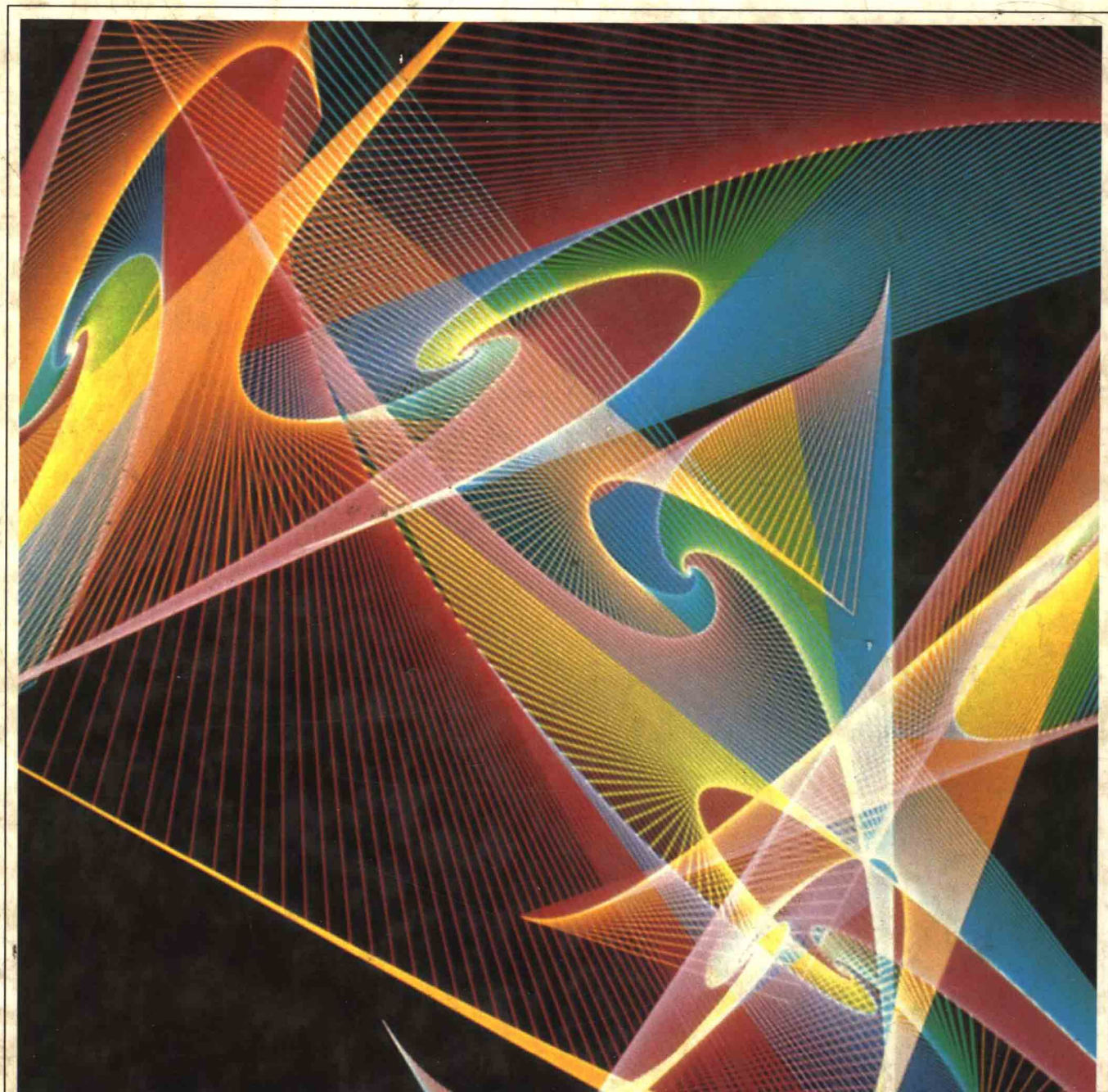
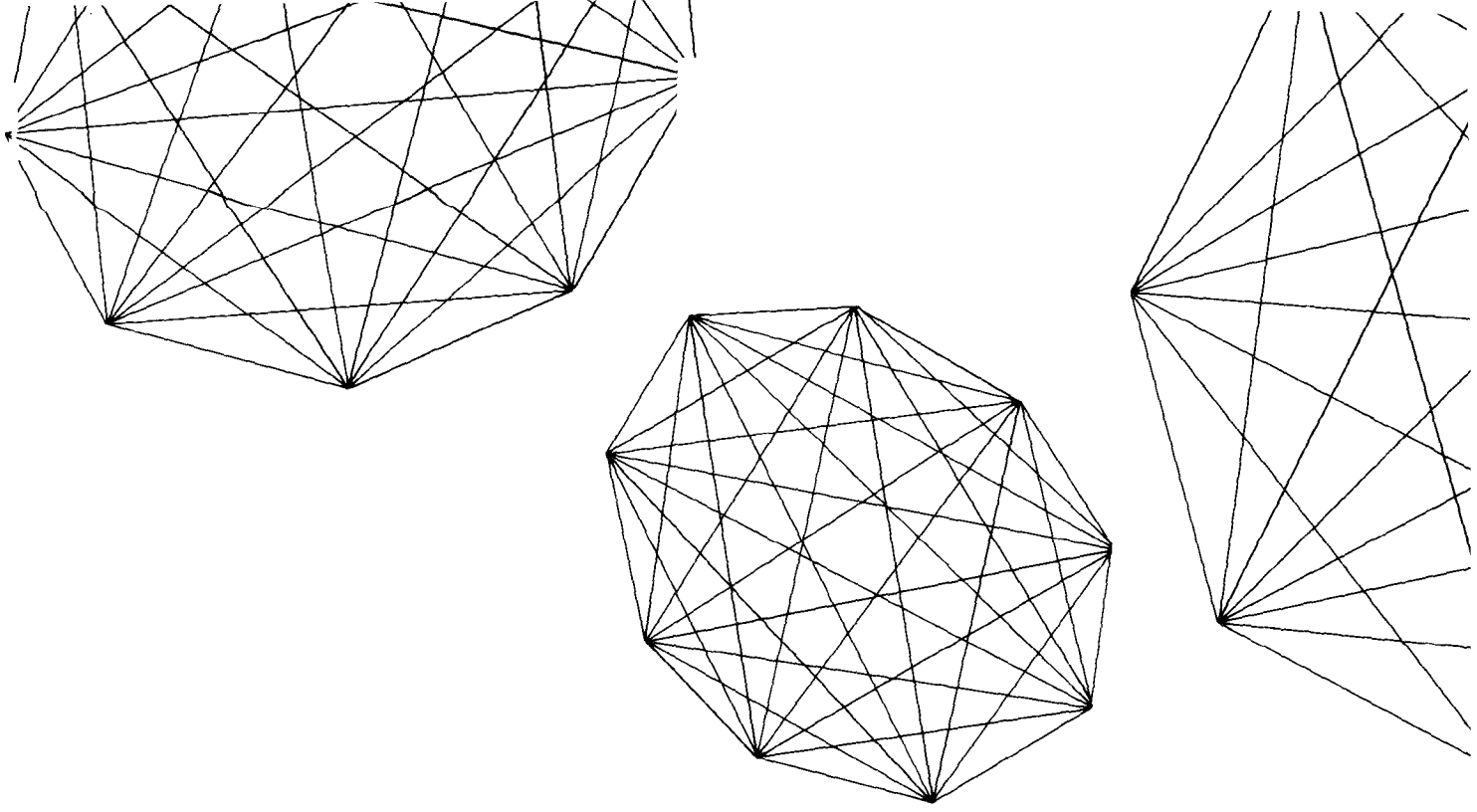
COMPUTER GRAPHICS

Donald Hearn / M. Pauline Baker





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PREFACE

Computer graphics is one of the most exciting and rapidly growing fields in computer science. Some of the most sophisticated computer systems in use today are designed for the generation of graphics displays. We all know the value of a picture as an effective means for communication, and the ability to converse pictorially with a computer is revolutionizing the way computers are being used in all areas.

This book presents the basic principles for the design, use, and understanding of graphics systems. We assume that the reader has no prior background in computer graphics but is familiar with fundamental computer science concepts and methods. The hardware and software components of graphics systems are examined, with a major emphasis throughout on methods for the design of graphics packages. We discuss the algorithms for creating and manipulating graphics displays, techniques for implementing the algorithms, and their use in diverse applications. Programming examples are given in Pascal to demonstrate the implementation and application of graphics algorithms. We also introduce the reader to the Graphical Kernel System (GKS), which is now both the United States and the international graphics-programming language standard. GKS formats for graphics-routine calls are used in the Pascal programs illustrating graphics applications.

The material presented in this text was developed from notes used in graduate and undergraduate graphics courses over the past several years. All of this material could be covered in a one-semester course, but this requires a very hasty treatment of many topics. A better approach is to select a subset of topics, depending on the level of the course. For the self-study reader, early chapters can be used to provide an understanding of graphics concepts, with individual topics selected from the later chapters according to the interests of the reader.

Chapter 1 is a survey of computer graphics, illustrating the diversity of applications-areas. Following an introduction to the hardware and software components of graphics systems in Chapter 2, fundamental algorithms for the generation of two-dimensional graphics displays are presented in Chapters 3 and 4. These two chapters examine methods for producing basic picture components and techniques for handling color, shading, and other attributes. This introduces students to the programming techniques necessary for implementing graphics routines. Chapters 5 and 6 treat transformations and viewing algorithms. Methods for organizing picture components in segments and for interactive input are given in Chapters 7 and 8.

Three-dimensional techniques are introduced in Chapter 9. We then discuss the different ways that solid objects can be represented (Chapter 10) and manipulated (Chapter 11). Methods for forming three-dimensional views on a graphics display device are detailed in Chapter 12. The various algorithms for removing hidden surfaces of objects are discussed in Chapter 13, and models for shading and color are taken up in Chapter 14. These five chapters treat both the standard graphics methods and newer techniques, such as fractals, octrees, and ray tracing.

In Chapter 15, we explore techniques for modeling different systems. Modeling packages provide the structure for simulating systems, which is then passed to the graphics routines for display. Finally, methods for interfacing a graphics package to the user are examined in Chapter 16.

At the undergraduate level, an introductory course can be organized with a detailed treatment of fundamental topics from Chapters 2 through 8 plus an introduction to three-dimensional concepts and methods. Selected topics from the later chapters can be used as supplemental material. For a graduate course, the material on two-dimensional methods can be covered at a faster pace, with greater emphasis on the later chapters. In particular, methods for three-dimensional representations, three-dimensional viewing, hidden-surface removal, and shading and color models, can be covered in greater depth.

A great many people have contributed to this project in a variety of ways. To the many organizations and individuals who furnished photographs and other materials, we again express our appreciation. We are also grateful to our graphics students for their comments on the presentation of this material in the classroom. We thank the many people who provided comments on the manuscript, and we are especially indebted to Norman Badler, Brian Barsky, and Steve Cunningham for their helpful suggestions for improving the presentation of material. And a very special thanks goes to our editor, Jim Fegen, for his patience and encouragement during the preparation of this book, and to our production editors, Tracey Orbine and Kathy Marshak. Thanks also to our designer, Lee Cohen, and the Prentice-Hall staff for an outstanding production job.

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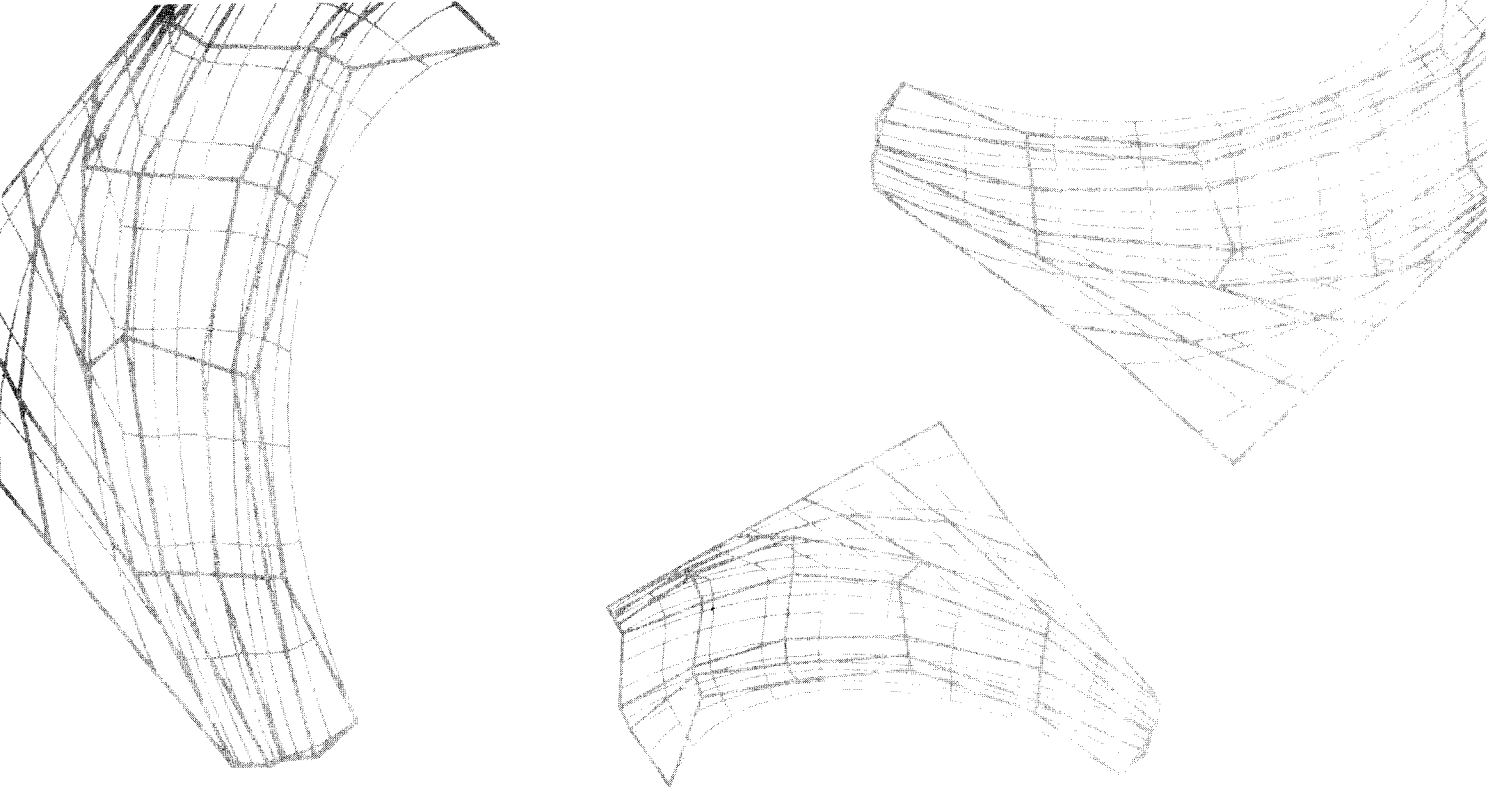

1 A SURVEY OF COMPUTER GRAPHICS

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 business, industry, government, art, entertainment, advertising, education, research, training, and medicine. Figure 1–1 shows a few of the many ways that graphics is put to use. Our introduction to the field of computer graphics begins with a tour through a gallery of graphics applications.

The focusing system in a CRT is needed to force the electron beam to converge into a small spot as it strikes the phosphor. Otherwise, the electrons would repel each other, and the beam would spread out as it approaches the screen. Focusing is accomplished with either electric or magnetic fields. For electrostatic focusing, the electron beam passes through a metal cylinder with a positive voltage, as shown in Fig. 2–5. The positive voltage forces the electrons to stay along the axis of the beam. Similar focusing forces can be applied to the electron beam with electromagnetic fields set up by coils mounted around the outside of the CRT envelope.

Another type of focusing is used in high-precision systems to keep the beam in focus at all screen points. The distance that the electron beam must travel to different points on the screen varies because the radius of curvature for most CRTs is greater than the distance from the focusing system to the screen center. Therefore, the electron beam will be focused properly only at the center of the screen. As the beam moves to the outer edges of the screen, displayed images become blurred. To compensate for this, the system can adjust the focusing according to the screen position of the beam.

The maximum number of points that can be displayed without overlap on a CRT is referred to as the **resolution.** A more precise definition of resolution is the number of points per centimeter that can be plotted horizontally and vertically, although it is often simply stated as the total number of points in each direction. Resolution of a CRT is dependent on the type of phosphor used and the focusing and deflection systems. High-precision systems can display a maximum of about 4000 points in each direction, for a total of 16 million addressable screen points. Since a CRT monitor can be attached to different computer systems, the number of screen points that are utilized depends on the capabilities of the system to which it is attached.

An important property of video monitors is their **aspect ratio.** This number gives the ratio of vertical points to horizontal points necessary to produce equal-length lines in both directions on the screen. (Sometimes aspect ratio is stated in terms of the ratio of horizontal to vertical points.) An aspect ratio of 3/4 means that a vertical line plotted with three points has the same length as a horizontal line plotted with four points.

Random-Scan and Raster-Scan Monitors

Refresh CRTs can be operated either as random-scan or as raster-scan monitors. When operated as a **random-scan** display unit, a CRT has the electron beam directed only to the parts of the screen where a picture is to be drawn. Random-scan monitors draw a picture one line at a time and, for this reason, are also referred to as **vector** displays (or **stroke-writing** or **calligraphic** displays). The component lines of a picture can be drawn and refreshed by a random-scan system in any order specified (Fig. 2–6). A pen plotter operates in a similar way and is an example of a random-scan, hard-copy device.

Raster-scan video monitors shoot the electron beam over all parts of the screen, turning the beam intensity on and off to coincide with the picture definition. The picture is created on the screen as a set of points (Fig. 2–7), starting from the top of the screen. Definition for a picture is now stored as a set of intensity values for all the screen points, and these stored values are "painted" on the screen one row (scan line) at a time. The capability of a raster-scan system to store intensity information for each screen point makes it well suited for displaying shading

in storage space if a picture is to be constructed mostly with long runs of a single color each. A similar approach can be taken when pixel intensities change linearly. Another approach is to encode the raster as a set of rectangular areas (**cell encoding**). The disadvantages of encoding runs are that intensity changes are difficult to make and storage requirements actually increase as the length of the runs decreases. In addition, it is difficult for the display controller to process the raster when many short runs are involved.

2–5 Graphics Software

Programming commands for displaying and manipulating graphics output are designed as extensions to existing languages. An example of such a graphics package is the PLOT 10 system developed by Tektronix, Inc., for use with FORTRAN on their graphics terminals. Basic functions available in a package designed for the graphics programmer include those for generating picture components (straight lines, polygons, circles, and other figures), setting color and intensity values, selecting views, and applying transformations. By contrast, application graphics packages designed for nonprogrammers are set up so that users can produce graphics without worrying about how they do it. The interface to the graphics routines in such packages allows users to communicate with the programs in their own terms. Examples of such applications packages are the artist's painting programs and various business, medical, and CAD systems.

Coordinate Representations

Most graphics packages are designed to use Cartesian coordinate systems. More than one Cartesian system may be referenced by a package, since different output devices can require different coordinate systems. In addition, packages usually allow picture definitions to be set up in any Cartesian reference system convenient to the application at hand. The coordinates referenced by a user are called **world coordinates,** and the coordinates used by a particular output device are called **device coordinates,** or **screen coordinates** in the case of a video monitor. World coordinate definitions allow a user to set any convenient dimensions without being hampered by the constraints of a particular output device. Architectural layouts might be specified in fractions of a foot, while other applications might define coordinate scales in terms of millimeters, kilometers, or light-years. Once the world coordinate definitions are given, the graphics system converts these coordinates to the appropriate device coordinates for display.

A typical procedure used in graphics packages is first to convert world coordinate definitions to **normalized device coordinates** before final conversion to specific device coordinates. This makes the system flexible enough to accommodate a number of output devices (Fig. 2–31). Normalized x and y coordinates are each assigned values in the interval from 0 to 1. These normalized coordinates are then transformed to device coordinates (integers) within the range (0, 0) to (x_{max}, y_{max}) for a particular device. To accommodate differences in scales and aspect ratios, normalized coordinates can be mapped into a square area of the output device so that proper proportions are maintained. On a video monitor, the remaining area of the screen is often used to display messages or list interactive program options.

plications. Without standards, programs designed for one hardware system often cannot be transferred to another system without rewriting the software.

International and national standards-planning organizations in many countries have cooperated in an effort to develop a generally accepted standard for computer graphics. After considerable effort, this work on standards led to the development of the **Graphical Kernel System (GKS).** This system has been adopted as the graphics software standard by the International Standards Organization (ISO) and by various national standards organizations, such as the American National Standards Institute (ANSI). Although GKS was originally designed as a two-dimensional graphics package, a three-dimensional GKS extension was subsequently developed.

The final GKS functions, adopted as standards, were influenced by several earlier proposed graphics standards. Particularly important among these earlier proposals is the **Core Graphics System** (or simply **Core**), developed by the Graphics Standards Planning Committee of SIGGRAPH, the Special Interest Group on Computer Graphics of the Association for Computing Machinery (ACM).

Standard graphics functions are defined as a set of abstract specifications, independent of any programming language. To implement a graphics standard in a particular programming language, a **language binding** must be defined. This binding defines the syntax for accessing the various graphics functions specified within the standard. For example, GKS specifies a function to generate a sequence of connected straight line segments with the descriptive title

```
polyline (n, x, y)
```

In FORTRAN 77, this procedure is implemented as a subroutine with the name GPL. A graphics programmer, using FORTRAN, would invoke this procedure with the subroutine call statement

```
CALL GPL (N, X, Y)
```

GKS language bindings have been defined for FORTRAN, Pascal, Ada, C, PL/I, and COBOL. Each language binding is defined to make best use of the corresponding language capabilities and to handle various syntax issues, such as data types, parameter passing, and errors.

In the following chapters, we use the standard functions defined in GKS as a framework for discussing basic graphics concepts and the design and application of graphics packages. Example programs are presented in Pascal to illustrate the algorithms for implementation of the graphics functions and to illustrate also some applications of the functions. Descriptive names for functions, based on the GKS definitions, are used whenever a graphics function is referenced in a program.

Although GKS presents a specification for basic graphics functions, it does not provide a standard methodology for a graphics interface to output devices. Nor does it specify methods for real-time modeling or for storing and transmitting pictures. Separate standards have been developed for each of these three areas. Standardization for device interface methods is given in the **Computer Graphics Interface (CGI)** system. The **Computer Graphics Metafile (CGM)** system specifies standards for archiving and transporting pictures. And the **Programmer's Hierarchical Interactive Graphics Standard (PHIGS)** defines standard methods for real-time modeling and other higher-level programming capabilities not considered by GKS.

REFERENCES

A general treatment of display devices is available in Sherr (1979). The conceptual design of display devices is discussed in Haber and Wilkinson (1982) and in Myers (1984). Storage tubes are surveyed in Preiss (1978), and flat panel devices are dis-