Chapter 1 A Survey of Computer Graphics

Computers have become a powerful tool for the rapid and economical production of pictures. There is virtually no area in which graphical displays cannot be used to some advantage, and so it is not surprising to find the use of computer graphics so widespread. Although early applications in engineering and science had to rely on expensive and cumbersome equipment, advances in computer technology have made interactive computer graphics a practical tool. Today, we find computer graphics used routinely in such diverse areas as science, engineering, medicine, business, industry, government, art, entertainment, advertising, education, and training. Before we get into the details of how to do computer graphics, we first take a short tour through a gallery of graphics* applications.

1.1 Computer-Aided Design

A major use of computer graphics is in design processes, particularly for engineering and architectural systems, but almost all products are now computer designed. Generally referred to as CAD, computer-aided design methods are now routinely used in the design of buildings, automobiles, aircraft, watercraft, spacecraft, computers, textiles, and many, many other products.

For some design applications, objects are first displayed in a wireframe outline form that shows the overall shape and internal features of objects. Wireframe displays also allow designers to quickly see the effects of interactive adjustments to design shapes. Figures 1-1 gives an example of wireframe displays in design applications.

![Figure 1-1](image_url)
Color-coded wireframe displays of body designs for an aircraft and an automobile. (Courtesy of (a) Evans & Sutherland and (b) Megatek Corporation.)

Software packages for CAD applications typically provide the designer with a multi-window environment, as in Fig. 1-2. The various displayed windows can show enlarged
sections or different views of objects.

Circuits such as the one shown in Fig. 1-2 and networks for communications, water supply, or other utilities are constructed with repeated placement of a few graphical shapes. The shapes used in a design represent the different network or circuit components. Standard shapes for electrical, electronic, and logic circuits are often supplied by the design package. For other applications, a designer can create personalized symbols that are to be used to construct the network or circuit. The system is designed by successively placing components into the layout, with the graphics package automatically providing the connections between components. This allows the designer to quickly try out alternate circuit schematics* for minimizing the number of components or the space required for the system.

*Figure 1-2
A circuit-design application, using multiple windows and color-coded logic components, displayed on a Sun workstation with attached speaker and microphone. (Courtesy of Sun Microsystems.)

*Figure 1-3
Simulation of vehicle performance during lane changes. (Courtesy of Evans 6 Sutherland and Mechanical Dynamics, Inc.)

*Figure 1-4
Operating a tractor in a virtual-reality environment. As the controls are moved, the operator views the front loader, backhoe, and surroundings through the
Animations are often used in CAD applications. Real-time animations using wireframe displays on a video monitor are useful for testing performance of a vehicle or system, as demonstrated in Fig. 1-3. When we do not display objects with rendered surfaces, the calculations for each segment of the animation can be performed quickly to produce a smooth real-time* motion on the screen. Also, wireframe displays allow the designer to see into the interior of the vehicle and to watch the behavior of inner components during motion. Animations in virtual-reality* environments are used to determine how vehicle operators are affected by certain motions. As the tractor operator in Fig. 1-4 manipulates the controls, the headset* presents a stereoscopic* view (Fig. 1-5) of the front-loader* bucket or the backhoe*, just as if the operator were in the tractor seat. This allows the designer to explore various positions of the bucket or backhoe that might obstruct the operator's view, which can be taken into account in the overall tractor design. Figure 1-6 shows a composite, wide-angle* view from the tractor seat, displayed on a standard video monitor instead of in a virtual three dimensional scene. And Fig. 1-7 shows a view of the tractor that can be displayed in a separate window or on another monitor.

Figure 1-5
A headset view of the backhoe presented to the tractor operator. (Courtesy of the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, and Caterpillar, Inc.)

Figure 1-6
Operator's view of the tractor bucket, composited in several sections to form a wide-angle view on a standard monitor. (Courtesy of the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, and Caterpillar, Inc.)

Figure 1-7
View of the tractor displayed on a standard monitor. (Courtesy of the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, and Caterpillar, Inc.)
When object designs are complete, or nearly complete, realistic lighting models and surface rendering* are applied to produce displays that will show the appearance of the final product. Realistic displays are also generated for advertising of automobiles and other vehicles using special lighting effects and background scenes (Fig. 1-8).

**Figure 1-8**
Studio lighting effects and realistic surface rendering techniques are applied to produce advertising pieces for finished products. The data for this rendering of a Chrysler Laser was supplied by Chrysler Corporation. *(Courtesy of Eric Haines, 3D/EYE Inc.)*

**Figure 1-9**
A CAD layout for describing the numerically controlled machining of a part. The part surface is displayed in one color and the tool path in another color. *(Courtesy of Los Alamos National Laboratory.)*

The manufacturing process is also tied in to the computer description of designed objects to automate the construction of the product. A circuit board layout, for example, can be transformed into a description of the individual processes needed to construct the layout. Some mechanical parts are manufactured by describing how the surfaces are to be formed with machine tools. Figure 1-9 shows the path to be taken by machine tools over the surfaces of an object during its construction. Numerically controlled machine tools are set up to manufacture the part according to these construction layouts.

**Figure 1-10**
Architectural CAD layout for a building design. *(Courtesy of Precision Visuals, Inc., Boulder, Colorado.)*
Architects use interactive graphics methods to lay out floor plans, such as Fig. 1-10, that show the positioning of rooms, doors, windows, stairs, shelves, counters, and other building features. Working from the display of a building layout on a video monitor, an electrical designer can try out arrangements for wiring, electrical outlets, and fire warning systems. Also, facility-layout packages can be applied to the layout to determine space utilization in an office or on a manufacturing floor.

Figure 1-11
Realistic, three-dimensional renderings of building designs. (a) A street-level perspective for the World Trade Center project. (Courtesy of Skidmore, Owings & Merrill.) (b) Architectural visualization of an atrium, created for a computer animation by Marialine Prieur, Lyon, France. (Courtesy of Thomson Digital Image, Inc.)

Realistic displays of architectural designs, as in Fig. 1-11, permit both architects and their clients to study the appearance of a single building or a group of buildings, such as a campus or industrial complex. With virtual-reality systems, designers can even go for a simulated* "walk" through the rooms or around the outsides of buildings to better appreciate the overall effect of a particular design. In addition to realistic exterior building displays, architectural CAD packages also provide facilities for experimenting with three-dimensional interior layouts and lighting.

Figure 1-12
Oriental rug pattern created with computer graphics design methods. (Courtesy of Lexidata Corporation.)

Many other kinds of systems and products are designed using either general CAD packages or specially developed CAD software. Figure 1-12, for example, shows a rug pattern designed with a CAD system.
1.2 Presentation Graphics

Another major application area is presentation graphics, used to produce illustrations for reports or to generate 35-mm slides* or transparencies* for use with projectors. Presentation graphics is commonly used to summarize financial, statistical, mathematical, scientific, and economic data for research reports, managerial reports, consumer information bulletins, and other types of reports. Workstation* devices and service bureaus exist for converting screen displays into 35-mm slides or overhead transparencies for use in presentations. Typical examples of presentation graphics are bar charts, line graphs, surface graphs, pie charts, and other displays showing relationships between multiple parameters*.

Figure 1-13
Two-dimensional bar chart and pie chart linked to a geographical chart. (Courtesy of Computer Associates, copyright 1992: All rights reserved.)

Figure 1-13 gives examples of two-dimensional graphics combined with geographical information. This illustration shows three color-coded bar charts combined onto one graph and a pie chart with three sections. Similar graphs and charts can be displayed in three dimensions to provide additional information. Three-dimensional graphs are sometime used simply for effect; they can provide a more dramatic or more attractive presentation of data relationships. The charts in Fig. 1-14 include a three-dimensional bar graph and an exploded pie chart.

Figure 1-14
Three-dimensional bar chart exploded pie chart, and line graph. (Courtesy of Computer Associates, copyright 1992: All rights reserved.)

Additional examples of three-dimensional graphs are shown in Figs. 1-15 and 1-16. Figure 1-15 shows one kind of surface plot, and Fig. 1-16 shows a two-dimensional contour* plot with a height surface.
1.3 Computer Art

Computer graphics methods are widely used in both fine art and commercial art applications. Artists use a variety of computer methods, including special-purpose hardware, artist's paintbrush (such as Lumens®), other paint packages (such as Pixelpaint and Superpaint), specially developed software, symbolic mathematics packages (such as Mathematics), CAD packages, desktop publishing software, and animation packages that provide facilities for designing object shapes and specifying object motions.

Figure 1-15
Showing relationships with a surface chart.
(Courtesy of Computer Associates, copyright O 1992. All rights reserved.)

Figure 1-16
Plotting two-dimensional contours in the ground plane, with a height field plotted as a surface above the ground plane.
(Courtesy of Computer Associates, copyright 1992. All rights reserved.)

Figure 1-17
Cartoon drawing produced with a paintbrush program, symbolically illustrating an artist at work on a video monitor. (Courtesy of Gould Inc., Imaging 6 Graphics Division and Aurora Imaging.)
Figure 1-17 illustrates the basic idea behind a *paintbrush* program that allows artists to "paint" pictures on the screen of a video monitor. Actually, the picture is usually painted electronically on a graphics tablet (digitizer*) using a stylus, which can simulate different brush strokes, brush widths, and colors. A paintbrush program was used to create the characters in Fig. 1-18, who seem to be busy on a creation of their own.

![Figure 1-17](image)

*Figure 1-17* illustrates the basic idea behind a paintbrush program that allows artists to "paint" pictures on the screen of a video monitor. Actually, the picture is usually painted electronically on a graphics tablet (digitizer*) using a stylus, which can simulate different brush strokes, brush widths, and colors. A paintbrush program was used to create the characters in Fig. 1-18, who seem to be busy on a creation of their own.

![Figure 1-18](image)

*Figure 1-18* Cartoon demonstrations of an "artist" creating a picture with a paintbrush system. The picture, drawn on a graphics tablet, is displayed on the video monitor as the elves look on. In (b), the cartoon is superimposed on the famous Thomas Nast drawing of Saint Nicholas, which was input to the system with a video camera, then scaled and positioned.

![Figure 1-19](image)

*Figure 1-19* A Van Gogh look-alike created by graphics artist Elizabeth O'Rourke with a cordless, pressure-sensitive stylus. *(Courtesy of Wacom Technology Corporation.)*

A paintbrush system, with a Wacom cordless, pressure-sensitive stylus, was used to produce the electronic painting in Fig. 1-19 that simulates the brush strokes of Van Gogh. The stylus translates changing hand pressure into variable line widths, brush sizes, and color gradations. Figure 1-20 shows a watercolor painting produced with this stylus and with software that allows the artist to create watercolor, pastel, or oil brush effects that simulate different drying out times, wetness, and footprint.
Fine artists use a variety of other computer technologies to produce images. To create pictures such as the one shown in Fig. 1-21, the artist uses a combination of three-dimensional modeling packages, texture mapping, drawing programs, and CAD software.

Figure 1-21
From a series called *Spheres* of Influence, this electronic painting (entitled, Whigmalaree) was created with a combination of methods using a graphics tablet, three-dimensional modeling, texture mapping, and a series of transformations.

Figure 1-22
This creation is based on a visualization of Fermat's Last Theorem, $x^n + y^n = z^n$, with $n = 5$, by Andrew Hanson, Department of Computer Science, Indiana University. The image was rendered using Mathematics and Wavefront software. (Courtesy of the Williams Gallery. Copyright 1991 by Stewart Dickson.)

Figure 1-20
An electronic watercolor, painted by John Derry of Time Arts, Inc. using a cordless, pressure-sensitive stylus and Lumena gouache-brush software. (Courtesy of Wacom Technology Corporation.)

Figure 1-23 shows an example of "mathematical" art. This artist uses a combination of mathematical functions, fractal procedures, Mathematics software, ink-jet printers, and other systems to create a variety of three-dimensional and two-dimensional shapes and stereoscopic image pairs. Another example of electronic art created with the aid of mathematical relationships is shown in Fig. 1-23. The artwork of this composer is often designed in relation to frequency variations and other parameters in a musical composition to produce a video that integrates visual and aural patterns.
Although we have spent some time discussing current techniques for generating electronic images in the fine arts, these methods are also applied in commercial art for logos and other designs, page layouts combining text and graphics, TV advertising spots, and other areas. A workstation for producing page layouts that combine text and graphics is illustrated in Fig. 1-24.

For many applications of commercial art (and in motion pictures and other applications), photorealistic techniques are used to render images of a product. Animations are also used frequently in advertising, and television commercials are produced frame by frame, where each frame of the motion is rendered and saved as an image file. In each successive frame, the motion is simulated by moving object positions slightly from their positions in the previous frame. When all frames in the animation sequence have been rendered, the frames are transferred to film or stored in a video buffer for playback. Film animations require 24 frames for each second in the animation sequence. If the animation is to be played back on a video monitor, 30 frames per second are required.

A common graphics method employed in many commercials is morphing, where one object is transformed (metamorphosed*) into another. This method has been used in TV commercials to an oil can into an automobile engine, an automobile into a tiger, a puddle of water into a tire, and one person's face into another face. An example of morphing is given in Fig. 1-28.
1.4 Entertainment

Computer graphics methods are now commonly used in making motion pictures, music videos, and television shows. Sometimes the graphics scenes are displayed by themselves, and sometimes graphics objects are combined with the actors and live scenes.

Figure 1-25
Graphics developed for the Paramount Pictures movie Star Trek-The Wrath of Khan. (Courtesy of Evans & Sutherland.)

A graphics scene generated for the movie Star Trek-The Wrath of Khan is shown in Fig. 1-25. The planet and spaceship are drawn in wireframe form and will be shaded with rendering methods to produce solid surfaces. Figure 1-26 shows scenes generated with advanced modeling* and surface-rendering methods for two award-winning short films.

Figure 1-26
(a) A computer-generated scene from the film Red’s Dream, copyright Pixar 1987. (b) A computer-generated scene from the film Knickknack, copyright Pixar 1989. (Courtesy of Pixar.)

Music videos use graphics in several ways. Graphics objects can be combined with the live action, as in Fig.1-27, or graphics and image processing techniques can be used to produce a transformation of one person or object into another (morphing). An example of morphing is shown in the sequence of scenes in Fig. 1-28, produced for the David Byrne video She's Mad.
Figure 1-27
Graphics combined with a live scene in the TV series Stay Turned. (Courtesy of Rhythm & Hues Studios.)

Figure 1-28
Examples of morphing from the David Byrne video She's Mad. (Courtesy of David Byrne, Index video. and Pacific Data Images.)

Figure 1-29
Color-coded diagram used to explain the operation of a nuclear reactor. (Courtesy of Las Alamos National laboratory.)
1.5 Education and Training

Computer-generated models of physical, financial, and economic systems are often used as educational aids. Models of physical systems, physiological systems, population trends, or equipment, such as the color-coded diagram in Fig. 1-29, can help trainees to understand the operation of the system.

**Figure 1-30**
A large, enclosed flight simulator with a full-color visual system and six degrees of freedom in its motion. (Courtesy of Frasca International.)

For some training applications, special systems are designed. Examples of such specialized systems are the simulators for practice sessions or training of ship captains, aircraft pilots, heavy-equipment operators, and air traffic control personnel. Some simulators have no video screens; for example, a flight simulator with only a control panel for instrument flying. But most simulators provide graphics screens for visual operation. An example of large simulators with internal viewing systems is shown in Fig. 1-30. Another type of viewing system is shown in Fig. 1-31. Here a viewing screen with multiple panels is mounted in front of the simulator, and color projectors display the flight scene on the screen panels. Similar viewing systems are used in simulators for training aircraft control-tower personnel. Figure 1-32 gives an example of the instructor's area in a flight simulator. The keyboard is used to input parameters affecting the airplane performance or the environment, and the pen plotter is used to chart the path of the aircraft during a training session.

**Figure 1-31**
A flight simulator with an external full-color viewing system. (Courtesy of Frasca International.)
1.6 Visualization

Scientists, engineers, medical personnel, business analysts, and others often need to analyze large amounts of information or to study the behavior of certain processes. Numerical simulations carried out on supercomputers frequently produce data files containing thousands and even millions of data values. Similarly, satellite cameras and other sources are amassing large data files faster than they can be interpreted. Scanning these large sets of numbers to determine trends and relationships is a tedious and ineffective process. But if the data are converted to a visual form, the trends and patterns are often immediately apparent. Figure 1-33 shows an example of a large data set that has been converted to a color-coded display of relative heights above a ground plane. Once we have plotted the density values in this way, we can see easily the overall pattern of the data. Producing graphical representations for scientific, engineering, and medical data sets and processes is generally referred to as scientific visualization. And the term business visualization is used in connection with data sets related to commerce, industry, and other nonscientific areas.

Figure 1-32
An instructor's area in a flight simulator. The equipment allows the instructor to monitor flight conditions and to set airplane and environment parameters. (Courtesy of Frasca International.)

Figure 1-33
A color-coded plot with 16 million density points of relative brightness observed for the Whirlpool Nebula reveals two distinct galaxies. (Courtesy of Los Alamos National Laboratory.)
There are many different kinds of data sets, and effective visualization schemes depend on the characteristics of the data. A collection of data can contain scalar values, vectors*, higher-order tensors*, or any combination of these data types. And data sets can be two-dimensional or three-dimensional. Color coding is just one way to visualize a data set. Additional techniques include contour* plots, graphs and charts, surface renderings, and visualizations of volume interiors. In addition, image processing techniques are combined with computer graphics to produce many of the data visualizations.

Mathematicians, physical scientists, and others use visual techniques to analyze mathematical functions and processes or simply to produce interesting graphical representations. A color plot of mathematical curve functions is shown in Fig. 1-34, and a surface plot of a function is shown in Fig. 1-35.

**Figure 1-34**
Mathematical curve function plotted in various color combinations. *(Courtesy of Melvin L. Prueitt, Los Alamos National Laboratory.)*

**Figure 1-35**
Lighting effects and surface rendering techniques were applied to produce this surface representation for a three-dimensional function. *(Courtesy of Wolfram Research, Inc, The Maker of Mathematica.)*

**Figure 1-36**
A visualization of steam surfaces flowing past a space shuttle by Jeff Hultquist and Eric Raible, NASA Ames.
A few of the many other visualization applications are shown in Figs. 1-36 through 1-41. These figures show airflow over the surface of a space shuttle, study of crack propagation in metals, a color-coded plot of fluid density over an airfoil, an air-pollution study, and a corn-growing study.

**Figure 1-37**
Color-coded visualization of stress energy density in a crack-propagation study for metal plates, modeled by Bob Haber. (*Courtesy of the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign.*)

**Figure 1-38**
A fluid dynamic simulation, showing a color-coded plot of fluid density over a span of grid planes around an aircraft wing, developed by Lee-Hian Quek, John Eickemeyer, and Jeffery Tan. (*Courtesy of the Information Technology Institute, Republic of Singapore.*)

**Figure 1-39**
A visualization of pollution over the earth’s surface by Tom Palmer, Cray Research Inc./NCSC; Chris Landreth, NCSC; and Dave Bock, NCSC. Pollutant SO₄ is plotted as a blue surface, acid-rain deposition is a color plane on the map surface, and rain concentration is shown as clear cylinders.

**Figure 1-40**
One frame of an animation sequence showing the development of a corn ear. (*Courtesy of the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign.*)
Although methods used in computer graphics and image processing overlap, the two areas are concerned with fundamentally different operations. In computer graphics, a computer is used to create a picture. Image processing, on the other hand, applies techniques to modify or interpret existing pictures, such as photographs and TV scans. Two principal applications of image processing are (1) improving picture quality and (2) machine perception of visual information, as used in robotics.

To apply image-processing methods, we first digitize a photograph or other picture into an image file. Then digital methods can be applied to rearrange picture parts, to enhance color separations, or to improve the quality of shading. An example of the application of image-processing methods to enhance the quality of a picture is shown in Fig. 1-42. These techniques are used extensively in commercial art applications that involve the retouching and rearranging of sections of photographs and other artwork. Similar methods are used to analyze satellite photos of the earth and photos of galaxies.

**Figure 1-41**
A prototype technique, called WinViz, for visualizing tabular multidimensional data is used here to correlate statistical information on pedestrians involved in automobile accidents, developed by a visualization team at ITT.

**Figure 1-42**
A blurred photograph of a license plate becomes legible after the application of image-processing techniques. (Courtesy of Los Alamos National Laboratory.)

Medical applications also make extensive use of image-processing techniques for picture enhancements, in tomography* and in simulations of operations. Tomography is a technique of X-ray photography that allows cross-sectional views of physiological systems to be displayed. Both computed X-ray tomography (CT) and position emission tomography (PET) use projection
methods to reconstruct cross sections from digital data. These techniques are also used to monitor internal functions and show cross sections during surgery. Other medical imaging techniques include ultrasonics and nuclear medicine scanners. With ultrasonics, high-frequency sound waves, instead of X-rays, are used to generate digital data. Nuclear medicine scanners collected digital data from radiation emitted from ingested radionuclides and plot color-coded images.

**Figure 1-43**
One frame from a computer animation visualizing cardiac activation levels within regions of a semitransparent volume rendered dog heart. Medical data provided by William Smith, Ed Simpson, and G. Allan Johnson, Duke University. Image-rendering software by Tom Palmer, Cray Research, Inc./NCSC. (Courtesy of Dave Bock, North Carolina Supercomputing Center/MCNC.)

Image processing and computer graphics are typically combined in many applications. Medicine, for example, uses these techniques to model and study physical functions, to design artificial limbs, and to plan and practice surgery. The last application is generally referred to as computer-aided surgery. Two-dimensional cross sections of the body are obtained using imaging techniques. Then the slices are viewed and manipulated using graphics methods to simulate actual surgical procedures and to try out different surgical cuts. Examples of these medical applications are shown in Figs. 1-43 and 1-44.

**Figure 1-44**
One image from a stereoscopic pair showing the bones of a human hand. The images were rendered by Inmo Yoon, D. E. Thompson, and W. N. Waggenspack, Jr., LSU, from a data set obtained with CT scans by Rehabilitation Research, GWLNHDC. These images show a possible tendon path for reconstructive surgery. (Courtesy of IMRLAB, Mechanical Engineering, Louisiana State University.)
1.8 Graphical User Interfaces

It is common now for software packages to provide a graphical interface. A major component of a graphical interface is a window manager that allows a user to display multiple-window areas. Each window can contain a different process that can contain graphical or nongraphical displays. To make a particular window active, we simply click in that window using an interactive pointing device.

Interfaces also display menus and icons for fast selection of processing options or parameter values. An icon* is a graphical symbol that is designed to look like the processing option it represents. The advantages of icons are that they take up less screen space than corresponding textual descriptions and they can be understood more quickly if well designed. Menus contain lists of textual descriptions and icons.

Figure 1-45
A graphical user interface, showing multiple window areas, menus, and icons. (Courtesy of Image-In Corporation.)

Figure 1-45 illustrates a typical graphical interface, containing a window manager, menu displays, and icons. In this example, the menus allow selection of processing options, color values, and graphics parameters. The icons represent options for painting, drawing, zooming, typing text strings, and other operations connected with picture construction.