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Picture Processing by Computer

Computers which process graphical material are new, powerful tools for science, engineering, education, and art.

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Barely two decades ago the digital computer, though an infant prodigy of great promise, gave little hint of some of the future wonders now considered commonplace. We discuss here one of the most interesting of these, picture processing.

The earliest use to which computers were put was straightforward numerical manipulation. Numbers were fed in, and the computer performed arithmetic calculations, yielding numbers as output. In the 20 years or so during which we have had flexible, high-speed, stored-program digital computers, a host of other uses has evolved. Some of these new roles embed the computer in a system in which a human is rarely, if ever, directly involved—for example, process control systems such as automatic pilots and refinery controllers.

The most prevalent supranumerical uses of computers involve people either at the machine's input or output, or both. These applications include speech analysis and synthesis, language translation, information retrieval, music synthesis, medical diagnosis, chess and checker playing, and picture processing. In most of these uses tangible progress has been relatively difficult to achieve. By contrast, however, advances in picture processing have been rapid, prolific, and extremely useful.

By picture processing we mean either the transformation of graphical material, or the generation of pictures from data or abstract rules alone, or combinations of these operations. There are thus four categories relative to the computer's input-output terminals, as shown in Chart 1.

Many of these processes have become immensely valuable. They provide new extensions of man's senses and effectors for utilitarian and esthetic purposes. The domain of computer picture-processing is now so enormous that we discuss only some highlights of the state of the art.

Equipment and Processes

Although we do not discuss specific hardware or software systems, it may be useful to mention some of the physical components for picture processing and several representations and manipulations within the computer. A typical arrangement for transforming a photograph is shown in Fig. 1.

Some real-world picture, typically a 35-millimeter film transparency, is scanned by a machine similar to a television camera. The resultant electrical signals, representing the brightness of successive picture elements, are changed by an analog-to-digital converter into numerical representations on magnetic tape. This provides a digital version of the input picture for computer processing.

A general-purpose, high-speed digital computer is programmed to process the picture according to one or more algorithms. When the processed picture is completed (still in discrete numerical form), the computer instructs a microfilm printer (through tape) to generate the new product. This is done in a manner which is the inverse of the original scanning: a television-like tube paints the picture with a moving spot of light, and a camera records it on microfilm to provide a photographic end product. Color pictures are possible, but the technology is not well developed; most microfilm systems yield only black-and-white output.

There are many variations on such input-output procedures and mechanisms. At the input, the picture can be specified by optical, mechanical, or electrical scanning and sensing devices, or even by abstract (programmed) description.

A particularly common arrangement in real-time interactive systems is to draw input pictures freehand. The usual computer-linked drafting tool is a "light-pen" (actually a photocell) or an electrical "stylus-tablet" (*1*). The experimenter draws crudely, and the computer instantaneously (insofar as the user's time sense is concerned) straightens lines, interpolates, and adjusts scale. In some applications the experimenter composes pictures by calling up substructures by push buttons or "light buttons" actuated by the light pen. A small repertoire of automatic operations such as copying, reflecting, joining, and rotating are available on request. Thus electrical circuit elements, mechanical parts, or architectural fragments, for example, can be evoked and manipulated with ease and speed.

Output displays include volatile (directly viewed cathode-ray tube) presentation, nearly instantaneous hard copy where electrical signals are converted into Xerox prints, direct electron beam to film transfer, or x-y plotting where line drawings are produced directly by a mechanically driven pen (which al-

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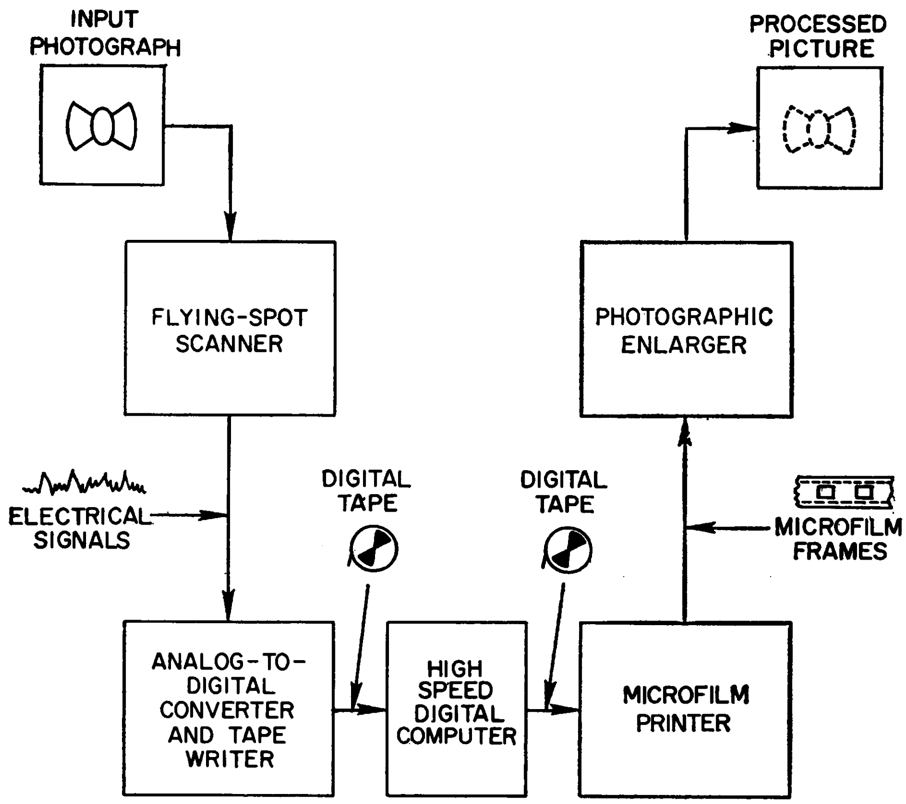
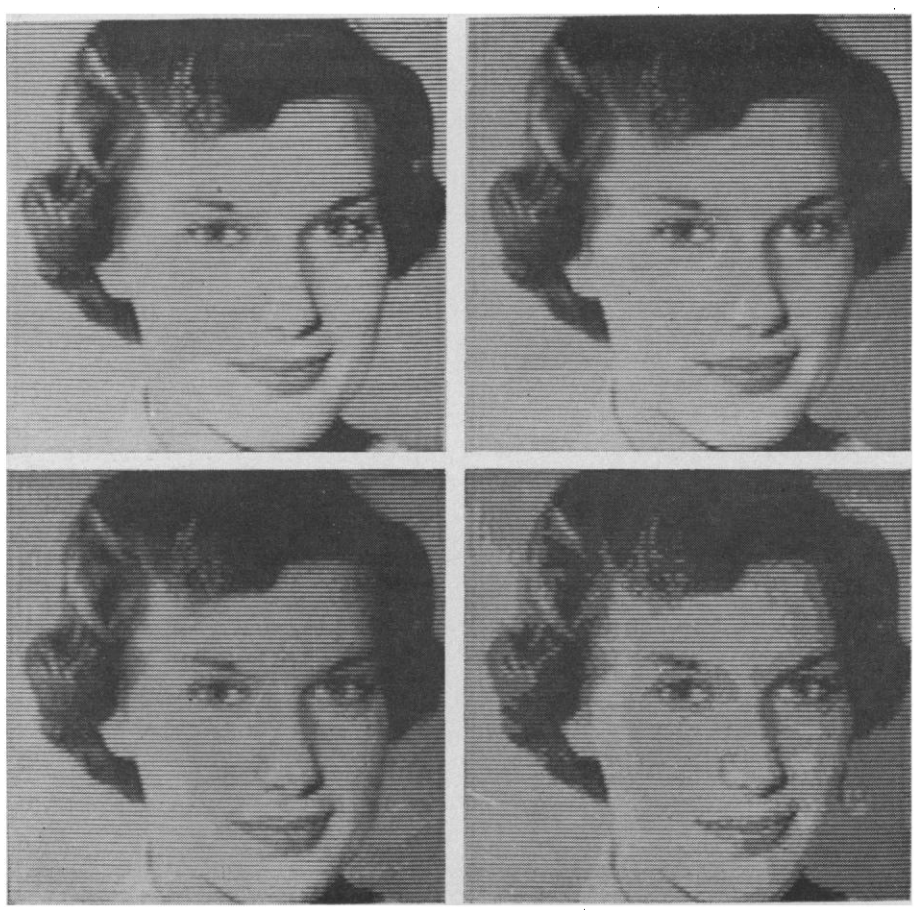


Fig. 1. Schematic of a widely used system for computer picture-processing. An input photograph is transformed into analog electrical signals by a scanner; these are converted to digital form and tape-recorded. A general-purpose computer manipulates this picture information, producing another digital tape after processing picture. Final output is obtained from high-resolution image produced by microfilm printer under computer (tape) control.



lows discrete colors to be easily obtained by using colored inks).

Electronic systems have an advantage of speed over mechanical systems because they can draw 10^4 to 10^5 points or lines per second. Mechanical systems are still superior, however, for the production of large drawings with extreme accuracy. The volatile displays have considerable flexibility and are dynamic. It is possible, for instance, to see the progressive result of an experiment while it is being run, and to modify variables essentially in real time while analysis proceeds.

Within the computer, pictorial information may be represented as a large two-dimensional array of numbers signifying light values, or as listings of coordinates in a two- or three-dimensional space of significant points which define lines, surfaces, and other relations. The operations which may be performed within the computer include smoothing, edge detection, edge sharpening, abstraction, correlation, searching for matches with patterns, distortion, rearrangement, and the addition of pseudo-random noise. These operations can be performed either locally or globally, and they can, of course, be made conditional on the results of previous operations. It is also possible, just before picture output, to make geometric calculations having to do with illumination and visibility of surfaces of internally represented objects which are "illuminated" and "viewed" from prescribed angles.

Picture-to-Picture

Computers were used more than a decade ago for research in television bandwidth compression (*2*). Pictures were stored on an element-by-element basis, and various information-reducing manipulations were introduced experimentally. By this technique, portions of a two-dimensional picture were controllably transformed in the computer domain and then were redisplayed to observers for assessment of the quality

Fig. 2. Early example of computer picture-processing experiments. Various brightness-encoding schemes were tried, and picture quality was assessed. All were displayed on television monitor. (Top left) Original image; (top right) six-bit (64-level) gray-scale result; (bottom left) four-bit (16-level) result; (bottom right) three-bit (8-level) result—too little information is preserved for satisfactory representation.

of hypothetical transmission systems.

Such experiments, to evaluate quickly the results of transforming millions of picture elements in many different ways, were among the earliest to demonstrate the immense capability of computers for visual man-machine interaction, particularly for very complicated stimulus presentation to humans.

An example of this early picture processing is shown in Fig. 2. All four pictures were taken from a cathode-ray tube displaying either input (top left) or the computer-processed output. In this experiment the computer simulated hypothetical transmission systems in which the brightness values of the picture elements were recoded to obtain transmission economy. Whereas the original picture has continuous density values, the processed versions are made discontinuous; that is, they have discrete quantization of gray scale. The example at the top right was quantized to 64 levels and is hardly distinguishable from the original. The one at the bottom left, quantized into only 16 levels, is still fairly good, but the eight-level picture at the bottom right is unacceptably degraded. These experiments led to techniques for achieving bandwidth savings of over 2:1.

More recent picture-transformation experiments use microfilm plotters rather than conventional television-tube displays. The essential distinction is that the conventional microfilm plotter is discrete; it constructs a picture in binary fashion, dot by dot, where all dots have either the same brightness or, at most, two values. By contrast the earlier displays were continuous in the sense that the sweep of the luminous spot along one scanning line was uninterrupted, and the spot brightness was analog-modulated to give picture tones, as in television.

Transformation
1) Picture → picture (some transformation is made)
2) Picture → abstraction (something is measured or recognized)

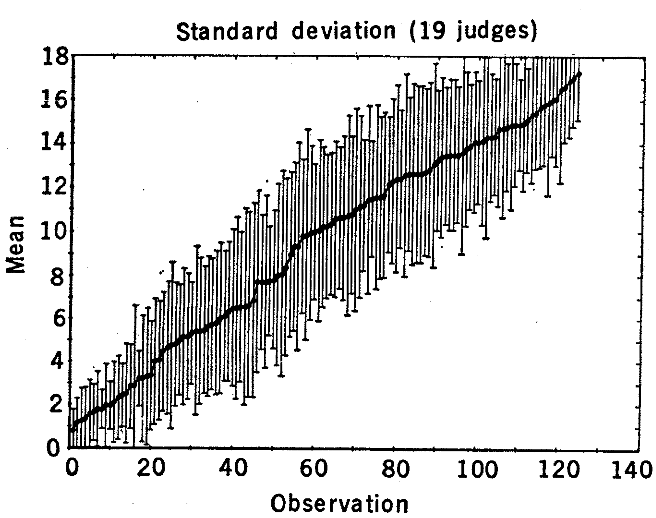
Generation
3) Data → picture (an invisible real-world phenomenon is made visible)
4) Abstraction → picture (a picture is synthesized from generating rules)

Chart 1.

The microfilm plotters usually produce graphical rather than pictorial output (Fig. 3). Despite the black-or-white output of most plotters, the fine resolution (typically more than 1000 dots along an edge) and the precise control available have tempted many experimenters to search for techniques for generating pictures having an apparently continuous gray scale of brightness values. Some fascinating tricks have emerged.

Figure 4 is an illustration of several of these gray-scale surrogates achieved by appropriate software (programming) procedures for manipulating the microfilm dot-plotter (*3*). An original photograph is shown at the upper left. The image to the right was produced by "over-writing," that is, by multiple exposure of individual dots; as many as ten exposures were used for the densest regions. (This takes advantage of the interesting but little exploited fact that conventional microfilm is not really completely binary; it has a short range over which gradations can be registered. Further, since the dot images do not have sharp edges, there is progressive buildup of diameter with successive exposures.) In addition, a "local neighborhood" spatial averaging was used to compute the exposure for each point in order to avoid sharp, unpleasant quantizing contours.

The picture at the bottom left of Fig. 4 shows how a halftone process can be simulated by modulating the widths of lines in an otherwise regular line structure. The circular "scan" used was chosen for novel effect. Pictures depending on spatial modulation (rather than intensity modulation) for gray scale must be viewed at distances sufficient to obtain fusion, that is, where the eye fails to resolve the fine modulating structure. Thus this picture, like the one on the cover and like conventional halftone prints, takes on a more and more photograph-like appearance with increased viewing distance (or when one squints to produce blurring integration).



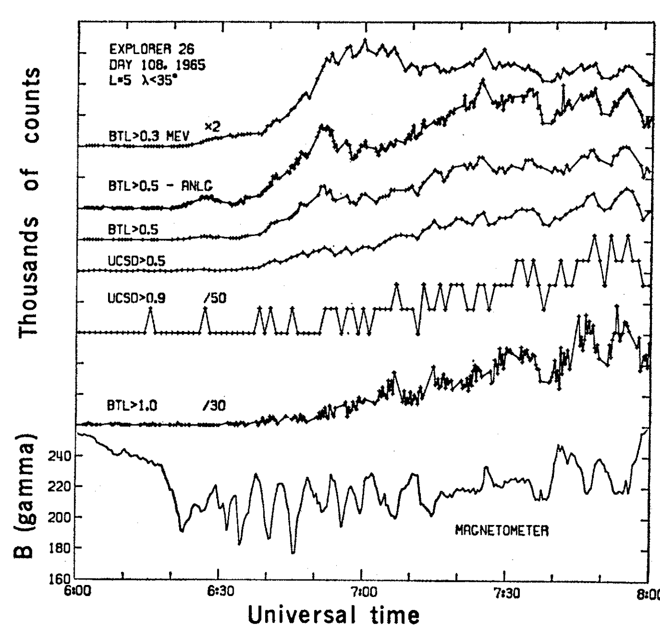


Fig. 3. Two examples of graphical material illustrating versatility of microfilm-plotted computer-output displays.

The illustration at the bottom right of Fig. 4 is the bizarre result of an experiment which applied width modulation to density-contour lines. In this case the fineness of the contour-line steps is insufficient to produce an acceptable replica, but a simple change of a constant in the computer program would accomplish this in all but the flattest regions.

Another process which results in apparently continuous-tone pictures from binary microfilm dot-plotting uses a technique analogous to the variable dot size process of conventional halftone engraving. In this case the various levels of gray are obtained by the local spatial density of uniform dots. The cover picture was made this way (*4*). A small section of the picture is displayed in Fig. 5, which shows equal areas of the original photograph and the (strictly speaking) binary output. The 16 steps of density from all black to all white were obtained by specifying in advance the number of black dots occupying an 11 by 11 square for each density. Then, rather than randomly scattering the black dots, the computer prints a variety of micropatterns, each consisting of approximately the right number of dots. At appropriately remote viewing distances where fine detail is lost, the eye interprets the square arrays as areas of average density. Pictures like this are produced for three reasons—to develop new computer languages which easily and quickly manipulate graphical data, to examine some aspects of human pattern perception, and to explore new art forms.

Among the most common and useful picture-transformation procedures are those that enhance photographs. This usually takes the form of crispening images and changing contrasts. Although contrasts can be changed by conventional optical techniques, images can be crispened by optical methods only with elaborate and time-consuming procedures. Image crispening by computer is fast and cheap; furthermore, like contrast changing, it can be controlled locally and minutely.

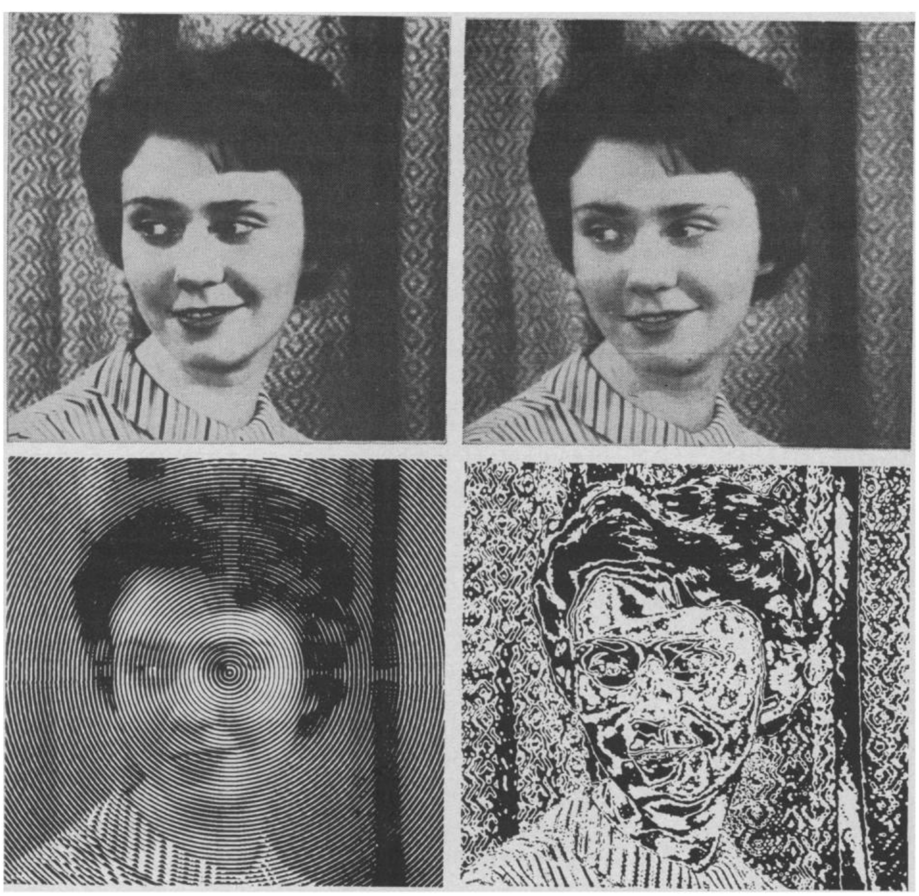


Fig. 4. Some techniques for obtaining apparently continuous-tone pictures from binary microfilm plotter. (Top left) Original photograph; (top right) multiple exposure of individual dots to ten density levels, maintaining proper "local neighborhood" average; (bottom left) gray scale obtained by width modulation of concentric circles; (bottom right) gray-scale equivalent obtained by width modulation of contour lines. [© 1968 Bell Telephone Laboratories]

An example of such improvement in a photographic image is shown in Fig. 6 where the picture on the left was processed to enhance detail and reduce dynamic range (*5*). The vastly improved result appears on the right.

The enhanced photographs familiar to most people are those transmitted back from space satellites, notably, for instance, the moon-surface pictures (*6*). There, computer processing removes some of the obscuring effects of transmission noise, sharpens "soft" detail, and enhances contrast to achieve greater resolution. Also it applies brightness field-flattening and geometric-projection corrections to obtain surface-normal views. Additional automatic operations are the superimposition of grid and fiducial marks.

Other examples of image enhancement are found in meteorological satellite cloud pictures, where enhanced-boundary processing facilitates weather analysis or even establishes surface pack-ice boundaries, and in x-ray and electron-microscopic photography where crispening and nonlinear density manipulations are frequently required for effective further processing, either by man or by machine (*7*).

Another kind of image transformation is that of reducing a stereoscopic pair to a single picture with the third dimension portrayed, for example, by contour lines, as in the automatic analysis of aerial stereoscopic photographs. There, elevation is automatically determined from the amount of shift required to achieve best local match. A special case of successful contour line and relative elevation portrayal from just one (monocular) picture is that of processing moon-surface pictures where the presumed uniform albedo of surface material permits conversion of brightness to slope (*6*).

Automatically deducing arbitrary three-dimensional geometry from a single picture is a much more difficult problem. Experiments in this direction are successful only when severe constraints are placed on permissible forms for attempted recognition. Figure 7 illustrates a situation in which the computer was asked to look for objects composed of rectangular slabs and wedges (*8*). After several steps of spatial differentiation, line thinning, gap filling, and line joining and straightening, the original photograph at the left was transformed into a line drawing. The computer then "constructed" a three-dimensional solid (not shown),

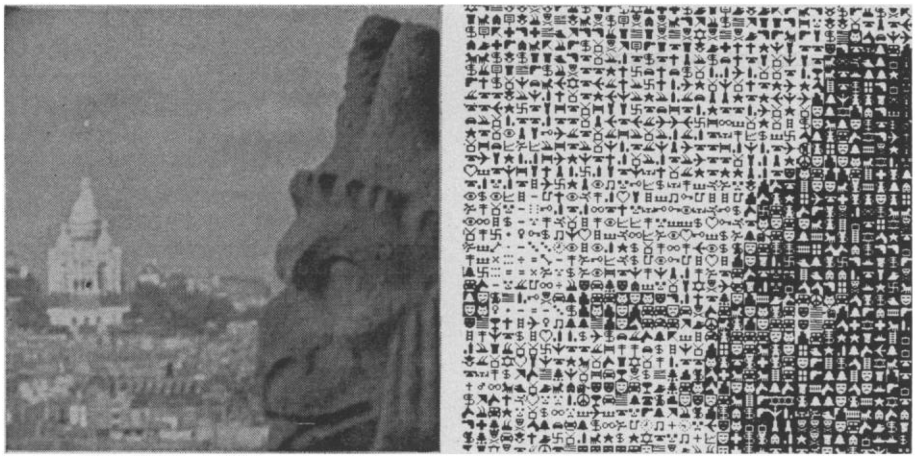


Fig. 5. Section of gargoyle picture which appears on cover. (Left) Original photograph; (right) computer-processed gray-scale equivalent where average spatial density of micropatterns determines regional picture brightness. [© 1968 Harmon and Knowlton]

compatible both with the drawing and with its understanding of permissible shapes, and finally it drew the two views at the right, showing how the deduced solid would look if viewed from different angles.

Picture-to-Abstraction

There are many situations requiring automatic analysis of a photographic image or a line drawing. Most of these cases can be loosely classified as "pattern recognition" (*9*, *10*). Generally, the output is some statement of recognition or some nominal, positional, or categorical listing. Occasionally, a transformed pictorial output is also obtained, as in nuclear-particle bubble-track analysis. (This example, among others, demonstrates that the four categories of Chart 1 at times overlap.)

In particle-track detection a single system may produce more than 10 million pictures a year. These must be screened to find and analyze that small proportion containing tracks of interest. Techniques are being developed to have computers accept photographs (including stereoscopic pairs of the particle tracks), refine the traces (by thinning lines, filling gaps), and then determine line segments, directions, lengths, and nodes (*11*). This information can be used to reconstruct idealized line images and even to select and print out only that subset which satisfies certain predetermined criteria. Although no system yet incorporates all these features in successful full-production operation, several have demonstrated excellent laboratory promise. An example of the "before" and "after" prints in one of the automatic track-following and "vertex-finding" operations (*12*) is shown in Fig. 8.

Another pattern recognition domain which may or may not produce pictures as output is that of chromosome analysis. Again the primary aim is to save enormous human drudgery. Microscopic slides containing chromosome spreads are scanned, and the resultant signals are computer analyzed by pattern recognition algorithms which (like most) use a priori constraints on permissible shapes to enhance recognition. Each chromosome after recognition is automatically classified by shape, measured (for example, length, area), homologously paired, and rank-ordered by size (*13*, *14*). Literal output statements may be supplemented by automatic printout of a neatly arranged drawing of the chromosomes. An intermediate stage is shown in Fig. 9—a photomicrograph processed to yield *in situ* drawings of the recognized chromosomes (*13*). As in bubble-track analysis, despite considerable progress, the totally automated techniques are not yet in full production; owing to difficulty of pattern recognition in some

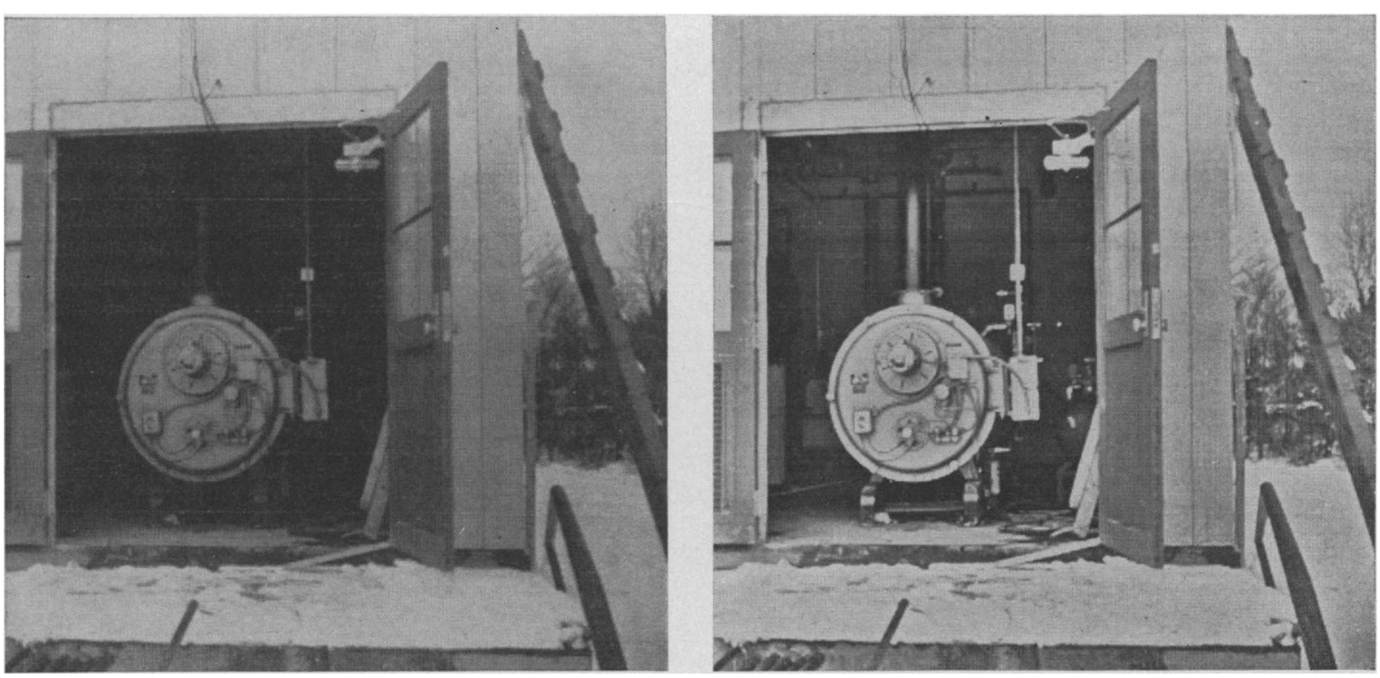


Fig. 6. Image enhancement by nonlinear remapping of picture tones. (Left) High contrast and blocking make picture quite poor; (right) processing to reduce dynamic range, enhance boundaries, and locally revise gray scale considerably improves picture.

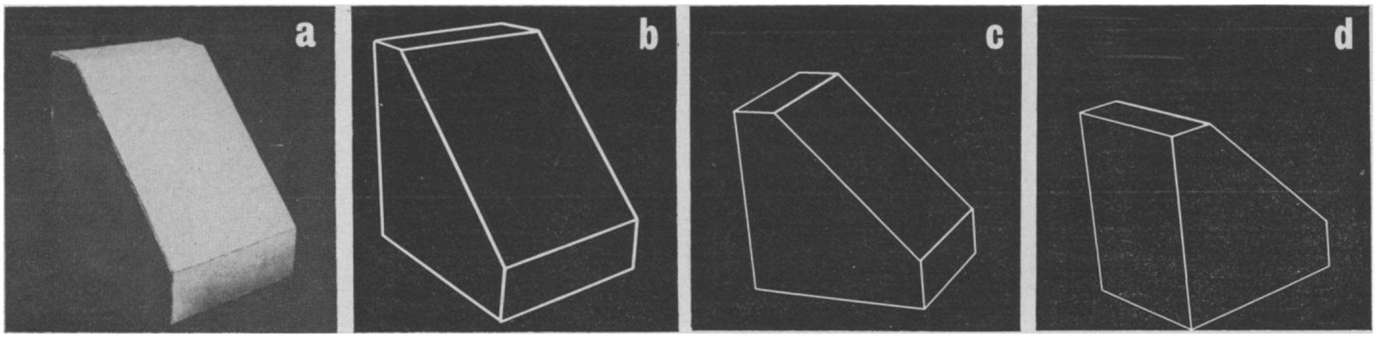
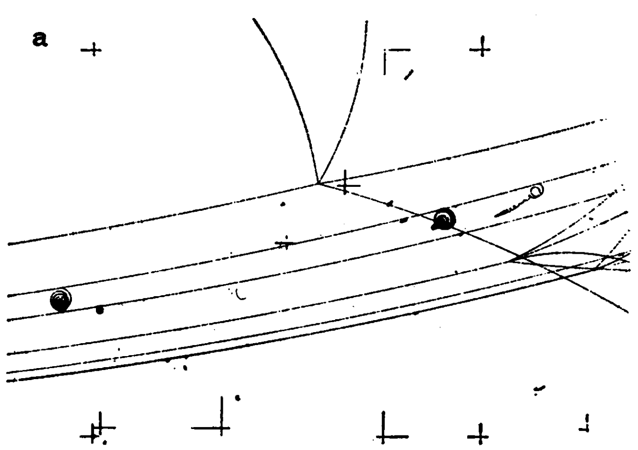


Fig. 7. Transformation of a continuous-tone photograph (a), first into a line drawing (b) from which the computer proceeds to "understand" the three-dimensional geometry of the object, then into other perspective views (c and d).

cases, they are still in the laboratory development stage.

The most common form of pattern recognition by computer does not yield a picture transformation. Rather, some decision-making process is initiated, or a literal or symbolic statement is produced. Machine reading of bank checks, credit-card imprints, and typescript are examples (*9*). Special-purpose input readers move the paper to be read past magnetic or photoelectric reading heads. Once again the resultant electrical signals constitute input for digital computer processing. Hundreds of characters per second are read with vanishingly small error, setting into motion many kinds of operations from bank accounting to automatic billing to (still at an early stage) mail sorting.

Although a myriad of computer experiments on picture pattern recognition have been run in research laboratories, few applications have met the criteria of reliability and low cost essential for everyday use. This is due to the extreme difficulty of achieving accurate recognition of complex patterns; many of the picture-processing feats that humans accomplish with little or no conscious effort are incredibly difficult to mimic with present technology. Some of the ventures which have met with partial success, primarily as laboratory curiosities, are automatic recognition of fingerprints, faces, and handprinted letters and script, and the automatic processing of cloud and aerial photographs and sound spectrograms.



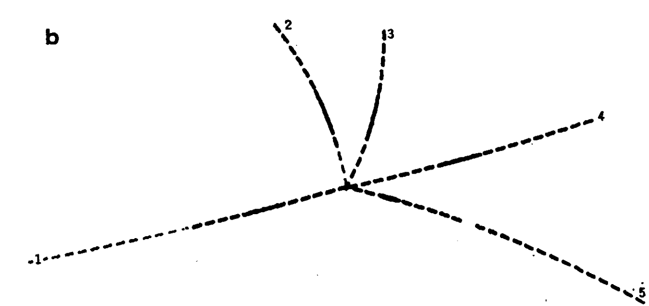


Fig. 8. (a) Before processing, a typical high-energy particle track photograph is rich in unnecessary detail. (b) Computer processing results in a cleaned-up reconstitution of tracks which satisfy specified geometrical constraints.

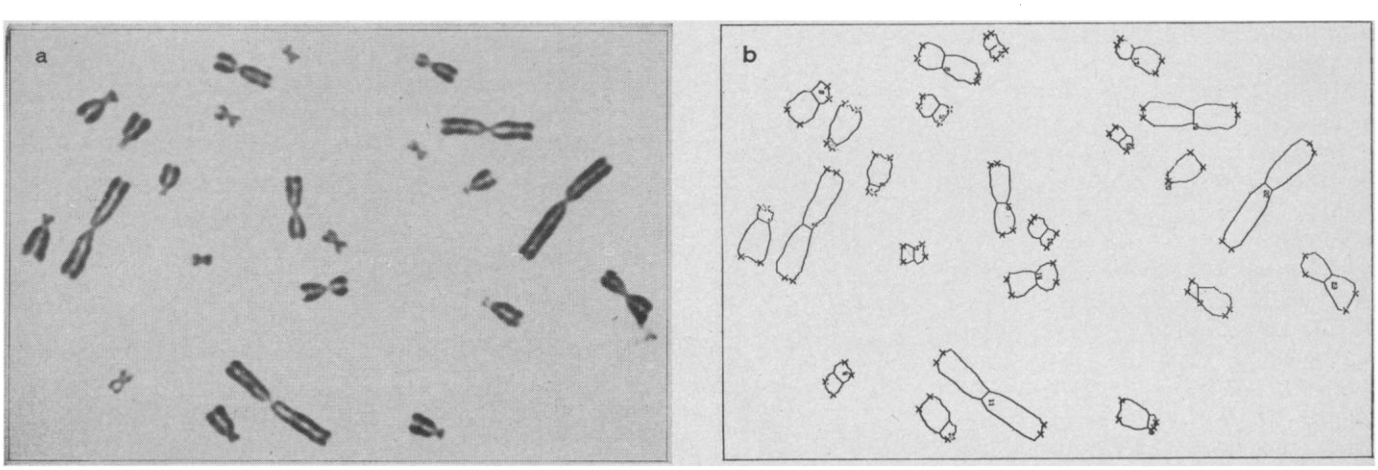


Fig. 9. (a) Photomicrograph of chromosomes; (b) computer-controlled pen outline drawing after pattern-recognition processing which applies geometrical and topological tests for chromosomes.

Data-to-Picture

Just as graphical plots permit the eye quickly to grasp regularities and patterns in numerical data, so too do pictures which are constructed from such data. Computer assembly and pictorial portrayal of masses of datum points permit one to see an otherwise invisible phenomenon. The original data may have represented insensible radiation fields, or the datum points may initially have had to be serialized either because of limitations on the detection equipment (perhaps no feasible focusing and imaging system exists) or of limitations on the illuminating equipment.

Examples are found in radar mapping where amplitude is plotted on coordinates derived from timing and angle of received signals, in radio astronomy mapping (two angles), and in range-Doppler mapping (timing, frequency). Rainfall over a large area can be plotted out as a two-dimensional picture where levels of gray quickly inform the eye as to the precipitation intensities. A particularly important example of spatial reconstruction for rapid integration by human vision is the volatile graphical display of air traffic in which a radar blip depicting an aircraft can be automatically accompanied by alphanumeric identification and flight information. Somewhat simpler two-dimensional reconstructions of real-world data are line-drawing plots such as contour mapping of particle radiation, molecular orbital densities, and magnetic and electromagnetic fields (*15*, *16*).

A simple but revealing dot plot produced by a microfilm printer is shown in Fig. 10. This fine-grained spatial sampling represents a cross-section contour map of proton intensity above the earth's surface (*16*). Somewhat more complicated dot displays reveal three-dimensional structure such as ion kinematics (*17*).

Another kind of data-to-picture transformation is that of map making, including the now relatively venerable computer plotting of weather maps. A more recent kind of map making of great utility produces series of demographic charts, each depicting different parameters. A large collection of data is stored, and from it any one of a number of displays showing, for instance, population density, economic levels, and housing conditions, can be generated on request. Less than 1 hour of computer processing and printing can produce a set of maps which replaces weeks of skilled human effort.

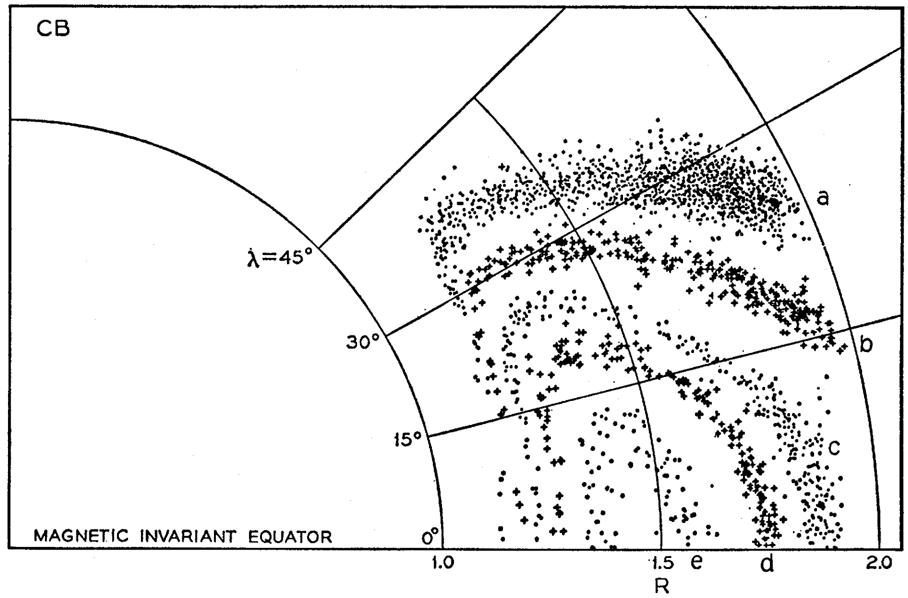


Fig. 10. High-energy proton data samples are sequentially taken by orbiting satellite and later reassembled by computer to give intensity cross-section picture.

Abstraction-to-Picture

The creation of graphical and pictorial material from literal and mathematical symbols or even from pseudorandom number generators serves many functions and takes many forms. Science, engineering, education, and art now lean heavily on these techniques.

A notable development is the generation of visual images via random-dot patterns (*18*). A microfilm printer produces black-and-white dot structures whose individual loci and whose statistics are flexibly manipulated for a wide variety of studies in human perception, notably stereopsis. The technique permits rich flexibility of stimulus generation and control impossible by other methods, even to the production of stereoscopically perceived images without a corresponding visible image in either of the two halves of the stereo pair. Many visual patterns produced by this technique and related processes can represent objects not physically realizable and thus provide an entirely new domain of sensory stimulation.

Figure 11 shows two frames, generated by the process, which demonstrate an aspect of monocular symmetry perception. The left image consists of four identical (randomly dotted) sections, one in each quadrant; the repetition is not readily perceived. In the right

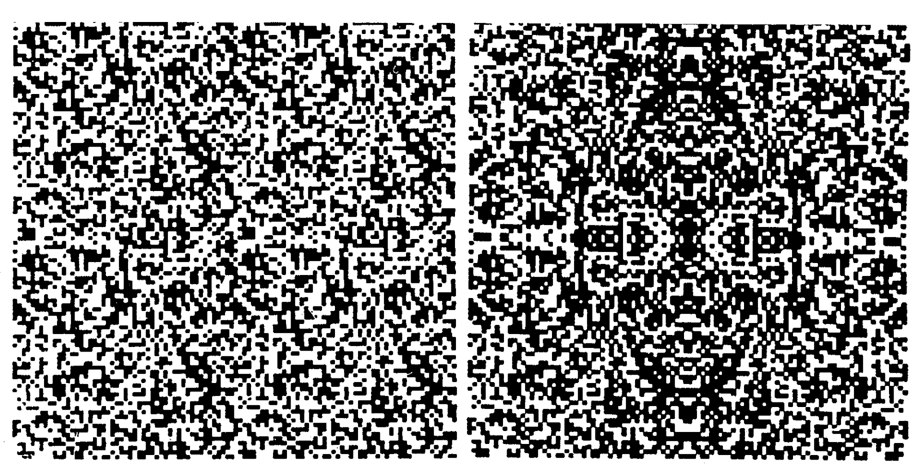
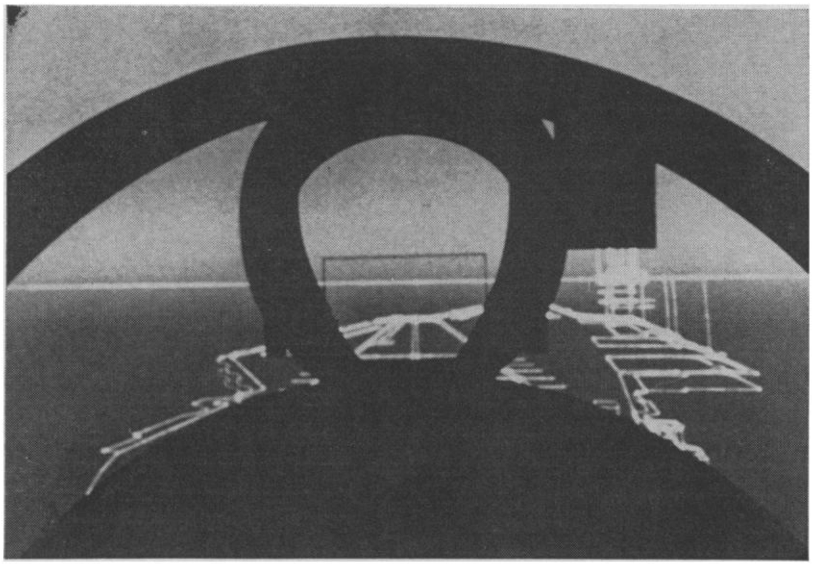


Fig. 11. Random-dot images. (Left) An identical random structure in each quadrant; (right) quadrants reoriented by reflection to provide symmetry about both horizontal and vertical midlines.



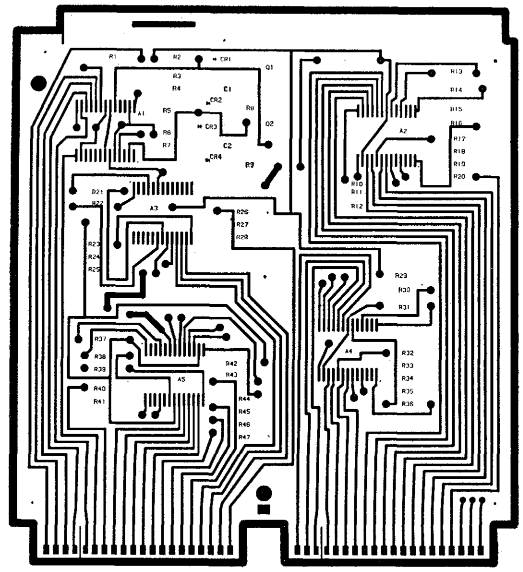


Fig. 12 (left). Computer-simulated pilot's view of aircraft-carrier flight deck from tentatively designed cockpit. From a movie showing last 10 seconds before touchdown on deck. Fig. 13 (right). A typical computer-produced printed-circuit master, this one made by an x-y mechanical plotter with a photographic writing head.

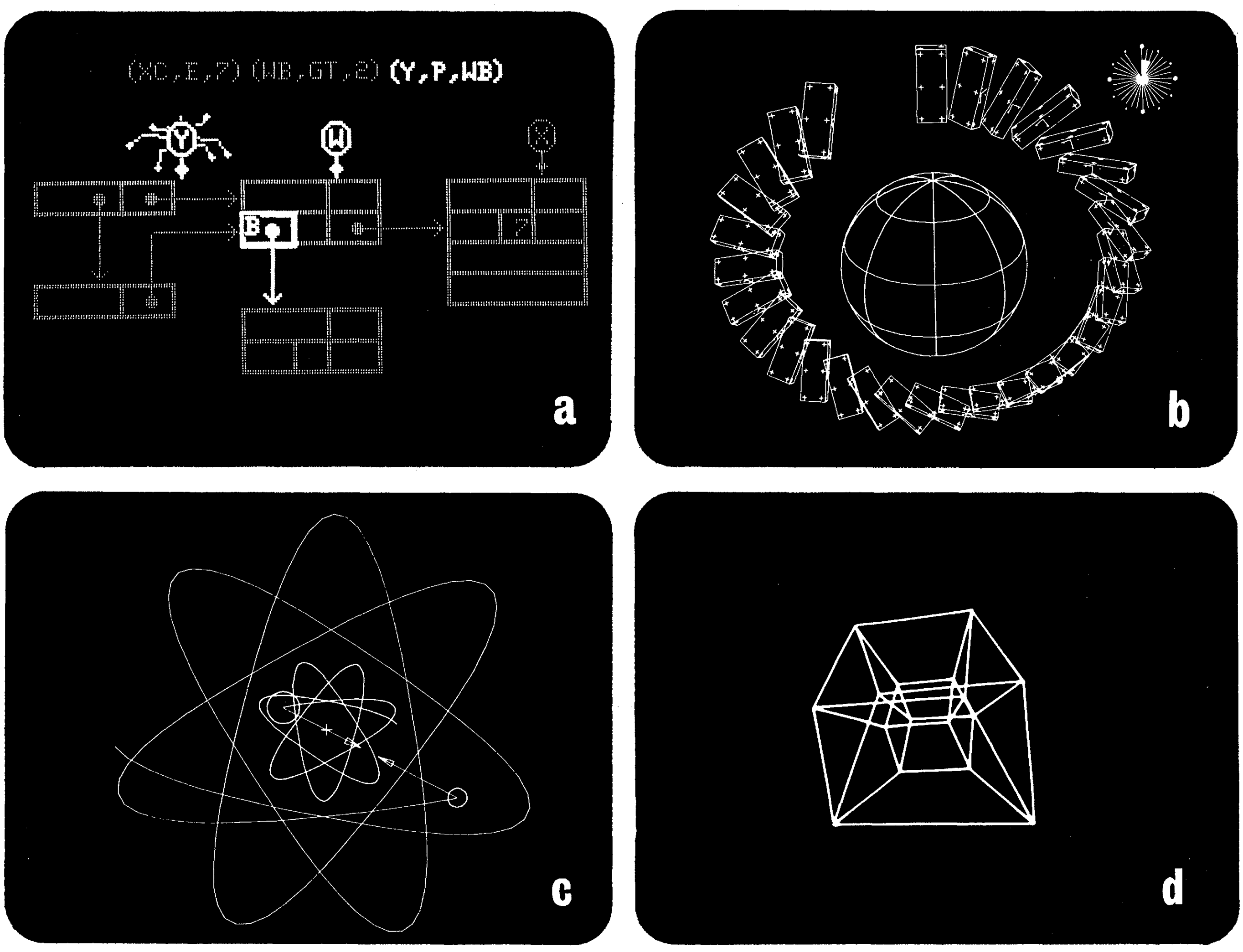


Fig. 14. Frames from computer-generated motion pictures. (a) Animated "bug" graphically illustrates sequences of operations in order to describe a new computer programming language; (b) the tumbling of a satellite, controlled by hypothetical stabilizing system, is accurately calculated and displayed (several frames superimposed); (c) intricate trajectories of two bodies attracted by arbitrary laws of gravity (in this case direct cube); (d) half of a stereoscopic frame showing a tesseract; a three-dimensional motion picture is used to enable visualization of a four-dimensional object.

image, three of these same sections are reflected to give symmetry about both horizontal and vertical axes.

Graphical and pictorial constructions generated from abstract specifications are useful in industrial design. The visual evaluation of preliminary architectural, mechanical engineering, and wiring layout design, for instance, permits great savings in time and effort (*19*). It is even possible to simulate both the eye position of the human viewer and that which is viewed, as in an interesting example of fenestration design (*20*). This is illustrated in Fig. 12, a pilot's view of an aircraft-carrier flight deck on landing approach. Many such frames, simulating different approach attitudes and altitudes, are used to find optimum design compromise of the aircraft's cockpit-window/equipment conflict. The simulation can even account for such subtle variables as the positions of the pilot's eyeballs after shock-absorber compression on landing.

Perhaps one of the most wonderful of these simulations permits an engineer to synthesize and activate a circuit by drawing a complicated electronic schematic on the face of a cathode ray tube (*21*). "Stock parts" are evoked from the computer memory, and the engineer types in component values and enters input signals. Within seconds he has displayed to him the plotted graphic response of the system to the specified input. Such instant breadboard combination of design, construction, de-bugging, and evaluation is as invaluable as it is impressive.

Still other uses of explicitly ordered pictures are the generation of type fonts (*22*) and the production of printed circuit designs and masks. In type synthesis the computer can behave like a virtually limitless-font typesetting machine, transforming, say, a teletype input into a typeset mask ready for type casting or photo-offset printing. Printed-circuit mask design permits computer trial-and-error adjustment of component and wiring configurations to optimize design within stated constraints. The computer then makes drawings or transparent-opaque masks for production etching (Fig. 13). In a related application, the photoreduction of similar masks permits integrated circuit components to be fabricated to 0.25-micron tolerances.

The ability to "see" mathematical models and the results of their application can provide powerful insights. Computers have been widely used in this respect, both for pedagogy (for example, *23*) and for research (for example, *24*). The moving, graphical representation of dynamic three-dimensional electrical fields or of hydrodynamic flow, for example, can impart a feeling for and an understanding of complex phenomena that no textbook or static illustration can match. Further, the laws of physics can be idealized, abstracted, or revised in ways which exceed by far the capabilities of realizable laboratory demonstration.

Motion pictures of these time-varying phenomena are typically made, frame-by-frame, on conventional microfilm printers. The dynamics of cochlear motion in the inner ear, of worldwide weather (for example, pressure, temperature, precipitation patterns), of satellite motion, and of explosive wavefronts prove illuminating and useful when displayed by mathematically precise computer-generated motion pictures.

Four representative frames from computer movies appear in Fig. 14. The two top frames are scenes from films which served as expository aids in scientific research not immediately concerned with display (*25*). The bottom scenes represent deliberate attempts to demonstrate the use of computers in displaying imaginary three- or four-dimensional situations (*26*).

An intriguing problem of economics arises in the monocular or stereoscopic depiction of three-dimensional situations. It has to do with what is popularly called the "hidden-line problem" of computer graphics. In general the required geometric calculations are quite straightforward, particularly if the

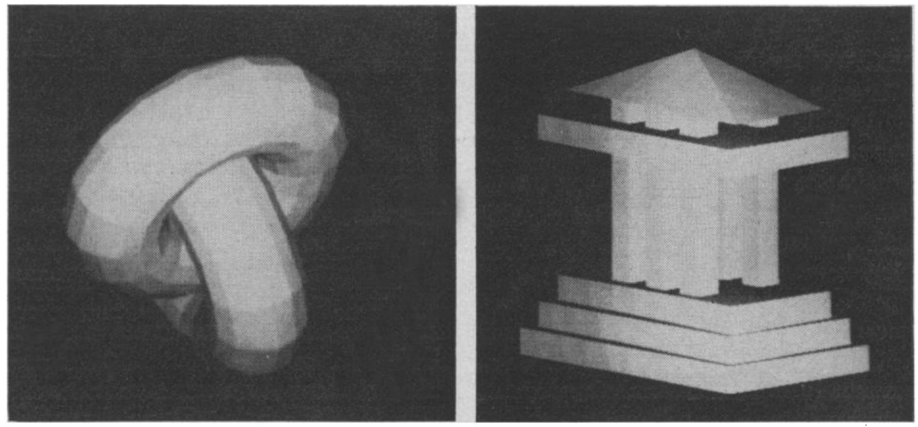


Fig. 15. Halftone portrayal of two three-dimensional objects that never existed; all surfaces and luminosity values are computed and displayed from abstract geometric specifications of polyhedra, viewing angle, and illumination source location.

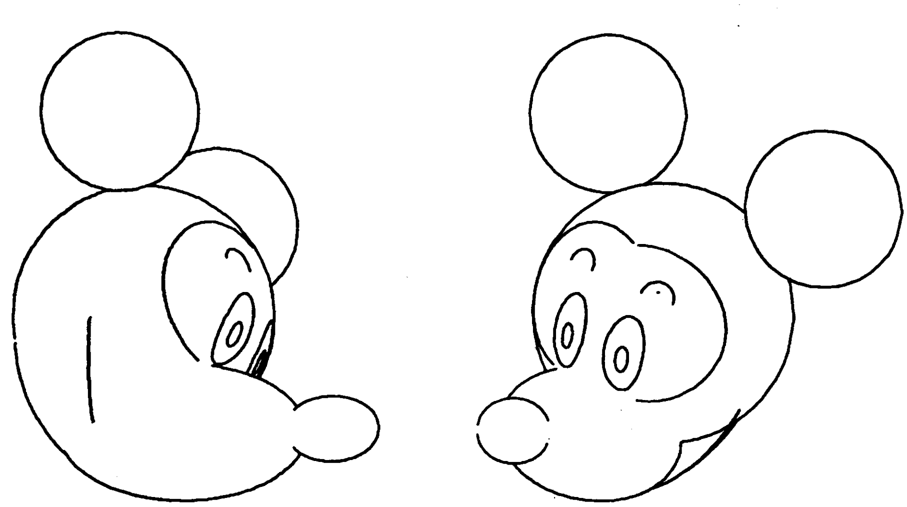


Fig. 16. Two views of a three-dimensional surface which is "moved about" in computer by simple instructions after its parametric specifications are entered. Novel viewing aspects (perhaps not visualizable by programmer) are printed out on command. [© Walt Disney Productions]

objects are polyhedra (*27*). Even so, if many surfaces or bodies are involved, or if some bodies are not convex, the automatic determination of edge visibility can require an inordinate amount of calculation. If one takes a naive approach the computations go up roughly as the square of the number of edges. For moderately complex situations, computation can thus become infeasible, even for modern computers and especially for movies requiring thousands of frames. (Sometimes the question is avoided entirely simply by drawing all lines, thus giving the "wire-frame" rendition.)

A great deal of effort therefore has been devoted to the development of efficient strategies for determining and remembering just which parts of which lines are obscured by which surfaces. Fairly good schemes have in fact been devised, not only for solving the visibility problem for edges (*8*, *28*, *29*) but also for halftone rendering of the visible parts of faces, as though the polyhedra were illuminated from specified directions. Two illustrative examples (*30*) appear in Fig. 15.

If the three-dimensional bodies are not polyhedra, the problem can be very difficult, though it has been handled well in some special cases. Quadric equations in rectangular coordinates can be used for defining surfaces and volumes; profits and intersections of such surfaces can readily be found by numerical means (*28*). Figure 16 shows a cartoon character rendered by computer after having been reduced to a set of quadric equations.

Arbitrary surfaces can be represented with another method which is straightforward but somewhat tedious with regard to both input and computation. It is simply depiction by a series of successive cross-sections, each represented numerically by a sequence of coordinates of sufficiently closely spaced points. (This is the abstract-specification analog of the natural-data example shown in Fig. 10). This procedure is currently used in the computer-aided design of automobile bodies (*31*).

An intriguing implement for artists is brought into being by all these techniques for transforming and especially for generating pictures. The computer with its manifold controls is a tireless tool permitting many rapid experiments. The cover photograph is but one of many kinds of "computer art" [see refs. (*19*) and (*32*) for a sampling of the variety]. One widely explored form is generated by x-y plotter pen tracings displaying solutions to simple harmonic equations. Figure 17 shows an attempt to produce a representational drawing by means of such equations; most people are more familiar with the Lissajous-figure type of nonrepresentational computer "art" (and, of course, many intermediate forms exist).

Finally, another kind of computer picture processing concerns data which when analyzed by humans are pictorial but which need not be pictorial before machine use. Electroencephalography and electrocardiography are examples. Thus while one thinks of electrocardiographic signals as visual patterns (commonly displayed as pen tracings), there is no need for any graphical, intermediate step in automatic analysis. Direct signal transmission from electrodes to computer gear is common. Of course, final output may very well be graphical to aid human judgment (*33*).

Summary

Computer picture-processing techniques provide important new tools for science, engineering, education, and art. The catalog is spectacular. Image analysis ranges from submicroscopic to cosmological and from natural phenomena to complete abstraction.

The utility, both quantitative and qualitative, is similarly spectacular. The primary quantitative gains are in labor, time, and money. Tedious human effort is saved; hours or days of delay are compressed to minutes; and processing,

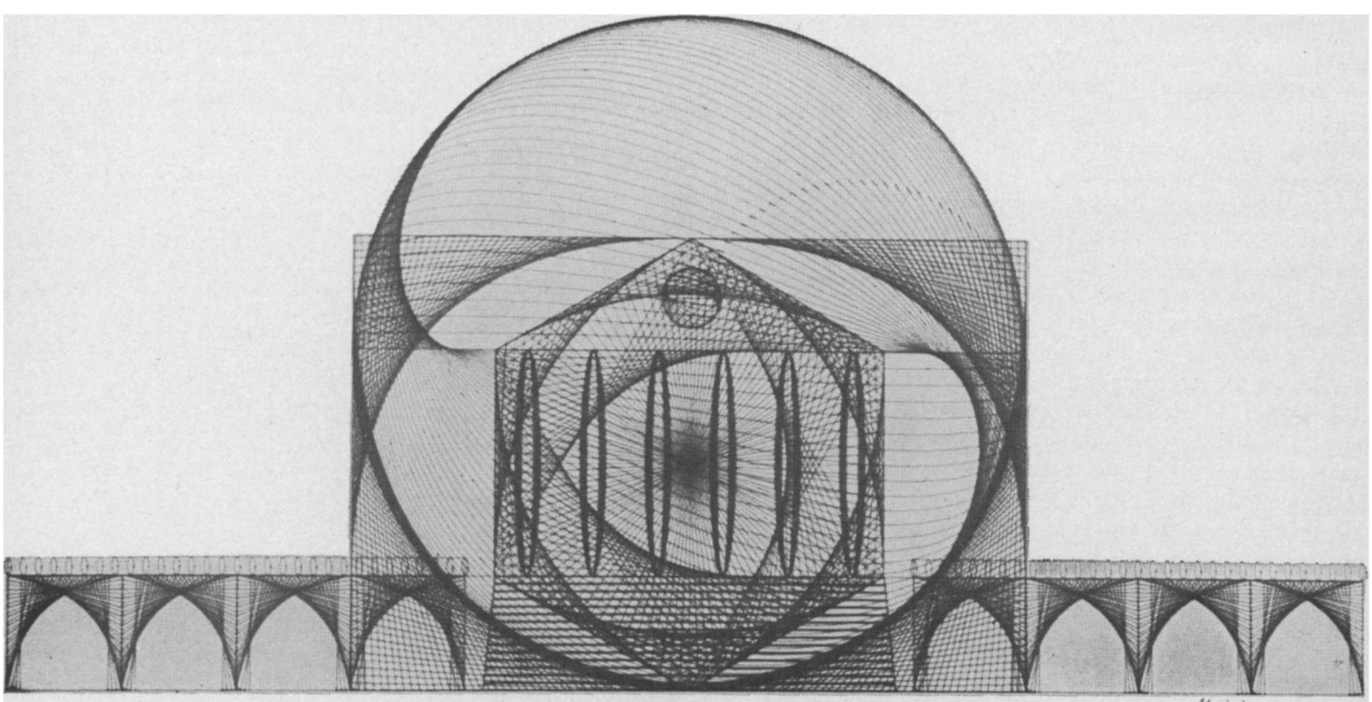


Fig. 17. "The Rotunda," an example of computer art for its own sake; an x-y plotter traces solutions to harmonic equations. [© 1967, Lloyd Sumner, Computer Creations]

which only a decade ago would have been exceedingly expensive, is now relatively cheap. Further, accuracy and repeatability are vastly improved.

The qualitative changes, however, are most impressive. The new technology makes it possible for one to "see" the invisible, enhances the exercise of imagination, and permits experiments to be done with a flexibility and rapidity that otherwise would make those experiments prohibitive or impossible.

The intellectual excitement here does not depend on the computer. The fundamental importance lies in the algorithms—the procedures and programs implemented by the machine. True, the great speed, economy, versatility, storage, and elegant calculations of modern digital computers are essential, but only as properties of a tool. The vital importance rests in the ideas which direct the motions of that tool, the algorithms.

Computer-processed pictures provide an excellent way to convey to a researcher the qualitative implications of his preliminary assumptions. This saves unnecessary analysis of incorrect guesses. Such reduction of time and effort permits the human to give greater attention to more demanding tasks, those which after data analysis and display require subsequent processing and further decisions.

In many cases these latter stages must still be relegated to people. This is true for two reasons. The eye and brain achieve an efficiency through parallel, associative operations which cannot be achieved with present-day computers. Those operations normally left to people—recognition, perception, contemplation—involve extremely complex cognitive processes on many levels of abstraction. We know very little about the nature of these processes, much less how to get a machine to replicate them in other than trivial ways.

The picture processing of modern computer technology has come a long way from last century's production of patterned weaving specified by punched cards in the Jacquard loom. And though difficult to envision, the accomplishments of the next decade (just the third in modern computer development) may be even more striking and useful. Even now the evolution from static portrayal of points and lines to shaded, moving, and colored presentations presages important new advances.

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