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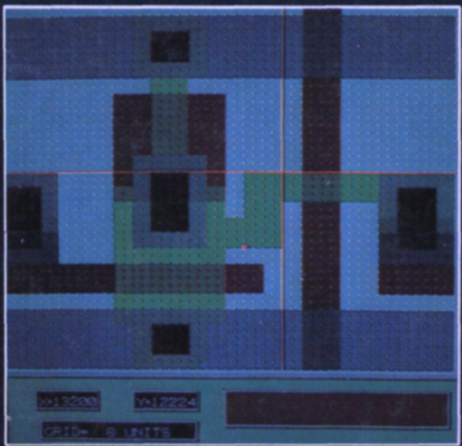

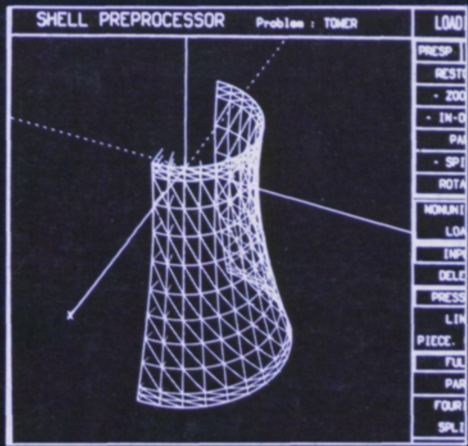

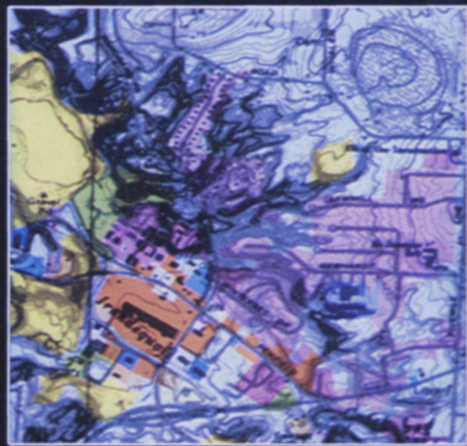

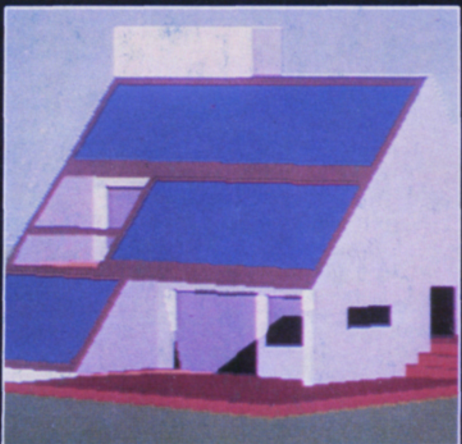

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THE ADVANCE OF COMPUTER GRAPHICS

IN THIS ISSUE

Professor Donald P. Greenberg, director of Cornell's Program of Computer Graphics and of the College of Engineering's Computer-Aided Design Instructional Facility (CADIF), explains an important and rapidly developing technology.

With the enthusiastic endorsement of faculty members and students, CADIF is established at the College of Engineering.

Three Cornell professors of structural engineering—John F. Abel, Anthony R. Ingraffea, and William McGuire—explore the potential of computer graphics in their discipline and describe Cornell research in this area.

John C. Dill, manager of the computer-graphics instructional facility (CADIF) at the College, draws on his industrial experience with the technology to assess the impact of computer-aided design and manufacture.

Cornell professor Daniel P. Loucks and his associates Peter N. French and Marshall R. Taylor discuss the significance of computer graphics in their field of research.

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Opposite:* *Students have access to a bank of color raster stations in Cornell's recently established Computer-Aided Design Instructional Facility (CADIF). The large student laboratory makes available, for course work throughout the engineering departments, the best computer-graphics equipment on the market today.

HOW COMPUTER GRAPHICS WORKS AND WHAT IT CAN DO

by Donald P. Greenberg

A sophisticated but easy-to-use tool that extends the perceptions and capabilities of designers has become economical as well. These facts—not any recent technological breakthrough or scientific discoveries—account for the current popularity of computer graphics in research, business, and industry. Display hardware is commonplace today and is certain to become more pervasive in the future. And as appropriate software is developed, highly effective computer-graphics systems are becoming available for a wide range of applications.

The reason these systems work so well is that they provide fast and easy visual communication. The reason they are economical is simply that computing and the production of electronic components have been steadily decreasing in cost. It is no longer feasible to ignore the graphics technology.

As a result, computer graphics has become a standard tool and the term has entered the everyday technological vocabulary. Yet there are many interpretations of what it means. This article attempts to define the technology, describe it, and indicate its diversity, complexity, and potential.

GRAPHICS DATA BOTH IN AND OUT

In many engineering industries, documents are automatically drafted using digital plotters to produce high-quality line drawings, and such operations certainly fall within the domain of computer graphics. The video games that are currently so popular are another illustration of the capability of machines to draw or display information. More impressive are the airplane simulation systems used for training pilots: realistic views of the terrain as seen from the cockpit windows are dynamically displayed.

These examples indicate the *display* capability of computer graphics. What is not as well known, but is perhaps even more important, is the ability of the user to draw or scan information into the computer. Graphic input can be two-dimensional, in the form of sketches or maps, or it can be three-dimensional, in the form of descriptions of solid objects such as mechan-

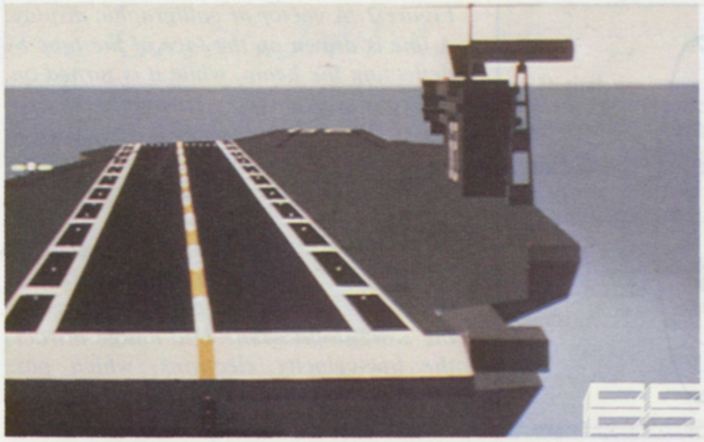
Figure 1. A sampling of applications, in addition to those in engineering, in which computer graphics has already been used. Many more are anticipated; the technological advances have moved so rapidly that they have outpaced the capacity for immediate application.

The programming for three of the images shown here was done by Cornell graduate students.

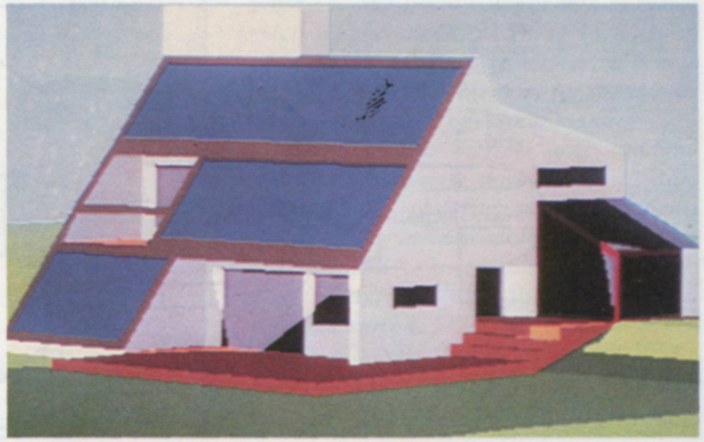
a. *Real-time digitally generated raster displays simulating views from the cockpits of aircraft and spacecraft were an early application. To be effective for pilot training, the images must be sufficiently real to provide all the necessary visual clues and they must be generated fast enough to simulate motion. (Reproduced by courtesy of the Evans and Sutherland Computer Corporation.)*

b. *Computer graphics will radically change the ways in which architects work and communicate with their clients and engineering colleagues. With the ready creation of textured or shadowed computer-graphics images, it will be possible to "walk around" a proposed building even before work on the construction documents begins. (The illustration shown is from a program by Peter Atherton.) The geometric modeling techniques not only will allow*

Figure 1a



1b



1c

1d

more designs to be evaluated at the preliminary design stage, but will create a database that can be shared by cost estimators and structural engineers. Drafting will be completely automated and the need for construction of elaborate scale models will be eliminated.

c. *In the field of medicine, computer-graphics systems are being used increasingly to present biomedical information for research, diagnosis, and treatment planning. For example, the capability of combining two-dimensional information from x rays or CAT scans into three-dimensional images can give medical specialists a better view of body structures; such pictures might reduce the need for exploratory surgery or help in planning radiation therapy for cancer patients. The surface representations of a human skull and brain shown here are examples of such three-dimensional images (these are from a program by Alex Sunguroff). Another kind of medical application is the use of color vector displays to model the attachment of drugs to protein molecules.*

d. *Cartoon animation is one of the most highly publicized applications of computer graphics. To create motion in an animated sequence, a large number of pencil sketches drawn by the animator are xeroxed on transparent celluloid, painted, combined with a background scene, and filmed with an animation camera. With computer-graphics technology, the pencil sketches can be digitized and automatically colored and merged. Recent developments will also allow the simulation of multiplane camera work and special effects. The figure shown here is one frame of a scene from Hanna-Barbera's forthcoming film* Heidi; *the frame was processed at Cornell according to a computer-graphics program by Marc Levoy and Bruce Wallace.*

Figure 2

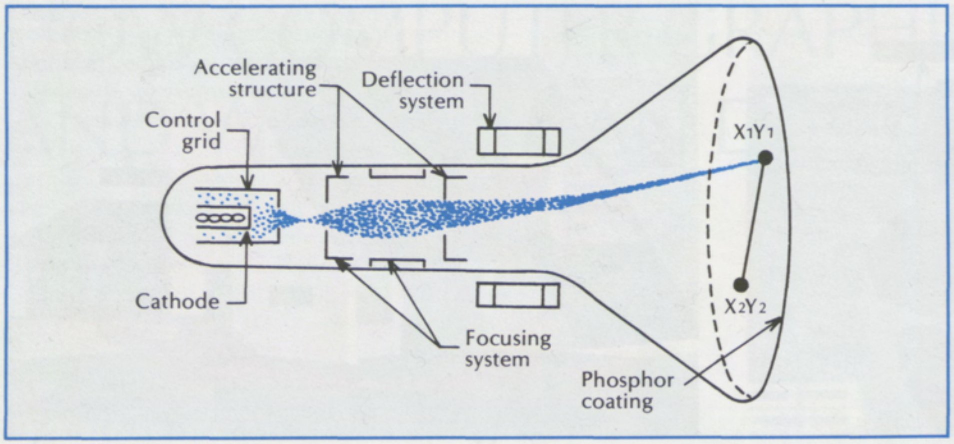


Figure 3

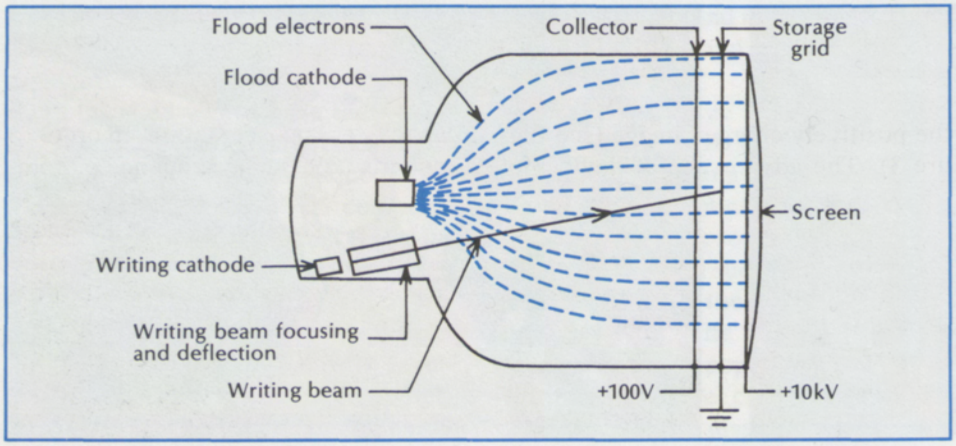


Figure 2. A vector or calligraphic display. A line is drawn on the face of the tube by deflecting the beam, while it is turned on, from one position (x_1, y_1) to another (x_2, y_2). A pattern of visible traces is developed to form the image, which is continuously refreshed to produce a steady picture.

Figure 3. The direct-view storage-tube vector display. The writing beam creates an image by depositing a positive charge on the storage grid. The grid image attracts the low-velocity electrons, which pass through the grid and strike the phosphorescent screen, reproducing the image.

ical parts or automobile bodies. This *input* into the system complements the display or *output*. Together they provide an effective means of dialogue or interaction between the user and the machine. A comprehensive description of computer graphics, therefore, includes the communication of graphics data both to and from the computer.

A distinction between passive and active computer graphics should also be made. The plotting of a drawing is an example of *passive* graphics: it can occur any time after the information has been created. Such an operation may be performed at locations different from the user site or at periods of low demand, such as night-time hours. *Active* computer graphics, on the other hand, requires two-way communication, and instantaneous feedback is necessary to make it effective. (How would one feel, in trying to draw, if the ink didn't flow from the tip of the pen as it moved, but instead the line appeared at some later time?) With *interactive computer graphics* the response is immediate: when commands to position elements or rotate objects are given, the displays are generated fast enough to give the appearance of active user control.

Although the fast response and dynamic displays required for interactive computer graphics place enormous demand on the computer system in terms of processing power, storage, and data transmission, such systems have the great advantage of being able to display not only graphical representations of the objects being modeled, but the results of analytical routines as well. This important feature allows the designer to participate in an interactive design loop, inserting human creativity into the decision-making process, and it constitutes the fundamental characteristic of effective systems for *computer-aided design* (CAD).

HARDWARE COMPONENTS OF GRAPHICS SYSTEMS

Two main types of computer display equipment are commonly available: calligraphic or vector displays and ras-

Figure 4

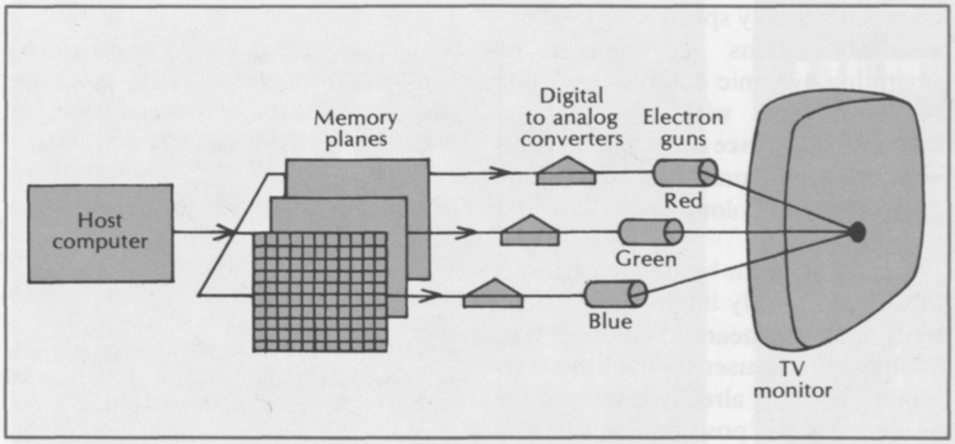


Figure 4. The basic components of raster video display devices. These include, in addition to the host computer, a frame buffer (a large, fast memory for storing the image data) and a television monitor.

Modern frame buffers use random-access integrated memory circuits to store a rectilinear array of picture elements (pixels). They are available in many different sizes with various resolutions and levels of intensity; currently, the most popular versions store a 512 x 512 or a 640 x 480 matrix of pixels, but devices with 1024 x 1024 resolution (more than a million memory locations) are now on the market.

ter video displays. Both kinds depend on the glow emitted by a phosphorescent screen when it is bombarded by a stream of electrons.

The vector displays are cathode-ray tubes with the ability to draw from one arbitrary (x_1, y_1) location on the screen to another (x_2, y_2) location. Electrostatic or magnetic fields are used to control the movement of the electrons and, therefore, the positioning of the beam (see Figure 2). If the beam is turned on when it is deflected to various parts of the screen, it leaves a visible trace, but in order to produce a steady, flicker-free picture, the pattern must be *refreshed* frequently. Fortunately, if successive images are drawn fast enough, the human visual response is to interpret them as continuous images. Motion can be simulated also by changing the picture content rapidly.

One early and still very popular type of vector display is the direct-view storage tube. In this device, a writing beam is used to deposit a positive charge, thereby defining an image on a storage grid mounted directly behind a phosphorescent screen. Then the image is transferred to the phosphor-coated surface by a flood of low-velocity electrons that are attracted to the positively charged image (see Figure 3). The advantages of devices of this kind are that they are dependable and relatively inexpensive and can maintain the picture information for long periods of time, allowing complex images to be drawn without the need for constant refreshing. The disadvantages are the slow writing speeds and the inability to selectively erase portions of the image—characteristics that prevent the simulation of motion except for very simple images.

For truly interactive graphics, fast vector-refresh display systems are favored. Although the complexity of images is limited, many thousands of vectors can be drawn every thirtieth of a second, allowing the simulation of dynamic motion. Also, current devices can effect dynamic rotations, translations, and perspective transformations—capabilities that enable the user to obtain a fully three-dimensional perception of the object being modeled. This type of display is still relatively costly, however.

A trend in vector-refresh hardware is to make more use of computing capacity at the user station. In order to generate a changing sequence of complex displays, the computer has to send large quantities of information to the display device very rapidly, and this places heavy demands on the central processing unit. New graphics systems can store the model description locally, however, so that only the information necessary to transform the views needs to be sent from the large host computer. With the advent of more powerful microcomputers, even the procedures for creating models and generating displays will probably be stored locally.

Raster video units, the other category of display devices, consist of two basic components (see Figure 4). One component, frequently called a *frame buffer*, stores the image data in computer memory and reads the memory at video rates. The digital output is converted to video output through a digital-to-analog converter (DAC) and is displayed on the second component, a standard or high-resolution television monitor.

Frame buffers store images as arrays of picture elements, or *pixels*, each of which has an x,y location and an intensity value; an image is displayed, in a manner similar to the technique used by the pointillist painters, as a matrix of dots. The newest frame buffers can store a 1024 X 1024 matrix of pixels and require more than one million memory locations.

The intensity of the picture element is a function of the memory depth. A black-and-white image requires only one bit per location; eight bits can accommodate 2^8 or 256 different intensity levels. If color maps are being used, for example, the operator can select 256 colors from a very large range of possibilities. A three-channel display, each with eight bits, can generate 2^{24} colors simultaneously. To create a picture, it is necessary to write and store the appropriate intensity for each pixel in the image array. Once the image is stored, the information is traced out in *raster* fashion: line by line in an ordered and sequential manner. (All television systems use this rectilinear scanning system.)

Because of the economy of television monitors, the decreasing cost of computer memory, and the desire for color images, raster devices are rapidly becoming more popular. Their main advantage is their ability to display halftone and color images as well as vector images. The disadvantages are the large amount of memory needed to store the image, the time required to write the image, and the high data-transmission rate. At the present time, only specialized (and expensive) systems are capable of generating dynamic color images, but the trend—as with the vector devices—is to place more intelligence in the individual unit, potentially providing dynamic color display for ordinary use.

In addition to the hardware required for display, a truly interactive system needs to have a means of entering data graphically. The user should be able to "point" to items already displayed on the screen or to "position" new items. The most common graphical input devices are the light pen and the digitizing tablet with its accompanying stylus. The light pen is a passive photocell device, similar to an electric eye; when the operator points it at the screen of a cathode-ray tube, the position of the photocell is identified by means of a software tracking program in the computer. To use a digitizing tablet, the operator moves the stylus on the tablet to the desired location, as indicated by a cursor on the screen, and presses down; the location of the stylus is determined either electronically or acoustically and transmitted to the computer. In this way information can be graphically entered into the computer in the same way one would create a drawing.

THE MODEL: FIRST STEP IN PICTURE GENERATION

Creating a continuous-tone computer image of a simulated object consists of five major tasks: (1) creating a mathematical description; (2) transforming this into a two-dimensional perspective image; (3) removing lines and surfaces that are not visible to an

Figure 5. Vector displays illustrating methods of defining complex solid objects on computer-graphics systems. The images are from programs developed at the Cornell research facility.

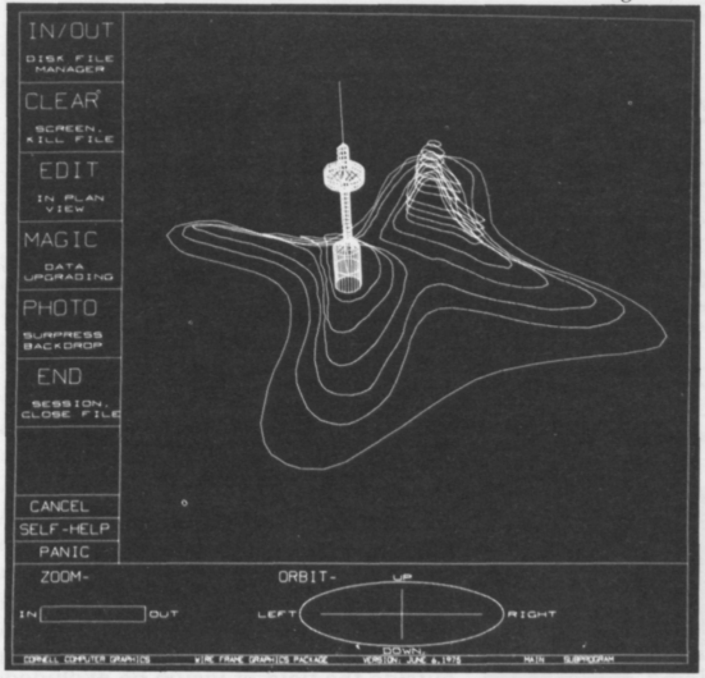
a. *A popular method of graphical input is* lofting. *A set of serial cross sections of an object is interactively defined in a manner analogous to tracing the contours from a topographical map. This display of a television tower on a mountain was defined in less than a minute according to a program by Marc Levoy. The tower was created by automatically repeating the contour at different elevations.*

b. *Another common graphical input approach can be thought of as an extrusion method: the system can generate a line from a point, a plane from a line, or a three-dimensional object from a plane. In each case, the direction of the extension has a unique relationship to the original two-dimensional definition. This "sweep representation method" is particularly appropriate for mechanical and architectural design. The display shown here is from a program by Wayne Roberts.*

c. *Graphical input of free-form surfaces can be made with "patch" definitions, as shown in this display from a program by Brian Barsky. Patches are used for sculptured surfaces, such as automobile bodies, that curve in two directions. The patch is a function of two variables, with continuity of slope and curvature and formulated to allow local control: the image can be interactively modified. Curved surfaces can be formed also by lofting (as shown in the figures on pages 30 and 31).*

d. *In procedural modeling the object geometry is not defined explicitly, but is generated according to a predetermined general shape. For example, a program by Eliot Feibush allowed the illustrated stair designs to be created with the input of only height, width, and type of stair.*

Figure 5a



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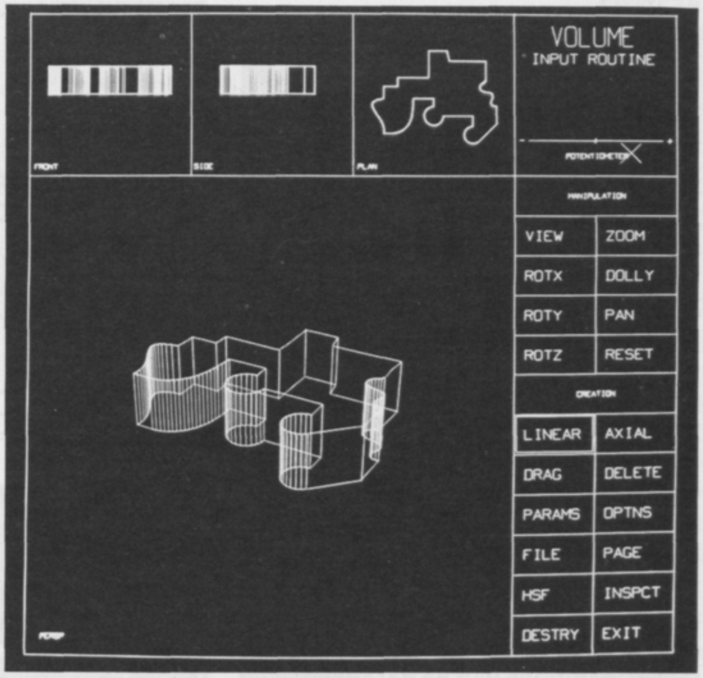

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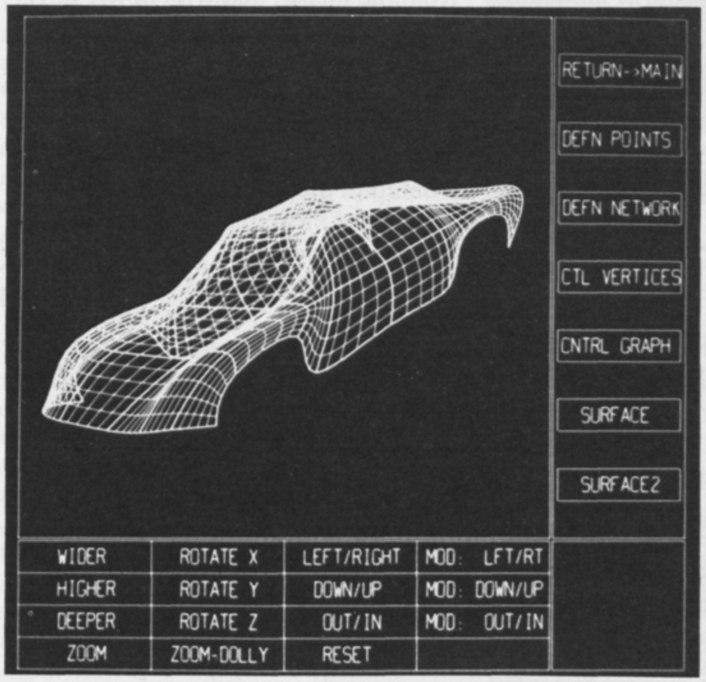

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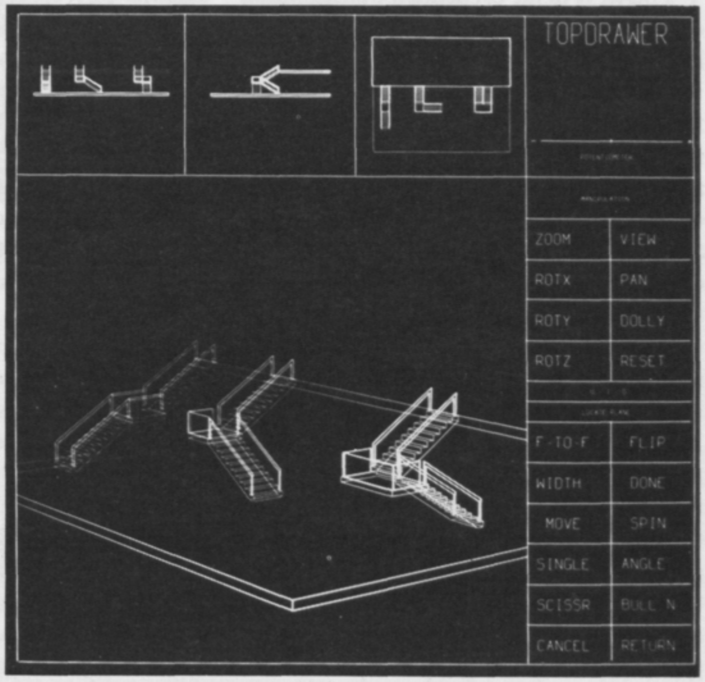
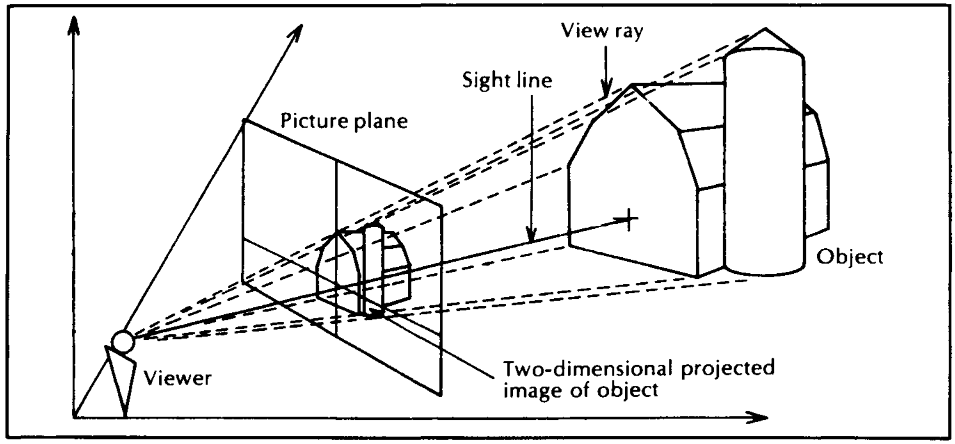


Figure 6. Perspective in computer-graphics images. To represent a three-dimensional object, the mathematical description must be transformed into a perspective image. The method is to determine the intersections of the view rays (the lines between the observer's eye and points in the environment) with an imaginary picture plane (perpendicular to and at a fixed distance from the observer). A perspective transformation matrix is used to calculate the ray intersection points on the screen. Portions of the image that are outside the "window" of the field of vision must be mathematically "clipped."

Figure 6



observer of the real object; (4) determining the color or shade of each surface or part of the environment; and (5) selecting the intensities of the three primary colors that will produce the coloring needed for the model. Each of these operations will be described.

The first task, creating a mathematical description of a geometric model, has been the chief hindrance to widespread adoption of computer graphics for design: cumbersome or mathematically complex input methods discourage or prohibit the use of automated design procedures. Viable input systems provide the ability to define an object easily, to manipulate and edit the object description, to combine elements, and to display the composite results rapidly for visual feedback, and such systems are now available.

Most of these new systems combine primitive elements to create descriptions of complex solid objects, descriptions that eventually provide the geometrical and topological information needed to define vertices, vertex coordinates, lines, and surfaces. The primitive elements may be defined in three ways: numerically, graphically, or procedurally. *Numerical* input, which is simply typed in through a keyboard, is accurate but cumbersome, time-consuming, and noninteractive. Figure 5 illustrates some of the many *graphical* input approaches and the powerful *procedural* modeling method that is likely to become very important in the future.

Regardless of how the initial objects are created, they must be combined to create composite objects. Computational functions such as the Boolean operations of union, intersection, and difference allow the hierarchical construction of complex solids.

DEALING WITH PROBLEMS OF PERSPECTIVE AND VISIBILITY

To create a display of the three-dimensional object that has been mathematically described, it must be transformed into a two-dimensional perspective image. The traditional mechanical-drawing way of doing this is to use vanishing points, where the view rays emanating from the observer's eyes intersect with an imaginary picture plane (see Figure 6). The same kind of operation can be performed mathematically with computer graphics through the use of a perspective transformation matrix. The technique requires that points and lines outside the field of vision be excluded from the image, and with newly developed display devices this can be accomplished as part of a single hardware matrix multiplication.

The so-called *visible line or visible surface problem,* which must be confronted in the next step of image creation, is the most difficult and computationally expensive part of all the software procedures. A computer does not know what it is not supposed to display; it must determine which surfaces are hidden from the view of an observer. This is basically a *sorting* problem, for which there are many available solutions.

For a polygonally defined environment, each polygon must be compared with every other polygon to determine their relative closeness to the observer. Of course, the more complex the environment, the greater the

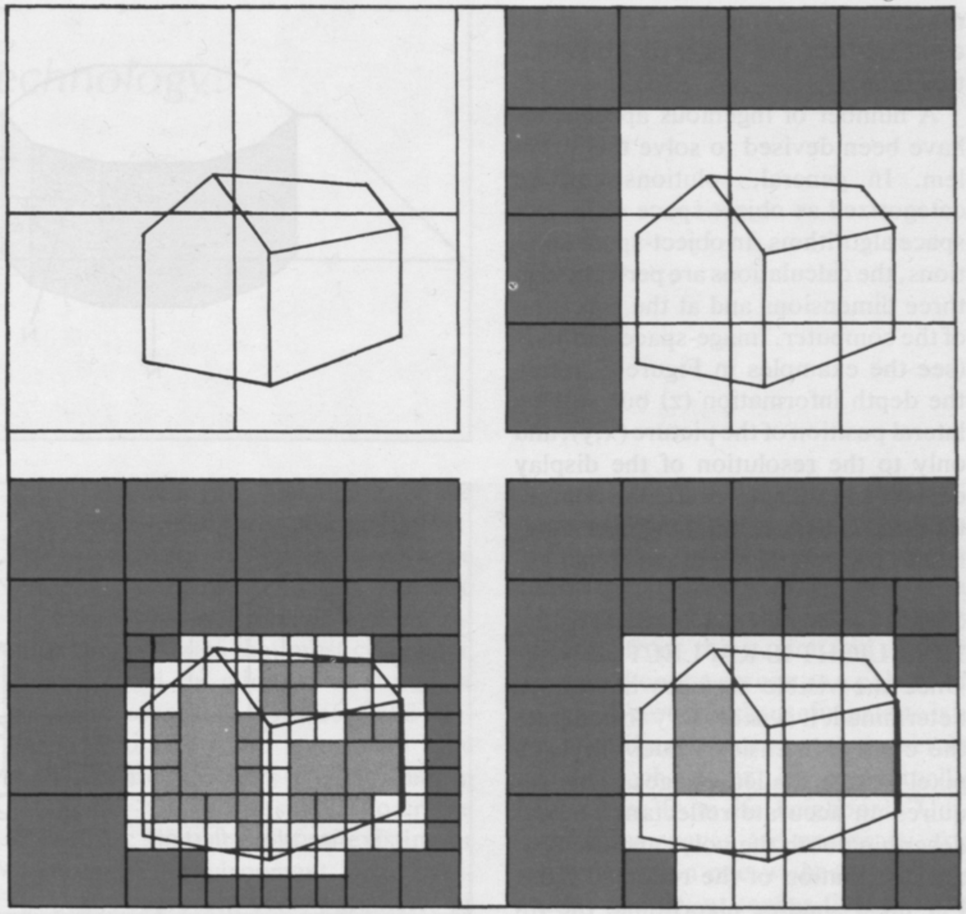
Figure 7. Approaches to the problem of how to display only those lines and surfaces that would be visible to an observer.

Of the so-called image-space methods, the simplest is the use of a depth-buffer *algorithm. The objective is to create a hidden-surface display by calculating, independently, the intensity of each pixel. In a polygonally defined geometry, each pixel may "cover" polygons from several surfaces (represented by different colors), and the idea is to select whichever polygon is closest to the observer. For each pixel with its* (x,y) *location, a value of* z *is obtained by solving each polygon's plane equation. The closest polygon is identified and information on its depth and color is stored in a depth buffer and an intensity buffer and subsequently displayed.*

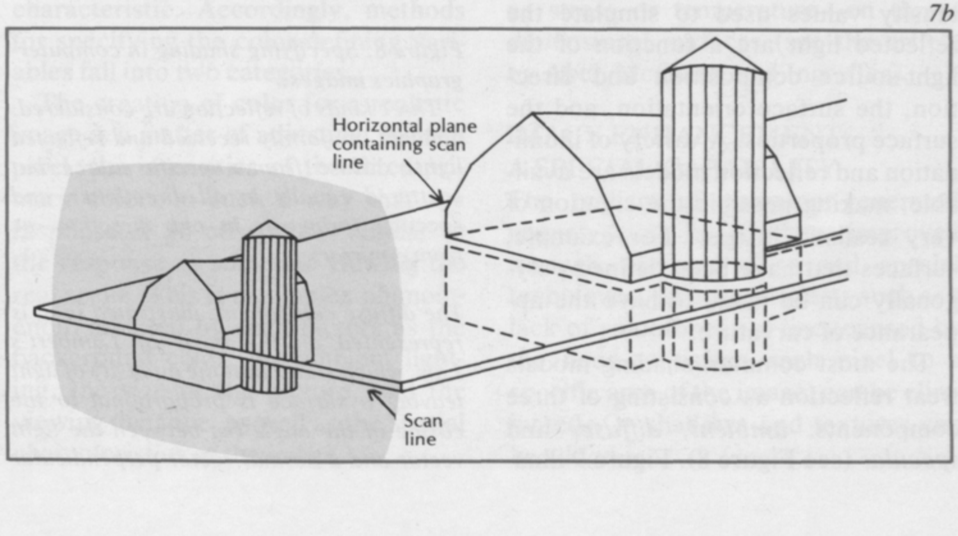
Another prevalent image-space method is to use a windowing *algorithm, illustrated in* a *(adapted from John Warnock of the University of Utah). Windowing algorithms recursively divide the image into smaller and smaller windows until either the visible contents are simple enough to determine or the window is as small as the desired resolution of the picture. (The figures, clockwise from the upper left, indicate the recursive subdivision.) In this method, subdivision occurs only where necessary; the computation time is roughly proportional to the visible complexity.*

Scan-line *algorithms, illustrated in* b, *provide a third image-space method. (This display was generated according to an algorithm by Gary Watkins of the University of Utah.) Such algorithms sort only those planes that are intersected by a plane containing the given scan line. Since a raster video display generates its image by sweeping horizontally across scan lines from top to bottom, the information from the algorithm is already ordered for the display.*

Figure 7a



7b



number of polygons that have to be compared and the longer the computation time.

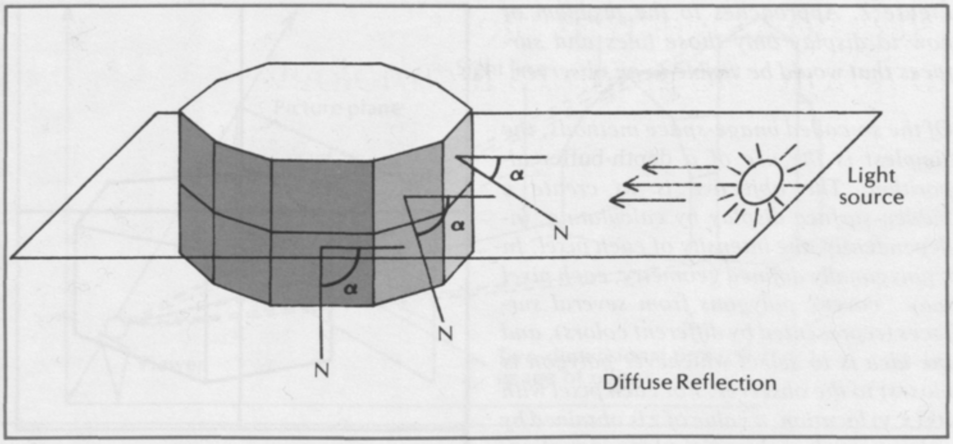
A number of ingenious approaches have been devised to solve this problem. In general, solutions can be categorized as object-space or image-space algorithms. In object-space solutions, the calculations are performed in three dimensions and at the precision of the computer. Image-space methods (see the examples in Figure 7) retain the depth information (z) but sort by lateral position of the picture (x,y), and only to the resolution of the display device. In order to reduce the computational expense, all standard algorithms use some form of *coherence*.

SHADING MODELS TO SHOW HOW LIGHT IS REFLECTED

Once the visible surfaces have been determined, it is necessary to compute the correct intensity values for each pixel in the shaded images. This requires an accurate reflectance model describing both the color and the spatial distribution of the reflected light. For most shading algorithms, the intensity values used to simulate the reflected light are a function of the light-source composition and direction, the surface orientation, and the surface properties. A variety of illumination and reflection models are available, making possible the creation of very realistic images. For example, surfaces that have been defined polygonally can be made to have the appearance of curvature.

The most common shading models treat reflection as consisting of three components: *ambient*, *diffuse*, and *specular* (see Figure 8). Figure 9 illus-

Figure 8a



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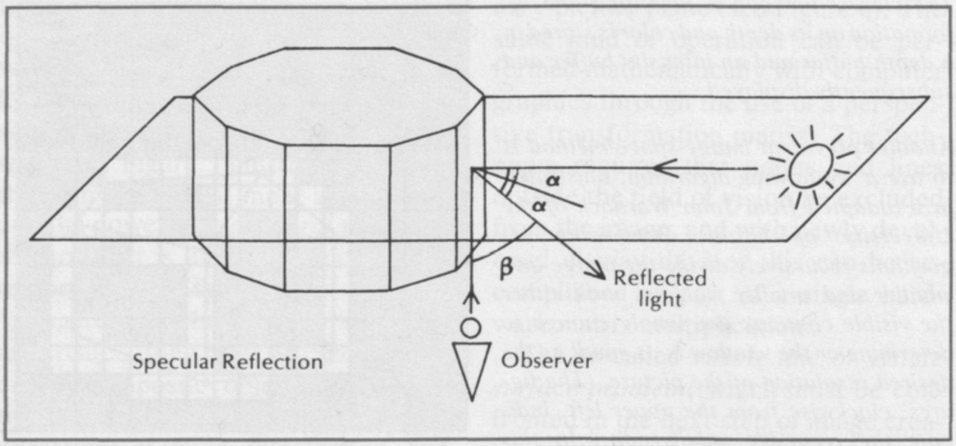


Figure 8. Specifying shading in computer-graphics images.

Three kinds of reflection are considered: ambient *(uniformly received and reflected light),* diffuse *(from a specific source, but scattered equally in all directions), and* specular *(primarily in one direction, as from a mirror).*

The diffuse component, illustrated in a, *is represented on the basis of Lambert's Law, which states that the intensity of light leaving a surface is proportional to the cosine of the angle (α) between the light vector and a normal vector perpendicular to the surface. The amount reaching an observer is independent of the observer's position.*

In specularly reflected light (b), *the angle of incidence is the angle between the light rays hitting the surface and the vector normal to the surface. Since such a ray reflects off the surface only at a specific angle, it can be seen by the observer only if the eye is located at a specific place. How much of the reflected light an observer can see depends on the angle β. This effect can be represented approximately by a cosine to a power function; higher cosine powers indicate more mirror-like surfaces.*

"It is no longer feasible to ignore the graphics technology."

trates how appearance—including the glossiness of a surface—can be affected by variations in the mathematical expression.

Recently published illumination models produce even more realistic images by accounting also for surface roughness and slope, material properties, and reflection geometry. The directional distribution and the spectral composition of the reflected light are represented, on a wavelength basis, as functions of these properties. Figure 10 shows two spheres that illustrate the Fresnel effect of angular variation in the spectral composition. When transmission of light and refraction are considered, transparent objects can also be modeled, as illustrated in Figure 11.

SPECIFYING COLOR FOR GRAPHIC IMAGES

A color television monitor has three electron guns, one for each of the three primaries, and the screen is composed of triads of red, green, and blue phosphor dots. A color is produced by controlling the voltages of each of the three electron guns and therefore the intensities of the three primary colors. It is possible to generate a large number of colors with this additive system. (The trichromatic generalization theory states that most colors can be matched by additive mixtures of suitable amounts of three fixed primary colors.)

There are two ways of using color in computer-graphics displays: to create a realistic simulation of an existing or hypothetical environment, or to symbolically represent some parameter or characteristic. Accordingly, methods for specifying the color-defining variables fall into two categories.

The creation of color for a realistic image is a matter of adjusting, in each pixel, the intensities of the three primary colors in such a way that the response of an observer is similar to the response of someone viewing the real scene. This is a complex phenomenon, affected by such factors as the background color, the ambient lighting, the size of the picture, and the viewing distance, as well as the spatial characteristics of the image.

For a symbolic representation, *pseudo colors* are selected from within the gamut that is available in the color-reproduction device. One of a large number of possible color scales is selected from the gamut and simply presented on the screen as a palette of colors. A particularly useful palette is a set of uniform color spaces—a set in which each color is perceptually equidistant from its neighbors. Uniform color spaces are necessary, for example, when one wishes to display scalar, vector, or tensor fields—such as stress or temperature—on three-dimensional surfaces (see the article by Abel, McGuire, and Ingraffea).

IMAGE ENHANCEMENT: A SPECIAL CAPABILITY

The realism of computer-generated images can be further improved through the use of several special techniques. Aliasing artifacts such as a lack of smoothness of line (caused by the need to assign each pixel to a specific area of the image) can be eliminated. Or shadows and textures can be added.

Figure 9

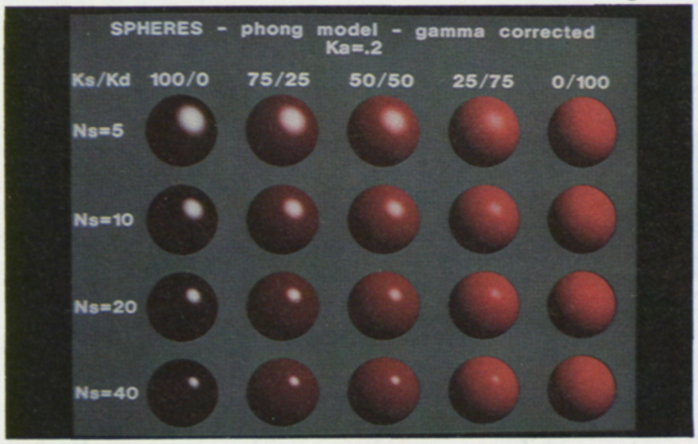


Figure 10

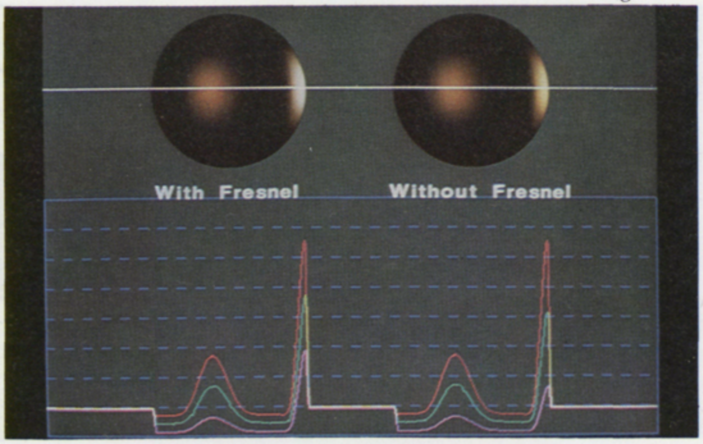


Figure 11

Figure 12

Figure 13

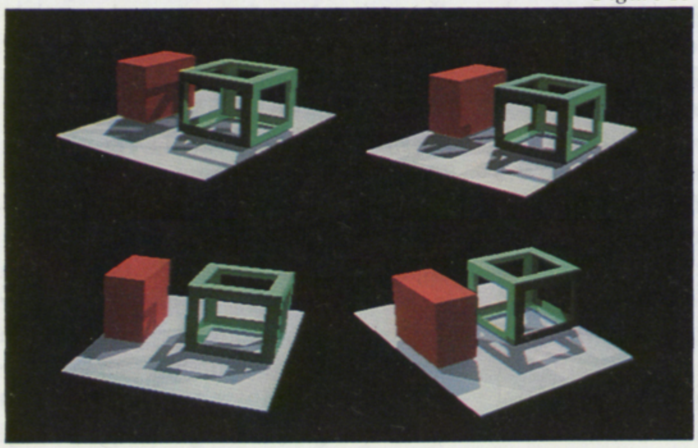
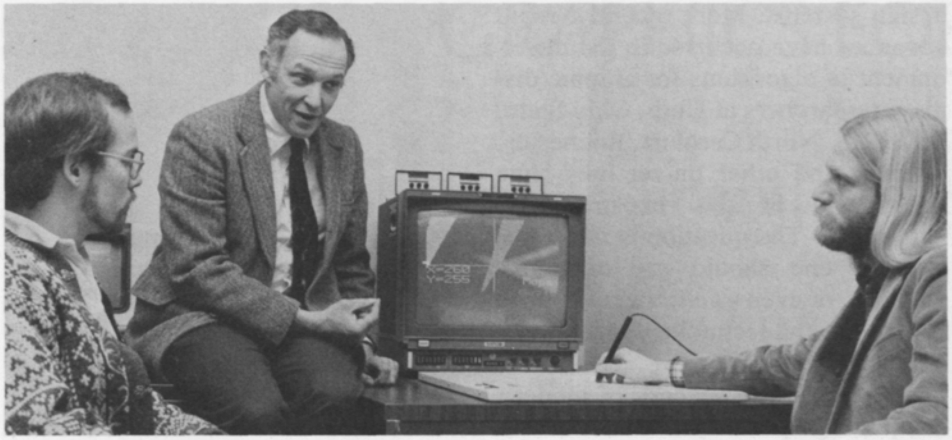


Figure 14



Left: Staff members of Cornell's Program on Computer Graphics discuss the development of techniques for creating color graphic displays. From left to right are Wayne Robertz, a research support specialist; director Donald P. Greenberg; and Ted Crane, a senior system programmer.

Figure 9. The appearance of surfaces in computer-graphics images as affected by the mathematical expressions for reflection. The figure (from a program by Roy Hall at Cornell) illustrates the effects of variations in the diffuse and specular coefficients and also in the specular exponent (as the exponent increases, the surface looks glossier).

Figure 10. Taking account of surface geometry in representing illumination. The two spheres in this display (from a program by Rob Cook at Cornell) illustrate the Fresnel effect of angular variation. The spheres are lit, identically, by one light near the observer and another light on the far side. Graphs at the bottom indicate the color values of every pixel on the scan line and also the color shift at near-grazing angles.

Figure 11. Modeling transparent objects. For objects such as this simulated champagne glass, the transmission and refraction of light, as well as the reflection, must be represented. (The program for this display was by Doug Kay at Cornell.)

Figure 12. Enhancing images by reducing aliasing problems such as a lack of smoothness of line. These problems are a result of assigning each pixel to a certain area of the image, even though it might "straddle" a boundary line. A solution is to assign to such a pixel a color that is a weighted average of the colors of the neighboring polygons. Note the smooth edges of the polygon facets in this display (programmed at Cornell by Rob Cook and Stu Sechrest).

Figure 13. Enhancing perspective images by shadowing. This display (from a Cornell program by Pete Atherton) shows shadowing caused by two light sources. Shadow descriptions are found by "viewing" the environment from the position of the light sources: by a hidden-surface kind of analysis, those polygons that are illuminated are distinguished from those that are in shadow.

Figure 14. Texturing for more realism. In this example (from a Cornell program by Eliot Feibush) the brick pattern was mapped from a "texture tile" onto the geometrically defined object. Techniques are now available to simulate either intensity or geometric pattern, and to "map" them onto either polygonal or parametrically defined curved surfaces.

One method for reducing aliasing problems is to increase the sampling rate by increasing the image resolution: the effects of aliasing are not eliminated but they are noticeably reduced. A more correct method is to filter the original function. For example, if an edge intersects the area defined by a pixel, the resultant color should be a weighted average of the colors of the two polygons on either side of the edge (see Figure 12).

The addition of shadows to a perspective image (see Figure 13) improves the depth perception of the display. A shadow is the darkness cast by an object intercepting light. Theoretically, then, no shadows are visible when the observer's position is coincident with that of the light source; they become visible as the observer moves away from the source of illumination. Shadowing in a computer-graphics image provides valuable positional information and improves the ability of the user to comprehend complex spatial environments.

Simulating the texture or patina of a surface also enhances the realism of an image. The patterns to be simulated might be variations in intensity and color, such as a wallpaper pattern or a photograph, or they might be variations in surface texture, such as the skin of an orange. To achieve a realistic effect without having to describe each minute element of the object surface, it is convenient to "map" the texture pattern onto the appropriate surfaces of the geometric model, a technique called *texturing* (see Figure 14).

THE CONTINUING EVOLUTION OF COMPUTER GRAPHICS

As we have seen, computer-graphics techniques are being introduced rapidly as applications proliferate. Developments in both hardware and software are making the technology increasingly useful in a large variety of disciplines.

The basic technique—the use of computers to draw pictures—is not, of course, new. Digital plotters and point-plotting displays existed thirty years ago. Solutions to differential equations were being displayed on a cathode-ray oscilloscope in MIT's Lincoln Laboratory in the early 1950s. The SAGE air-traffic-control system to detect and display the location of aircraft over the continental United States was introduced in 1953.

The impetus for interactive computer graphics can be traced to Ivan Sutherland's SKETCHPAD system developed at MIT in 1962. Subsequently, several manufacturers, particularly in the aerospace, automotive, and shipbuilding industries, began to develop and use interactive computer graphics as part of the computer-aided design systems. More recently, rapid advances have occurred in the development of algorithms for graphic display; researchers at Utah, Ohio State, MIT, RPI, North Carolina, Rochester, Cornell, and other universities have contributed to this expansion of knowledge. The question is no longer *whether* one should use computer graphics, or even *when*; the problem is *how* to use the technology most beneficially.

The key to the success of modern computer-graphics systems is the natural mode of communication it makes possible between the user and the machine. It is fast, permitting conversation-like interaction, and it is pictorial, presenting information in the form people are most accustomed to. For we live in a visual world. Information can be obtained faster visually than with any of our other senses and we acquire most of our knowledge through our eyes. Most of us depend on visual images to help us comprehend our world and its complexities: it is much easier to understand a picture than a verbal or numerical description of the same information.

With computer graphics, a user can concentrate on the picture and entrust the data and its manipulation to the computer. The immense advantage is expressed in a computer-jargon variation of a common saying: a picture is worth 1024 words.

Donald P. Greenberg is director of both the University's Program on Computer Graphics and the College of Engineering's Computer-Aided Design Instructional Facility. A professor in the College of Artchitecture, Art, and Planning, he teaches in the fields of architecture, structural engineering, and computer science.

He studied both architecture and engineering at Cornell and at Columbia University and earned two Cornell degrees—a baccalaureate in civil engineering and a doctorate in structural engineering. As a consulting engineer with Severud Associates of New York City during the 1960s, he worked on numerous building projects, including the St. Louis Arch, the New York State Theater of the Dance at Lincoln Center, Madison Square Garden, the Princeton University Athletic Cage, and the Air Force Museum. He joined the Cornell faculty in 1968.

Greenberg has been teaching and conducting research in computer graphics since 1966. His specialties include hidden-surface algorithms, geometric modeling, color science, and synthetic image generation. In addition to publishing numerous articles on these subjects, he worked with the General Electric Visual Simulation Laboratory to produce a film, "Cornell in Perspective," using computer-graphics techniques. He is currently on the editorial boards of three professional journals on computer graphics.

COMPUTER GRAPHICS FOR STUDENTS

A Fun Way to Learn Faster and Better

The rapid advent of computer-based methods in the nation's engineering workplaces has required parallel new instructional programs in the engineering schools. Computer graphics, which is fast becoming a standard tool of the profession, is an outstanding current example.

Fortunately, computer graphics is also a remarkable educational tool. Students can not only learn to use a new skill, they can use the new techniques to help them learn. Both simple and complex concepts, especially those involving motion and geometric relationships, are more readily grasped when they can be visualized on the display screen of a dynamic interactive computer-graphics terminal. The learning process is faster, easier, and better; moreover, it is fun.

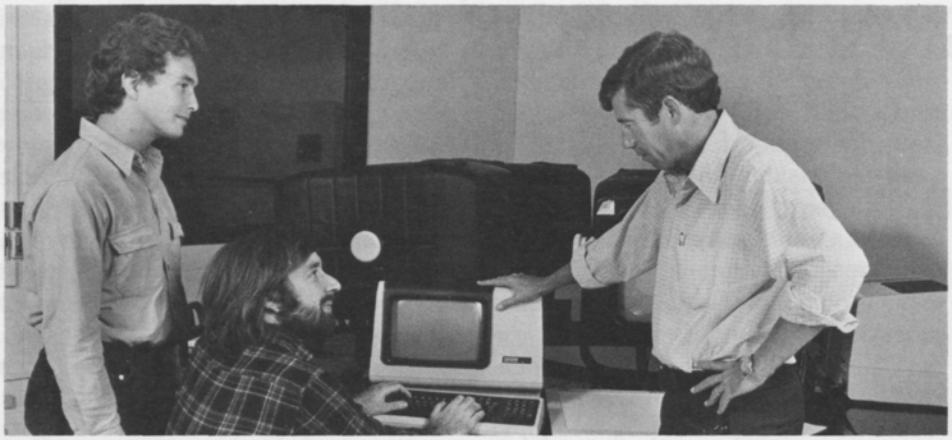
At Cornell about two hundred undergraduate engineering students were exposed to computer graphics during the spring term last year and in the fall more than three hundred took courses that included instruction in the new techniques. Soon all students in the College of Engineering will have the opportunity to learn with the help of computer graphics and to prepare themselves to use the techniques in their various areas of engineering practice and research.

What has made this fast and substantial development possible is the establishment of the Computer-Aided Instructional Facility (CADIF) at the College of Engineering as the educational arm of the University's computer-graphics facility. Staffed by experts and equipped with an impressive array of the best equipment available, CADIF is one of the most advanced instructional facilities in computer graphics in the world. Functional after less than two years of preparation, it is ready to adapt its services to course work in every department of the College.

THE CADIF LABORATORY, EQUIPMENT, AND STAFF

The refurbished laboratory space for CADIF is on the ground floor of Hollister Hall, just inside the entrance that opens directly on the engineering quadrangle. This is a covenient location both for structural and environmental engineering students—primary users, whose school is centered in the building—and for students from other departments. The space includes a large laboratory for student use, a laboratory for software development, an air-conditioned machine room, offices, and consulting rooms.

The equipment in the machine room includes two central processing units with large memory capacity, and peripheral processing units for the graphics stations. There are four disk drives for mass storage and a tape drive for backup and for transferring programs and data between installations. Operations are carried out at any of eighteen user stations: six each of the color raster, vector-refresh, and Tektronix storage tube types. Each station is provided with a digitizing tablet and pen for entering and manipulating the data and the images on the display units. Also, a total of twenty-four alphanumeric editing and command-system terminals are provided at the user stations and in the software development laboratory. The



Left: Key staff members at CADIF are John Dill, manager (at right); Garry Wiegand, systems programming (center); and Channing Verbeck, applications programmer (at left). Professor Donald P. Greenberg (author of the lead article in this issue) is the director.

Table I. CADIF HARDWARE

Unit	Number	Make or Description	Function
Host computers	2	DEC* VAX 11/780 and 750	Central processing
Peripheral processors	5	DEC PDP 11/44	Display control
Stations			
Vector refresh	6	Evans and Sutherland Multipicture Systems (2 with 3 displays each)	Dynamic graphic and alphanumeric display
Color raster	6	Grinnell GMR 270 (resolution: 512 x 512, 8 bits deep, 4 overlay planes)	Full-color graphic and alphanumeric display
Storage tube	6	Tektronix 4014	Graphic and alphanumeric display
Editing and command system terminals	24	DEC VT 100	Alphanumeric input and display
Digitizing tablets and pens	18	CalComp/Talos Wedge	Data and image input and manipulation
Disk drives			Mass storage
67-megabyte	2	DEC RM03	
256-megabyte	2	DEC RM05	
Tape drive	1	DEC TU77	Archival storage
Printers	3	DEC LA 120	Alphanumeric hardcopy
Plotter	1	Versatek V80	Graphic hardcopy

**Digital Equipment Corporation*

vector-refresh units and the digitizing tablets all utilize minicomputers, which reduce the demand on the central processing unit and provide enhanced graphic response. Additional equipment includes three printers and a plotter. A summary of the hardware is shown in Table I.

Effective use of the excellent facilities depends on the experience and availability of the staff. The director of CADIF is Donald P. Greenberg, who is also the founder and director of the University's research program in computer graphics. The manager is John C. Dill, who assumed the position after ten years in computer-aided design at General Motors. Others on the technical staff include a systems programmer, an applications programmer, and several part-time student assistants. As a College facility, CADIF comes under the supervision of the dean, Thomas E. Everhart, who is advised by a special faculty board.

HOW THE FACILITY HELPS TO EDUCATE ENGINEERS

With the advent of CADIF at Cornell, both the mode of teaching and the content of many courses are changing. Concepts difficult to explain and understand can be successfully incorporated into course work. Assignments previously thought too time-consuming can be included. Problems

The three types of stations available at CADIF are illustrated in these photographs taken at the facility.

1. A color raster station is being used by this student. The unit includes an alphanumeric editing and command system, a television monitor, and a digitizing tablet and pen.

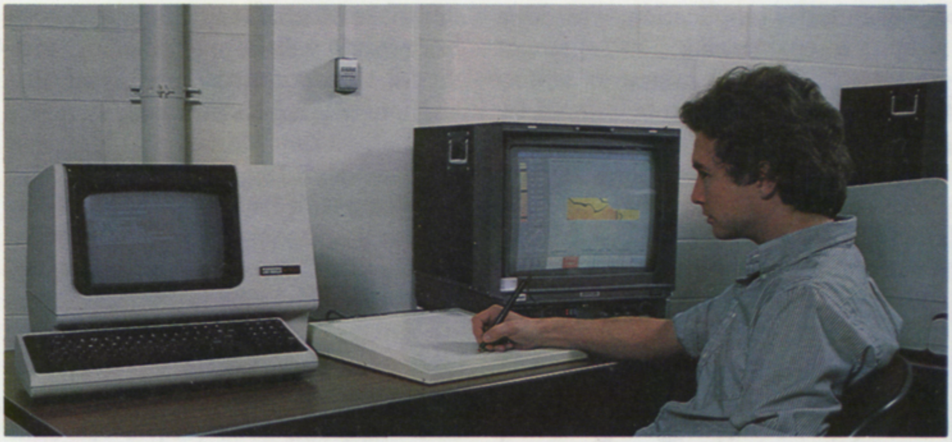
2. A vector-refresh station includes equipment similar to that in a color raster device, except that the display is a black-and-white line drawing. The image can be easily altered in any detail and subsequently analyzed. A special feature of this hardware is the capability for dynamics: the position or orientation of an object can be continuously changed.

3. A Tektronix storage-tube station includes a display unit, an alphanumeric keyboard, and a digitizing tablet and pen. Using this display device is comparable to drawing on a child's slate; once an image is drawn, it cannot be altered very much. In this respect it is less adaptable than the vector-refresh unit, which permits complete changes of the image instantaneously. Its advantages include its ability to display a large amount of information and its relatively low cost.

more like those encountered in "real life" can be attacked.

The courses that can benefit most are related to design or involve two- or three-dimensional information or combinations of temporal and spatial variables. Many of these courses have been identified and CADIF is already being used in some of them. One of the earliest instructional uses at Cornell was an obvious one: laboratory work in Greenberg's course in computer graphics, which is offered by the Department of Computer Science.

1



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Another early application was in a structural engineering course taught by John F. Abel. A course in water-resources planning is to be offered by Daniel P. Loucks. (The remarkable potential of computer graphics in these last two fields is explored in other articles in this issue.) By last fall the structural engineering department had added two additional courses, taught by Peter Gergely and Anthony R. Ingraffea, that incorporate computer-graphics techniques. During the past year, Dean L. Taylor of the mechanical and aerospace engineering faculty developed software that is now being used in several of his courses.

Instructional possibilities are still being worked out in several courses. One of these is being proposed jointly by the School of Civil and Environmental Engineering and the School of Mechanical and Aerospace Engineering as one of the new Introduction to Engineering series for freshmen and sophomores. The assignments, involving what might be called engineering graphics or descriptive geometry (a modern extension of drafting), will be designed to help the students understand geometrical relationships, especially three-dimensional ones.

In the Department of Theoretical and Applied Mechanics, Richard H. Lance is planning to introduce computer graphics as a teaching aid in two introductory courses. Students in Dynamics will be able to "see" graphically what they are analyzing mathematically in class assignments—to observe the mechanical effects of changing parameters such as mass, spring stiffness, or shock-absorbing capacity in vibrating systems. In Mechanics of Solids, laboratory work will be extended by additional "experiments" performed at a computer-graphics terminal.

In the Department of Materials Science and Engineering, Rishi Raj (working with Paul R. Dawson of Mechanical and Aerospace Engineering) proposes to introduce computer-graphics techniques in the Macroprocessing of Materials course. The plan is to use CADIF facilities for instruction in time-dependent metal-working processes such as superplastic forming and isothermal forging. Initially the students will use computer graphics to learn how microstructure and material properties can influence formability; later, simulations of processes involving ceramics and polymers will be included.

In a number of departments, the course applications have been or are being developed by faculty members who are heavily involved in the use of computers in their research. Keith Gubbins, for example, proposes to use CADIF in Chemical Engineering Thermodynamics to help students understand three-dimensional phase diagrams that are drawn with the help of perspective and color. A computer-graphics program will enable students to "zoom in" on various sections of a diagram, or rotate it in order to view different surfaces from different angles, or "slice through" the diagram along, say, a surface representing constant temperature.

In geological sciences, Larry D. Brown is exploring the use of computer-graphics techniques for modeling geophysical measurements

continued on page 22

The following are comments entered into the computer by student users of CUFF (see opposite page). Some additional technical suggestions were subsequently implemented in the program.

"CUFF is a lot of fun and it really makes you think about what different constraints, loadings, and configurations will do to an actual structure."

"It has helped me quite a bit in determining deflections just from loads and constraints. I can imagine how useful a system like this would be for design."

"I find the program very practical in that it gives us the chance to spend our time in thinking about the way we should solve the problem instead of in trying to use the computer."

"I think this is really great. I hope I have more opportunity to use it. When will there be library problems made up for us to solve?"

"I think the program is a great help. Can I use it on the test?"

■ One of the major uses of CADIF is in structural engineering courses. After several years of software development, two programs were introduced this year in courses taught by Peter Gergely and Anthony R. Ingraffea. Seventy students used the facility during the fall term.

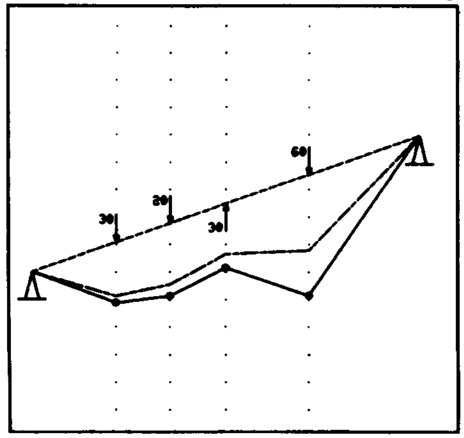
These computer-graphics exercises did not replace any course material, Gergely points out. Their function is to greatly facilitate learning. In a one-hour session at the console, a student can accomplish what would take perhaps twenty hours at a desk or could not be done at all. The ready comparison of many solutions develops the "feel" for structural behavior that is essential to good engineering.

GISMA, the introductory program, is very easy to use: for example, the input data are provided simply by selecting menu items with use of the stylus. Results (as *1*) are displayed as deflected shapes, internal forces, and moment diagrams; the effects of input changes are immediately observable.

CUFF (for Cornell University Funicular Form-Finding) is used to study cable structures. Each student solves selected problems involving the effects of parameters such as loading, span, and cable geometry. The analyses display such information as sag, tension, and horizontal force. A valuable feature is that the student must anticipate results: shapes must be chosen before the computer will display results for comparison. The image in *2* is a trial shape, together with the correct solution; *3* shows solutions for several different input values.

The programs were developed by graduate students Daron Libby and Eric Fan under the supervision of John F. Abel.

3



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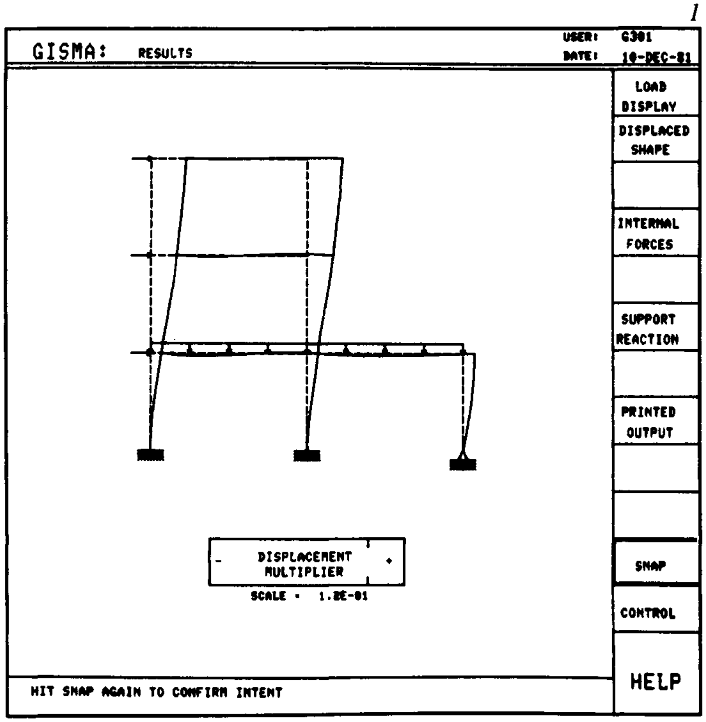

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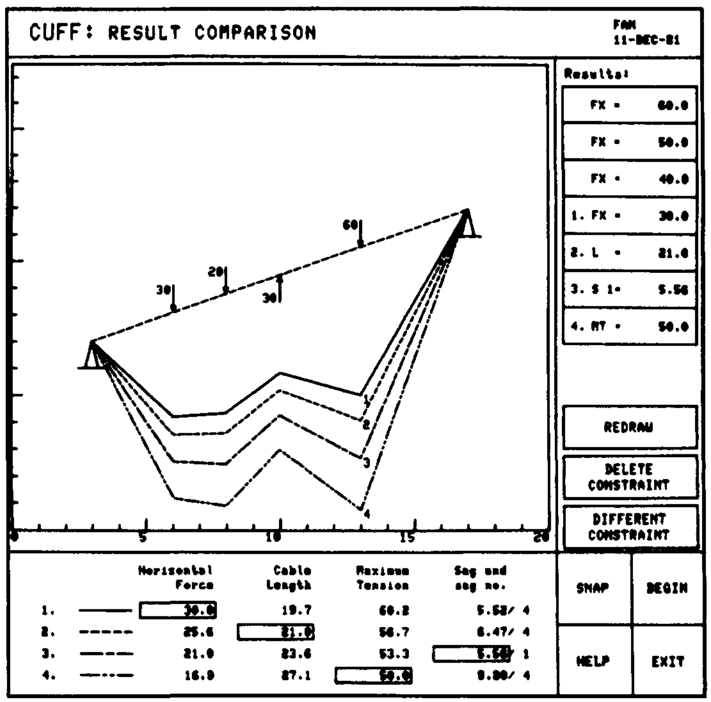


■ Mechanical and aerospace engineering professor Dean L. Taylor is using the CADIF facilities as teaching aids in his introductory course in systems dynamics and in his advanced course in mechanical vibrations.

The graphics equipment most helpful for understanding three-dimensional motion is the dynamic vector-refresh unit. For example, a drawing of a mechanical structure can be displayed and then its configuration or motion under various loads pictured dynamically. The operator gives commands or makes design changes using the digitizing tablet and pen.

An example is illustrated in *1*, which is a composite of images of a vibrating radar dish. (This one was originally designed for use on a satellite.) The operator has called up the basic sketch and has asked the computer to demonstrate the motion (the natural response mode) of the dish under a specified load such as might be caused by an earthquake or wind excitation. The figure reproduced here shows two "stills" selected by the operator for hardcopy printing. (The color has been added during the printing of the magazine to help distinguish the two images and suggest the motion.)

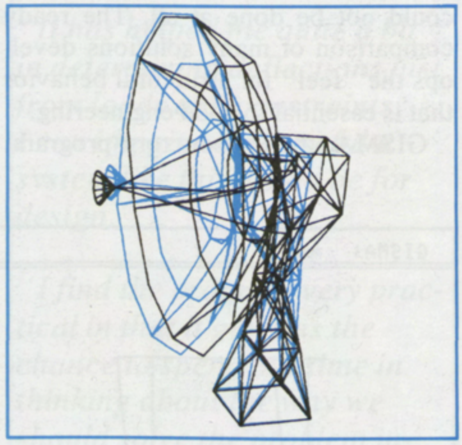
The graphic images are driven by a computer simulation of the physical device. The accuracy of the simulation can be tested easily by the visualization of the system response. The program for this classroom exercise uses a basic graphics software package developed in the University's computer-graphics research facility; the simulation and the interface were written by Taylor.

Another mechanical system Taylor has set up at CADIF represents a four-bar linkage. Superimposed "stills" taken from the dynamic imaging on the vector-refresh display unit are shown in *2*. (The color has been added.) The student can interactively select any combination of rod lengths. Observing the resulting motion helps not only in visualizing the changing spatial configurations, but in understanding the dynamics of the various elements. The comparative speeds of motion are indicated by the lengths of the dashes in the coupler curve.

Other images already available with CADIF programs include aircraft and automobile simulations. Last year, for example, students in Taylor's course in systems dynamics worked on the design of an autopilot for a helicopter. The dynamic vector-refresh imaging helped them specify and optimize the design parameters.

Professor Dean L. Taylor demonstrates a computer-graphics simulation of a large mobile sculpture. On the table is the physical model that was used as the basis of the computer simulation.

1



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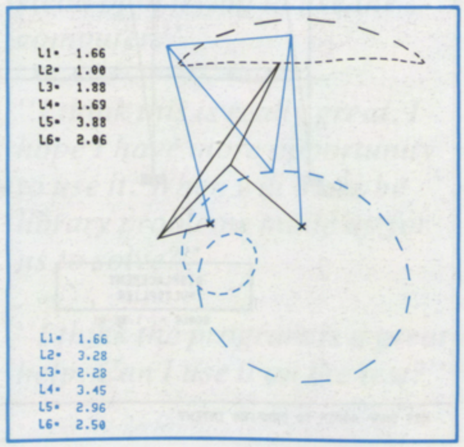

■ Cornell students in an advanced electrical engineering course learn how to design VSLI (Very Large Scale Integrated) circuits (chips) using computer graphics.

The process of fabricating a chip begins with the design of a set of *masks*, which are patterns for chemical processing on a silicon wafer. A computer-controlled optical *pattern generator* executes the design according to instructions provided through a program called a *layout editor*.

In *1*, Professor Christopher Pottle demonstrates the use of a simple layout editor developed for CADIF by graduate student George Cavanaugh. The orange cursor on the screen corresponds to the point on the digitizing tablet where Pottle is locating the pen.

An introductory student exercise produced the drawing in *2*: two six-binary-digit shift registers. Five superimposed layers are each drawn in a different color.

A zoom-in (*3*) shows one shift-register cell. (This was automatically replicated in *2*.) The crossing of a polysilicon area (red) over a diffusion layer (green) results in a transistor; there are three in this cell.

The editing features of the system are illustrated in *4*. The yellow mask has been removed and a green rectangle defined by the orange dot and the cursor will be deleted by the next pen depression (the item ERASE and the green level have been selected on the menu).

The student-designed chips have been actually fabricated and tested by the General Electric Company.

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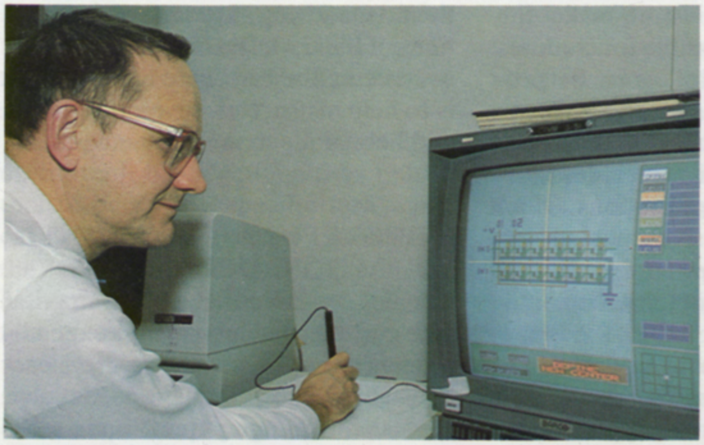

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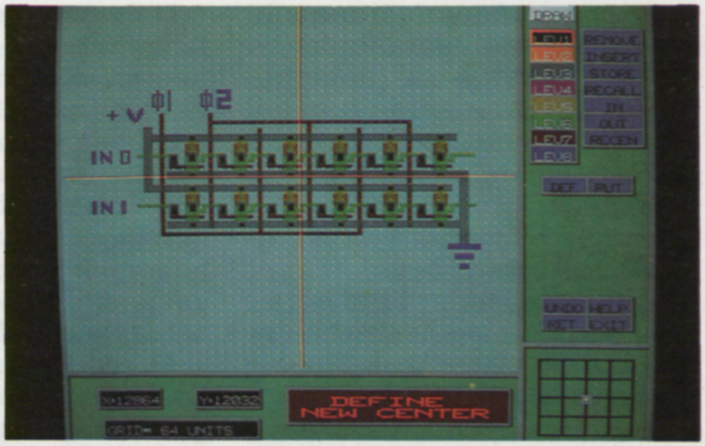

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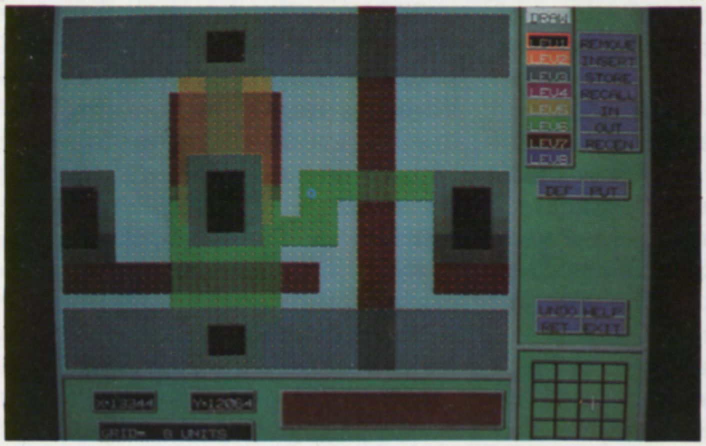

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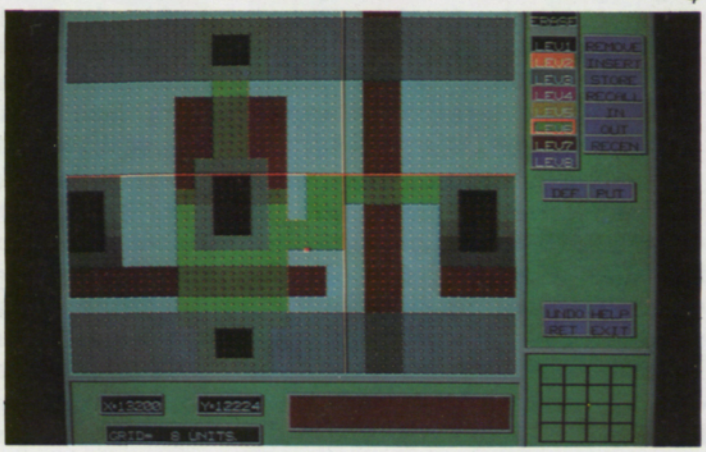


continued from page 18
and he plans to introduce the method in course work. In electrical engineering, Christopher Pottle is using CADIF in a recently introduced course in VLSI (very large-scale integrated) circuit design. Students employ state-of-the-art color graphic techniques to prepare a layout of the circuit masks that are used in fabricating a silicon chip.

The initial use of CADIF in the operations research and industrial engineering curriculum is an exercise devised by Professors William L. Maxwell and Lee W. Schruben and programmed by Christopher V. Jones for a course in industrial systems analysis that was taught last fall by Schruben. A problem in cash-flow management illustrates how computer-graphics techniques can be useful in solving economic analysis problems.

The policy of the facility is to concentrate on undergraduate education, at least initially, and to select courses on the basis of proposals submitted by the academic units. At the present time, each school or department is entitled to develop one or two courses, or parts of several courses, subject to approval by the faculty advisory board and the facility personnel.

Table II. CURRENT MAJOR FUNDING FOR CADIF

General Purposes	Source
Capital equipment; development of laboratory areas	ARCO Foundation Digital Equipment Corporation The Garrett Corporation Grumman Aerospace Corporation Joseph N. Pew, Jr. Trust
Development of instructional programs and specific courses; software development	Alfred P. Sloan Foundation The Boeing Company Western Electric Company Westinghouse Educational Foundation Xerox Corporation

DEVELOPING THE SOFTWARE FOR CADIF APPLICATIONS

Course assignments require suitable software. Sometimes programs developed at the University's research facility (the Program of Computer Graphics) can be adapted for classroom use with appropriate software interfaces or application routines. But often completely new programs must be devised.

The primary aim is to make the facility as easy as possible for students to use. On-line "help" must be provided, for example, and each instructional package must be accompanied by a user's manual that includes illustrative examples of applications. Often a more comprehensive manual explaining the internal program logic and giving references to other documentation is also provided.

An additional aim is to write programs in such a way that they can be readily adapted to new applications. Programming languages are currently restricted to PL/1 or FORTRAN, and standard screen layouts are used for menu items. Many applications require data bases, sometimes extensive, and software developers are encouraged to design their data structures so that future users working on different problems can readily gain access to the information. A minimum of data-base formats is used, and existing structures are preferred to new ones.

Often faculty members must learn how to use computer-graphics techniques themselves before they can use them as teaching aids. One of the functions of the CADIF staff, in addition to overseeing the hardware applications, is to help instructors develop software and help students understand and use it.

SUPPORT FOR A SIGNIFICANT EDUCATIONAL INNOVATION

Keeping engineering education vital and current requires major expenditures of time, effort, and money, particularly when innovations involve sophisticated equipment and techniques.

CADIF at Cornell was advocated by Director Greenberg, strongly supported by Dean Everhart, and funded largely by outside sources. It is being utilized under expert management with the enthusiastic cooperation of departments and individual faculty members and the equally enthusiastic participation of students. It is a good example of how both a college and the industry it serves can recognize the importance of a new educational program and then proceed to implement it.—G. McC.

IN THE VANGUARD OF STRUCTURAL ENGINEERING

by John F. Abel, William McGuire, and Anthony R. Ingraffea

Interactive computer graphics is about to affect structural engineering as much as the computer itself did a decade or so ago.

Computer graphics is obviously a useful tool, but regarding it as only a tool to perform a specific task more easily is as simplistic as considering the electronic computer merely a high-speed calculating device. In addition to performing calculations that would otherwise be difficult or impossible, the digital computer extends in other ways the perceptions and abilities of those who use it; engineers who understand the new methods that have been developed in response to the capabilities of the computer have a better insight into the behavior of the systems they work with. Now computer graphics is beginning to make a similar impact. In the profession of structural engineering, for example, designers and analysts, interacting with their graphics systems, can acquire a better understanding of the structures they are working on and do their jobs more effectively and imaginatively as well as more quickly.

For the past six years Cornell researchers have been contributing to this new surge in computer-aided design and analysis of structures. The focus in the program is on the development of computer-graphics techniques for research in structural mechanics—work that anticipates and demonstrates how these techniques will dramatically improve engineering practice. The Cornell program is aimed particularly at problems in structural and mechanical stress analysis, an area that according to recent estimates is second only to business and administration in the industrial and professional use of digital computation nationwide.

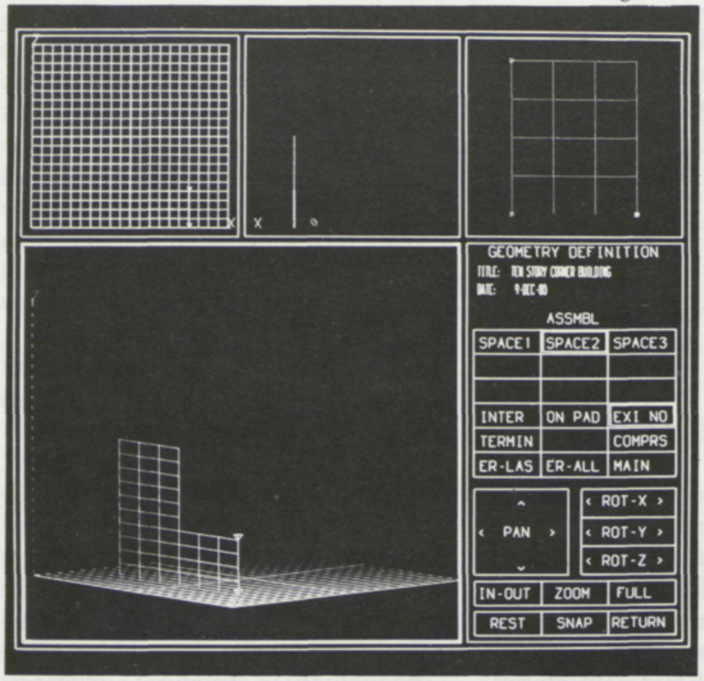
PRODUCTIVITY AND USER CONTROL: PROBLEM AREAS

Despite the widespread adoption of computing for structural and stress analysis (see Richard H. Gallagher, "Consulting the Computer: A New Resource for Structural Engineers," "*Engineering: Cornell Quarterly* 7:21, Spring 1972), there are still at least two serious obstacles to overcome if the full potential of computer methods is to be realized. These obstacles are related to *engineering productivity* and to *control by the engineer* of decision-making in the design-and-analysis cycle.

Productivity in structural and stress analysis involves more than just the actual analytical operations. In the initial part of the process, extremely voluminous and complex descriptions of problems must be prepared and fed into the computer; at the other end, vast quantities of results must be sifted and evaluated to make design decisions. These two aspects—input preparation or *preprocessing* and result interpretation or *postprocessing*—not only consume the preponderance of time and manpower, but also, by their nature, are subject to human error. The need is for greater efficiency and reliability, and one way to achieve these is through better man-machine communication, an auspicious advantage of interactive computer graphics.

Proper control of decision-making in the design also depends heavily on analysis, for structural designers are

Figure 1a



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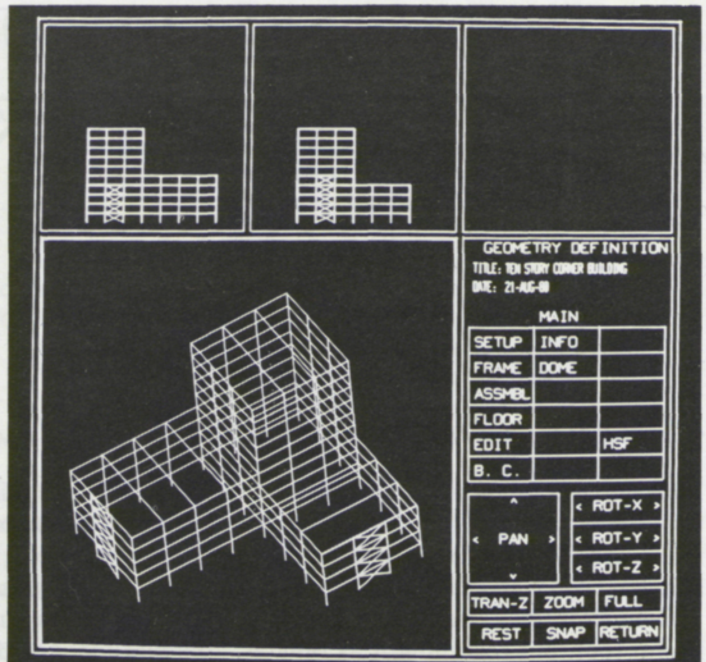

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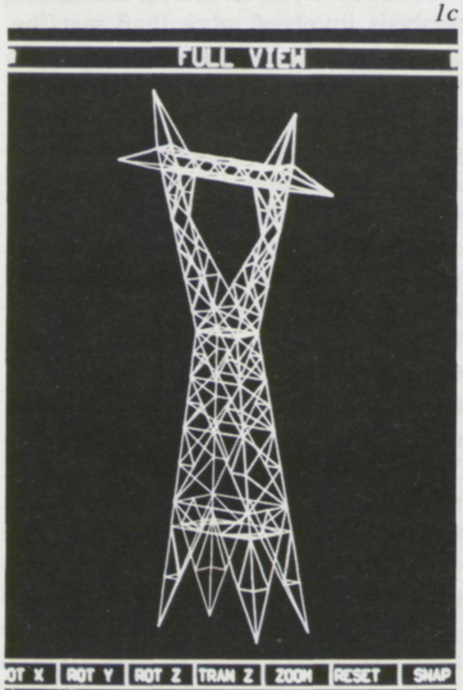


Figure 2

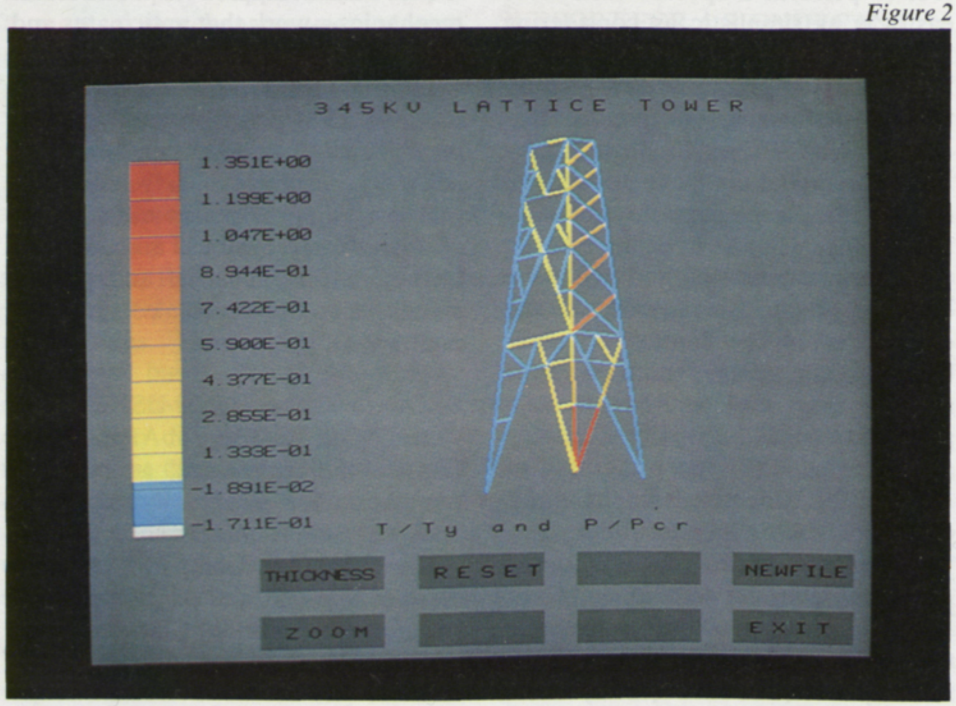


Figure 1. Framed-structure preprocessing.

The images in a *and* b *show two stages in the geometrical description of a ten-story building. Each planar component, such as the sidewall shown in* a, *is generated by specifying column spacing and story heights using a numerical keypad that can be displayed in a corner of the screen. In the figure the keypad has served its purpose and has been replaced by controls for moving the sidewall image to facilitate assembly of this and later frames. A complete structure generated in this fashion is shown in* b.

*The transmission tower in Figure 1*c *is another structure that has been defined in this same way.*

(The programs used for the work illustrated here and in Figure 3 were developed by Cornell graduate student Carlos I. Pesquera.)

Figure 2. Framed-structure postprocessing, or display of the results of analysis. This example illustrates three-dimensional color display of a portion of a transmission tower, showing the effects of a vertical displacement of one support. Levels of stress are indicated by color, as coded on the display.

faced more and more often with complex problems requiring highly sophisticated analytical techniques. In particular, there is greater need for nonlinear analysis than anyone imagined a decade or two ago. Nonlinear analysis is required for predicting rationally and reliably the structural integrity of a variety of designed objects—traditional structures such as buildings, bridges, and dams; industrial structures such as reactor containments, fusion devices, and cooling towers; and the whole range of vehicles, including automobiles, ships, airplanes, and spacecraft. Most of these analyses cannot be performed without computers. On the other hand, such analysis and design is far from automated, and the engineer must be able to exercise judgment effectively in making key decisions. The roles of the machine and the engineer must be kept in proper balance. This too is a problem for which interactive computer graphics offers some solutions.

The research at Cornell relates computer graphics and structural engineering. On the structural research side, the work has been concerned with nonlinear analysis, including ultimate or collapse analysis, fracture propagation, and buckling. On the graphical research side, the emphasis has been on three-dimensional input and representation, high-speed or dynamic line-drawing displays, and the use of color. The implications of this work for structural engineering practice and for industry may be inferred from examples of how it has been applied to research on predictions of structural integrity.

CORNELL RESEARCH ON STEEL FRAMED STRUCTURES

A traditional approach in steel design is to view structures as assemblies of planar systems; each planar structure is analyzed separately by linear elastic methods to make sure that each member, as an isolated entity, is capable of resisting the calculated forces. This method has been used in creating many of the most remarkable works of man, yet there are fundamental objections to it, for structures are three-dimensional, they behave nonlinearly

> *"The roles of the machine and the engineer must be kept in proper balance."*

Figure 3

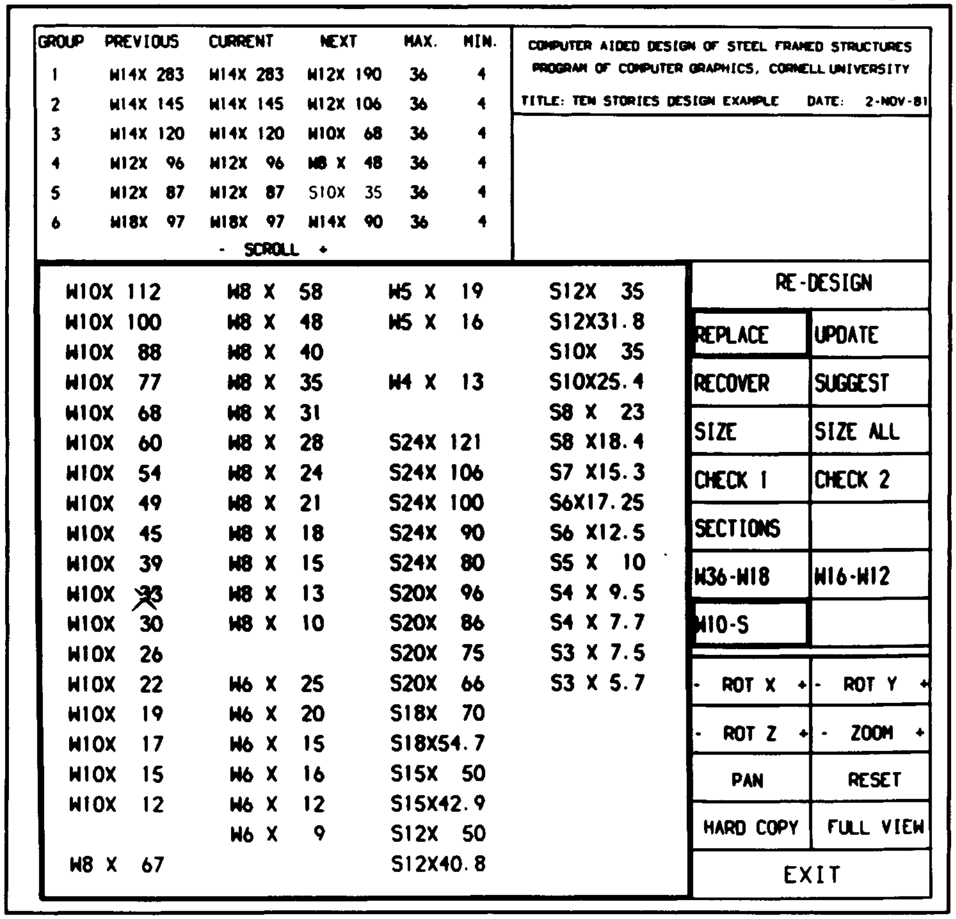


Figure 3. Designating the properties of the sections of structural steel members to arrive at the most economical design. In the box at the top left side of the figure, the first column lists some of the sections that were assigned in a preliminary design (during the preprocessing procedure); the second column lists sections used in the current analysis; and the third column lists the sections the engineer plans to try in the next iteration. The main "window" of the display contains the menu of sections from which the selection is being made.

before they reach their load-carrying capacity, and their members are interdependent, not isolated. These facts have been known for a long time, but before the advent of the computer it was impossible to treat structures—except for the very smallest—in all their complexity. Even with the computer, it is generally too difficult and costly to do so.

The aim of one of the Cornell projects is to help alter this situation by developing applicable interactive computer-graphics techniques. The goal is to achieve practical methods for the nonlinear analysis and design of steel structures as realistic three-dimensional systems. This is being attempted in three ways: by making it easier to define the structural problem to the computer, by improving the efficiency of advanced analytical procedures, and by helping the engineer interpret the analytical results.

A complete definition of the problem is necessary for analysis. The dimensions of the structure and the cross-sectional and material properties of the members must be specified, and information must be supplied about how the members are connected to each other, how the structure is supported, and how and where the loading is applied. In computerized analysis, these data are usually supplied through punched cards or by typing entries on the alphanumeric keyboard of a computer terminal. In the Cornell project, structural engineering graduate students have developed a technique of *three-dimensional frame preprocessing* that allows the information to be transmitted through the digitizing tablet of a computer-graphics system (see other articles in this issue for descriptions of the hardware). This process is normally much faster than the conventional ones, and it gives the analyst an opportunity to inspect the results immediately.

The examples shown in Figure 1 illustrate how this technique is used. Figure 1*a* and 1*b* are images created at two stages in the geometrical description of a ten-story building; Figure 1*c* shows a similar treatment of a transmission tower. To designate the properties of specific structural members,

Figure 4a *4b*

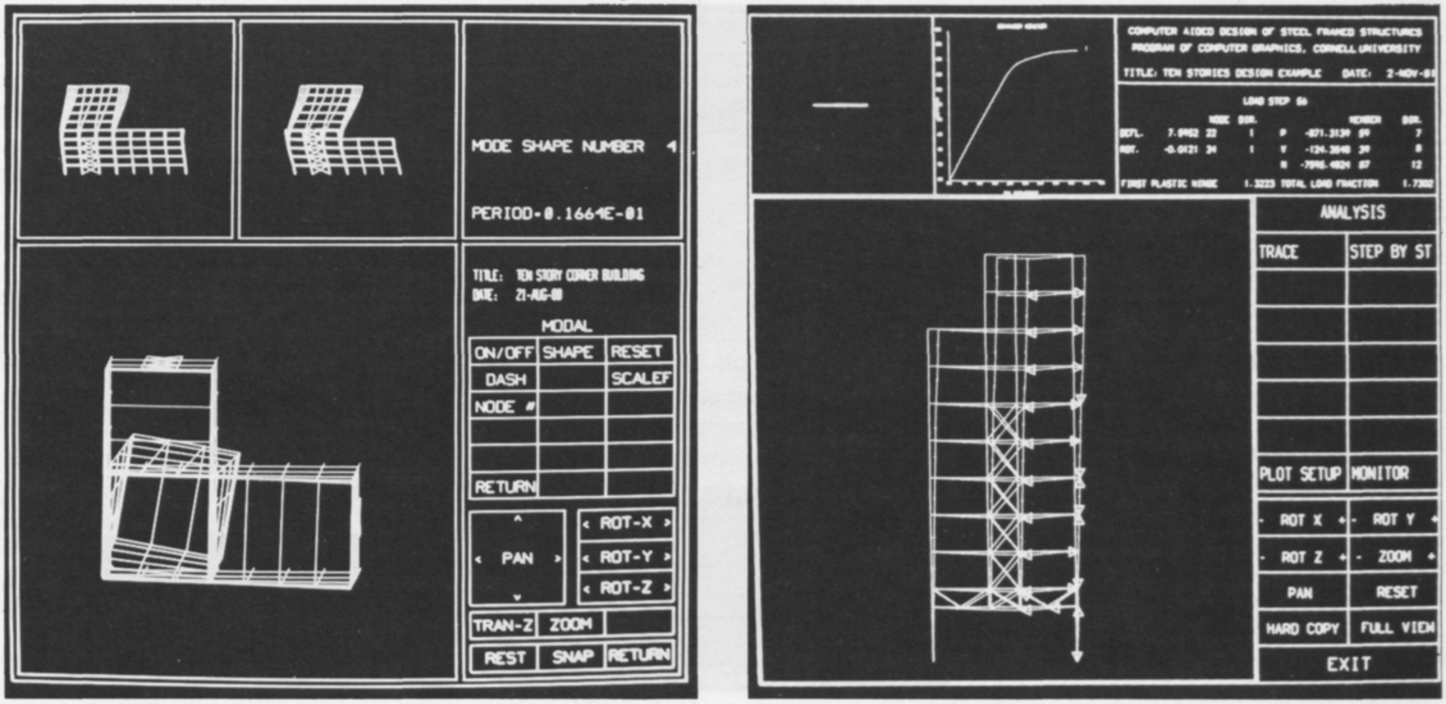


Figure 4. Three-dimensional framed-structure postprocessing. Photographs taken during dynamic displays simulate a mode of vibration of a ten-story building (a) *and the collapse of a planar frame* (b). *In* b *the location of yield stresses is indicated, a load-displacement diagram is displayed, and numerical data indicative of the state of loading and various critical force components are tabulated. The dynamic displays help the engineer interpret the physical significance of the analytical results.*

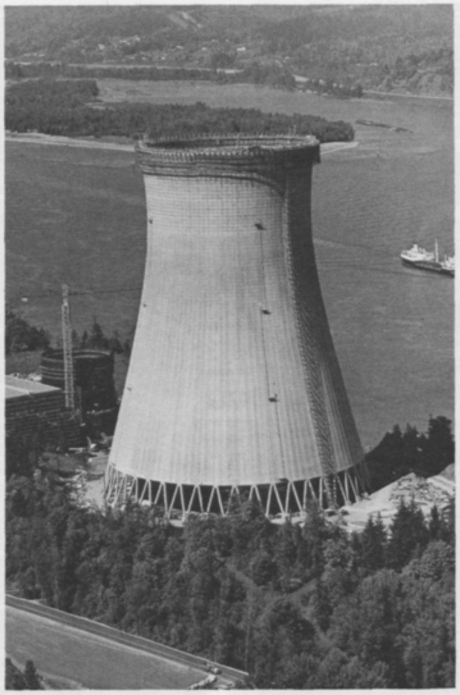
(The programs for the work illustrated here and in Figure 2 were developed by graduate students Carlos I. Pesquera, Marcelo Gattass, James G. Orbison, John L. Gross, and Michael A. Schulman.)

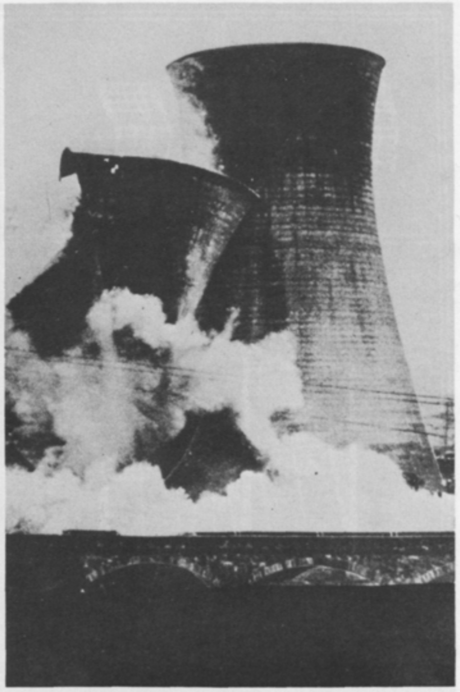
one merely needs to display a catalog of rolled-steel sections, compile a list of sections to be used in each member, and then assign the appropriate sections by pointing with the stylus of the computer-graphics design station. Figure 3, which is taken from a later portion of the program, illustrates the process and one of its extensions.

Once a structure has been fully described, *analysis* can begin. The engineer has four options for static analysis: linear elastic analysis and three types of higher-order nonlinear analysis. The first of the nonlinear types accounts for the effects of displacements only, the second for the effects of material yielding only, and the third for both displacement and yielding—that is, for full geometrical and material nonlinearity. This last is the most exact, but it is also the most complicated and time-consuming. Each kind of analysis has its place in design; it is up to the engineer to judge which is the most appropriate in a given situation. Tests have indicated that programs already developed at Cornell are capable of efficient handling of full nonlinearity in relatively large three-dimensional structures, and further improvements are being attempted.

To assist in interpreting the results of any analysis, the Cornell researchers are developing the capability of extensive *three-dimensional frame postprocessing*. Figure 4 shows examples of this. Figure 4*a*, taken from a dynamic display, shows one free-vibration mode of a ten-story building; this kind of display helps the analyst

Natural-draft cooling towers, such as the nearly five-hundred-foot Trojan Power Station (pictured at right) near Portland, Oregon, are examples of a type of shell for which buckling must be considered in design. Problems of strength and stability analysis were brought to the forefront of attention by the collapse in 1965 of three towers in England (far right). Cornell research in this area is developing computer-graphics techniques for instability analysis.





interpret the physical significance of a particular kind of vibration. Figure 4*b* shows the deflected shape of a planar frame at a state of collapse and presents pertinent numerical data. Figure 2, representing a portion of a transmission tower, illustrates the effectiveness of color in conveying at a glance the effects of a particular loading.

GRAPHICS IN ANALYSIS OF SHELL STABILITY

A special form widely used in construction and industry is the curved surface, known as a *shell* in structural applications. It is used for roof structures (domes and hypars), industrial structures (cooling towers and tanks), the bodies of vehicles (automobiles, trucks, aircraft, spacecraft, ships, and submarines), pressure vessels (boilers and reactor containers), machine parts (tubing, pipes, and housings), and vacuum tubes (dewars, CRTs, and TV tubes). Because the surfaces of such structures have a three-dimensional configuration, the preparation of input for computer analysis is especially challenging. In particular, curved surfaces may or may not have a closed-form mathematical description, but regardless of whether or not an appropriate equation exists, the engineer must be able to ascertain the coordinates, the slopes, and possibly the curvatures at any point on the surface.

Because most shell structures are relatively thin, problems of large deflections and buckling are of concern. This requires the use of geometrically nonlinear analysis during the design process. Natural-draft cooling towers are examples of a type of shell for which buckling must be considered. These towers are often five hundred feet high, yet their concrete walls have a minimum thickness of only six to ten inches; in contrast, a hen's egg enlarged to this scale would have a shell two to three feet thick. Although there has never been a cooling-tower collapse in the United States, the failure in a windstorm of three 375-foot towers in Ferrybridge, England, in 1965 has made designers acutely aware of the problems of strength and stability analysis of these forms. The collapses helped trigger a continuing worldwide research effort in shell analysis and design. Work in this area at Cornell has been aimed at more accurate and efficient instability analysis with the use of interactive computer graphics.

The first phase of the Cornell research was concerned with *surface representation*—the development, at the computer-graphics console, of a variety of surfaces. These are built up from planar curves consisting of segments that may have a mathematical representation (such as circular arcs or parabolas) or may be arbitrary in form. The arbitrary segments are "traced" directly into the computer with a digitizing tablet and pen and are then approximated by a continuous piecewise polynomial, called a *spline*, which the engineer interactively adjusts to obtain the desired quality of representation; this process constitutes the creation of a mathematical representation of the arbitrary curve. With planar curves, a surface may be generated in any of three ways: by rotation of a curve about an axis; by translation of one curve along another, perpendicular curve; and by fitting a spline surface to several sectional curves. An illustration of surface representation is given in Figures 5*a* and 5*b*, which are taken from vector-refresh graphic displays generated in the course of the analysis of a cooling-tower shell.

In the second phase of the research, the focus was on *preprocessing*, in which the complete data for analysis of a shell are generated by means of interactive computer graphics. The data include not only the geometry and topology of a finite-element mesh, but also all the necessary structural attributes, such as shell thicknesses, material properties, boundary conditions, and loadings. The engineer, seated at a graphics station, can in a matter of minutes or hours construct a complete analysis problem that would have taken weeks to accomplish without interactive computer graphics. A feature of the technology that is essential throughout preprocessing is that all user actions not only have a readily apparent graphical manifestation, but can be changed or corrected if necessary. Figures 5*c*, 5*d*, and 5*e* provide glimpses of this process as applied to the cooling tower in 5*a* and 5*b*.

Processing, or the analysis itself, was considered in the third phase of the research. Recent contributions to the effort include the development of a new, highly effective tool: a finite-element formulation for the linear and nonlinear analysis of doubly-curved shells. It is significant that this new formulation depends on the geometrical and preprocessing capabilities that were developed earlier in the project; without interactive graphical means for creating geometrical descriptions of arbitrary shell surfaces, the new approach would not be feasible.

The fourth aspect of the work is research on *postprocessing* of analysis results—the graphical display of the displacements and stresses that have been calculated. The selection and manipulation of these depictions is entirely under the control of the engineer at the graphics work station. Figure 5*f* is an example of such a selected representation; it shows the buckling-mode shape of a cooling-tower shell subjected to wind pressure.

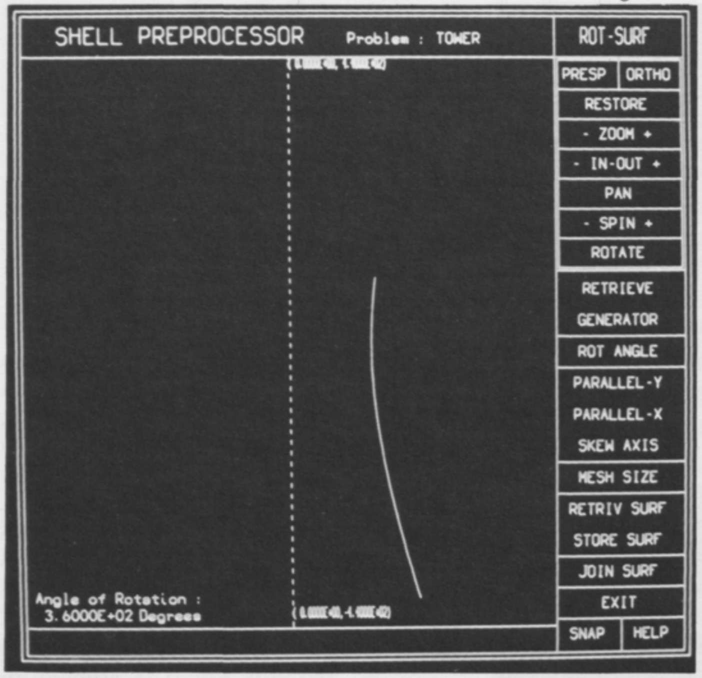
In current work in this project, the use of color for three-dimensional postprocessing of stresses is being developed. An example is shown in Figure 2; the technique is discussed briefly later in this article.

MODELS FOR PREDICTING FRACTURE PROPAGATION

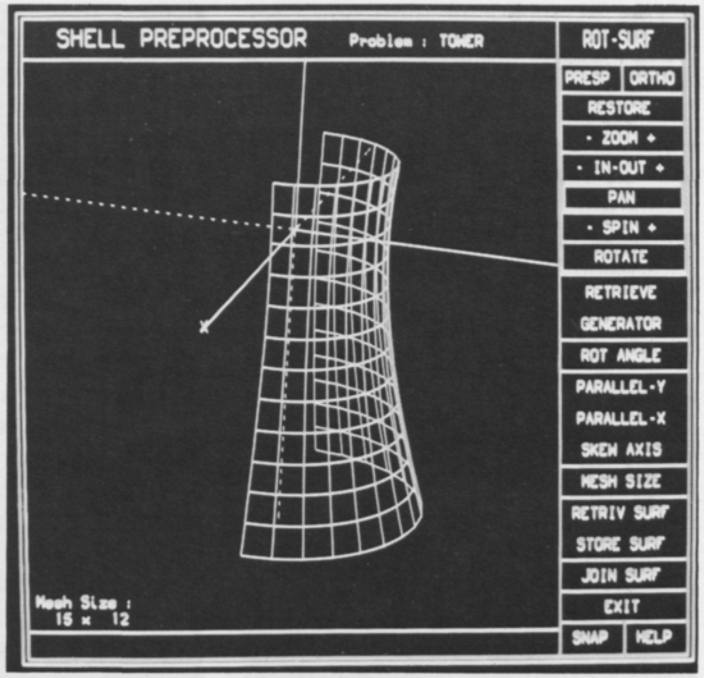
Because a crack can cause sudden, catastrophic loss of integrity in a structure, the study of fracture propagation is an important research area. At Cornell it is one of the problems in structural engineering that are being studied in conjunction with the development of techniques for interactive computer graphics.

In a brittle material such as rock or unreinforced concrete, the initiation of a crack usually leads immediately to rapid, unstable fracture propagation. This might result in collapse, or the fast-moving crack might arrest somewhere within the structure without causing total structural failure. In contrast, unstable fracture propagation in more ductile materials such as metals

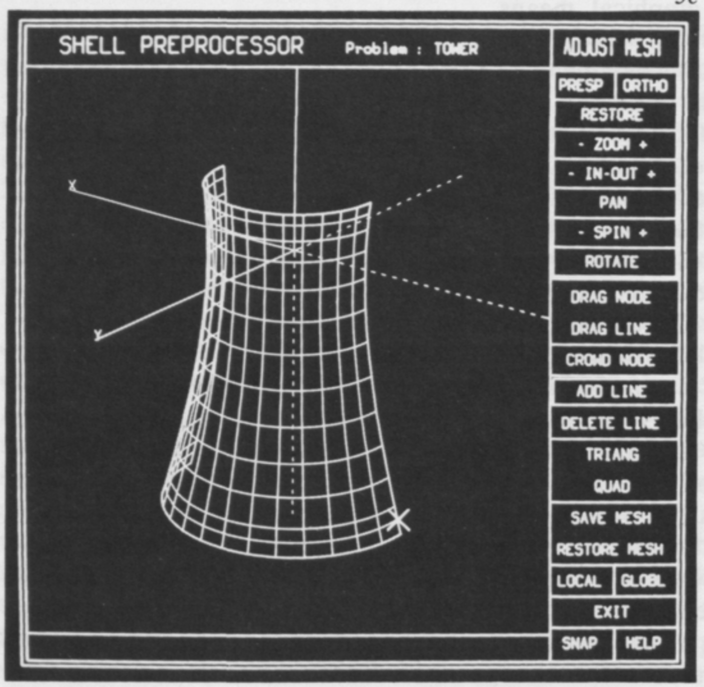
Figure 5a



5b



5c



5d

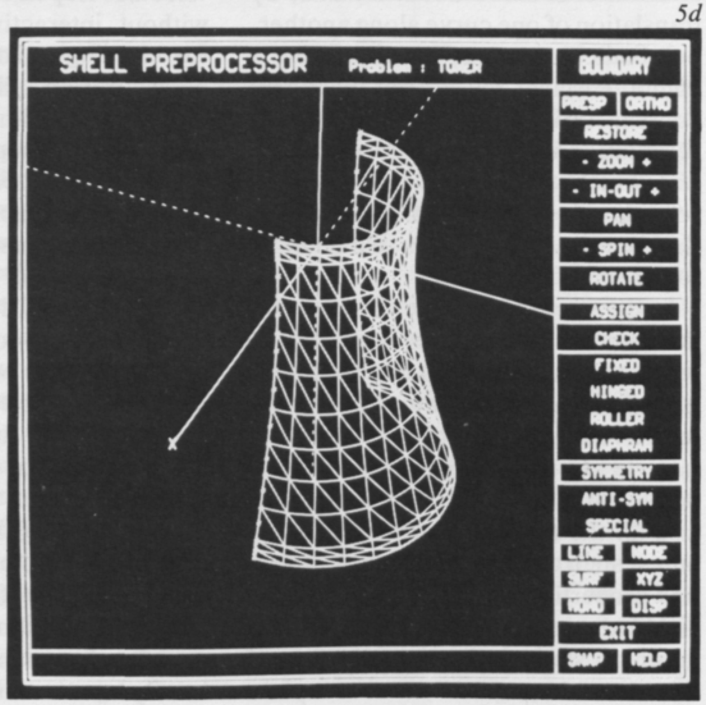


*Figure 5. Photographs taken from vector-refresh graphic displays illustrating steps in the stress analysis of hyperboloidal shells for natural-draft cooling towers. The steps include surface representation (*a *and* b*), preprocessing (*c, d, *and* e*), and post-processing (*f*).*

(Programming was by graduate students San-Cheng Chang, Sheng-Chuan Wu, and Samir Hanna.)

a. *The curve used to define a shell is drawn. It consists of two segments: an hyperbola and a short straight line at the lower end.*

b. *The curve is rotated 180° about the dashed vertical axis to produce the shell surface. Only half the shell is needed because the wind load is symmetrical about the shell diameter that is parallel to the direction of the wind.*

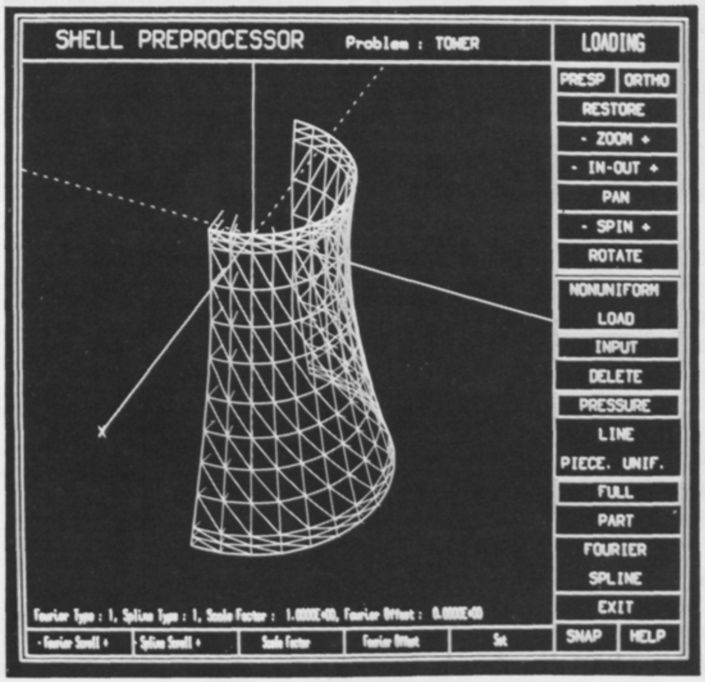
c. *The finite-element mesh is modified as needed. Here a mesh line is being added at a position selected by the user by pointing with the pen on the digitizing tablet; this location is indicated on the display by the X-shaped cursor.*

d. *Boundary conditions are applied. In this case, the symmetry conditions along the meridional cuts are being assigned by pointing to these lines, and their successful assignment is indicated by the appearance of blinking symbols at all the nodal points on these lines.*

e. *The specification of wind pressures is checked. The local intensity of pressure is indicated by lines of proportional length perpendicular to the shell. One can see that the wind causes an inward pressure on the windward meridian, an outward suction about 70° from the windward direction, and essentially zero pressure on the leeward half of the tower.*

f. *Analysis results are graphically displayed. (This design is different from the one shown in the preceding illustrations.) This display occurs in the postprocessing stage, after the analysis has been performed. Here the tower has buckled under the force of a specified wind pressure. Included in the finite-element mesh is a 300° section of the shell; the windward direction is opposite the 60° opening.*

5e



5f

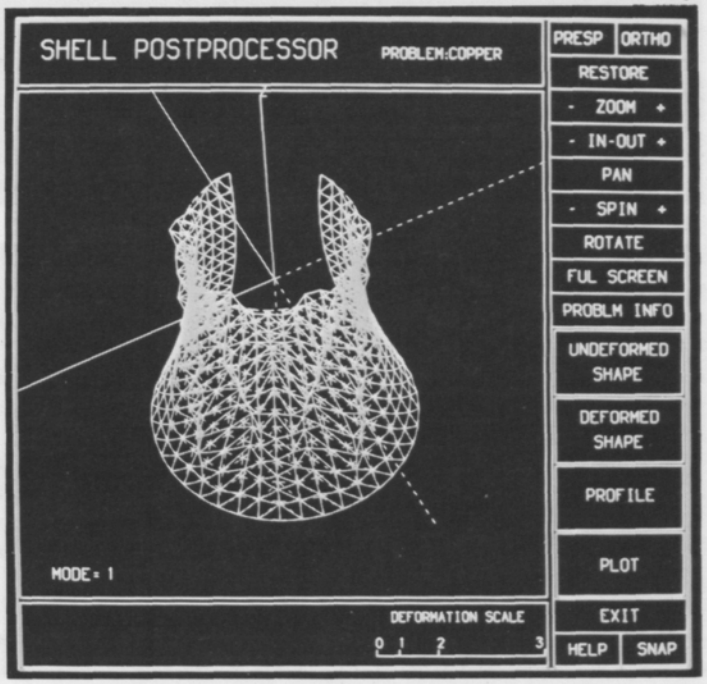
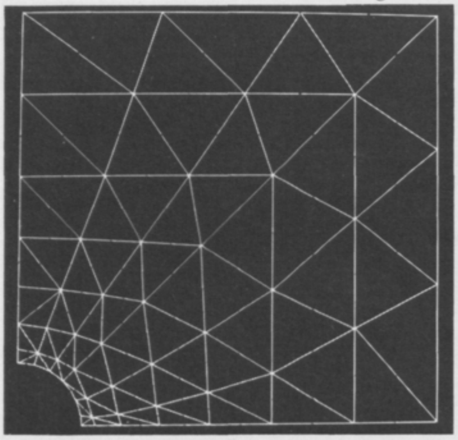
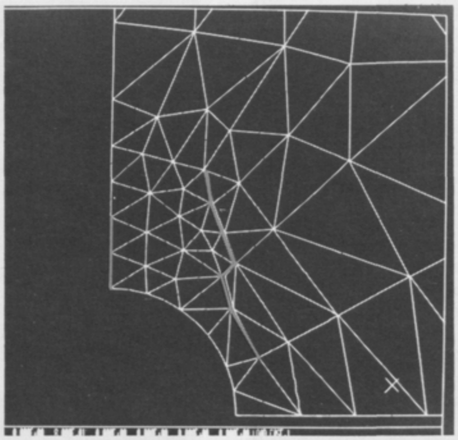


Figure 6a



6b



6c

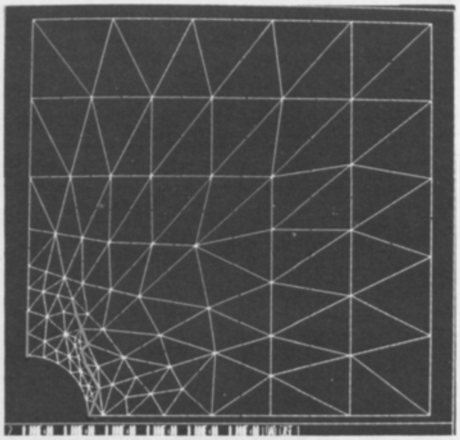
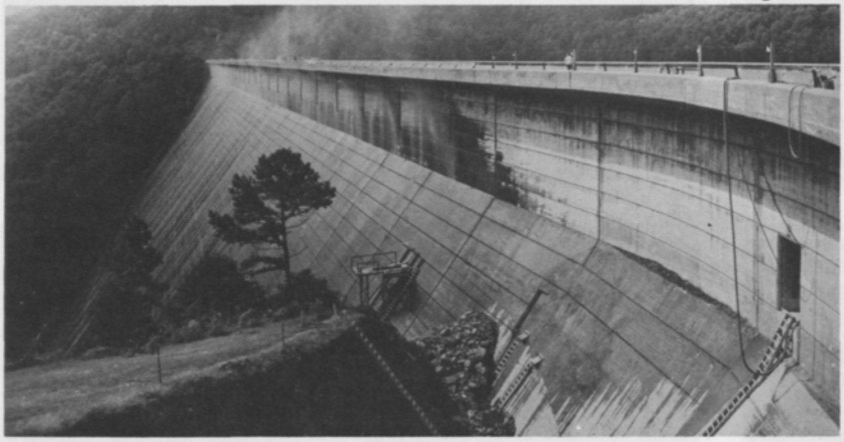


Figure 7a



7b

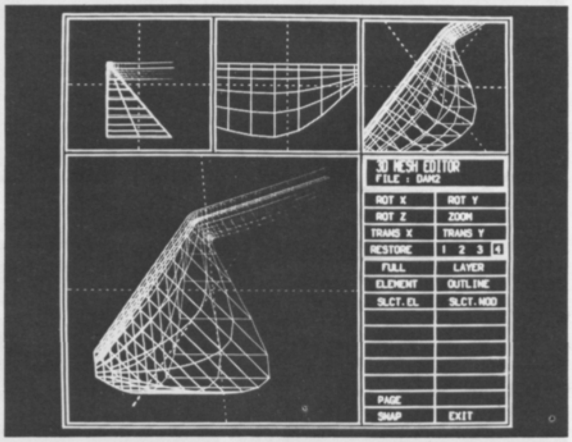


Figure 8

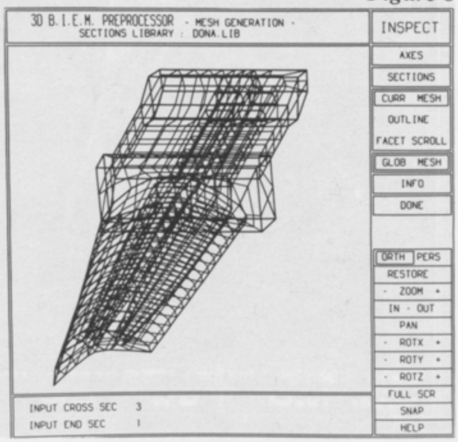


Figure 6. A study of the propagation of two cracks (shown in blue) in the rock surrounding a tunnel. The three images show steps in the sequential remeshing of the finite-element model.

(Programming was by Robert B. Haber, Mark S. Shephard, and Tao-Yang Han.)

Figure 7. The analysis of a crack in the TVA's Fontana Dam (a) *and the finite-element model* (b) *used in analyzing the fracture propagation. The position of the crack can be discerned in the right foreground of the photograph by the discontinuity in water flow. For the repair, fill has been removed and scaffolding erected. The dam was saved from further damage by cutting transverse slots across monoliths, a procedure that effectively isolated the damaged section from the thermal influences driving the crack.*

Figure 8. Predicting the fatigue life of a jet-engine turbine blade. The calculation requires first a prediction of where the cracking will begin and then the interactive computer-graphics modeling of crack propagation.

(Programming for the work shown in Figures 7 and 8 was by Renato Perucchio.)

Figure 9. The use of color in postprocessing of stresses. The object that has been analyzed in this two-dimensional simulation is a bracket clamped at the left edge. The maximum principal stresses resulting from horizontal loading at the two bolt holes are displayed in color as indicated on the scale. Stress of a particular value is highlighted in this example by the substitution of black for the original shade in the yellow-to-red range.

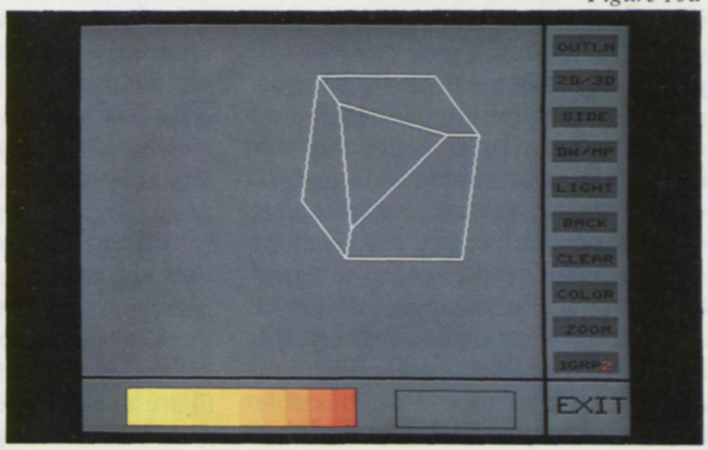
(Programming was by Richard S. Gallagher and Michael A. Schulman.)

Figure 10. A demonstration of the use of color to show the results of analysis of three-dimensional objects. In a *a cubic solid has been sectioned to expose an interior plane. In* b *the surface has been colored, as in Figure 9, to represent the variation of a parameter such as a stress; the object now appears two-dimensional. In* c *the principles of diffuse reflection have been used to modify the color on each surface according to its orientation in relation to light rays from a point source; a three-dimensional perception is regained.*

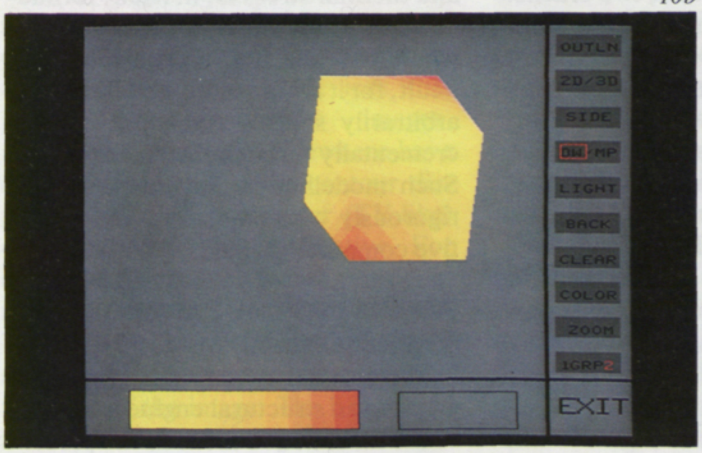
(Programming was by Michael A. Schulman.)

Figure 9

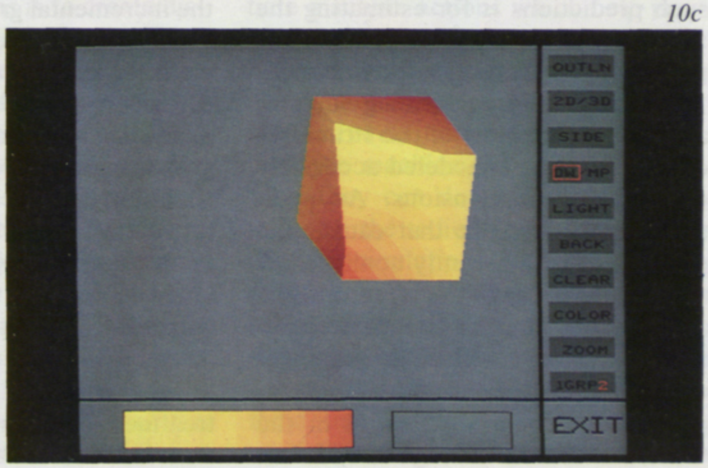
Figure 10a



10b



10c



is almost always preceded by a period of slow, stable crack growth; an example is the gradual extension of a fatigue crack in a metal part that is undergoing cyclic loading. To ascertain the susceptibility of a structure to failure through unstable crack propagation, it is necessary to predict the point of crack initiation, the crack-initiation load, the trajectory and growth rate of a crack growing in a stable manner, the fracture-propagation load, and, ultimately, the trajectory of the unstable fracture. The practical usefulness of such predictions is for estimating the safe life of a structure or possibly for preventing or correcting the fracture.

A difficulty in performing such an analysis is that most of the structures of interest can be modeled accurately only in three dimensions. An additional difficulty, one that causes the problem to be inherently nonlinear, is that the topology of the structure, the applied loads, and the boundary conditions can change with each increment of cracking. These formidable complexities are being addressed in the Cornell research through the development of preprocessors which permit a user to create and display interactively a geometrical and analytical description of a complex three-dimensional object. Data input is faster by an order of magnitude than it would be with keypunching; also, the immediate display of the structure and its attributes results in a marked decrease in data errors. This quantum jump in the speed and accuracy of problem description permits the rigorous analysis of a class of fracture problems that were previously intractable: three-dimensional problems that require successive redefinition with each crack increment.

A major focus in the research program has been the study of geotechnical structures. An example is a finite-element simulation of fracture propagation around a tunnel in rock (see Figure 6). The structure, as modeled on the computer-graphics console, is subjected to high vertical compressive stress, typical in tunneling at depths of thousands of meters. The figure shows three phases of the sequential remeshing that is mandated by the incremental growth of two cracks.

Such successive changes in a finite-element grid require the intervention of the engineer during the course of analysis, and interactive computer graphics is particularly valuable in such a process: changes in topology, properties, or configuration can be accommodated properly by the combined actions of the analyst and the computer. The technique is called *interactive-adaptive analysis*.

An example of a three-dimensional treatment of fracture in a geotechnical structure is illustrated in Figure 7. The photograph in *a* shows the cracked, downstream face of the Tennessee Valley Authority's Fontana Dam; the computer-graphics displays in *b* show multiple views of its initial finite-element simulation. Projections of the growth and trajectory of the crack can be made with interactive-adaptive analysis, providing information needed for effective treatment. (For a more detailed discussion of this particular crack analysis, see an article by Anthony R. Ingraffea in the April, 1979, issue of this magazine.)

Another area of study has been problems of metal fatigue. The purpose of this research is to adapt techniques of interactive computer graphics to applications such as a prediction of the life of a jet-engine turbine blade. In addition to a complex three-dimensional surface geometry, a blade and its integral attachment root have an internal topology created by the presence of air passages for cooling (see Figure 8). The task of predicting where, in this complex geometry, a crack would start when the blade is subjected to extremes of mechanical and thermal stress is, in itself, formidable. The subsequent task of predicting the fatigue life is even more difficult, for it requires the modeling of an arbitrarily shaped crack growing incrementally through the blade or root. Such modeling cannot be performed rigorously without the aid of interactive computer graphics.

IMPROVING THE PARTNERSHIP OF PERSON AND MACHINE

In the Cornell research on computer graphics in structural engineering, one of the most active areas at the present

" . . . both the machine and the person do what they can do best."

time is the development of techniques for contour depictions in color to display stresses in various kinds of structures. It is an aspect of graphical postprocessing that is promising for both two-dimensional and solid structures, as has been mentioned in connection with the research on steel structures, shells, and fracture mechanics.

The basic technique is to display the results of stress analysis in the form of contours of equal stress drawn on the surface of the shell or solid. In the case of a three-dimensional solid, one might wish to make sectional cuts to reveal interior stress patterns. Although such contour displays can be created on vector or line-drawing devices that produce black-and-white images, studies at Cornell and elsewhere have demonstrated that color contour displays produced on a raster (TV-like) device are much more effective. For example, Figure 9 is a two-dimensional representation in color of stresses in a bracket; the stress values displayed are identified in a color scale given at the edge of the image. The figure also illustrates a further capability of the system: wishing to discern more clearly one particular level of stress, the user has pointed to a location on the bracket and thus caused that particular color to change to black for greater contrast. In addition, critical portions of the display can be enlarged. These techniques provide the engineer with a highly effective means of comprehending the variations of any stress component or parameter.

A current effort is to extend this approach for more effective use with three-dimensional structures. One of the principal problems is to create displays rapidly enough for an interactive environment. A second challenge is to use color in a way that conveys information not only about the stresses being displayed, but also about the three-dimensionality of the geometry; some early experimental results are shown in Figure 10. This approach holds promise for the development of a general postprocessing procedure to display stresses in both surface structures and solids. Such a system would provide the structural engineer with a much better grasp of the information needed to control the interactive design process.

As the examples given in this discussion demonstrate, interactive computer graphics is making dramatic changes in how structural analysis and design can be accomplished. Paradoxically, its use brings, in some ways, a return to a more traditional mode of engineering—one in which designers gather around drawings and someone says, "What happens if we change this over here?" The difference now is that such natural gestures as pointing initiate machine actions which help provide answers to the questions.

Some might say the computer has an even more auspicious role. With an interactive computer-graphics system, both the machine and the person do what they can do best: the machine takes on the tedious calculations, the data manipulation, and the figure-drawing, and the person visually integrates and evaluates patterns of behavior. Effectively, the engineer and the computer become active partners in the design process.

The three authors of this article are all members of Cornell's Department of Structural Engineering.

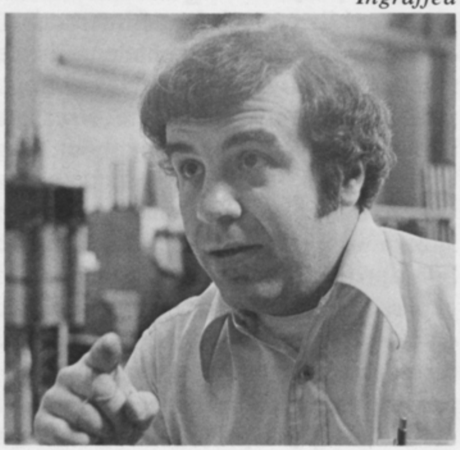
John F. Abel, an associate professor, specializes in finite-element analysis and computer graphics. He holds three degrees in structural engineering: the B.C.E. from Cornell, the M.S. from Stanford University, and the Ph.D. from the University of California at Berkeley. Before coming to Cornell in 1974, he served for two years as a research engineer in the Army Corps of Engineers' Waterways Experiment Station in Vicksburg, Mississippi, and for four years as a lecturer and research associate at Princeton University. He is an author, with C. S. Desai, of Introduction to the Finite Element Method, published in 1972 by Van Nostrand Reinhold, and he is currently on the editorial board of the International Journal for Numerical Methods in Engineering. He is registered as a professional engineer in Mississippi.

William McGuire, a full professor since 1960, has been on the Cornell faculty for thirty-two years. After receiving a baccalaureate degree in civil engineering from Bucknell University, he studied at Cornell for a master's degree in structural engineering. His experience includes several years as a structural engineer with Jackson and Moreland in Boston and with the Pittsburgh–Des Moines Steel Company. He taught at the Asian Institute of Technology in Bangkok from 1968 to 1970, served as a visiting fellow at the University of Western Australia in 1973, and was a visiting professor at the University of Tokyo in 1979. Over the years he has been a consultant to a number of structural engineering firms, steel companies, and utilities, as well as to the architectural firm of Buckminster Fuller and to the National Bureau of Standards, and he was one of the planners of the world's largest radio-radar telescope, built by Cornell in Puerto Rico.

Abel

McGuire

Ingraffea



He is the author of a textbook, Steel Structures, published by Prentice-Hall in 1967 and a coauthor, with Richard H. Gallagher, of Matrix Structural Analysis, published by John Wiley in 1979. In recent years he has concentrated his research on computer-graphics techniques applied to the design of steel frames and other structures.

Anthony R. Ingraffea, a specialist in structural, rock, and fracture mechanics, became an assistant professor in 1977 and is currently manager of experimental research in the structural engineering department. His academic degrees are the B.S. in aerospace engineering from the University of Notre Dame, the M.S. in civil engineering from the Polytechnic Institute of New York, and the Ph.D. in civil engineering from the University of Colorado at Boulder. He has worked at the Grumman Aerospace Corporation and taught at Colorado (he is a licensed engineer in that state). As an engineer in the Peace Corps in Venezuela in the early 1970s, he was responsible for all technical services to a county of forty thousand people and directed development projects and an urban-renewal plan. Ingraffea received the 1978 National Research Council/U.S. National Committee for Rock Mechanics award for outstanding research in rock mechanics. At Cornell he was elected professor of the year in the School of Civil and Environmental Engineering in 1978 and received the Excellence in Engineering Teaching Award at the College in 1979.

The research and development described in this article were supported by grants from the National Science Foundation and from various industrial and engineering companies.

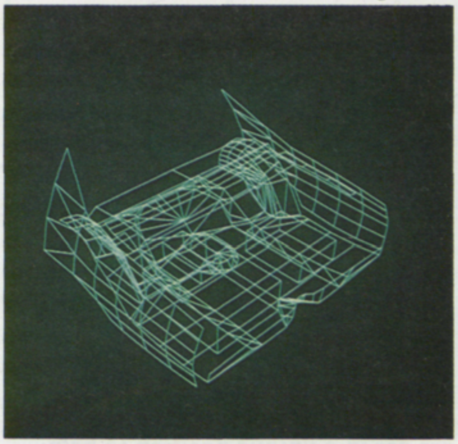
CAD/CAM: INDUSTRIAL TAKEOVER BY DESIGNING COMPUTERS

by John C. Dill

When the oil crisis struck in 1973, General Motors was beginning work on the design of a new full-size body for 1977 passenger cars. After considering such drastic responses as dropping the large-car line entirely, the corporation decided to attempt a major reduction in size and weight, and despite a nine-month delay in getting started, a smaller model was designed and ready for production on schedule.

The technology that made this possible is computer-aided design, or CAD, which, along with its first cousin CAM (computer-aided manufacturing), is rapidly gaining importance in engineering industries. An essential feature of CAD is computer graphics, which greatly enhances the immense resources of the computer by making them more accessible, easier to use, and compatible with the way people perceive objects and develop ideas. While traditional computer systems work only with numerical data, computer graphics systems can also store, manipulate, and display geometric or graphic information. With computer graphics, designers and analysts can *see* the results of their operations and can *interact* with the computer in performing them.

Figure 1a



1b

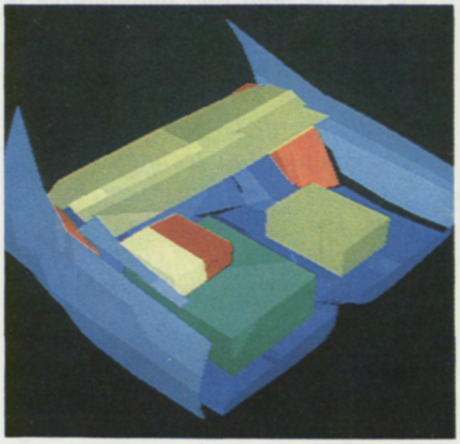


Figure 1. An example of the use of computer graphics in the automobile-manufacturing industry. Both the wire-frame image (a) *and the image in color* (b) *represent a car trunk with luggage. A designer can "manipulate" luggage to determine the best arrangements for specifying the trunk capacity.*

Both a *and* b *use the same database in General Motors' CADANCE design system. The advantage of the wire-frame version, at least with today's technology, is that it can be manipulated rapidly. The colored version is more readily understood but takes much more time to produce.*

FROM PHARMACEUTICALS TO STRUCTURAL DESIGN

The industrial applications of computer graphics are extremely wide-ranging, extending into areas as diverse as medicine and structural engineering. At their design consoles, scientists in a pharmaceutical laboratory can screen drugs for particular properties. Architects and engineers

Figure 2a

2b

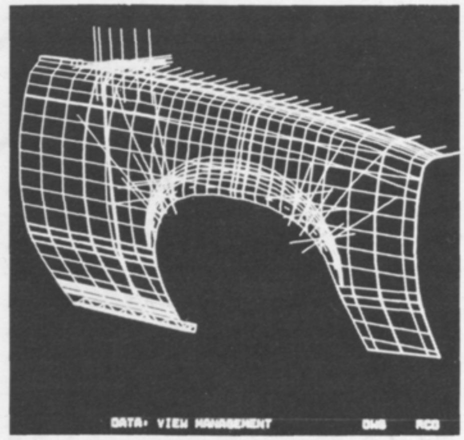


Figure 2. The use of a CAD system. The design station in a *has a typical console layout, including several interactive devices: keyboard, light pen, and function buttons. Here the designer is requesting that an operation be performed by touching the light pen to the appropriate item in the menu displayed on the screen. The partial image in* b *shows a design detail that has been called up by the engineer.*

can design and analyze large buildings. Automobile manufacturers can design bodies or parts, or simulate a crash to see how far into the passenger compartment the steering wheel would project after impact. On their computer-graphics screens, engineers can plan the large-scale layout of a complicated piping system for a petrochemical plant, the small-scale design of a printed-circuit board, or the submicroscopic arrangement of one hundred thousand transistors on a ¼-inch silicon chip (a job that cannot be accomplished without a computer). Other applications include process control, seismic data processing (used by the petroleum industry), and cartography. Computer graphics is also finding a place on the management side of industry—for the development of management-information systems (which are now often referred to less auspiciously as decision-support systems) and even for the preparation of graphs and charts for reports and presentations.

The single most significant application, though, is CAD/CAM.

PRODUCTIVITY: THE MAJOR REASON FOR CAD/CAM

The heavy use of CAD/CAM is explained by the word *productivity*. The compelling need for increased industrial productivity and the potential of computer-aided processes in helping to achieve it were expressed by W. A. Kuhrt, a United Technologies Corporation senior vice president, in the July 1981 issue of *Production:*

The United States is in trouble, and manufacturing engineers and managers are in a unique position to help . . . if we will be bold and imaginative in developing and using new manufacturing technologies.

It has been estimated that some applications of computer and advanced machine tool technology could increase machine utilization by 600 percent. The resulting reduction of indirect capital and labor costs and improvement in productivity could be as high as tenfold.

Time savings possible through CAD can make a significant contribution, as GM's experience with the 1977 large passenger-car body demonstrates. (This was the so-called B body, as in the Chevrolet Caprice. Corporation representatives later estimated that without CAD/CAM, the 1979 X body would have taken an additional year to produce.) In the aerospace industry, the same technology was important in the design of Boeing's 767 jet aircraft. In fact, examples of time (and therefore money) saved can be found in industries of all kinds. A crankshaft design that once took weeks to complete now takes days. The time needed to obtain finite-element data for structural design, or parameters for tool design, has been cut by a factor of four.

HOW CAD IS USED BY DESIGN ENGINEERS

With a computer-graphics display unit, an engineer interacts with a design not by typing a command to the system, as would be done with a typical alphanumeric terminal, but by pointing at the command name with a *light pen* or stylus. Lists or *menus* of operations that the user can order are displayed on the screen alongside the graphical or geometric representation. With this technique, new lines and surfaces can be defined rapidly and made a part of the design database, and as the design progresses, parameters such as location, size, and physical attributes can be specified. Components from a library in the database may be added simply by selecting the appropriate name with the light pen. Different or even dynamic (moving) views are easily available.

At any point the engineer may request analytical procedures, such as a simple dimensional tolerancing or even a full finite-element analysis for determining how a part would behave under load. And at any stage of the design process, the engineer can request a paper *hardcopy* of the design to take back to his or her desk. Once the design is considered satisfactory, it is filed for future access, making it available not only for the immediate application, but for future uses as well.

To proceed toward manufacture, the design is used to generate a tape that provides numerical control of a milling machine. Such a numerical-control (NC) tape is actually a program to drive a cutter that will machine a part from a blank, and since it may contain errors, another program to verify the generated cutter path is likely to be requested.

In summary, then, the steps in a typical CAD project are:

1. Prepare a preliminary design sketch on paper, if necessary.
2. Using a CAD station, select and invoke various geometric construction processes to define the two- or three-dimensional geometry, which is displayed as images on the screen.
3. At any stage, manipulate or change the design as desired.
4. Add nongeometric design parameters to the database.
5. Perform functional analyses of the design in order to study, for example, stress distribution, heat transfer, or aerodynamic properties; if desired, create simulations to test such things as the operation of an integrated circuit.
6. Generate and verify the cutter path for NC milling or the mask for an integrated-circuit layout.

Figure 3

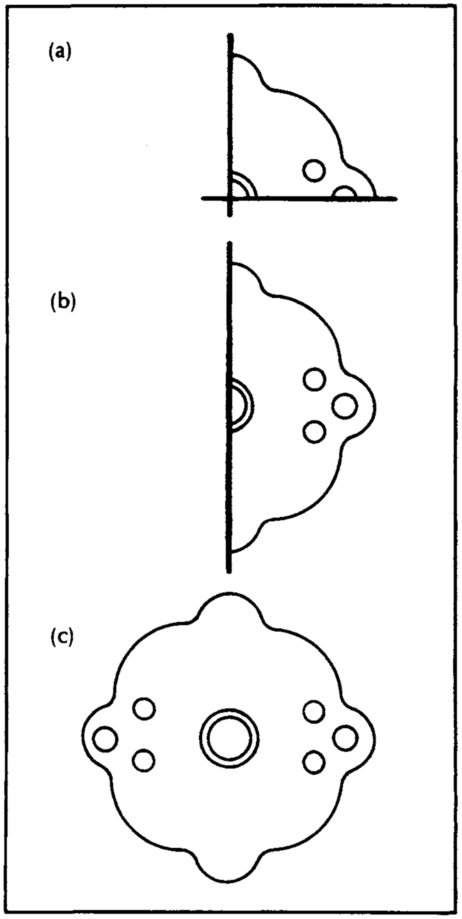


Figure 3. Rotational symmetry as a shortcut in computer-graphics design. The original drawing is in a*; simple reflections about the horizontal and vertical axes result in* b *and then the final design* c.

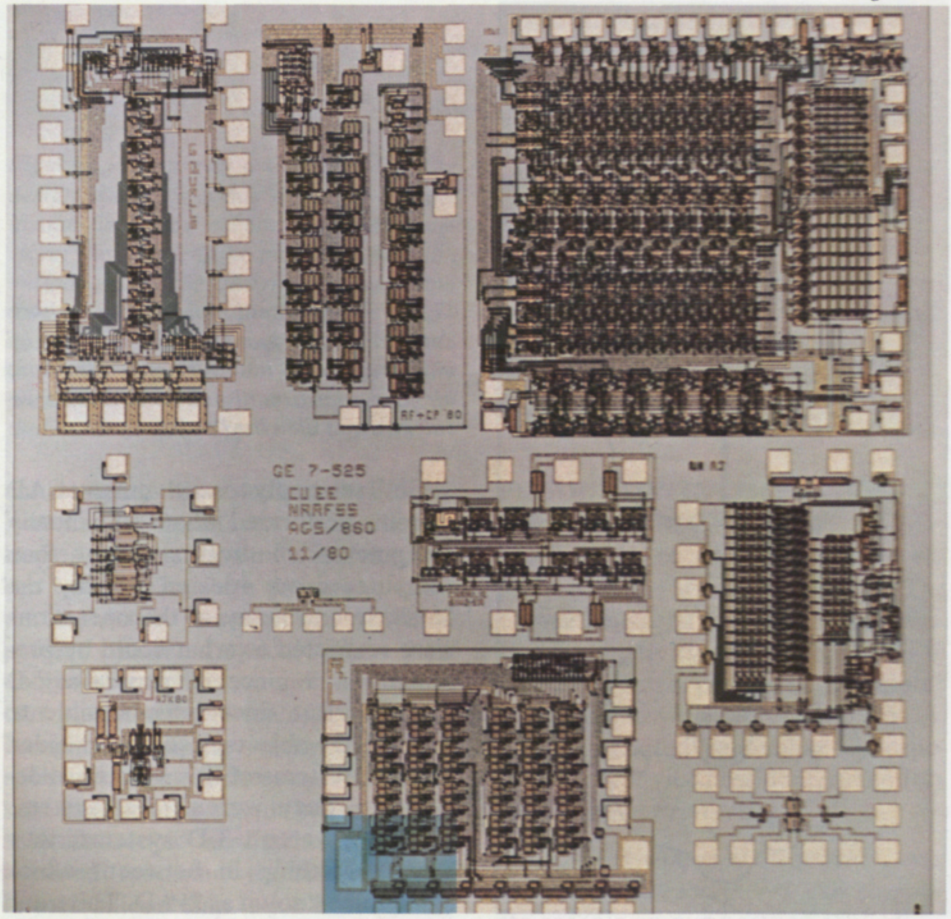
Until relatively recently, many CAD systems performed what was actually computer-aided drafting rather than computer-aided design, and the database and many of the operations were restricted to what could be presented on a piece of paper—a 2-D quantity. But since it is possible to draft 3-D objects, computer-aided drafting systems of this kind were developed. They weren't 2-D systems and they weren't 3-D systems; they were something in between, which came to be known as 2½-D. The trend now is to use full 3-D systems for mechanical and structural design.

CHARACTERISTICS OF EFFECTIVE CAD SYSTEMS

What are the critical components that make a CAD system effective?

Completeness of function—that is, access to all the necessary operations at the appropriate levels—is certainly one. For example, a designer would want to take advantage of any symmetry in the part to be designed (see Figure 3). In any CAD system there are bound to be "work-arounds"—

Figure 4a



4b

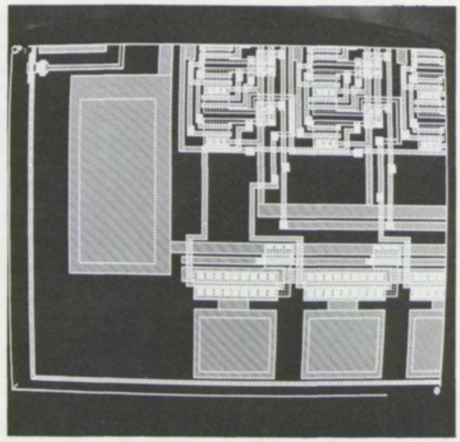
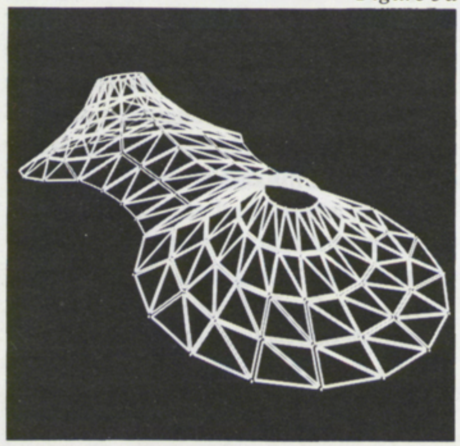
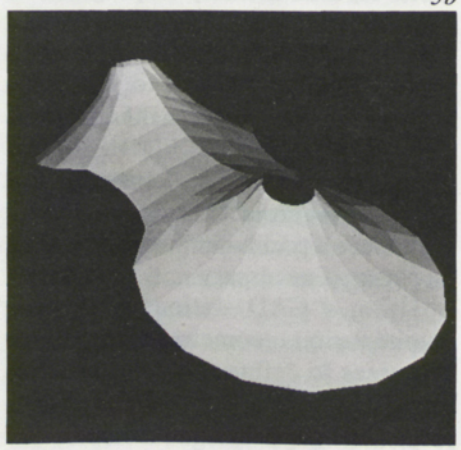


Figure 5a



5b



operations for which the system has no direct facility—but in good systems there are relatively few of them.

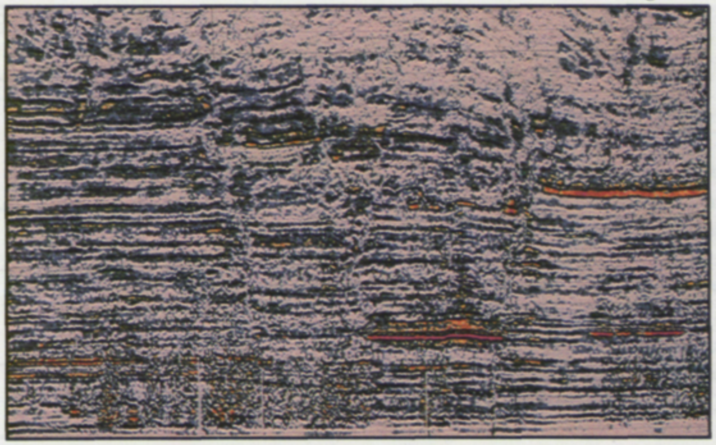
A second criterion is the ease with which operations are accomplished; a good CAD system takes into account human factors, an aspect called *ergonomics* or human engineering. The features involved can be as simple and straightforward as the computer's response time; if the system is too slow in making a requested design modification, the interactiveness or conversational nature of the relationship between user and machine can be completely lost. (As an analogy, one can imagine the frustration of a composer unable to hear a piano note until minutes after the key was struck!) Of course, there are practical limits to the usefulness of reducing response time: doubling the cost of an expensive system in order to perform an operation in 10 milliseconds instead of 25 would be a waste. More subtle, but just as important, are characteristics such as the capability for visual feedback. A user selecting a portion of a design for re-

Figure 4. The layout of large-scale integrated circuits (chips), an important industrial use of computer graphics. The photomicrograph in a *shows a chip (actually about ¼-inch on a side) that was designed by Cornell students and fabricated in a General Electric laboratory. Design work for the part of the chip that is shaded in blue is shown in* b, *which is a display on an Applicon console in Cornell's submicron facility. This 4-bit parallel multiplier, designed by Rich Linderman, is laid out in a series of superimposed masks for subsequent optical processing. Note that the mask layers are identified by shading; with a color graphics system, different colors would be used instead (see also page 21).*

*Figure 5. An example of the use of computer graphics in structural design, a primary area of application today. These images are a vector-refresh display (*a*) and a color display (*b*, shown here in black and white) of structures designed with a program developed at Cornell by graduate students Robert B. Haber and John Hollyday. The work was done as part of a project sponsored by Birdair Structures Division of Chemfab, Inc.; the program turned out to be so good that it is now being used by Birdair for the design of cable-reinforced fabric roof structures, both air-supported and prestressed.*

Figure 6. Color graphics in geological exploration. One technique is to enhance seismic sections showing formations below the earth's surface. This trace, obtained by computer processing of seismic data recorded off the shore of Louisiana, has been color-coded to display reflection strength. The red areas may represent oil or gas pockets, which are expected to cause strong reflections. (Reproduced by courtesy of Seiscom Delta United, Inc.)

Figure 6



moval or modification must have some confirmation, through visual feedback, that the item intended is the one actually called up. Such feedback might be in the form of a brightening of the item selected from the menu. Other desirable characteristics include logical, natural groupings of menu items and physical considerations such as easy-to-reach interactive devices, good lighting, and noise control.

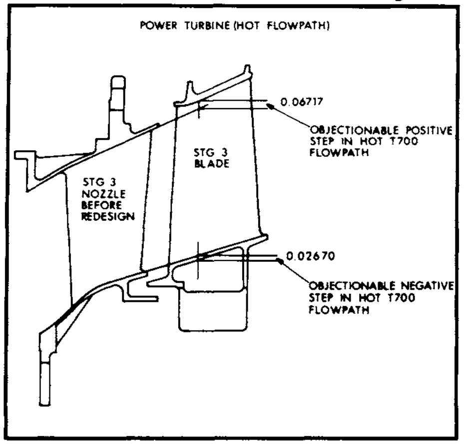
The single most important characteristic, though, is one that is not directly visible: the common database. To be effective, a CAD system must be supported by a "spine" of engineering data running from the initial creation of a design to the generation of an NC tape. The common database, available for all applications, is what enables designers, analysts, and manufacturing engineers to communicate without having to produce large numbers of complex drawings. Geometric design, heat-transfer analysis, finite-element analysis, interference analysis, and simulation all depend on the same common database, accessible to any user at any place, at any time.

The biggest advantage of current CAD systems is not in the initial design stage, as the popular press might lead one to conclude. The truly significant savings occur when changes must be made. Instead of starting all over again, the designer just retrieves the original design from the database (the ubiquitous database) and works only on the modifications. The concept is the same as the one that has made word-processing so useful: the operator of a word processor types a whole manuscript once, and thereafter works only on changes.

A problem in the design of a jet engine provides an interesting example of some of these special capabilities of CAD systems. Garth A. Grimmer of the General Electric Company describes the situation in the *CAD/CAM Handbook* (published in 1980 by Computervision Corporation). Tests on GE's T700 engine showed poor performance under hot running conditions, and an incorrect match between nozzle and blade was suspected as the cause. The effects of temperature and centrifugal force on the geometry of

Figure 7. A mechanical diagnosis performed with the aid of computer graphics. When General Electric's newly designed T700 jet engine showed poor performance under hot running conditions, the problem was identified by means of a graphics simulation of the geometry of the hot section. A discontinuity in the airflow path was discovered and the nozzle was redesigned. (Reproduced from The CAD/CAM Handbook *by courtesy of Computervision Corporation.)*

Figure 7



the hot section were calculated, the changed geometry was studied using computer graphics, and a discontinuity in the flow path was discovered. These findings were verified by x-ray photographs made during actual operation with further help of CAD resources: the same database was used to determine the proper camera position, which was critical because of an extremely narrow field of view. The photographs confirmed the computer-graphics analysis, the deficient nozzle was redesigned, and the performance of the engine improved. Using the CAD approach saved GE a month of design time and six hundred man-hours of drafting.

Figure 8

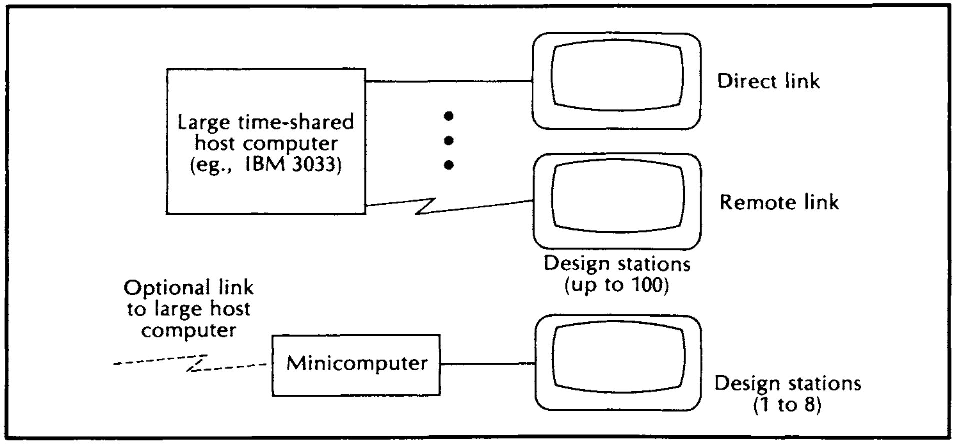


Figure 8. CAD system configurations. Large and sophisticated systems such as the one sketched at the top are used in complex manufacturing: the production of automobiles and aircraft, for example. "Stand-alone" systems such as the one sketched below are generally more feasible for smaller operations.

CONFIGURATIONS OF CAD SYSTEMS IN INDUSTRY

The major hardware components of all CAD systems are the design station and the computer. In addition, each station has a link to the computer and the computer itself is equipped with permanent disk storage. These components are organized in quite different ways, however (see Figure 8).

A configuration often used in large and sophisticated systems such as those of the aerospace and automotive industries is the integration of many stations in a very large time-sharing computer system. Such systems offer economies of scale, but they require extensive and powerful software, which is typically developed in-house.

At the other end of the scale are much smaller stand-alone systems using a minicomputer and capable of supporting, at most, a few stations. These systems have the advantage of much lower entry cost and are often available from turnkey vendors in hardware-and-software packages.

Not shown in the figure is the most important and most expensive component of the total CAD system: the software. Producing a "sweet" curve through a set of data points at the press of a button requires the prior preparation of extensive programmed computer instructions, painstakingly created by skilled professionals. When one considers the number of individual operations carried out with a major CAD system, it is not hard to see why the software runs to hundreds of thousands of lines of code and why its development time is measured, literally, in man-centuries.

"Computer graphics in automotive design is no longer an experiment, or even a pilot operation. It is a mature tool, in full production use."

CADANCE: STATE OF THE ART IN CAD

A good illustration of the use of computer graphics in an industrial CAD system, and one with which I am familiar, is GM's powerful system called CADANCE (the acronym for Computer Aided Design and Numerical Control Effort). This advanced system is the one I cited as instrumental in meeting the design goals for GM's 1977 B car.

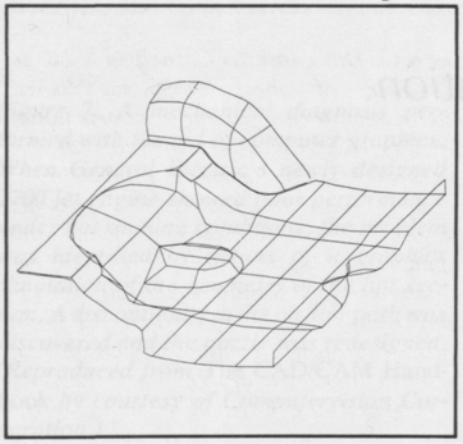
The construction, acceptance, and effective implementation of this technology has been a long and arduous process. It started in the late 1950s with the DAC-I (Design Aided by Computer) system pioneered by the General Motors Research Laboratories (GMR). The console, which was a one-of-a-kind unit with vector-refresh display, was specified jointly by GMR and IBM and constructed by IBM.

Though intended primarily to establish feasibility, the system was actually used to design several parts during its 1963–1968 lifetime. It performed well, reducing design time as much as one-third. It wasn't until the early 1970s, however, that this early promise was fulfilled and CADANCE was ready for significant use in production. The lag was owing to the time needed for software research and development in a variety of areas. The requirements included time-sharing systems for multiple design consoles, languages for high-level programming and database manipulation, virtual memory files, sculptured-surface mathematics, and an improved graphical man-machine interface.

A true 3-D system from database to display, CADANCE is best described as a collection of applications supported by a utility system. It runs on large IBM systems, each of which serves upward of seventy design consoles. These consoles are high-performance vector-refresh units from DEC, IBM, and Adage. The utility system performs functions common to all applications while insulating the application programmer from graphics and database details and providing a uniform, consistent environment for the graphics user. The primary entity is the data; programs are brought in, as required, to view and modify the data. Since these programs are requested through console actions such as light pen selection, the user can maintain a constant view of the database, cause programs to act on selected portions of the data, and see the results reflected in the display. An important benefit of the system is the capacity for communication among different users: designers, for instance, can transmit designs easily and accurately to manufacturing divisions, where the addition of features such as reinforcements, flanges, or inner panels takes place.

A major application of CADANCE, as we have seen, is body design, and it is also one of the most highly developed. The procedure for designing the sculptured outer surface of an automobile begins with the construction of a full-sized clay model. Data defining the surface are digitized and read into a file. Then the designer, working at the computer-graphics console, uses the raw data to produce smooth lines and to combine them into a mathematically continuous, esthetically pleasing

Figure 9a



9b

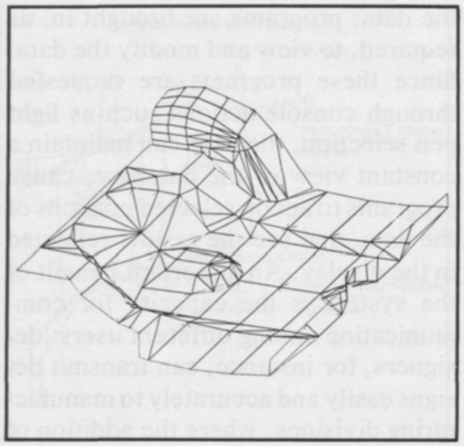


Figure 9. Computer graphics in automobile design. The images, obtained with the use of General Motors' CADANCE system, were taken as hardcopies during the design process. A major use is in body design: raw data obtained from a physical model are processed to produce the basic lines. The example in a *shows the trunk. Structural modeling is another major application area. The computer-graphics system is used to construct a finite-element model* b *for structural analysis. (Reprinted with permission © 1980 Society of Automotive Engineers, Inc.)*

Figure 10. Growth patterns in the industrial use of CAD/CAM.

Figure 11. A current trend in CAD: the use of color raster graphics as an aid in visualizing and understanding designs. A wire-frame representation such as a *can be ambiguous as well as confusing. It can be interpreted in several ways, one of which is shown in* b. *(Can you think of some others?)*

Figure 10

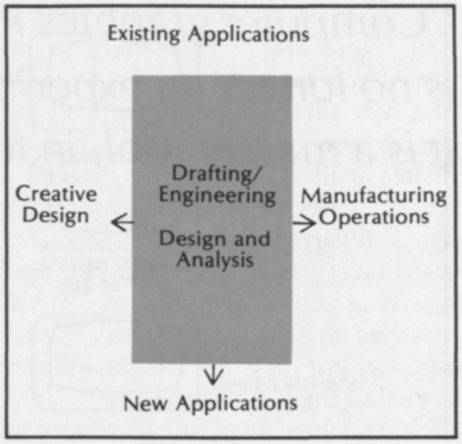
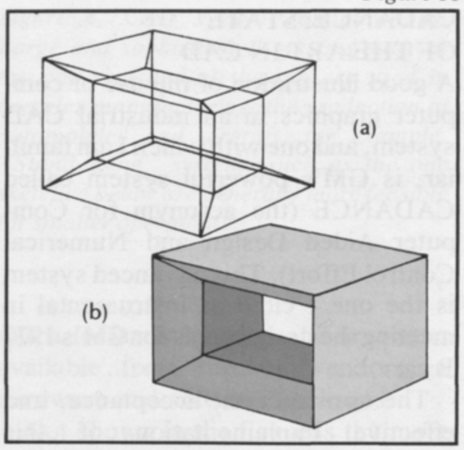


Figure 11



surface (see Figure 9*a*). Different views may be shown, at any scale and in any combination, for overview or close examination, and sections may be "cut" at any point. Various analytical measures of smoothness can be ordered and examined.

Another important area of application is structural modeling. At the console, the engineer can construct finite-element models (see Figure 9*b*) for analysis by such programs as NASTRAN. Also available are numerous aids for reviewing the output of such analysis routines. Other CADANCE operations are designing roll dies and performing visibility studies. Roll dies are used for manufacturing parts, such as moldings, that have uniform cross sections. The visibility assessments, which are carried out early in the design process, determine what is visible to 95 percent of drivers, on the basis of the Society of Automotive Engineers' standard for the ellipse defined by eye position.

PROSPECTS FOR GRAPHICS IN MANUFACTURING

Computer graphics in automotive design is no longer an experiment, or even a pilot operation. It is a mature tool, in full production use. Designers are no longer reluctant to try the techniques; indeed, they often demand to know why they can't have a higher priority for use of a console. The challenge is no longer to try to "sell" the use of computer graphics; rather, the problem is to manage the growth.

The benefits of CAD do not come cheaply, of course. Typical systems cost from $150,000 to $800,000 or more (though the prices are declining). Nevertheless, computer graphics is cost-effective because of the significant reduction it makes in the time required to perform design and drafting operations.

In addition to the direct financial cost, there are other matters to be considered in decisions about CAD. The new technology is complex, requiring new ways of doing things by people at all levels, from the designers who must learn to use the hardware and software to corporate managers who must understand where, and where not, to apply computer-aided techniques. Managers must deal also with opposition from employees who are set in their ways, or possibly anxious about a loss of privilege or prestige. All these situations generate retraining costs that are often neglected or underestimated.

A more serious problem, experienced by universities and government as well as industry, is the shortage of skilled software developers; to find these specialists, companies are increasingly turning to professional recruiting firms. Turnkey vendors often claim that no software development is necessary in order to use their equipment—that the system can be just plugged in and put into operation—but although this may be the case for the initial application for which the system was purchased, new uses sometimes require additional software.

What does the future hold? For industrial applications, the current thrust is to extend the use of computer graphics to include both earlier stages of design and post-design manufacturing processes (see Figure 10). Technical improvements are involved in these efforts, of course.

One trend is toward the use of more color. Most systems generate so-called wire-frame images, like pencil lines on paper, but when parts or assemblies are complex, these images can be difficult to interpret, misleading, or ambiguous. The use of color to produce solid, shaded images can remove such ambiguity and make complicated designs understandable (see Figure 11). Color is beginning to be used also in imaginative quantitative ways—for example, to show variations in stress (as discussed in this issue in the article by Abel, McGuire, and Ingraffea). Cost-effective color raster systems are now available and are being used increasingly not only in engineering applications, but in business operations such as market analysis.

Another area of development is the modeling of solids. Most current systems, even 3-D ones, can deal only with surfaces and are unable to calculate internal properties such as mass, volume, or moment of inertia. Solid-modeling systems are just beginning to become available commercially.

As powerful as current CAD systems seem, the new and anticipated improvements will make them more so. Innovative uses of color and solid modeling, and also mathematical developments to facilitate shape design and analysis, will make possible the expansion of CAD into new areas of manufacture (the CAM part of CAD/CAM). They will also make computer graphics more useful in the creative early phases of design.

Indeed, as the vendors keep telling us, CAD/CAM may have more potential to increase productivity than any development since the advent of electricity. It is an important technology, well on the way to becoming essential for industry.

John C. Dill came to Cornell in 1980 as manager of the newly established Computer-Aided Design Instructional Facility (CADIF) after ten years at the General Motors Research Laboratories. As a senior research scientist there, he was responsible for developing systems and applications for color graphics in computer-aided design (CAD). In his Cornell position, he also conducts research; current projects include applications of color to interactive design.

In May Dill will teach, as he has in the past, in a Cornell summer-session short course on computer graphics and CAD. (The other instructors will be Professors Abel and Greenberg, who are also contributors to this issue of the Quarterly.) Dill has also conducted professional-development courses and seminars in computer graphics for the Association for Computing Machinery and for Wayne State University's night-school program.

He received his undergraduate education in engineering physics at the University of British Columbia and earned the M.S. in biomathematics at North Carolina State University and the Ph.D. in information science at the California Institute of Technology.

FRIENDLY COMPUTERS WITH COLOR PICTURES

New Tool for Resource and Environmental Planning

by Daniel P. Loucks, Peter N. French, and Marshall R. Taylor

User-friendly computer programs and terminals that can display both graphs and full-color pictures are transforming the way engineers and planners approach problems involving the management of natural resources. Techniques of interactive computer graphics are proving to be exceptionally useful, for example, in the area of water resources—for planning the design and operation of dams, hydroelectric power plants, water-distribution and wastewater-collection systems, and pollution-control facilities, and for assessing their economic and environmental impacts.

Imagine, for instance, that there is a threat of flooding in a river basin because of a weakened dam or the possibility of a heavy rainstorm. An engineer could sit down in front of an interactive color computer-graphics terminal, call up color-coded maps of the flood plain, enter information about the potential flood conditions and alternative control strategies, and observe a transparent blue color spread over the areas where flooding would probably occur under any given set of circumstances. Even the predicted depth of flooding or the extent of damage would be depicted by color shading.

Far from being an esoteric notion, such a scenario is a real possibility today. The hardware is available and decreasing in cost as computer technology rapidly improves, and the necessary software is catching up. Databases containing geographic, economic, and other relevant information are expanding and becoming computerized. Mathematical models for predicting surface and subsurface water quantity, flow, and quality are widely available. And computer programs capable of combining the data and the models are beginning to be developed in research centers and in the universities.

INTERACTIVE PROGRAMS FOR COMPUTER-AIDED PLANNING

At Cornell such computer-aided planning (CAP) programs are being designed to help define and evaluate the economic and environmental impacts of alternative water-management and land-use plans. Because they present the results very effectively, in the form of graphical or pictorial displays in color, they foster an improved understanding of these impacts by everyone involved in a project—those who are responsible for design, execution, and operation, and those who will be affected by the implementation of the project.

Specifically, CAP programs can help planners use the extensive geographical and other pertinent data that are becoming increasingly available, on magnetic tape, from government agencies. These programs facilitate interaction between person and machine—between the engineer or planner and the computer technology—and provide a link between the technology and the various mathematical models that have been developed for resource planning. They help in adapting the models to problems at specific sites and in making use of various models and databases.

The CAP programs developed at Cornell consist of an interconnected network of subroutines (see page 52) for

"The hardware is available and decreasing in cost . . . and the necessary software is catching up."

entering, analyzing, and displaying the geographical and other data. The programs developed so far can assist in:

- Creating and evaluating possible solutions to problems in surface-water runoff and associated flooding.
- Assessing measures for managing point and nonpoint pollution that affects the quality of the water in the rivers and their tributaries.
- Planning for the operation of reservoir systems so as to accommodate multiple uses and objectives.
- Forecasting and controlling, conjunctively, surface and subsurface water quantity and quality. (This program should be helpful, for example, in the search for solutions to problems of toxic-waste disposal and nonpoint pollution such as that caused by runoff from fertilized argicultural land.)
- Predicting the flooding and flood damage associated with a large storm or a dam failure.

Work is proceeding on the development of interactive programs for a variety of related applications:

- Studying hydrology problems in urban environments.
- Predicting the concentration and transport of pollutants in lakes and estuaries.
- Handling more effectively the geographical data from different regions, each of which may have many attributes that vary over time, and improving methods of entering, manipulating, and displaying time-varying three-dimensional data.

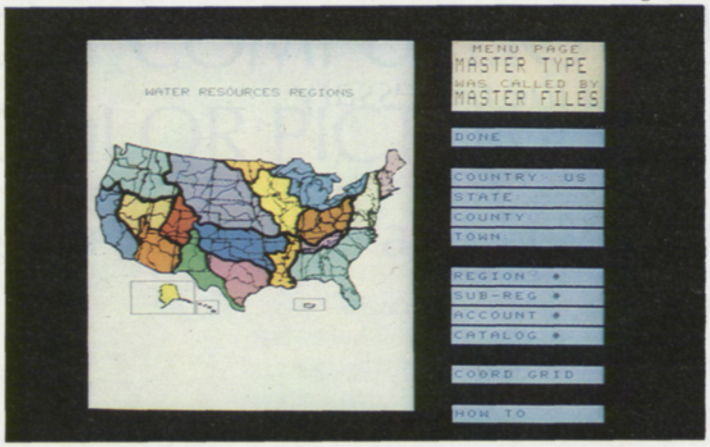
THE HARDWARE AND ITS USE WITH CAP PROGRAMS

The equipment in use at Cornell is described in some detail in other articles in this issue. Essentially, input is made with a digitizing tablet or a video camera, or both; analyses are conducted using interactive terminals; and results are displayed alphanumerically, graphically, and pictorially in color on raster (television) devices. Peripheral equipment includes graphics hardcopy units and devices for making pictures and videotapes of both the vector and the raster displays.

The tablet and its electronic pen are used to select and execute various commands shown on a display device, to draw in geographical or graphical data, and sometimes to enter numerical data with the aid of a key pad on the display device. The video camera digitizes two-dimensional maps and other images for display on color-television monitors. The third dimension can be defined by cross-sectional drawings or contours on maps; for example, a three-dimensional representation of a geographic area could be prepared by drawing cross sections at various sites and interpolating between them, or by tracing selected key elevation contours and elevation points and interpolating between them, or by using both of these methods. The result is a three-dimensional geographic database that includes the elevation of each point, or pixel, on the television display. With this kind of information, watershed boundaries and stream paths can be easily computed and displayed.

The use of color presents some special problems for resource planning. Over sixteen million different colors can be displayed on 24-bit computer-graphics screens, but for ease of in-

Figure 1



Files of regional water-resources maps can be created and accessed by beginning with a map of the entire country, displayed with the needed program menu items (Figure 1). The regions are defined by the Federal Water Resources Council.

The Great Lakes area, for example, is selected by pointing with the electronic pen to Region 4 to obtain the display shown in Figure 2. Alternately, the Region 4 map could be accessed in response to a question on the alphanumeric terminal.

One can "zoom in" on specific areas by accessing successively more detailed topographical maps (Figures 3 and 4) from

Figure 2

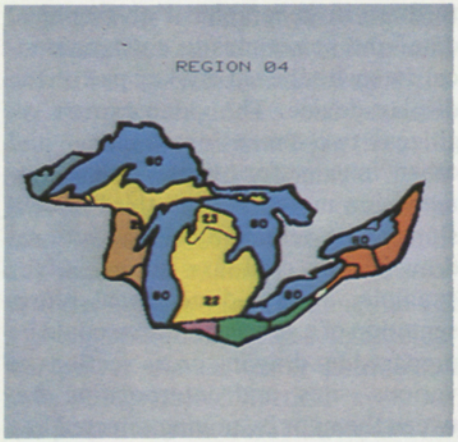


Figure 3

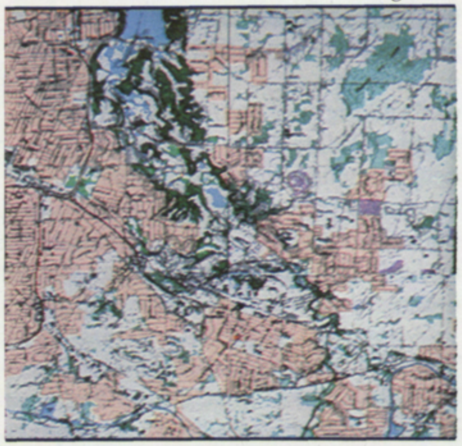


Figure 4

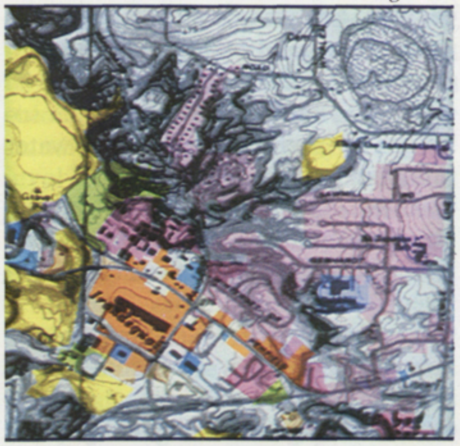


Figure 5

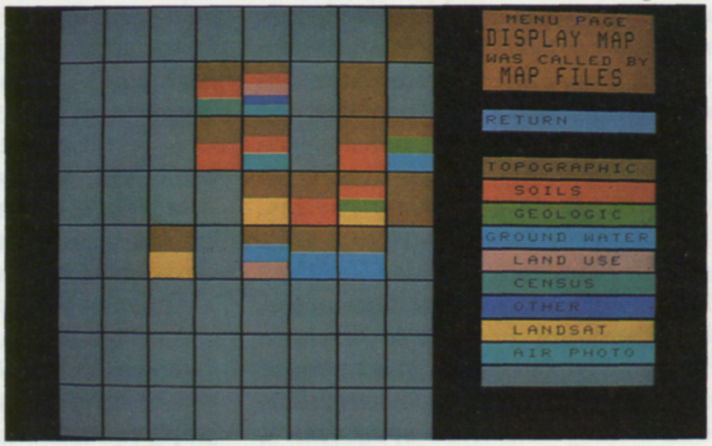
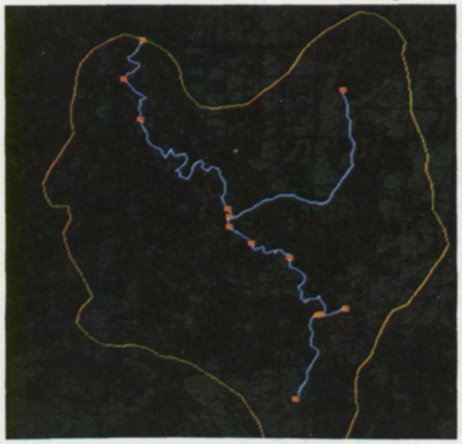


Figure 6



the regional map. The colors represent various land uses, whose colors and corresponding areas are identified on an alphanumeric terminal.

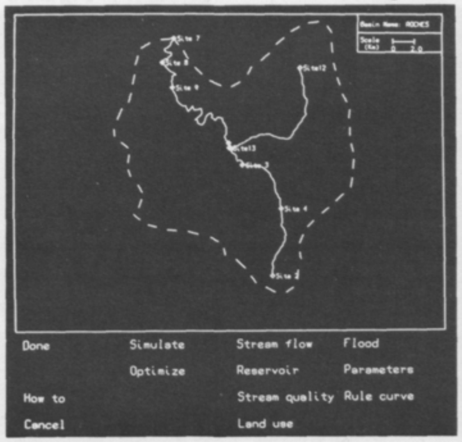
An alternative method of accessing map files is to make a selection from a display grid. Figure 5, for example, shows sixty-four 7 1/2-minute maps that are available. The types of maps are denoted by different colors; they include topographic, soils, geological, groundwater, land-use, and census maps. Digital Satellite Imagery or air-photos could also be utilized.

A vector representation is another kind of map that can be accessed. Figure 6 shows a color display and Figure 7 was obtained from a black-and-white vector-display device. (The image in Figure 7 includes menu items.) These displays depict a part of the river basin shown in Figure 3.

terpretation, images used in resource planning need to have a much smaller selection of colors: each one should represent a distinguishable feature, as blue for water or green for vegetation. CAP programs, therefore, must include provisions for effective color editing and selection.

The Cornell CAP programs have been written for implementation on minicomputers and the display devices described. Provisions have been made for transferring the programs to other equipment, however. In particular, we hope eventually to adapt the CAP programs to microcomputers, which could be used either as intelligent terminals or as stand-alone computers, depending on the application and need for computer power. The use of microcomputers should substantially reduce the cost of implementing CAP programs using high-resolution interactive computer graphics.

Figure 7



USING THE COMPUTER GRAPHICS EQUIPMENT

In using a CAP program for a water-resource application, one might begin by calling from a disk or magnetic tape the geographical area to be studied, along with its associated database. A particular region might be accessed by beginning with a map of the entire country (as in Figure 1) and successively zooming into the special area of interest (as illustrated by the sequence of Figures 2, 3, and 4). Another way of accessing a specific map is to enter alphanumerically the latitude and longitude, or the name, of the area or basin and then to select from the resulting matrix of map images (Figure 5) the ones that are appropriate (for example, Figures 3 and 4). A basin shown on the color television monitor (for example, Figure 3) can be represented also as a vector display (as in Figures 6 and 7).

Each vector and raster display is divided into a picture section and a menu section. The menu section consists of various commands that permit the manipulation of the picture displays and of the associated databases, and the execution of a wide variety of operations, including menu changes and access to additional programs and other displays. Each menu item is executed by placing the digitizing pen on the tablet in a position that places the X (cursor) on the display over the menu item, and pressing down on the spring-loaded pen point.

An example of the information that can be obtained is illustrated in Figures 8–10 (see page 50). These map displays resulted from the implementation of models for studying alternative flood-control and land-use-management policies for flood-prone areas (such as the one in Figures 3, 6, and 7). Another example is shown in Figures 11 and 12 (see page 51); these displays were obtained in a study of the impact of different agricultural land-use policies and wastewater-treatment facilities on the quality of a stream. All these displays—Figures 8 through 12—were obtained by using various analytical models and overlaying different sets of geographical data and model solutions.

An application of the CAP methodology may involve nothing more than

Figure 8

Figure 9

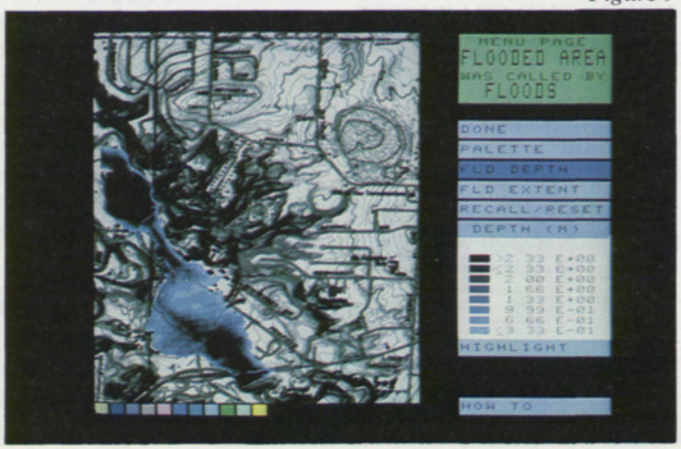
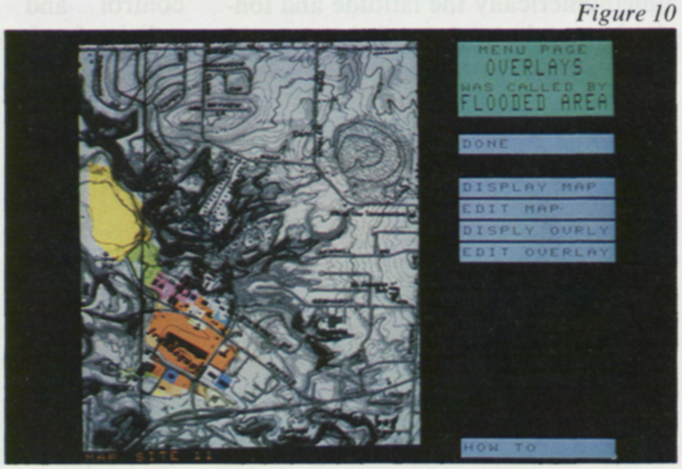


Figure 10



Projections of flooding can be shown graphically on maps displayed on a color-raster device. Figure 8 is a topographical map of a river-basin area (part of the map area shown in Figure 3). The transparent blue color denotes the extent of flooding projected according to a standard prediction method and a given flood-control alternative. This display results from rainfall-runoff and backwater profile models as well as a three-dimensional geographic database. In Figure 9 the predicted depth of flooding is depicted by color shading.

Information about the types of land use in the areas that would be flooded is shown graphically in Figure 10. Overlays show the extent of flooding (as in Figure 8) and the various land uses (Figure 4). Numerical information relating the projected flooding to the different kinds of land use could be displayed on an alphanumeric terminal.

The use of computer-graphics techniques in studying agricultural land-use policies and wastewater treatment methods is illustrated in Figures 11 and 12.

Figure 11 is a vector display of the variations, over a twenty-four-hour period, of four selected parameters that affect the water quality at a selected site on a river. The parameters that have been modeled and can be accessed include light, temperature, amount of nondecaying material, coliforms, nitrogen (in the form of ammonia, nitrite, or nitrate), phosphorus, algae, biochemical oxygen demand, and dissolved oxygen. Also available are vector displays showing variations over distance along the river at a specified time of day.

Figure 12 is a color television display showing variations in water temperature along a river at a given time of day; a series of such displays shows how the temperatures change as time passes. (The nonriver portions of the map have been darkened to highlight the colors that indicate the different temperatures.) Other parameters, such as the concentrations of various con-

Figure 11

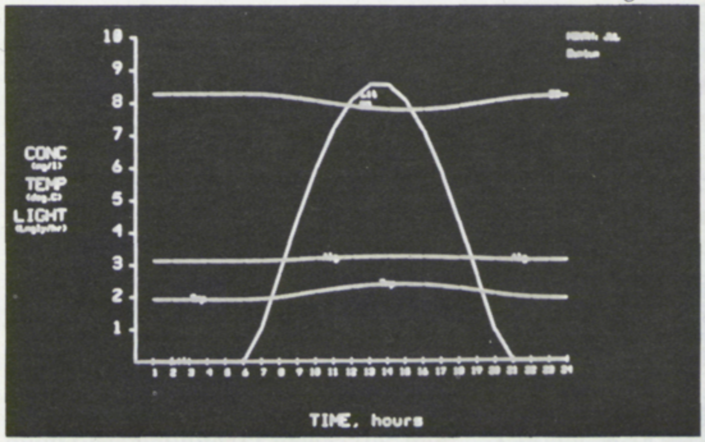


Figure 12

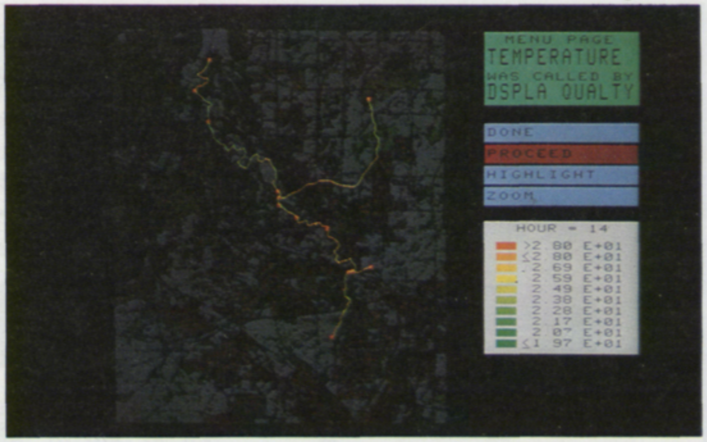


Figure 13

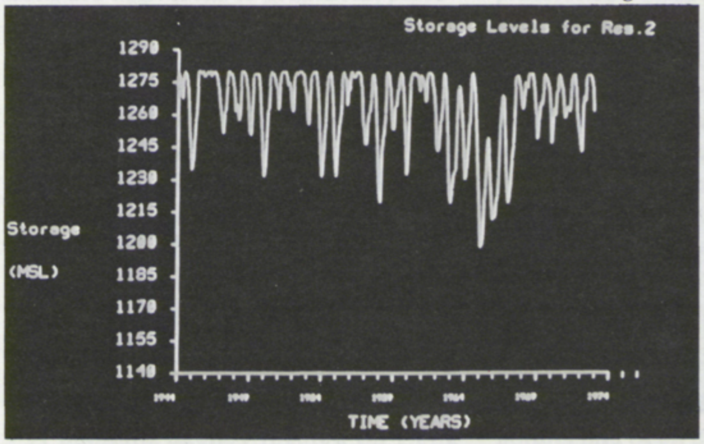
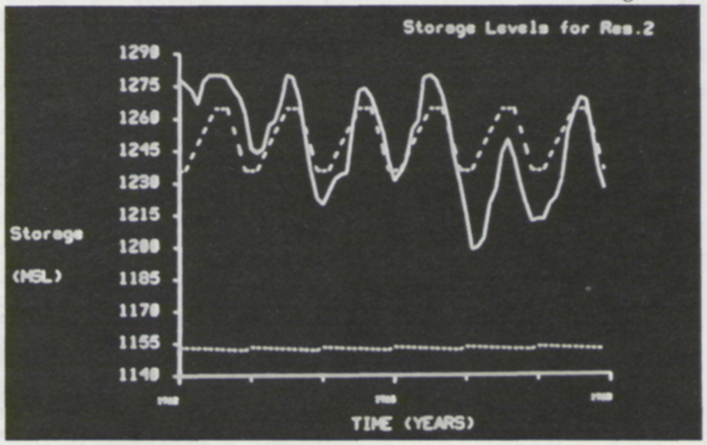


Figure 14

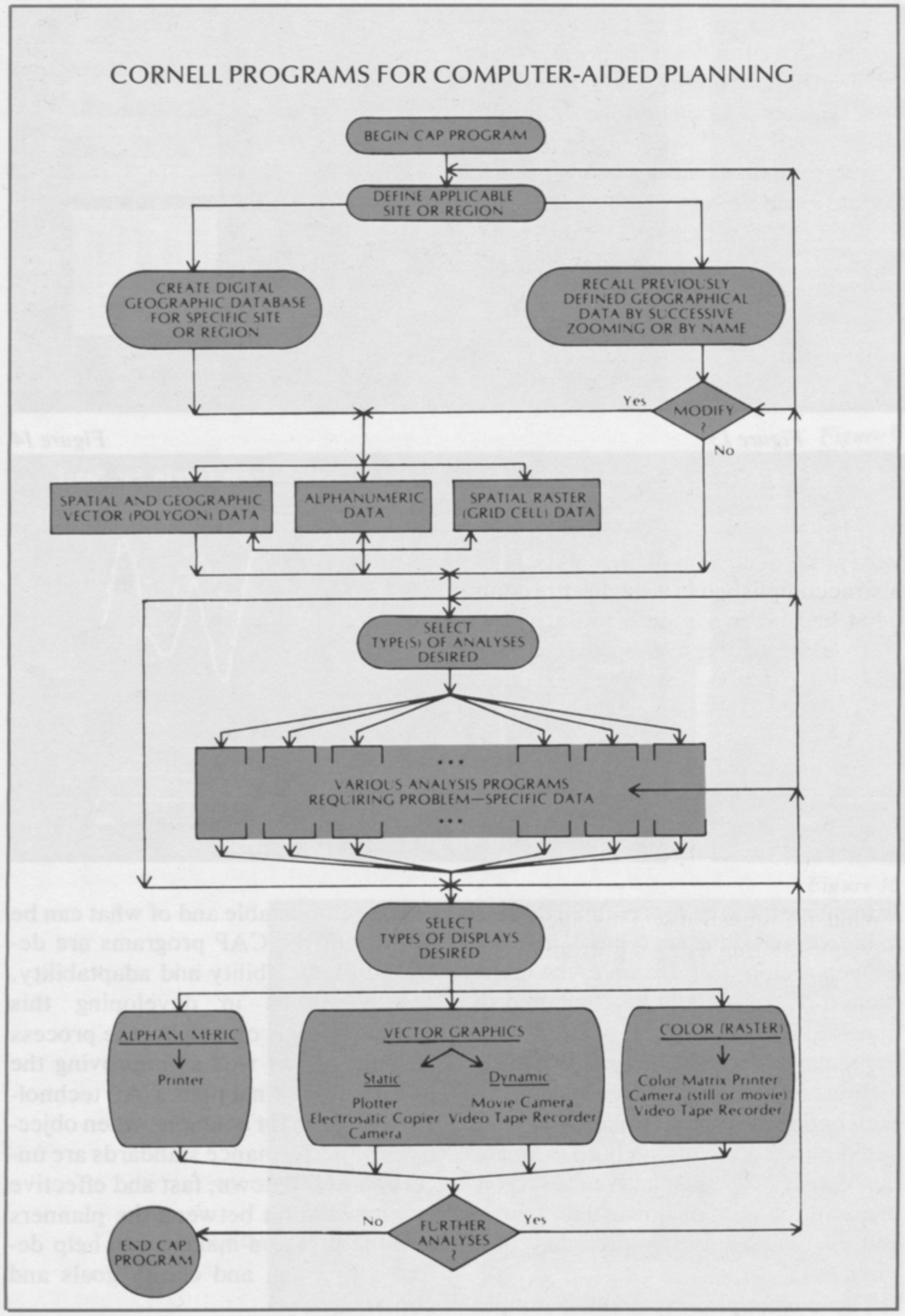


stituents, can be selected for similar display.

An example of the use of a CAP program to study policy alternatives is illustrated in Figures 13 and 14. The vector display in 13 shows reservoir storage volumes over a period of years (from 1944 to 1974), as predicted according to a computer simulation of a particular operating policy; 14 is an expanded, rescaled portion (from 1962 to 1968) of that time series. The dotted lines reflect the seasonal operating policies; when storage levels fall below these policy levels, water releases allocated for specified purposes must be restricted.

computing the area represented by various colors on different types of maps of a given region. For example, the intersection of areas could be computed to find the acreage of corn planted on a particular watershed and political jurisdiction. In a more complex operation, both optimization or simulation models could be used interactively to estimate the impact of alternative reservoir operating policies on downstream flows and diversions during droughts (see Figures 13–14).

These examples are a small sample of what is available and of what can be displayed; the CAP programs are designed for flexibility and adaptability. The emphasis in developing this methodology is on helping the process of planning, as well as improving the quality of the final plan. CAP technology is useful, for example, when objectives or performance standards are uncertain or unknown; fast and effective communication between the planners and the decision-makers can help define a problem and clarify goals and constraints.



COMPUTER-AIDED MODELS: A BASIC REQUIREMENT

The effectiveness of CAP programs depends not only on the interactive and display capabilities of the hardware, but on the underlying analytical models.

Some of the models incorporated in the current Cornell CAP programs were developed for various government agencies and engineering consulting firms, and are widely used throughout the United States. They include, for example, a rainfall-runoff model prepared for the federal Department of Agriculture's Soil Conservation Service, a water-surface-profile model used by the Army Corps of Engineers, and a simulation model developed by the Environmental Protection Agency to predict the concentrations of numerous substances, including algal biomass, in river waters. The reservoir-simulation CAP program is based on a model developed by the New York State Department of Environmental Conservation. Other models and algorithms for assessing water-resource facilities have been developed at Cornell and at other universities. These include most of the optimization and simulation models that are used for preliminary screening of various designs and operating policies and for reliability studies of the alternative plans.

Of course, the use of such models entails calculation of the required parameters. For example, it might be necessary to calculate upstream drainage areas, land acreage used for certain designated purposes, runoff coefficients, or channel slopes. Many of these calculations depend on a three-dimensional, digitized map of a region—a representation that can be obtained using the inputting and interpolation techniques described above.

Once the input data are calculated, they are converted, by means of matrix generators and other subroutines, to a format suitable for the models or algorithms being used. If a model needs to be calibrated, this can be accomplished with the aid of interactive statistical tests built into the program. Next, the models are used to obtain numerical solutions. Finally, the solutions are converted to graphical, pictorial, or simply numerical output.

SOME EXPERIENCES IN USING THE CAP PROGRAMS

The CAP programs that have been developed so far at Cornell have been applied to some actual planning processes. The varied reactions of the users have both reinforced our conviction that the methodology is valuable, and helped us identify areas in which addition research is needed. Here are some cases in point.

- A planning agency located on Long Island had reached an impasse in trying to solve a problem involving land-use planning and its impact on groundwater quantity and quality. To obtain information on present and projected land-use areas within various political subdivisions, the planners decided to try CAP. They now claim that they could spend less money and time and get more information than they had originally thought possible.
- A state planning agency, on the other hand, is reluctant to continue to use CAP programs for a needed study of reservoir operations policies and for a study of nonpoint-source pollution control in a rural and urban watershed until sufficient funding and staff assistance become available for in-house CAP capabilities. Such financial concerns are, indeed, valid today, but they should become less significant in the future as CAP programs become more available and better documented, and as the improvements in computer hardware increase capacity and decrease cost.
- A federal planning agency applied a Cornell CAP program to one of its watershed rainfall-runoff problems. The program included one of the agency's own models for rainfall-runoff prediction. Not only did the agency verify the accuracy of the results—it also accomplished in a single afternoon what had taken a month to do, much less satisfactorily, at the home office. This was partly because the procedure at the home office required the computer input to be mailed to another part of the country for a model solution. Also, without the CAP capabilities for display and interaction, agency personnel had been unable to obtain quick answers to a sufficient number of "What if" questions. This agency is now considering using a portion of the CAP program for watershed planning at its offices throughout the United States.

These and other experiences have convinced us that successful, widespread use of CAP programs will require computer facilities at the places in which the planning is carried out. As computer technology and the necessary software and documentation become less expensive and more commonplace, the acquisition of CAP

"Successful development and implementation . . . is as much an art as it is a science."

systems in many of the smaller regional offices of public agencies and in many engineering consulting firms will become increasingly feasible.

DESIGNING EFFECTIVE CAP PROGRAMS

To be supportive of the planning process, the CAP program must be adaptable to both the substance of a problem and—no less important—the style of the particular planners, managers, or decision-makers. The program must be able to mesh the behavioral, or judgmental, aspects of the planning process with the technical capabilities. Being a service rather than a product, the methodology must constantly grow, adapt, and learn from experience. Successful development and implementation of a computer-support system is as much an art as it is a science.

Friendliness and flexibility of program software has been of particular concern during the development of CAP programs.

What makes a program friendly? It must be written in such a way that the user need not have extensive knowledge about either computer hardware or software. All commands to the computer and questions asked by the computer should be in simple English (or other language). Also, a friendly program allows for user mistakes and eliminates the need, if a mistake has been made, for redoing what has been accomplished satisfactorily.

Program flexibility requires software that is applicable to a problem at any specific site, and an organizational structure that permits manipulation. There should be ready access to numerous commands and ready display of desired information in a logical, simple, fast, and orderly manner. The user should be able to create databases through input and editing, and to have access to them for any set of analyses. There should be provision for the overlaying and display of various databases. Subroutines should be available for answering a wide variety of "What if" questions, when and as desired.

THE EFFECTIVE USE OF COMPUTER-AIDED PLANNING

Improvements in computer technology and the development of its applications go hand in hand. The growth of computer-aided planning has been fostered by the increasing availability of computer software and hardware; and congruently, one reason for the rapid development of these analytical and computational tools is the recognition that they are very useful in predicting the economic, political, and environmental impacts of engineering projects or planning policies. In the field of water-resources planning and environmental management, interactive computer-graphics technology should become increasingly practical as more and more software becomes converted to hardware and as programs become more standardized, more adaptable to different kinds of hardware, more flexible, more powerful, and friendlier. At the same time, successful use of these techniques should stimulate their further development.

Interactive computer graphics offers some special advantages for resource planning. With its striking ability to access, combine, analyze, and effectively display information, it is particularly valuable for assessing alternative solutions or strategies. It can also deal with problems that are not well handled by other computer techniques. For example, some problems, classed as semistructured, are only partially quantitative and therefore not readily adaptable to algorithms for finding optimal or even efficient solutions. Such situations arise when there are conflicts among individuals or interest groups, or when the various desires or objectives are unknown or uncertain,

The authors have their picture taken with a group portrait they have just displayed on the TV monitor of their computer-graphics equipment. Left to right are Peter N. French, Marshall R. Taylor, and Daniel P. Loucks.

or if the impacts of alternative policies or decisions are difficult to estimate. Planning in semistructured situations often involves redundancy and false starts; it always requires adaptation and learning. Computer graphics can adapt and can assist in that learning process.

The advantages of properly used computer-aided planning (CAP) virtually assures that it will become as commonplace in firms and agencies concerned with resource planning as computer-aided design (CAD) and computer-aided manufacturing (CAM) have become in industry. CAP is not a replacement for managerial judgment, of course, only a support. Success in its use depends on the nature of the problem, the quality of the software, the style and attitudes of program developers and users, and the receptiveness of clients. Above all, it depends on imaginative and appropriate application and interpretation.

Daniel P. Loucks completed work on the manuscript for this article the day before he left Cornell for Schloss Laxenburg in Austria, where he is spending a year's sabbatic leave at the International Institute for Applied Systems Analysis. At Cornell Loucks is a professor of civil and environmental engineering; and just before his leave he had served for a year as associate dean of the College of Engineering, with responsibility in the areas of research and graduate education. He has also been chairman of the Department of Environmental Engineering. His research is in the field of environmental systems engineering, including water-resource planning and environmental control, and he has been active internationally as a consultant in these areas. His honors have included the Walter L. Huber research prize of the American Society of Civil Engineers and a Fulbright-Hayes fellowship. He joined the faculty here in 1965 after earning the B.S. degree at The Pennsylvania State University, the M.S. at Yale University, and the Ph.D. at Cornell.

Peter N. French has worked with Loucks as a research associate since he completed his Ph.D. studies in 1980. His thesis was on water-quality modeling using interactive computer graphics. French was graduated from the University of North Carolina with a major in chemistry, and continued his studies there for the M.S. in environmental chemistry and biology. Before coming to Cornell for doctoral study, he spent three years as a water quality specialist for a regional planning commission and council of governments in North Carolina. His efforts included the preparation of information used by the governor to plan a waste-treatment-management area, the first in the nation to be approved and funded by the Environmental Protection Agency under the 1972 amendments to the Federal Water Pollution Control Act.

Marshall R. Taylor is a graduate student and research assistant in environmental engineering, working in the area of water-resources systems; his research has included the application of computer graphics to the management of water and related land resources. Before coming to Cornell, he earned the M.S. in civil engineering from Virginia Polytechnic and State University in 1976, and then spent two years as a research technologist at the Water Resources Center of the University of Nebraska at Lincoln. His work there was concerned with the application of mathematical programming techniques to water-management problems.

The Advance of Computer Graphics

A major new technology and its impact in industry, in research, and in education are surveyed in this issue of the *Quarterly*.

In particular, the articles show what is going on at Cornell. With access to the facilities of the University's Program on Computer Graphics, graduate students and faculty members have the opportunity to help develop the technology or to use computer-graphics techniques as aids in their project work. And from now on, thanks to the new Computer-Aided Instructional Facility (CADIF) at the College of Engineering, all Cornell engineering graduates will have an understanding of computer graphics, and they will have had the opportunity to acquire a working knowledge of how to use it.

The material in this issue reveals some of the areas in which computer graphics is being used most actively at the present time at Cornell. There are others: work at the National Research and Resource Facility for Submicron Structures is only alluded to, for example—it will be explored in greater detail in a subsequent issue on the submicron facility. The fact is that computer graphics is applicable to a very great many problems in research and in engineering design and analysis. It is the kind of innovation, like the advent of the digital computer itself, that rapidly takes hold, becomes indispensable, and effectively revolutionizes whole systems of operation. We are gratified that Cornell is at the forefront of this development, with outstanding and up-to-date equipment and knowledgeable personnel.

We note that "the Advance of Computer Graphics" has pushed some of the material for this issue right off the pages and into the next *Quarterly*. If you miss *Faculty Publications, Register,* and *Letters,* be assured that they will return in the spring.

We thank the Program on Computer Graphics for financial help in producing this special issue (it is not often that we have the chance to use four-color printing), and the people at CADIF for initiating us into the fascinating world of computers that can communicate with pictures as well as with words and numbers. Along with the students who have used CADIF, we can attest that computer graphics is not only a marvelous tool, but fun.

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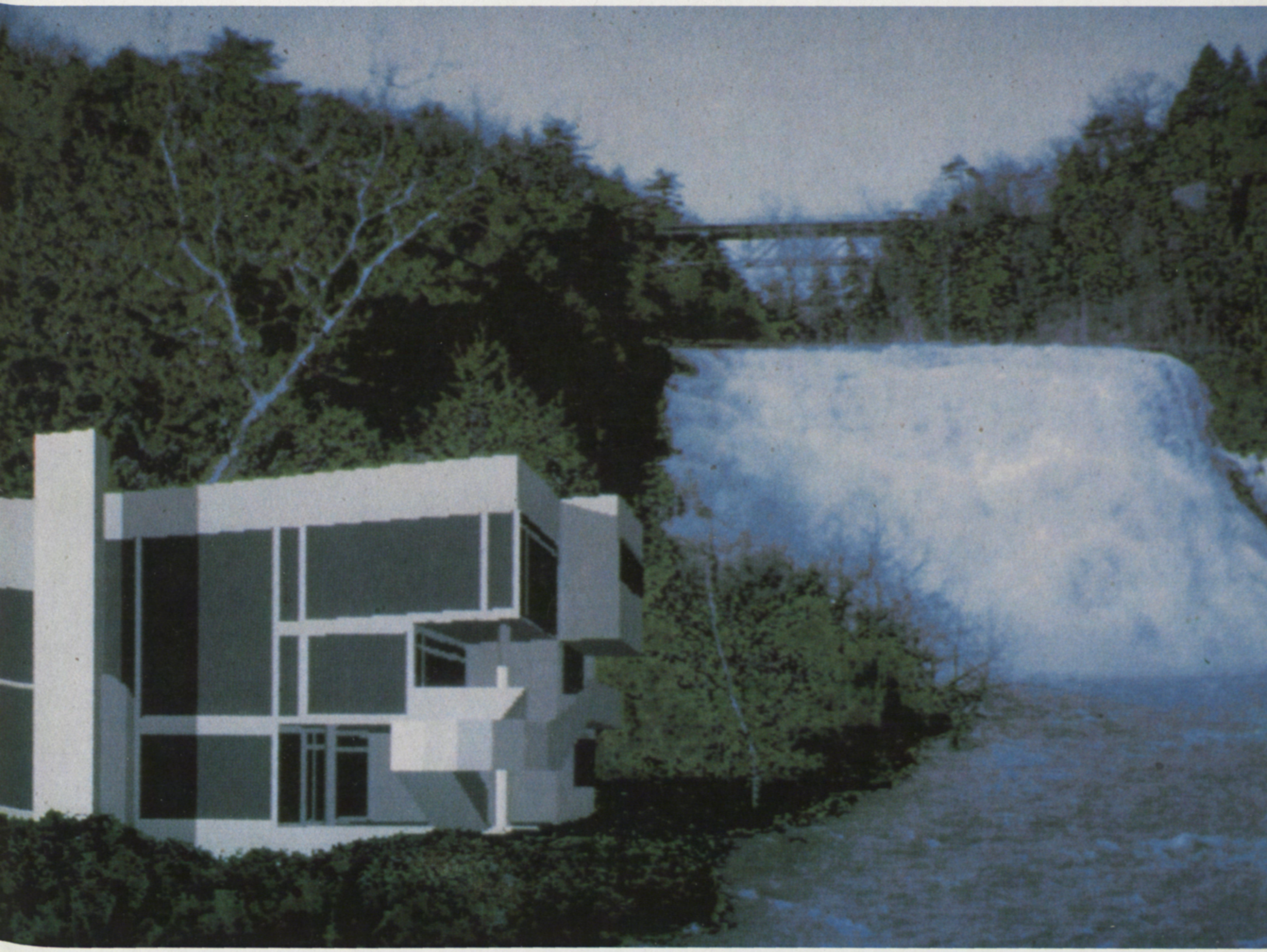

On a color raster screen an unbuilt house appears in a gorge familiar to Cornellians. This example, from the University's Program on Computer Graphics, illustrates an architectural application of computer graphics. (Programmed by Kevin Weiler.)

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