Becoming Comfortable with Computer Graphics

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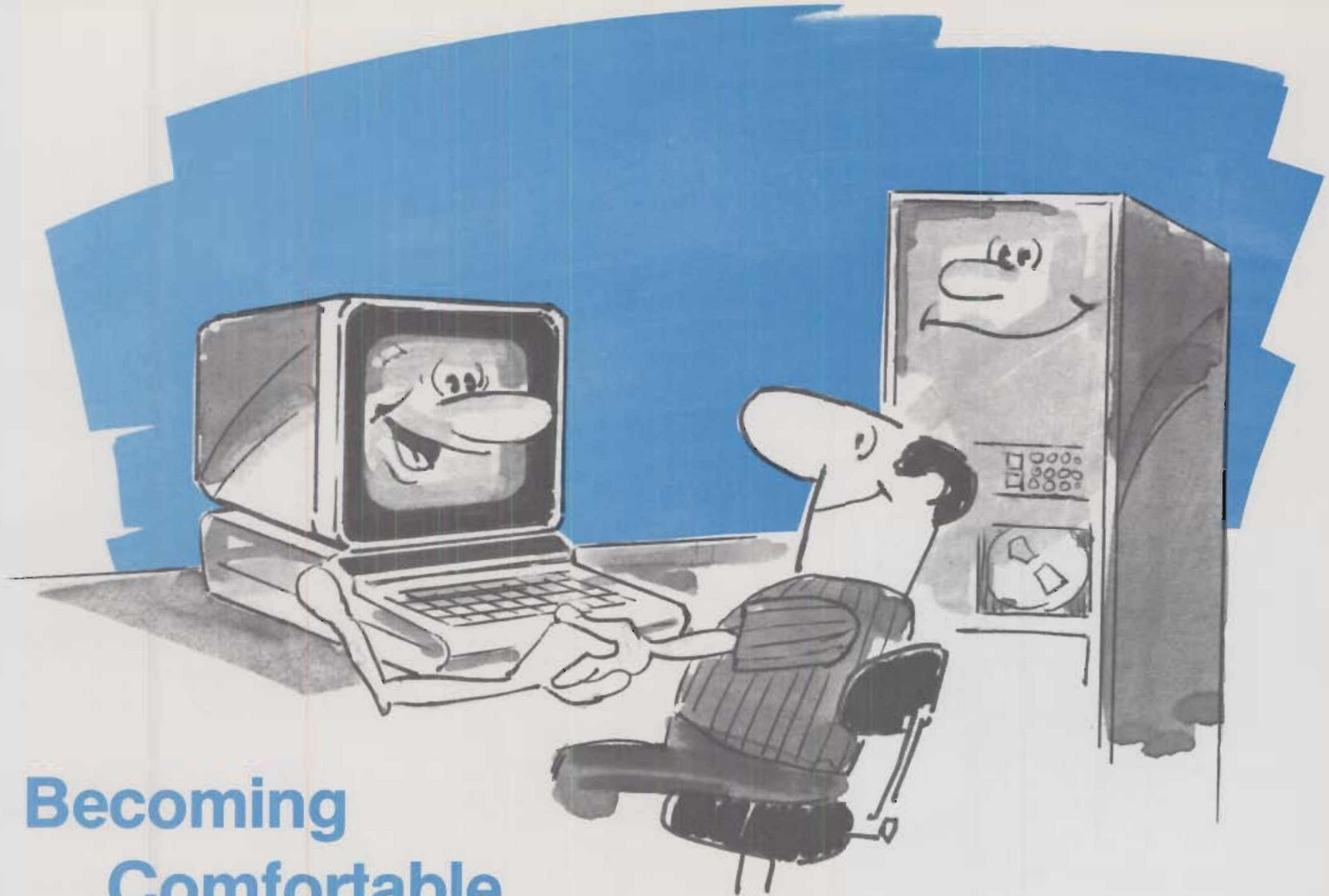
Virginia Pollack, a native of Connecticut, received her BA degree in mathematics from Wellesley College in 1959. While residing in Syracuse, New York, she completed her MS degree in computer science at Syracuse University. Virginia joined HP as a technical writer in 1979. She has written graphics documentation for the 9845C desktop computer and HP-85 software, as well as for plotters produced by the San Diego Division. She is the mother of two teenage sons, and enjoys golf, tennis and swimming. Her numerous other interests include music (viola), sewing, bridge, antiques and teaching about computers.



Becoming Comfortable with Computer Graphics

This booklet is designed to introduce you to the exciting field of computer graphics. Hopefully, when you finish reading it, you will regard graphics in much the same way you regard a wise friend — as being easy to converse with, as conveying all kinds of vital information, and as being fun to be with. You don't need to be a computer whiz to read this; you don't even have to like computers. Perhaps you need a knowledge of graphics in your job. Perhaps you want to know if you can use graphics. You may be just beginning to learn graphics programming. This book is for you. When you realize how effectively computer graphics can present information, how quickly you can see relationships when graphed, as opposed to when hidden in columns of figures, you will want to use and promote computer graphics to get ideas across.

Reading this booklet will not make you an expert graphics programmer, even though some example programs are developed here. This booklet will teach you the buzz words and basic concepts so that, at the very least, when you call on a customer, go to a cocktail party, or have a conference with your boss, you can talk intelligently about graphics.

The material is presented in the following order. The first section includes an introduction, the definition and history of computer graphics, a discussion of the types of graphs, and some common applications. Then comes the section on graphic concepts in easy to understand form — no formulas, and no long words (that aren't defined). In this section you learn about coordinate systems, plotting limits, choosing graph sizes, and obtaining different pictures of the same data. The third section is the "how to" section. It includes drawing axes and grids, plotting data and shapes, labeling, and methods of creating characters. The last section dips into some more concepts, including the characteristics of different kinds of graphics systems, graphics programming languages, and data generation. One simple line graph is created two ways, using the HP-GL and AGL graphics languages. The section concludes with a glossary of commonly used words. If you encounter a word you don't understand, check the glossary first.

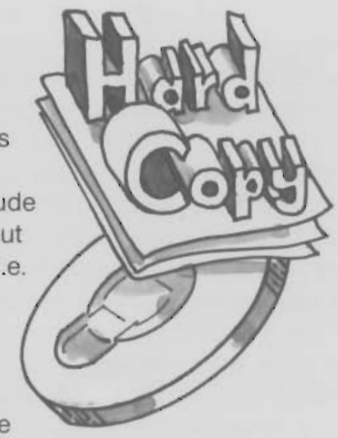
This booklet is designed to be informative to everyone interested in graphics without regard to a particular graphics system. The material presented here is equally valid for all users' mainframes; mini- and micro-computers, as well as instrument controllers, can all generate graphics output. Now that you know what is contained in these pages, make yourself comfortable and enjoy an hour or two of pleasant and profitable reading.

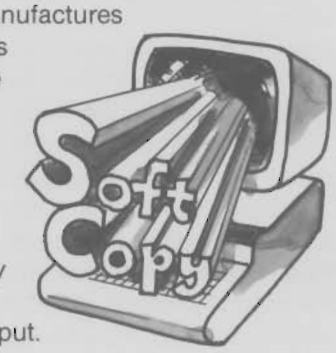
What is Computer Graphics?

Let's start by saying that computer graphics is a pictorial or graphic representation displayed or produced by a computer. I know you are saying that's not a very good definition, because now you need to know what a "graphic representation" is. Here at Hewlett-Packard, we believe, as Webster says, that graphic means " . . . marked by or capable of clear and lively description or striking imaginative power." Indeed a picture is worth more than 1000 words or numbers.

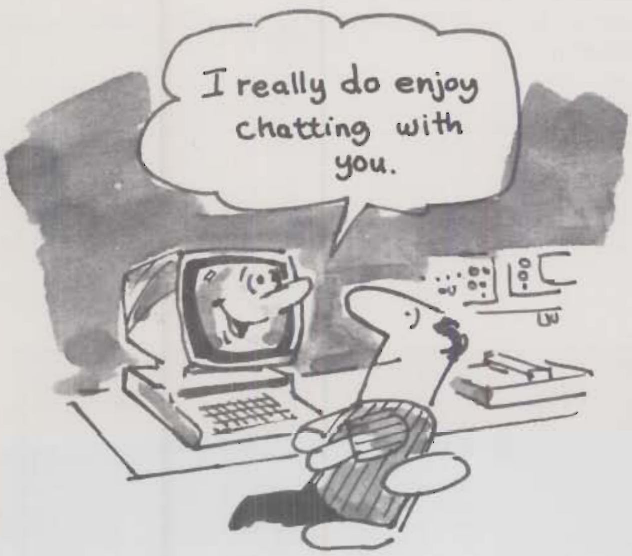
There are two essential parts of the original definition; first, creating the graph or picture, and second, the role of the computer. Computer-produced graphics may be displayed on a CRT (Cathode Ray Tube), formed by deposits of ink on paper or transparency film, recorded on photographic film, or printed on a line printer. Graphics may be in black and white or in color. As for the role of the computer, it may create a picture by converting numeric information into graphic format, modify graphic information, or merely produce the picture from previously stored plot commands.

Computer graphics can be subdivided into several classifications. In San Diego, where this booklet was written, Hewlett-Packard manufactures graphic plotters, plotter/printers, and printers which produce hard copy you can hold in your hand. The term "hard copy graphics" usually means graphics on paper but is sometimes extended to include other non-volatile output of computer pictures (i.e. output that will not be destroyed when the power is turned off). Thus we could stretch the definition to include copies of pictures saved on tape or disk and also photographs or slides. At other locations Hewlett-Packard manufactures CRT graphic devices which create volatile or "soft" graphics. When you turn the power off, poof! No picture remains. Depending on the application, you may use either or both types of graphic output.





Another term you hear increasingly often is "interactive computer graphics." The word interactive is subject to many interpretations, but it always means there is some communication between the user and the computer in "real time" while the program that creates graphics is running. Most interactive applications involve the use of a graphics display (CRT), but this is not a requirement. Digitizers (see glossary) can be used to input data and plotters to output it in an interactive manner, as can an alphanumeric keyboard, without the presence of a CRT. In some



interactive applications, the user selects from a menu or list which picture is to be drawn, or perhaps its size or color. In other applications, when the user sees the picture or plot, he chooses a suitable program branch or course of action. For example, in process control, he may turn a machine off or close a valve depending on what he sees. In a third type of application, data may be entered while the program is running, using an input device such as a light pen (see glossary) or digitizer.

A Brief History

Like many of the new technologies of recent years, computer graphics were first developed for U.S. military applications. In the mid and late fifties, the SAGE (Semi-Automatic Ground Environment) air defense system used a display screen to give visual indication of the position of aircraft. Following this, in the early 60's, Ivan Sutherland, in a federally funded project at MIT's Lincoln Labs called Sketchpad, pioneered the areas of data structure and software necessary for today's high performance graphics systems.

Computer graphics at this time required the largest and most expensive computers, and only universities, government, and large industries, such as automotives and aircraft, could afford the high price tag. Several computer-aided design (CAD) systems for automobile, aircraft or missile design came about independently during the 1960's. These systems allowed the engineer to alter design parameters and then see the changes in design displayed on the screen. Data on how the new parameters would affect other areas, such as cost, strength, and aerodynamic efficiency were also immediately obtainable.

Also in the 60's, a variety of display screens capable of character generation, but limited to a small number of lines with a fixed number of characters per line, were developed. These were the forerunners of today's high resolution raster graphics devices. (We'll get to raster later). In the late 60's a new type of display appeared on the market place, the storage tube display. This was the first low-cost terminal priced between $4,000 and $15,000. Its introduction stimulated the development of other technologies, such as lower-cost stroke writing refresh tubes and raster scan converters, the two main types of display devices used today.

As you can see, the first applications of computer graphics were mainly concerned with "soft" output. Hewlett-Packard's efforts during this time centered on medical displays, the first of which appeared in 1966. These small screen, high resolution displays, which used analog input, were the forerunners of today's medical monitors and were used for such things as fetal monitoring. In 1970 HP entered the large screen display area with a high resolution radar display. HP introduced its first graphics terminal for commercial data processing in 1978. A small color vector display was introduced in 1979 and a desktop computer with color CRT in 1980.

Hard copy graphic devices developed separately. Graphics plotters were first introduced in 1958. Calcomp's drum plotters and Tektronix's dry silver copiers were significant contributors to the development of hard copy graphics. While Hewlett-Packard had previously manufactured X-Y recorders which produced hard copy from analog data, its first plotter was introduced in May 1969. Plotters are now available, industry wide, in drum and flatbed models with ink or thermal printout. You can now draw graphs that range in size from 8½ x 11 in. (A4) to over 20 feet in length.

New applications of computer graphics continue to be found. In fact, business applications of computer graphics first became significant in the late seventies. The growth of computer graphics has been made possible by both the expansion of available software and advances in technology. Software ranges from packages that simplify the generation of plots to complete turnkey systems. Hewlett-Packard has developed graphics software, graphics peripherals and graphics systems for OEMs (original equipment manufacturer) and end users. Programming languages and subsets of languages have been developed specifically to plot graphics. Hewlett-Packard Graphics Language (HP-GL) and A Graphics Language (AGL) are two examples of HP's contributions in this area.

Microprocessor technology and the drastic price reductions for computer memory have made dramatic reductions in the cost of computer graphics possible. Use is no longer limited to the governmental agencies, large corporations, and universities. Graphics displays and plotters are both available for under $3000. Computer games and electronic toys, as well as commercial systems, use forms of computer graphics unimagined 25 years ago.

The field will continue to grow at a rapid pace. Technological advances in the area of raster displays, color hard-copy, and computers in general will cause increases in the number of graphics devices on the market. A further stimulation to the growth of graphics is the research which shows that graphics is an effective way to communicate large quantities of information quickly and clearly in a non-verbal manner. In coming years, the user will be able to increase communication through pictures by creating graphics at a faster rate, of higher quality, and in full color, while using friendlier, easy-to-use systems.

Graphics Generation Methods

Current computer graphic output devices are of two main types, raster and vector. Both soft and hard copy devices can be classified in this way.

A vector device creates graphics by drawing continous lines from one defined point to another. In general, vector devices provide high quality output with high resolution. On a vector display, lines are drawn on the CRT by an electron beam moving directly from one endpoint of a line to the other. The beam excites phosphors on the face of the CRT so the lines become visible. A vector display is sometimes called a stroke writer; vector devices are also called calligraphic devices. A vector display has a limit to the total length of lines that can be drawn without flicker becoming a problem. Unless all lines can be redrawn within the refresh cycle (normally 1/60 of a second), the plotted data will appear to flicker on the screen. Stroke writers are found in the most expensive turnkey systems. On a vector plotter, lines are drawn with a pen just as when you write

Figure 1.
HP vector plotters are available in single or multiple pen models with HP-IB or RS-232 interface.

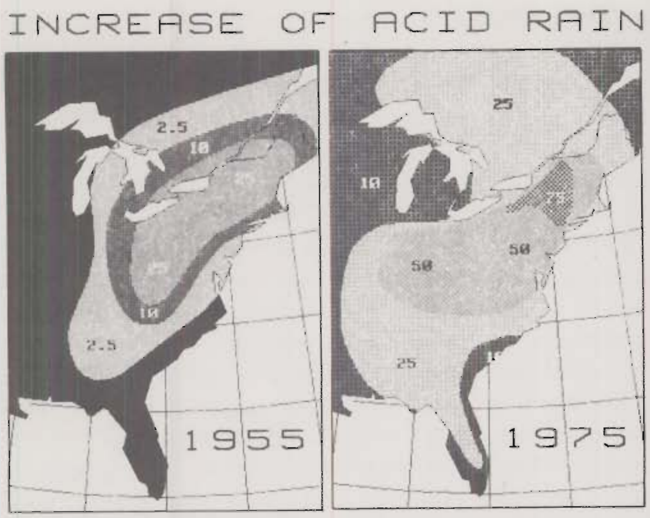


Figure 2.▲
A dump of the graphics raster of the 9845C color desktop produces a monochromatic printout as shown above.

Figure 3.▶
The same graph is visible on an HP 2647 terminal and an HP 7310 graphics printer. Both are raster devices.

with a pen. Pen speed on a vector plotter is sacrificed somewhat for line quality. Two examples of vector plotters are the HP 9872 and the HP 7225 Graphics Plotter.

A raster device, on the other hand, creates graphics in an entirely different manner. To understand this you need to know what constitutes a raster. A raster device has a fixed number of dots or locations, arranged in a fixed number of rows and columns. You can think of raster as being a two-dimensional matrix or as an area divided into smaller areas, like a sheet of postage stamps. A raster is sometimes described by the number of rows and columns. Thus, a sheet of 100 U.S. postage stamps is a 10 x 10 raster. The resolution of a raster device depends on, and increases with, the number of rows and columns per unit area. Imagine a giant sheet of postage stamps spread over a section of a college football stadium. This sheet of postage stamps has greater resolution than the card cheering section located in the same area (where each student sitting in the section holds a large "card" over his head to produce a picture) because there are more stamps than cards per unit area. On a device which creates graphics each location in the raster or matrix corresponds to a location in the computer's memory. Raster devices are growing in popularity and resolution as computer memory decreases in price and increases in availability.

A raster device creates graphics by selectively turning dots on or off. Again, a raster device can be a CRT or a hard copy device. On a raster graphics printer, dots which are "on" are printed on paper; dots which are "off" result in blank paper. Raster plotters or printers can be either impact (like a typewriter), or thermal (where heat creates print on special paper) or electrostatic (where an electric charge on the paper attracts toner). On a raster display, dots correspond to screen locations which are either on or off (illuminated or not illuminated). To determine if a dot is on, a raster device "scans" or examines an area of computer memory many times each second. A raster is usually scanned from top to bottom, one row at a time, left to right in each row. The larger the print or display area, the greater the resolution, and the more colors that can be displayed, the more computer memory is required. Because a location in computer memory can change value instantaneously, raster graphics on the CRT can be updated in real time. In fact, the image could change every refresh cycle. Raster devices can create filled areas quickly; there is no limit to the amount of a screen's area that can be illuminated. Flicker is not a problem. Raster printers generally can plot complex graphs more quickly than vector plotters but with less resolution. The HP 7310 Graphics Printer is a raster device. The HP 7245, while usually operated as a vector plotter, has raster capability. Both devices can receive and print the contents of the display memory of the System 45 desktop computer or the HP 2647 or HP 2648 Graphics Terminals, two HP devices with raster displays.

Color Graphics At A Glance

Color graphics is a microcosm of the larger world of graphics. The same generation methods, raster and vector, exist in the color world. The same trends toward increased quality and resolution are evident. Vector plotters have progressed from one pen models to models with multi-color automatic pen selection. Some stroke writing displays, inside and outside HP, use a beam penetration technique to excite phosphors of different colors deposited in distinct layers on the face of the CRT. In the raster world, more colors are possible, and, each year new systems with better color, both CRT and hardcopy devices, appear on the market. Skeptics say you don't need color for graphics, but most people involved in graphics will secretly admit that color is the name of the game. The development of color graphics will parallel the development of color TV; the thrust is toward reduced cost and improved quality.

Improvements in the quality of color raster displays imply some advances in technology. To be able to specify color implies additional memory, for along with the position you must specify the color of a point or line. In a raster device, using three primary colors to create eight colors takes three times as much memory for storage of the raster image. If you want colors displayed in various shades and intensities, say hot pink or deep purple, you need to add 3 to 16 times more memory depending on how many colors you have and how you specify them. Combining these color improvements with the trend toward increased raster resolution, it is obvious that a large increase in memory is required for even a small increase in resolution when color is included.

To achieve higher resolution requires more complex circuitry to drive the CRT. Color systems already in production have video circuitry six times as fast as that in your color TV set. Higher resolution CRTs will require further advances in this area. Color systems also require more powerful microprocessors to handle the more complex algorithms necessary to display color graphics. Improvements in color will require development of both microprocessors and algorithms. Finally, development of color hard copy to accurately and inexpensively reproduce raster CRT images lags behind CRT development. There are those who believe color graphics will not really take off until good solutions to the raster hard copy problem exist.

Uses of Computer Graphics

The field of computer graphics is growing at the rate of 25% per year (measured in sales $). This growth can also be seen in the increasing number and kinds of graphics systems available, the number of installations using graphics and the variety of applications which have developed. Applications of computer graphics are sometimes broken down into two classifications. One is data display or data presentation graphics; the other is design and image graphics.

Data display graphics provide symbolic representation of numerical data. This data can be from scientific investigation, industrial monitoring and testing,

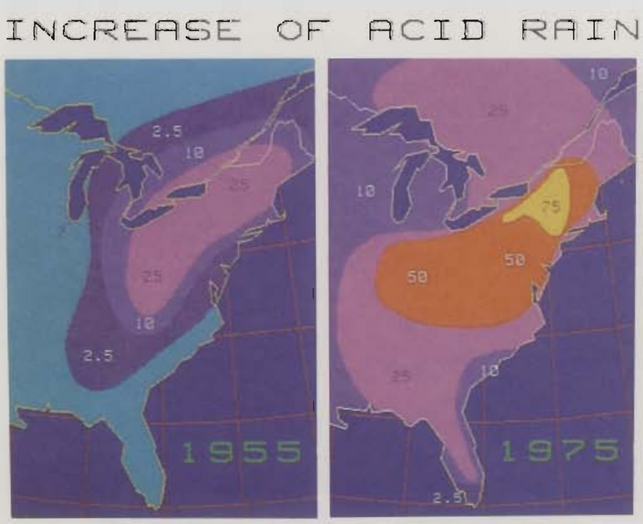


Figure 4.
A map showing acid rainfall in the U.S. is drawn on the HP 9845C color desktop computer.

Figure 5.
An HP 7221S plotter with paper advance capability is used to output data from a large computer system - a data display application.

or management statistics. Most of Hewlett-Packard's graphics customers use graphics for data display applications. The common forms of display graphics are bar charts, line graphs and pie charts. Such graphics are designed for human appeal and clarity.

Design graphics, on the other hand, represent actual physical or geographical data. The form of the graphics depends entirely on the application. Generally speaking, design graphics require higher resolution devices than data display graphics and have a high degree of interactiveness. Design graphics include computer-aided design (CAD), computer-aided manufacturing (CAM), image processing and mapping. Historically, the first computer graphics users fell under the design category and used graphics in military and computer-aided design applications. CAD has now spread well beyond the automotive and aircraft industries where it had its beginnings. Design graphics play an important part in the manufacture of printed circuit boards, and in electronic design. Other design applications include apparel graphics (pattern and fabric cutting), structural engineering (finite element analysis), and mechanical drafting. Turnkey systems and large plotters are frequently used in design graphics applications.

Another group of design graphics applications can be classified as image processing. Image processing started with the analysis of satellite resource photos. Computer-aided tomography (CAT) for medical analysis of X-rays is a recent addition to the list of image processing applications. Closely related to image processing is mapping. Mapping includes construction of maps from census data, maps for business planning (store locations and demographics), surveying and civil engineering maps, and maps to monitor utilities and natural resources. As you can see, the uses of computer graphics are varied and widespread.

Figure 6. ▲
An HP plotter and an HP X-Y recorder are integrated into this Dupont thermal analysis system.

◄ Figure 7.
An illustrator can create a schematic drawing using a CRT and a light pen. A completed drawing will be plotted on a vector plotter.

Good Graphic Form(s)

In the previous section we divided computer graphics into two types, design graphics which are used interactively to create pictures, and data display graphics which usually produce graphs from stored data. In this section we will discuss the three common types of graphs used in data display graphics: line graphs, bar charts and pie charts. The object is to give all of you (including you mathophobics) some insight into the variety of graphs that can be created to convey numerical information, and to teach you some principles of good graphic form. Please do not be concerned, at this point in time, that you do not know enough about graphic programming to write the program to actually draw the graph. Just try to understand each form so you can judge which one is best suited to a particular application and what makes the form effective.

What is good graphics form? There is no easy answer. To measure the success of a graphic presentation, you would need to test whether the information was correctly conveyed in less time than could have been done verbally or in text. From graphics, the viewer should gain some information about mathematical or numerical relationships between data.

In designing a graph you need to consider the nature of the data, the medium of presentation (CRT, slides, paper, in color or black and white), the purpose of the chart, the audience (size and type) and the time available for preparation and presentation. Some of these concerns are more important than others. One danger of a primer like this is that you, the reader, sometimes think you must take everything presented as gospel. The ideas presented here are not absolutes; they are suggestions, not limitations. The only absolute you need remember is this: if your graphics convey your idea with speed and accuracy, they are "good" graphics.

Line Graphs

Let us first consider the line graph, sometimes called a rectilinear coordinate chart. Line graphs are used in both business and scientific applications. The points in a data set are connected, in order, by a single line, sometimes curved and sometimes straight. More than one set of data points can be represented on a single graph, with each line differentiated by color or line type (dotted, dashed or solid). While line graphs usually have linearly scaled perpendicular axes, one or both axes may be scaled logarithmically. These graphs are called semi-log and log-log graphs respectively. Logarithmic scaling is used where data extends over a wide range of values and appears most frequently in scientific, as opposed to business, applications. A line chart is frequently used to plot some variable versus time; the X-axis usually denotes time. Other uses of line charts include frequency distributions and any charts where data is a function of two variables. Examples of a linear and a semi-log line graph follow.

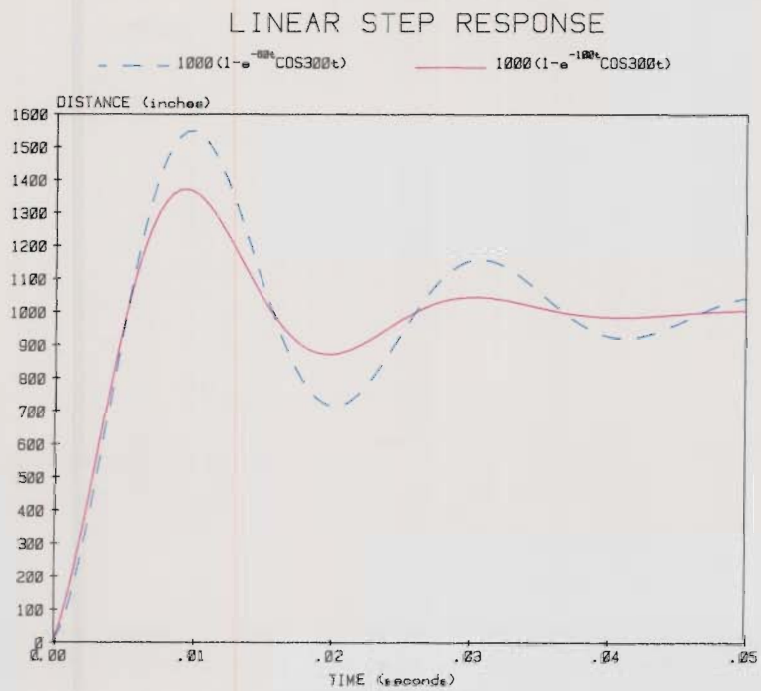
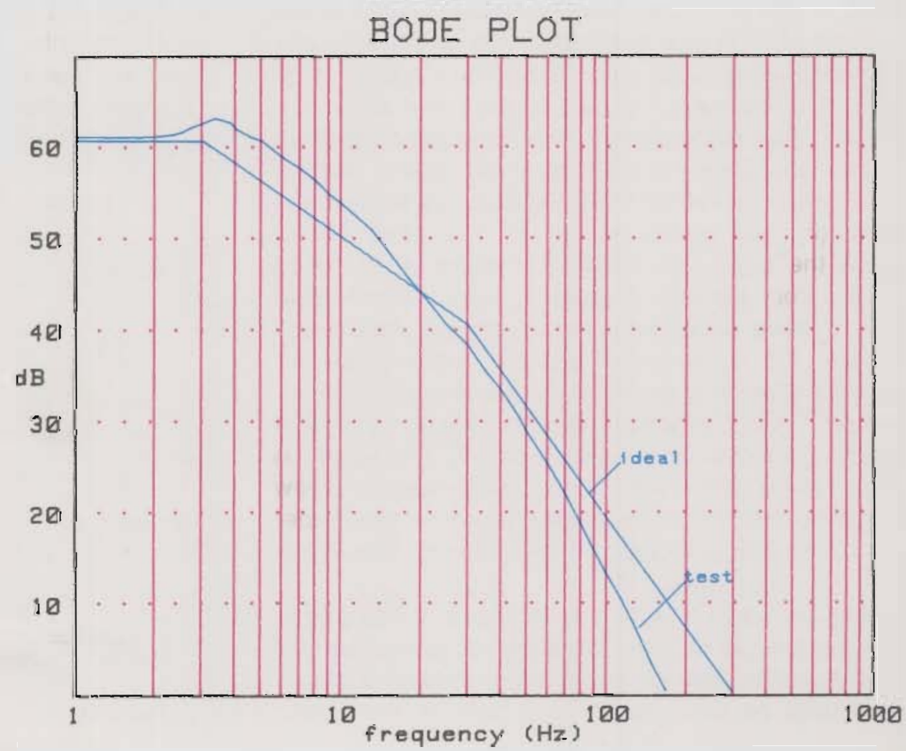


Figure 8. ▲
A linear line chart showing step response over time.

Figure 9. ▶
A semi-log plot where the X-axis is logarithmic and the Y-axis linear.



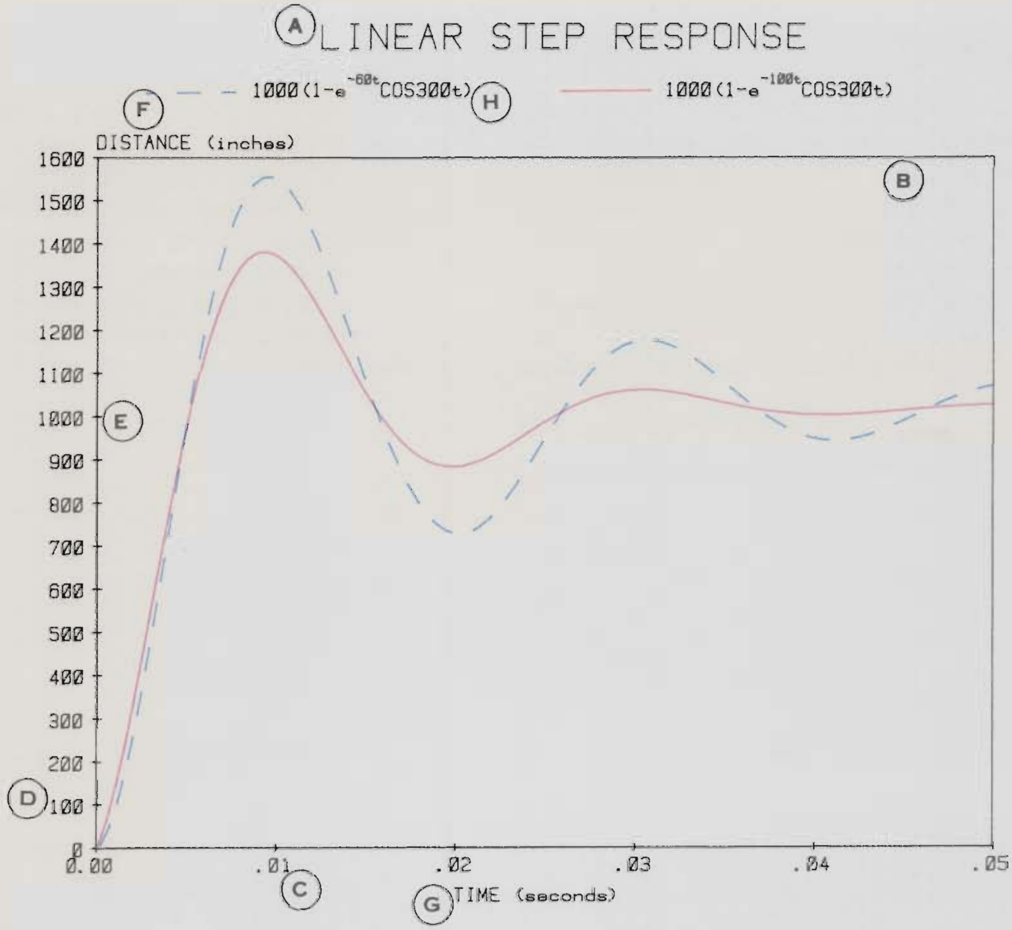


Figure 10

We will use the line graph shown previously to illustrate the essential parts of almost all graphs. Every graph should have a title (A) which states what, where and how. The title is best placed above the picture. The area covered by the graph is usually framed (outlined) (B) and that area is scaled to fit the data. The axes are marked with this scale (C), (D) and tick marks (small lines at regular intervals) (E), or grid lines (which extend across the plotting area) are drawn along the axes. Axes are labeled and titled, (F), (G) usually with horizontal labels placed below the X-axis and above the Y-axis so as not to detract from the data presented. It is common practice to leave superfluous zeros off axis labels and indicate the multiplier in the title. When there are multiple lines on a graph, each line should be identified with either a horizontal label near the line or a legend placed away from all lines (H). The legend is often placed to the left of the Y-axis labels or below the title. The most important point to remember when annotating a graph is that nothing should detract from the plotted data.

Now for some common variations of a line graph. One variation is to have two separate scales in the X or Y direction, one for each of two lines of a graph. Care must be taken to interpret data on the proper scale. Look at the following graph and determine when the number of tractors equalled the number of horses or mules.

If you did not examine the scaling on both sides, you probably said 1945, but on closer examination you will see that in 1945 there were approximately 2.2 million tractors and 12 million horses or mules. The two values are never equal on this graph.

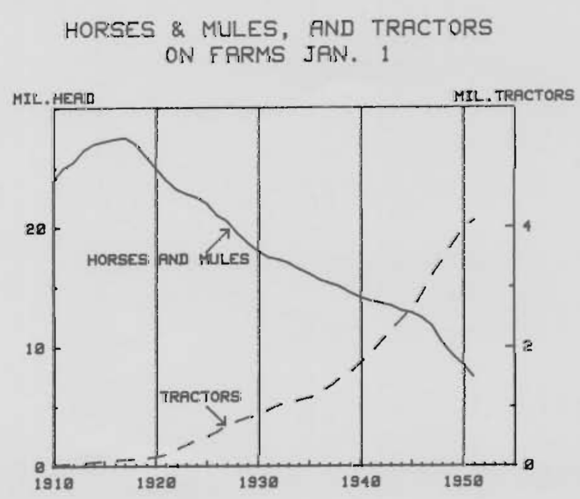


Figure 11

Another simple variation is the plotting of more than one time period on the same axis. Figure 12 shows sales figures for three years. It is much easier to compare January figures in successive years on this graph than if it were spaced out over 36 months in the X-axis. In a third variation, an extra reference line is plotted; for instance the cost of living line might be plotted on a graph designed to show the index of new orders and real GNP as in Figure 13.

The final variation we will illustrate is a surface chart. Here the areas between lines are shaded. Surface charts are not well suited to vector graphics because of the length of time required to do area fill. They are, however, well suited to raster graphics. A surface step chart is shown in Figure 14. On a step chart, a horizontal line is drawn at the proper Y value. This line extends over one whole time interval. The line then steps to the next value.

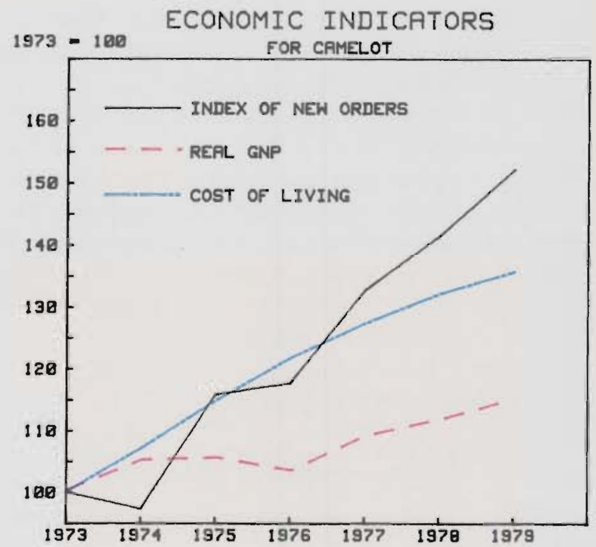


Figure 13

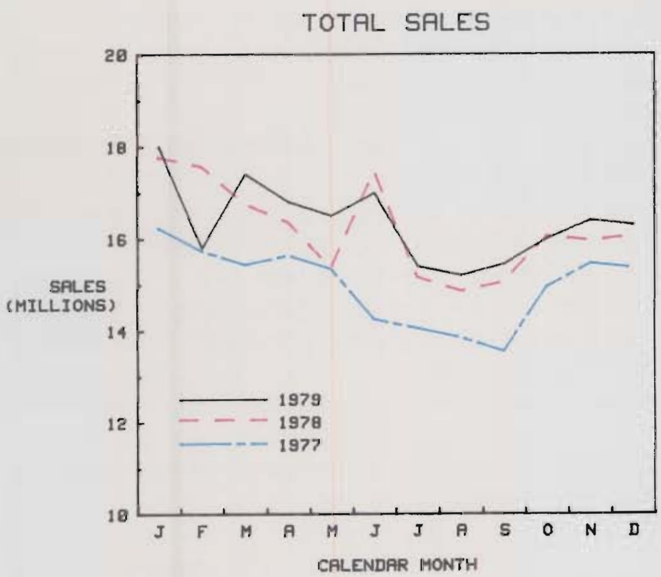


Figure 12

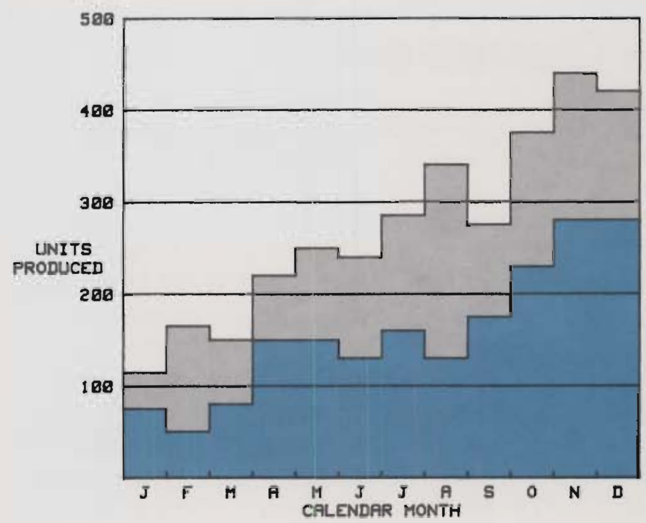


Figure 14

Bar Charts

The bar chart is a popular chart especially appropriate for comparing size or parts of a total. The length of each bar is proportional to the quantity or amount of each category represented. We will make no distinction between bars that are horizontal and bars that are vertical. However, some people call graphs with vertical bars column graphs. There are many variations of the simple bar graph. Illustrated here are six variations of the bar graph.

Figure 15 is a simple bar chart consisting of five bars representing sales volume for each of five items. Five is sometimes cited as the upper limit for the number of items represented on one chart. This however depends on the data; for instance, there is no reason why ten years of sales data showing a trend could not be represented on a graph of total sales. Five is probably a valid limit if the sales graph shows a year's sales by region and is to be used to compare regions with one another.

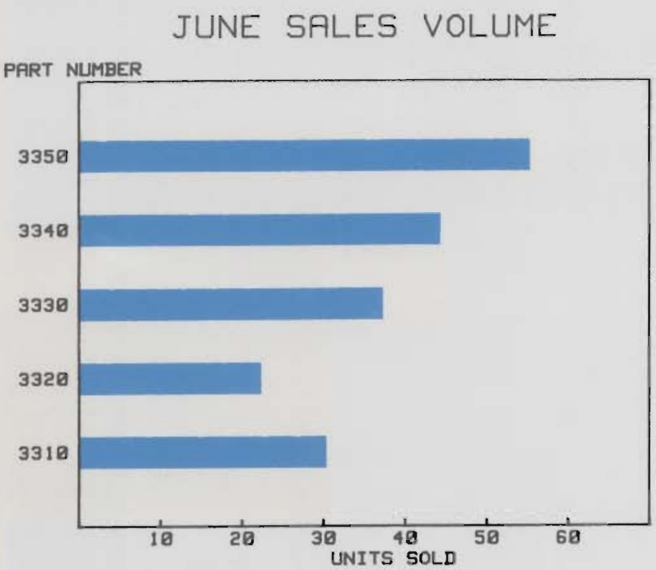


Figure 15.
A simple bar chart.

Figure 16 shows sales by region for three divisions over a four year period. When more than one bar refers to the same X-axis value and the bars for that value are close together or touching, we call the graph a clustered or comparative bar chart. Again there is an upper limit to the number of bars that can be "clustered" and still be an effective graph. Each bar of the cluster is usually a different color or hatched using a distinct pattern. This means a four color plotter can produce a graph with four shaded bars per cluster. A monochromatic graph can also have four; one solid bar, two with hatching (narrow and wide), and one clear area. The solid shading should be in the smallest segment because it is easiest to interpret the value of a shaded area. For easy pattern recognition, a large hatch pattern should be reserved for large areas. You seldom put a large patterned floral wallpaper in a 9 x 10 foot room!

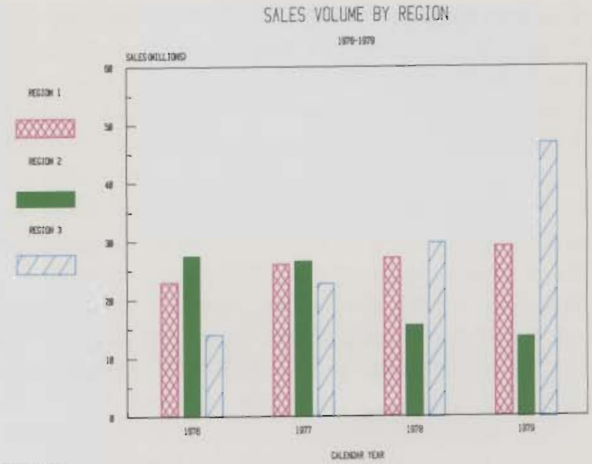


Figure 16.
A clustered bar chart.

Figure 17 is a deviation bar chart. Note that the zero line, instead of being at the bottom of the scale, is in the middle. Thus positive and negative values are easily displayed. This type of graph is useful when showing an increase or decrease in quantity, or profit and loss. On charts like this, positive values are often one color and negative values another. This particular deviation bar chart shows the percentage change in attendance from month to month. Note that this graph tells you nothing about the % increase or decrease for the year as a whole, except that, because you see more bars above the line, you might assume attendance increased. Total attendance figures might be added to this chart using a second Y-axis scale, or the data plotted in line graph form, if the main interest was in the total attendance. The graphic form you use will depend somewhat on the ideas you wish to convey.

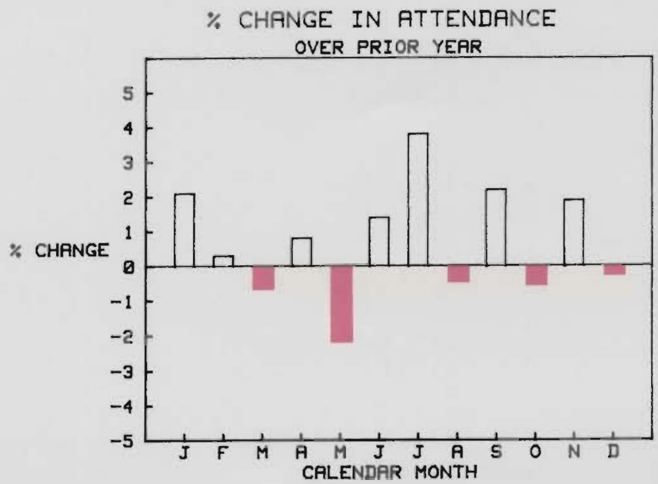


Figure 17.
A deviation bar chart.

A segmented or stacked bar graph, Figure 18, consists of one bar for each X-axis value, with portions of each bar colored or patterned to represent the Y-value for one component. In this example, which uses the same data used in Figure 16, the whole bar represents the total sales in a given year. Each pattern identifies that part of the total attributed to one region. The most important segment is usually placed on the bottom of the "stack." Each bar could be represented as a separate pie chart (see next section).

Figures 19 and 20 are less frequently used forms. Figure 19 is a sliding bar chart where the length of the bar is significant and shows the range of values of one variable over one unit of time. This form is frequently used to chart stock movement as shown by this plot of the Dow Jones Industrial average. Figure 20 is a non-standard bar graph where the second axis is circular and concentric circles determine the value of the bars, while the direction of the bars parallel the positions on a 24 hour clock and thus relates to hours. Other non-standard bar graphs might place bars on map locations or on a variety of symbols.

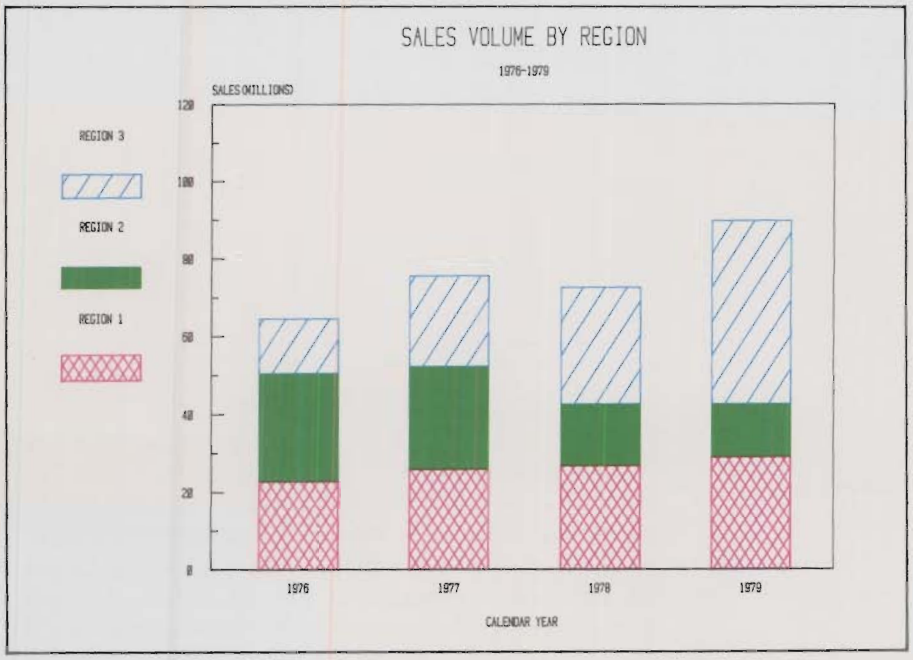


Figure 18.
A segmented bar chart.

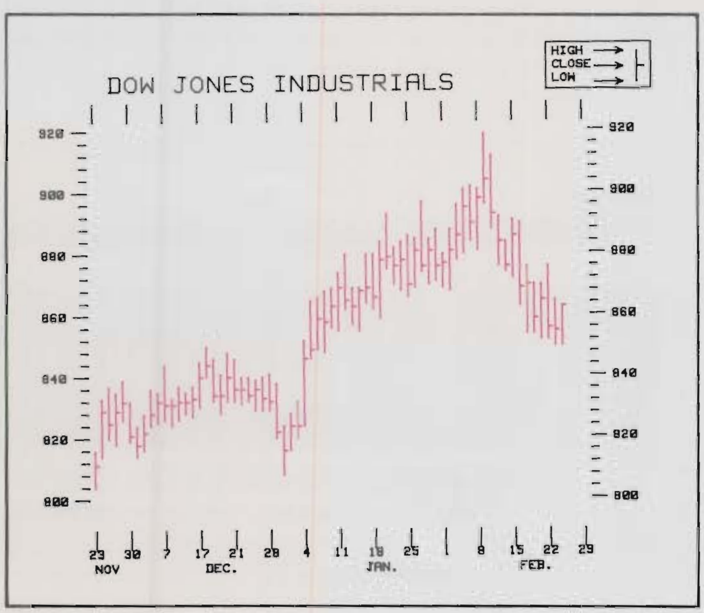


Figure 19.
A sliding bar chart.

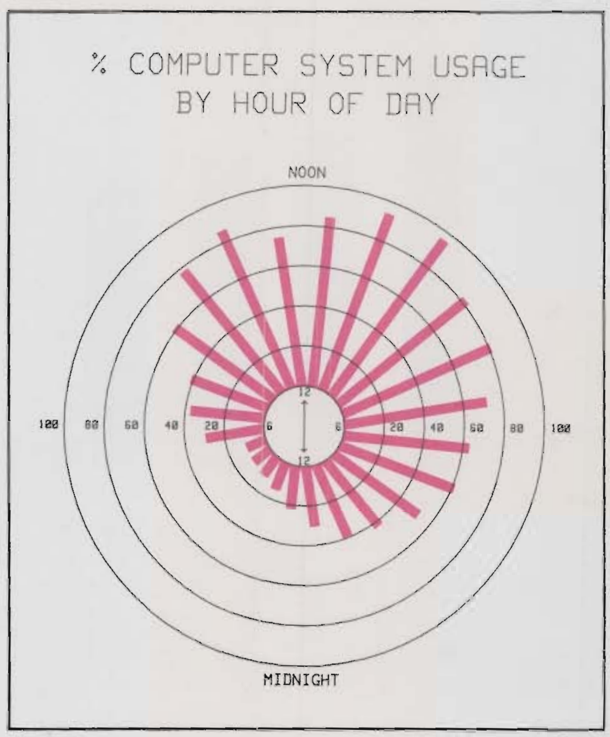


Figure 20.
A non-standard bar chart.

Certain practices should be followed when creating bar charts. The bars should be of uniform width with evenly spaced bars. Minimum spacing is half the width of the bars and maximum spacing should still enable the eye to move from one bar or cluster to the next. The scale should always include the zero value. If you look at Figures 21 and 22 below you are apt to say, Figure 21 indicates a much greater rate of decrease in sales. Actually the two graphs portray the same data, but the Y scales start at different values.

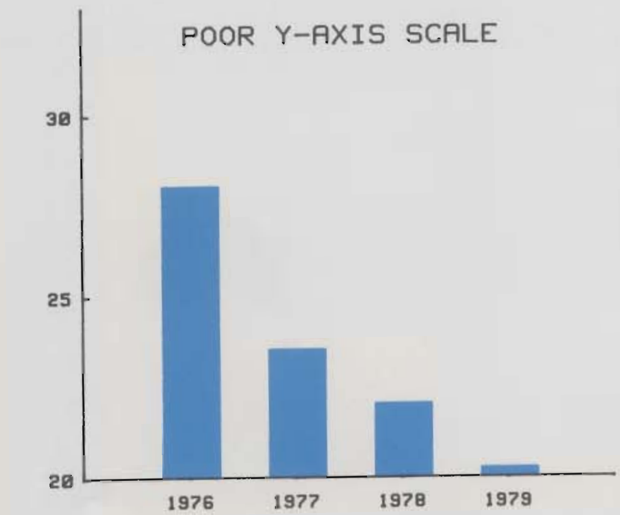


Figure 21

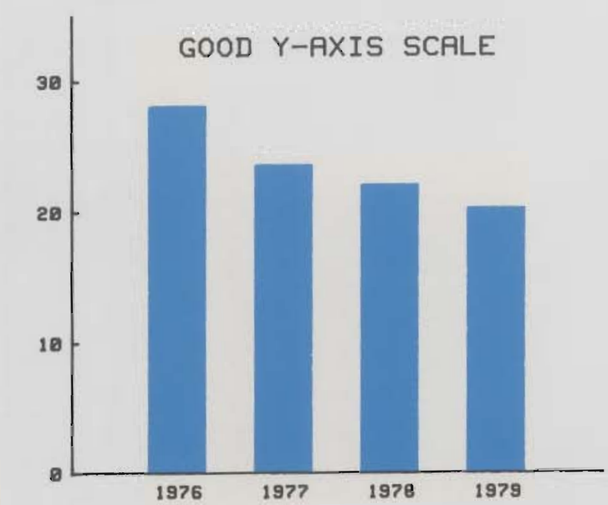


Figure 22

Another poor practice is to cluster values that are widely different in value. The eye probably cannot evaluate both columns in one glance. Try it with the following chart as opposed to Figure 16 previously shown. Are you a believer now?

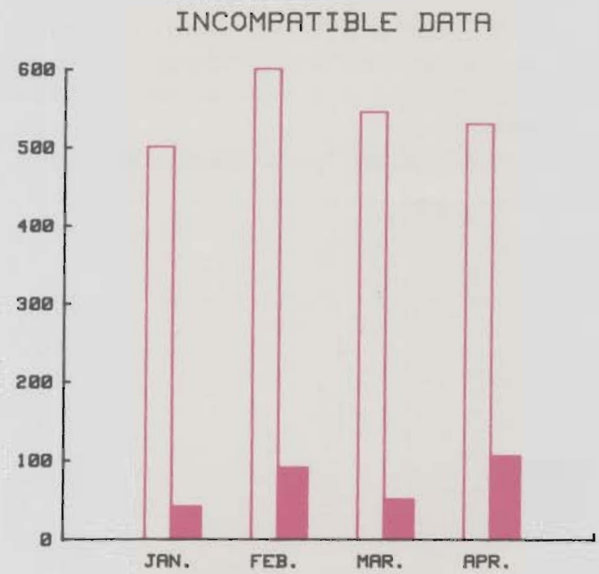


Figure 23

A software package, such as the HP Multiplot, can greatly simplify the task of constructing a bar graph. Below is a printout of the CRT screen with the completed Multiplot specifications used to create Figure 16. Examine the input and the graph to see which entries created the various parts of the graph. Using Multiplot with the HP 2647 terminal, it is also possible to create pie charts and line graphs by only entering the data, the title, and the color and/or hatching pattern. The mechanics of axis drawing, labeling and hatching are handled by the system. The output of Multiplot can be displayed on the CRT and/or plotted on an HP 9872 plotter.

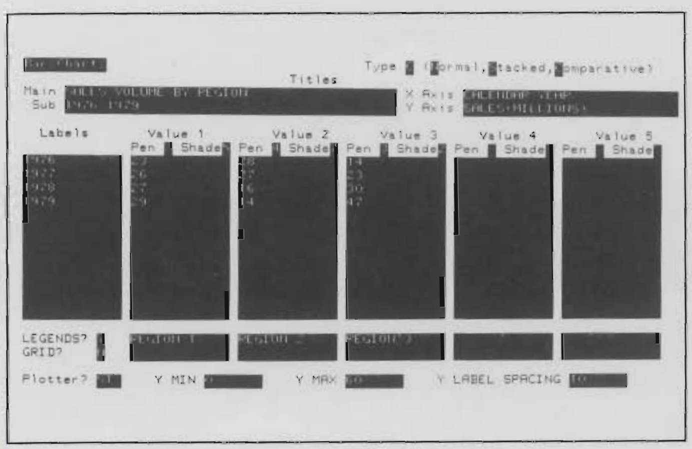


Figure 24

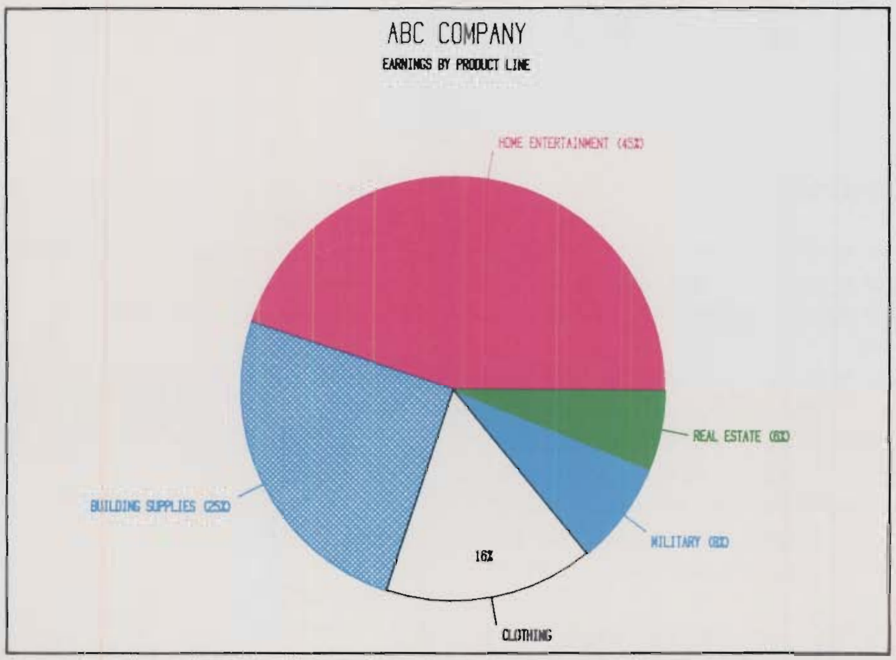
Pie Charts

The final graphic form we will discuss is the pie chart. Pie charts show parts of a whole entity. The slices of the pie are the component parts. There are two variations on the pie chart. First, one or more slices may be "exploded", that is offset slightly from the center as if partially removed from the pie plate. Second, a third dimension can be added to the pie so that it resembles a coin or disc. Examples of all three kinds of pie charts follow.

To construct a pie chart, the data is computed as a percentage of the total and each data value (percent) is converted to its appropriate segment of a full 360 degree circle. Sections are usually arranged according to size and differentiated by color or hatching. Each segment is labeled; the labels are best placed outside the pie; labels placed inside tend to distort the information. Percentage values are sometimes included with the labels and may be placed inside the pie.

The pie chart is not well suited to graphs with many segments (more than 6) or with several segments of small size (3 degrees or less). It is often advisable to group these small segments as "other" and if necessary show a breakdown of "other" in a separate segmented bar or in the accompanying text. Pie charts have great appeal with non-technical audiences, perhaps because they are frequently found in the general press and there is no necessity for the viewer to calculate the coordinate position of a point or bar.

Figure 25.
A standard pie chart



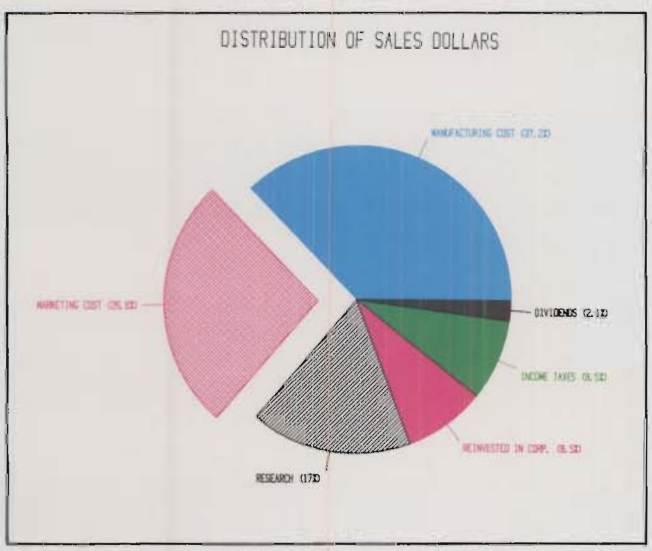


Figure 26. An "exploded" pie chart

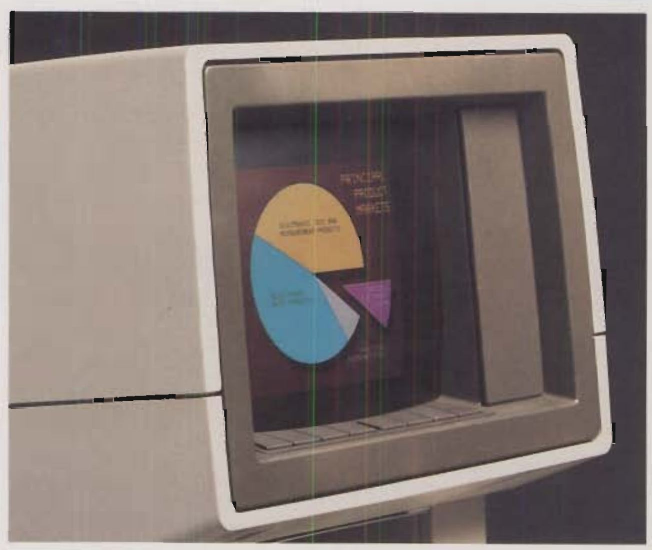
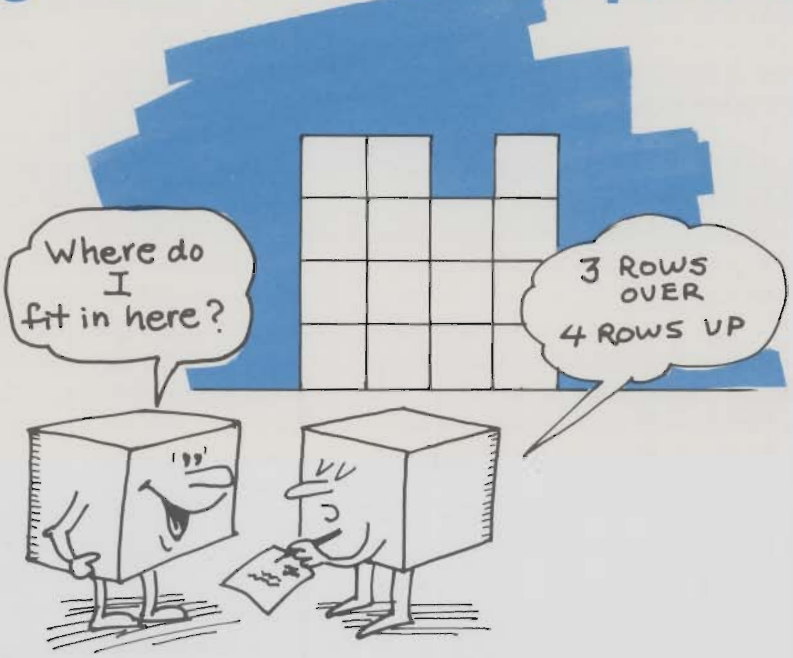


Figure 27. A three-dimensional pie chart drawn on a CRT

Converting Your Data to Graphic Form



Coordinate Systems

Now that you have learned something about types of graphs and graphic devices, you are ready for some basic concepts which relate to conversion of data to pictorial format.

Computer graphics relate a piece of data to a corresponding physical location on the plotting surface. This relationship is always numeric. Even in applications where the graphics have no numeric interpretation, such as the generation of an organization chart, the graphics are placed at a location on the plotting surface by specifying the pen location numerically.

The plotting surface is viewed as a two-dimensional Cartesian coordinate system and, in simple applications, the origin or intersection of the X- and Y-axes is located at the bottom left corner of the plotting area. For those of you unfamiliar with Cartesian coordinates, think of the plotting area as a rectangle and the base of the rectangle as a horizontal line or X-axis. This axis is divided into units of equal size. The number of units will depend on both the device and the application program; assume for now there are 100 units in the X-axis. Likewise think of the left side of the plotting area as a vertical line or Y-axis, also containing 100 units. Plotting areas are not always square, nor do they always have the same number of units in X and Y. But for now we're keeping things simple.

You can specify any point on the plotting surface as a coordinate pair (X,Y) where the X-coordinate denotes the point's distance along the X or horizontal axis and the Y-coordinate denotes the distance along the Y or vertical axis.

The X- and Y-axes, the origin, and the pairs (10,10) (40,75, and 99,99) are represented below. The three X,Y coordinate pairs represent three points. Connecting any two of these points creates a line and the three lines create a triangle.

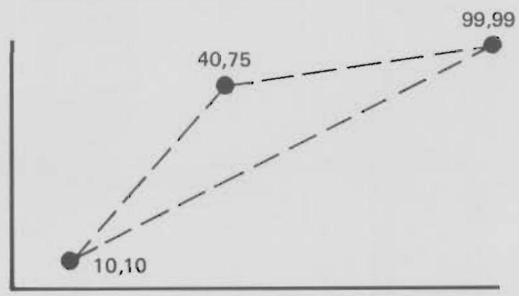


Figure 28

Expanding on this, we can represent any figure or figures as a sequence of X,Y pairs, some of which are connected by lines. When we have more than three points, the order in which they are connected becomes important. Four points connected in order become a rectangle or two triangles, depending on their order. Note that to close a figure, the first and last points must be connected.

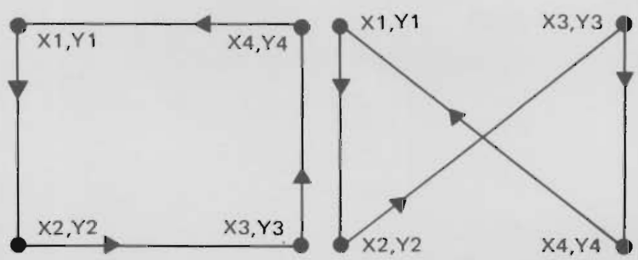


Figure 29

Three-Dimensional Systems

All computer graphics are created by extending this idea. Many applications involve only two-dimensional objects but it is possible to plot a representation of a three-dimensional object on a two-dimensional surface. The rules for doing this are well-defined mathematical relationships but are beyond the scope of this primer. You should be aware that there are computer systems with applications software for plotting three-dimensional objects and even for removing lines and surfaces that would not be visible to an observer located at a specified point. Three-dimensional graphics are common in design graphics applications. The picture of the space shuttle is a good example of hidden line and surface removal in computer graphics.

Color As A Dimension

Recent developments in color graphics have made it possible to add a third or fourth dimension or variable to a plot using color. You have all seen photographs of a hot steel sheet or rod. You know how hot the steel is by its color which ranges from white (hottest) to black (cold). Color has been used to show temperature ranges of the space shuttle in the illustration below. That same variation, and similar color variations, might indicate altitude, material density or any other variable. This use of color is most effective in raster graphics where subtle variations in color can be created. As time passes, color will become more important as a dimension; indeed, it might be called the coming dimension in computer graphics.

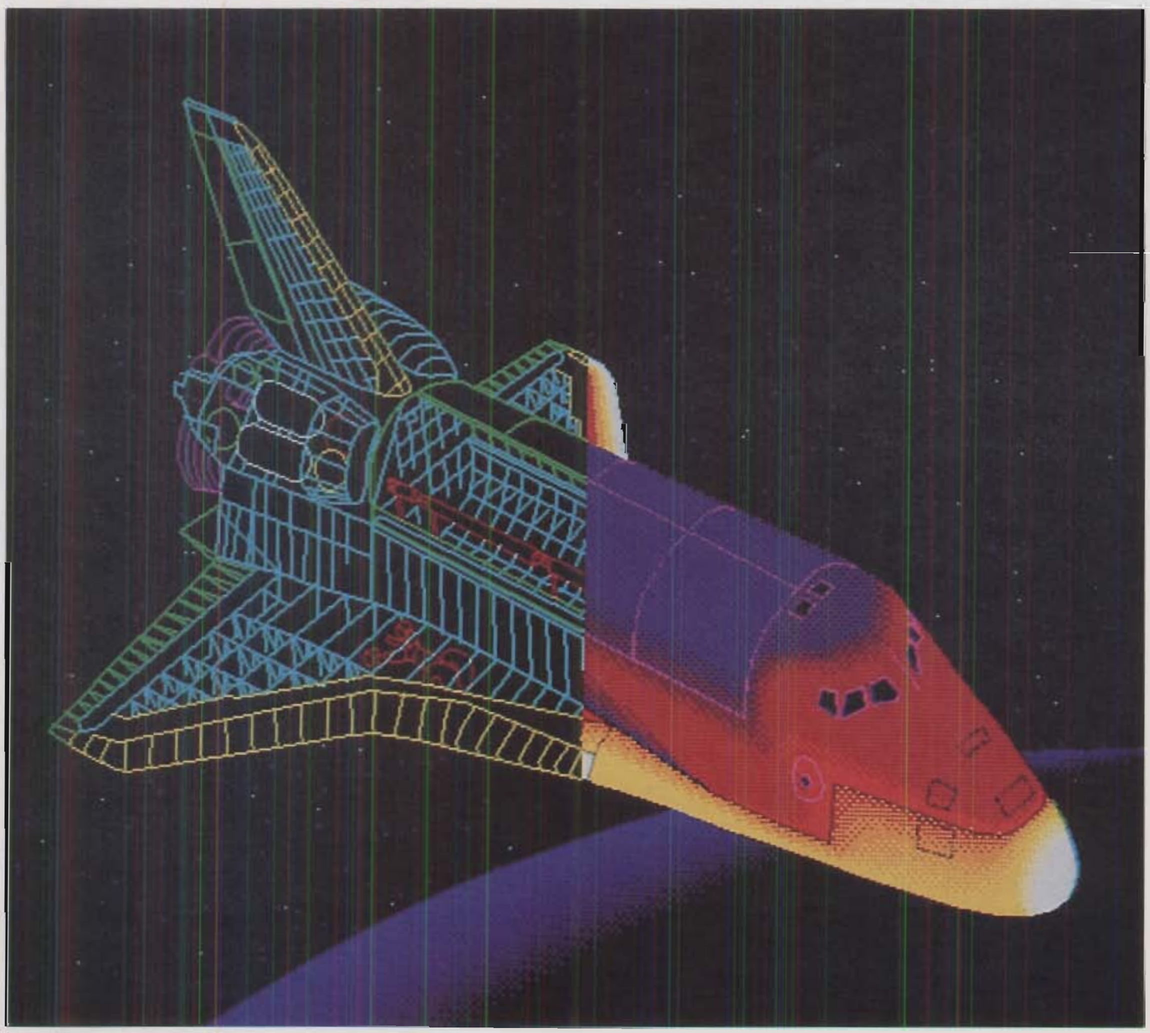
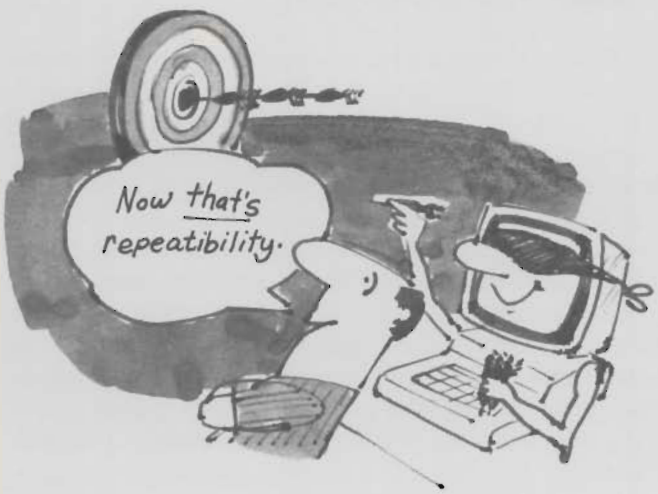


Figure 30.
Half of the space shuttle is portrayed in a wire frame drawing with hidden lines removed. The front of the shuttle is colored to show gradation of heat on the surface of the vehicle.



Resolution, Repeatability and Accuracy

The terms resolution, repeatability, and accuracy are important physical measurements which affect plot quality. Resolution concerns the distance between distinct plotter locations. The resolution of a plotter can be no better than the smallest possible move of the pen for a vector device, or the distance between adjacent dots for a raster device. Hence, resolution provides a measure of how smooth lines will appear in a chart, or how round a circle will be, on both raster and vector devices. If the resolution of a plotter is one centimetre, then the points represented in centimetres by (3,1.6) and (3,2.1) are the same pen location since the Y-coordinate 1.6 is rounded up to 2 and the Y-coordinate 2.1 is rounded down to 2. If the resolution is one millimetre, the same two points are five pen movements apart (1.6 to 2.1 cm in 1 mm steps). The resolution of today's vector plotters is much finer than centimetres. The HP 9872 Plotter has a resolution of 0.025 mm (0.001 in. for those of you who have not mastered metric measure). This means there are 1000 plottable points in a one inch line.

Repeatability concerns a vector plotter's ability to return to precisely the same point each time it is commanded to do so. It is affected by both the mechanical operation of the plotter and the uniformity of the pen or pens. Accuracy concerns the relationship between the commanded and actual length of a line. If the plotter is told to draw a two inch line, does the completed line measure two inches? Repeatability is one factor of accuracy; other factors are related to mechanical tolerances. How do these specifications affect you? That depends on your application. A photoplotter used in the manufacture of printed circuit boards must have extremely high resolution and accuracy. Resolution is always important since it affects line quality. Diagonal lines look perfectly smooth on a high resolution device, but like a staircase when drawn by a device with less resolution. In general, raster devices have less resolution than vector devices.

Physical Specifications for a Device

There are two sets of physical dimensions of concern to the user. Most obvious is the total size of the graphics device. You might ask, "Will it fit on my desk or table?" More important from the user's point of view, is the size of the platen or plotting area. The platen is the flat area of a flatbed plotter on which you lay the plotter paper. Plotting areas on flatbed plotters range from 7 x 10 in. to 8 x 24 ft. A second kind of plotter is a drum plotter where paper rolls over a roller or drum. Drum plotters may use roll or sheet paper, depending on design. Plot size is always limited by the width of the drum which commonly ranges from one to six feet.

Paper Sizes

When you read sales brochures you often find no mention of platen area but rather a phrase like "accommodates C size paper." Since most of you are not walking encyclopedias, here is a handy chart of paper sizes, both American (ANSI) and metric (ISO). The columns are staggered to show how the U.S. sizes fall between the metric sizes. The ISO sizes listed start with A4 since most plotters are at least that large.

This table should be a great help when reading sales literature and provide information useful when ordering paper for your plotter. You'll find, however, that some paper is actually not one of the standard sizes listed below, so a plot can be folded for inclusion in smaller reports and yet be opened when the report is bound.

ISO	DIMENSIONS IN MILLIMETRES	ANSI	DIMENSIONS IN INCHES
A4	210 x 297	A	8½ x 11
A3	297 x 420	B	11 x 17
A2	420 x 594	C	17 x 22
A1	594 x 841	D	22 x 34
A0	841 x 1189	E	34 x 44

Figure 31

Units of Measure

Absolute Plotter Units

Hewlett-Packard uses the term absolute plotter unit (APU) to mean the smallest possible move by the plotting device. On a raster device it is one dot. Thus the graphics raster of the 9845 CRT, which has 455 x 560 dots, has 455 APUs in the vertical direction and 560 APUs in the horizontal direction. A move of one APU in the horizontal direction is to the next raster dot to the right. An HP 9872 Plotter has 16000 APUs in the horizontal direction and 11400 in the vertical direction. One APU is 0.025 mm which is about 1/10 the width of a standard pen.

Graphic Display Unit

Just as all Latin scholars know that all Gaul is divided into three parts, all graphic programmers using HP's AGL (A Graphics Language) know that all plotting surfaces have 100 GDUs in their shortest dimension. A GDU or Graphic Display Unit is a relative unit of measure. It varies in length from device to device and, on a given device, it changes each time you redefine the plotting area. You can be sure however, that the shortest side of the plotting area will contain exactly 100 GDUs. A square plotting area will have 100 GDUs in each direction. The length of the longest side of a rectangular plotting area will vary from 100 on upward. If a plotting area is twice as long in one direction as the other, the long side will have 200 GDUs. If it is 1½ times as long, the plotting area will be 100 x 150 GDUs as shown in Figure 32.

By defining this coordinate system that is not related to a specific device, software programs can produce graphs on any graphic device without modifications to the program.

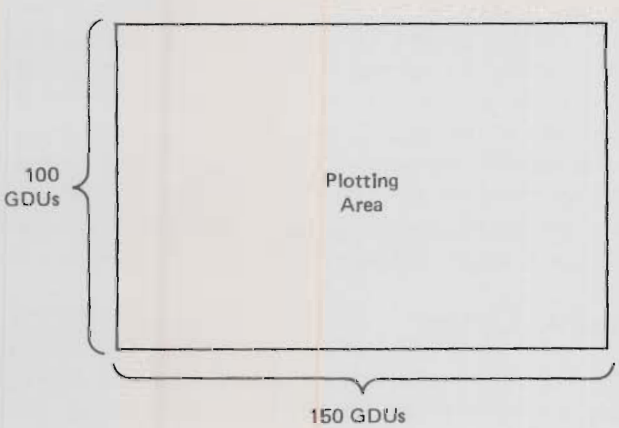


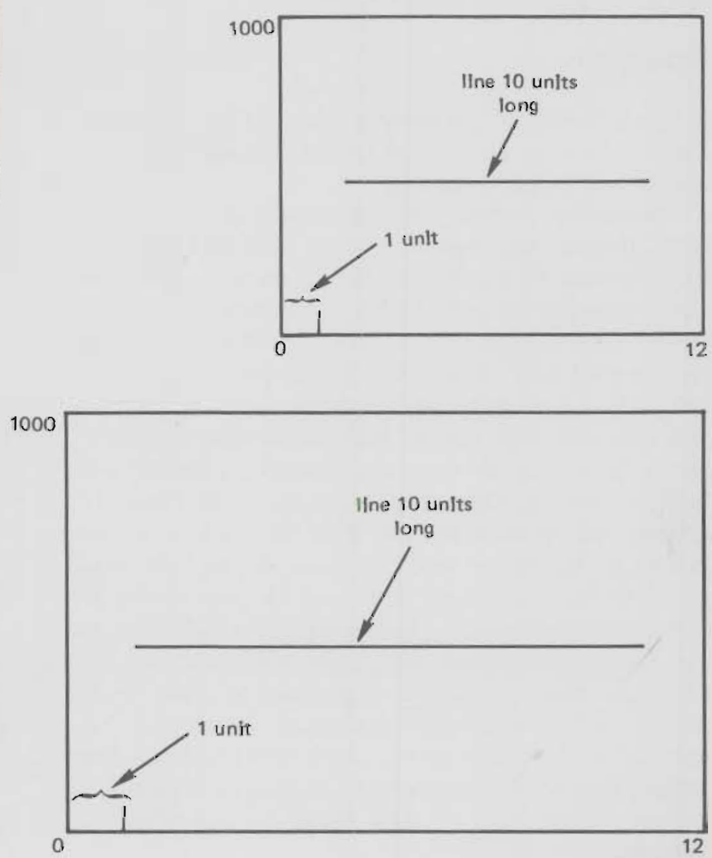
Figure 32

User Units

Every graphics programmer wants to talk to the computer in units of measure that relate directly to his application. Most graphics systems can be addressed in user units which are defined by some software instruction that scales the physical plotting area to contain the specified number of units. If you are plotting business graphs, your X-axis will often represent time, possibly months or years. Your Y-axis will often represent units sold or the value of sales perhaps in dollars, yen, or marks.

User Units (UU), except for the special cases of millimetres or inches discussed later, can vary in size depending on the plotting area. If an 11 x 17 in. and an 8½ x 11 in. paper were each divided into 1000 units in Y and 12 units in X, it is obvious that a line 10 units long, in either the X or Y direction, would be longer on the larger paper and yet still represent 10 units. The length of user units varies with the size of the plotting area and the range of values.

Figure 33.
Two areas are divided into 12 units in X and 1000 units in Y.
The size of a user unit varies.



Millimetres and Inches

Millimetres and inches are special kinds of user units which have wide appeal in engineering and drafting applications. Some software packages and plotter ROMs (read-only memories which contain graphic instruction sets) allow you to specify points and lines in inches and/or millimetres. If no special software or ROM is available, you can scale your own device into inches or millimetres if you know the resolution of the device and the dimensions of the plotting area. When a plotting device has been scaled using software in units which are physical units of measure, e.g. inches or millimetres, one unit is the same distance in the X- and Y-directions. When units are the same length on the X- and Y-axes, we call the scaling "isotropic scaling."

When plotting in inches or millimetres, the range of plottable values is the physical size of the plotting area. In some systems you can assign the lower left corner an arbitrary value other than 0,0. Then all plotted data will be relative to that origin. For instance, if you were plotting in inches and called the lower left corner 10,10 then a point 4 inches above that would be addressed as 10,14. If you called the lower left -2,-2, the point four inches above that would be -2,2.

If your plotting must have a direct correlation to physical values, you want to be sure your system has this capability.

Scaling

The process of converting from APUs (Absolute Plotter Units) or GDUs into User Units suitable to an application is called scaling.

The earliest plotters allowed plotting only in plotter units. If your data was in millions of dollars per year for a period of years, you would have to calculate how many plotter units in the X-direction would represent one year and how many in the Y-direction represented one dollar. The computer which drove the plotter was easily able to do this kind of calculation but this was hardly friendly, simple programming. Now most plotters and graphic systems have built-in scaling. You need only say what range of values you wish a certain axis to cover and the plotter or computer will take care of the rest. You might divide the plotting area into 12 units in the X-direction representing months and into 100 units in the Y-direction representing units sold, and ask the plotter to move one unit in any direction. How many discrete pen movements that move takes is of no concern to the programmer. Some plotters only allow integer scaling. The plotter can then only distinguish integer values and all data must be converted to integers.

Scaling on some systems is so automatic that you can set the graphic limits on the plotter to successively larger limits and obtain the same plot in various sizes. Then you can obtain the same plot to fit in a small booklet, an 8½ x 11 report or an 11 x 17 presentation by only changing the settings on the front panel of the plotter. The same number of User Units are mapped onto each area.

Graphic Boundaries

You've heard the expression, "There's a limit to everything." Graphics is no exception. There are limits to what you can plot! These limits arise for many reasons. This section discusses the various reasons plotting is limited. Limits are sometimes imposed by the device and sometimes by the programmer. The names given to the limits may vary from system to system, so, when reading, concentrate on the concept of a particular limit, not its name.

Mechanical Limits

There are physical limits to plotting on any device. We call these the mechanical limits, the limits beyond which the pen cannot draw. The mechanical limits correspond closely with the maximum paper size a given plotter can hold. They are the limits of movement of the plotter's pen when lowered to draw, or the edge of the graphics raster on a CRT, or the limits of the print area on a printer/plotter. Mechanical limits are inherent to a device and do not change from day to day or program to program.

Graphic Limits

The second kind of limits are graphic limits, commonly set by buttons P1 or lower left and P2 or upper right on HP plotters. Graphic limits are inside the mechanical limits and are set to correspond with the CRT size or the paper size actually in use. We will use P1 and P2 when referring to these limits. Plotting devices have default graphic limits which become effective if you do not specify any limits. On all HP plotters, you can set P1 and P2 from the front panel of the plotter as well as from a program. HP graphics programming statements automatically read these limits to determine the location and size of the plotting area, and the default conditions for the remaining limits discussed in this chapter.

Graphic Display Space

The graphic display space is the area divided into GDUs as discussed earlier under Units of Measure. Whenever a new P1 and P2 are read, the graphic display area changes accordingly. At the time P1 and P2 are read, the region of interest, the hard and soft clip limits (see glossary and below) are set to the P1, P2 values. These limits remain at P1 and P2 unless changed by a software statement.

Region of Interest

At this point your head is probably swimming in various limits. Relax, the worst is over. The nice things about the remaining limits is that if you do nothing special, they remain at P1 and P2. However, you may change some or all of these limits to meet specific application needs. Let's talk about region of interest first. If you think of what that phrase means outside the world of graphics, you will probably come up with a good idea of its meaning in graphics. It is the area in which your data will be plotted and, in reality, that is where your interest lies. The LOCATE statement is common to several HP systems and sets the region of interest to other than its default value.

Hard Clip and Soft Clip Limits

The final two limits are related to clipping. Again if you think about the word clip in general terms, you'll be close to its meaning in graphics. If you've been clipped, you had something cut off or taken away. Clipping involves eliminating all plotting when data is outside the clipping limits. In the case of hard clipping, all plotting is eliminated outside the hard clip limits. With soft clipping you can plot data inside the soft clip limits and can label, but not plot data outside the soft clip (but still inside the hard clip) limits. This leaves a border between the soft and hard clip limits for labeling. See Figure 34. LIMIT is a common statement to establish the hard clip limits while CLIP is commonly used to set soft clip limits different from those established by a LOCATE statement or by default.

Let's summarize the uses of various limits. First, you will choose a graphic device that can accommodate the size output your application requires. Second, by examining the physical limits, you can adjust to a certain output size within the mechanical limits of the device, such as a small piece of paper, by changing the hard clip limits. You can position your plot and/or plot only that portion of the data you want to view by soft clipping. Combining these concepts you can enlarge, or reduce any plot or section of a plot and draw it anywhere within the mechanical limits of the plotter. In other words, you can plot almost anything and everything you'd want.

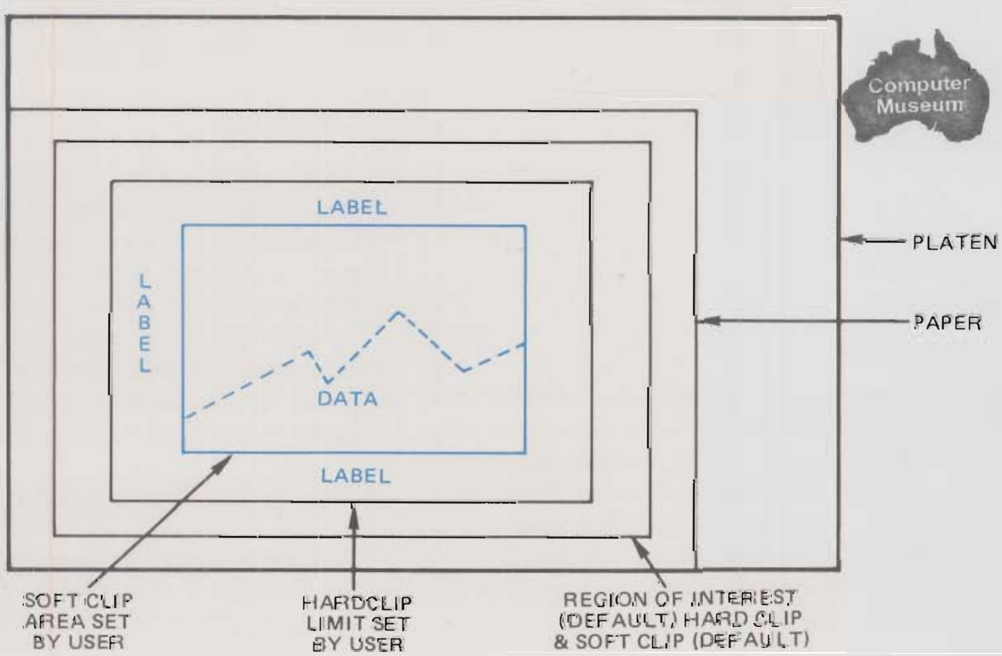


Figure 34.
Region of interest (default) hard clip and soft clip limits (default)

Graph Annotation

Earlier we referred to the saying, "One picture is worth ten thousand words." A corollary of that is, "A well-annotated graphic is worth 2000 words." Careful annotation of a graph makes interpretation easier and thereby increases a viewer's comprehension. Graph annotation includes both the drawing of axes and grids, and labeling.

Axes and Grids

Axes are intersecting lines which define the coordinate system. Axes usually intersect at the origin 0,0. The axes are divided into units; the units are marked off by short lines at regular intervals, called tick marks. Axes can have two kinds of tick marks, major and minor ticks. Major ticks are longer than minor ticks. Tick marks should be at major scale divisions, e.g. 10,20,30 as opposed to 11,17,23, and frequent enough to make accurate data interpretation possible, but not excessive so that tick marks or labels run together. The axes below divide the plotting surface into four quadrants. In many plotting applications only the first quadrant is shown.

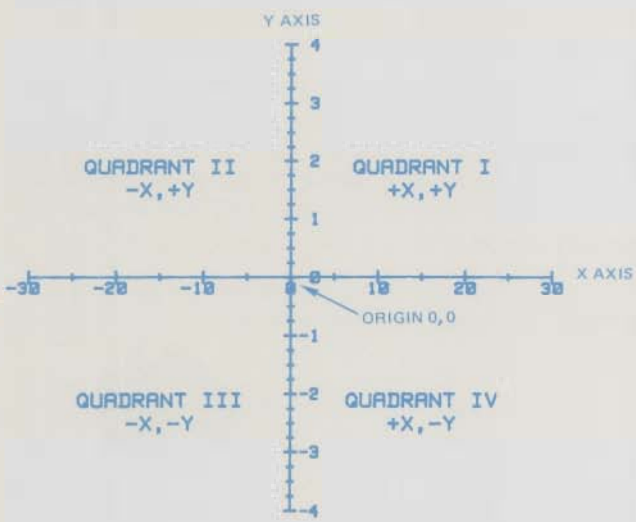


Figure 35

Grids are axes where the major tick marks extend all the way across the plotting area. Grid lines may extend in the horizontal and/or vertical directions. The yard lines on a football field form a grid with lines in only one direction. A complete grid and a grid with minor tick marks are shown in Figure 36.

Some graphics systems include software instructions just for drawing grids. In other cases the user

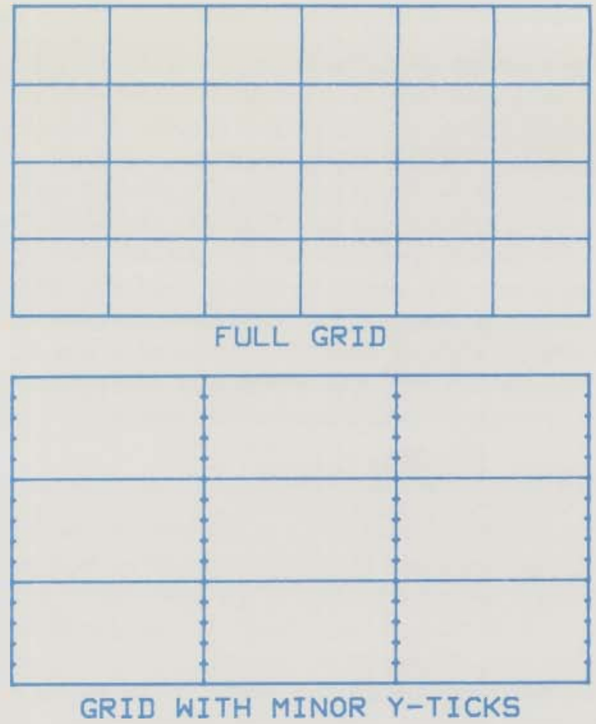


Figure 36

must create a grid by setting the tick length equal to the plotting area length or width, depending on whether X- or Y-ticks are being drawn. Grid lines should not be so numerous as to detract from the data. Making grid lines green on a white background or blue on a black CRT background and drawing them in a dotted linetype are two ways of de-emphasizing grid lines.

In most cases axes and grids are labeled. This means that major tick marks or grid lines are numbered according to the current scaling. Labels are usually written horizontally for easy reading. Some systems have software commands which create labeled axes. In other systems you must rely on your own program statements to label the axis.

Labeling

Labels include not only axis labels, but also titles of graphs, labels of individual lines and, plain text. Labels can be written in various sizes, with or without slant, at different angles and sometimes in either dot matrix or drawn format. In most cases the title is in a larger character size than other labels. Two or three character sizes are usually sufficient for any one graph. The characters used to label are the subject of the next section.

Character Generation

Characters, the individual letters or symbols in labels, are generated in one of two ways. Characters are either drawn using a series of vectors, or they are dot matrix. Dot matrix characters have been used for many years on some computer printers, and are formed by dots. Some common sizes for dot matrix characters are 7 x 9 dots and 5 x 7 dots. A dot matrix character is shown at right. Dot matrix characters on a given device are always the same size (i.e. composed of the same number of dots). While some sophisticated devices can vary the row and/or column spacing to make the character slightly larger, typically dot matrix characters can only be made larger by printing two or more dots where only one was previously printed. (See Figure 37.)

On vector plotters, such as the 9872, characters are drawn. Each letter is a small plot where a line is drawn for each part of the character. Figure 37 shows magnifications of characters drawn on a 7245, using dot matrix and drawn character fonts. Note the drawn characters are composed of continuous lines while the dots in the dot matrix character are visible as separate dots.

Drawn characters can be any size. It is interesting to note that if drawn characters are displayed on a raster device, they are converted back into dot matrix. They can only assume a finite number of sizes corresponding to the dots on the raster. It is therefore possible to observe a change in the character size on a peripheral plotter and yet not see any change in lettering on the CRT. (The plot commands which draw the character are converted to the nearest dot locations. It is not possible to turn on half a dot). You might call this a third type of character, specified as drawn but displayed in dot matrix.

Character sets can be classified in a second way depending on where they are defined. HP plotters have built-in character sets. That means that the plot instructions (character stroke tables) necessary to create the letter are contained in the microprocessor within the plotter. Software characters, on the other hand, are created by the host computer and the plot instructions sent to the plotter which has no idea if it is plotting characters or data. It takes 9 or 10 movements with the pen up and/or down to create the average letter. The diagram in Figure 38 below illustrates the difference in the creation of built-in and software-generated characters.

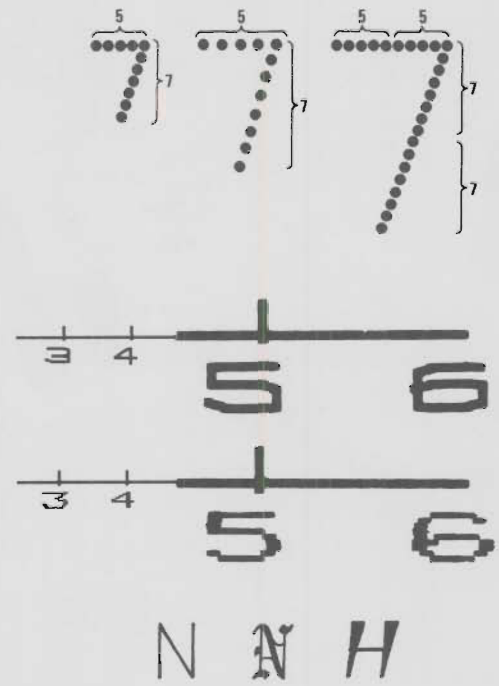


Figure 37.
Above: The numeral seven as a dot matrix character of normal size, with expanded spacing, and twice normal size.
Middle: Part of an axis labeled in the drawn (above) and dot matrix (below) character sets of the HP 7245 plotter/printer.
Below: A variety of character styles including built-in, Gothic and user designed characters.

HP plotters have multiple built-in character sets which include foreign characters and special symbols. A number of HP software packages for use on large computers include fancy character fonts such as script, triplex, Roman, and Gothic. These fonts are frequently used for overhead slides or design graphics applications. It is possible to create other interesting character styles using only the standard plotter lettering by moving the character's starting point slightly or changing the slant slightly and replotting the character. Most applications do not require fancy lettering; simple block letters of suitable size are very effective because they are easily recognizable.

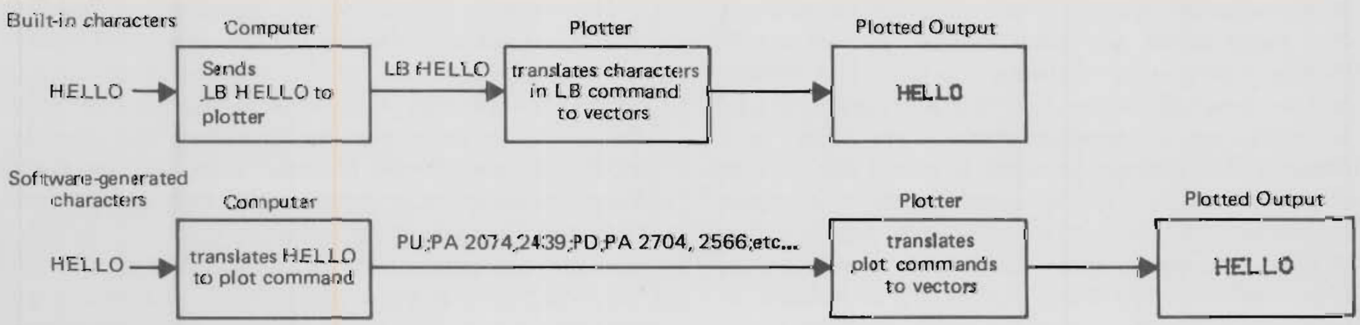
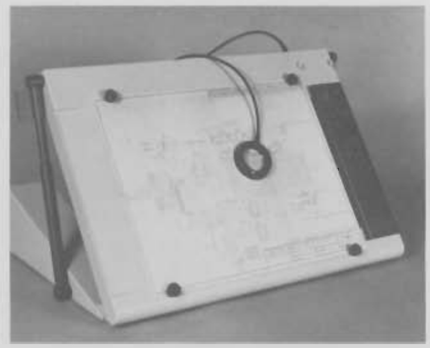


Figure 38.
Steps in creating labels using Built-in and Software-Generated Characters.

Figure 39
Left: A variety of plots created on HP plotters.
Below: The HP 9874A digitizer with its cursor. A circuit layout is mounted for digitizing.



Plotting

Why, you might ask, does it take this much reading before getting down to plotting — which is, after all, the essence of computer graphics. As with education in general, the more exposure you have, the more apt you are to go out and achieve your maximum potential and use graphics in really creative ways. What you may have lost in time you've gained in sophistication.

There are three types of plot instructions. First, and most direct, is absolute plotting. In absolute plotting, you tell the pen exactly where to go; that is you give an X,Y coordinate in user units, in GDUs, or APUs. The X,Y parameters are relative to an absolute origin that remains constant for a given plotting area and a given scaling. The pen moves from its current location to the specified location or as far as possible toward that point until it hits the hard clip boundaries.

The second type of plot instruction does relative or incremental plotting. There is some variation in how these words are used from HP system to HP system. However, it is always the case that relative and incremental plotting use the X,Y parameters of an instruction as increments which are added to a previous X,Y position or what is called the current origin. In relative and incremental plotting, it makes a difference where you've been; the previous pen position determines where you'll go. In absolute plotting, where you've been makes no difference in where you'll go; you always go to the specified absolute X,Y coordinate.

The third type of plot instructions simplifies plotting of common geometric forms. These are instructions that draw arcs, circles, rectangles and polygons using only one instruction for each figure. Not all systems have these instructions, in which case, geometric equations must be used to compute X,Y coordinates on the perimeter or circumference. These points must be connected by a series of straight lines to approximate a polygon or circle. The programmer must decide how many points to use in the approximation, what portion of the figure he wishes to draw and from what starting point. More and more, the sequence of instructions necessary to plot arcs, circles, and rectangles is built into the plotter or included in software packages.

In all types of plotting, the pen is controlled by either separate pen control statements, (pen up or pen down), or by a parameter of the plot statement or of the subroutine call.

The reverse of plotting is "digitizing." Digitizing asks the question, "Where is the pen now?" HP manufactures digitizers just for the purpose of converting physical location to a numeric value. You can also use a plotter as a digitizer. Digitizers are used to input map coordinates, physical dimensions on such things as X-rays, and digital values from strip charts. With a digitizing sight or the cross hairs on a plotter, you can precisely define a location and input it to the computer. If your application involves large amounts of digitizing, you probably want both a digitizer and a plotter.

Graphics Programming

Graphics programming resembles other kinds of computer programming in that it can be done in high- or low-level languages. High-level languages tend to be English-like and friendly, and they generate several machine instructions (in this case, plotter instructions) for each high-level language instruction. Let's illustrate languages by discussing HP's graphics languages. AGL is our high-level language and it is implemented in one of two ways. It is either included as an extension to the high-level language implemented on the system, as done on the 9835 or 9845 desktop computers in BASIC, or it is included as subroutines callable from any high-level language available on a computer. GRAPHICS/1000 Graphics Plotting Software (GPS) is an implementation of AGL in subroutine form.

These high-level languages are translated into lower level languages understood by the graphics peripheral. Each graphics peripheral has an internal language that was determined to be optional for that device and user environment. The HP 7221 understands compacted binary, a language designed to minimize data communications to remote sites. While it is possible to learn the escape code sequences and encoding procedures to program directly in the internal language of the 7221, it is seldom done. A subroutine implementation is usually used. All other Hewlett-Packard plotters have HP-GL as their internal language. The plotter ROMS for the 9835 and 9845 translate AGL instructions into HP-GL. It is also possible to program directly in HP-GL on a desktop or any other computer. An example of the instruction to draw to the location 1000,1000 is given below in various languages.

Language	Instruction
AGL, 9845 ROM	PLOT 1000,1000,-1
HP-GL	PD;PA 1000,1000;
compacted binary	q g400
AGL, PLOT/21	CALL PLOT (1000,1000,+02)

Further examples of AGL and HP-GL programs can be seen at the end of this section. Of course there are other vendors of software and hardware in the graphics market. Hewlett-Packard also has software available to support HP plotters in non-HP computer environments. Our plotters are also supported by several timeshare systems. Hence, HP offers graphics solutions in many markets.

Data Generation

You might wonder how the plotter knows what to plot. Remember graphics is one form of computer output, so plot data can come from any data source accessed by the computer. First, and simplest, is data entry from the keyboard of the computer system. This can be done when entering the program by using data statements internal to the program. If this is the case, the data and results are the same each time the program is run (unless the data statement itself is changed). Another kind of keyboard entry is done at program execution time. At each run of the program, the data is entered from the keyboard when requested by the program. Personnel data regarding benefit packages, hiring plans, and salary administration might be entered in this manner. Once entered, the data is, or can be plotted, and saved or updated. This interactive mode always requires that an operator enter data at execution time.

The second kind of data is obtained from test results in some kind of measuring system. An HP measuring device such as a counter, digital voltmeter or spectrum analyzer might be interfaced, using an HP-IB interface cable, to a desktop computer. Data obtained from these instruments can be plotted in real time as it is generated, or can be recorded on a mass storage device (tape or disk), or placed in a data base for later retrieval and plotting. Similar to test data is data input from a digitizer. A digitizer can be used interactively with a graphics program or digitized data can be placed in a data base for later retrieval. Test measurement results and digitized data are only two examples of information which might be in a data base. Any data base such as a management information systems, can be used as a source of data for a graphics program.

The final way of obtaining data is computer generation using some algorithm or formula. It is possible to completely generate data in this fashion, for instance, plotting a function such as $Y = X^2$ for the range of values $X = -10$ to 10. As you can see, all these methods of data generation are no different from those you would use to obtain any computer output. Graphics is simply another kind of computer output, a very effective one at that!

Device and Language Independence

Device independence is another term you hear in computer circles. It has a variety of interpretations; its meaning depends somewhat on your point of view. When speaking of software, device independent portions are those sections of code which are not concerned with output to a particular device. This meaning is not restricted to graphics. In graphics software, device independent software most often means that graphics applications can be developed without consideration for any peculiarities of a graphics device, such as its size, number of colors, or generation method. The plot will come out in the same proportion when plotted on any device.

Language independence is the second term often used to describe HP graphics software. It refers to subroutines callable from any high-level programming language implemented on a particular computer. GRAPHICS/1000 can be used with FORTRAN, PASCAL or BASIC and is hence, language independent.

The two terms imply flexibility and, in the ideal case, device independent software would allow the addition of any graphics peripheral to a system and have the same plot produced on the new device without software modification. True language independence would mean you could develop graphics output from an application program written in any high-level programming language familiar to you.

A Sample Graphics Program in HP-GL and AGL

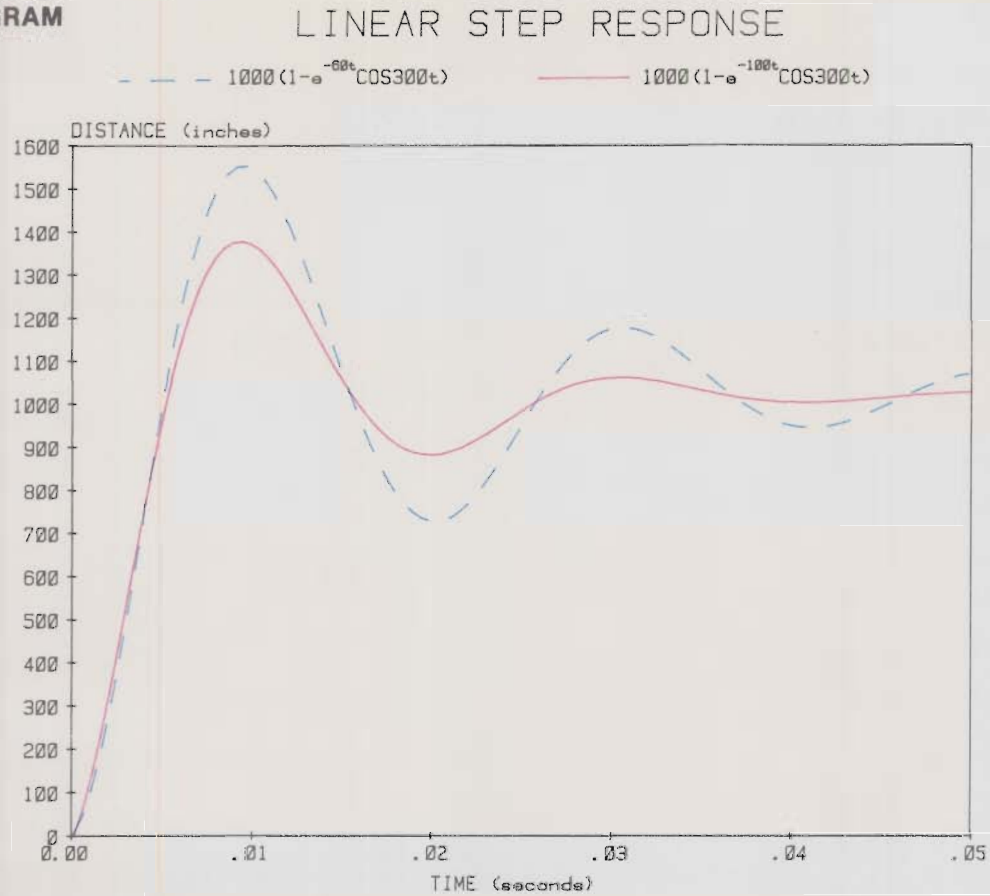
The two programs which follow create the same line graph used in Figure 10 of this primer to illustrate the essential parts of a graph. The first listing, a program written for an HP 9835 or HP 9845 desktop computer, uses HP-GL instructions sent to the plotter by PRINT statements. The second listing, also for a 9835/9845, uses only AGL graphics statements found in the 9835 plotter ROM. If you look carefully you will find a few differences in the graphs. (Look at the tick marks, the position of the X-axis title and the size of the main title.) The object here was not to eliminate all differences; it was only to graph the function in a straightforward manner. While the HP-GL program has fewer program lines, most lines contain several HP-GL statements and so there are more graphics commands in the HP-GL program then in the AGL program.

A program to create this same graph using AGL subroutines (GRAPHICS 1000-GPS) would be similar to the second program, except that the ROM statements would be changed to CALL statements.

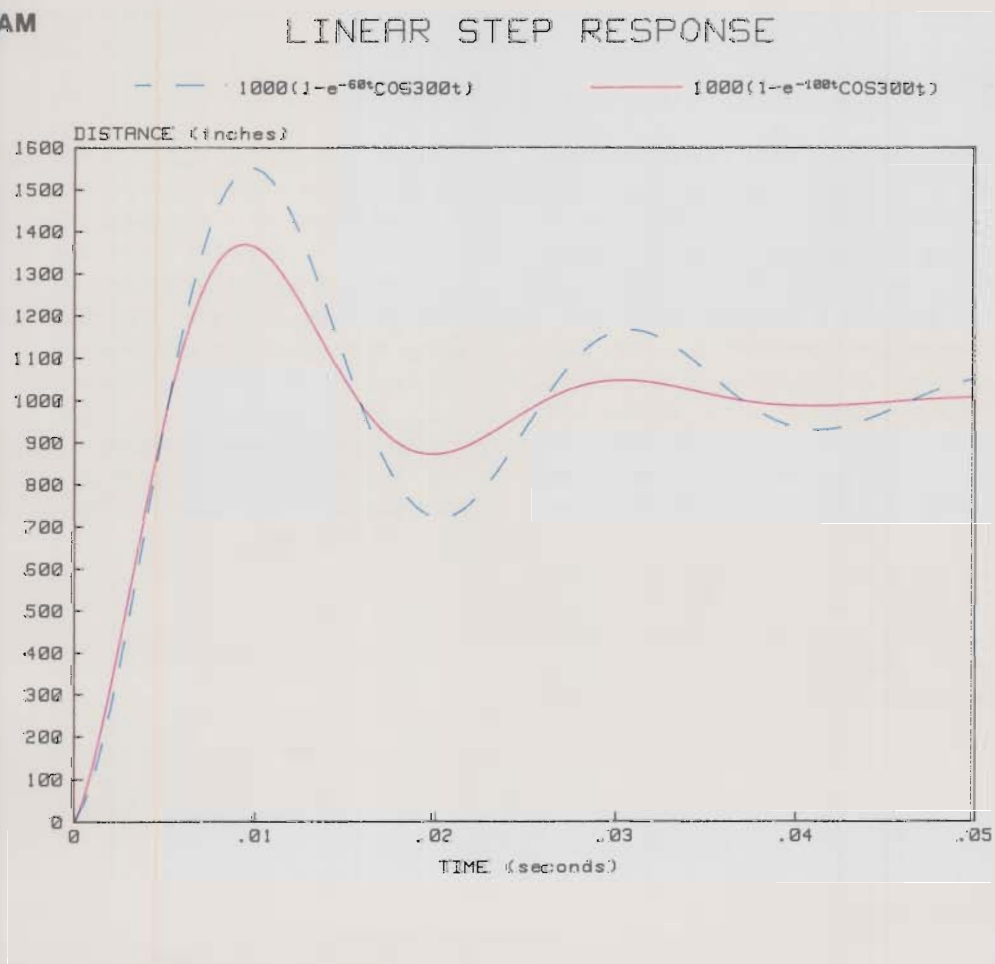
HP-GL PROGRAM

```
10   PRINTER IS 7,5
20   ! ****ESTABLISH AND FRAME PLOTTING AREA****!
30   PRINT USING "K";"IN;IP1528,1000,9028,6760;SP1"
40   PRINT USING "K";"PU;PA1528,1000;PD"
50   PRINT USING "K";"PA9028,1000,9028,6760"
60   PRINT USING "K";"PA1528,6760,1528,1000"
70   ! ********SCALE AREA************!
80   PRINT USING "K";"SC0,500,0,1600"
90   ! ********TITLE GRAPH***********!
100  PRINT USING "K";"PU;PA125,1850;SI.35,.5"
110  PRINT USING "K";"LBLINEAR STEP RESPONSE"
120  ! ********DRAW X AXIS*************!
130  PRINT USING "K";"PA0,0;PD"
140  FOR X=0 TO 500 STEP 100
150  PRINT USING "K";"PA",X,",0;XT;PU;SI.175,.28"
160  PRINT USING "K";"CP-2.4,-.9"
170   PRINT USING "2A,D.DD,A";"LB",X/10000,""
180  PRINT USING "K";"PA",X,",0;PD"
190  NEXT X
200  ! ********LABEL X AXIS************!
210  PRINT USING "K";"PU;PA200,-125"
220   PRINT USING "K";"LBTIME (seconds)"
230  PRINT USING "K";"PA0,0;PD"
240  ! ********DRAW Y  AXIS **********!
250  FOR Y=0 TO 1600 STEP 100
260  PRINT USING "K";"PA0,",Y,";YT;PU"
270  PRINT USING "13A,4D,A";"CP-4.9,-.3;LB",Y,""
280  PRINT USING "K";"PA0,",Y,";PD"
290  NEXT Y
300  ! ********LABEL Y AXIS***********!
310  PRINT USING "K";"PU;PA0,1620"
320  PRINT USING "K";"LBDISTANCE (inches)"
330  PRINT USING "K";"PA0,0;PD"
340 ! ********PLOT 1ST LINE *********!
341  PRINT USING "K";"SP2"
350  FOR T=0 TO .05 STEP .0005
360  Y=1000*(1-EXP(-100*T)*COS(300*T))
370  X=T*10000
380  PRINT USING "2A,DDDD,A,DDDD";"PA",X,",",Y
390  NEXT T
400  PRINT USING "K";"PU;PA0,0;PD;LT2;SP4"
410  ! *******PLOT 2ND LINE *********!
420  FOR T=0 TO .05 STEP .0005
430  Y=1000*(1-EXP(-60*T)*COS(300*T))
440  X=T*10000
450  PRINT USING "2A,DDDD,A,DDDD";"PA",X,",",Y
460  NEXT T
470  ! **********DRAW LEGEND**********!
480  PRINT USING "K";"PU;PA30,1740;PD;PR 50,0;PU;SP1"
490  PRINT USING "K";"LB 1000(1-eCP0,.5;SI.12,.19"
500  PRINT USING "K";"LB-60tSI.175,.28"
510  PRINT USING "K";"CP0,-.5;LBCOS300t)"
520  PRINT USING "K";"PU;PA260,1740;LT;SP2;PD;PR 50,0;PU;SP1"
530  PRINT USING "K";"LB 1000(1-eCP0,.5;SI.12,.19"
540   PRINT USING "K";"LB-100tSI.175,.28"
550   PRINT USING "K";"CP0,-.5;LBCOS300t)"
560  END
```

HP-GL PROGRAM



AGL PROGRAM



AGL PROGRAM

```
10     PLOTTER IS "9872A"
20     ! *******ESTABLISH AND FRAME PLOTTING AREA******!
30     LIMIT 0,210,10,187
40     LOCATE 9*RATIO,98*RATIO,6,85
50     FRAME
60     ! ********TITLE GRAPH**********!
70     MOVE 54*RATIO,100
80     CSIZE 4.8
90     LORG 6
100    LABEL USING "#,K";"LINEAR STEP RESPONSE"
110    ! ********SCALE AREA***********!
120    SCALE 0,.05,0,1600
130    ! ********DRAW AXES************!
140    AXES .01,100
150    ! *******LABEL AXES************!
160    CSIZE 2.5
170    LORG 6
180    FOR X=0 TO .05 STEP .01
190      MOVE X,0
200      SETGU
210      IPLOT 0,-1,-2
220      SETUU
230      LABEL USING "#,K";X
240    NEXT X
250    SETGU
260    MOVE 54*RATIO,0
270    LORG 4
280    LABEL USING "#,K";"TIME (seconds)"
290    LORG 8
300    SETUU
310    FOR Y=0 TO 1600 STEP 100
320      MOVE 0,Y
330      LABEL USING "#,K";Y," "
340    NEXT Y
350    SETGU
360    MOVE 9*RATIO,86
370    LORG 1
380    LABEL "DISTANCE (inches)"
390    SETUU
400    ! ********PLOT 1ST LINE *********!
410    PENUP
420    PEN 2
430    FOR T=0 TO .05 STEP .0005
440      Y=1000*(1-EXP(-100*T)*COS(300*T))
450      X=T
460      PLOT X,Y
470    NEXT T
480    ! *******PLOT 2ND LINE *********!
490    MOVE 0,0
500    PEN 4
510    LINE TYPE 4
520    FOR T=0 TO .05 STEP .0005
530      Y=1000*(1-EXP(-60*T)*COS(300*T))
540      X=T
550      PLOT X,Y
560    NEXT T
570    ! **********DRAW LEGEND**********!
580    SETGU
590    MOVE 15*RATIO,92
600    SETUU
610    UNCLIP
620    RPLOT .005,0,-1
630    LORG 2
640    LINE TYPE 1
650    PENUP
660    PEN 1
670    LABEL USING "#,K";" 1000(1-e"
680    CSIZE 1.7
690    RPLOT 0,20,-2
700    LABEL USING "#,K";"-60t"
710    CSIZE 2.5
720    LABEL USING "#,K";"COS300t)"
730    SETGU
740    MOVE 60*RATIO,92
750    SETUU
760    PEN 2
770    RPLOT .005,0,-1
780    PENUP
790    PEN 1
800    LABEL USING "#,K";" 1000(1-e"
810    CSIZE 1.7
820    RPLOT 0,20,-2
830    LABEL USING "#,K";"-100t"
840    CSIZE 2.5
850    LABEL USING "#,K";"COS300t)"
860    END
```

What Next?

In the preceding pages you have been introduced to many aspects of computer graphics. Where you go from here depends entirely on your goals. While this primer may have answered some of your questions, we hope you have a new set of questions to ask. Perhaps you can visit a business which has a graphics system already in operation. You may want to look at data sheets on various sytems, plotters, and software. You can become quite familiar with graphics programming by spending an afternoon experimenting with the HP-85, referring to its plotter/printer ROM manual and the Beginner's Guide for the 7225A plotter for additional assistance. If you have a 9845 desktop computer available, you might want to use the training tapes on graphics. Other possibilities are to read the graphics ROM manual for any desktop computer or the software manual for your graphics system. Perhaps a trip to the library is in order.

Most university or technical libraries will be able to refer you to articles or books on computer graphics A comprehensive paperback, "Tutorial: Computer Graphics" is available from the IEEE Computer Society. This contains articles on graphics in general, hardware, software, algorithms, and applications along with references and bibliographies. Finally, talk to others employed in the field of computer graphics. From them you'll get the most up-to-date information and a sense of direction about what's coming. We at the San Diego Division of Hewlett-Packard hope you become as excited about computer graphics as we are.

Glossary

Absolute plotting	Plotting to a coordinate which has its X and Y values specified in current units from a fixed origin.
AGL	**A** **G**raphics **L**anguage, HP's high-level language implemented either as subroutines or as an extension to the computer's high-level programming language.
CAD	**C**omputer **A**ided **D**esign, use of a computer with graphics capabilities to design anything to be manufactured. Such systems usually have CRT's, light pens, or data tablets, and are highly interactive.
CRT	**C**athode **R**ay **T**ube, a vacuum tube in which an electron beam is projected on the fluorescent screen to produce a luminous spot.
Digitizer	A device for graphics input which converts physical location on a tablet or flat area to digital data understandable by a computer.
Drum plotter	A graphics plotter on which the paper moves over a round cylinder or drum. The pen is usually limited in movement to horizontal moves in a straight line along the top of the drum. Plotting in the other dimension is accomplished by moving the drum to which the paper is attached.
Flatbed plotter	A plotter which has a flat area (platen) on which the paper is placed. The pen is free to move in any X or Y direction.
GDUs	**G**raphics **D**isplay **U**nits, an X, Y reference system which defines any plotting area in units, such that the shortest dimension of the plotting area has 100 units and permits device independent operation.
Graphic limits	The plotting area of the graphics peripheral within its mechanical limits.
Hard clip area	The limits of the plotting device beyond which no line can be drawn. The limits can be set programmatically, or by default and are not necessarily the physical dimensions of the maximum plotting area.
Hard copy	Output on paper or transparency material. It remains when the power to the system is turned off.
High-level language	A programming language in which each instruction generates several machine instructions. Generally speaking, it is English-like and the statement's name suggests the statement's function.
HP-GL	**H**ewlett-**P**ackard **G**raphics **L**anguage, the 2-letter mnemonic graphics language understood by some HP graphics devices (mostly plotters and digitizers). Serves somewhat like an assembly language in graphics applications in which AGL is available.
Incremental plotting	Plotting relative to the last (previous) pen position.
Light pen	An optical device used interactively in a graphics system to select or position an item.
Machine language	The language understood by a computer or microprocessor which is directly translatable into electronic circuitry operation.
Raster scan	The process of tracing out a picture on a display as a series of intensified points along horizontal lines.

Glossary (cont.)

Refresh cycle	The time between successive raster scans, or passes through the list of vectors displayed on a vector display. The phosphors on the face of the CRT are excited by one pass of the electron beam each refresh cycle.
Refresh memory	That area of computer memory which holds values indicating whether a particular dot of the graphics raster is on or off. In color displays it also contains information on the color of that location.
Refresh rate	The rate at which the display phosphor is re-excited in a CRT. This level is normally set to a level that eliminates flicker (the fading and brightening of the screen image). Refresh rates are typically 1/60th and 1/30th of a second depending on whether each line of a raster or every other line of a raster is refreshed each time. A limiting factor is the length of time the phosphors on the screen remain excited.
Relative Plotting	Plotting relative to a local or temporary origin.
Soft clip area	The limits of the plotting device which restrict pen movement for data. Labels may be placed outside this area (but within the hard clip region).
Soft copy	A copy of computer output or graphics which is displayed on a device from which the image will disappear if the power is turned off — typically a CRT display or graphics terminal.
UDU's	**U**ser **D**efined **U**nits, defined by the graphics program to whatever units of X and Y measure are convenient for a specific application, e.g., years, months and dollars.

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