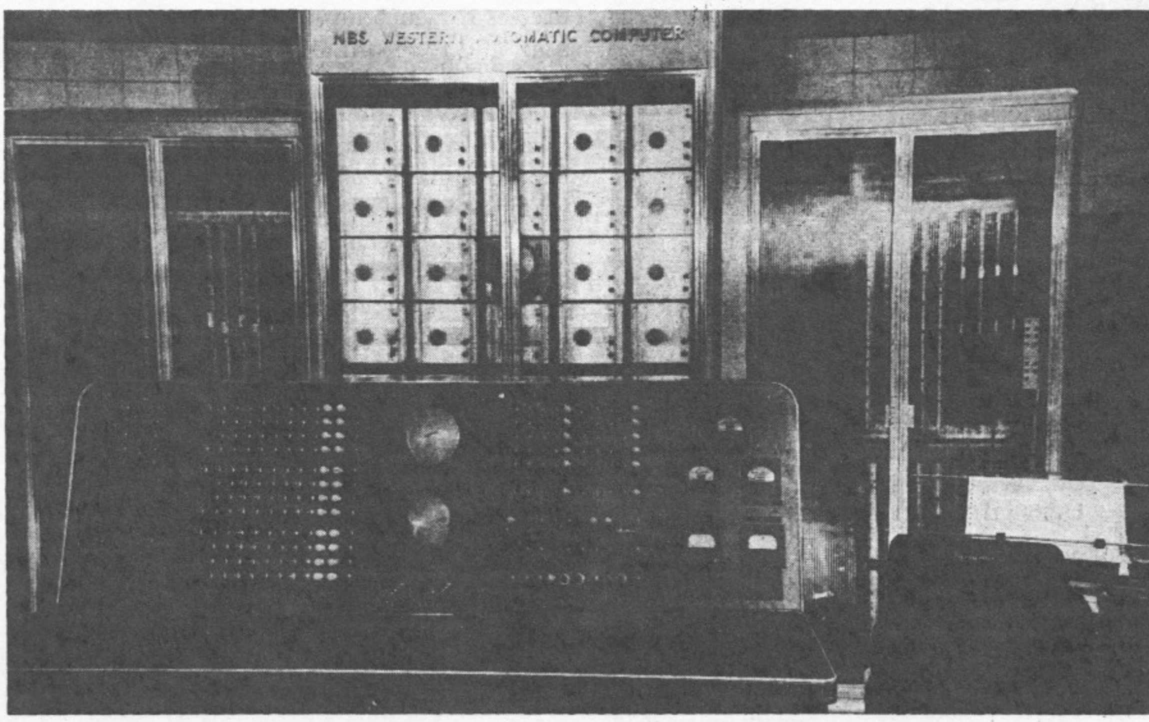


Fig. 2—The main SWAC computer, control console, and input typewriter.

Three pulse positions are left blank on the drum between words. The number arriving from the drum is shifted into one of the arithmetic registers, and it can be recorded in the electrostatic memory during the three-pulse time gap. Likewise, a new number can be read from the electrostatic memory and be ready to be recorded on the drum in this time interval. Thus, numbers can be handled in sequence in transferring to or from the drum.

A word-pulse channel drives a counter in the magnetic-drum circuits; this continuously keeps track of which particular addresses in the magnetic memory are available for reading or writing. Whenever a number is to be transferred to or from the drum, the address in this counter is sent to the Williams-tube selection circuits where it determines the five least significant digits of the memory address. The three most significant digits are specified by the command. This explains how the access time to the drum is reduced to approximately 500 μsec per word, since thirty-two words are transferred in, at most, one revolution plus one word time, or about 17 msec.

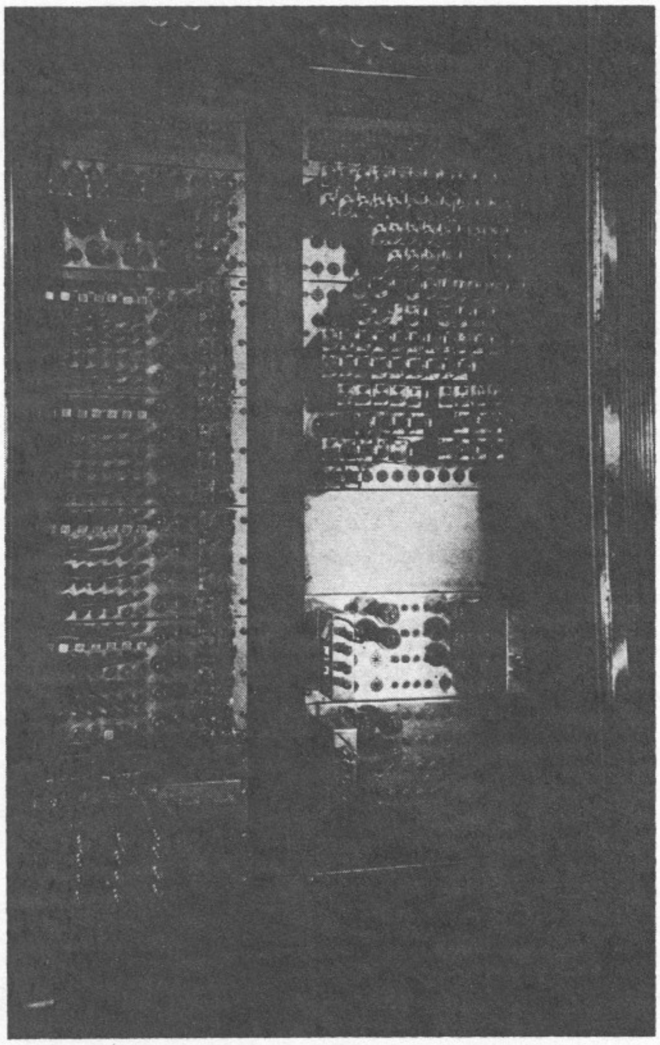


Fig. 3—Magnetic drum switching matrix and control circuits.

Operating Experience

It may be of engineering interest that few tubes have been lost on account of heater failure. The heaters are turned on with transtats by hand and operated at rated voltage. The largest percentage of tube failures result from low emission and intermittent shorts. The average tube life in the SWAC ranges between 8,000 and 10,000 hours.

As is well known, there are two features of the Williams-tube type of memory which give trouble in computing machine applications. One of these is the presence of flaws on the face of the tube, which will not store information satisfactorily. The other is spill-over, or redistribution of charge, which limits the number of times the neighbors of a particular spot may be read before the spot in question must be regenerated. At the present time the only solution to the flaw problem seems to be particular care in manufacturing. Commercially available cr tubes are used in the SWAC and all tubes have some flaws in them. Therefore, the installation of circuits which eliminated most of the drift in the patterns on the face of tubes, provided the first substantial improvement in useful operating time on the computer.

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

In the course of operation, certain logical facilities have been added to make the operation more efficient. A loudspeaker and buffer tube were added, 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-kc note. A certain problem involving generation of pseudorandom digits has produced sequences of tones christened "random symphony."

Additional Williams tube chassis have been inserted into the computer and arranged to record those addresses to which answers involving overflow have been sent, and to record all addresses in which answers have been inserted.

Recently, with 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. This is accomplished by multiplying by the base, printing and deleting the integral part of the result, and repeating this process for the number of digits desired, up to a maximum of 11. Nonfractional numbers are handled by pre-multiplying by the appropriate constant.

Problems Done on the SWAC

During the eight month period ending June 1, 1953, the SWAC spent on the average 53.2 hours per week in computing. More than 50 problems were handled in the past year, problems whose running time ranged from minutes to hundreds of hours. During this interval, the punched card input-output system was operative, but the magnetic drum was not as yet installed.

Problems solved on the SWAC originate from two sources. The staff of the Institute for Numerical Analysis originates problems in pure mathematics, in application to pure science, and in numerical analysis. Other government agencies and their contractors originate problems in applied mathematics and in engineering.

One of the most interesting problems in pure mathematics on which the SWAC has worked has been the study 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, numbers which are the sum of all their integral divisors excluding themselves. The present list of values of p which yield prime numbers is:

$$p = 2, 3, 5, 7, 13, 17, 19, 31, 61, 89, 107, 521, 607, 1279, 2203, \text{ and } 2281.$$

The last five values were added to the list by the SWAC as a result of the systematic testing of all prime numbers up to 2297. This project took 453 hours of time spread over 18 months of operation.

One application of mathematics to other fields of pure science is the study of Fourier Synthesis of X-ray diffraction patterns of crystals. Such studies, 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.

A classical problem in numerical analysis is the solution of systems of linear equations. Most of the methods in common use are variations of the elimination method that dates back to Gauss. A different approach to the problem is the conjugate gradient method developed by Hestenes, Lanczos, and Stiefel of the Institute staff. The numerical tests needed to perfect this method were made on the SWAC.

The applied problems supply examples of many of the primary fields of numerical analysis. In the field of linear equations, the SWAC has solved many systems of equations of order 10 to 15. Codes are prepared for the solution of systems of any order up to 45, but no system of that high order has as yet been solved. The characteristic values and their associated vectors have been found to 9 significant decimal digits for a 45th order system, as well as for systems of order 10 to 20. The large system took about 300 hours of SWAC time to reach a complete solution.

In the field of differential equations, a large amount of time was devoted to the study of Associated Legendre Functions, $P_n^m(x)$. The specific problem was the determination of the nonintegral values of the order (n) which, for fixed values of the degree (m) and argument (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. The SWAC found the first thirty values of n corresponding to one value of x and three values of m.

Many applied problems deal with the reduction of large blocks of data. Such a problem handled by the SWAC arises from a study of the large-scale circulation patterns in the earth's atmosphere. Some 750,000 pieces of data, each of five decimal digits in length, were processed to yield about the same number of answers. SWAC spent 325 hours on this problem.

Problems in the evaluation of definite integrals have arisen from studies in probability and statistics. One such problem, the computation of a table of kill-probabilities, 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, used in biological experiments for probit analysis when the exact level of the dose is unknown, required the evaluation of 7,500 single integrals, this time with an infinite lower limit and a finite upper limit.

Finally, the SWAC has been used on several combinatorial problems. In some it has exhaustively searched through all possible combinations of several discrete variables. Such a problem is that of finding "difference sets," that is, a set of n numbers such that all $n(n-1)$ non-zero differences give distinct remainders on division by n^2-n+1.

The various examples cited indicate the types of problems that the SWAC has successfully solved. No attempt has been made to achieve complete coverage in this survey.