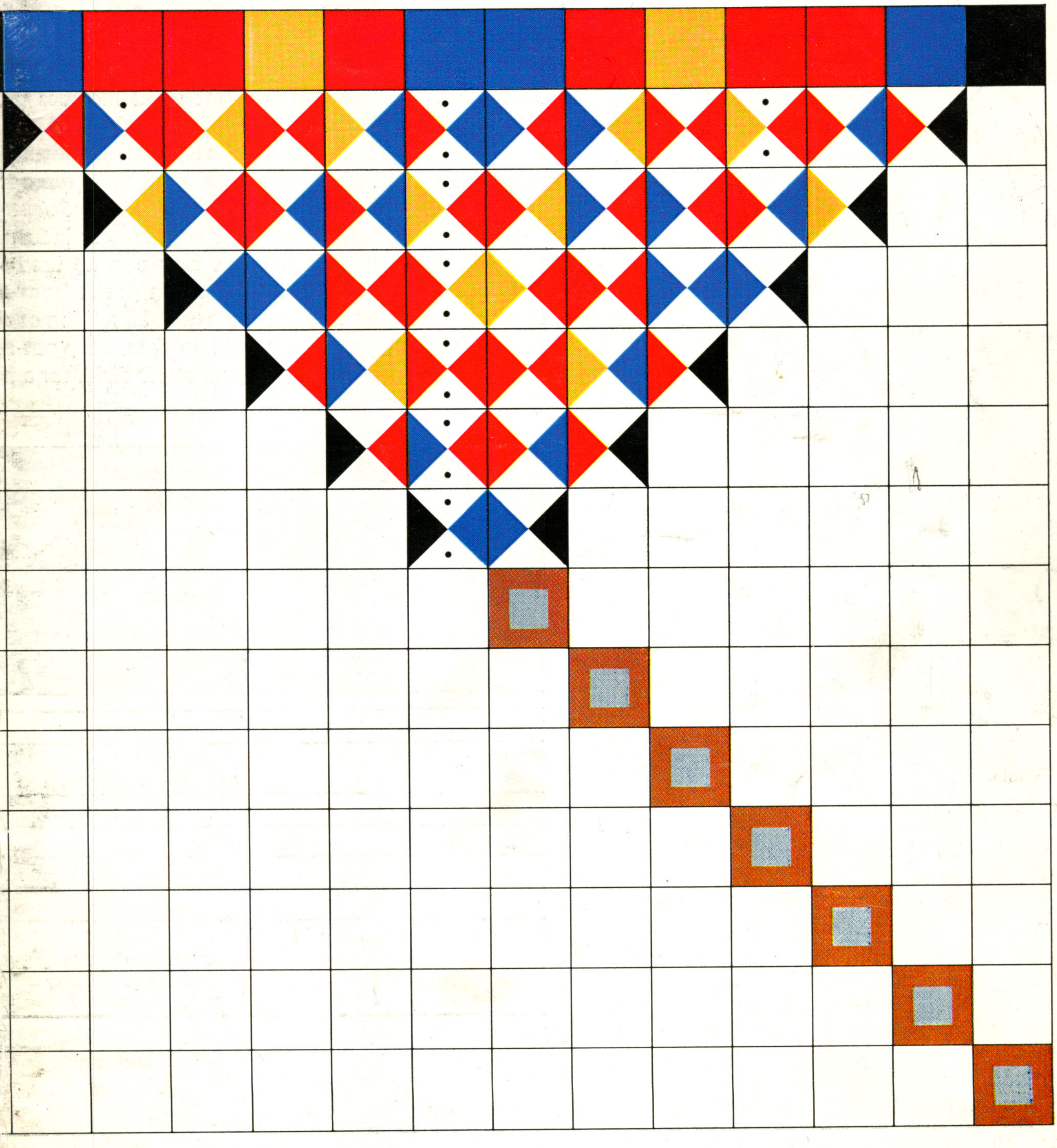
SCIENTIFIC AMERICAN



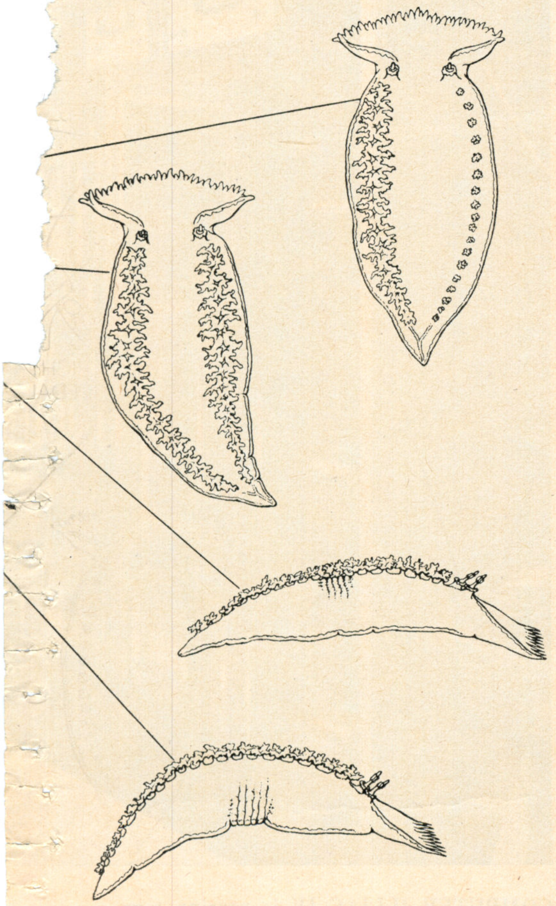
CELLULAR AUTOMATON

ONE DOLLAR

February 1971

ly) are far from the cell bodies in which the electrodes are placed and transmission of impulses from one cell to another cannot always be observed directly. We can, however, detect interactions and infer connections between cells by various means, such as using electrodes to obtain simultaneous records of activity from several cells (as many as six) at once. These records show the phase relations of the several cells in guiding swimming activity and suggest patterns of connectivity.

There is reason to be confident that within a few years the cellular exploration of the nervous systems of *Tritonia* and other simple animals will provide a clear enough understanding of their nervous apparatus and mechanisms to describe these systems in the definitive terms usually reserved for man-made machines. These investigations should also help greatly in determining the general relations between the brain and behavior in the vast number of simple animal species comprising most of the animal kingdom—and ultimately in more complex animals.



ganglia. Neurons on pleural ganglia generally control bilateral responses; one neuronal group triggers the escape response.

THE FASTEST COMPUTER

ILLIAC IV is made up of 64 independent processing units that by operating simultaneously will be capable of solving complex problems in a fraction of the time needed by any other machine

by D. L. Slotnick

The computer ILLIAC IV, which is now nearing completion, is the fourth generation in a line of advanced machines that have been conceived and developed at the University of Illinois. ILLIAC I, a vacuum-tube machine completed in 1952, could perform 11,000 arithmetical operations per second. ILLIAC II, a transistor-and-diode computer completed in 1963, could perform 500,000 operations per second. ILLIAC III, which became operational in 1966, is a special-purpose computer designed for automatic scanning of large quantities of visual data. Since it processes nonarithmetical data it cannot be compared with the earlier ILLIAC's in terms of operational speed. ILLIAC IV, employing the latest semiconductor technology, is actually a battery of 64 "slave" computers, capable of executing between 100 million and 200 million instructions per second. Even that basic rate, although it is faster than that of any other computer yet built, does not express the true capacity of ILLIAC IV.

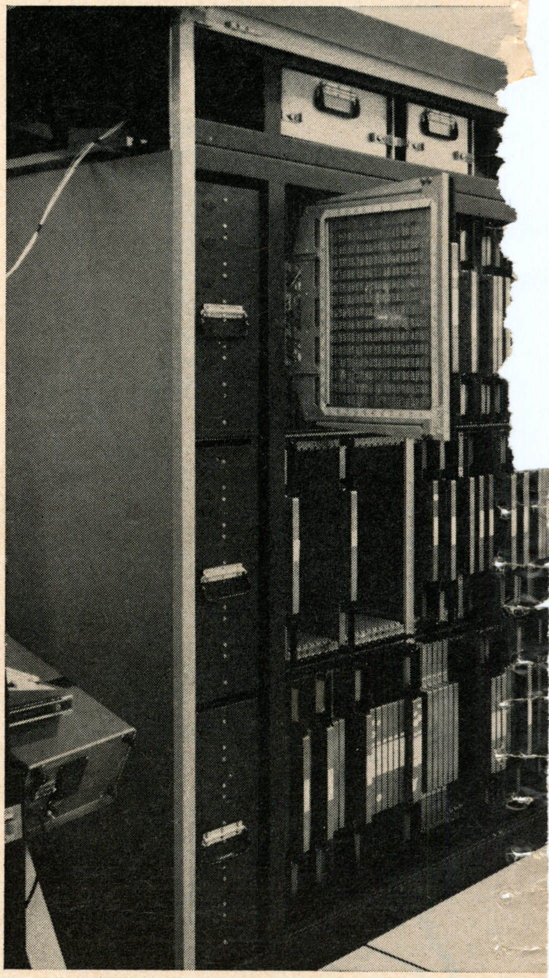
Unlike its three predecessors and all computers now on the market, which solve problems by a series of sequential steps, ILLIAC IV is designed to perform as many as 64 computations simultaneously. For such a computing structure to be utilized efficiently the problem must be amenable to parallel, rather than sequential, processing. In actuality problems of this kind constitute a considerable part of the total computational spectrum, ranging from payroll calculations to linear programming to models of the general circulation of the atmosphere for use in weather prediction. For example, a typical linear-programming problem that might occupy a large present-generation computer for six to eight hours should be solvable by ILLIAC IV in less than two minutes—a time reduction of at least 200 to one.

Subsystems for ILLIAC IV are being manufactured in a number of plants and are being shipped to the Burroughs Corporation in Paoli, Pa., for final assembly and testing. When the machine is finished a few months from now, it will be available over high-speed telephone lines to a variety of users, including the Center for Advanced Computation of the University of Illinois.

The ultimate limitation on the operating speed of a computer designed to operate sequentially [*see illustration on page 81*] is the speed with which a signal can be propagated through an electrical conductor. In practice this is somewhat less than the speed of light, which takes one nanosecond (10^{-9} second) to travel about one foot. Although integrated circuits containing transistors packed together with a density ranging from several hundred to several thousand per square inch have helped greatly to reduce the length of interconnections inside computers, designers have been increasingly aware that new kinds of logical organization are needed to penetrate the barrier set by the speed of light.

Over the past 10 years designers have introduced a number of variations on the strictly sequential mode of operation. One stratagem has been to overlap the operation of the central processing unit and the operation of input-output devices (such as magnetic-tape readers and printers). By means of a fine-grained separation of the computer's functional units a high degree of overlapping has been attained. Current efforts in "pipelining" the processing of "operands" will allow a further significant increase in speed.

Overlapping and pipelining, however, are both fundamentally limited in the advances in speed they can provide. The approach taken in ILLIAC IV surmounts fundamental limitations in ultimate computer speed by allowing—at least in principle—an unlimited number of computational events to take place simultaneously. The logical design of ILLIAC IV is patterned after that of the SOLOMON computers, prototypes of which were



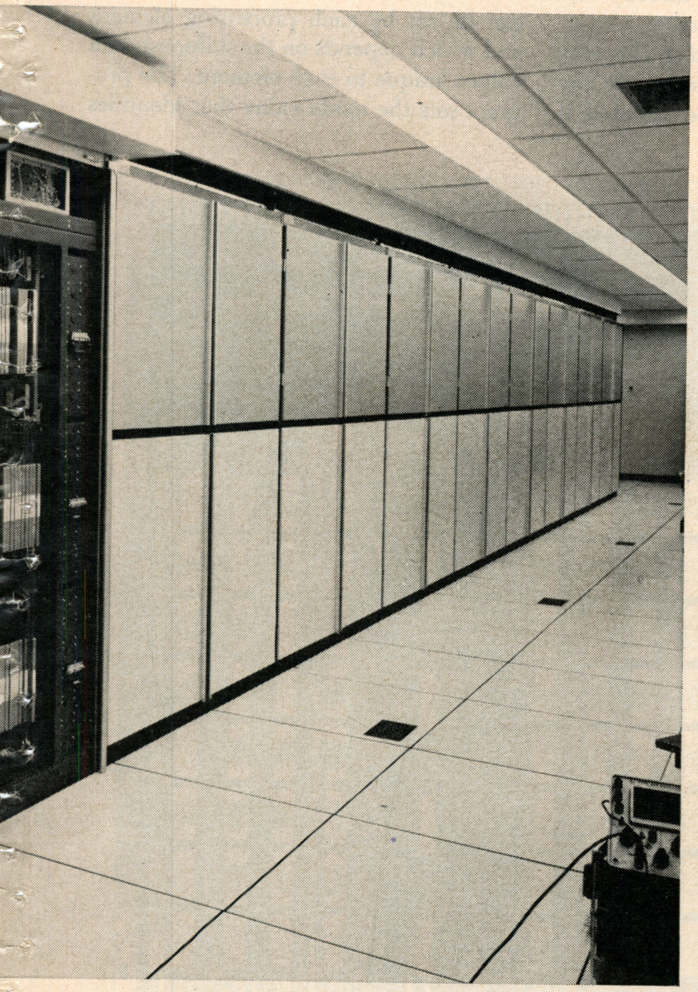
COMPUTER ILLIAC IV is nearing completion at the Great Valley Laboratories of the Burroughs Corporation in Paoli, Pa. Unlike conventional computers, which carry out logical and arithmetical operations in

built by the Westinghouse Electric Corporation in the early 1960's. In this design a single master control unit sends instructions to a sizable number of independent processing elements and transmits addresses to individual memory units associated with these processing elements ("processing-element memories"). Thus, while a single sequence of instructions (the program) still does the controlling, it controls a number of processing elements that execute the same instruction simultaneously on data that can be, and usually are, different in the memory of each processing element [*see top illustration on page 82*].

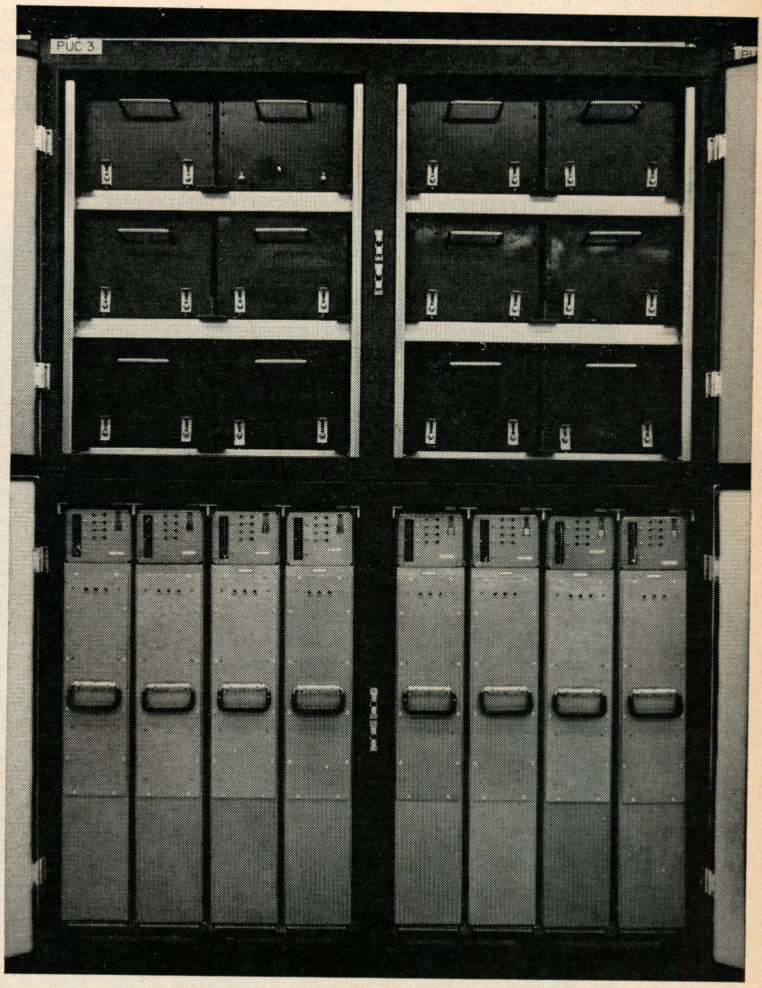
Each of the 64 processing elements of ILLIAC IV is a powerful computing unit in its own right. It can perform a wide range of arithmetical operations on numbers that are 64 binary digits (bits) long, where a digit is either 0 or 1, corresponding to the two "positions" of an electronic device with two stable states. These numbers can be in any one of six possible formats; the number can be processed as a single number 64 bits long with either a fixed or a "floating" point (corresponding to the decimal point in decimal notation), or the 64 bits can be broken up into smaller numbers of equal length. Each of the memory units has a capacity of 2,048 64-bit numbers. The time required to extract a number from memory (the access time) is 188 nanoseconds, but because additional logical circuitry is needed to resolve conflicts when two or more sections of ILLIAC IV call on memory simultaneously, the minimum time between successive operations of memory is increased to 350 nanoseconds.

Each processing element has more than 100,000 distinct electronic components assembled into some 12,000 switching circuits. A processing element together with its memory unit and associated logic is called a processing unit [*see illustrations on next two pages*]. In a system containing more than six million components one can expect a component or a connection to fail once every few hours. For this reason much attention has been devoted to testing and diagnostic procedures. Each of the 64 processing units will be subjected regularly to an extensive library of automatic tests. If a unit should fail one of these tests, it can be quickly unplugged and replaced by a spare, with only a brief loss of operating time. When the defective unit has been taken out of service, the precise cause of the failure will be determined by a separate diagnostic computer [*see top illustration on page 80*]. Once the fault has been found and repaired the unit will be returned to the inventory of spares.

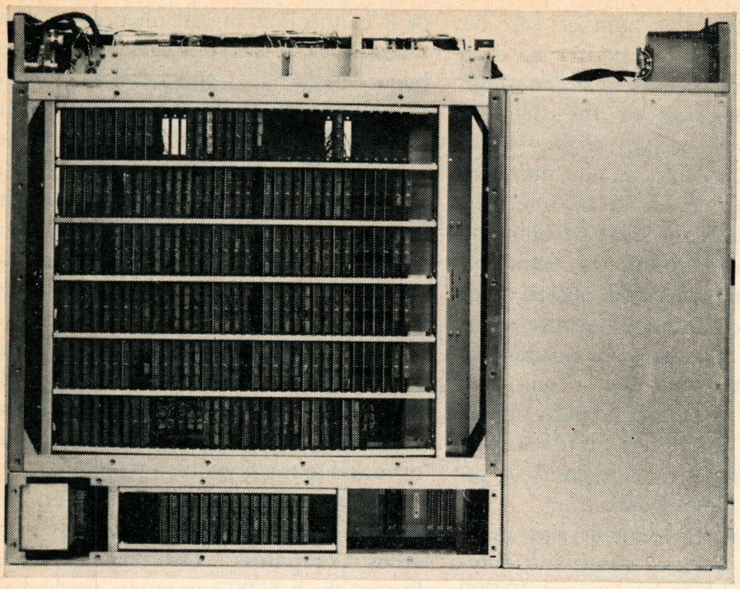
ILLIAC IV could not have been designed at all without much help from other computers. Two medium-sized Burroughs B 5500 computers worked almost full time for two years preparing the artwork for the system's printed circuit boards and developing diagnostic and testing programs for the system's logic and hardware. These formidable design, programming and operating efforts

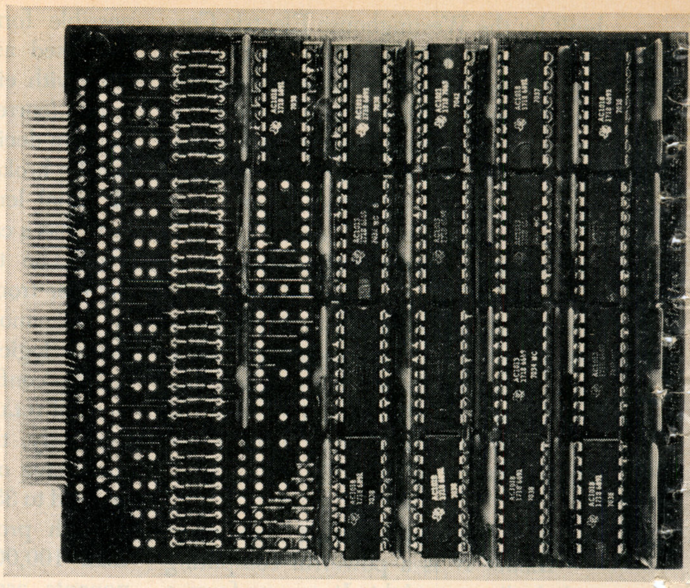


strict sequence, ILLIAC IV will solve complex problems in an all-at-once manner by coordinating the simultaneous operation of 64 "slave" computers, or independent processing units. ILLIAC IV was conceived and developed at the University of Illinois Center for Advanced Computation.



OPEN DOORS OF ILLIAC IV reveal vertical cases holding eight of the big machine's 64 independent but centrally controlled processing units. The 12 drawers at the top of the picture hold the power-supply modules associated with the eight processing units. A group of four processing units lies behind each of the 16 bottom doors in the photograph at the left.



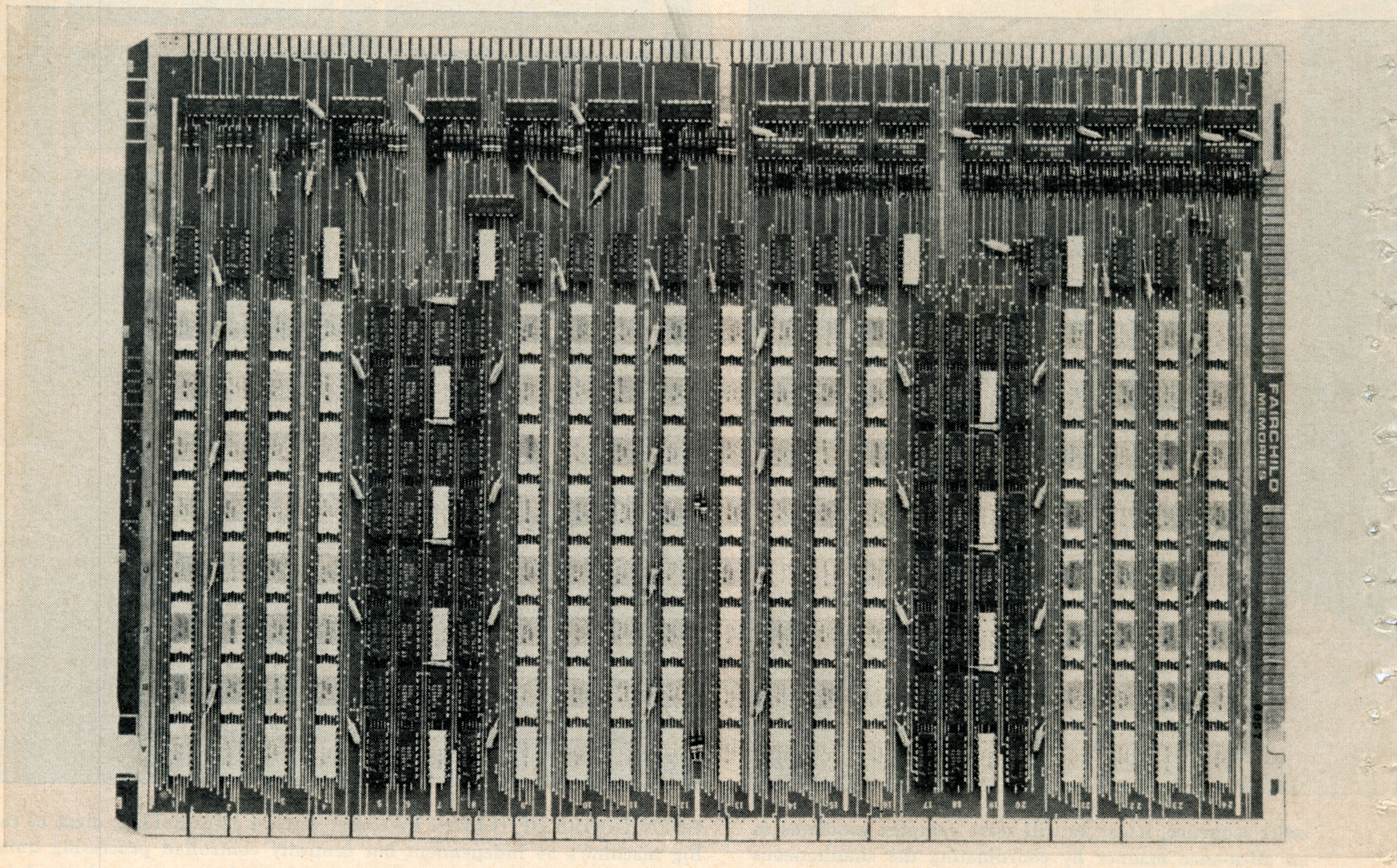


BACK-PLANE ASSEMBLY (*far left*) of one of ILLIAC IV's 64 processing elements contains up to 210 printed circuit boards arranged in six rows of 35 columns. Each circuit board (*second from left*) holds up to 20 "dual-in-line" packages (four rows by five columns) as well as some other electronic components such as resistors. Each dual-in-line package (*third from left*) contains 16 pins, which

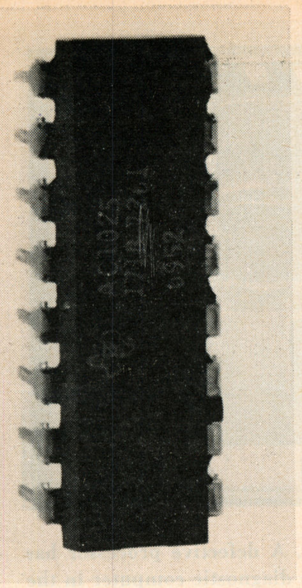
were under the direction of Arthur B. Carroll, who during this period was the project's deputy principal investigator.

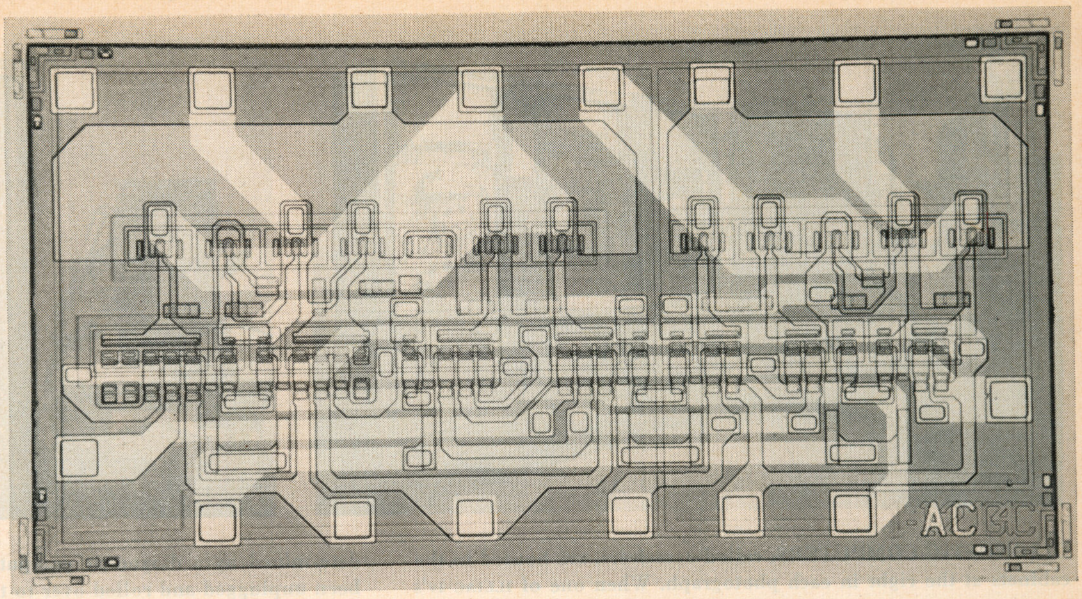
In the course of a calculation it is frequently necessary to transfer data from one processing element to another; data paths are provided for this purpose [*see bottom illustration on page* 83]. In solving certain problems these data paths can be used to simulate directly the problem's geometric structure.

Although the 64 processing elements are under centralized control, only the simplest problems could be handled if the elements did not have some degree of individual control. Such control is provided by means of a "mode value," which can be set by each processing element and which depends on the different data values unique to each element. The program sets the mode value that identifies



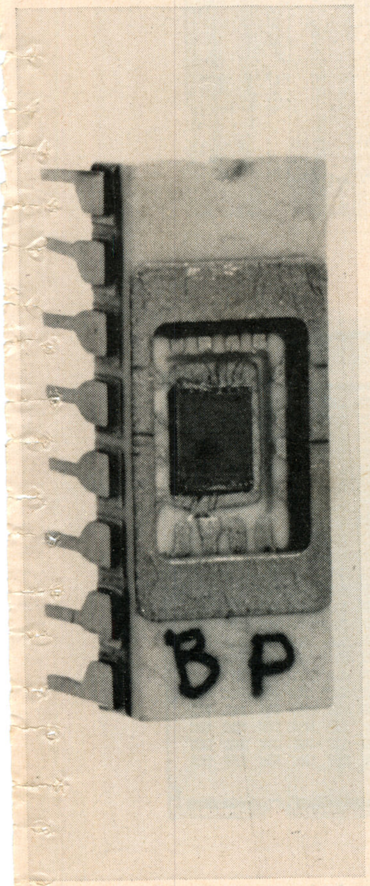
MEMORY ARRAY BOARD (*left*) is one of four that together constitute the high-speed, 131,072-bit memory associated with each of the 64 processing elements in ILLIAC IV. Each board holds up to 128 dual-in-line packages. Each package (*middle*) holds one chip and

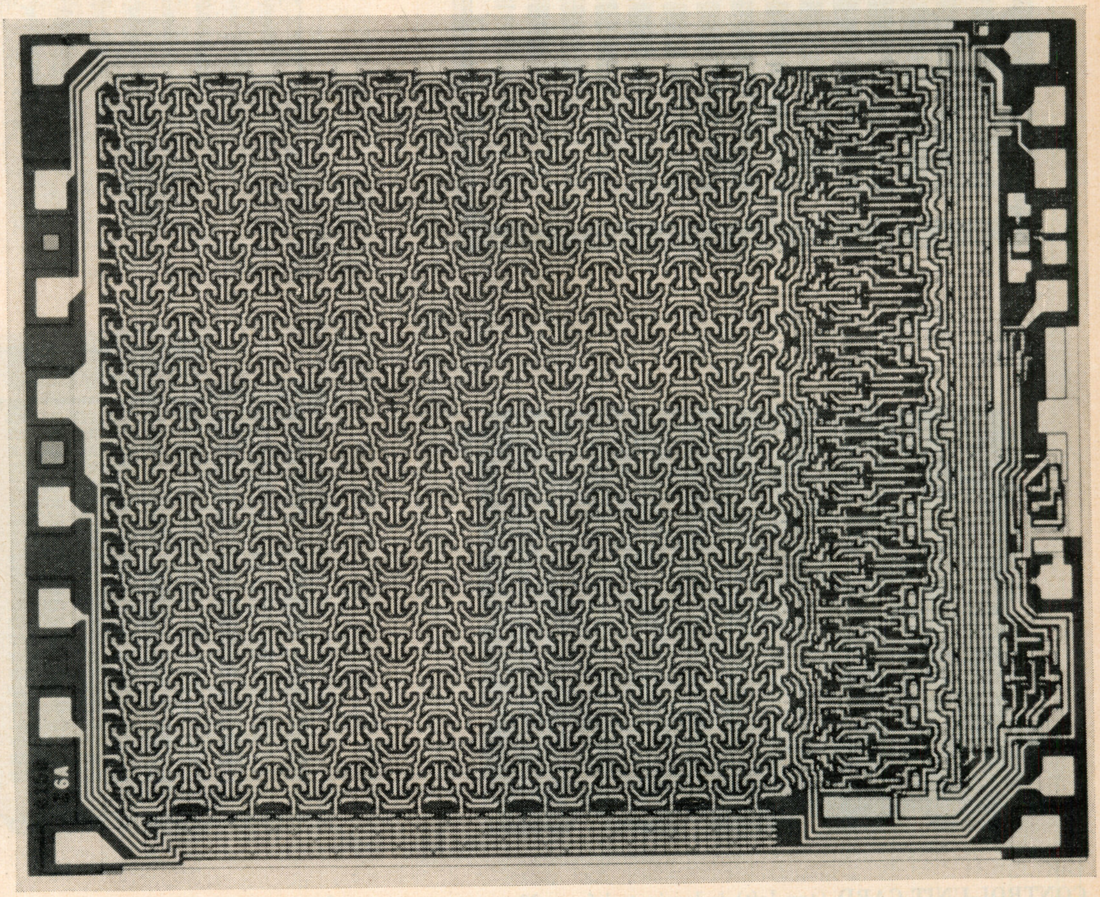




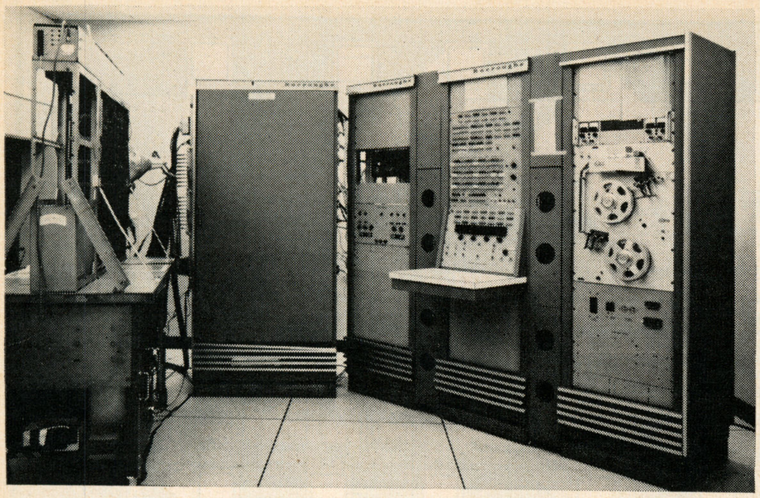
connect to an integrated circuit built up on a single chip of silicon measuring .095 by .05 inch. The integrated circuit, magnified 55 diameters at the far right, contains 34 transistors organized into seven "logic gates." The circuit chips are manufactured by Texas Instruments Incorporated. In all more than a quarter of a million chips will be used in ILLIAC IV's 64 processing elements.

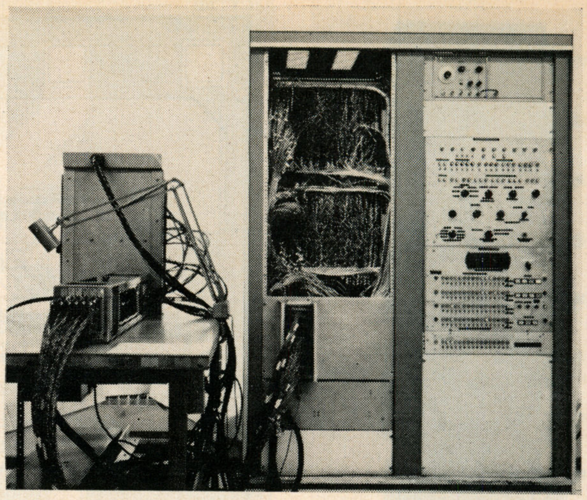
those processing elements whose state (as defined by their mode value) enables them to respond to a given instruction or sequence of instructions. The elements not in this state are turned off. As a simple example, suppose at the start of a problem all mode values are set to 1, or "on." Now the program causes the control unit to "broadcast" to all 64 processing elements: Search your memory for *X* (some particular value). Each element carries out the search, and any element finding the value *X* sets its mode value to 0, or "off." The control unit may now issue a sequence of instructions to be performed only by those elements whose mode value is still 1, which allows them to keep operating. Similarly, the contents of two registers within a processing element can be compared, and the mode value can be set on the outcome of the



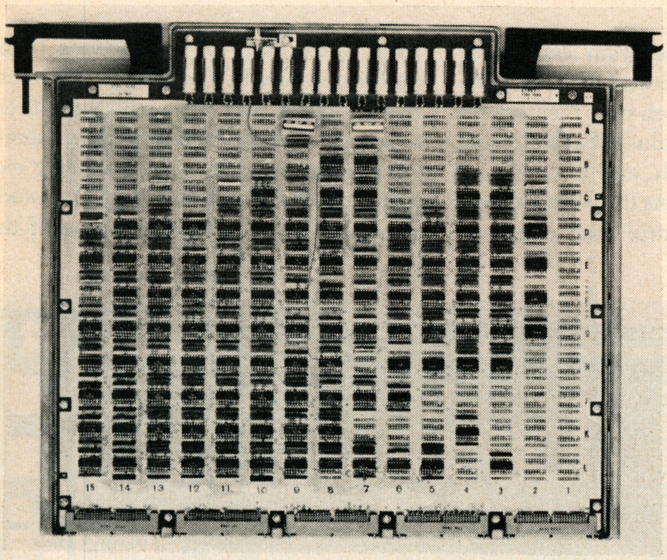


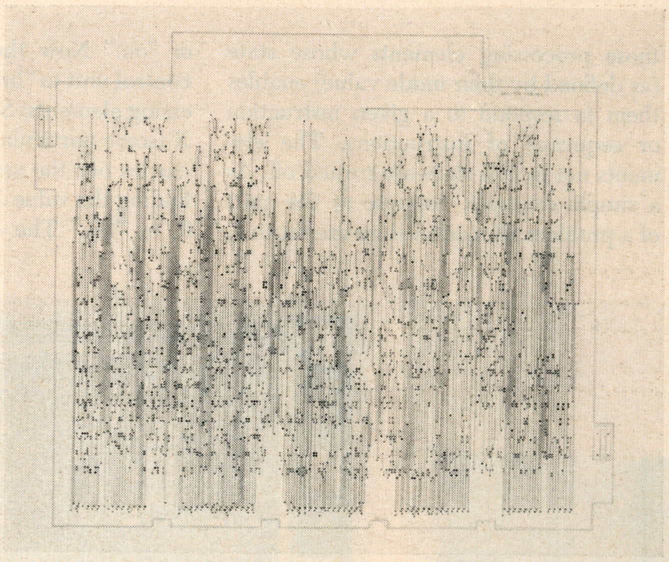
each chip contains integrated semiconductor circuits (*right*) with a storage capacity of 256 bits. The chips, each containing 2,485 transistors, resistors and diodes, were developed by the Semiconductor Division of Fairchild Camera and Instrument Corporation.

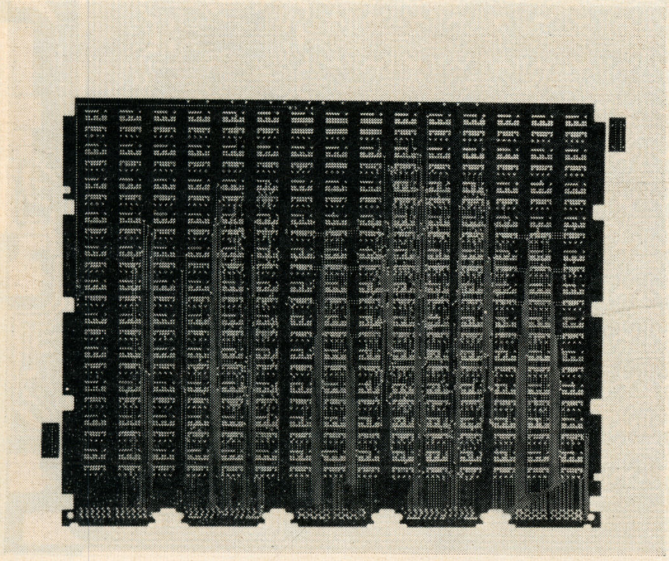


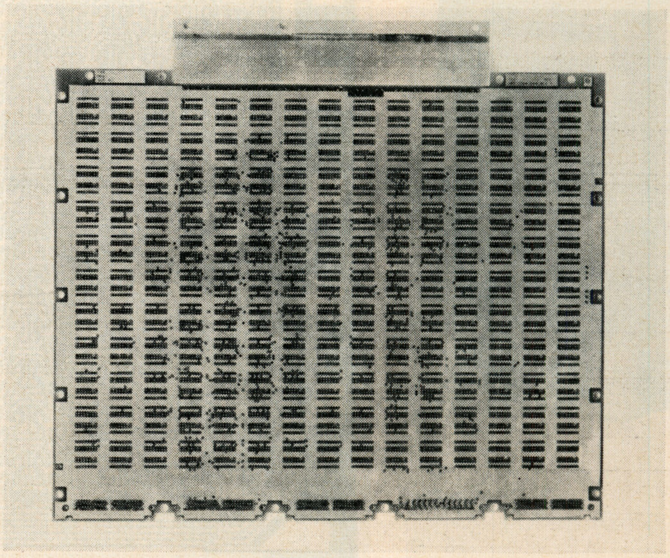


DIAGNOSTIC COMPUTERS, called exercisers, are housed in the cabinets at the right in each photograph. When one of ILLIAC IV's processors or memory units fails, it is immediately unplugged and replaced with a spare unit. The exact cause of the failure is then determined by a diagnostic computer. A defective processor has been unplugged and rolled over to the diagnostic computer in the photograph at the left; a defective memory unit is being examined by a different diagnostic computer in the photograph at the right.









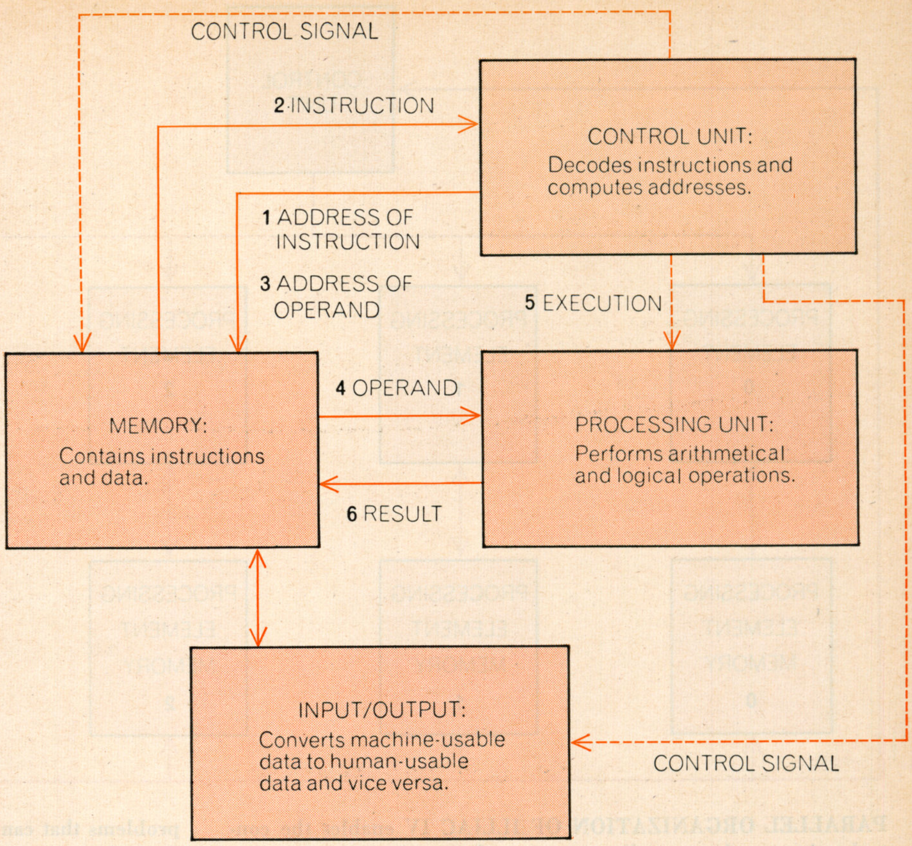
CONTROL-UNIT CARD *(top left)* is laminated from 12 separate layers that embody the complex wiring pattern for interconnecting several thousand electronic components. Three of the glass photographic positives of wiring patterns and etched copper wiring layers are shown in the other photographs. ILLIAC IV requires 64 control-unit cards, each of which can be removed for test or replacement.

comparison. Mode values are also used to determine when an iterative calculation should be terminated or when quantities have exceeded specified numerical limits. In short, mode values are the principal means for imposing a data-dependent, logical structure on a program.

In addition to the high-speed primary memories associated with each processing element, ILLIAC IV has two memories that are somewhat slower but have capacities that are considerably larger. The total capacity of the 64 primary memories is 64 × 2,048, or 131,072, numbers, each 64 bits in length. Thus the total high-speed storage is some 8.4 million bits. Most of the problems suitable for ILLIAC IV will require data capacities far exceeding this primary storage.

The additional data can be held either in a rotating-disk magnetic memory or in a new "archival" memory whose writing mechanism is a laser beam. The rotating-disk memory has a capacity of a billion bits, or about 120 times the capacity of the primary memory. The disk has 128 tracks, each with its own reading and recording head. The access time is determined by the time required for the disk to rotate into the position where the desired datum is under one of the fixed heads. Since the disk revolves once in 40 milliseconds, the average access time is 20 milliseconds, which is about 100,000 times slower than the access time of the primary memory. Once the disk is in position, however, data can be transferred to any of the 64 primary memories at the rate of half a billion bits per second, or roughly 100 times the rate at which data can be transmitted over a standard television channel. The archival memory, which has a capacity of a trillion bits, has a longer access time and a lower data-transfer rate [*see top illustration on page 83*].

These memory subsystems plus the more conventional peripheral equipment (punched cards, disk and tape units, printers, displays and so on) are under the direction of a medium-size general-purpose computer, the Burroughs B 6500 [*see bottom illustration on next page*]. This computer also bears the major responsibility for translating programs from the various programming languages available to the users into the detailed, hardware-determined language of the computer itself.



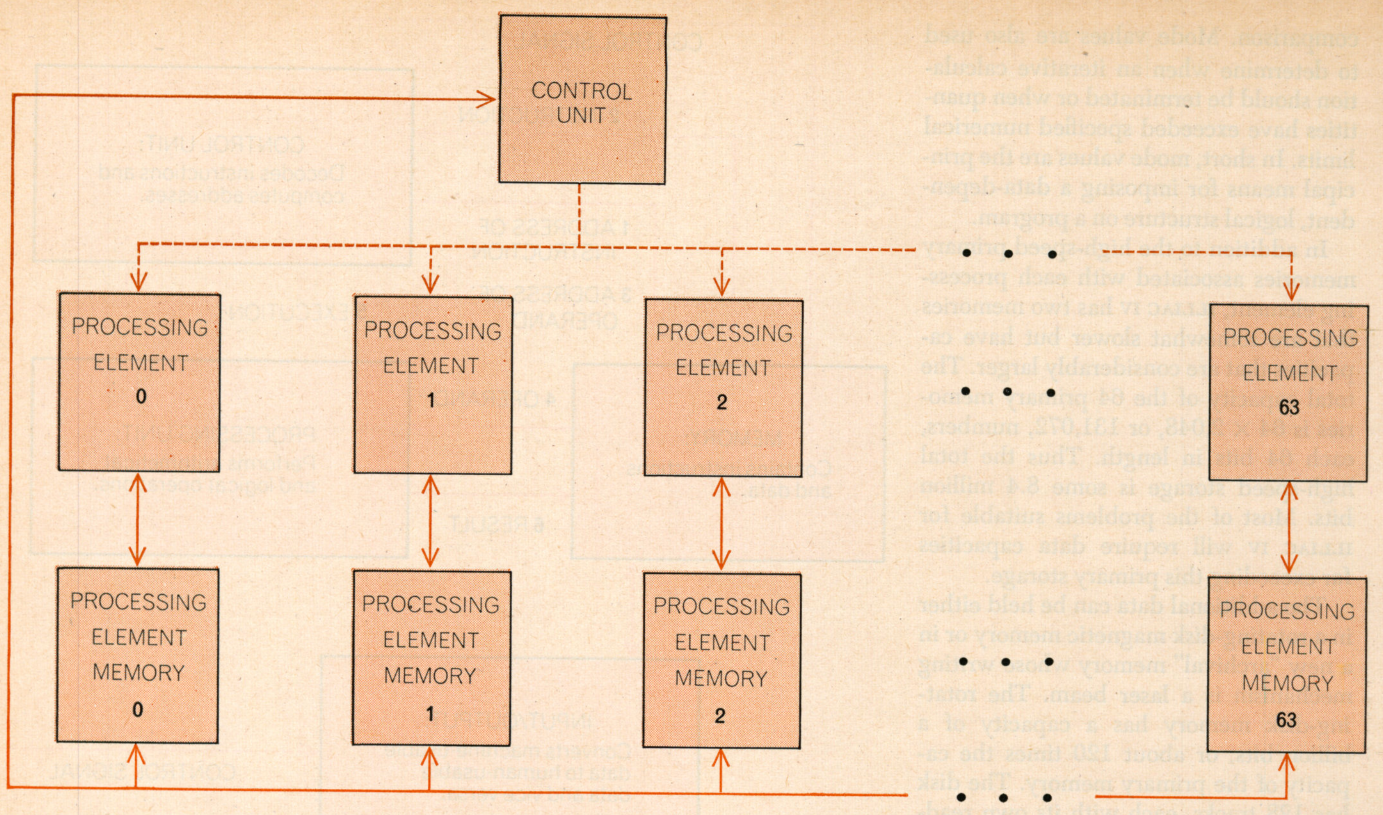
CONVENTIONAL COMPUTER is organized to carry out operations in sequence. A counter in the control unit determines the address of the next instruction in the sequence to be executed and transmits the address to the memory (*1*). The memory returns the instruction to the control unit (*2*). The instruction contains the address in the memory of the data (operand) on which an arithmetical or logical operation (also specified) is to be performed. This address is sent to the memory (*3*). The memory furnishes the selected operand to the processing unit (*4*). The control unit then transmits to the processor a sequence of electronic signals that contains the fine structure of the arithmetical or logical operation required by the program (*5*). The calculated result is then stored at a specified location in memory (*6*) for use in a subsequent operation or for conversion to printed form for the user of the machine. Advanced computers carry out this entire sequence in a few millionths of a second. Billions of repetitions may be needed to solve a complex problem.

Let us now examine how ILLIAC IV can be used to solve a simplified problem in mathematical physics. The problem belongs to the very large class of problems whose calculation can be performed in an "all at once" manner, using either ordinary or partial differential equations. The problem we shall trace requires the solution of Laplace's partial differential equation describing the distribution of temperature on the surface of a slab. Even the reader who is unfamiliar with such equations should be able to follow this example because the method for reaching a solution relies completely on the commonsense notion that the temperature at any point on the slab tends to become the average of the surrounding values.

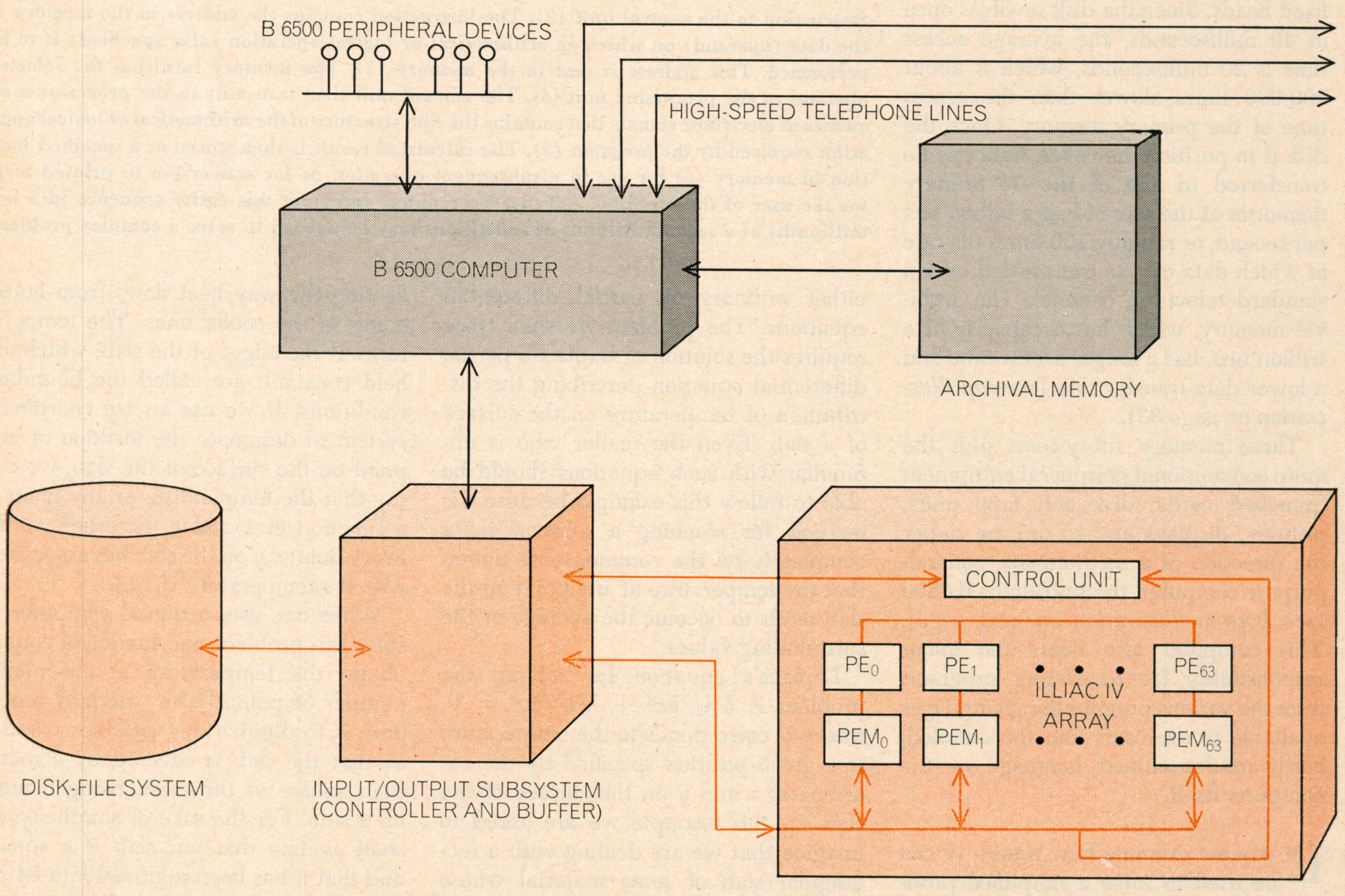
Laplace's equation for solving the problem is $\delta^2U/\delta x^2 + \delta^2U/\delta y^2 = 0$, where U corresponds to the temperature at a given position specified by the coordinates x and y on the surface of the slab. In this example we are asked to imagine that we are dealing with a rectangular slab of some material whose four edges are maintained at different temperatures. Eventually all the points on the surface of the slab will reach a steady-state temperature distribution reflecting the way heat flows from hotter edges to the cooler ones. The temperatures at the edges of the slab, which are held constant, are called the boundary conditions. If we use an x-y coordinate system to designate the location of any point on the surface of the slab, we can say that the temperature at any point is a function of x and y. In other words, every point x,y on the slab has associated with it a temperature $U(x,y)$.

When one uses a digital computer to solve this problem, one cannot, of course, obtain the temperature at an infinite number of points. The standard procedure is to digitize the variables x and y so that the slab is covered by a mesh, each square of the mesh being h units on a side. For the sake of simplicity we shall assume that our slab is a square and that it has been digitized into 64 x,y values or mesh points [*see illustration on pages 84 and 85*].

The method of solution can now be stated very simply: The temperature at



PARALLEL ORGANIZATION OF ILLIAC IV enables the control unit to orchestrate the operation of 64 processing elements, each with its own memory. There is a large class of mathematical problems that can be solved in an all-at-once manner by independent processors operating simultaneously, each about twice as fast as the single processor in an advanced sequential computer.



BLOCK DIAGRAM OF ILLIAC IV SYSTEM shows how the ILLIAC's control unit, together with its 64 processors and primary memory units, will be connected to ancillary pieces of equipment. A secondary memory is provided by a disk-file system with a capacity of a billion bits (binary digits). A tertiary memory is provided by a new "archival" memory system, which uses a laser beam for reading and writing. Accessed through a medium-size Burroughs B 6500 computer, it will have storage for a trillion bits.

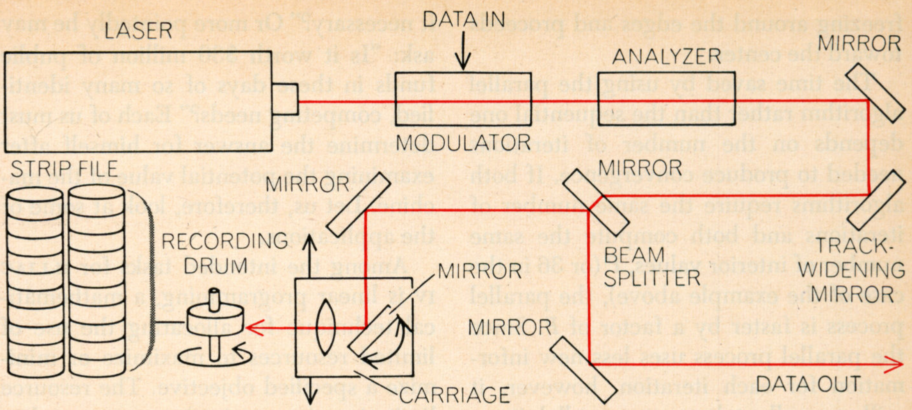
any interior mesh point is the average of the temperatures of the four closest mesh points. Thus the value of $U(x,y)$ equals the sum of four neighboring values of $U(x,y)$ divided by four. When this equation is made true for all points, there can be only one correct value for each point. This method is called "relaxation."

When the relaxation method is applied with a sequential, or conventional, computer, the usual procedure is to start at the top left of the slab and apply the basic equation at each interior point moving from left to right along each row of points and proceeding downward row by row. Since the 28 boundary points in our example are already specified, the equation would have to be applied 36 times (64 minus 28) to produce one relaxation of the relaxation method. As succeeding relaxations are performed on the set of mesh points the values of the temperatures converge to the exact solution. When values for two successive relaxations are very close to each other (within a specified error tolerance), one stops the process and says that the steady-state solution has been reached.

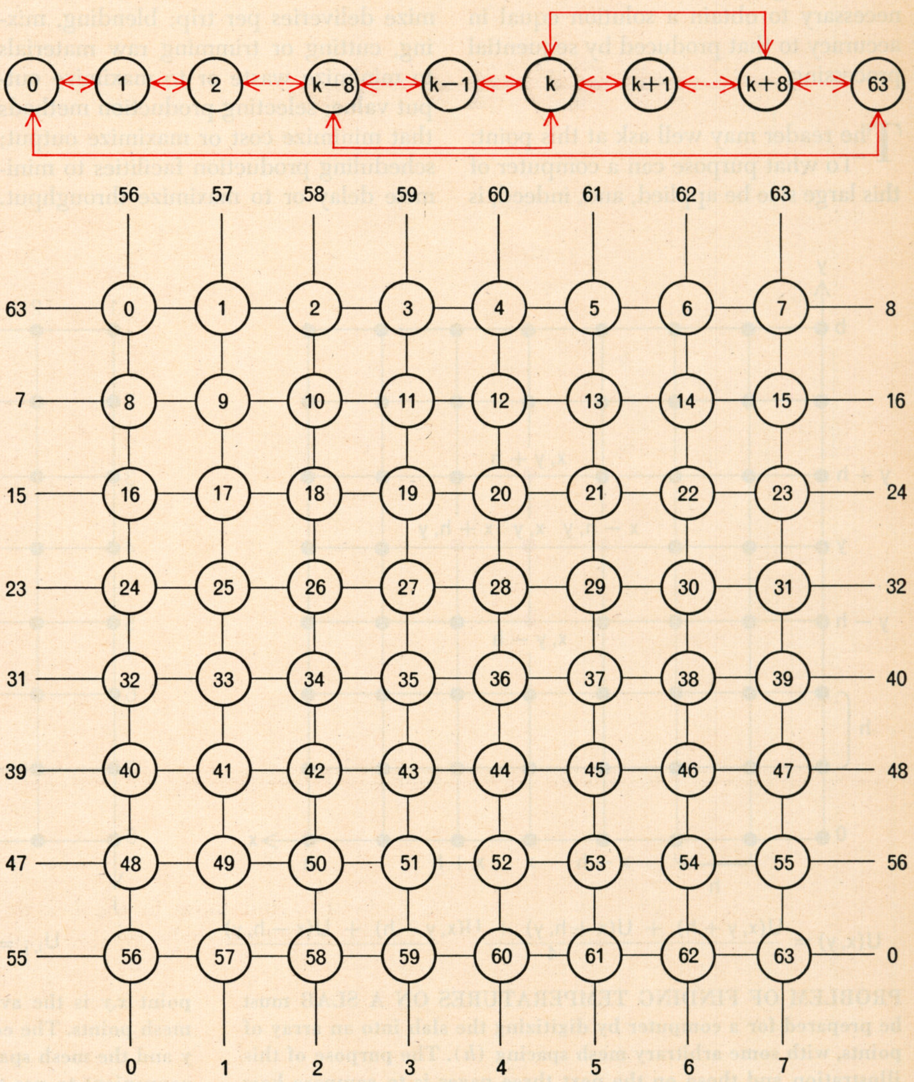
Let us now consider how this same problem could be solved by parallel processing on ILLIAC IV. If one stored each value of U in a separate processing element, all 36 inner values could be calculated simultaneously. A program could be written to compute new values for $U(x,y)$ not from top left to bottom right but all at once. When the first set of relaxation values for all 36 inner points has been obtained by simultaneous calculation, these values are available for the second relaxation.

Not only are the two algorithms, or mathematical routines, different for sequential and parallel computation but also the way the temperatures converge is different [*see illustration on pages 86 and 87*]. In the sequential method the temperatures at bottom right converge faster to the exact solution than those at top left. This happens because in sweeping from top left to bottom right the last computations in each relaxation sequence contain more new data than the computations made at the start of the sequence.

When the parallel algorithm is used, the values closest to the edges converge faster than those in the center of the mesh. The reason is that the outer values are closest to the boundary values, and at each iteration they have more new data available than the inner values. The convergence process can be likened to freezing. The sequential algorithm begins freezing at bottom right and proceeds to top left; the parallel algorithm begins



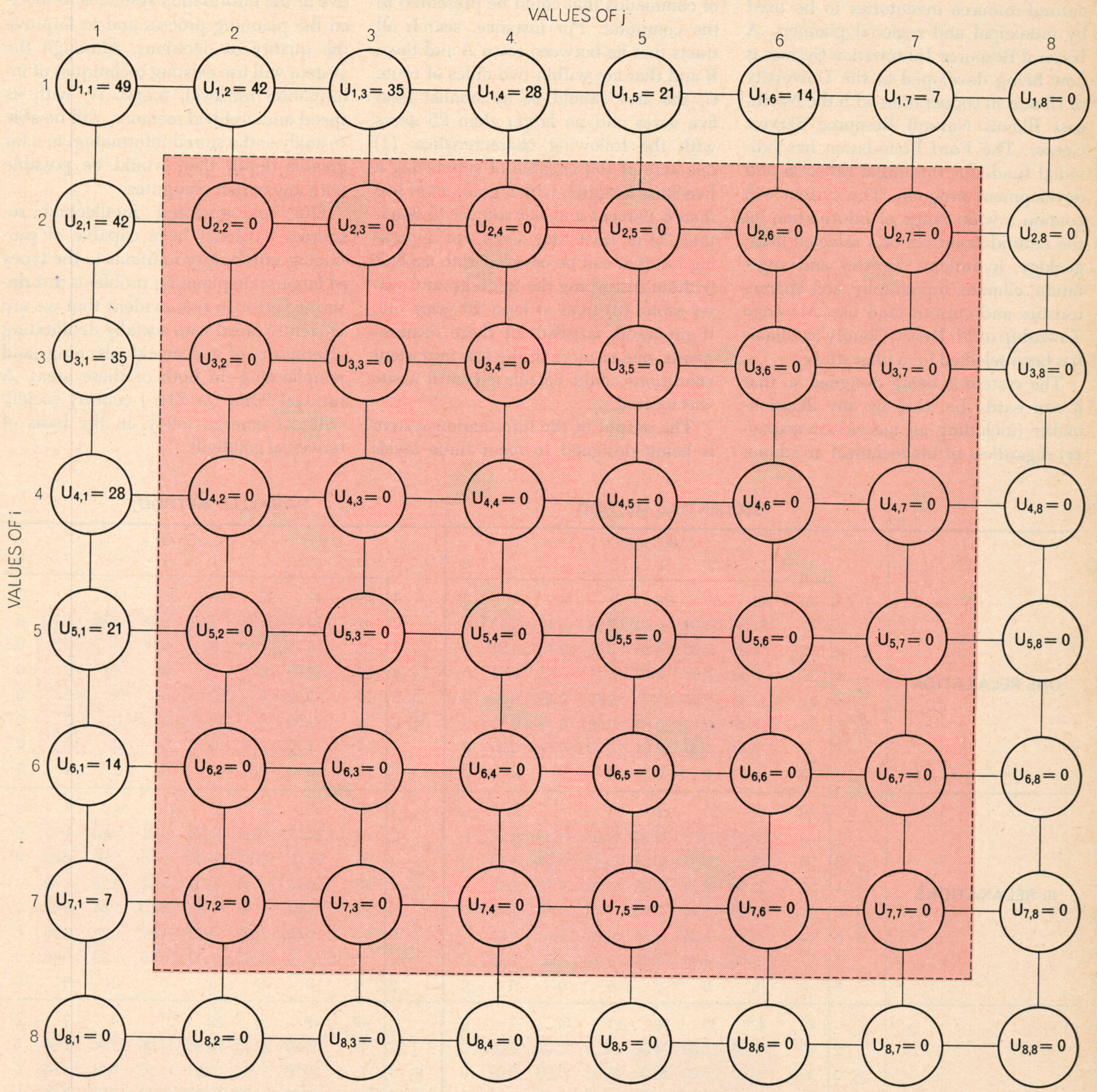
ARCHIVAL MEMORY is a new high-capacity secondary memory, developed by the Precision Instrument Company. The beam from an argon laser records binary data by burning microscopic holes in a thin film of metal coated on a strip of polyester sheet, which is carried by a rotating drum. Each data strip can store some 2.9 billion bits, the equivalent of 625 reels of standard magnetic tape in less than 1 percent of the volume. The "strip file" provides storage for 400 data strips containing more than a trillion bits. The time to locate data stored on any one of the 400 strips is about five seconds. Within the same strip data can be located in 200 milliseconds. The read-and-record rate is four million bits a second.



ARRAY OF 64 PROCESSING ELEMENTS in ILLIAC IV is connected in a pattern that can be regarded in either of two ways, which are topologically equivalent. The elements can be viewed as a linear string (*top*) with each processing element connected to its immediate neighbors and to neighbors spaced eight elements away. Equivalently, one can regard the processing elements as a square array (*bottom*) with each element connected to its four nearest neighbors. One can imagine the array rolled into a cylinder so that the processing elements in the top row connect directly to those in the bottom row. The last processing element in each row is connected to the first in the next row to produce a linear sequence.

ming models of a region or nation can also recognize constraints involving social costs, for example the harm done by the intensive application of nitrogenous fertilizers, the use of certain pesticides (such as DDT) or cultivation practices with long-term deleterious effects on the productivity of the land.

It must be pointed out that in order to apply linear programming to an entire economic sector one must incur considerable expense in gathering the data to be used in the model. Here too, however, the computer can help by making experimental trials and estimating the accuracy with which various input data need to be known in order to secure answers with a given level of precision. It is also possible to simulate alternative policies on the computer and estimate their effects on agricultural productivity. To test such



36 interior points are initially set to zero. When the problem is solved sequentially, the computer starts with the top left interior point $U_{2,2}$ and calculates its value using the numbers given above:

$$U_{2,2} = \frac{U_{1,2} + U_{2,3} + U_{3,2} + U_{2,1}}{4} = \frac{42 + 0 + 0 + 42}{4} = 21.$$

The computer then calculates the value of $U_{2,3}$ using the *new* value of $U_{2,2}$ just obtained, which is 21, instead of the initial value, 0:

$$U_{2,3} = \frac{U_{1,3} + U_{2,4} + U_{3,3} + U_{2,2}}{4} = \frac{35 + 0 + 0 + 21}{4} = 14.$$

The equation is similarly solved for the remaining 34 interior points, using at each step all the new values previously calculated. This sequence of 36 calculations is one "relaxation" of the relaxation method. If the problem were programmed for ILLIAC IV, on the other hand, each of the 36 interior points could be assigned to a separate processing element and 36 simultaneous solutions of the equation obtained. In this method the first relaxation consists of the 36 simultaneous solutions using *only* the numbers initially given. Thus the first solution of $U_{2,3}$ is $(35 + 0 + 0 + 0) \div 4 = 8.75$ rather than the value of 14 obtained in the sequential method. Succeeding simultaneous relaxations, however, can make use of values obtained previously. The way the two methods converge to yield the final answer is shown in the tables on the next page.

policies directly "in vivo" can be very costly. There is no reason why a computer program should not be the white rat or guinea pig for a proposed cure to a social problem.

Another application contemplated for ILLIAC IV is the establishment of natural-resource inventories to be used by municipal and regional planners. A Natural Resource Information System is now being developed at the University of Illinois in cooperation with the Northeast Illinois Natural Resource Service Center. The Ford Foundation has provided funds for the initial research and development program. The system will contain a wide range of information on the natural resources of a selected area: geology, hydrology, forestry and vegetation, climate, topography, soil characteristics and current land use. Marengo Township of McHenry County in Illinois has been selected for a pilot study.

The system is being designed so that it can easily be used by any decision-maker (including an individual taxpayer) regardless of his technical or administrative training. For example, an individual may want to know whether or not he can have a housing subdivision (or a tennis court or a fishpond) on his land. On the other hand, county administrators may be looking for the best site for a new hospital. The search for a hospital site could be reformulated into a series of commands that could be presented to the computer. For instance, search all tracts that lie between town *A* and town *B* and that are within two miles of route *C;* the area should be no smaller than five acres and no larger than 25 acres with the following characteristics: (1) one acre of soil capable of supporting a five-story hospital, with a gradient of less than 8 percent and not subject to flooding; (2) at least four acres (for a parking lot) that can be covered with asphalt without disturbing the underground water table; (3) trees at least 20 years old. If no tracts satisfied all these requirements, one or more of the less important conditions could be relaxed until a site was located.

The output of the information system is being designed to meet three levels of need. The simplest level will consist of a concise inventory listing. The next level will be an interpretation of the computer's search in prose that should be clear to an educated layman. The third level will be a highly technical description suitable for use by a specialist, such as a geologist or an ecologist. The objective of the information system is to shorten the planning process and to improve the quality of decisions. Although the system will use existing techniques of information retrieval, ILLIAC IV, with its speed and archival memory, will be able to analyze the stored information to a far greater depth than would be possible with any earlier computer.

Our unaugmented intellectual resources have not been capable of producing satisfactory solutions to the types of large-scale planning problems just described. It is in fact evident that we are currently faced with socially debilitating aftermaths of piecemeal planning—and nonplanning—in both of these areas. A rational 20th- (or 21st-) century society will not emerge solely on the basis of universal goodwill.

SEQUENTIAL METHOD

ONE RELAXATION

VALUES OF i \ VALUES OF j	1	2	3	4	5	6	7	8
1	49	42	35	28	21	14	7	0
2	42	21.00	14.00	10.50	7.88	5.47	3.12	0
3	35	14.00	7.00	4.38	3.06	2.13	1.31	0
4	28	10.50	4.38	2.19	1.31	0.86	0.54	0
5	21	7.88	3.06	1.31	0.66	0.38	0.23	0
6	14	5.47	2.13	0.86	0.38	0.19	0.11	0
7	7	3.12	1.31	0.54	0.23	0.11	0.05	0
8	0	0	0	0	0	0	0	0

10 RELAXATIONS

VALUES OF i \ VALUES OF j	1	2	3	4	5	6	7	8
1	49	42	35	28	21	14	7	0
2	42	35.37	29.01	22.90	17.03	11.31	5.66	0
3	35	29.01	23.41	18.24	13.44	8.88	4.44	0
4	28	22.90	18.24	14.05	10.26	6.75	3.38	0
5	21	17.03	13.44	10.26	7.44	4.88	2.44	0
6	14	11.31	8.88	6.75	4.88	3.19	1.60	0
7	7	5.66	4.44	3.38	2.44	1.60	0.80	0
8	0	0	0	0	0	0	0	0

50 RELAXATIONS

VALUES OF i \ VALUES OF j	1	2	3	4	5	6	7	8
1	49	42	35	28	21	14	7	0
2	42	36.00	30.00	24.00	18.00	12.00	6.00	0
3	35	30.00	25.00	20.00	15.00	10.00	5.00	0
4	28	24.00	20.00	16.00	12.00	8.00	4.00	0
5	21	18.00	15.00	12.00	9.00	6.00	3.00	0
6	14	12.00	10.00	8.00	6.00	4.00	2.00	0
7	7	6.00	5.00	4.00	3.00	2.00	1.00	0
8	0	0	0	0	0	0	0	0

PARALLEL METHOD

ONE RELAXATION

VALUES OF i \ VALUES OF j	1	2	3	4	5	6	7	8
1	49	42	35	28	21	14	7	0
2	42	21	8.75	7.00	5.25	3.50	1.75	0
3	35	8.75	0	0	0	0	0	0
4	28	7.00	0	0	0	0	0	0
5	21	5.25	0	0	0	0	0	0
6	14	3.50	0	0	0	0	0	0
7	7	1.75	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0

10 RELAXATIONS

VALUES OF i \ VALUES OF j	1	2	3	4	5	6	7	8
1	49	42	35	28	21	14	7	0
2	42	34.27	27.05	20.53	14.81	9.60	4.74	0
3	35	27.05	19.87	14.08	9.48	5.90	2.83	0
4	28	20.53	14.08	9.06	5.62	3.22	1.49	0
5	21	14.81	9.48	5.62	3.09	1.61	0.69	0
6	14	9.60	5.90	3.22	1.61	0.73	0.28	0
7	7	4.74	2.83	1.49	0.69	0.28	0.10	0
8	0	0	0	0	0	0	0	0

50 RELAXATIONS

VALUES OF i \ VALUES OF j	1	2	3	4	5	6	7	8
1	49	42	35	28	21	14	7	0
2	42	35.98	29.96	23.96	17.96	11.96	5.98	0
3	35	29.96	24.94	19.92	14.92	9.94	4.96	0
4	28	23.96	19.92	15.90	11.90	7.92	3.96	0
5	21	17.96	14.92	11.90	8.90	5.92	2.96	0
6	14	11.96	9.94	7.92	5.92	3.94	1.96	0
7	7	5.98	4.96	3.96	2.96	1.96	0.98	0
8	0	0	0	0	0	0	0	0

DIFFERENT STAGES IN RELAXATION PROCESS are compared for sequential relaxations and parallel relaxations. The exact values are given in the array on the opposite page. The two methods for calculating the temperature of each of 36 interior points on a slab are described in the illustration on the preceding two pages. There one sees that a standard computer using sequential methods would obtain a value of 21 for point $U_{2,2}$ and 14 for $U_{2,3}$ in performing one relaxation. Here it is seen that after 10 relaxations by the sequential method the value of $U_{2,2}$ has climbed to 35.37 and the value of $U_{2,3}$ to 29.01. After 50 relaxations $U_{2,2}$ and $U_{2,3}$ have reached their exact values: 36 and 30. Using parallel relaxations ILLIAC IV would converge on the exact solution in a distinctly dif-

A quite different assignment for ILLIAC IV is numerical weather prediction, which early computer theorists such as John von Neumann regarded as one of the important motivations for their work. Numerical techniques developed over the past two decades are now in daily use and yield good results for periods of from 24 to 48 hours. These techniques involve the simulation of complex atmospheric processes by a mathematical model that combines extensive knowledge of the relevant physical processes with sophisticated mathematics and advanced computer technology.

The physical basis for all numerical simulations of the atmosphere is the conservation of mass, momentum and energy. These conservation principles are embodied in sets of differential equations (Laplace's equation is an example of a differential equation describing heat distribution on a slab), which cannot be solved without a computer. The physical scales of atmospheric phenomena that are simulated on the computer range from the microphysical processes of clouds to the continental motions of frontal systems. At the upper end of the physical scale there are general-circulation models that describe the atmosphere as a heat engine driven by the sun.

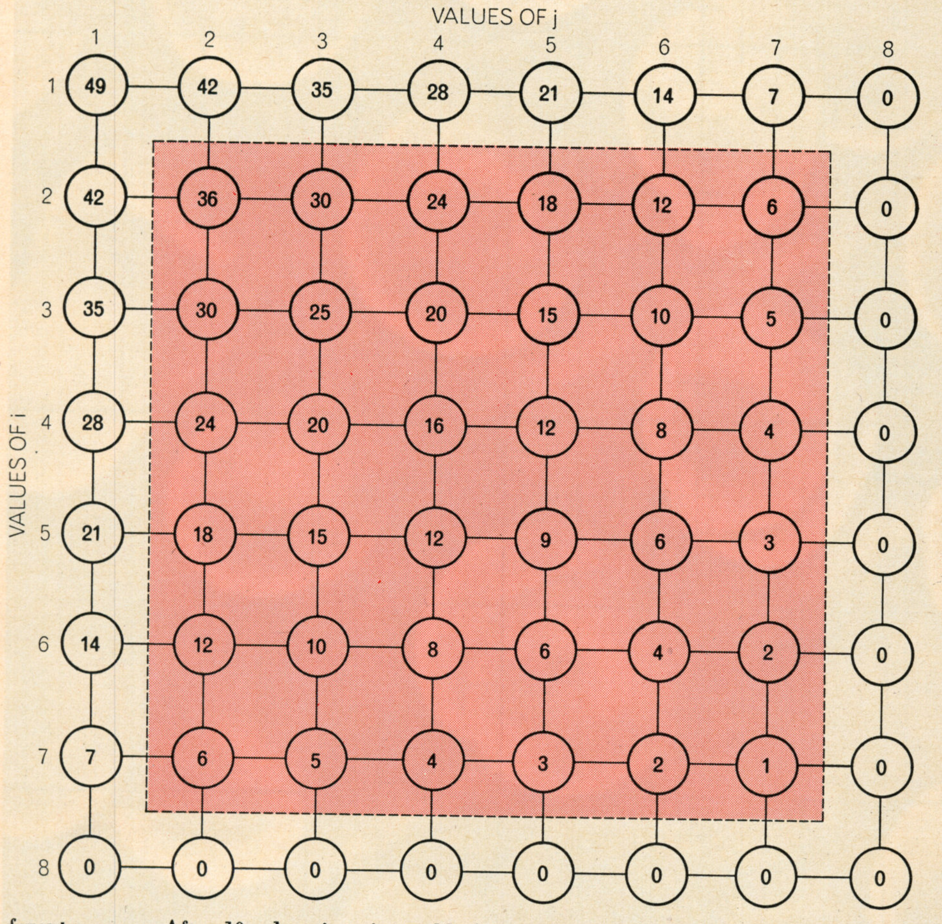
The complexity of these models is illustrated by the operational model of the atmosphere used by the National Weather Service in its daily forecasts. The atmosphere over the Northern Hemisphere is represented by six horizontal slices ranging from sea level to the stratosphere. Each slice contains 3,000 points at which initial values of wind velocity, temperature and pressure are inserted. The computer then applies the appropriate equations to predict what the velocity, temperature and pressure will be in the future at 10-minute intervals. A 24-hour forecast requires about an hour of computing time on a computer that can execute 300,000 instructions per second, or more than a billion instructions in all.

If the distance between the grid points were to be halved, the number of grid points would be quadrupled and the computer time needed for a 24-hour forecast would be increased eightfold. In other words, a third of a day would be consumed merely in making a 24-hour prediction. If the model yields significantly better short-range predictions than the 3,000-point model now in use, there is a good chance that numerical forecasts can be extended to five days with an accuracy comparable to that of the 48-hour forecasts now being generated.

The actual computer techniques of weather forecasting can be advanced by testing them on ILLIAC IV. Until now investigators have been reluctant to experiment with a new predicting technique when it might involve many computer simulations, each of which could take up to 100 hours of computing time. When ILLIAC IV can reduce the running time from 100 hours to one hour, extensive experimentation will become feasible.

Mathematical models exist today for a large variety of physical systems and are in constant use as the basis for calculation aimed at prediction. Biological and biochemical systems have not been modeled with the same intensity of effort or success. There are a number of reasons for this. One can, for example, write a system of ordinary differential equations that might plausibly seem to describe the growth of a living cell. One can even measure initial concentrations with seemingly sufficient accuracy to do meaningful calculation. The number of equations in the system, however, corresponds to the number of genes in the chromosome, which is just too large a number to be handled in the cases of most interest. On the scale of real ecological systems, on the other hand, population models can be developed but measurements are extremely elusive. (How many alewives are in Lake Michigan?) Calculations would have to be performed with statistical variables to estimate a population range for each species of organism. This consumes computational capacity of a higher order of magnitude than deterministic calculation. Even the methodology of such calculation poses significant theoretical problems.

To summarize, I believe computers on the scale of ILLIAC IV will remove some of the very real barriers of capacity from certain calculations that have a direct bearing on our ability to produce a rational and enduring basis for life. Counterpoised is the computer's potential to play a significant role in the depersonalization and disordering of society. Scientists must not share the neutrality of the computer to the outcome.



ferent manner. After 10 relaxations it would obtain values of 34.27 and 27.05 for $U_{2,2}$ and $U_{2,3}$ respectively. The results after 50 relaxations, however, would be virtually the same. For this particular problem the parallel method requires a few more relaxations than the sequential method to achieve comparable results. ILLIAC IV, however, will be able to carry out 36 complete relaxations (and as many as 64 given a suitable problem) in the time that a comparably fast sequential computer would need to carry out one sequential relaxation.