THREE-DIMENSIONAL STRUCTURES were created by a computer using programs developed by Gary Watkins, a graduate student at the University of Utah. The simple "wire frame" version of the interlocking blocks (*top left*) is readily produced because no effort is made to remove hidden lines. By using special programs, however, the hidden lines can be identified and the structure can be displayed as a solid (*top right*). In this case the electron beam in the display tube generates surfaces by a raster technique, point by point and line by line; the entire process takes about a minute per image. To make pictures in color three different black-and-white images are created on the screen, one for each primary color, and then photographed through filters on color film. As the two pictures at the bottom demonstrate, the computer program can also create highlights, as if the pictures were taken with a flashbulb.

COMPUTER DISPLAYS

Pictures "painted" rapidly and accurately by an electron beam under computer control are helping designers and engineers at many tasks. Computer displays can also help to clarify complex physical phenomena

by Ivan E. Sutherland

Whereas a microscope enables us to examine the structure of a subminiature world and a telescope reveals the structure of the universe at large, a computer display enables us to examine the structure of a man-made mathematical world simulated entirely within an electronic mechanism. I think of a computer display as a window on Alice's Wonderland in which a programmer can depict either objects that obey well-known natural laws or purely imaginary objects that follow laws he has written into his program. Through computer displays I have landed an airplane on the deck of a moving carrier, observed a nuclear particle hit a potential well, flown in a rocket at nearly the speed of light and watched a computer reveal its innermost workings.

My interest for some years has been the programming of computers to draw pictures on the face of a cathode ray tube. Obviously computers can produce pictures in other ways, such as by means of mechanical plotters or by printing arrays of symbols, but because the essential problems in creating pictures by computer can be understood by considering images produced by electron beams I shall ignore these other forms of output. I shall also ignore the kinds of computer-driven picture tubes that present modest amounts of text at high speed in such places as airline terminals and brokerage offices; their operation is straightforward.

Computer displays have become of major importance to two groups of people. One group has a pictorial problem in the workaday world for which it would like computer help. These users, for example, may want to shape a metal part on a computer-controlled machine tool; they begin by describing the part to a general-purpose computer, which draws a picture of the part and verifies that the description is accurate. Other users employ computers to produce the intricate high-resolution photographic masks required for making integrated electronic circuits [*see bottom illustration on next two pages*]. Similar pictorial problems in which computers can help arise in highway planning, automobile and aircraft design, topographical mapping, architecture, the layout of publications and the production of clothing patterns. In these and many more areas, written language is far from adequate.

The other group using computer displays is interested in gaining insight into complex natural or mathematical phenomena. These users simulate physical situations of various kinds in the computer and use display devices to present the results of the simulation. For example, an organic chemist may want to synthesize a particular molecule; he creates a picture of the molecule on a display screen and then initiates a program by which the computer presents a selection of simpler molecules from which the desired substance can be synthesized [*see illustrations on pages 72 and 73*]. An engineer designing a communication circuit asks the computer for a graph showing how circuit response varies with frequency. A physician studying how blood flows through the arteries obtains a plot that reveals high vorticity at exactly the locations where the lesions of atherosclerosis are most common. A physicist programs a computer to illustrate how elementary particles interact with their own electric fields to give his students some feeling for quantum-mechanical behavior. A circuit designer draws a circuit and asks a computer to simulate its operation and to plot its performance in a graph of voltage and current. A feedback theorist describes the location of poles and zeros on a complex plane and watches as the computer plots the root locus. A mathematician enters the equations for conformal mappings and observes the maps produced by each equation. A pilot practices takeoffs and landings on a simulated airfield that can assume any orientation on the display screen as he operates "controls" for engine power and aircraft attitude. All these people, interested in educating themselves or others, use computer displays as one of many tools for gaining deeper understanding of a problem.

Two Kinds of Display

Two broad classes of computer-display systems are now in common use: calligraphic displays and raster displays. Calligraphic displays "paint" the parts of a picture on the cathode ray tube in any sequence given by the computer. The electron beam in a calligraphic display is moved from place to place in a pattern that traces out the individual lines and characters that make up the picture. Raster displays make pictures in the same way that television sets do: the image is painted in a fixed sequence, usually from left to right and from top to bottom. The calligraphic display has the advantage that information to be displayed can be stored in computer memory in any order, whereas information for a raster display must first be sorted from top to bottom and from left to right so that it can be put on the screen in the correct sequence. On the other hand, the deflection amplifiers, deflection yokes and other electronic components needed for a raster display are much less costly than those required for a calligraphic display, not only because they need not be so carefully made but also because suitable components are now mass-produced.

57
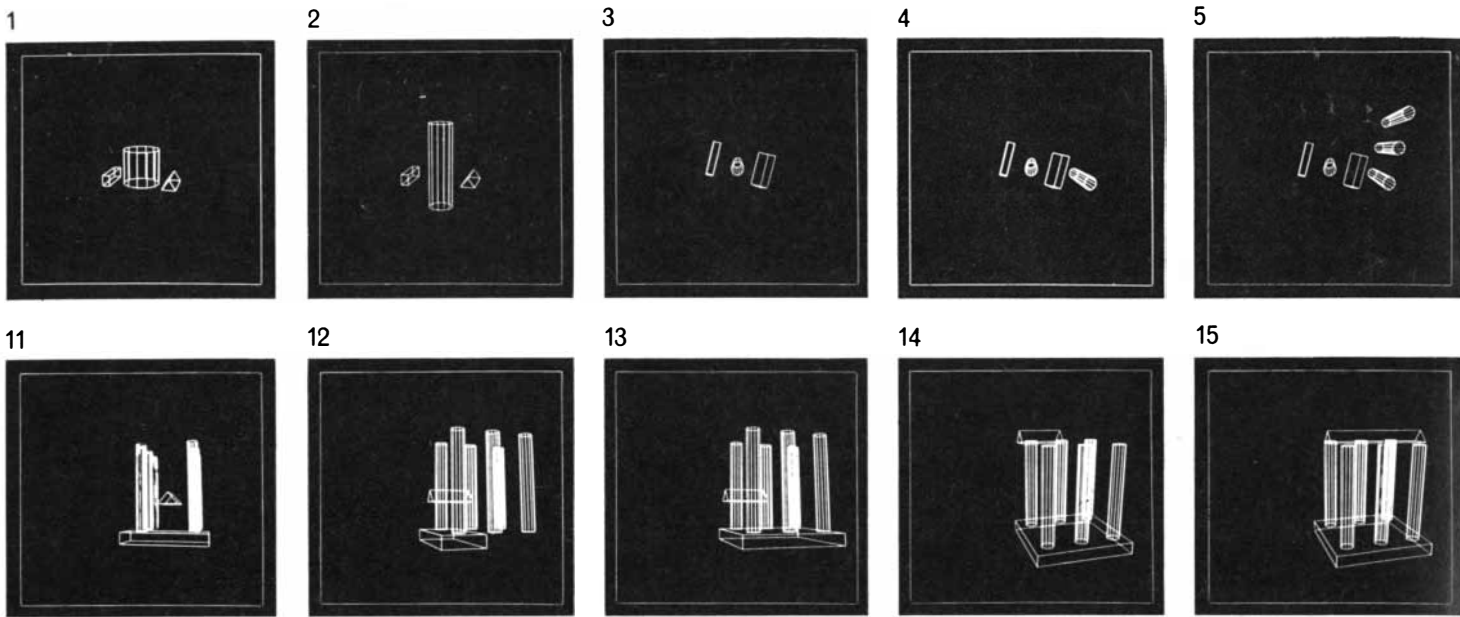
COMPUTER DESIGN OF "GREEK TEMPLE" demonstrates the versatility and speed of present-day graphic displays and computer programs. The sequence was photographed at the International Business Machines Research Laboratory; the computer was an IBM 1130 with a 2250 display unit. The "draftsman" begins by ask- ing the computer to display three geometric solids selected from a library of shapes on file in a disk memory: a hexahedron, a cylinder and a triangular prism (1). The remaining operations are carried out by pressing keys on an "interactive" console that can copy, move, rotate or distort anything placed on the screen. The drafts-

The task of sorting information from top to bottom and from left to right for presentation on raster displays has largely precluded their use for anything but presentations of text. In principle, however, a raster display has the potential of producing pictures with a range of light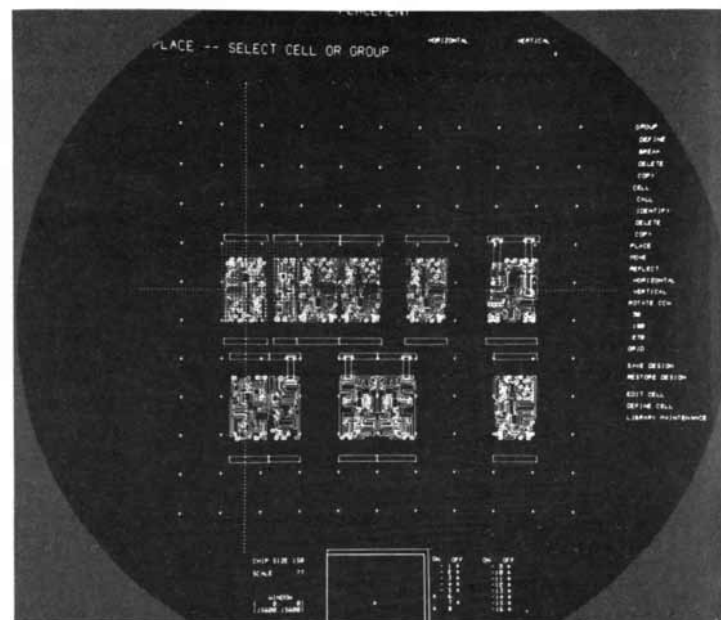 and dark tones, in color if desired, that provide a realism unequaled by the line drawings of a calligraphic display. The potential of this type of presentation can be seen in the pictures on page 56, which were made in our laboratory at the University of Utah by photographing a low-speed simulation of a raster display. I shall describe later some recent algorithms, or mathematical routines, for sorting picture information to eliminate hidden surfaces in making raster displays. I believe such displays will have become a common form of computer output within a very few years.

The information to be projected on the face of a computer display tube is speci-
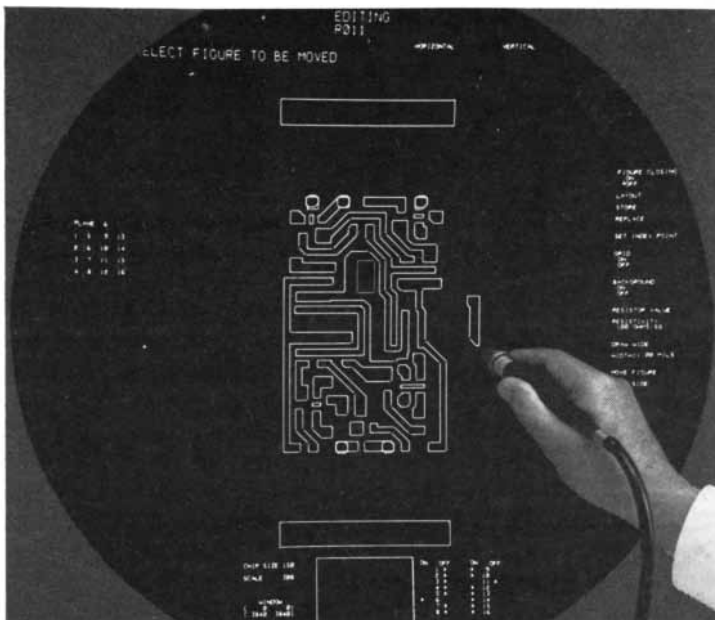
DESIGN OF INTEGRATED CIRCUITS exploits the flexibility and precision now provided by interactive computer displays. This sequence, photographed at Fairchild Semiconductor, was made with a Sanders display unit coupled to an IBM 1130 computer. The goal in this application is to end up with photolithographic masks in which line patterns are located with an accuracy of 50 millionths of an inch. The resolution of the display is defined by a coordinate grid of 1,024 lines and 1,024 columns. The coordinates of the lines drawn on the face of the cathode ray tube are recorded magnetically and then used to control digitally driven machines that cut greatly enlarged versions of the masks. Subsequently the masks are optically reduced in size to the tiny dimensions characteristic of

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man lengthens the cylinder (2) and rotates the three elements to a plan view (3). He then adds five more columns (4, 5, 6, 7). The display is rotated (8) until the columns are viewed at eye level (9). The hexahedron is then moved to a position below the columns (10) and widened (11). The emerging temple is rotated to a side view (12) and the hexahedron is lengthened until it becomes a floor slab (13). The prism is raised (14) and lengthened (15). Again the temple is rotated (16) and the prism is widened to form a roof (17). The finished temple is displayed from above (18). Back at ground level the viewer walks toward it (19) and enters (20).

fied in terms of a coordinate system that covers the tube face. This coordinate system can be thought of as a grid of points that covers the face of the tube even though the grid is not actually etched on the glass. The resolution of the display system can be specified by saying how many rows and columns of points there are in the coordinate system. Most modern display systems have a minimum resolution of 1,024 rows and 1,024 columns and a few systems have four times as many rows and columns. To specify a point on a 1,024-by-1,024 array requires that each x and y value contain 10 binary digits, or "bits" ($2^{10} = 1,024$); to specify a point in a 4,096-by-4,096 array requires 12 bits for each coordinate. Higher resolution is not generally sought because it is difficult to maintain accuracy at higher resolutions and also because the diameter of the electron beam is so large that having higher deflection resolution improves the appearance of

integrated circuits. This circuit will be 150 mils on a side and contain a total of 16 "cells" of seven different types. The pattern in frame 1 is a mask that specifies the location of metal interconnections in a logic cell containing 13 diodes and transistors. In designing the pattern the operator uses a light pen to indicate the two end points of a line segment and the display program automatically completes the line. The pen is also used to move elements around. In this frame the ultimate cell is magnified 308 diameters. In frame 2, at lower magnification (77 diameters), a variety of cells are being summoned up from memory and are being moved into position with the help of grid points. In frame 3 the routing for one level of metal interconnections is being added. In frame 4 the job is done.

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the picture only slightly. Recently, however, workers at the Bell Telephone Laboratories have built a device that uses a very fine laser beam to produce computer-controlled film images with a resolution of 32,000 lines and 26,000 columns. The device is being used to make high-resolution circuit masks [see top illustration on pages 66 and 67].

Although modern calligraphic displays have the ability to post dots, straight lines and text, the earliest display systems could post only individual dots on the screen. The computer specified the x and y coordinate for each dot to be posted. The coordinate specifications were converted from digital form to analogue voltages, which were then amplified to drive the deflection system of the cathode ray tube [see top illustration on page 65]. After the transients in the conversion process and the deflection system had subsided, the electron beam was turned on for a microsecond or so to plot the indicated dot. Characters and lines could be built out of individual dots, but of course not very quickly.

To speed up the process of drawing lines and characters, special analogue circuits have been developed that automatically trace outlines on the screen in a continuous process. To post a character the character-generator circuit produces a wave form for the x and y deflection systems and an associated pattern for turning the beam on and off; the two combined cause the character to appear [see bottom illustration on page 65]. To post a straight line on the screen, the analogue line generator will produce coordinated "ramp" wave forms for the x and y deflection systems so that the electron beam moves smoothly and continuously from one end of the straight line to the other. Modern display systems can produce characters in about five microseconds each and straight lines in three to 40 microseconds, depending on length. Some display systems include analogue equipment for producing simple curves, such as circles, automatically, but such facilities are still rare.

To produce a straight line all the way across a display screen in 40 microseconds is a prodigious feat of electrical engineering. The human eye has a remarkable ability to detect even slight deviations from straightness. Moreover, if two lines are plotted end to end, any error in their length such as might be produced by overshooting or a failure of the electron beam to be turned on promptly will show up either as an overlap or as a gap in the lines. The lines must be traced not only straight but also at a constant rate because any change in the beam's rate of motion will show up as a change in the brightness of the line. To be sure, one can compensate for changes in the writing rate of the line by changing the electron-beam current, but such a compensation circuit must be accurate or discrepancies will be visible. No display system that I know of is entirely satisfactory in performance, and even the best need periodic tuning to keep operating well. Considering the difficulty of the task, it is amazing that the systems work at all.

The Logic of Displays

In addition to the analogue circuits for generating lines and characters, a computer-display system must incorporate digital logic circuits to connect the display to the computer. Because the logic needed for this purpose often has characteristics in common with the processing unit of a computer, I have come to call these digital circuits the display processor. The display processor fetches information from a memory where the picture to be posted is defined and converts it to the elementary driving signals for the analogue circuits that generate lines and characters.

The display processor interprets different formats of information in the memory to give them meaning in terms of the picture produced. For example, it may interpret sequences of characters to produce rows of text on the screen, or it may distinguish sequences of connected line segments from isolated line segments, in each case producing the individual commands required by the analogue line generator to yield the desired picture. The display processor accounts for more than half of the cost of many display systems and strongly af-
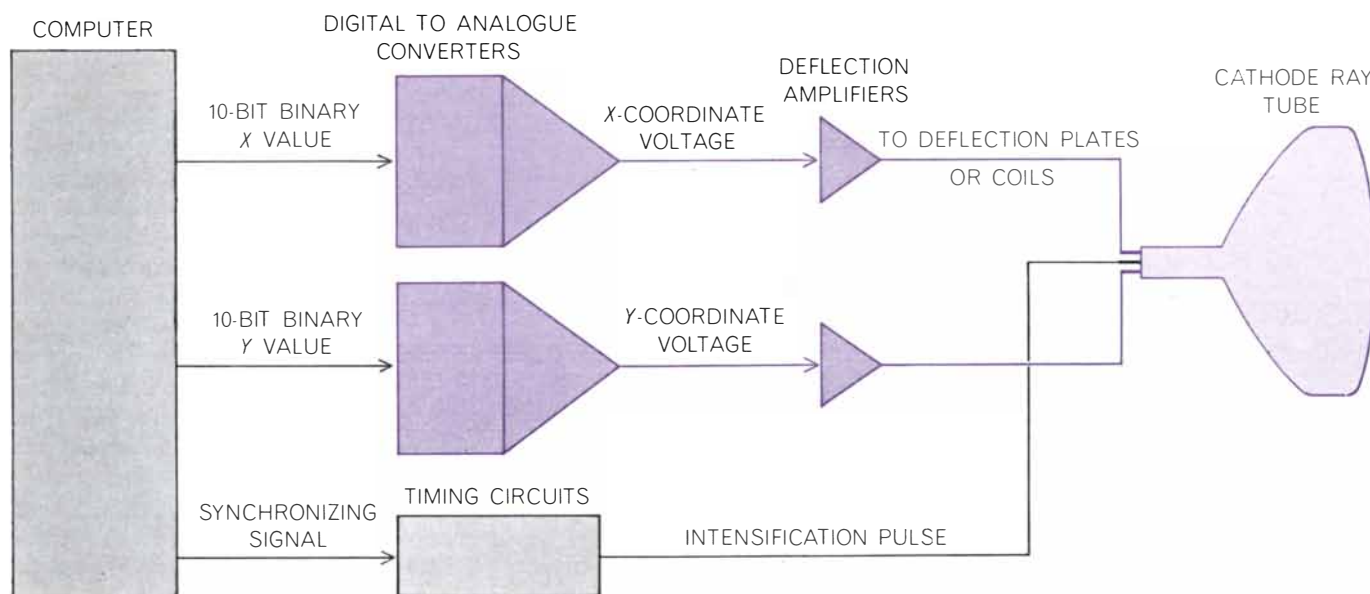
COMPUTER DISPLAY EQUIPMENT consists basically of a digital computer, which specifies the point-by-point coordinates of the desired display, together with circuits that convert the digital output into analogue form for deflecting the electron beam in a cathode ray tube. If the values of x and y are each specified by 10 binary digits (0's and 1's), the electron beam can be directed to any point in an array consisting of 1,024 lines (the y axis) and 1,024 points per line (the x axis). With only the circuits shown here, the image on the screen would have to be built up from discrete points. More modern displays include analogue function generators to sweep the electron beam in a continuous fashion to generate smooth lines, numbers, letters of the alphabet and special symbols.

The sun breaks through a winter overcast to light the undercast of the New York metropolis.

RYSZARD HOROWITZ

The September issue of **SCIENTIFIC AMERICAN** will be devoted to

the single topic of

TECHNOLOGY AND THE ENVIRONMENT

under the title of

THE BIOSPHERE

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fects the programming techniques that must be used with the system. Moreover, not much progress has been made in standardizing the design of display processors. For these reasons prospective users must carefully weigh the characteristics of competitive systems.

For the past six or seven years my own professional interest has been in improving the design of display processors. My colleagues and I have designed or influenced the design of a series of display processors of increasing complexity. Although we know that the evolution of display-processor design is far from complete, we have learned much about how the design of a display processor interacts with the programming requirements for the display system. Like computer systems themselves, displays require a great deal of programming to make them useful; enlightened display-processor design simplifies the programming task.

The objective of most computer-graphics programs is easily stated: to represent objects of some kind and to provide a means for manipulating them. For example, if one is designing the mask for an integrated electronic circuit, the objects to be represented are the transistors, resistors, gates, wiring and other elementary components from which the circuit is to be built. In depicting an organic molecule the objects to be represented are the individual atoms of the molecule and the bonds between them. In each application the objects are represented in the memory of the computer in a format suitable to the application. For instance, it may be convenient to list the atoms one after another in a table, giving the type and the three-dimensional coordinates for each atom. It may be convenient to represent the bonds by listing each bond in a table with the index numbers of the two atoms it joins. Such a storage format is convenient not only for display but also for the scientific programs that will manipulate this "data base."

The data base for a computer-display application is utilized in many ways. If the user wants to change the program he is working on, he may give commands that cause the computer to change the data base by replacing, adding or deleting information. Thus the user might add a new atom to his molecule. If he is exploring some line of thought, he may ask that computations be done on the data base. For example, the computer might compute the total weight of the molecule represented, or it might compute new coordinates for the atoms corresponding to some quantum-mechanical law the user is trying to understand. Finally, the user

will want to see some pictorial representation of the data base on his computer-display system. It is important to note that the pictorial representation of the information in the data base is only one of many ways the information is used.

The Data behind the Display

The format of the information in the data base is not usually suitable for direct use by the display processor. The data base represents all the relevant facts about the objects being considered, whereas the display processor needs information about the particular appearance of the objects. For instance, the data base may distinguish among different types of chemical bond, all of which look the same on the display. Or the data base may identify different kinds of atoms according to their atomic number, whereas in the display they are

to be presented with a different code letter, such as C or H or N. The appearance of the objects can be derived from the data base by a suitable program and stored for use by the display processor. The results of this computation form a "display file" [see bottom illustration on next page]. The display file is a secondary representation of the objects stored in the data base.

Conversion of the information from the data base to the display file involves geometric computation, selection of the relevant information and expansion of compact notations into individual lines and characters for display. Thus the two-dimensional coordinates required to make a perspective presentation of the molecule from a selected viewpoint might be computed from the three-dimensional coordinates known for each atom. If a magnified view of some portion of the object is desired, it can be
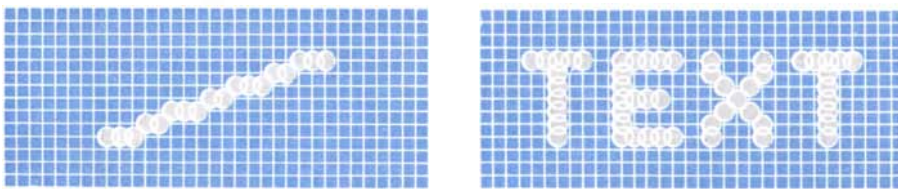
DOT-BY-DOT method of generating lines and characters was originally used in computer graphics. Newer analogue techniques are much faster and create cleaner images (see below).

READY FOR
NEXT CHARACTER
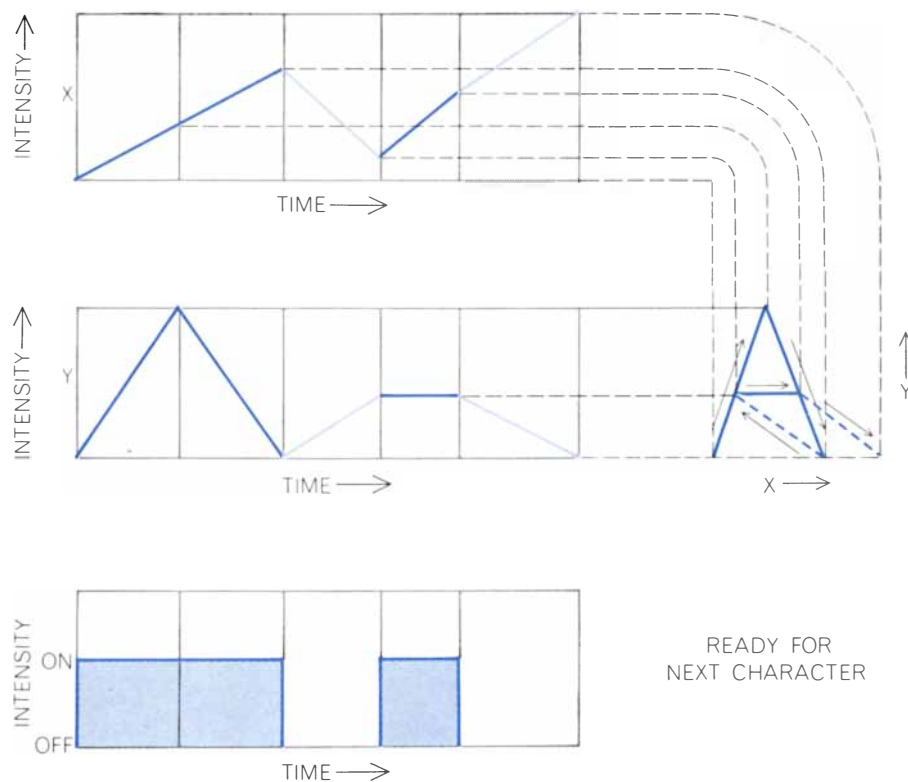
ANALOGUE CHARACTER GENERATOR produces separate wave forms for the x and y deflections of the electron beam, along with an on-off intensity pattern. Such display systems can write a character in a few microseconds and a page of text in several milliseconds.

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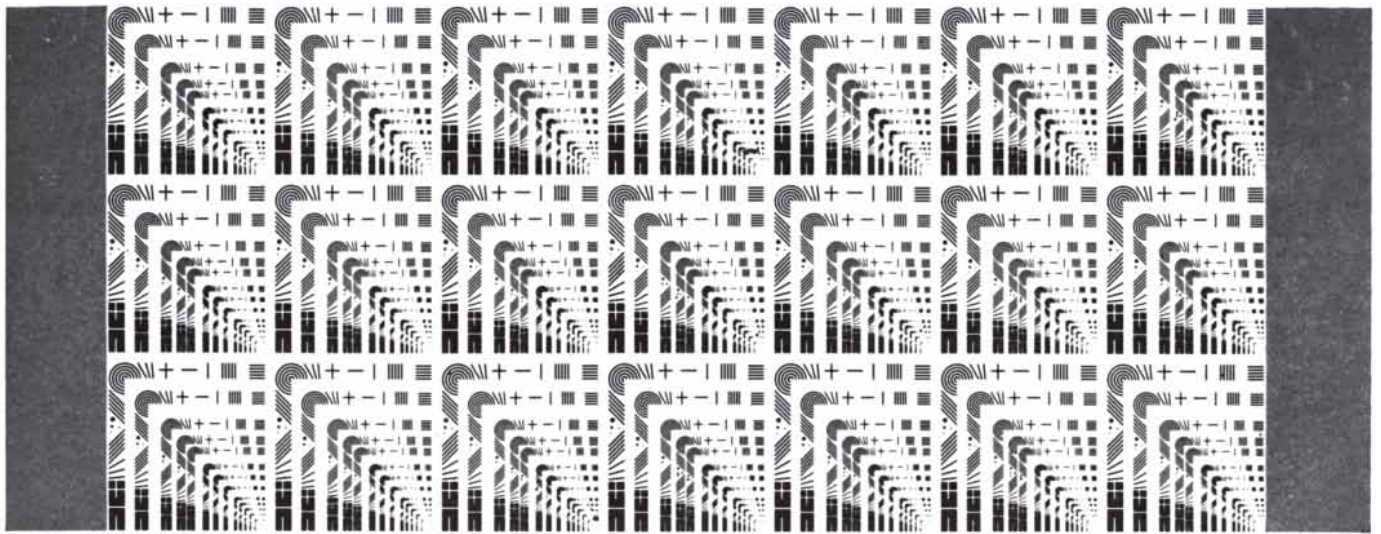
HIGH-RESOLUTION LASER BEAM produced this test pattern using a new computer-display technique developed by the Bell Telephone Laboratories. One-third of the 15-by-21-centimeter test pattern is reproduced here actual size. Normally the device is used to make masks for integrated circuits. Modulators and lenses control the fine beam of an argon laser, which is deflected to scan a photographic plate by a 10-sided mirror rotating on air bearings. The laser beam produces an image consisting of 32,000 scan lines with 26,000 image points per line. The accuracy of the beam can be controlled to better than one arc second, equivalent to a deviation of less than a third of an inch in a line a mile long. Not only is the device extraordinarily accurate but also it can produce

provided by geometric scaling as the display file is prepared. Particular items of information in the data base can be selected for display or omitted entirely. For example, it may be desirable to omit from the picture all hydrogen atoms and all bonds connected to them so that the heavier part of the molecule can be seen more clearly. Finally, the compact notations of the data base can be expanded into appropriate symbols on the screen. Each atom might be converted into a circle with a letter in it; each bond might be converted into a pair of lines (in perspective, if that is desired).

It has long been recognized that the dual representation commonly used in display applications—the data base and the display file—leads to a complex program. In many display systems the user can point to an object of interest on the screen by using a light pen, a device that identifies a specific point on the screen by producing a brief pulse when the electron beam sweeps past that point. This tells the computer that some object in the display file is to be changed. The
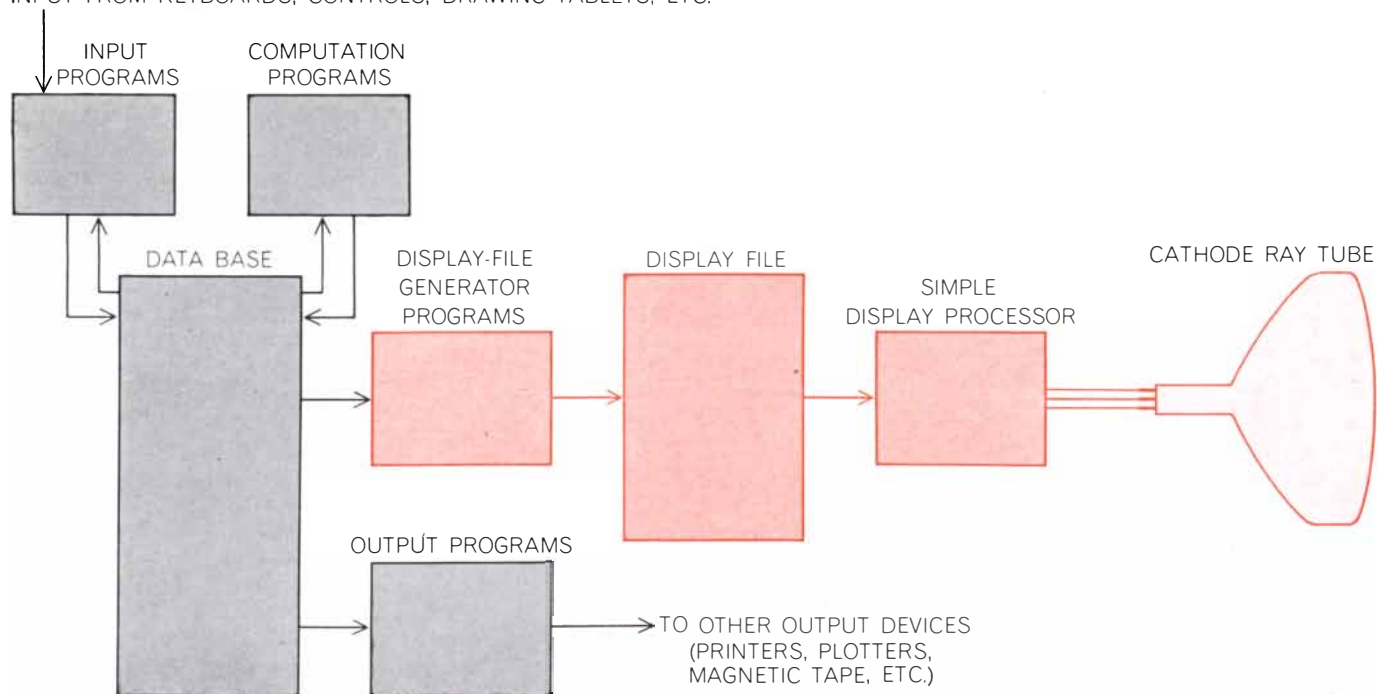
TYPICAL PROGRAM STRUCTURE for computer displays has the form shown here. Information about objects is stored in the data base. Information about the appearance of the objects is stored in the display file. The actual appearance of the objects is specified by programs in the display-file generator. These programs perform geometric operations and expand the definition of objects.
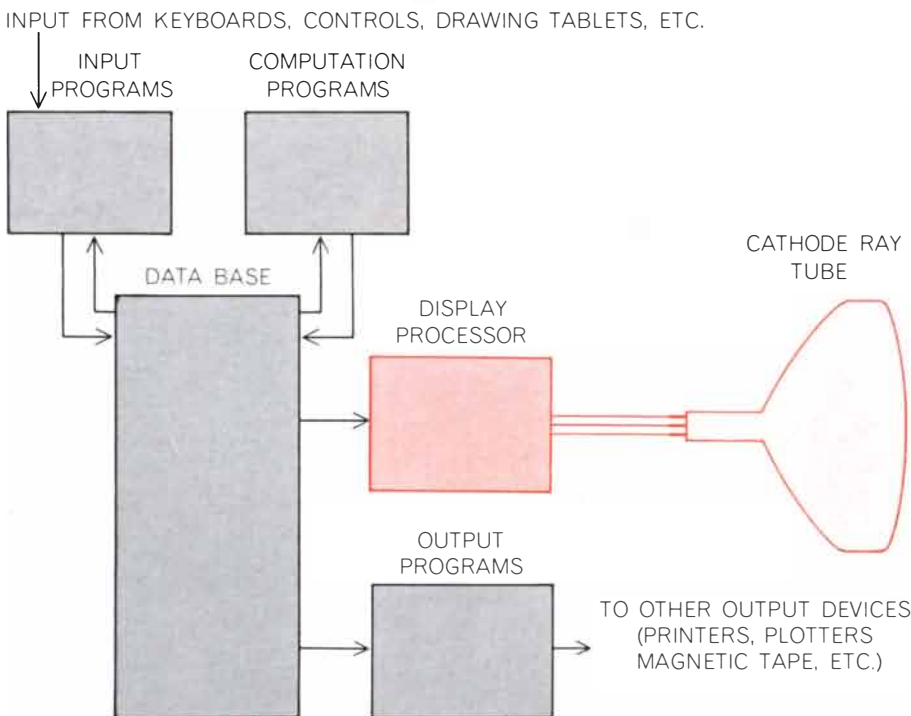
66
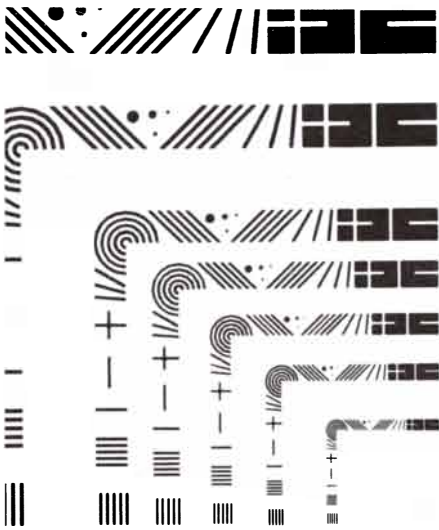
in 12 minutes a circuit mask that formerly took 12 hours of machine time. A portion of the test pattern is enlarged 10 diameters at the right. The effective resolution exceeds 40 lines per millimeter, which is remarkable over a field measuring 15 by 21 centimeters.

computer must somehow be able to relate each item in the display file to the item in the data base that caused it to appear.

If, having identified the item in the data base, the computer is instructed to change it, the computer must then also change the relevant parts of the display file. If the display picture is to be kept up

to date so that changes appear promptly after they are initiated, computation of the display file must be done quickly. Unfortunately general-purpose digital computers are not well suited to this kind of geometric computation. For all these reasons designers of display processors have begun to provide more computing capability in the display processor to enable it to interpret the data base directly, thus eliminating the need for a display file altogether [see illustration below]. If the design is successful, changes in the data base will instantly be reflected in the picture and an identification of a part of the picture will instantly identify the corresponding item in the data base. Specialized display processors designed to handle such graphical computations are now beginning to reach the market.

An early innovation in display processors, now almost universal, provided them with the ability to display many symbols from a single symbol definition in memory. With this capability the display file can contain a single definition of a transistor symbol and several references to that symbol's definition. For each reference the display processor fetches the individual lines of the symbol from the single definition and traces the transistor symbol again in a different position on the display screen [see "a" in illustration on page 79]. Obviously all coordinate information in the symbol is

INPUT FROM KEYBOARDS, CONTROLS, DRAWING TABLETS, ETC.

INPUT PROGRAMS

COMPUTATION PROGRAMS

DATA BASE

DISPLAY PROCESSOR

CATHODE RAY TUBE

OUTPUT PROGRAMS

TO OTHER OUTPUT DEVICES (PRINTERS, PLOTTERS MAGNETIC TAPE, ETC.)

ADVANCED DISPLAY PROCESSOR eliminates the display file and display-file generator by providing more powerful computation and selection functions. This simplifies programming by eliminating elaborate cross-references between the data base and the display file.

67
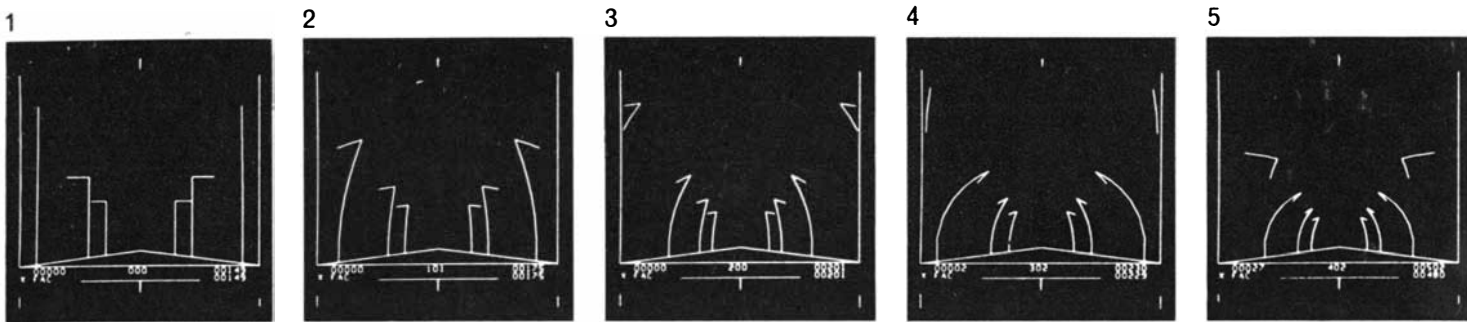
RIDE IN "ROCKET CAR" down a "country road" was programmed by a group under Judah L. Schwartz at the Massachusetts Institute of Technology, which has found computer displays valuable in demonstrating abstruse physical phenomena. The road is lined with telephone poles shaped like inverted *L*'s. The middle number under the picture shows the rocket's velocity as a decimal fraction of the velocity of light (the decimal point before the first digit is omitted). The number at bottom left of the screen is the number of telephone poles passed. The upper number at bottom right is the reading of clocks by the side of the road; the lower number shows the time aboard the rocket. The rocket-borne clock shows a lower cumulative reading than the roadside clocks do,

stored with respect to the location of the symbol, and the location for the symbol must be established before the symbol definition is called on. This symbol capability in display processors is identical with the subroutine capability found in all general-purpose computers. Like the subroutine capability, it makes possible more compact coding because many symbols can be created from a single definition.

Unfortunately including subroutine capability in the display processor tends to introduce new complexities in the display programming. A display processor capable of handling subroutines must remember during the execution of each subroutine the location of its call; if the display file is changed, such information may be lost. Moreover, the number of parameters that can be provided to display subroutines is generally limited to a simple indication of position. Symbols of different sizes must have different definitions in the display file even though the size of an object may be represented in generalized form in the data base. The display file for a processor equipped for subroutining takes on a structure that may correspond in part, but not entirely, to the structure of the data base, and the display-programming system has to decide when to call on this structure. The subroutining capabilities in the display processor prove most useful when the structure that the display processor can interpret is sufficiently rich to represent everything wanted in the data base. If the symbol parameters available in the subroutining capability cannot handle the variability of the symbols represented in the data base, it is often not worth the effort of using the subroutining capability at all.

The fact that information in display subroutines can be specified with respect to a symbol origin makes it possible to specify a position that is outside the boundary of the display screen. Unfortunately a capacity of only 10 or 12 "bits" of information is usually provided in the memory registers that hold the screen coordinates. Thus if the displacement of an image produces values that lie outside the screen, those values will be truncated to the required 10 or 12 bits by the removal of the most significant parts of the sum.

The "Windowing" Problem

The effect of such truncation is that the coordinate positions immediately beyond the right edge of the screen appear at the left edge of the screen, and the coordinate positions just above the top of the screen appear at the bottom of the screen. Symbols that overlap an edge of the screen will reappear at the opposite edge. Consequently if screen coordinates are merely truncated to 10 or 12 bits, the screen will appear to have
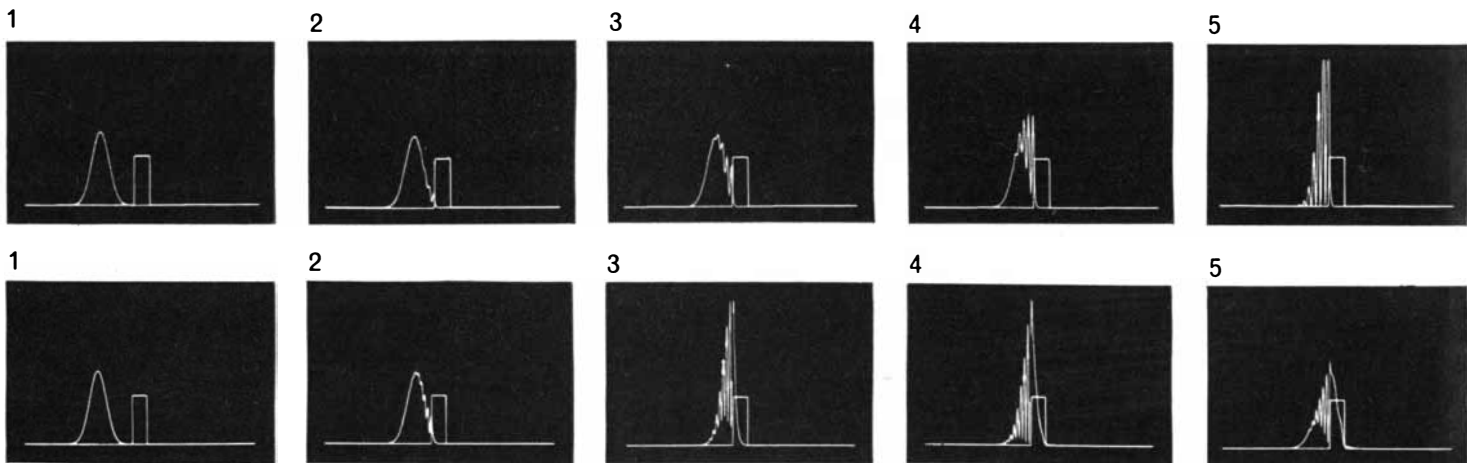
QUANTUM-MECHANICAL SCATTERING, representing what happens when a particle of given energy meets a barrier, is depicted in these M.I.T. computer displays. The particle is represented by a Gaussian curve, or wave packet, which is the probability distribution for finding a particle, such as a proton, in a given region of space. In the upper sequence the particle has only half the energy needed to pass through a square barrier. Nevertheless, at the peak of the collision (*frames 5, 6*) the wave packet penetrates the barrier, thereby indicating a finite probability for finding the particle in a region that should be inaccessible to it according to

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| 6 | 7 | 8 | 9 | 10 |
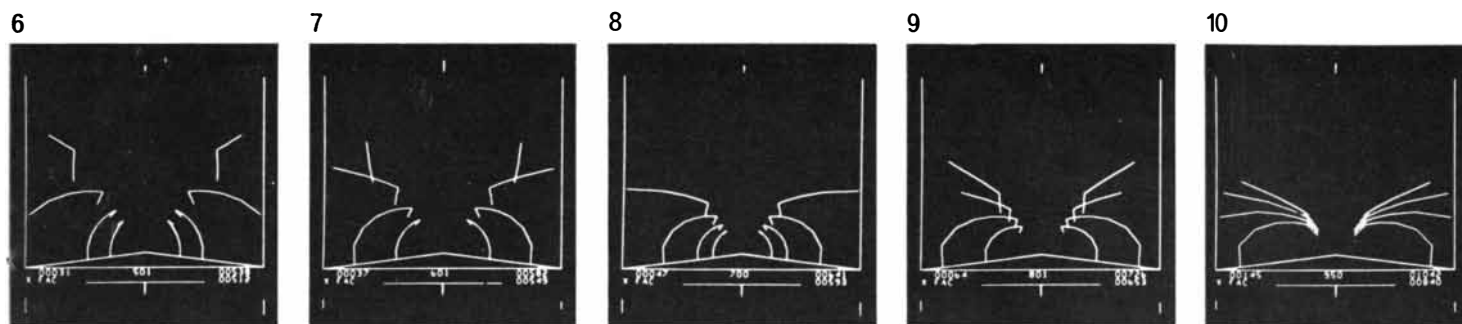
demonstrating the dilation of time experienced by objects (and observers) traveling at a large fraction of the velocity of light. As the rocket car accelerates, the telephone poles appear to bend over the road, as viewed by an observer in the car. Actually they are leaning away from the observer because the tops of the poles are farther away from him than the bottoms of the poles and thus light from the tops takes slightly longer to reach his eye. Therefore he sees the top of each pole at an earlier point in time, hence farther down the road, than the bottom of the pole. The horizontal members atop the poles appear to rotate away from the observer and finally to bend down. This is a more complicated result of the special theory of relativity and was not put into computer program.

the topology of a torus. The phenomenon is particularly annoying if one end of a short line moves off the edge of the screen only to reappear at the other edge. The line between such end points will cross the entire screen going in the wrong direction.

The cures for these well-known difficulties all provide the display user with a drawing area much larger than the actual display screen. By one means or another the display tube is made to behave as if it were a window through which this much larger drawing can be seen. The computations involved in providing this illusion are called windowing. When properly provided, windowing seems to be a natural part of the way the display operates. Objects that move off the screen disappear smoothly at a well-defined edge. Only when windowing is missing from a computer-display system is the absence of this feature immediately evident.

There are two basic methods of windowing. One method is to provide the display system with larger analogue deflection voltages than are needed for covering the screen itself and simply to blank out the beam anytime it is deflected beyond the edge of the screen. This procedure, although it is widely used, has the shortcoming that it places an additional burden of accuracy on the analogue deflection system and that it must of necessity operate slowly, since there is no way to speed up the beam when it is drawing parts of the picture outside the viewing area. The second method of windowing is to provide a mechanism to precompute digitally the actual coordinates of the part of the picture that should appear in the window. In this method the display tube is provided only with valid data and so does not waste time drawing invisible parts of pictures. This alternative, often called clipping, is widely programmed in software for sophisticated computer-graphics systems.

Windowing is the most important of several kinds of geometric computation needed in preparing information for presentation on a display screen. Unfortunately the programs required for windowing in an ordinary general-purpose digital computer, even a big and fast one, can process only about 1,000 line segments per second. If additional computations are needed, for instance to present a two-dimensional perspective view of a three-dimensional object, the operation takes substantially longer. Recently my colleagues and I have spent much time developing special display processors that overcome these delays by transferring the necessary computations to high-speed, special-purpose digital circuits. These processors make it easy to obtain rapid, dynamically changing views of three-dimensional objects [see *top illustration on next two pages*].

| 6 | 7 | 8 | 9 | 10 |

| 6 | 7 | 8 | 9 | 10 |
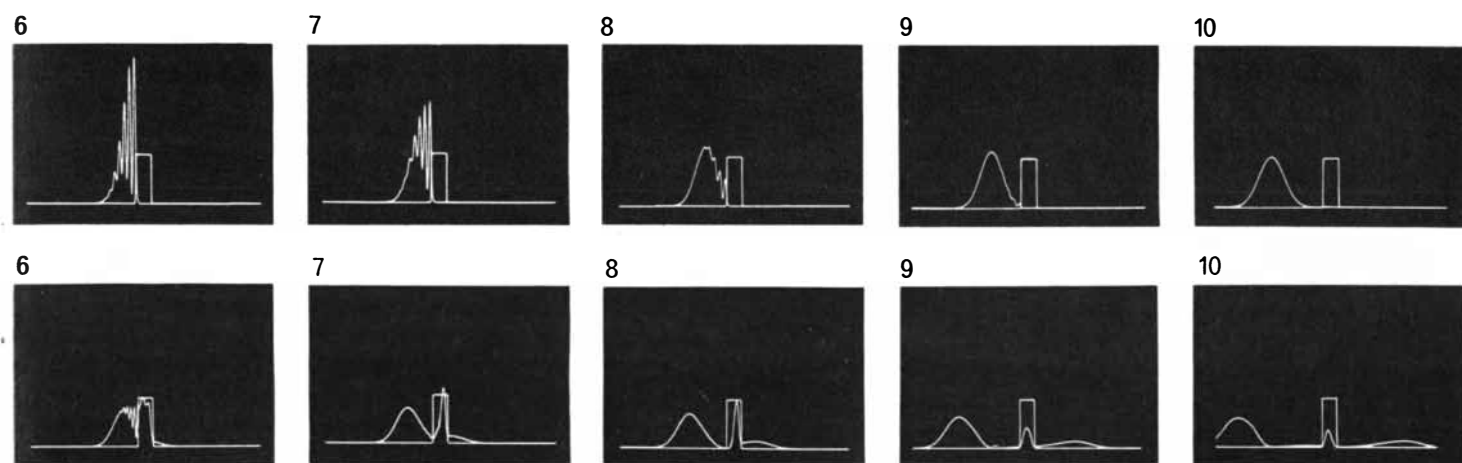
the pre-quantum-mechanical description of nature. Subsequently the packet is reflected and the probability distribution is flattened. In the lower sequence the energy of the wave packet is exactly equal to the barrier height. In classical physics the particle should lose all its energy on entering the barrier and remain there forever. In quantum physics a small probability packet gets temporarily trapped inside the barrier (*frames 7, 8, 9, 10*) while most of the packet is reflected. In addition a small, flat packet is transmitted. This indicates the probability of a particle's "tunneling" through the barrier when the experiment is repeated many times.

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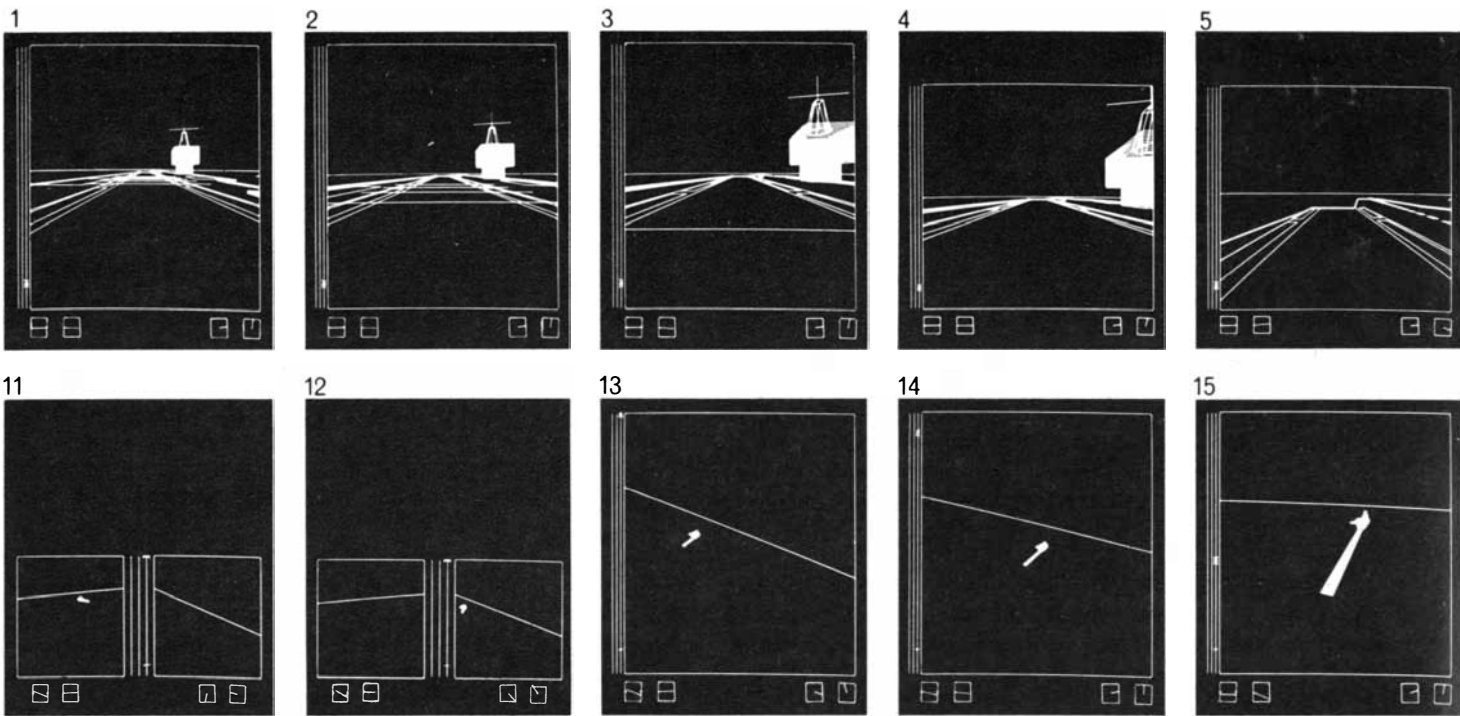
TAKEOFF AND LANDING ON AIRCRAFT CARRIER have been simulated by the Evans & Sutherland Computer Corporation for the Naval Training Device Center. The display system used for this demonstration is installed at Bolt, Beranek and Newman Inc. It follows the design illustrated at the bottom of page 67, in which circuit hardware in the display processor replaces a "software" program for handling information stored in the data base. Only such a system provides the computing speed needed for this kind of real-time simulation in which two complex objects are moving rapidly in three-dimensional space. Frame 1 shows what the "pilot" sees looking down the deck before takeoff. Through a keyboard on the computer he can adjust the engine throttle and the attitude of the aircraft. At the left of the screen is a vertical line with a cross that indicates the aircraft's altitude. The two boxes at the bottom right

I became involved in the development of such high-speed displays through a desire to present an observer with a simulated three-dimensional environment. My idea was very simple: Mount miniature cathode ray tubes on the user's head, one tube in front of each eye, so that the computer can control exactly what he sees. Measure the position of the user's head and compute a perspective picture appropriate to that viewing position. As the user turns his head, the perspective picture should change just as if the object portrayed were really in the room with him. There is no need to measure his eye position because the picture presented on his glasses is not changed by the part of it on which he chooses to focus. Because the three-dimensional objects he sees will appear to remain stationary in space as he moves around
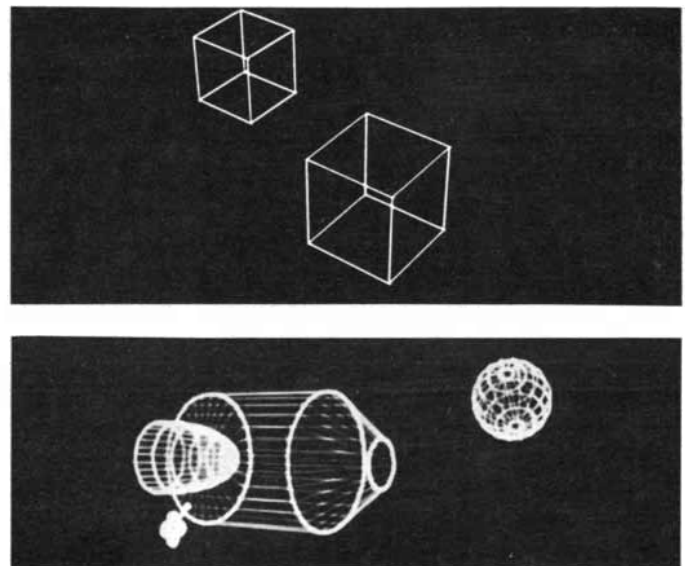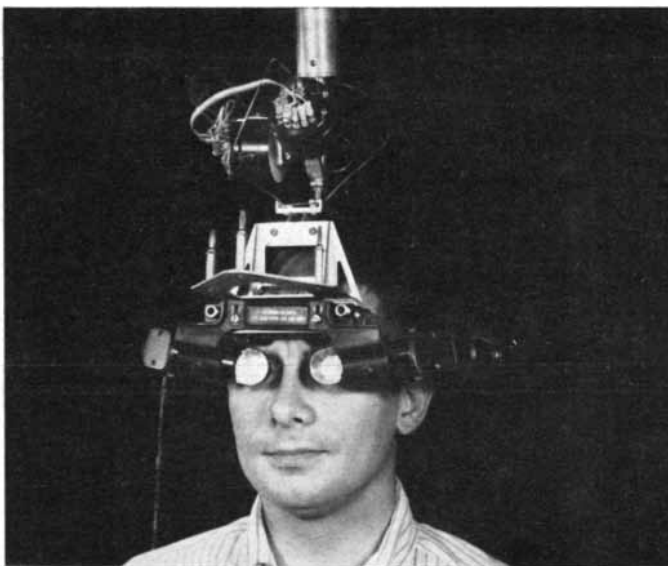
HEAD-MOUNTED DISPLAY at the University of Utah employs a display processor similar to that used for the aircraft carrier sequence. Two miniature cathode ray tubes are built into the goggles. A mechanical linkage tells the computer where the viewer is looking at each instant. The display processor instantaneously supplies the correct image for each head position. The viewer is free to look anywhere in a 360-degree circle and can look up and down through an angle of about 45 degrees. Two samples of what he sees are shown at the right. The objects grow larger or smaller and move with relation to one another as the observer moves around.
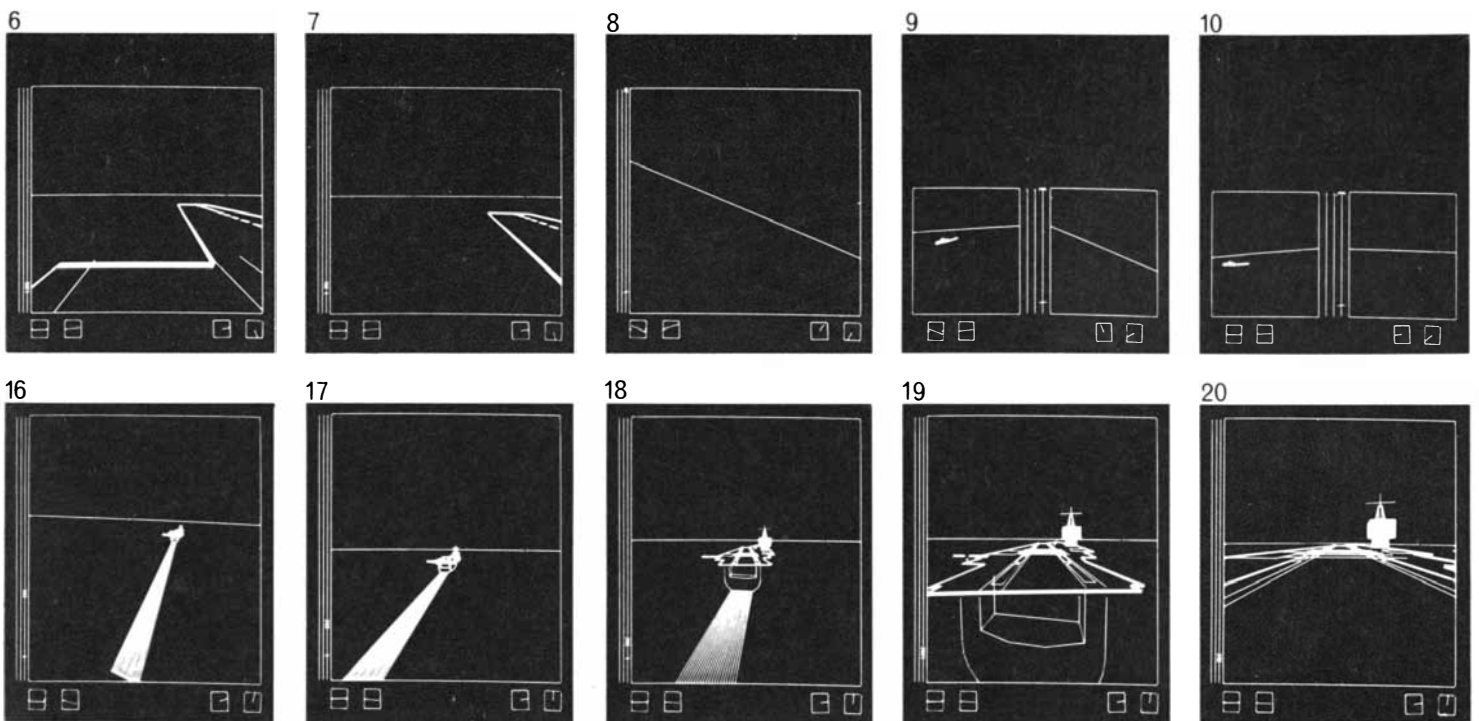
of the screen indicate the aircraft's compass heading (east at take-off) and the direction to the carrier's superstructure. At bottom left are an artificial horizon and a rate-of-climb indicator. Frames 2 through 7 show the aircraft moving down the deck and becoming airborne. The pilot sees the horizon tilt (8) as he banks to the left. In the next four displays (9, 10, 11, 12) the view from the left window of the aircraft is shown on the left half of the screen while the view ahead appears on the right half. Ordinarily the two windows are on separate screens in their normal relation to the pilot. As the pilot continues to bank, the carrier disappears from the left window and reappears in the front window (12, 13). Still flying counterclockwise in a large circle, assisted by being able to see the carrier's wake, the pilot lines up the carrier for his approach (14, 15, 16, 17), and then finally levels off for a perfect landing (18, 19, 20).

them, an illusion that the objects are present in the room with the observer should be created. The equipment illustrated at the bottom of the opposite page was designed to create this illusion.

The head-mounted display does indeed provide the illusion of seeing three-dimensional objects at identifiable locations in the user's environment. Because the objects presented are transparent and made of glowing lines essentially free of texture, no one is fooled into thinking they are real. On the other hand, even naïve observers are able to identify the size of the objects portrayed and are able to move themselves into an appropriate viewing position to examine a particular feature of the objects portrayed.

Logic of High-Speed Displays

The significant thing about the head-mounted display project is not the operational results but rather that it forced us to think carefully about the problems of presenting a real-time perspective picture. We needed a solution to the windowing problem in three dimensions because as the user turns his head away from objects they move out of the field of view provided by the optical system. If the objects are to move smoothly out of view, the correct end points for the parts still in view must be very rapidly computed, and prompt decisions must be made in order to omit parts that are entirely out of view. Since no general-purpose digital computer is capable of doing these computations fast enough to present dynamic views of any but the most trivial objects, we were forced to design and build special-purpose equipment to do rotation, windowing and perspective computation. Having a good solution to the windowing problem in three dimensions quickly led us to a solution in two dimensions for our latest design for a display processor.

Computing a perspective picture of a "wire frame" three-dimensional object is really rather easy. The position of each part of the object on the screen is computed by projecting the object onto the screen in straight lines [see top illustration on page 74]. Fortunately straight lines in three-dimensional space project into straight lines on the screen. Thus the rotation and projection computations for each line segment need be done only for the ends of the line; the center parts of the line can be filled in by the two-dimensional analogue line generator. If windowing or clipping in three dimensions is done before projection, the problems of dividing by a zero or a negative depth coordinate are avoided [see bottom illustration on page 74]. The digital processing equipment we developed for the head-mounted display project is able to accept information in three dimensions, convert it to an appropriate viewpoint and viewing direction and present valid display-screen coordinates to an ordinary line generator for drawing a perspective picture on the screen.

We have found it particularly useful to have a display system in which a three-dimensional computing engine is built into the display processor. In the first place, coordinate information for display can be in three dimensions instead of in two. Symbols can be scaled on the drawing as well as merely being positioned, and three-dimensional symbols can be rotated to any desired angle with respect to other objects in the drawing. Since clipping is done in the display processor, the processor can accept the stored data to a resolution much finer than the actual resolution of the display itself. Such data can be regarded as a drawing on a huge piece of paper (a piece covering a square mile, say), any part of which, or all of which, can be presented on the display screen. For many applications such capabilities can eliminate the need for a display file altogether and so greatly simplify the programming of the display. Again our hope is to operate the display

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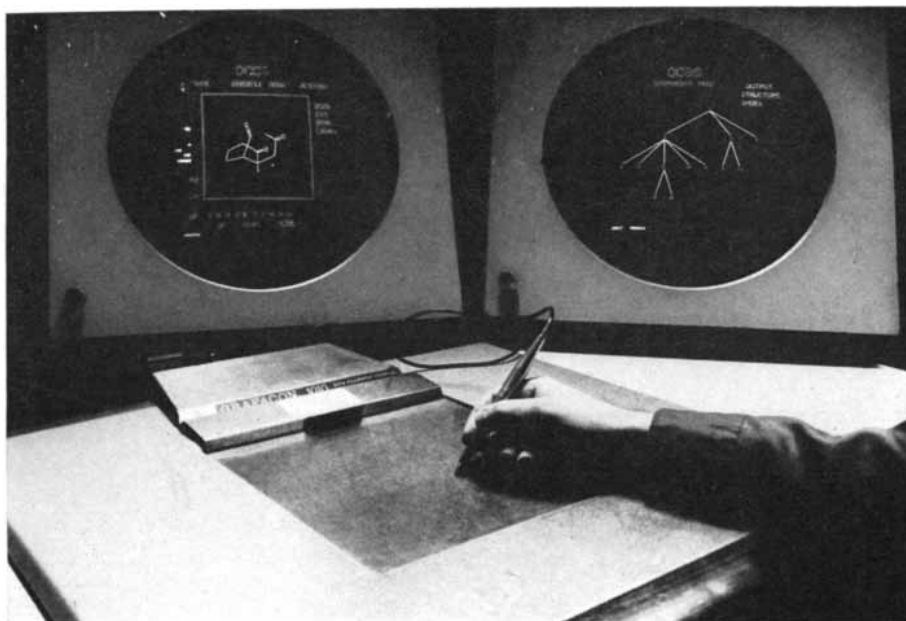
COMPUTER-AIDED CHEMICAL SYNTHESIS program was developed at Harvard University by W. Todd Wipke under the direction of Elias J. Corey. The computer is supplied with a library of chemical compounds and chemical reactions, together with a program for manipulating this information. By interacting with the computer the chemist can select the most efficient way to synthesize a desired compound. The chemist starts his "conversation" with the computer by drawing the structure of the target molecule on a writing tablet. The tablet contains a coordinate grid that relays the position of the pen to the display screen. Here a molecule related to the target molecule appears on the screen at the left, while the screen at right displays a variety of chemical pathways to the target in the form of a "tree." The development of these displays is depicted in the pictures at bottom of these two pages.

processor directly on the data base so that changes in the data base are instantly reflected in the display.

To provide for flexibility in the format of the data bases, we have chosen four typical forms in which information commonly appears in applications [see illustration on page 79]. In the first form a sequence of coordinate values is simply connected by a sequence of straight lines. This form is the common one for connecting data points on a graph. In the second form disjoint lines are represented by pairs of pointers that indicate the location of the coordinate data to be used for the end points. This format would be useful for representing the bonds in a molecule. The coordinates can be either two- or three-dimensional. The disjoint-line format is useful in a variety of pictorial representations.

The third form is the simple subroutine, where standard format parameters for position, size and rotation are provided. For all fixed-geometry symbols, such as those used in making circuit diagrams, this form is adequate. We have also designed the display processor so that it does not execute any subroutine that is entirely outside the viewing area. This provision greatly
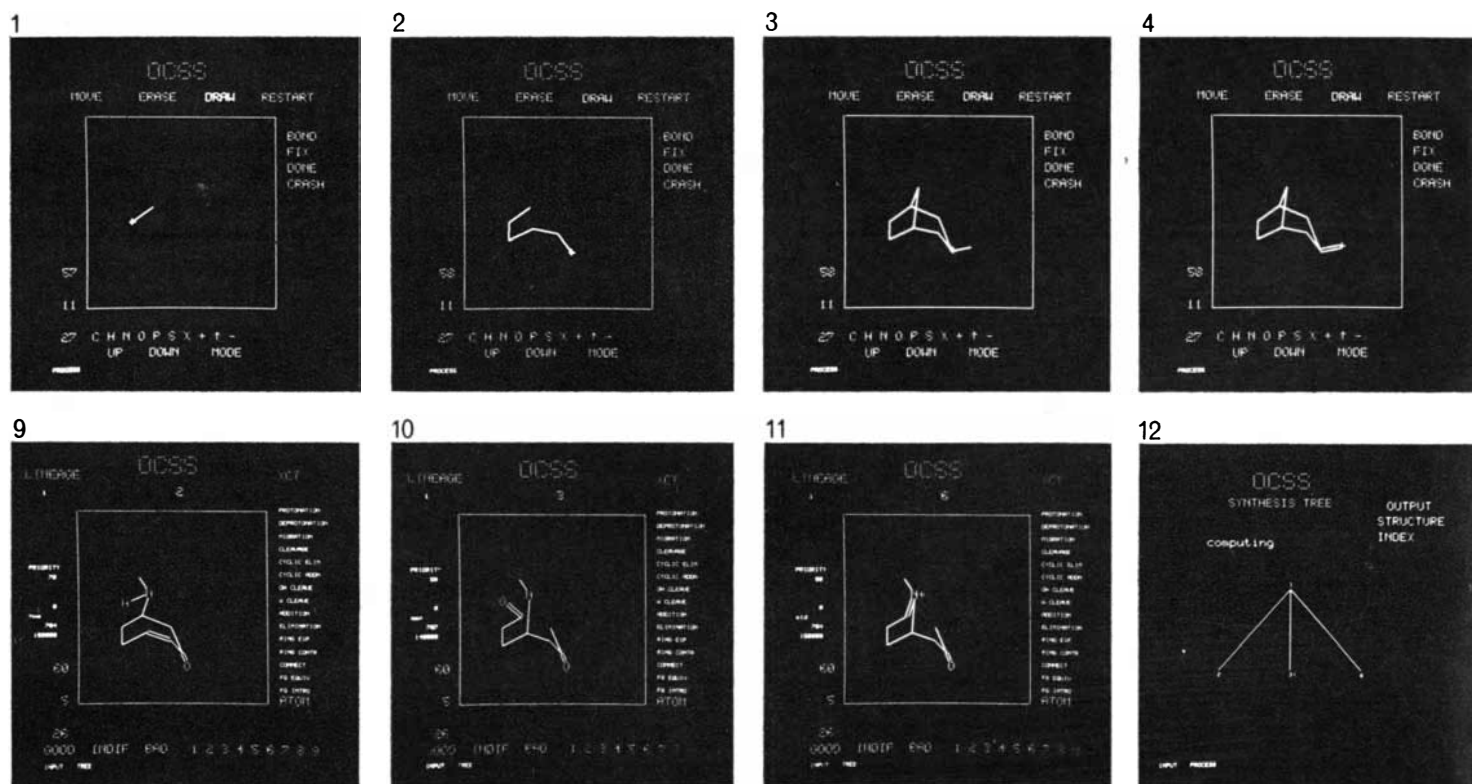
CHEMICAL SYNTHESIS PROBLEM is presented to a venerable PDP-1 computer at Harvard by a chemist who uses a writing tablet to draw a picture of the molecule he wants to make. By frame 3 he has drawn the basic structure of a molecule with eight carbon atoms. He adds a double bond at the extreme right of the molecule (frame 4), then bends the bond into the proper stereochemical configuration (5, 6). Addition of an oxygen atom (O), a nitrogen atom (N) and another carbon atom (indicated by the line projecting from the nitrogen) completes the skeleton structure of the target molecule: longifolene (7). The computer is now asked to search for somewhat simpler compounds that can be converted to longifolene in a single chemical step. The result of the search is shown by the tree in frame 8. Longifolene is designated by the 1 at the top of the tree; three related compounds, designated 2, 3 and 6, are

speeds up the display of magnified views of complex objects. Finally, complete subroutines are available for displaying objects that are similar in a nongeometric way. For example, cross-hatched boxes can be defined by position, size and type of cross-hatching. Such boxes are not geometrically similar because the number of cross-hatch lines must be computed from the size of the box; moreover, the angle of the cross-hatching must be constant regardless of the size or orientation of the box.

The Hidden-Surface Problem

In spite of the advances that have been made in computer graphics in the past decade, most of the objects displayed are still in the form of line drawings. It is difficult to present solid objects with today's computer displays; indeed, only half a dozen research installations even try. The preliminary efforts are nonetheless rewarding. The difficulty is in computing what parts of an object are visible from a given viewing position and what parts are not. If an object represented in three dimensions is to be rendered as being solid, some parts of the object must be able to obscure other

parts hidden behind it. Many workers have tackled this "hidden-surface problem," and in the past few years several interesting solutions have been developed.

The effectiveness of a solution to the hidden-surface problem can best be described in terms of the growth of the solution time with the complexity of the situation. Almost any method will work adequately with very simple situations, but because the computation time required by some methods grows with the square of the situation complexity, much computation time may be required for complex situations. Four years ago I showed in *Scientific American* a computer-drawn picture of a solid object produced by Lawrence G. Roberts, which was typical of the best then available [see "Computer Inputs and Outputs," by Ivan E. Sutherland; SCIENTIFIC AMERICAN, September, 1966]. His program took 1.5 minutes to draw a picture containing 40 separate blocks from which hidden lines had been removed; the computing time was roughly proportional to the square of the number of objects examined. Today general-purpose computers of not much greater power can produce pictures such as those shown on page 56 in about a third

of the time, and the growth law of these programs appears to be about $N \log N$, where N is the number of objects.

The traditional approach to the hidden-surface problem was to compare each object in the picture with every other object to see which was obscured. This procedure requires $N - 1$ comparisons for the first object, $N - 2$ for the second object, $N - 3$ for the third object, and so on, for a total of $(N^2 - N) \div 2$ comparisons. Moreover, the computations must be executed in three dimensions with high precision because they are done before projection onto the screen. The new methods consider only the task of computing the picture rather than the task of comparing objects. If a picture of the television type is to be produced, there are, after all, only some 250,000 points on the television screen at which intensities can be displayed. Why bother to compute to any better precision than that?

The most elegant, although perhaps not the fastest, algorithm to date is one invented by John Warnock of the University of Utah and somewhat embellished by others (including myself). Warnock's algorithm concentrates on computing shades for parts of the
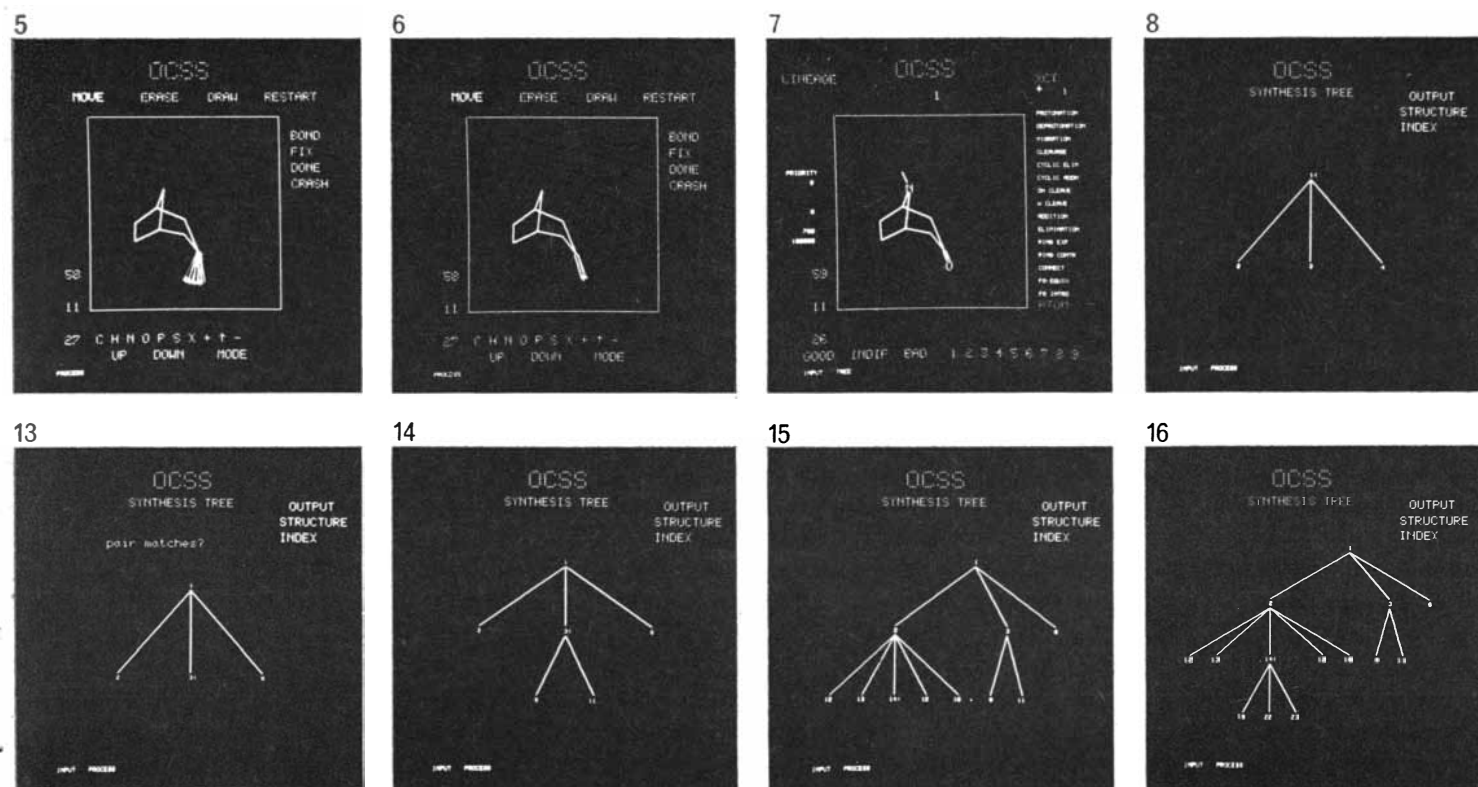

listed at the ends of the branches of the tree. The chemist asks to see the structures of these three molecules and they are presented to him in frames 9, 10 and 11, together with coded information at the left of the screen that describes the chemical reaction that will convert each to longifolene. The computer also evaluates each reaction and assigns a priority, or preference. The computer is then asked to find related compounds that can be converted into compound No. 3. While the search proceeds the computer can be asked what it is "thinking." The words "Computing" (*frame 12*) and "Pair matches?" (*frame 13*) appear on the screen. The last remark indicates the computer is puzzled whether a particular molecular structure is identical with another one. Two routes to compound No. 3 appear in frame 14 and five routes to compound No. 2 appear in frame 15. In the last frame the search is carried still deeper.

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$$X_S = \frac{XD}{Z} \qquad X'_S = \frac{X'D}{Z'}$$

$$Y_S = \frac{YD}{Z} \qquad Y'_S = \frac{Y'D}{Z'}$$
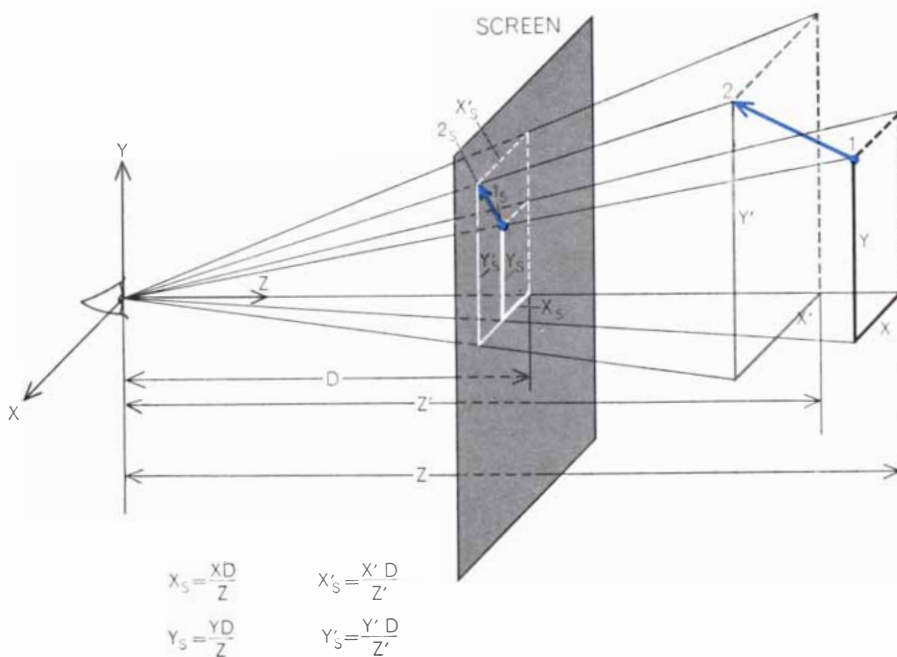
PERSPECTIVE PROJECTION for a computer display is obtained by placing the origin of the coordinate system at the observer's eye. The projection of all points on the screen is then readily computed from the geometry of similar triangles. The diagram shows how the two end points, *1* and *2*, of an arrow are projected to the points 1_s and 2_s. The first equation states that x_s is to x as the distance to the screen, *D*, is to *z*. Other dimensions are obtained similarly. Objects extending beyond the screen must be "clipped," as shown below.
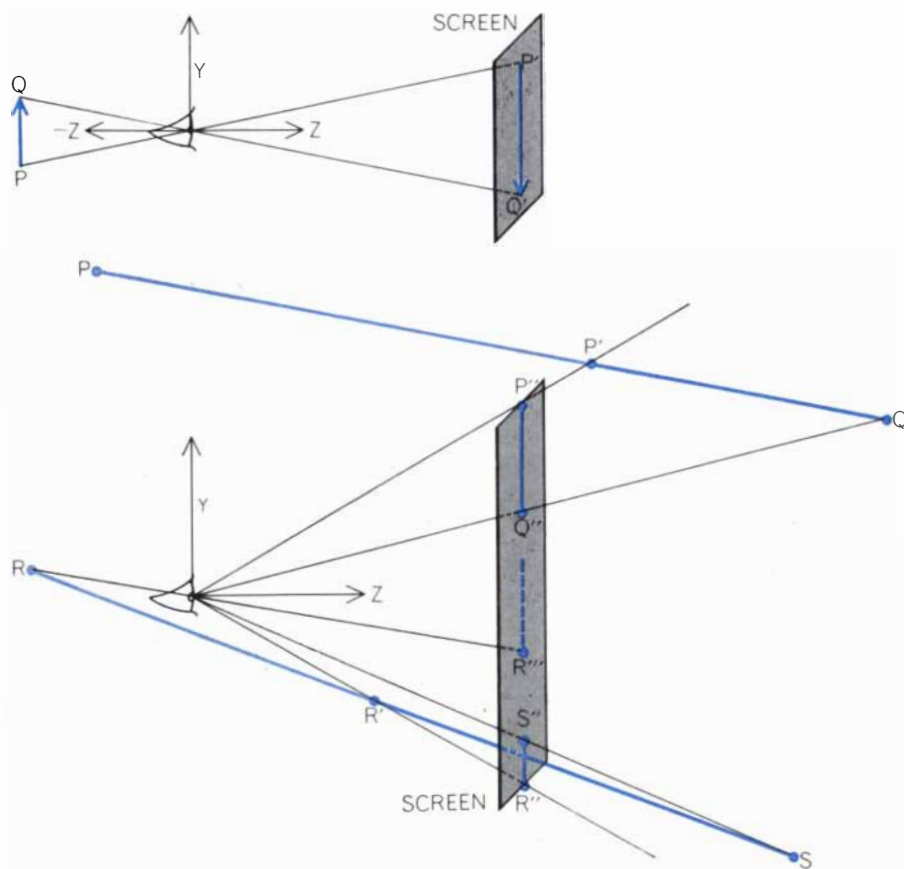
"CLIPPING," OR "WINDOWING," PROBLEM arises when objects in real space extend beyond the limits of the screen or lie behind the observer. In the latter case (*top*) *z* has a negative value. Although the equations are correct for such points, the result would be to project the object upside down. The problem can be avoided (*bottom*) if all lines are first clipped off at planes defined by the edges of the screen. If one applied the usual equations to the point *P*, a numerical overflow would result. Point *R* in the line *RS* would project to point *R'''*, and points close to *R* would project upward on the screen. By proper windowing, or clipping, the line *P'Q* appears on the screen correctly as *P"Q"* and *R'S* appears as *R"S"*.

screen, and also on computing shades for as large an area as is possible at one time. I shall describe Warnock's algorithm in some detail not only because it shows much ingenuity in the solution of a difficult problem in computer graphics but also because it utilizes a particularly appealing technique of computation.

Data for Warnock's algorithm are defined in terms of a collection of surfaces that form the objects to be shown. The simplest computations result if these surfaces are planes bounded by straight lines, but the algorithm could be applied to more complex surfaces. Each surface is assigned a color and a shade, and each surface is considered to be opaque. Rotation and translation are used to get the surfaces into the observer's coordinate system, and a perspective division is performed to position the objects on the screen. Depth information is preserved through the perspective projection.

Warnock's program now breaks the screen up into a few subregions and applies a standard procedure to each one. The standard procedure is to sort all surfaces by *x* and *y* position to determine whether they are entirely outside the subregion, surround it or partially intersect it. This sorting is done by first considering gross measures of the surface's position (such as: Is its leftmost point to the right of the subregion?) and then considering, if necessary, the individual edges of the surface. Obviously surfaces that are outside the subregion need not be considered further. The algorithm then considers the surfaces that surround or intersect the region and attempts to prove that certain of them are hidden by others. For example, if a surrounding surface can be shown to be in front of all other surfaces throughout the region, all the other surfaces are eliminated and the program can shade the entire region according to the shade of that surface. If there is only a single edge in the subregion, perhaps the program can fill in the appropriate pair of shades.

The important thing about Warnock's algorithm is its response to a subregion in which the situation is too complicated to handle. In such cases the algorithm simply subdivides the subregion into smaller regions. The sorting task for a subdivided region is simpler than it was for its predecessor because all surfaces that surrounded the predecessor will surround any of its subdivisions, and all surfaces that were found to lie off to the side of the predecessor will also lie to the side of its subdivisions. Only those surfaces that partially intersected the prede-

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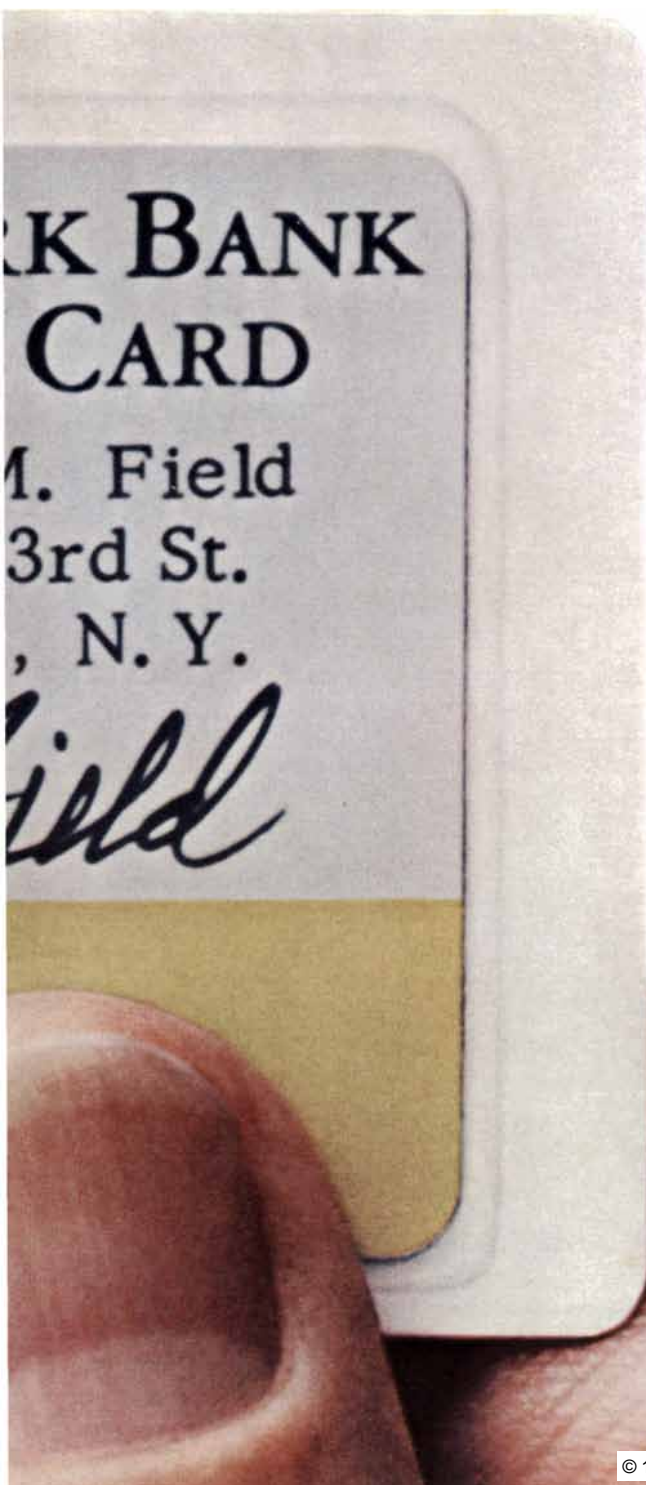**Dayton, Ohio 45409**
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The number of credit cards in Americans' wallets has zoomed to 300,000,000. And the upsurge has been a bonanza for the swindler.

Credit cards are stolen from wallets, handbags, bureau drawers, and mailboxes. Some are thrown carelessly in trash baskets, and are found by scavengers uninhibited by scruples.

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Worst of all, the efforts by law enforcement and private agencies to stop the thievery have had little success. The problem has been attacked by state and federal legislatures. But the losses keep mounting.

However, there is an answer. Of all the methods devised to keep credit cards out of the hands of criminals, none has proven as effective as the Polaroid Portrait ID System.

It puts the owner's picture (in full color) and pertinent data on a single piece of film, and seals it with a chemically bonded lamination.

It's almost impossible to alter it without detection.

As a result, few criminals would be foolish enough to try to use a Polaroid ID card.

They can forge a signature, but not a face.

Recently, there has been dramatic evidence of the degree of its security. One of the many banking institutions that have installed the Polaroid Portrait ID System gave their cardholders a guarantee of complete and unconditional freedom from financial loss due to lost or stolen cards. No deductible; no limit based on date of notification; simply no loss at all.

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One of John's customers manufactures concrete statues. He casts them in 900 pound steel molds which must be cleaned of residual concrete with a hot mineral acid after each casting.

Hot acid cleans away concrete easily. So easily, that if left unchecked, it can also attack and pit the steel molds. That's why John's customer was testing MAIN™ 33S acid inhibitor—for the safety, economy and prolonged bath life it promised. But he didn't expect to test it under such severe conditions.

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And it would have been too if it weren't for MAIN 33S. This unscheduled acid exposure test proved that MAIN 33S establishes a barrier between the steel mold and the acid, preventing corrosion.

John knew MAIN 33S could effectively inhibit acid corrosion under normal acid cleaning conditions. But it took his customer's particular acid cleaning operation and a power failure to substantiate our claims that MAIN 33S is effective even under severe acid exposure conditions.

This MAIN 33S success is only one example of the way Abbott Chemicals works to help you find solutions to your chemical problems.

One of our jobs as the chemical marketing arm of Abbott Laboratories is to find industrial applications for many of the 1000 chemicals Abbott synthesizes each year.

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cessor region have to be considered in dealing with its successor regions. Thus the number of surfaces to be considered in each subregion becomes quite small as the area of the subregion decreases. If the situation in a subregion of the smallest possible size is too complex, the algorithm simply picks a shading rule from the nearest adjacent surface, because such a choice affects only a single point on the display screen.

Many varieties of the Warnock algorithm are possible, depending on how complex a situation the algorithm can handle without having to subdivide, and also on the method of subdivision. Warnock's own programs always divided regions into four equal parts and yielded an output only when the entire square was the same shade. The subdivision of such an algorithm is shown in the illustration at top left on page 81. A smarter display program, which avoids subdivision when there is only a single edge in view, will produce the subdivision pattern shown in the adjacent illustration on the same page. This program, of course, requires slightly more time for the computation of each square. Thus there is a trade-off between the complexity of the display program and the number of subareas that need to be considered. We are currently investigating this trade-off statistically in an attempt to discover what kind of algorithm may be the best.

The work of Gary Watkins and Gordon Romney of the University of Utah has developed some interesting statistics about the pictures we are drawing. The most significant and surprising fact is that the sorting task in the hidden-surface problem is not complicated in depth but is quite complicated laterally. The pictures shown in this article, although complicated, are not very deep. That is, if you penetrate the picture with a ray at any particular position, you will hit fewer than 10 surfaces in all but specially contrived cases, and the average number of surfaces struck is more nearly three. We have concluded that the problem in producing hidden-surface pictures of the type shown here is largely the problem of sorting the pictures in the x and y directions to discover those few surfaces for which a depth computation is required.

Once the hidden-surface problem is solved, shading and color are relatively easy to introduce. The hidden-surface computation develops information to tell which surface is visible at each point on the screen. Since each surface in the computer includes a color, as well as other properties, the program can compute precisely what hue, saturation and
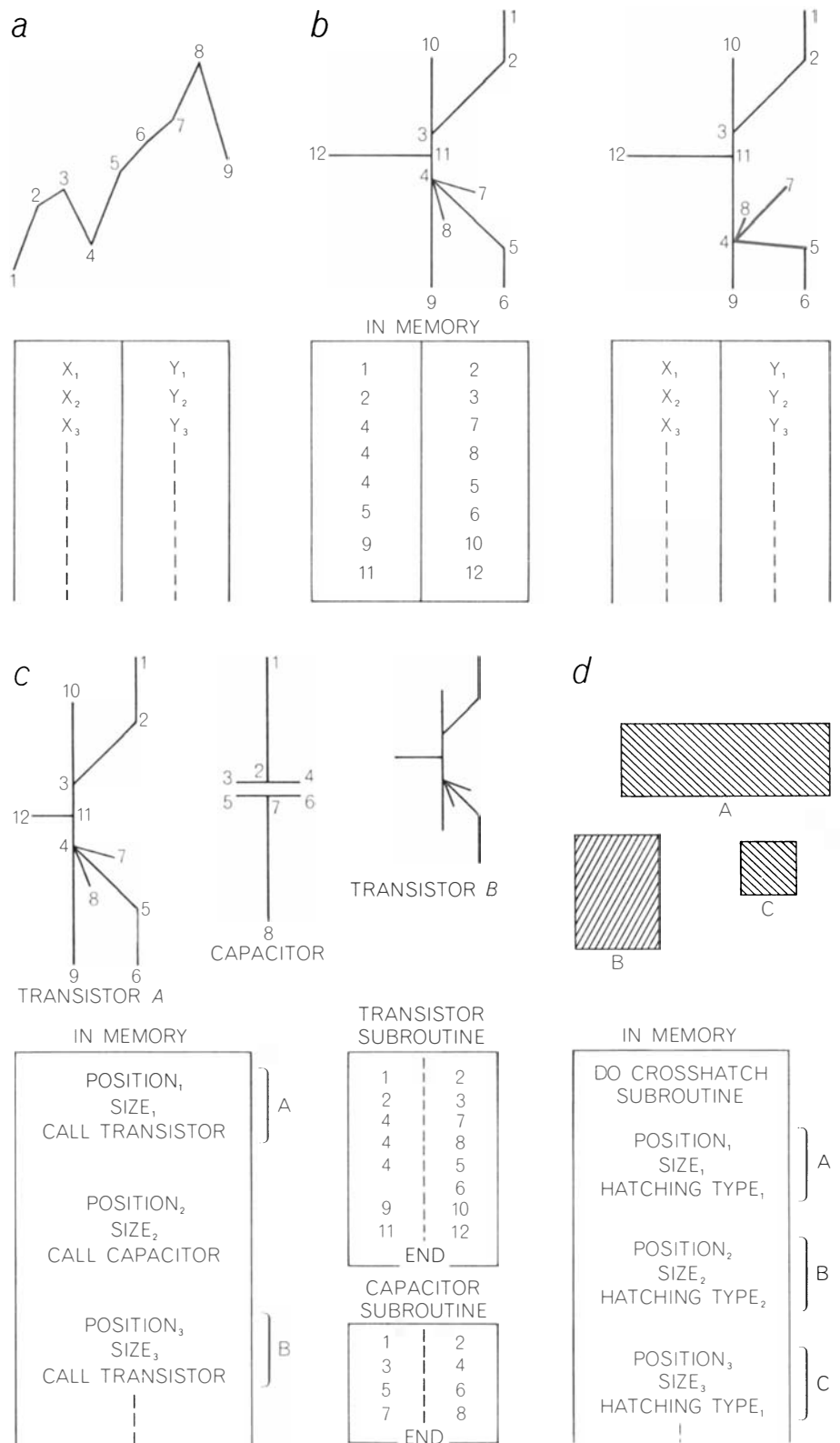
REPRESENTATION OF OBJECTS IN DATA BASE takes four principle forms. Line segments can be represented either as strings of connected coordinates (a) or as sets of disjoint lines, each connecting two coordinates (b). Once such linear displays have been created they can be stored in the memory for recall at any future time. The representation at the upper left in b is the symbol for a transistor. If point No. 4 were shifted downward by changing y_4, all the lines terminating at No. 4 would be shifted simultaneously without, however, destroying the topology. Another common representation (c) stores symbols of fixed geometry, such as elements for designing circuits. These can be called to the screen, placed in any desired location and scaled to any size. The record in the memory will then list "Position," "Size" and a code for calling the subroutine that draws the device. If the device is a transistor, the subroutine might read like the sequence of numbers in b. A capacitor will be called by its own subroutine. Another representation scheme (d) defines a class of objects that are similar in some simple but nongeometric way, such as hatched boxes.

SCIENCE/SCOPE

A high-speed digital MODEM transceiver -- one of the smallest, lightest, most versatile in the defense communications field -- was delivered to the U.S. Air Force recently by Hughes. The 70-lb. MODEM (modulator-demodulator) replaces a current 250-lb. device. It transmits or receives 1200 or 2400 digital bits per second in a narrow frequency range over normal telephone circuits, and will be used in conjunction with military computers, teletypes, radars, and other sensors.

Switzerland's computerized air defense system -- built in California by Hughes but code-named "Florida" by the Swiss -- has been accepted and put in operation. It consists of several radar stations that provide simultaneous range, bearing, and height data to the high-speed Hughes computer, nerve center of the system. Should a target be identified as an immediate threat, the commander can request all-weather aircraft or surface-to-air missiles to intercept and destroy.

New uses for lasers developed by Hughes include cutting clothing patterns for Genesco, Inc., Nashville garment manufacturer; prototype of the computer-controlled system can cut different patterns singly from a variety of materials much faster than a blade....and trimming thick or thin film resistors with a laser resistor trimmer that can cut nichrome, gold, chromium, and tantalum films as well as standard inks; its single Q-switched laser is split and distributed to as many as four individually controlled trimming stations.

Three custom-designed calibration vans, first of their kind, have been delivered to the U.S. Navy by Hughes. The mobile vans conform to interstate highway requirements and will be driven to the dock to calibrate the Pacific fleet's electronic and ordnance equipment -- eliminating the present expense of removing ships' equipment to land-based laboratories and substantially reducing down-time.

Current programs at Hughes Research Laboratories include: 1) Study of the physics and applications of low-voltage gas discharges. 2) Study of "double stream" plasma instabilities, noise generation in plasmas, and behavior of plasmas in crossed electric and magnetic fields. Physicists or electrical engineers with experience in solid-state microwave are needed. Accredited degree and U.S. citizenship required. Please write: Mr. Al J. Simone, Hughes Research Laboratories, Malibu, California 90265. Hughes is an equal opportunity employer.

Millimeter wave frequencies -- which offer great promise for future space communications and data links -- will be studied in an experiment Hughes is building for NASA's ATS-F satellite. Advantages include: wide bandwidth, plasma penetration, reduced spectrum crowding, reduced size and weight of components. The Hughes-built equipment for the experiment includes the millimeter-wave tube.

A new, all-electronic mass memory device developed by Hughes promises to make computer information processing faster, simpler, and more efficient. Trademarked DYNABIT, it stores vast quantities of information on magnetic wire thinner than a human hair. It has no moving parts, can withstand severe environmental conditions, and can be adapted to new or existing computer applications.

Creating a new world with electronics

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HUGHES
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HUGHES AIRCRAFT COMPANY
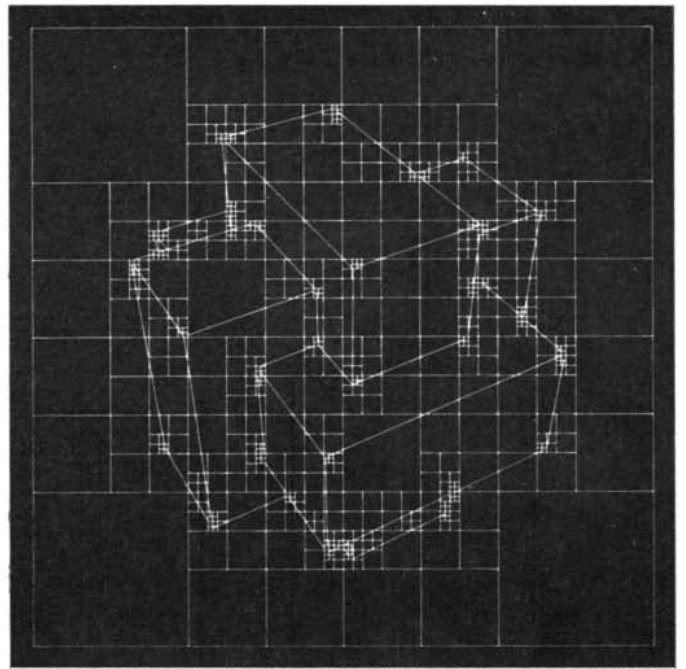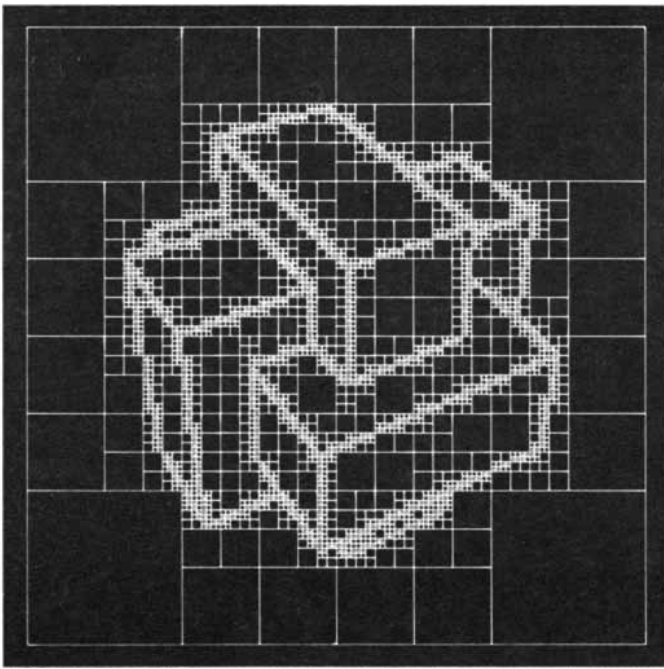
HIDDEN-SURFACE PROBLEM has been solved by special algorithms that answer the question: Which of several surfaces lies in front of all the others? It is no trick, for example, to have a computer draw transparent structures such as that shown at top left on page 56. The computer plots above represent algorithms for analyzing such a structure and removing hidden lines. The approach at the left, invented by John Warnock of the University of Utah, employs an algorithm that systematically divides the screen into subregions (in this case units of four) and applies a standard procedure to each one. All the surfaces that occur in a given subregion are sorted out and the subregion is divided, if necessary, to end up with only a single surface that lies in front of all others. The method is described more fully in the text. A similar algorithm, which often proves faster, is represented at the right. It avoids subdivision when only a single edge appears in any subregion. Improvements on these algorithms led to the "solid" figures on page 56.

brightness to display. In the simplest pictures the surface is simply displayed in its appropriate color. It is only slightly more difficult to compute the shade, or brightness level, based on a two-part reflectance property: one part for diffuse reflectance and the other for specular reflectance. The photographic output routines can also compensate for the color sensitivity of the film used in photographing the display, so that the resulting prints come out exactly as desired. As a surface of a given color becomes more nearly perpendicular to the observer's line of sight, its specular reflectance dominates its diffuse reflectance and it becomes whiter as well as brighter. This effect can give objects a shiny appearance if much specular reflection is included, or a dull appearance if only the diffuse reflectance is used.
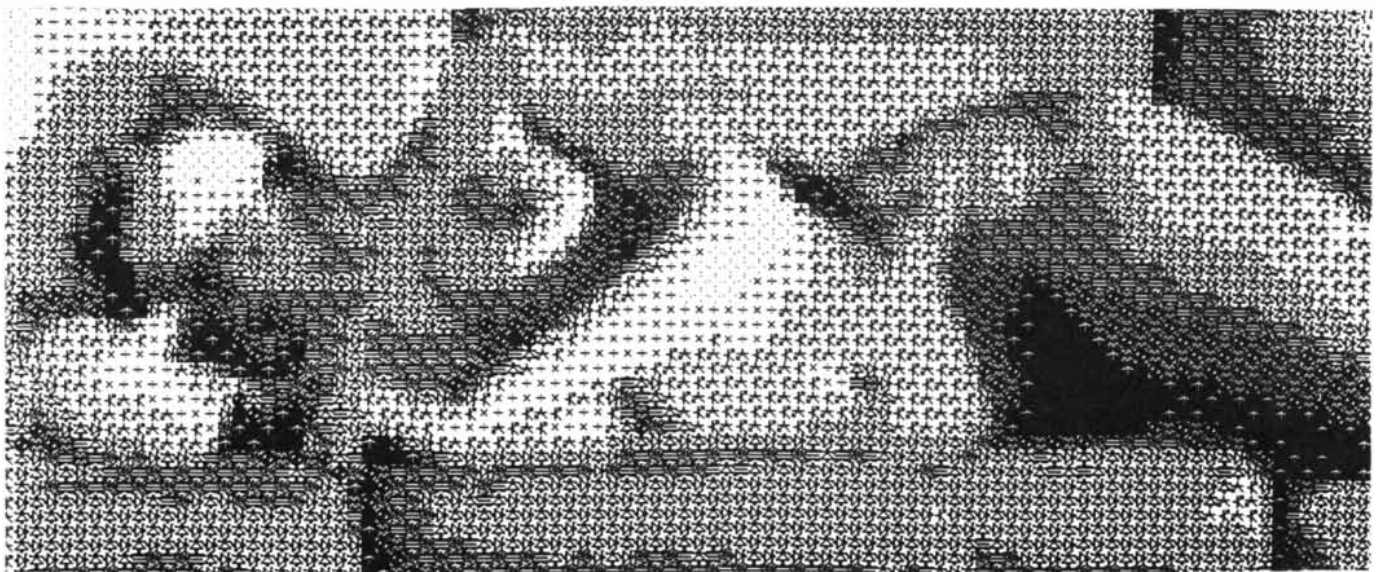
BELL LABORATORIES EXPERIMENT illustrates how a photograph can be analyzed by computer and then redrawn with arbitrary symbols. In this case the Greek letter "alpha" was used as a primary symbol to build up more complex patterns that range from very light to very dense in terms of average density per unit "cell." These cells were then assigned by a computer to match the point-by-point reflectivity of the photograph. Leon D. Harmon and Kenneth C. Knowlton did the experiment as a study in perception.