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System 45 is Hewlett-Packard's most powerful desktop computer—the top of the line. Born in 1977 as System 45A, it gives engineers and scientists a single compact unit that contains all the elements needed to solve complex design and analytical problems. It has an interactive keyboard, a large memory, a graphic display, two fast processors, a line printer, and dual magnetic tape drives. Standard computer peripherals such as disc drives and plotters can be added if their capabilities are needed.

The latest version of this powerful computer, System 45C, adds color to the display and puts a light pen in the user's hand to make it easy to pick out and move elements of the displayed picture. Owners of older System 45 models can have these new capabilities, too, since upgrade kits are available. With color, a wide range of new problems can be addressed. In mechanical design, for example, high-speed performance of a machine can be simulated, with different colors showing degrees of stress or various modes and frequencies of vibration. Manufacturing processes can be modeled, with color showing operational status and problem areas. An engineer can use the color display to visualize radio wave patterns around antennas, and a meteorologist can study weather patterns and the dispersion of pollutants or acid rain. In motion-picture production, a color graphics computer like System 45C can serve as an electronic storyboard, simulating complex animation and special effects before any film is shot. We've chosen to illustrate this application on our cover, and we thank Lucasfilm, Ltd. for the background shot.

Although System 45C's display is similar to a color television picture tube, adding color wasn't a simple matter of exchanging a black-and-white tube for a color tube. A highly stable color convergence system had to be designed so that colors would remain clear and sharp across the entire display. A new approach to coloring areas provides 4913 distinct shades. Thirty-five new and enhanced graphics commands and optional 3-D graphics utility programs make all of the advanced color and light pen capabilities readily accessible even to programmers who haven't had a lot of experience. Perhaps the most formidable design challenge was adding a light pen to a raster-scan display, a feat that was widely thought to be impractical. The scanning beam remains at the same vertical level on the screen for quite a while, so the vertical position of the light pen is easy to establish. The horizontal position is much harder to establish, since the beam scans past the pen very swiftly and the pen's light-detection sensitivity is different for different colors. How these design challenges were met is detailed in the articles in this issue. Reading these articles, you'll see why the System 45C display unit has about the same electronic complexity as the rest of the computer.

December is our annual index issue. You'll find our 1980 index in the center of this issue, where it's easy to remove in case you want to file it separately.

-R. P. Dolan

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Color Enhances Computer Graphics System

The addition of a color CRT, extensive graphics control statements and faster vector generation to a desktop computer provides a comprehensive graphics system for the display and interpretation of complex data.

by John B. Frost and William L. Hale

SYSTEM 45C of Hewlett-Packard's 9800 Series of desktop computers, also known as Model 9845C, is a completely integrated color-graphics computer system. It features a high-quality color display, a 9845T mainframe with dual tape transports, 187K-byte read/write memory, and a high-speed thermal line printer. New extended BASIC-language statements in 48K bytes of ROM provide easy access to the graphics capabilities of the color CRT.

User interaction is simplified through the use of a light pen to track a CRT cursor and to pick out and place objects on the display screen. User-defined softkeys (Fig. 1) are located on the display module below the CRT and their definitions can be dynamically displayed on the bottom portion of the CRT to help the user interact effectively with the graphics system.

System Design

Development of the System 45C (Fig. 2) was heavily influenced by 9845A/B customers using the optional graphics capability. Strong interest in the performance of the CRT display indicated a need for greater information density and faster display rates. Even more important was the need

for maintaining an evolutionary growth path—allowing the portability of existing programs and data and providing interchangeability between the detachable displays of the System 45 Desktop Computers.¹

An emerging demand for color graphics directed the definition of the System 45C. Of two reasonably priced color display technologies, beam penetration and shadow mask, the beam penetration technique provides better resolution but an insufficient spectrum of colors. Raster-scanned CRTs are more compact and provide resolution compatible with the internal 560-dot-per-line thermal printer. High-performance color CRTs are becoming available as derivatives of high-volume, low-cost TV receiver tubes. While these shadow-mask CRTs are electromagnetically scanned and favor raster techniques, they can provide bright, crisp lines, pure, uniform shades, and alphanumeric text within a physical space consistent with the System 45.

Four major goals guided the design toward a more versatile and conversational graphics system:

- Develop explicit BASIC-compatible statements to support the new color and performance features
- Increase the display writing rate or vector generation rate
- Maintain display interchangeability
- Improve the psychological aspect of user interaction with the graphics display.

Language development concentrated on the coupling of the natural relationships between pictures and actions using a vocabulary derived from existing BASIC graphics statements and taking advantage of increased vector drawing rates. For example, a rectangle is a common geometric figure used in applications involving representations of bar charts. Replacing a series of four plot statements, the new statement RECTANGLE significantly increases execution speed and simplifies programming. An even more general form of n-sided figures is provided by the POLYGON statement. Furthermore, the image of a colored area or surface bounded by such figures is viewed as a natural extension of these geometric forms. Selection of the color in such polygonal areas is made available with a single BASIC statement and minor additions to the previous 9845 vector generation scheme.²

Considerable emphasis was placed on significantly increasing the vector generation rate. This not only fulfills the need to transform vector end points into picture elements (pixels) quickly, but also provides the many additional vectors required to generate displayed surfaces within a

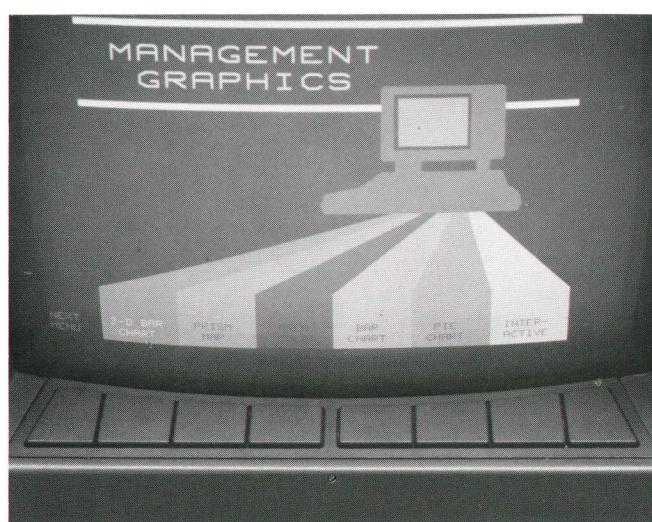


Fig. 1. Eight softkeys are located on the bezel below the color CRT. The current label for each softkey can be displayed on the CRT immediately above the key.

reasonable time. These strong influences led us to change the existing ROM-based pixel-conversion algorithm into a hardware scheme using conventional bit-slice microprocessor components. Thus the graphics firmware in the System 45A becomes a standard hardware processor in the System 45C.

Display interchangeability reduces the customer investment required to upgrade existing 9845 Computers. It also lowered the development cost and shortened the development schedule for the System 45C. Because the display is modular, tooling, electronics, and firmware development efforts were incremental investments and benefitted from the well-established electrical/mechanical interface and computer operating system of the 9845A/B.

User interaction is a goal achieved partially by the incorporation of two display input devices—the softkeys and the light pen—and partially by a set of unified graphics input statements. With these controls providing a direct method of pointing to or selecting one of many displayed objects (either characters, symbols, or other illuminated areas), the foundation of a more natural man-machine interface is established. Complementing these devices and merged within the additional graphics firmware is the second ingredient for interaction—a means of translating the meaning of hand/eye movements to control within the user's program. For example, if an illuminated pixel within the 560×455 pixel display is singularly identified by pointing to it with the light pen and cross-hair cursor, the CURSOR statement returns the cross-hair coordinates in user-defined units to a designated BASIC program variable.

Color Display

The color display module is self contained and has its own power supply. This design enables older 9845 Computers to be easily upgraded to have color graphics capability. The CRT has sharp focus, good contrast, and rich, crisp, clear colors. The high-resolution display area (560 by 455 pixels) is highly visible in ambient lighting. Eight colors are available for the alphanumeric display and an extensive range of colors (4,913 "eye-averaged" shades) is available for graphics images. This range of colors can be used very effectively to color areas within a variety of shapes to highlight subtle variations of complex data or to give form to

spatial objects (Fig. 3).

Thirty-nine convergence potentiometers are provided behind an access door to the right of the display. An easy-to-use, quick-to-do, firmware-assisted process enables the user to make stable adjustments of these controls for near-perfect color convergence over the entire CRT viewing area.

Graphics Language

Simple statements give the user control of the colors and shapes used in the display. Two color models—cubical and cylindrical—are available for easy specification of a desired color using the AREA INTENSITY and AREA COLOR statements, respectively. Commonly used shapes are plotted easily by using the RECTANGLE and POLYGON statements.

The plotting of more complex shapes can be simplified by using the MAT PLOT, MAT RPLOT and MAT IPLOT statements with the X-Y coordinate data for each point in a shape stored in an array. All shapes can be shaded inside with a previously selected color by adding the FILL command to the shape statement.

Other commands allow the user to specify desired graphics input and/or output devices for the system, define and label the softkey functions, track the movement of the cursor on an input device by marking its relative position on an output device, and select the color assigned to each of the three display memory planes.



Fig. 2. The System 45C is an integrated computer graphics system with a high-resolution color display, thermal printer, two tape cartridge drives, light pen, high-performance I/O, and mass storage capability.

Warren Pratt for his superior technical direction of the hardware and design of the video deflection and convergence circuits.

References

1. W.D. Eads and J.M. Walden, "A Highly Integrated Desktop Computer System," Hewlett-Packard Journal, April 1978.
2. J.C. Keith, L.T. Schulte, and A.K. Vogen, "System 45 Hardware Design," Hewlett-Packard Journal, April 1978, p 19.

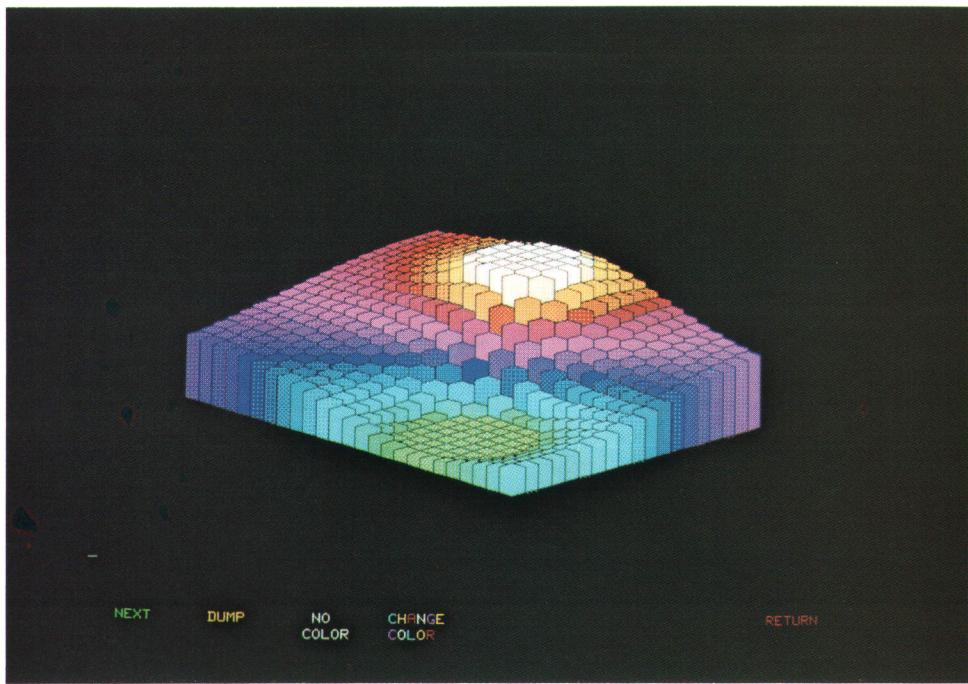


Fig. 3. Some of the colors and shapes that are easily obtained on the color display are shown at the left. Here a complex function is presented in three dimensions using hexagonal prisms whose height is emphasized by the use of color.



William L. Hale

Bill Hale joined HP in 1966. He has worked on ac standards, low-frequency spectrum analyzers, and digital voltmeters. Bill is project manager for the 9845C color display. He is a coinventor for several patents and the author of an HP Journal article on the 3580A (September, 1973). Bill was awarded the BSEE and MS degrees by Ohio State University in 1965 and 1966, respectively. He is a native of Columbus, Ohio, is married, and lives in Loveland, Colorado. Outside of work Bill enjoys Puccini operas, restoring a new house, and private aviation—he teaches flying and maintains his own aircraft.



John B. Frost

A native of Poland, Ohio, Jack Frost attended Ohio State University where he was awarded the BEE degree in 1968. He joined HP in 1973, worked on market development and the 9845A Computer, and is now project manager for the 9845C firmware and light pen. Jack's earlier experience includes R&D work on MOS/LSI circuit design and electrooptics, and service in the U.S. Marine Corps. He is a member of IEEE, the author of several papers, and a coinventor for one patent. He is married and lives in Loveland, Colorado. Jack enjoys cross-country skiing, racquetball, motorcycling, studying wildlife, and beekeeping. He has served on the housing authority for the city of Loveland, and is currently developing a sanctuary for migratory and indigenous birds on a 10-acre homesite in the Rocky Mountain foothills.

SPECIFICATIONS HP Model 9845C Computer

DYNAMIC RANGE: -10^{99} to -10^{-99} , $0_{-}+10^{-99}$ to $+10^{99}$
INTERNAL CALCULATION RANGE: -10^{511} to -10^{-511} , $0_{-}+10^{-511}$ to $+10^{511}$

READ/WRITE MEMORY

OPT. 001: 56,060 bytes
STANDARD: 186,904 bytes

OPT. 205: 317,820 bytes

OPT. 206: 448,700 bytes

TAPE CARTRIDGE (two drive units)

CAPACITY: 217,000 bytes, each

ACCESS: Directory (stored in RW memory), file-by-name.

SEARCH SPEED (bidirectional): 2286 mm/s (90 in/s).

AVERAGE TRANSFER RATE: 1440 bytes/s.

CARTRIDGE SIZE: 63.5 x 82.5 x 12.7 mm (2.5 x 3.25 x 0.5 in).

THERMAL LINE PRINTER

PRINT SPEED: Up to 480 lines/minute.

PLOT SPEED

Normal Mode: 25.4 mm/s (1 in/s).

CRT Transfer: 3.5 to 25 mm/s (0.14 to 1 in/s).

CHARACTER MATRIX: 5 x 7 dots (7 x 12 field).

NOISE LEVEL

9 hr, 100% Duty Cycle: 69 dB(A) (max).

0.5 hr, 100% Duty Cycle: 55 dB(A) (avg).

PAPER FEED

Automatic load.

LINE WIDTH: 560 dots, 80 characters.

PAPER WIDTH
English: 216 mm (8.5 in).
Metric: 210 mm (8.27 in).

PAPER TYPE: Thermal, either black print, perforated page separation or blue print, continuous roll.

COLOR CRT

SCREEN SIZE: 330 mm (13 in) diagonal.

SCREEN BRIGHTNESS: Manually adjustable from 12 to 40 foot-lamberts (white).

REFRESH RATE: 60 Hz (independent of line frequency).

TUBE PHOSPHOR: P22.

DOT SIZE: 0.343 mm (0.0135 in).

ALPHANUMERIC DISPLAY

Raster Size: 247 x 154 mm (9.72 x 6.06 in).

Screen Capacity: 26 lines x 80 characters (2080 characters).

GRAPHICS DISPLAY

Raster Size: 192 x 156 mm (7.5 x 6.1 in).

Display Speed (vectors/s, overlapped and not clipped)

For/Next: Approximately 95

Matrix Plot: Approximately 200

Absolute Plot: Approximately 5000

Linearity: <2% full screen.

Array Size: 560 x 455 pixels.

CURSOR

Plotting Mode: Full screen or small crosshair.

Letter Mode: Blinking underline.

Character Editing: Overstrike in letter mode.

LIGHT PEN

SIZE: 20.2 mm (0.8 in) diameter by 157 mm (6.18 in) long.

WEIGHT: 125 g (4.4 oz).

TRACKING SAMPLING RATE: 60 Hz.

CURSOR POSITIONING ACCURACY: 1 pixel.

MINIMUM INTENSITY FOR PICK OF SINGLE PIXEL: 10 foot-lamberts (white, blue, or green).

SYSTEM SIZE/WEIGHT

SIZE: HWD 546 x 482.5 x 762 mm (21.5 x 19 x 30 in).

SHIPPING WEIGHT (Standard 9845C): 81.8 kg (180 lb).

CUBE: 0.2 m³ (7.09 ft³).

POWER REQUIREMENTS

SOURCE: 110 or 220 Vac (selected by rear panel switch) +15%, -20%.

LINE FREQUENCY: 48 to 66 Hz.

POWER CONSUMPTION

Mainframe: 275 W (max).

CRT Display: 550 W (max).

POWERLINE SUSCEPTIBILITY: Withstands ± 400 Vac pulse (800-ns duration, 1-ns risetime, 60-Hz repetition rate).

ENVIRONMENTAL RANGE

OPERATING TEMPERATURE: 5°C to 40°C.

STORAGE TEMPERATURE: -40°C to +65°C.

RELATIVE HUMIDITY: 5% to 80%, 40°C.

PRICE IN U.S.A.: Standard 9845C base price, \$39,500.

MANUFACTURING DIVISION: DESKTOP COMPUTER DIVISION

3404 E. Harmony Road

Fort Collins, Colorado 80525 U.S.A.

The System 45C User's Firmware Interface

by Robert A. Jewett and Robert W. Fredrickson

THE FIRMWARE ENHANCEMENTS in the System 45C are designed to give the user an easy interface to the new capabilities provided by the color display. These enhancements are primarily made to the existing graphics language (a part of 9845 enhanced BASIC) and are given to the user in the form of extensions to that language. These extensions are grouped in two major areas: graphical input and color/area fill.

Graphical Input

On previous 9845 Computers, input and output devices are treated the same. That is, one can digitize from a plotter or plot to a digitizer. In the System 45C the input and output functions are separated. Although users can still digitize from a plotter or plot to a digitizer, they must explicitly declare these devices to be input or output. Expanding on the form of the earlier output declaration (PLOTTER IS "<identifier>") the System 45C has added a similar input declarative (parameters enclosed by [] are optional):

```
GRAPHICS INPUT IS [select code[bus address],]<identifier>"
```

The current input identifier strings can be LIGHT PEN, ARROW KEYS, DIGITIZER or HPGL. For example:

```
GRAPHICS INPUT IS "LIGHT PEN"
```

Thus, when graphical input is required by the system (e.g., read the cursor position (CURSOR X,Y)) the coordinate data is retrieved from the current active input device. Both output devices and graphic input devices can be made active or inactive:

```
GRAPHICS INPUT <select code> IS ON  
GRAPHICS INPUT <select code> IS OFF
```

Although most of the graphics statements are dedicated to output devices or input devices, several of the statements can be applied to both types of devices. In these cases the same statement is retained for the newly defined input/output device. For example, the SCALE statement defines the user units for a device and can be logically applied to either an input or output device. Therefore, the SCALE statement applies to all active devices, be they input or output. This sharing of statements provides the user with a non-confusing limited set of graphical statements. In the case of statements intended solely for input or output, only the device type to which the statement applies is used. For example, when DRAW X,Y is executed, only current active output devices are sent the X-Y coordinate data to draw a line. Any active input device is not sent the data.

In addition to the input statements of earlier 9845 Computers, the System 45C adds a few new input statements to provide the user with added flexibility and increased capability. The first of these is the ability to couple an output

device to an input device and follow the movement of the input device's cursor by observing the resulting movement of an output device's marker. This capability is termed tracking and is invoked by the statement:

```
TRACK <output select code> IS ON
```

Once this statement is executed, the system, at the end of each executed BASIC program line, reads the location of the input device's cursor (CURSOR X,Y) and places the output device's marker at the same location (POINTER X,Y). This tracking link is valid although the two devices may have different SCALE factors. This gives the user full flexibility to expand, shrink or invert the input device's cursor movements as they are tracked by an output device.

This tracking occurs as long as the BASIC program is executing or until tracking is turned off:

```
TRACK <output select code> IS OFF
```

This link of an input device to an output device has several uses. One of the most common is that of menu selection from a digitizer. The menu can be displayed on the graphics CRT and the input device (say a 9874A Digitizer) linked to this graphics output device by the TRACK statement. When the user moves the digitizer's cursor (the 9874A's puck), immediate visual feedback is provided by the position of the marker on the CRT. Thus, the user can quickly locate a position on the digitizer's platen.

Another new feature of the System 45C graphics system is the ability to interrupt normal program flow from an input device. Most input devices have some sort of button that can be used to provide an interrupt similar to that provided by the special function keys located on the system's keyboard (ON KEY# GOTO ... etc.). The graphics input device's buttons are linked into this system by the statements:

```
ON GKEY GOTO <program element>  
ON GKEY GOSUB <program element>  
ON GKEY CALL <program element>  
OFF GKEY
```

As with the ON KEY# statement, a priority can be included in the ON GKEY statement to provide a priority interrupt scheme. Thus, the user has full interactive capability from an input device. For example, the simple program below allows the user to digitize points with the light pen and immediately draw the corresponding vector from the previous digitized point:

```
10 GRAPHICS INPUT IS  
    "LIGHT PEN" ! Define input device  
20 POINTER 50,50 ! Light pen cursor on screen  
30 PLOTTER IS "GRAPHICS" ! Define output device  
40 ON GKEY GOSUB      ! Enable interrupts  
    Get_point
```

```

50 GOTO 50          ! Wait for interrupts
60 !
70 Get__Point: DIGITIZE X,Y ! Read digitized point
80      DRAW X,Y ! Draw to digitized point
90      RETURN ! Return to wait loop

```

Note that the DIGITIZE statement in line 70 will not cause the program to pause since a point has already been digitized by pressing the light pen button to activate the ON GKEY branch. A much more exotic program can be envisioned that allows both MOVE and DRAW operations or places the coordinate data into a data base or allows additional menu selections.

Output device and input device statements are not device dependent. Thus, once a program is written and running properly, the user may change the input device by simply changing the GRAPHICS INPUT IS declarative. For example, in the program above, line 10 can be changed to GRAPHICS INPUT IS "DIGITIZER" and, when the program is run again, all the X-Y coordinate data will be read from the 9874A digitizer. This unified graphics language provides easy transportability from one system configuration to another.

Color/Area Fill

Color is specified on the System 45C by using one of two geometric color models. These models give users an easy way to visualize color space and specify a color within that space. The standard CIE (Commission Internationale de l'Eclairage) specifications could have been used, with the user providing three tristimulus values for the desired color. However, the visible color range is device dependent (actually CRT phosphor dependent), and the CIE coordinates are not as easy to remember or visualize as those from the geometric models. A numeric specification (as opposed to a word specification such as "red") is used to provide a mapping from a geometric model to the capabilities of the display.

On the System 45C the user may declare an area-fill color from either of the two models. The two models provide an equal number (4913*) of colors and it is merely a user convenience to have the option of picking a color from the model that the user understands better or best fits the user's application. Once a color is selected, the firmware generates the proper pixel patterns for the display, relieving the user of this task. Since the parameters are specified by numeric values, the user can easily make small adjustments to a chosen color until the desired result is attained.

One of the models is the color cube, which has as its three axes the three primary additive colors: red, green and blue (see Fig. 1). The user specifies a color in this model by providing a point in cubic space, which gives a red, green and blue intensity on an increasing intensity scale from

* The number of possible colors for lines, characters, and area fill is determined by the geometric design of the pixel—a single picture element. Each pixel is composed of three phosphor dots—red, blue, and green—arranged in a triangular pattern. Eight basic colors—red, blue, green, magenta, cyan, yellow, white and black—are possible for each pixel, depending on which phosphor dots are turned on or off. Because lines and characters are composed of arrangements of single pixels, lines and text can only be shown in these eight basic colors.

The colors for area fill are the result of arranging the pixels in 4×4 arrays. The intensity of each phosphor color is determined by how many of the 16 dots in the array are turned on. Hence, there are 17 discrete area-fill intensity values for each phosphor color—the seventeenth is when all dots are turned off. Thus, the total number of color area-fill combinations is 17 cubed = 4913. See Fig. 9 on page 31 for an illustration of this pixel array pattern.

zero through one. The BASIC statement thus has three parameters:

AREA INTENSITY <red value>, <green value>, <blue value>

For example:

AREA INTENSITY .75, .75, 0

specifies a yellow (red plus green) of three-fourths intensity. The eight basic colors are specified as follows:

White	....	AREA INTENSITY 1,1,1
Red	....	AREA INTENSITY 1,0,0
Yellow	....	AREA INTENSITY 1,1,0
Green	....	AREA INTENSITY 0,1,0
Cyan	....	AREA INTENSITY 0,1,1
Blue	....	AREA INTENSITY 0,0,1
Magenta	....	AREA INTENSITY 1,0,1
Black	....	AREA INTENSITY 0,0,0

The other method of color declaration uses the color cylinder model, which allows the user to declare colors by specifying the three HSL parameters: hue, saturation and luminosity (see Fig. 2). Hue is the angular measurement (the primary colors are red=0, green=1/3 and blue=2/3), saturation is the radial measurement, which specifies the extent to which the hue appears to be mixed with white, and luminosity is the height measurement, which specifies the intensity per unit area. The three parameters range from zero through one and specify a point in cylindrical three-space. The BASIC statement has three parameters:

AREA COLOR <hue>, <saturation>, <luminosity>

For example:

AREA COLOR 1/3,1,.75

specifies a green (hue = 1/3) that is fully saturated (1 = no white) with three-fourths luminosity. The eight basic colors in this model are specified as follows (X implies the value does not matter):

White	....	AREA COLOR X,0,1
Red	....	AREA COLOR 0,1,1
Yellow	....	AREA COLOR 1/6,1,1
Green	....	AREA COLOR 2/6,1,1
Cyan	....	AREA COLOR 3/6,1,1
Blue	....	AREA COLOR 4/6,1,1
Magenta	....	AREA COLOR 5/6,1,1
Black	....	AREA COLOR X,X,0

Several factors were involved in the selection of these two color models. The color cube was selected on the basis of its one-to-one mapping with the display hardware and the existing base of users who are familiar with this model. The HSL cylinder model was selected over other HSL models because the three cylindrical parameters are independent (allowing the full 0 to 1 range regardless of positioning on the model), cylindrical coordinates are easy for the novice

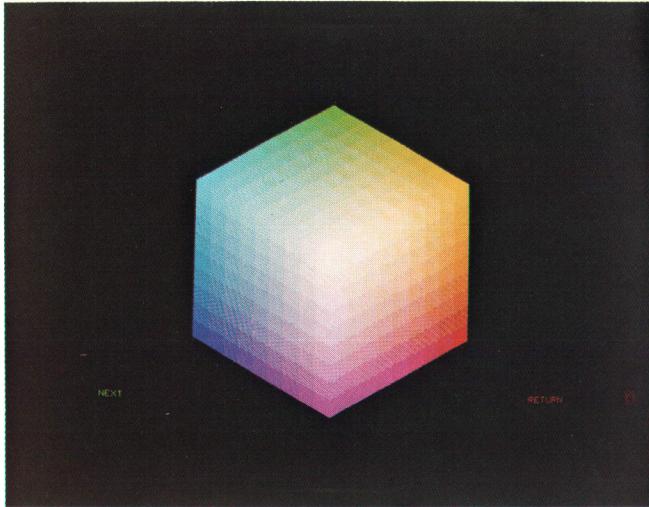


Fig. 1. Color cube model. Area-fill colors can be specified by selecting a point within this unit cube. The three coordinates for the point indicate the fractions of red, blue, and green required for the specified color.

user to visualize and the model contains no discontinuities (this allows straight-line interpolation of shading values).

Once a color is selected there are several means by which the user may fill or color an area. The syntax for this requires the addition of the declarative FILL to the end of the new polygon drawing statements.

Rectangles can be drawn by specifying in current user



Fig. 2. Color cylinder model. Area-fill colors can be specified by selecting a point within this unit cylinder. The angle indicates the combination of red, blue, and green required, the radius specifies the amount of white, and the height corresponds to the luminosity.

units the widths and heights from the current pen position. These rectangles can be rotated by an arbitrary angle specified by a separate statement (PDIR, for plot direction angle). These rectangles can be filled with the color specified by the last AREA INTENSITY or AREA COLOR statement. For example:

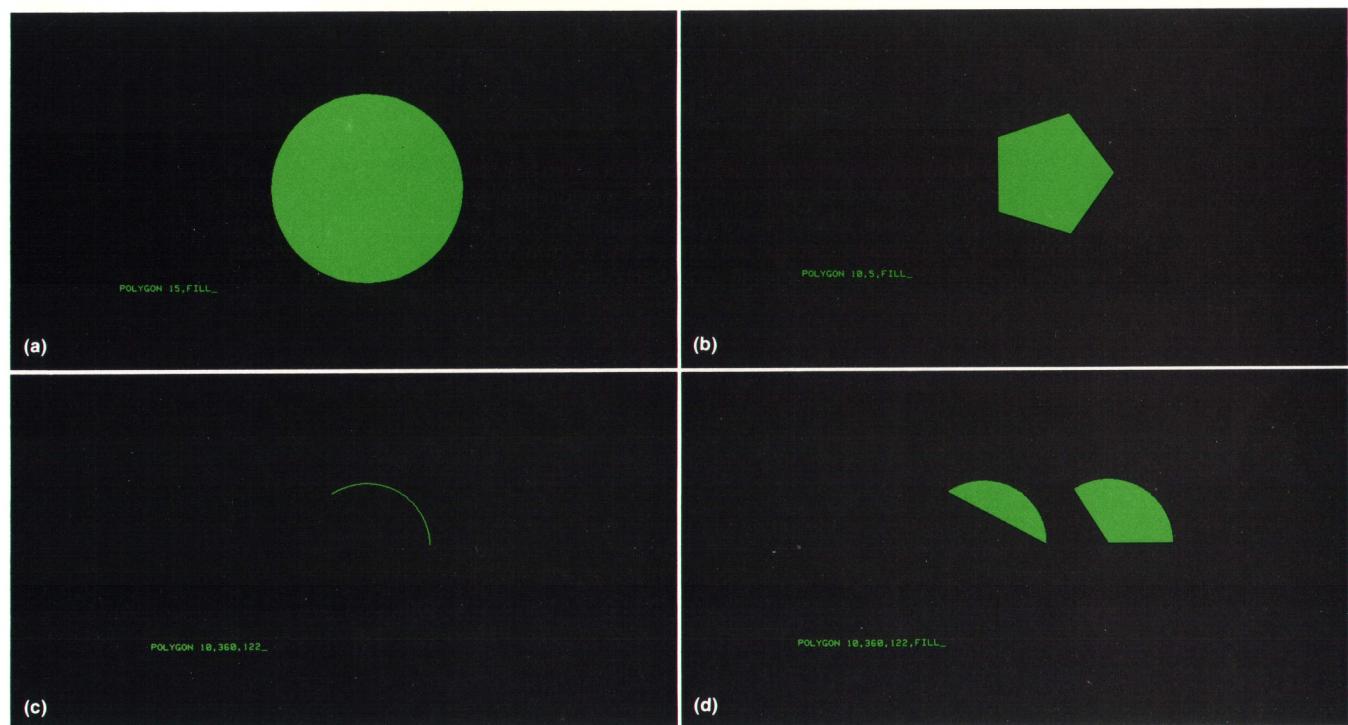


Fig. 3. (a) Circle drawn and filled by the POLYGON 15, FILL statement using the default value of 60 sides for the polygon. (b) Pentagon drawn and filled by the POLYGON 10, 5, FILL statement. (c) Arc drawn by the POLYGON 10, 360, 122 statement. (d) When the FILL declarative is added to the statement in (c), the shapes shown are obtained for the two cases where the pen is up or down prior to execution. The area-fill algorithm connects the first and last points of a line to fill in an area.

RECTANGLE 10,20,FILL

fills a 10 by 20 rectangle with the current specified color.

Regular polygons (equal-length sides) can be similarly drawn and filled. For example:

POLYGON 15,FILL

fills a circle (60-sided polygon) with a radius 15 user units from the current pen position (Fig. 3a). The number of sides of the polygon can be changed from the default value of sixty. For example:

POLYGON 10,5,FILL

fills a five-sided polygon where each vertex of the polygon is 10 user units from the current pen position (Fig. 3b).

Further, a portion of the number of sides of the polygon can be specified. For example:

POLYGON 10,360,122

draws a 122-degree arc (122 sides of a 360-sided polygon (Fig. 3c)). This arc can be filled (Fig. 3d) by adding FILL to the end of the statement. Note that two different fill results are possible depending on the state of the pen (up or down) before executing the statement. The position of the first vertex of the polygon can be rotated through any angle by specifying a plot direction angle (PDIR).

Irregular polygons are specified by placing the coordinates of the vertices in an array and using the matrix plotting facilities of the System 45C. This data is organized in the array by columns, with the first column containing the X coordinates and the second column the Y coordinates. An optional third column contains pen control information. Again, the polygon can be filled by adding the FILL parameter to the end of the statements. For example:

MAT PLOT A,FILL

fills the polygon described by the coordinate vertices stored in the array A. Incrementally defined polygons can be drawn or filled by the MAT IPLOT and MAT RPLOT statements, which use the 9845 definitions of IPLOT (the origin point (0,0) moves with the current pen position) and RPLOT (the origin point (0,0) is fixed at the initial pen position when RPLOTING starts).

The filling algorithm is a simple left-to-right scan algorithm. The algorithm numbers the intersections of the

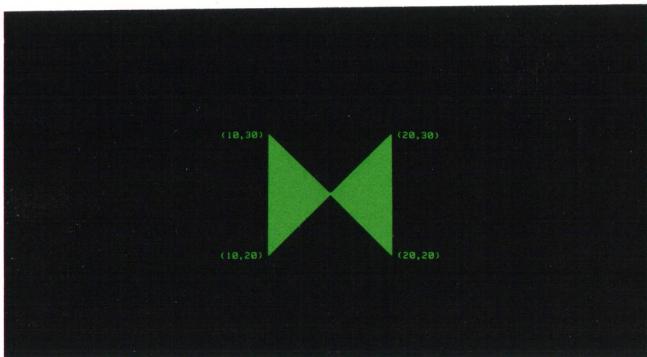


Fig. 4. This "bowtie" shape is obtained after execution of MAT PLOT B, FILL where the values in array B are as shown.

polygon's vectors with each raster scan line in ascending order (left to right) and then fills from each odd-numbered intersection on the scan line to the following even-numbered one. The process then moves to the next scan line and repeats the intersection calculation. This provides an easy and quick means of filling areas. For example, if the two column array B is dimensioned to have four rows and the values stored in B are:

10	20
10	30
20	20
20	30

then the statement MAT PLOT B,FILL would fill inside the "bow tie" defined by these coordinates, as shown in Fig. 4. Note that, in filling, the firmware automatically connects the last coordinate to the first, thus generating a closed polygon.

Acknowledgments

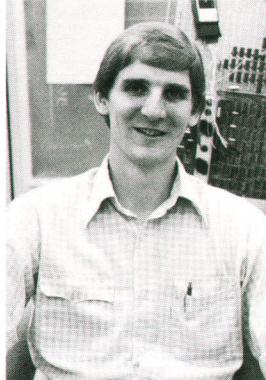
The authors would like to thank all of the people who contributed to the quality assurance effort for the firmware ROM, especially Ken Lewis, Ron Tolley, Xuan Bui, Alan Ward and Dave Hodge.

Robert A. Jewett



Bob Jewett earned a BS degree in physics and mathematics from the University of Puget Sound, Washington, in 1967. After serving in the U.S. Army from 1969 to 1971 he returned to his studies and was awarded an MS degree in computer science by Purdue University, Indiana, in 1972. With HP since 1973, Bob has worked on applications programming for the 9830 Calculator and on firmware and graphics ROMs for the 9845A, 9845B, and 9845C Computers, and is currently involved with future graphics products. He is a coinventor on one patent for the 9845A, and is a member of the Special Interest Group on Graphics of the Association for Computing Machinery (SIGGRAPH-ACM). Bob is a native of Tacoma, Washington. He is married, lives in Loveland, Colorado, and coaches fifth and sixth grade football. His outside interests include golf, volleyball, basketball, and fly fishing.

Robert W. Fredrickson



Bob Fredrickson is a native of Salt Lake City, Utah, and came to HP after receiving the BSEE degree from the University of Utah in 1978. He developed graphics input and light pen support firmware for the System 45C and now is doing R&D on graphics displays. Bob is married, has one son, and lives in Fort Collins, Colorado. He enjoys softball, basketball, hunting and camping.

Light Pen Aids User Interaction with Display

Here's how a light pen works with a raster-scan display.

by Frederick J. Porter

AN IMPORTANT PART of any graphics system such as the Hewlett-Packard System 45C is the interaction that the operator has with the machine. This interaction is accomplished by use of graphics input devices, graphics output devices (displays and plotters), and computational algorithms. Many different devices are used on currently available graphics systems.¹ Some devices supplied by HP include the keyboard on the machine, arrow keys on the keyboard, the 9872A Plotter, the 9874A Digitizer, and the 9111A Graphics Tablet. In addition to these, the System 45C provides softkeys and a light pen. All of these graphics input devices enable an operator to interact in varying degrees with the system.

Much of this article deals with the problem of using a light pen on a raster-scan CRT. These problems are notable because they have been publicized in the technical press and learning institutions as making impractical the use of a light pen with a raster-scan system.

Interactive Graphics

Primary interactive functions that need to be implemented on a graphics system are those for picking and positioning items on the display area.

The pick function is the act of identifying a symbol among several choices. Picking a symbol may start the computer performing a task or it may set the conditions for some future task. The overlay on the user-definable keys can be thought of as a list of symbols from which to pick. On graphics systems, the list of symbols is often displayed on

the screen. This is done for two reasons. One is to allow the list to be dynamically changed depending on the program segment being executed. The other is to allow the operator to concentrate on the display without having to switch attention to some other device. This capability is possible when using the softkeys and/or the light pen. The softkeys are located on the display case directly below the CRT; this allows a label to be displayed on the CRT near its corresponding key. The light pen can pick from any area on the screen that has an image displayed. This allows greater format flexibility for the displayed symbol table. The X-Y coordinates returned to the system by the light pen determine the item picked.

The positioning function is the act of specifying a point in the display area. Once a point has been specified, an operation relative to that point can be performed, or that point can be stored for some future operation. An example is the drawing of a line between two points. First one point is specified and stored. When the second point is specified, a line is drawn from the first point to the second. Since it is sometimes desirable to make changes during the interactive development of an image, these operations are usually performed on a CRT. Thus, the CRT is normally used as the display device although some other devices could be the display for a particular application.

One application where both picking and positioning can be used is a geometric drawing program. The format of this example is shown in Fig. 1. The first operator interaction with the computer is picking the green block on the left side of the display by pointing the light pen at the green block and pressing the button on the pen. This indicates to the computer that future operations will be done in the color green. In a similar manner the operator picks the word CIRCLE from the list on the display. This indicates that the input data is to be used to draw a circle. The operator then indicates the position of the center of the circle by positioning the light-pen tracking cursor at the desired location. The button on the pen is pressed to allow the machine to capture the data for that point. The radius is then defined by positioning the cursor at any point on the circumference of the circle to be drawn. The machine responds by drawing a green circle of the desired radius at the specified position (Fig. 1). Other graphics input devices can perform these fundamental operations. The selection of a particular graphics input device depends on the specific application and operator preference. For example, the light pen allows the operator to manipulate images on the CRT—a high degree of man/machine interaction. The operator simply points the pen at appropriate locations on the face of the CRT to achieve the desired result. This direct interaction with the CRT is the light pen's fundamental advantage over other input devices.

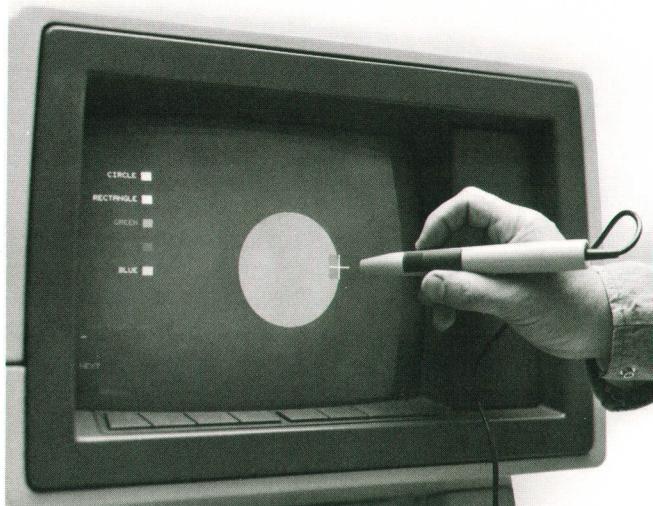


Fig. 1. The System 45C light pen can be used to pick displayed objects or menu items and to place objects or indicate dimensions.

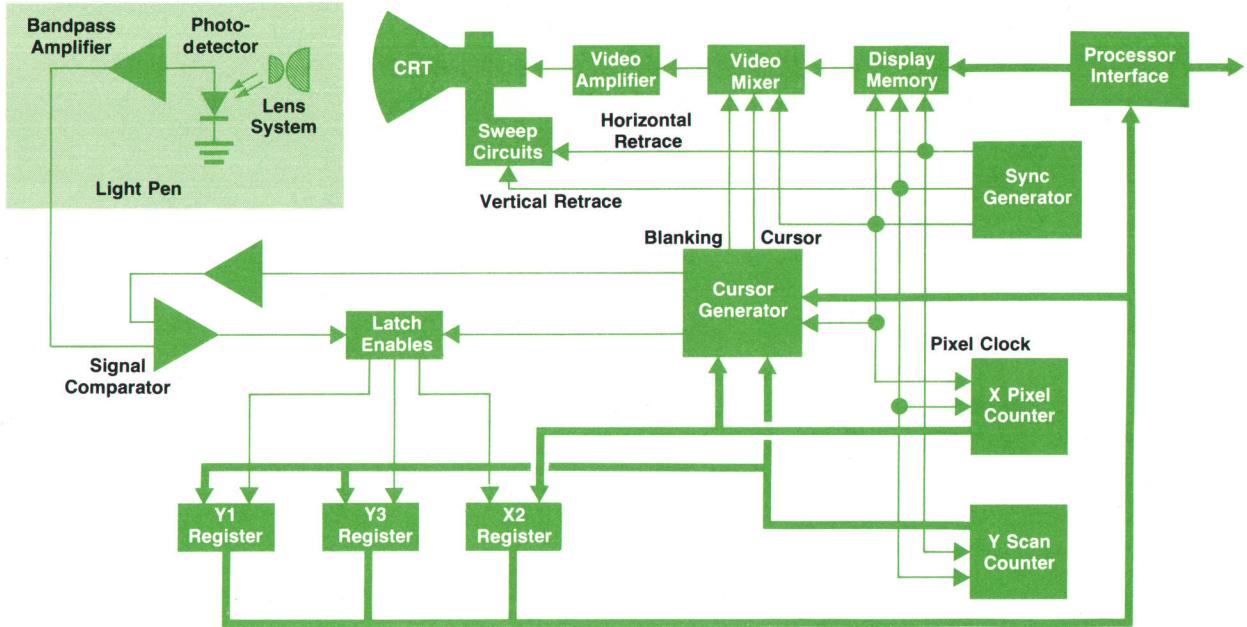


Fig. 2. Block diagram of light pen system in the 9845C Computer.

Light Pen Architecture

The system for the light pen used on the 9845C CRT display is shown in Fig. 2. The light pen consists of a system of lenses, a high-speed PIN photodiode, a video amplifier, a comparator to detect the peak amplitude of the light emitted by a phosphor within the pen's optical field of view, and digital circuitry to latch the X and Y scan addresses when detections are made. As an example of a field of view for an optical system, consider a lens system that is located about one-half inch away from a CRT. The PIN photodiode can detect light on the CRT in a nearly circular area centrally located with respect to the optical axis of the lens system. This is called the optical field of view. If a vertical line is displayed on the CRT, the detected peak amplitude of the light emitted from the phosphors along that line will have an attenuation pattern due to the optical system. This is shown in Fig. 3a. The envelope of the attenuation pattern takes the form of a raised sinusoid (i.e., $K(1+\cos(\omega R))$) for $-\pi \leq \omega R \leq \pi$. The attenuation pattern will vary with many factors, such as the distance to the screen and the type of phosphor. The comparator threshold is set so that those pixels emitting light above the threshold will create a detection signal while those whose emitted light does not exceed the threshold are not detected. For this case the area in which pixels are detected is called the single-dot field of view—a subset of the optical field of view.

If the line displayed on the CRT is horizontal, there is a different effect. On the System 45C, the decay time for the blue and green phosphors is 8.7 μs . For the red phosphor the decay time is 870 μs . Thus, for a horizontal line there is an additive effect caused by the long decay times of the phosphors. As each pixel becomes illuminated, the energy detected by the PIN photodiode is added to the detected energy from previous pixels. This is shown in Fig. 3b. The same effect does not occur in the single-dot field of view because the detected pixels are separated in time by the length of a scan line. This period of time (34.4 μs) allows the

phosphor's energy to decay sufficiently before the detection of the next pixel in a vertical line.

Therefore, for the case of a horizontal line the comparator sees a signal due to the collective energy of the pixels because the energy emitted from each pixel has not decayed sufficiently before the next pixel is detected. The region where the total energy detected exceeds the threshold is called the horizontal-line field of view. The signals created by the horizontal lines are much greater than those created by single pixels. As a reference point, threshold level A in Fig. 3b is equivalent to the threshold level in Fig. 3a. The other threshold levels shown in Fig. 3b illustrate the effect on the horizontal-line field of view as the threshold is increased. The edge of the horizontal-line field of view remains circular as the threshold changes. In fact, there is a threshold level for the horizontal-line field of view that will create an edge having the same radius as the boundaries of the single-dot field of view at a lower threshold level. As shown in Fig. 4, the fields of view are offset from one another by an amount that remains nearly constant because of the sinusoidal nature of the optical field of view.

One of the properties of the light pen with respect to the human eye should be noted. The light pen detects the peak energy emitted by the phosphor. The human eye detects the total energy emitted by the phosphor. That being the case, the red phosphor's peak energy is about 1/100 of that of the blue and green phosphors because the red phosphor has a much longer decay time and need not have as great a peak to present the same amount of total energy to the eye. This makes it more difficult for the light pen to detect red. In fact, it takes about five consecutive red pixels for the light pen to detect a red image where it only takes one pixel to detect green or blue. Turning on multiple phosphors at a pixel location gives that pixel the desirable attributes, for light-pen detection, of the faster phosphors.

The occurrence of the detection signal is correlated in time with the current position of the beam sweeping the

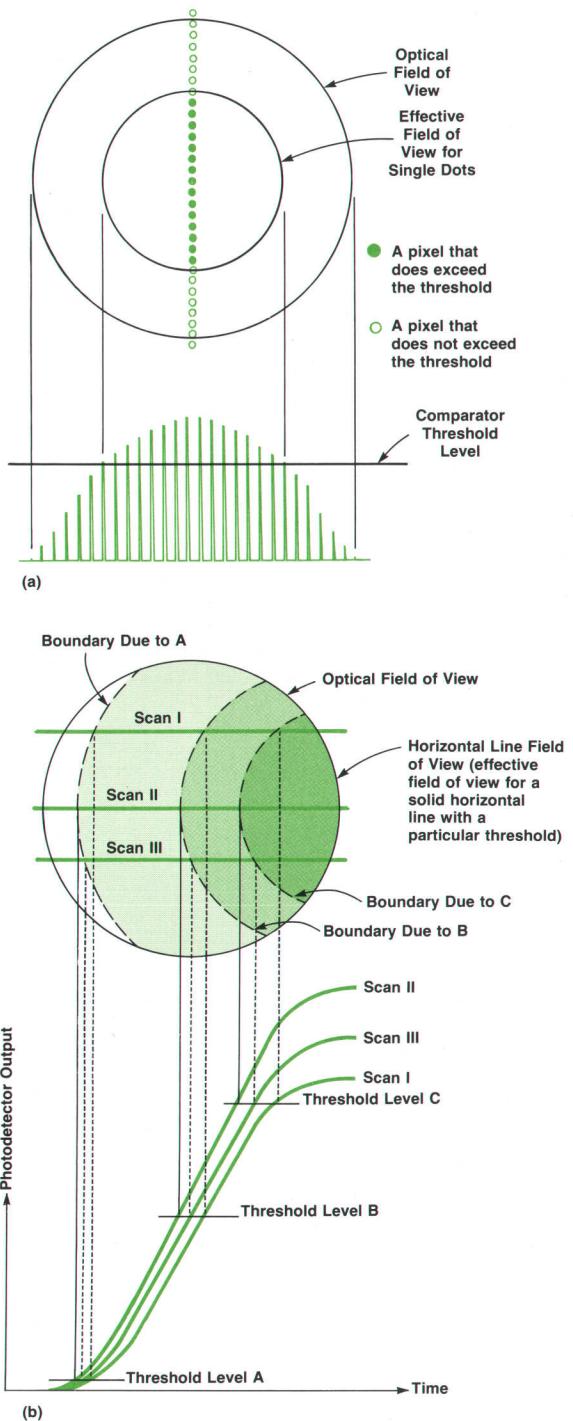


Fig. 3. (a) Single-dot field of view. Because each pixel in a vertical line is separated in time by the period between adjacent scan lines, distinct signal peaks are detected for each pixel in the effective field of view. (b) Horizontal-line field of view. Here the light emitted by each pixel in a horizontal line is added to the light from other pixels in the field of view determined by the threshold level. As the threshold is increased from Level A to Level B and to Level C, the effective field of view diminishes as shown. The center of the horizontal-line field of view is offset to the right because of the light summation required to exceed the higher threshold level.

display. On a vector-scanning display this can be directly related to the event of a particular vector being written on the display. On a raster-scan display the relationship is to an X-Y position on the display. Locating a particular vector on the screen requires finding the vector in the display data base that passes through the X-Y position.

Since the position of the pen is determined by correlating the peak detected amplitude with the current electron beam position, it can be seen that the single-dot field of view is centered on the pen's optical axis. However, the horizontal-line field of view is located to the right of the optical axis because the pixels in view of the pen are still emitting energy although the position of the electron beam has moved out of the field of view to the right.

Other problems deal with the speeds at which data is displayed, optical variations such as intensity and physical position, and the PIN photodiode response time. On the System 45C the pixel display rate is 30 MHz. Because it takes 200 ns for the light pen to respond with a detect signal, six pixels are displayed after the illumination of the pixel causing the detection. This presents no difficulty in detecting the vertical position because the time between adjacent scan lines is much longer. However, if not corrected, this delay causes an error of six pixels in determining a horizontal position. This is one of the reasons that the use of light pens on raster-scan systems was restricted to only pick modes or coarse positioning. The System 45C has overcome this restriction, thus providing the ability to track a cursor on a raster-scan CRT and to specify positions to the resolution and accuracy of a single pixel on the screen.

Tracking Cursor

A tracking cursor is used to achieve single pixel resolution and accuracy on the System 45C. In other words, the operator actually points with a cursor, using the light pen to move the cursor on the screen.

The tracking cursor is implemented for several reasons. The glass faceplate of the CRT is about one-half inch thick, creating a parallax problem between the light pen, the phosphor and the operator. For this and other reasons discussed earlier, it is impossible to indicate a single pixel precisely with only the light pen. The center of the tracking cursor becomes, by definition, the pixel at which the light pen is pointing. A predictive tracking algorithm is used to have the cursor track the movement of the light pen by an operator's hand. The predictive algorithm requires that an accurate estimation of the center of the field of view be made. This is the single largest problem with a tracking cursor on a raster-scan CRT. The field of view is determined by the optical path from the phosphor to the PIN photodiode and the intensity of the light impinging upon the diode from individual pixels. The cursor is used to determine the limits of the field of view. On a vector-scan CRT, the light pen can wait until the cursor vectors are displayed. With some ingenuity in the method by which the cursor is displayed, the top, bottom, left, and right sides of the field of view can be determined. From that, it is a simple task to determine the center of the field of view on a vector-scan CRT. Although the field of view is always dependent on the intensity of individual pixels and the operator's habits, other factors make the estimation of the center of the field of view on the raster-scan CRT even more difficult.

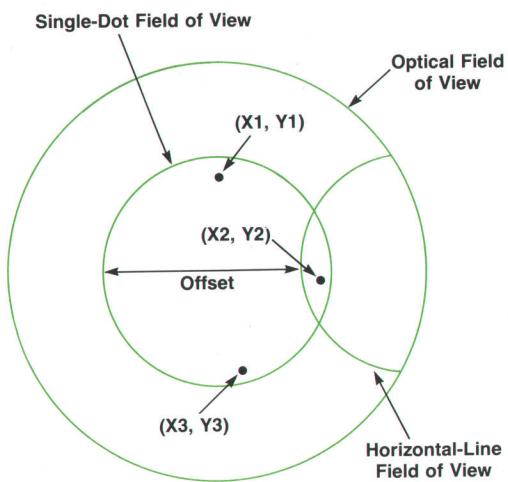


Fig. 4. Relationship between the shapes and locations of the single-dot and horizontal-line fields of view. The horizontal offset is caused by the higher threshold level for a horizontal line as shown in Fig. 3b and by the detection circuit delays.

On a raster-scan CRT, graphical data, cursor and picture, are displayed in sequence as the scan progresses across the screen. This means that some of the pixels making up a picture may be displayed closely in time and space to those pixels that make up the tracking cursor. When the light pen is pointed at the CRT, the PIN photodiode senses the first illuminated pixel on a scan line within the field of view and a detection is registered. Since the light energy of the phosphor decays slowly, any other pixels that occur in the field of view on that scan line add to the energy from the first pixel. Using an ac-coupled video amplifier and a slicing threshold scheme the light pen detects only one pixel per scan line. This effectively masks out the detection of the cursor if picture pixels have occurred in the field of view on the same scan line before the display of the cursor pixels.

Center Estimation

For purposes of explanation, assume that all pixels except cursor pixels are not illuminated. The upper and lower boundaries of the field of view can easily be determined. However, because there is only one detection per scan line, only the left boundary can be determined (the scanning on the System 45C is from left to right and top to bottom). With three points defining a circle, a set of equations is used to derive the center of the field of view. A first approximation can assume that the field of view is circular. In this case the following equations apply:

$$Y_{\text{center}} = \frac{Y_1 + Y_3}{2}$$

$$X_{\text{center}} = \frac{(Y_1 - Y_{\text{center}})^2 - (Y_2 - Y_{\text{center}})^2 + X_1^2 - X_2^2}{2(X_1 - X_2)}$$

where (X_1, Y_1) and (X_3, Y_3) are the endpoints of a vertical chord through the field of view, (X_2, Y_2) is another point on the left perimeter of the field of view and $(X_{\text{center}}, Y_{\text{center}})$ is the center of the field of view. Consider the geometry of a cursor in the field of view. The cursor is made up of two

orthogonal lines, one horizontal and one vertical. Each line is 49 pixels long (greater than the diameter of the field of view) and crosses the other line at its midpoint. Since the firmware algorithm positions it, the cursor's X-Y center coordinates are known. If these coordinates are used to make the center estimation, X_1 , X_3 , and Y_2 are already known. All that remains to be determined are X_2 , Y_1 , and Y_3 . If the cursor can be separated from other displayed information, the data for Y_1 and Y_3 can be very accurate.

The data for X_2 remains a major problem. The signal producing X_2 will be a horizontal line, creating a large amplitude, long duration signal from the PIN photodiode. If the threshold of the comparator in the light pen is increased during the display of the horizontal component of the cursor, the signal-to-noise ratio will also increase and a more predictable X_2 detection will occur. An offset constant is added to allow X_2 to represent a position on the edge of the single-dot field of view.

Interleaving

This leaves the problem of collecting Y_1 and Y_3 and being sure that the data originates only from the cursor. Part of this problem is caused by the differences in the horizontal-line and single-dot fields of view. Detections from the vertical line of the cursor are governed by the single-dot field of view. However, picture data creating horizontal lines may occur outside and to the left of the single-dot field of view. This causes corruption of the Y_1 and Y_3 data. This must somehow be masked out. One method is to blank out all of the data in the vicinity of the cursor, but this makes it difficult for the operator to line up the cursor on some image already on the screen. The alternative used on the System 45C is interleaving. As shown in Fig. 5, every other scan line in the vicinity of the cursor is blanked, while on the next frame the alternate scan lines are blanked. This has the effect of dimming the background data near the cursor but still allowing the operator to see all of the displayed data at a 30-Hz rate.* The cursor is not interleaved but is displayed continuously without blanking of any of its elements. In tracking mode, the digital circuitry accepts detections only on the blanked scan lines to assure that the data is a result of detecting cursor pixels.

Three values are transmitted to the system mainframe during each frame to allow the firmware to position the cursor for the next frame. These three points are Y_1 , X_2 , and Y_3 . The conditions by which these are gathered are as follows:

Latch Y_1 if: a) the detection is the first detection of the frame or

b) the detection is the first detection to occur on a scan line blanked by interleaving.

Latch X_2 if: a) the detection is the first detection of the frame or

b) the detection occurs on the horizontal line of the cursor.

*Another effect on visual perception is caused by the fact that light emitted from each pixel decays in each frame. The human eye does not detect flicker of a light source until the rate is less than approximately 54 Hz and then only over large areas in the peripheral view. In fact, in small areas of less than four square centimeters, flicker is hardly detectable at a 30-Hz rate.

- Latch Y3 if:
- there has been no detection on a blanked scan line or
 - there has been a detection on a blanked scan line and the current detection is from a blanked scan line.

There are two conditions for latching the data in each register. The first condition (a) exists because it is not known a priori that the pen is near enough to the cursor to detect any pixels forming it. This is a mode that is useful in picking, where the cursor is not necessarily being displayed and there is a window of 10 to 20 pixels to specify an operation. If there is data from the cursor the second condition (b) is used for latching the data registers. Since the maximum data range (0-559) requires only 10 bits of the 16-bit word for each data point, some of the remaining bits are used to help the firmware determine the status of the information it is receiving. This information includes:

1. Whether the data is from a valid detection.
2. Whether the Y data is from detections on blanked scan lines.
3. Whether the X data is from a detection on the horizontal line of the cursor.
4. Whether the button on the light pen is pressed.

From this information, the firmware can quickly detect whether or not the cursor has been captured to allow tracking. If the cursor has not been captured, then an approximation of the pen's position is made and stored in a user accessible location.

Tracking Algorithm

However, if the cursor is close enough to track light pen movements (i.e., detectable by the light pen), the firmware

invokes a tracking algorithm. This algorithm is an adaptive, second-order predictive algorithm that allows smooth, precise motion of the cursor at slow speeds, while still keeping up with rapid changes in motion at faster speeds. Using the estimated center position of the light pen as determined above, three values are calculated. The first is an error value E which is the difference between the current pen center estimate (calculated in the previous frame) and the current position of the cursor. Second, a pen velocity value V is calculated from the difference between the current pen center estimate and the pen center estimate of the previous frame. The final calculation is a pen acceleration value A. This value is the difference between the pen velocity value of the current frame and the pen velocity value calculated in the previous frame. The location of the pen center for the next frame, and hence the desired cursor position (New_cursor), is predicted as follows:

$$\text{New_cursor} = K_1 \times E + K_2 \times V + K_3 \times A + \text{Old_cursor}$$

where Old_cursor is the present cursor position, K1 and K2 are functions of the current velocity and K3 is a function of the current acceleration and error. Provided that the predicted position is close enough to the actual new position of the light pen, cursor detections will again be made on the next frame so the procedure can be repeated.

Acknowledgments

We would like to thank the various service groups in HP's northern Colorado divisions for their support and the following individuals for their contributions. Kevin Allen was responsible for the mechanical system for the light pen. Chuck Bain was responsible for the industrial design on the

(continued on page 19)

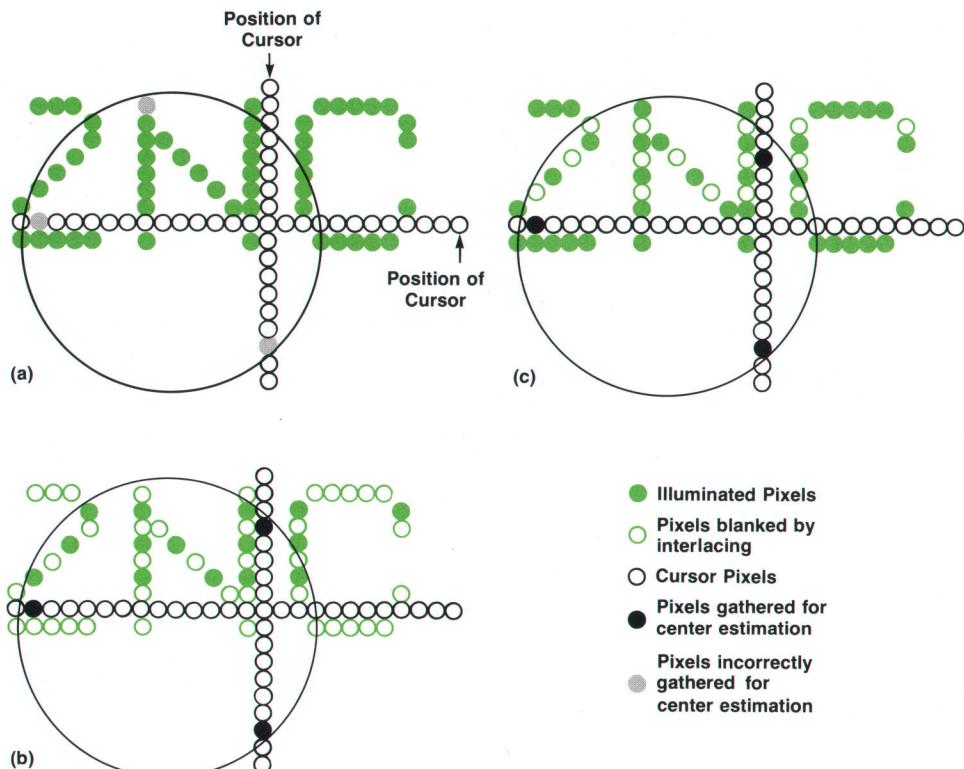


Fig. 5. (a) Displayed data in field of view obscuring cursor and causing incorrect center estimation. In the System 45C, the scan lines in the tracking cursor area are alternately blanked except for cursor pixels and detections are considered valid only when made on a blanked line as indicated in (b) where the odd-numbered lines are blanked, followed by (c) where the even-numbered lines are blanked. Thus, the display area in the vicinity of the cursor is switched (interlaced) between conditions (b) and (c) for accurate center estimation.

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Jan. 1980	Communications system measurements	3779A/B	
Oct. 1980	Compiler, Pascal	64000	
July 1980	Computer, personal	HP-85	
Apr. 1980	Converter, frequency, 40 GHz	5355A	
Sept. 1980	Coordinate measurements, large-scale, non-contact	9845T, 3820A	
Apr. 1980	Counter, microwave, 26.5 GHz	5343A	
Apr. 1980	Counter system, 40 GHz	5345A/55A/56A	
Apr. 1980	Counter, universal	5345A	
Aug. 1980	CPU design	HP-85	
Dec. 1980	Cursor, tracking	9845C	
Apr. 1980	CW frequency measurements	5355A, 5345A	
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Sept. 1980	Deflection measurement	9845T, 3820A	
July 1980	Delta-distance code, tape storage	HP-85	
May 1980	Demultiplexing buses	1610B, 1611A	
Oct. 1980	Development system, logic	64000	
Feb. 1980	Diffraction gratings, holographic		
July 1980	Digital servo design	HP-85	
Oct. 1980	Directed-syntax softkeys	64000	
June 1980	Disc management software		
Sept. 1980	Distance correction, air temperature and pressure	3820A	
June 1980	Distance measurement, electronic	3850A	
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Nov. 1980	ECG monitoring	78501A, 78502A	
Nov. 1980	Echoplex	78501A, 78502A	
Oct. 1980	Electronic bench		
June 1980	Electronic distance meter	3850A	
Sept. 1980	Electronic total station	3820A	
Nov. 1980	Emulator, IBM 3270	32229A	
Oct. 1980	Emulators, microprocessor	64000	
Jan. 1980	End-to-end measurements	3779A/B	
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May 1980	FDM system testing	3586A/B/C	
Nov. 1980	Fibrillation detector	78501A, 78502A	
Jan. 1980	Fixtures, impedance test	16091/2/3/4A	
Aug. 1980	Floating audio source	8903A	
Apr. 1980	Frequency measurements to 26.5 GHz	5343A	
Apr. 1980	Frequency measurements to 40 GHz	5355A	
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May 1980	Generator, level, synthesized	3336A/B/C	
Sept. 1980	Glossary, optical and mechanical terms	3820A	
Dec. 1980	Graphical peripheral control	9845C	
Dec. 1980	Graphics, color, CRT	9845C	
July 1980	Graphics, personal computer	HP-85	
Sept. 1980	Gravity sensing system	3820A	
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Apr. 1980	Harmonic heterodyne frequency converter, 40 GHz	5355A	
Apr. 1980	Heads, frequency converter	5356A/B/C	
Sept. 1980	Height-of-standards error	3820A	
July 1980	HP-IB interface, personal computer	82937A	
Sept. 1980	HP-IB interface, distance meter	38001A	
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Nov. 1980	IBM/HP 3000 interactive mainframe link (3270 emulator)	32229A	
Jan. 1980	Impedance analyzer, 1-1000 MHz	4191A	
June 1980	Industrial distance meter	3850A	
Nov. 1980	Inquiry and development facility (IDF)	32229A	
July 1980	Integer processing, fast	HP-85	
July 1980	Integrated circuit, buffer	HP-85	
Aug. 1980			
July 1980	Integrated circuit, CPU	HP-85	
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July 1980	Integrated circuit, CRT controller	HP-85	
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July 1980	Integrated circuit, keyboard controller	HP-85	
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July 1980	Integrated circuit, printer controller	HP-85	
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July 1980	Integrated circuit, RAM controller	HP-85	
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July 1980	Integrated circuit, read/write amplifier	HP-85	
Aug. 1980			
July 1980	Integrated circuit, ROM	HP-85	

Aug.	1980	Integrated circuit, ROM		HP-85	Aug.	1980	Polysilicon resistors	HP-85		
July	1980	Integrated circuit, tape controller			June	1980	Position control	3850A		
Aug.	1980				July	1980	Power supply, personal computer	HP-85		
July	1980	Integrated circuit, translator(TC)		82937A	July	1980	Preallocation, variable	HP-85		
Aug.	1980	Integration, numerical, by calculator		HP-34C	Apr.	1980	Prescaler, 0.4-1.6 GHz			
Nov.	1980	Intelligent network processor (INP)			Jan.	1980	Primary multiplex analyzer	3779A/B		
Nov.	1980	Interactive Mainframe Link/3000 (IML/3000)		32229A	Mar.	1980	Printed circuit hybrid technology	HP-41C		
Oct.	1980	Intermediate language	64000		Mar.	1980	Printer, thermal	82143A		
Sept.	1980	Interpolation, sinusoidal patterns	3820A		July	1980	Printhead, thermal	HP-85		
Nov.	1980	Intrinsics, IML/3000	32229A		Oct.	1980	PROM programmer	64500A		
July	1980	I/O interfaces, personal computer	82937A		Apr.	1980	Pulsed RF frequency measurements	5355A		
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Aug.	1980	Keyboard controller IC		HP-85	Nov.	1980	QRS-matched filter	78501A, 78502A		
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Oct.	1980	LALR parsing	64000		Aug.	1980	RAM cell, two-read/one-write	HP-85		
Sept.	1980	Lasing diode, GaAs	3820A		Aug.	1980	RAM controller IC	HP-85		
May	1980	Level generator	3336A/B/C		July	1980	Random number generation	HP-85		
Dec.	1980	Light pen, raster-scan CRT	9845C		Nov.	1980	Reconfiguration, automatic	78501A, 78502A		
Oct.	1980	Linker, table-driven	64000		Jan.	1980	Reflection coefficient measurements, 1-1000 MHz	4191A		
Mar.	1980	Liquid crystal display	HP-41C				Sept.	1980	Refractive index, air, group velocity	3820A
Oct.	1980	Logic development system	64000				Oct.	1980	Resource allocation	64000
May	1980	Logic state analyzer	1611A	Opt 001			Jan.	1980	RF impedance analyzer	4191A
May	1980	Logic state analyzer					Sept.	1980	Roelof's prism adaptor	11429A
Aug.	1980	LSI circuit design		HP-85						
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June	1980	Mass storage management software			Nov.	1980	SDLC	78501A, 78502A		
Dec.	1980	Memory design, color graphics display	9845C		May	1980	Selective level meter	3586A/B/C		
Mar.	1980	Memory modules	82106A		Nov.	1980	Self-test system, four-level	78501A, 78502A		
Apr.	1980	Microcode development technique			May	1980	Signal generator, synthesized	3336A/B/C		
Oct.	1980	Microprocessor development system	64000		Aug.	1980	Signal-to-noise measurements	8903A		
May	1980	Microprocessor testing	1610B, 1611A		Aug.	1980	SINAD measurements	8903A		
Apr.	1980	Microwave frequency measurements	5343A		Aug.	1980	Software development system	HP-85		
Apr.	1980	Microwave frequency measurements	5355A		June	1980	Software for mass storage management			
Mar.	1980	Microwave spectrum analyzer	8559A		Feb.	1980	Spectrophotometer, ultraviolet/visible	8450A		
Sept.	1980	Mirror mount	3820A		Mar.	1980	Spectrum analyzer 0.1 to 21 GHz	8559A		
June	1980	Moving target measurements	3850A		Aug.	1980	State-variable filters	8903A		
Sept.	1980	Multifunction sequence	3820A		June	1980	Static monitoring	3850A		
May	1980	Multiphase clocking	1610B, 1611A		Nov.	1980	Superaster	78510A		
Jan.	1980	Multiplex system analyzer	3779A/B		May	1980	Synthesizer/level generator	3336A/B/C		
Nov.	1980	Multi-processor architecture	78501A, 78502A							
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Aug.	1980	NMOS circuit design		HP-85	Sept.	1980	Telescope, catadioptric	3820A		
Aug.	1980	Notch filter, digitally tuned		8903A	Jan.	1980	Telephone system measurements	3779A/B		
Aug.	1980	Numerical integration by calculator		HP-34C	May	1980	Thermal converter, rms-to-dc			
		O			Dec.	1980	3-D graphics, dominant area shading	9845C		
Sept.	1980	Optical angle encoder	3820A		Sept.	1980	Tilt meter, gravity sensing	3820A		
Feb.	1980	Optical system, folded	8450A		Nov.	1980	Trends monitoring	78501A, 78502A		
Sept.	1980	Optical system, total station	3820A		Sept.	1980	Triangulation	9845T, 3820A		
Aug.	1980	Oscillator, audio	8903A							
July	1980	Output control, vectored	HP-85							
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Oct.	1980	Pascal compiler	64000		Aug.	1980	Two-read/one-write memory	HP-85		
Nov.	1980	Patient information center	78501A, 78502A		Feb.	1980	Ultraviolet/visible spectrophotometer	8450A		
Nov.	1980	Patient monitoring	78501A, 78502A				V			
Jan.	1980	PCM system analyzer	3779A/B		Dec.	1980	Vector generation	9845C		
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					May	1980	Wave analyzer	3586A/B/C		

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Model	Product	Month/Year	1611A Opt 001	Logic State Analyzer	May	1980
HP-34C	Calculator	Aug. 1980	3336A/B/C	Synthesizer/Level Generator	May	1980
HP-41C	Calculator System	Mar. 1980	3586A/B/C	Selective Level Meter	May	1980
HP-85	Personal Computer	July 1980	3779A/B	Primary Multiplex Analyzer	Jan.	1980
1610B	Logic State Analyzer	Aug. 1980	3820A	Total Station	Sept.	1980
		Aug. 1980	3822A	Coordinate Determination System (9845T, 3820A)	Sept.	1980

3850A	Industrial Distance Meter	June 1980	16094A	Probe Fixture	Jan. 1980
4191A	RF Impedance Analyzer	Jan. 1980	32229A	IML/3000	Nov. 1980
5316A	Universal Counter	Sept. 1980	38001A	HP-IB Distance Meter Interface	June 1980
5335A	Universal Counter	Sept. 1980			Sept. 1980
5343A	Microwave Frequency Counter	Apr. 1980	64000 64100A	Logic Development System	Oct. 1980
5345A	Electronic Counter	Apr. 1980	64300A	Development Station	Oct. 1980
5355A	Automatic Frequency Converter	Apr. 1980	64500A	Logic Analyzer	Oct. 1980
5356A/B/C	Frequency Converter Heads	Apr. 1980	78501A	PROM Programmer	Oct. 1980
8450A	UV/Vis Spectrophotometer	Feb. 1980	78502A	Patient Information Center	Nov. 1980
8559A	Spectrum Analyzer 0.1-21 GHz	Mar. 1980	78510A	Patient Information Center	Nov. 1980
8903A	Audio Analyzer	Aug. 1980	78511A	Display	Nov. 1980
9845C	Color Graphics Computer	Dec. 1980	78571A	Equipment Cabinet	Nov. 1980
9876A	Thermal Graphics Printer	Nov. 1980	78572A	Single-Channel Recorder	Nov. 1980
10264A	General-Purpose Personality Module for 1611A	May 1980	82104A 82106A	Dual-Channel Recorder	Nov. 1980
11429A	Roelof's Prism Adaptor	Sept. 1980	82143A	Card Reader	Mar. 1980
14451A	Circuit Analyzer Board	Nov. 1980	82903A	Memory Modules	Mar. 1980
16091A	Coaxial Fixture Set	Jan. 1980	82936A	Thermal Printer	Mar. 1980
16092A	Spring Clip Fixture	Jan. 1980	82937A	HP-85 16K RAM Module	July 1980
16093A/B	Binding Post Fixture	Jan. 1980		HP-85 ROM Module	July 1980
				HP-85 HP-IB Interface	July 1980

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G			McDonley, P. Alan		
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Hanna, Kim L.	Nov. 1980		Morganthaler, Mark P.		
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Hopkins, George W.	Feb. 1980		Muterspaugh, Milo E.		
T			Nairn, John H.		
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project, including the human factors and the initial mechanical design. Bob Fredrickson designed and implemented the firmware tracking algorithm and interrupt service routine. Lowell Kolb assisted in the design and testing of the detection circuitry in the light pen. Nick Mati worked on developing the optical path, detection circuitry, and mechanical design. Special thanks to Jack Frost, the project manager for the light pen, for the direction he provided.

Reference

1. W.M. Newman and R.F. Sproull, "Principles of Interactive Computer Graphics," McGraw-Hill Book Company, New York, 1979.



Frederick J. Porter

Fred Porter was born in Detroit, Michigan, has an AB degree in mathematics and physics awarded by Albion College, Michigan in 1974 and the BS and MS degrees in electrical engineering from the University of Michigan in 1974 and 1975, respectively. He has been with HP since 1976 and has worked on the display for the 9845A Computer and the control logic for the light pen used in the System 45C. Fred is now working on future graphics displays. He is a member of the National Society of Professional Engineers and a charter member of the Twin Towers Lounge Club at Albion College. Fred acts in the Loveland Community Theatre and makes his home with his wife and two daughters in Loveland, Colorado. His interests also include playing the piano and organ, camping, hiking, and N-gauge model railroading.

A Precision Color Raster-Scan Display for Graphics Applications

by Warren C. Pratt

THE ADAGE "a picture is worth a thousand words" certainly applies to a graphics display. A properly designed and used graphics display can transfer many types of information from machine to user much more rapidly and efficiently than can a verbal or numerical description. Such a display must have an information content greater than or equal to the amount of data to be transferred, provide sufficient display accuracy so that nothing is misinterpreted in the transfer, and be free from anomalies that would tend to distract the user. The color display for the Hewlett-Packard System 45C was designed with these criteria in mind.

- Information content. The display area is 720 pixels wide by 455 pixels high (the area available for graphics display is 560 pixels wide by 455 pixels high). The information density in this area is greatly increased through the use of color. Three primary colors, red, green, and blue, are mixed to provide eight basic colors.
- Display accuracy. The System 45C display circuits correct for display nonlinearities caused by CRT geometry and component variations. These circuits ensure that each pixel is located precisely relative to the other pixels on the CRT screen. Therefore, straight line segments appear straight (not curved) and circles appear circular (not oval or irregularly shaped).
- Freedom from distracting anomalies. How many times

have your favorite television stars been stretched by the "conehead effect" as they ventured too close to the edge of a television screen? When was the last time you watched a TV movie in which the entire population had acquired a green flesh color? The System 45C display is specifically designed to provide a high degree of data integrity free from such distracting anomalies.

The System 45C display uses raster-scan technology. Electron beams transfer serial data to phosphors on the CRT screen, beginning in the upper left corner and scanning from left to right as they slowly move down the screen. When the beams reach the bottom of the screen, completing one frame, they rapidly return to the top, beginning the next frame. Beam deflection is accomplished magnetically using a deflection yoke containing two orthogonal sets of windings for vertical and horizontal deflection. The vertical deflection winding is excited by a current waveform whose frequency (60 Hz) equals the number of frames per second. The horizontal deflection winding is excited by a similar waveform at a much higher frequency, providing a fixed number of horizontal scans per frame.

The display incorporates a delta-gun, shadow-mask, color CRT. Three electron guns are arranged at the vertices of an equilateral triangle located in the neck of the CRT (Fig. 1). The three electron beams pass through openings in a shadow mask near the CRT faceplate. After passing through

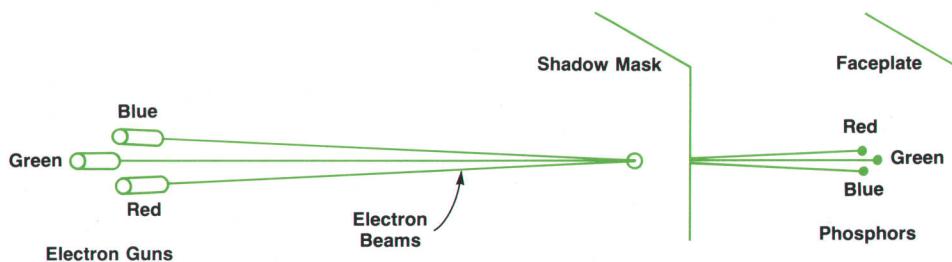


Fig. 1. Three electron guns are arranged in a triangular pattern in the neck of the color CRT. The beams from these guns all pass through a single hole in the shadow mask to excite a triangular arrangement of red, blue, and green phosphor dots on the faceplate.

the shadow mask, each beam strikes a dot of either red, green, or blue phosphor on the faceplate, depending upon each beam's angle of entry into the shadow mask (the angle of entry depends upon the gun location). The arrangement of phosphors is such that each gun consistently strikes a particular color. This tri-beam color system allows independent control of the primary colors: red, green, and blue. However, it is not free from difficulties in implementation. Two key concerns are ensuring that each beam excites only its assigned phosphor (color purity), and ensuring that as the three beams are deflected over the faceplate, they will all strike the same screen location for any combination of vertical and horizontal deflection currents (convergence).

In addition to the deflection, purity, and convergence circuits, the CRT requires three video amplifiers (one per gun) to modulate the electron beams with the serial video data. Each of these amplifiers must generate a 40-volt drive signal from TTL data streams at 30 megabits per second.

The CRT drive circuits (Fig. 2) are divided into four categories for further discussion—vertical deflection, horizontal deflection, convergence and purity, and video amplification.

Vertical Deflection Circuit

The System 45C provides a flicker-free display by refreshing the CRT at a 60-Hz rate; hence, the vertical deflection current is repetitive at a 60-Hz rate. The required deflection current is made up of three components (Fig. 3):

1. A large sawtooth-like component. The signal amplitude changes at a slow rate to scan the beams from the top to the bottom of the CRT. It ramps back to its initial value at a much faster rate, quickly repositioning the beams at the top of the screen for the next frame scan. We denote the scan time as T_s and the retrace time as T_r , hence, $T_s + T_r =$

- 1/60 Hz = 1/60 second.
2. A small velocity-correction component. Due to CRT geometry, the path length of the deflected beam will vary as a direct function of the vertical deflection angle. More specifically, this occurs primarily because the radius of curvature of the CRT faceplate is much greater than the distance from the deflection yoke to the faceplate.

If a perfectly linear drive waveform is applied, higher scan velocities are obtained at the top and bottom of the screen than at the center. Under these conditions, information displayed at the vertical extremes of the screen is larger vertically when compared to the same information displayed near the center. This form of nonlinearity is avoided by adding a velocity-correction term that produces a slight S-shaping of the deflection current waveform, that is, a more gradual slope at the beginning and end of the ramp portion of the waveform.

3. A pincushion-correction component. The deflection path length increases at the horizontal and vertical extremes of the screen. This tends to create a display that bows inward at the top and bottom and at the left and right sides. This effect is known as pincushion distortion. Note that inward bowing at the top and bottom is a vertical error and therefore must be corrected by the vertical deflection field. In monochromatic systems, this correction is generally done with a static field created by carefully positioned permanent magnets. This technique is not practical for a precision tri-beam color system. Since the vertical pincushion error is a function of both horizontal and vertical position, we generate the waveform for the correction field from both horizontal-rate and vertical-rate components.

The vertical deflection system (Fig. 4) uses an output stage and three deflection-current waveform generators.

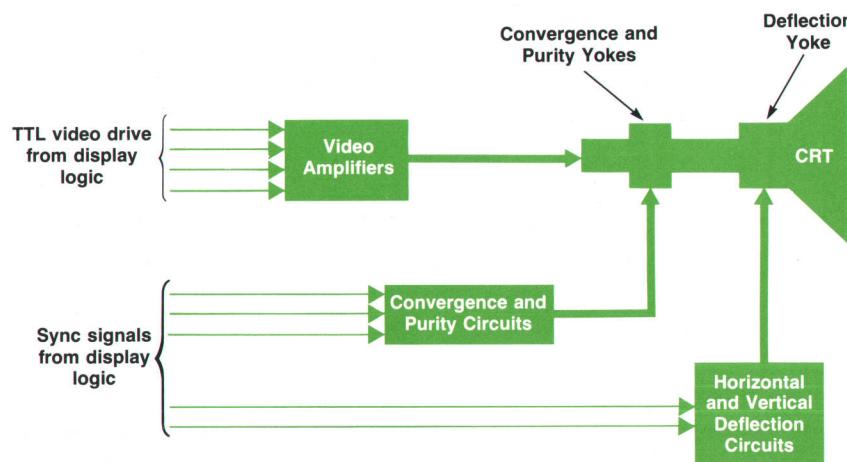


Fig. 2. Block diagram of drive circuits for the System 45C color CRT.

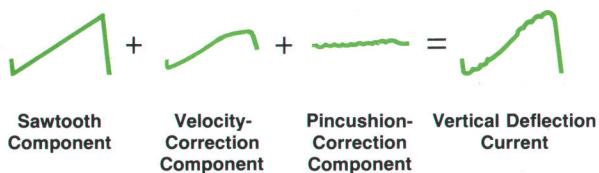


Fig. 3. The vertical deflection current is the sum of three components as shown above.

Vertical drive circuits for precision displays generally contain output stages configured as current sources. The output amplifier obtains feedback from a current-sense resistor in series with the vertical deflection winding. This configuration performs admirably for the 60-Hz vertical-rate component of the sweep current waveform; however, it does not have adequate frequency response performance for the horizontal-rate component of the pincushion-correction waveform. The vertical output stage shown in Fig. 4 provides a solution to this problem.

The vertical output amplifier will, within its gain-bandwidth limitations, force $V_s = (-R_2/R_1) \times V_i$. When R_2 is large enough so that the voltage drop across the winding resistance R_s is negligible, V_s becomes the inductive voltage component across the winding. Note that this is the same voltage that is present across the inductive component of the driven winding. From the V-I relationship for an inductor,

$$I_y = (-R_2/R_1) (1/L_y) \int V_i dt$$

It can be easily shown that this configuration provides sufficient bandwidth for horizontal-rate signal components. Relative to the integration performed by the output circuit, we note two things: the drive waveform V_i must be the derivative of the desired yoke current waveform I_y and the circuit has no inherent dc stability.

Since differentiation is distributive over addition, V_i can be formed as the sum of the derivatives of the three current-waveform components discussed above. The derivative of the sawtooth-like component is a rectangular waveform obtained by switching between two voltage levels. The voltage level used during the vertical scan is constant and controls the picture height. The voltage level used during retrace is an error voltage obtained by comparing the average value of voltage applied to the vertical deflection winding to an adjustable reference. This error voltage is the feedback that provides dc stability in the output stage. Also, because the average amplifier output voltage determines the dc component in the deflection winding, adjustment of the reference voltage modifies the vertical position of the data displayed on the CRT.

The velocity-correction component of the current waveform is approximated by a cubic function that is repetitive at the vertical scan rate. The derivative, required as a component of V_i , is a parabolic waveform that is generated by integrating the output of a 60-Hz ramp generator.

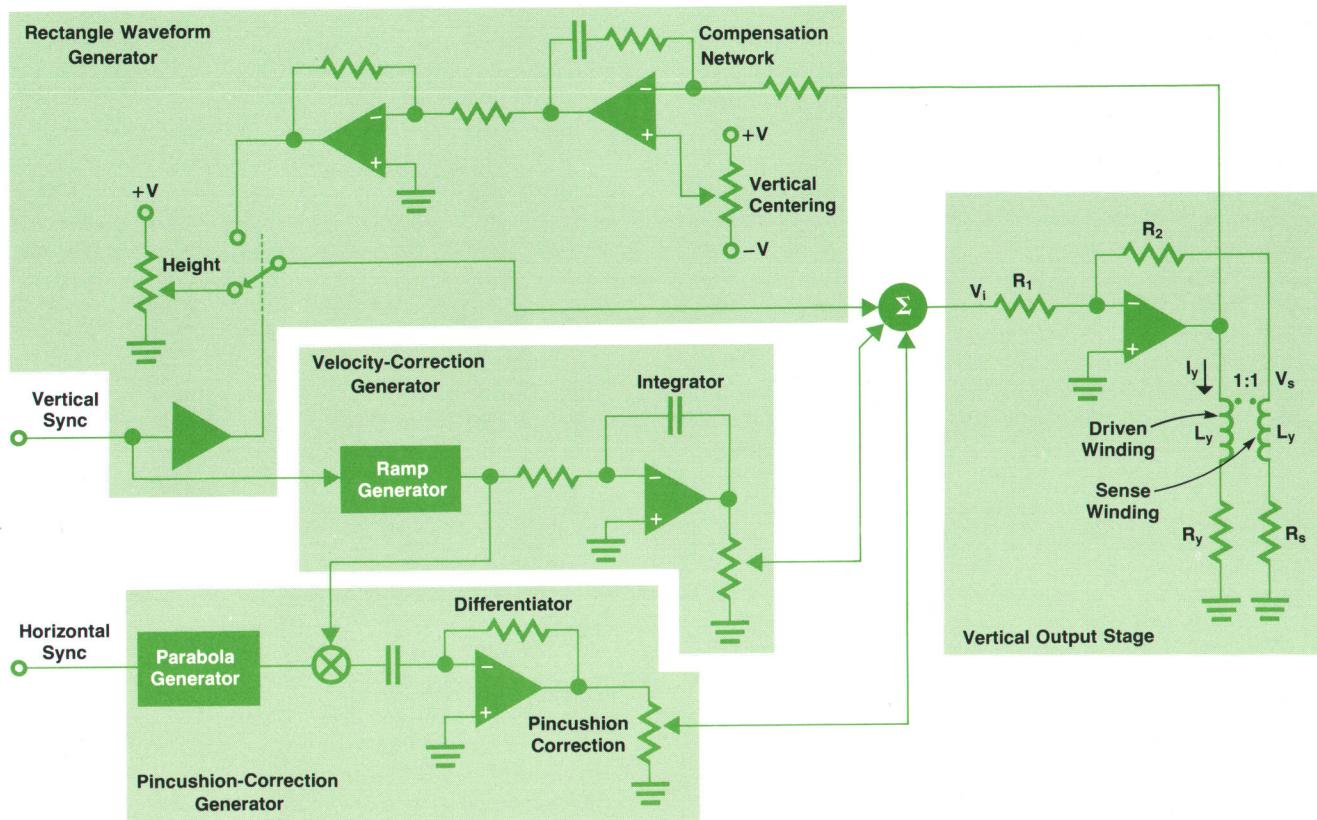


Fig. 4. Vertical deflection system. The three vertical deflection current components shown in Fig. 3 are generated in the respective function blocks above and summed in the vertical output stage.

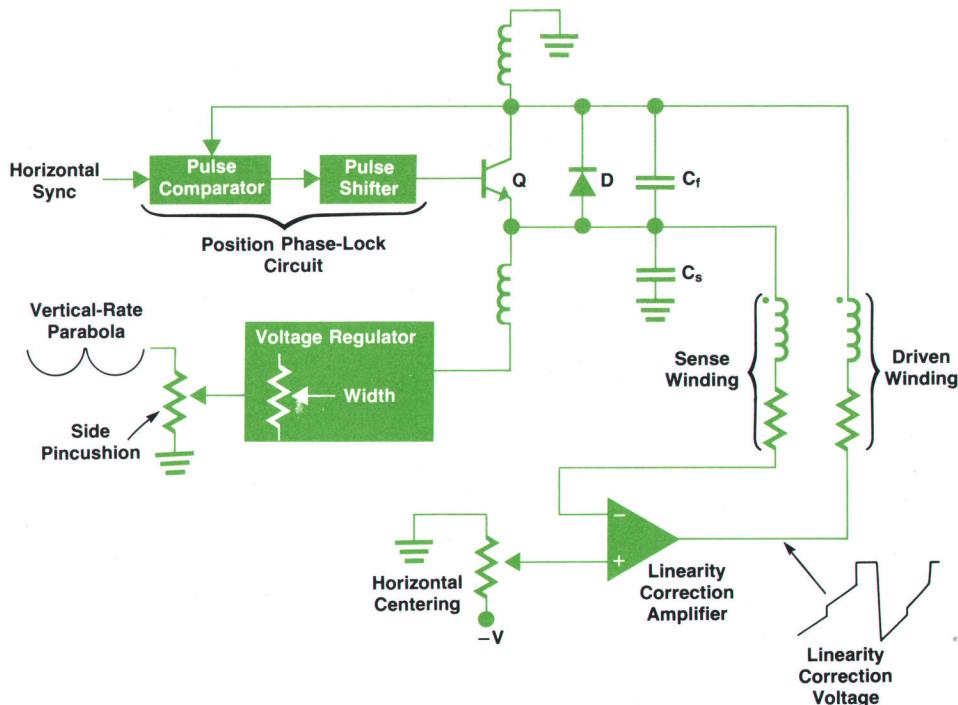


Fig. 5. Horizontal deflection system. A standard flyback circuit is used with a phase-lock circuit controlling the horizontal position. Linearity and side pincushion correction components are added as indicated.

The top-to-bottom pincushion-correction component requires a relatively large amplitude at the top of the screen that decreases to zero at vertical center, and becomes large again, but of opposite polarity, as the scan approaches the bottom of the screen. Also, the required correction is approximately parabolic at the horizontal rate, that is, this vertical distortion must be corrected dynamically each time the beam scans across the screen. Hence, the top-to-bottom pincushion-correction component of I_y is approximated by the product of a vertical-rate ramp waveform and a horizontal-rate parabolic waveform. The corresponding component of V_i is obtained by differentiating this result.

Horizontal Deflection Circuit

The horizontal deflection circuit (Fig. 5) uses a flyback drive circuit, a position phase-lock circuit, a voltage regulator circuit, and a linearity correction circuit. The standard flyback drive circuit contains a power switching transistor Q, a damper diode D, a flyback capacitor Cf and a velocity-correction capacitor Cs. During the first half of a horizontal scan, horizontal deflection current flows through the damper diode. Just before the scan reaches the center of the screen, the switching transistor is turned on. At approximately screen center, the deflection current reverses direction and begins to be conducted by the switching transistor rather than the damper diode. When the switching transistor is turned off, the damper diode is initially reverse-biased and the deflection current flows through the flyback capacitor, returning to its starting value to begin another cycle. The velocity-correction capacitor yields a small amount of S-shaping in the deflection-current waveform.

The position phase-lock circuit compares the beginning of the horizontal scan with the leading edge of the horizontal sync pulse. It then delays the drive pulse to the switching transistor by an appropriate amount so that the two

events are coincident. This ensures that the displayed data is positioned accurately on the CRT screen, independent of switching-transistor storage-time variations.

The voltage regulator controls the supply voltage to the flyback drive circuit. Adjustment of this voltage sets the width of the display. Also, recall that pincushion distortion at the left and right sides of the screen is a horizontal error. Correction for this error is applied in the form of a vertical-rate parabolic modulation of the horizontal sweep current. This is accomplished by modulating the horizontal supply voltage via the regulator circuit.

Linearity correction uses a technique developed by Bernard M. Oliver.¹ A horizontal deflection sense winding in the deflection yoke senses the inductive component of horizontal drive voltage. A linearity correction amplifier forces the sum of this voltage and the voltage across the velocity-correction capacitor to be constant during a horizontal scan. It does this by varying the voltage across the horizontal deflection winding. The correction voltage generated by the amplifier consists of a ramp component caused by the resistive drop in the horizontal deflection winding and a step from the sum of the forward voltage drop across the damper diode and the switching-transistor saturation voltage. The step occurs when the yoke current changes direction (i.e., when scanning through screen center).

Convergence and Purity

Convergence and purity are controlled by two CRT yokes containing six sets of windings. Three of these sets are known simply as convergence coils. One set of convergence coils is located in close proximity to each electron gun primarily to control the direction of the beam originating from that gun (the direction of beam movements caused by these convergence coils is shown in Fig. 6). Color purity is controlled by two additional sets of windings that affect all

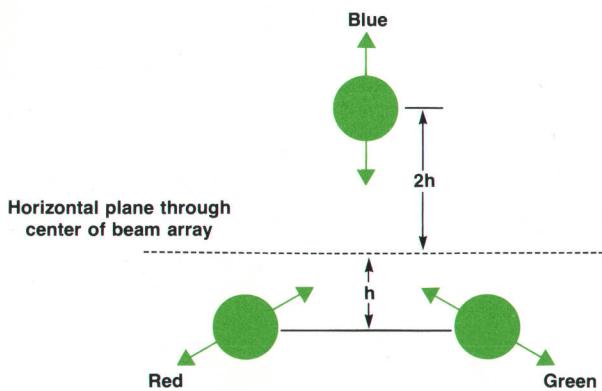


Fig. 6. The three color beams are arranged in a triangular pattern. The convergence coil for each beam can move the beam in the directions shown by the arrows. Because the vertical position of the blue beam is farther from the center of the triangle than the vertical position of the red and green beams, the blue beam is horizontally deflected slightly differently from the red and green beams. The blue lateral convergence coil corrects this error by moving the horizontal position of the blue beam relative to the red and green beam positions.

three guns. One of these sets (X-purity windings) affects horizontal beam positioning while the other (Y-purity windings) affects the vertical beam positioning. The remaining set of windings is the blue lateral-convergence coil. This coil controls the horizontal position of the blue color beam relative to the other two beams.

Many displays incorporate permanent magnets to perform some or all of the above functions. The permanent magnet approach has the advantages of simplicity and

lower cost. However, it does not provide the precise control (corrections varying as a function of scan position) and ease of adjustment required for the high-resolution color graphics provided by the System 45C display.

Each of the three convergence coils is driven by a current source whose output consists of three components: a dc or static component, a vertical-rate dynamic component resembling a parabolic waveform, and a horizontal-rate dynamic component that also resembles a parabolic waveform. The static component affects convergence over the entire display screen and is adjusted to yield convergence at the center where both dynamic components have, by design, zero values. With the static component adjusted for zero convergence error at the center, the beams tend to diverge at other scan positions by an amount proportional to the square of the distance from the center. This distance from center may be considered as consisting of a vertical component and a horizontal component. The square of the distance from center equals the sum of the squares of its vertical and horizontal components. Therefore, the convergence errors in the vertical and horizontal directions, and hence the corrections required, will be second-degree functions of the vertical and horizontal positions. This geometric analysis yields the requirement for correction signal waveforms that are approximately parabolic. However, there are many factors which may require deviations in these waveforms. Some of these factors are CRT electron gun misalignments, convergence coil anomalies, deflection yoke anomalies, and external magnetic fields. These factors vary greatly with different sets of components and somewhat with time and different operating environments. To obtain precise convergence, it is necessary to tailor the convergence correction waveforms to

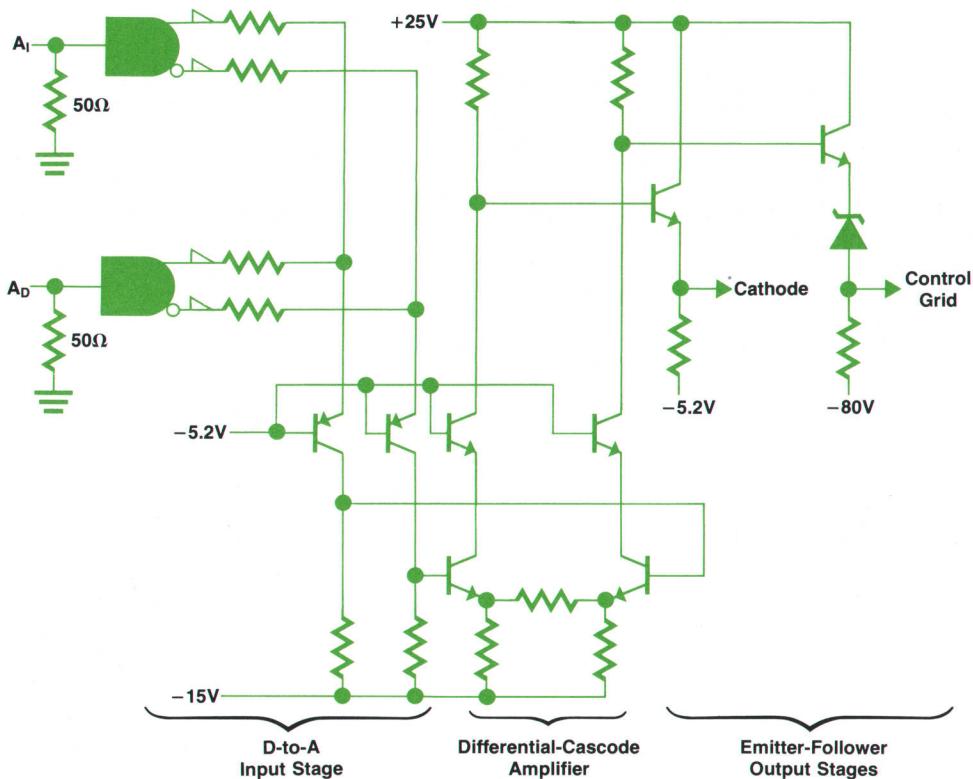


Fig. 7. Video amplifier. The cathode and control grid for each electron gun is driven differentially by the emitter-follower stages. These stages are driven as shown.

each machine and operating environment.

The System 45C provides the capability to vary the amplitude and curvature of the vertical and horizontal convergence parabolas. Furthermore, independent adjustment of the two halves of each of these parabolas (e.g., for the vertical-rate parabola, the first half corresponds to scanning the top half of the screen, while the second half corresponds to scanning the bottom half of the screen) can be done.

Control of static convergence and of the amplitude and curvature of each half of both the vertical-rate and horizontal-rate parabolic waveforms requires a total of nine adjustments per beam. With these adjustments, convergence errors on the CRT vertical axis (horizontal center) and horizontal axis (vertical center) are reduced to negligible levels. Convergence errors on the remainder of the screen are also generally small. However, in some cases significant errors may exist in the corners of the screen. These errors are minimized by the introduction of product terms that are obtained by analog multiplication of the vertical-rate and horizontal-rate parabolic waveforms. An additional four adjustments per beam (one per corner) are available to provide this additional convergence accuracy. These four adjustments, in addition to the nine described above, yield a total of thirteen adjustments per beam ($\times 3$ beams = 39 adjustments total). These adjustments are accessible to operators so that, through the use of firmware prompts, the operators can obtain precise convergence in their particular operating environment.

The blue lateral-convergence coil corrects errors caused mainly by a horizontal deflection field that is slightly nonuniform relative to the location of the three beams in the neck of the CRT. Given the CRT orientation chosen for the System 45C, the blue beam originates at a position twice as far from a vertically centered horizontal plane in the CRT as do the red beam and the green beam (see Fig. 6). Therefore, it is possible that the blue beam will not be horizontally deflected by precisely the same amount as the other beams. The blue lateral convergence coil generates fields which move the blue beam horizontally in one direction while moving the other two beams horizontally in the opposite direction. The coil is driven by a current source whose output consists of a dc component and a horizontal-rate parabolic component. Each half of the parabola is adjustable in both amplitude and polarity because the magnitude and direction of the required correction cannot be readily predicted. Blue lateral convergence is also slightly affected by the vertical scan position. No dynamic correction is provided for these minor errors.

Video Amplification

One video amplifier is required to modulate the beam from each of the three electron guns. About 40 volts is required to control the beam over the full usable range of brightness. This voltage is applied differentially between the control grid and the cathode of each gun (each receives about 20 volts with respect to circuit ground).

The serial data rate to the video amplifiers is about 30 megabits per second. Hence, each serial bit of information corresponds to a scan time of about 33 nanoseconds. To yield consistently crisp dots and lines the time required to turn the beam on and off must be small relative to the 33 ns

per bit. Ten-to-ninety-percent rise and fall times for the System 45C video amplifiers are 6 ns. Even though these transition times are quite short, turn-on peaking is provided on video drive waveforms to compensate for the light output normally lost during turn-on transitions.

As shown in Fig. 7, each of the three video amplifiers consists of a two-bit D-to-A converter (DAC), a differential-cascode voltage amplifier, and two emitter-follower stages corresponding to the two phases of the differential output voltage. One emitter-follower stage provides drive to the cathode of a gun while the output of the other is level-shifted by -68 volts to provide drive for the corresponding control grid. The DAC input encoding is shown below.

A1	A0	Brightness
0	0	Beam off
0	1	Normal brightness
1	0	-Unused-
1	1	Full brightness

The normal brightness level is used for both alphanumeric information and graphic information. Full brightness is used only for graphics cursors.

Acknowledgments

The author thanks Mike Ramsay for his collaboration in the design of the wideband vertical deflection circuitry, and Virgil Schuetz for his efforts in design evaluation.

References

1. U.S. Patent No. 3,434,002, "Horizontal Deflection Circuit With Monitor Winding Inductively Coupled To Yoke," issued to Bernard M. Oliver.



Warren C. Pratt

Warren Pratt has BSEE (1974) and MSEE (1975) degrees from the University of Kentucky and earned a Ph.D. degree from the University of Illinois in 1977. He joined HP that same year and has worked on several designs for the 9845C. Warren is now a project manager at HP's Desktop Computer Division in Fort Collins, Colorado. He was born in Lexington, Kentucky, and taught courses in digital design and circuits during graduate study at the University of Illinois. His hobbies include photography and amateur radio (WD0EYT). Warren and his wife live in Loveland, Colorado, and just welcomed a new addition to the family.

Display System Designed for Color Graphics

System 45C's graphics architecture yields high-speed color picture generation with area shading.

by Harold L. Baeverstad, Jr. and Clark C. Bruderer

THE HUMAN MIND is an incredible visual processor. The simple act of recognizing a familiar face is one example of the associative processing capability available to all of us. Computer graphics is fast becoming a medium of visual communication between man and machine, allowing improved data interpretation, higher productivity, and complex problem solution. The addition of color greatly increases the amount of information that can be provided by a single picture. The proper use of color can aid in simplifying the interpretation of large amounts of complex data. Examples are visual representations of semiconductor die yield (Fig. 1a) and thermal gradients (Fig. 1b).

Time is a crucial variable in the generation of color computer graphics. All the advantages of visual communication may be lost if typical response times in picture generation are slow. To provide high-speed picture generation, the System 45C graphics architecture (Fig. 2), uses a dedicated graphics controller, a 96K-byte graphics memory, high-speed bit-slice vector generator, linotyping/area shading logic that can generate 4913 area colors, and 30-MHz sweep timing for display control.

Graphics Controller

The graphics controller is a ROM-based state machine that issues microcommands to various logic functions in response to macrocommands and status conditions (Fig. 3).

The state machine receives macrocommands from the mainframe via the IOD bus interface and sends microcommands to the graphics cursor logic, I/O address register, graphics memory controller, color assignment hardware (color map), and vector generator.

The graphics controller coordinates all data transfers between the display and the mainframe including the softkey logic and the light pen. The macrocommands executed by the graphics controller are

- LXA Load the X address used in a graphics memory I/O operation
- LYA Load the Y address used in a graphics memory I/O operation
- SMG Store memory control data used in enabling memory planes and specifying input data
- SLT Store select code for linetype/area shading
- SCM Select the color of the memory planes (color map)
- LEP Load vector endpoint coordinates to the vector generator
- LYC Load the Y coordinate of the graphics cursor
- LXC Load the X coordinate of the graphics cursor
- MRC Perform a graphics memory I/O read cycle
- MWC Perform a graphics memory I/O write cycle

96K-Byte Graphics Memory

A random-access memory (RAM) in the System 45C display is dedicated as the graphics display buffer. This mem-

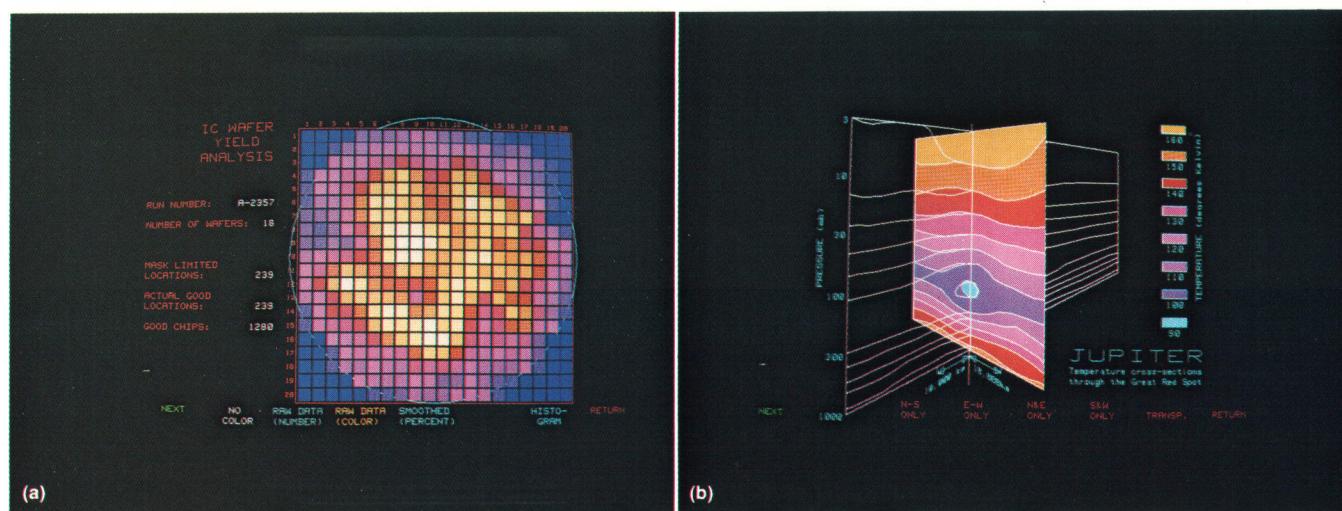


Fig. 1. Changes in color can be used to depict complex variations in system parameters. (a) Die yield versus location on semiconductor wafers. (b) Thermal cross-section of Jupiter's Red Spot.

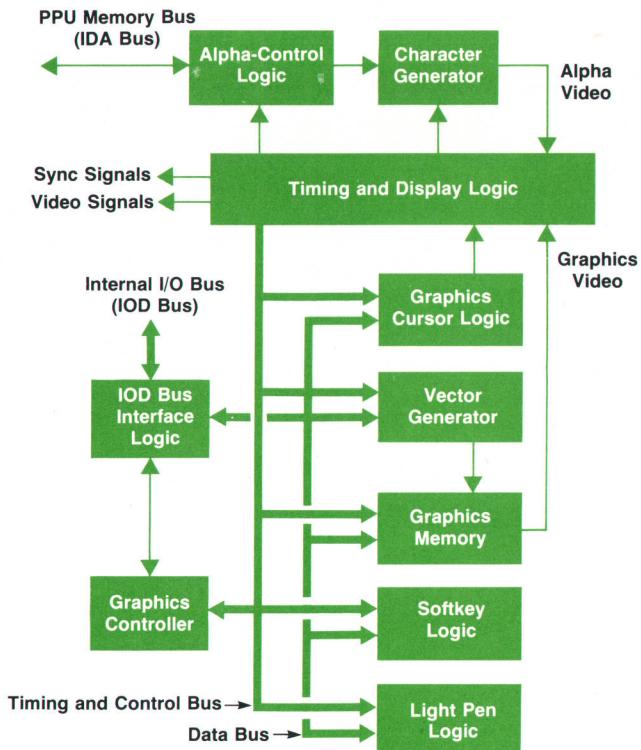


Fig. 2. Block diagram of graphics system.

ory is configured as three 32K-byte planes, each mapping a single bit into each picture element (pixel) in the 560-by-455-pixel graphics raster (Fig. 4). Hence there are three bits per pixel. This memory refreshes the display of the graphics raster at a 60-Hz rate. Since a raster scan is the method used to refresh the display, memory cycles are performed during each horizontal sweep to provide the video data required to generate an image stored in the graphics memory. During horizontal and vertical retraces, memory cycles are used by either the hardware vector generator or the mainframe PPU (peripheral processing unit) to access the memory.

Because the composite alphanumeric and graphics raster (720×455 pixels) is swept every 1/60 of a second, pixel information must be updated every 33 ns. Forty-eight $16K \times 1$ dynamic RAMs are used for the graphics memory and are arranged into three blocks of 16 RAMs each, corresponding to the three memory planes (Fig. 5). Each plane is accessed by a 16-bit word. A word from each plane is read every 528 ns during the horizontal sweep and a parallel-to-serial conversion creates the three-bits/pixel video data.

This video data is assigned color in a section of hardware affectionately known to the designer as "musical memories" (Fig. 6). The meaning behind the name lies in the fact that any of the three memory planes may be arbitrarily assigned to represent any of the eight basic colors. In a typical case one plane is assigned to red, one to green, and the third to blue. This allows the generation of images containing all eight colors. An additional feature of this hardware is the ability to change the color assignment of the memory planes without redrawing the picture.

The graphics memory may be addressed from three sources (Fig. 7)—raster sweep timing chain, I/O address register, and bit-slice vector generator. The timing chain

provides an address corresponding to the X-Y position of the electron beam as it sweeps the raster. This address is used during horizontal sweeps to access the proper memory locations for video data. A benefit of refreshing the display by accessing sequential X-Y addresses is that the dynamic RAMs are also refreshed, so no additional refresh hardware is needed to retain data integrity within the graphics memory.

During horizontal and vertical retraces the graphics memory may be addressed by either the vector generator or the I/O address register. The I/O address register is used to transfer 16-bit data words between the graphics memory and the mainframe PPU. Common uses of this capability are raster dumps to the internal thermal printer, loading the graphics memory from an array containing pixel data, or storing pixel data from the graphics memory to an array.

Vector Generator

The ability to generate vectors is a basic requirement for a computer graphics system. In a raster-scan display, such as the System 45C, vectors are generated by calculating the memory addresses of the pixels on the screen that most closely approximate a straight line between two given points. To maximize the vector generation rate, memory addresses are calculated and vector data is stored into memory by dedicated vector generator hardware. The majority of this hardware is a bit-slice processor system.

To display a vector, two endpoints must be specified first. The first endpoint is given by executing a MOVE X1,Y1 command. Following the MOVE X1,Y1 command with a DRAW X2,Y2 command will cause a vector to be plotted from X1,Y1 to X2,Y2. Once these endpoints have been communicated to the vector generator hardware, the following algorithm computes the memory addresses of the pixels mak-

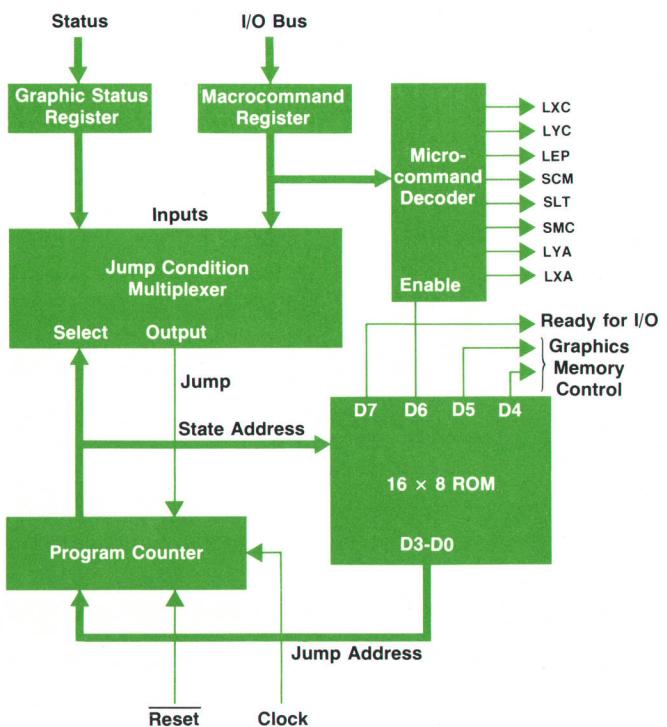


Fig. 3. Block diagram of graphics controller.

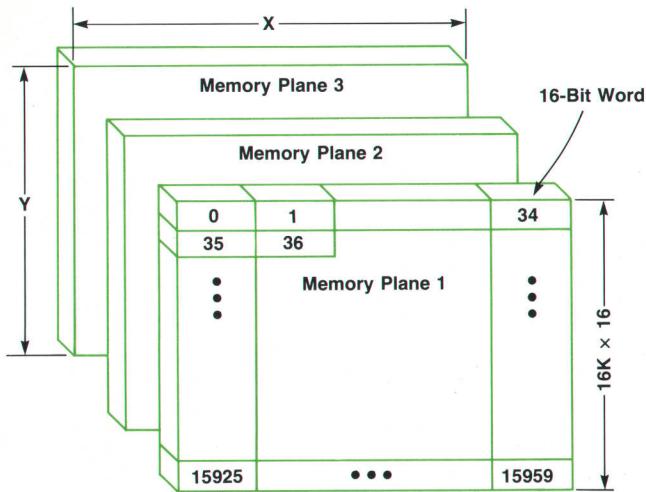


Fig. 4. Graphics memory configuration. Identical memory planes are used for each of the three basic colors selected by the user (normally red, blue, and green).

ing up that particular vector.

- Step 1: $X_2 - X_1 = \Delta X$ and $Y_2 - Y_1 = \Delta Y$ are computed to determine which direction has the greatest difference.
- Step 2: The slope of the vector is then calculated so that it is always less than 45° . Slope = smaller Δ /larger Δ .
- Step 3: The loop counter is loaded with the value of the larger Δ .
- Step 4: The slope is then added to the contents of a fraction register (initialized to 0.5) and the sum is stored in the fraction register.
- Step 5: The address counter corresponding to the direction of larger Δ (X or Y) is automatically incremented by one. The address counter corresponding to the direction of smaller Δ is incremented only when an integer overflow of the fraction register is detected.
- Step 6: Decrement the loop counter

Step 7: Repeat steps 4 through 6 until the loop counter equals zero.

The hardware bit-slice system shown in Fig. 8 is a special-purpose processor system dedicated to high-speed vector generation. The 2903-series bit-slice processors are used because of the high computation speeds obtainable and the versatility they give in system design.

The system is nonpipelined and runs at a clock speed of 3.7 MHz. Six 8-bit ROMs form a 48-bit microcontrol word that enables many events to be controlled simultaneously. This 48-bit microcontrol word contains instruction bits, register addresses and control signals for the processors, and jump addresses, control bits and instruction bits for the 2910 sequencer. A 4-bit instruction to the sequencer determines the next state address. The next state address is latched on each rising edge of the clock into the microstore address latch. This new address produces at the ROM outputs a new word that controls the next program step.

Two counters external to the processor system generate the memory addresses for plotting vectors (see Fig. 8). These are designated as X and Y counters and contain the current X - Y coordinates of the pixel plotted on the screen. These counters are parallel-loaded with the X , Y coordinates from a MOVE X_1, Y_1 statement. Then when a DRAW X_2, Y_2 statement is executed, the counters increment or decrement under processor control until their outputs equal the endpoint X_2, Y_2 . The processor simply controls incrementing and decrementing of the counters instead of transferring two 12-bit addresses for each point plotted. This method increases plotting speed by roughly 60%.

Each time the counters are updated, a handshake signal (AVC) is generated to signal the graphics memory that the current address is stable. The pixel is stored in memory according to the address given and the graphics memory generates a return signal (SVC). This signals the vector generator that the pixel has been stored in memory and the next address may be computed.

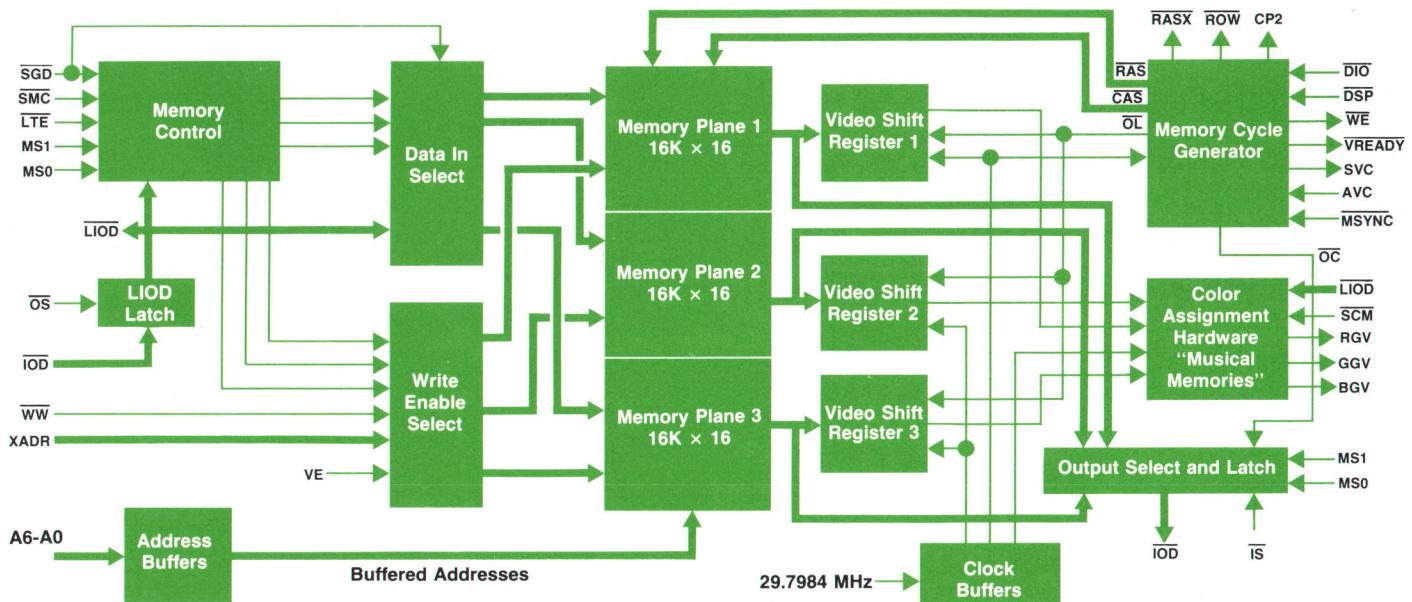


Fig. 5. Graphics memory system block diagram.

System 45C Power Supply Considerations

by J. Steven Becker

Among the noticeable external features of the System 45C are the two power cords coming out of the back. This is because there are two separate power supplies. The mainframe is powered by the same supply used in the System 45B. The color display has an internal supply that provides more power than the mainframe supply. This makes it possible to upgrade 9845 Computers to have a color display without the worry of additional power requirements from the mainframe.

The display supply contains three separate switching supplies and a linear supply. The three switching supplies provide power for the display logic, sweep and convergence circuitry, and the high-voltage flyback transformer. The linear supply provides the power used by the switching supply circuits and the tube filament. In all, nine voltages are generated with a combined output power of 400 watts.

One of the peculiar requirements imposed by the display is that various sections of circuitry must be powered up in the proper order or they will not work. For example, the logic clock must be operational before the sweep circuits, which are synchronized with it, can operate. The sweep circuits, in turn, must be functioning before high voltage is applied to the CRT or the beam would simply burn a dot into the center of the screen. To prevent this, the switching supplies are turned on sequentially.

To sequence the supplies, one voltage output from each of the first two supplies is fed into a monitoring circuit primarily consisting of voltage comparators. Each supply has an inhibit line which is used to turn the supply on and off. The outputs of the voltage comparators are connected to these lines.

At machine turn-on, the first supply turns on softly, taking about 100 ms to come up to full power. When the +5V line reaches 4.5V, the inhibit signal is removed from the second supply and it begins a soft start. When this supply is up to about 85% of its output voltage the third supply softly starts. The combination of sequenced supply starts and rather long (100 ms) starting times insures that the supplied circuits become operational in the proper sequence.

Another important consideration in the power supply is protection, both for the supply itself and for the circuits connected to it. When a supply is designed to operate over a wide range of line voltages, sufficient power can be developed to destroy circuitry under an overload condition. If a supply voltage goes too high, damage can result to the components it supplies. If a load shorts, the resulting high currents can damage the supply. Therefore, some manner of protection is essential.

The display power supply is protected in three ways (not counting that old reliable last resort, the fuse). The starting sequence circuits described above provide one form of protection. If, for example, there were a short on the +5V line, dropping it below 4.5V, the other two supplies would shut down immediately. This is all very well for those other two supplies, but what about the one actually connected to the short? This is where the second protection method comes in. Each of the three switching supplies monitors the current in the primary of its switching transformer. If a

short occurs on an output of a supply, it is reflected back into the primary of its transformer and the primary current sensor inhibits the supply.

The third protection method is the overvoltage, overcurrent (OV-OC) monitoring circuit. This circuit monitors certain selected output voltages and one output current (that of the -80V line; because of the nature of the load the high current pulses may be of such brief duration that the primary sensor would miss them). It also monitors the temperature of the large heat sink that dissipates close to 200 watts. If any one of the monitored parameters exceeds its preset limits, all three supplies are shut down immediately and kept shut down. The outputs of the OV-OC sensors are latched. The latches keep the supply shut down until the System 45C is turned off and on to reset them.

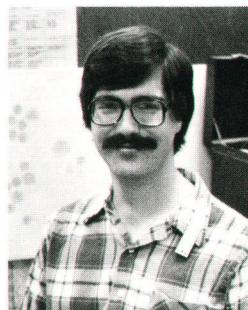
Besides shutting the supply down, the OV-OC monitoring circuit enhances the serviceability of the entire display. Each of the latches activates an LED that is visible outside the power supply when the top cover of the display is removed. When a fault condition shuts down the power supply, the LED corresponding to that fault lights. This LED remains lit even if the power switch on the System 45C is turned off. With this knowledge of what caused the power supply to shut down, service personnel have a valuable piece of information. Without this information, a person knows that at least one of eight faults has occurred, but which one? The speed of the protection circuit sensors is such that it is difficult to see the fault conditions, even with an oscilloscope. Therefore, the LED indicators, which are also connected to the inhibit lines of each of the three supplies, give service personnel a picture of what is happening inside the supply. This allows them to trace the fault much more rapidly than would otherwise be possible and still lets the sensors shut down the power supply quickly enough to prevent major secondary damage to other circuits not related to the original fault.

Acknowledgments

Thanks to Lonnie Miles who developed the initial supply architecture as well as designing some of the circuits used in the supply. Also thanks to Les Hoy and Rex Seader who packed a very large number of parts into a very small space.

J. Steven Becker

Steve Becker came to HP in 1978 after completing his studies for the BSEE degree at the University of Kentucky. He started in the lab working on the power supply for the 9845C color display and now has production responsibility for the analog circuitry in the display. Steve was born in Louisville, Kentucky, and enjoys sailing, music, camping, bicycling, and wine and beer making. He and his wife live in Loveland, Colorado.



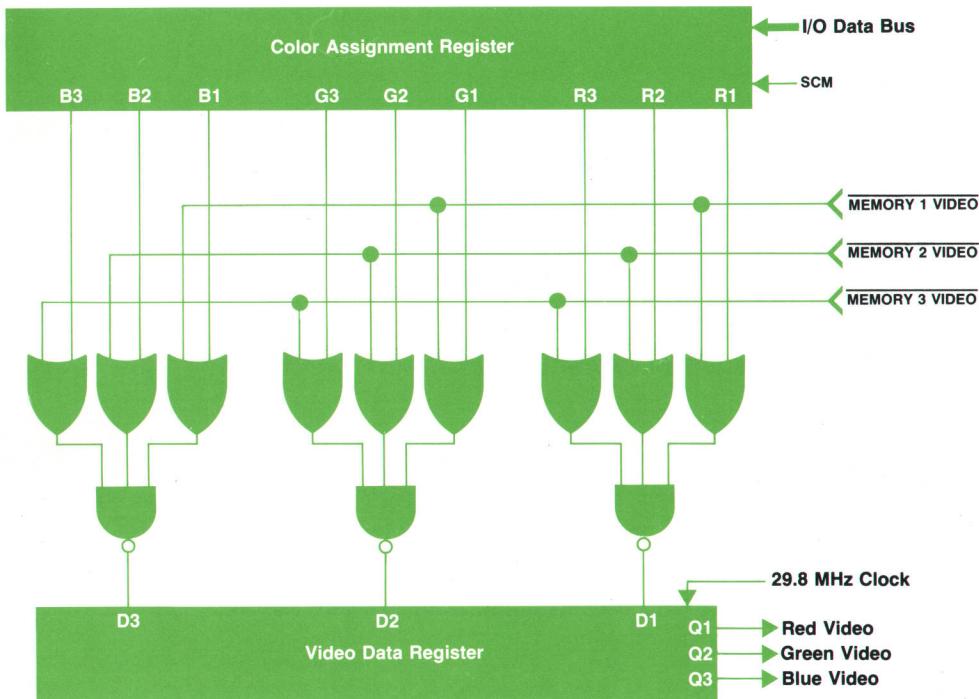


Fig. 6. Logic diagram for the musical memories.

The vector generator clock is synchronized perfectly with each memory cycle by use of the timing signal (MSYNC). This enables faster handshaking and thus faster transfer of data. With this scheme, the vector generator is capable of storing data during every consecutive memory cycle. Since vector points are plotted only during retrace time, approximately 35 pixels can be plotted during each horizontal retrace. This translates to an approximate speed of 10,000 one-inch vectors per second—a plotting speed 50 times faster than previous 9845 displays.

The vector generator has the ability to address individual bits within a word; therefore, its X-Y address has four additional bits of addressing in the X direction. These bits are used to control the write-enable input to any of the 16 RAMs within a memory plane. Because the memory planes are arranged into $16K \times 16$ blocks, an X-Y position does not

directly map into an absolute memory address. Instead, the memory address = $35 \times Y + X$. This function is implemented by a combinational logic circuit that can generate a valid memory address within 90 ns, worst case, given a change in X and Y.

When a line is drawn in the graphics memory, more than just the pixel coordinates of the line approximation are required. Color adds another variable to line drawing and must be completely specified before the line is generated.

Linetype/Area Fill

Eight basic colors are available for lines: red, blue, green, magenta, yellow, cyan, white, and black. For coloring areas, over 4,000 different colors may be obtained by combining different patterns in each of the eight display colors. The area-fill pattern for each color memory is specified by an internal intensity number that covers a range of seventeen patterns. Upon examining Fig. 9, each of the seventeen patterns may be observed by first choosing an intensity number between 0 and 16. Then place a dot over each number in the cell that is less than the intensity number chosen. The example in Fig. 9 shows the pattern for an intensity number of 8.

This scheme of area-fill pattern generation is implemented in hardware by using a PROM that has the cell number pattern programmed into it. A lookup table is created by using the two least-significant bits of the X and Y vector addresses to access the ROM. This table indicates if the current pixel being plotted in each color memory plane is less than the internal intensity number derived from the current AREA COLOR or AREA INTENSITY statement. If it is, then a pixel is stored in graphics memory. Otherwise, no pixel is plotted. Thus, area fill is possible in many different patterns without slowing the vector plotting speed.

Linetype patterns are stored within the same PROM described above, and can be accessed when areas are not being filled. There are ten basic linetypes which can be enlarged

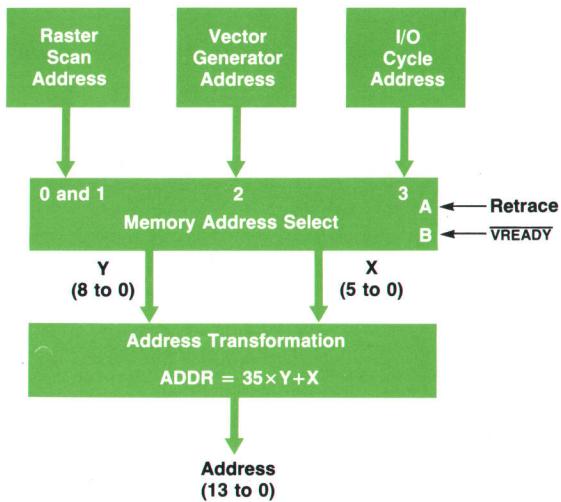


Fig. 7. Graphics memory addressing.

Display Characteristics and Timing

The System 45C color display employs raster-scan technology that produces a matrix on the screen to display desired data. The total matrix scanned is 720 pixels horizontal and 455 pixels vertical. Within this total display area are two smaller, overlapping display areas. The graphics area is 560 pixels wide by 455 pixels high and the alphanumericics display encompasses a 720 by 420 pixel area (see Fig. 1). The latter display area gives 26 lines of 80 characters each, with two lines at the bottom of the screen for softkey labels. Each character occupies a 9×15 pixel cell.

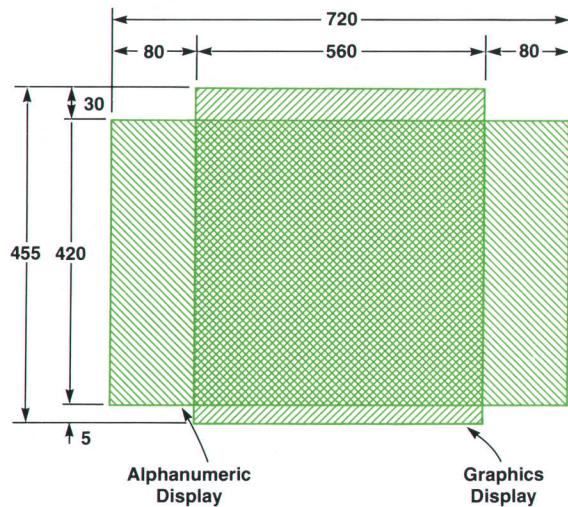


Fig. 1. The pixel dimensions of the graphics and alphanumeric display areas are shown above. These displays can be viewed individually or superimposed on one another.

Unlike the System 45B display, only one raster is scanned. Portions of the overall scan are simply blanked out to give the alphanumeric and graphics display areas. This enables the user to view either the graphics or alphanumeric display individually, or at the same time, one display superimposed on the other.

Timing for the display is obtained by decoding signals from two sets of counters, an X counter and a Y counter. The display scans 720 pixels in the horizontal direction with approximately 10 μ s for

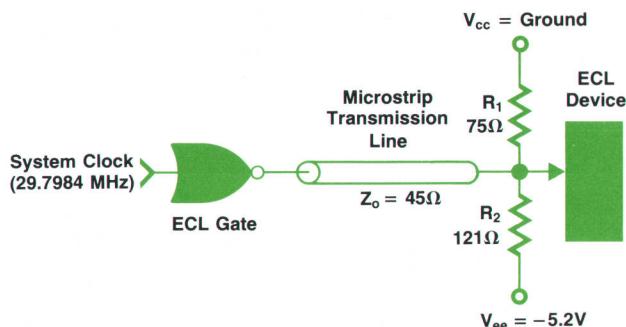


Fig. 2. Microstrip transmission lines are used to transmit clock signals over distances greater than five to eight centimetres. This minimizes reflections and maintains signal integrity.

horizontal retrace. In the vertical direction, retrace is approximately 750 μ s and 455 lines are scanned. The frame refresh rate is 60 Hz, the horizontal scan frequency is 29.1 kHz and the pixel frequency is 29.8 MHz.

The X counters must, therefore, count at a high rate of almost 30 MHz. To operate reliably at this frequency, a monolithic crystal oscillator chip and emitter-coupled logic are used in the X counter design and associated circuitry. Great care is taken to buffer the 30-MHz clock adequately so that rise and fall times and signal integrity are maintained. In instances where the clock signal must be transmitted over distances of more than five to eight centimetres, terminated microstrip transmission lines are used to avoid reflections and maintain clean clock signals (see Fig. 2).

The 10-bit horizontal counters count 1024 counts every horizontal scan. At the end of each horizontal scan, the vertical counters increment by one and count a total of 485 counts per frame before resetting. Because the vertical clock rate is much slower (29.1 kHz), the vertical counters use low-power Schottky logic.

Signals are decoded from the X and Y counters to synchronize both the horizontal and vertical deflection and the convergence waveforms. Alphanumeric and graphic timing is likewise decoded from these counters and care is taken in transmitting these signals to insure signal integrity.

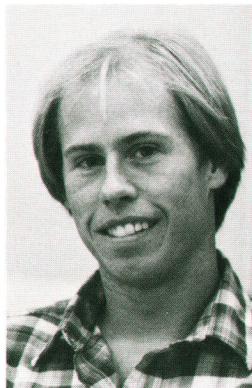
Clark C. Bruderer

Clark Bruderer is a native of Salt Lake City, Utah, and attended the University of Utah, receiving a BSEE degree in 1977. He joined HP then and has progressed from development engineering work on the System 45C to his current responsibility as lead production engineer for the 9845C. He is the author of one paper and is the Scoutmaster of a Boy Scout troop in Loveland, Colorado. Clark is married, has two children, and lives in Loveland, Colorado. His outside activities include scouting, camping, sports (handball, volleyball, and swimming), woodworking, home improvements, and, most of all, spending time with his family.



Harold L. Baeverstad, Jr.

Harry Baeverstad joined HP in 1977 as a design engineer for the System 45C. He worked on the graphics memory and alphanumeric controller, and is currently concerned with graphics display architectures. He is a native of Denver, Colorado, and has BSEE (1975) and MSEE (1977) degrees from the University of Kentucky. Harry has written two papers on computer color graphics and taught seminars on microprocessor design. He makes his residence in Fort Collins, Colorado, and enjoys sailboat racing, downhill skiing, racquetball, woodworking, and photography.



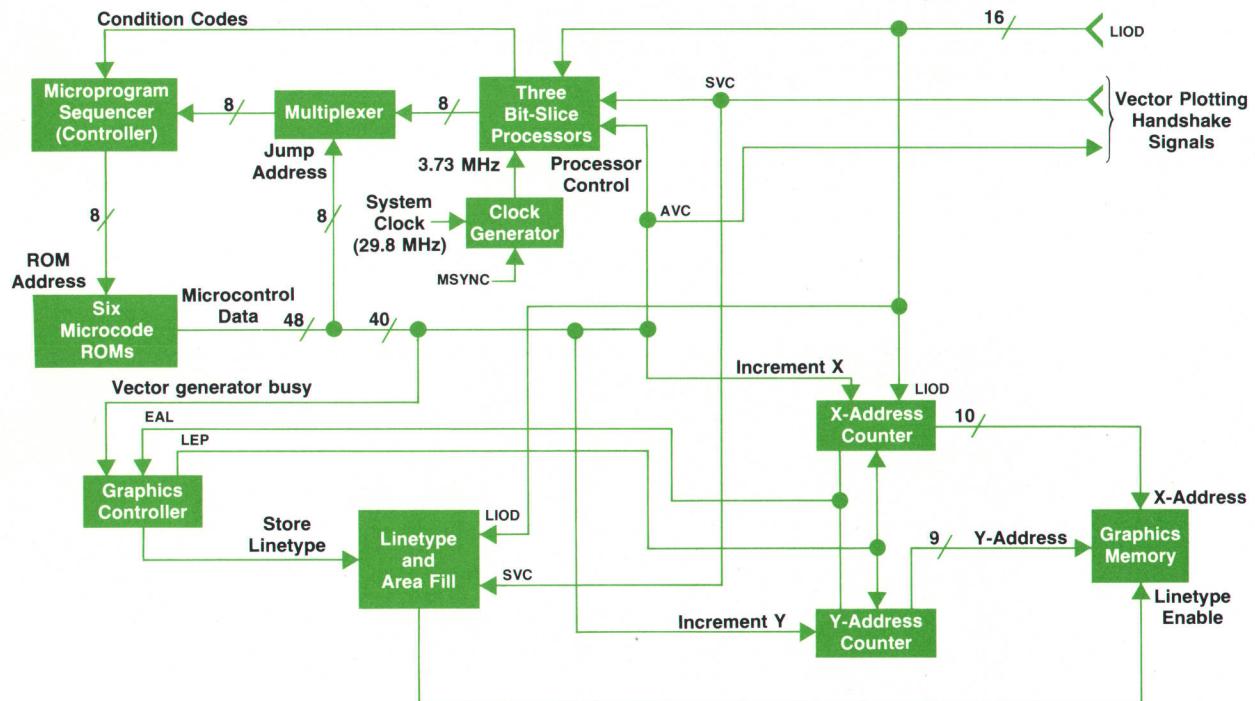


Fig. 8. A bit-slice processor system in the 9845C replaces the vector-generation firmware algorithm used in the 9845A/B. This approach makes the vector generation rate up to 50 times faster than for earlier 9845 Computers.

up to 16 times. The linetypes are clocked out of the PROM by a divide-by-N counter where N is the current scale factor.

Dominant/Nondominant Color

There are two things to consider in selecting a color: the hue of the color (i.e., red, yellow, green,...), and whether the intersection with existing colors by the color to be drawn is to be dominant or nondominant.

In dominant line drawing, the intersection of a green line drawn over a red line is green. In the nondominant case the intersection is yellow. The ability to draw lines using both modes is necessary to handle different applications. The memory controller can be commanded to control color and dominance and is implemented in hardware by controlling the write-enables to each of the three memory planes as well as the data written into each.

Another case of dominance arises from the use of

linetypes and area fill. In linotyping a decision must be made as to what happens within a space in a dashed line. Is the space black, or does the line leave the background unchanged? Again, both capabilities are needed and each can be specified by programming the memory controller.

Dominant area fill occurs when all three memory planes are treated as a single plotter. The color specified to fill an area does not combine additively with a previously existing color in the fill area. Instead, dominant area fill yields the last color specified and erases any previous color in that area. An example of the use of this capability is the simple generation of three-dimensional objects with hidden surface removal. In Fig. 10 the three-dimensional bar chart is drawn from the back to the front with dominant area colors. This accomplishes the task of removing any surfaces which are behind the most forward parts of the image.

Nondominant area fill is exhibited in Fig. 11, where the color green combines additively with the previous colors so that all information is retained in the image. This is done by treating each memory plane as a separate plotter, which allows the green color memory to be filled without disturbing the contents of the red or blue color memories.

Acknowledgments

The authors thank Paul Kirby for his valuable support and advice, and Bob Jewett and Colin Cantwell for their imaginative thinking and impact on the use of color in the design of the System 45C graphics hardware.

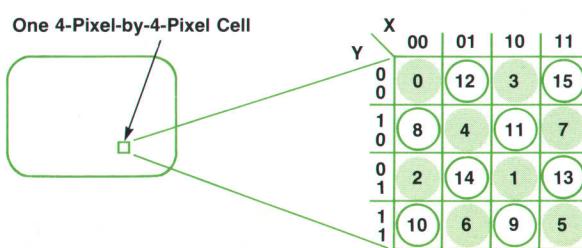
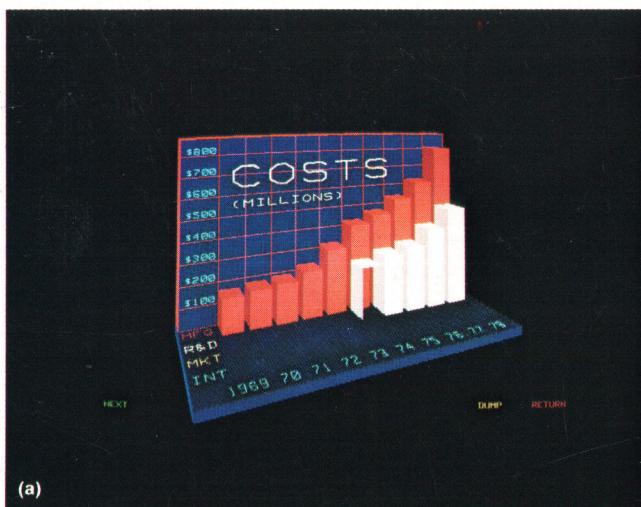
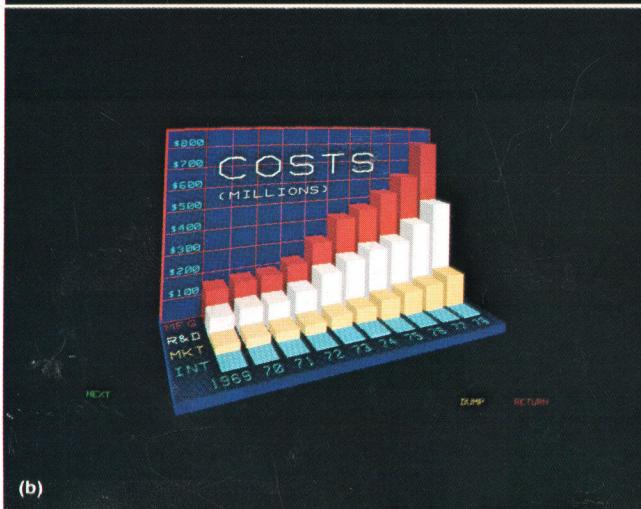


Fig. 9. Area fill colors are obtained by varying the pattern in 4 × 4 arrays of pixels. These patterns are generated in response to the parameters specified by the AREA COLOR or AREA INTENSITY statements.

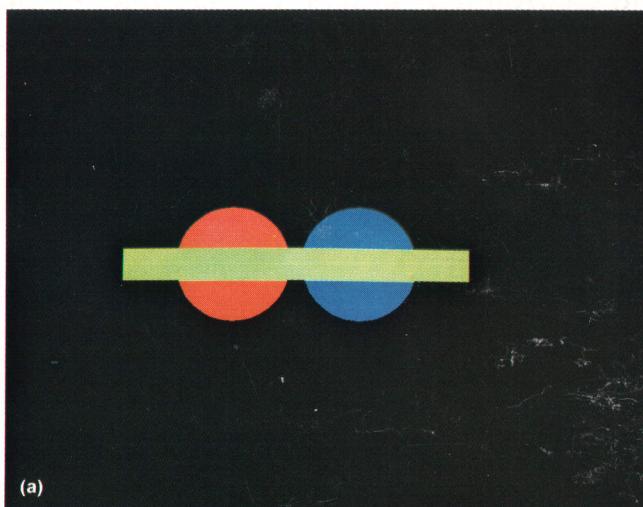


(a)

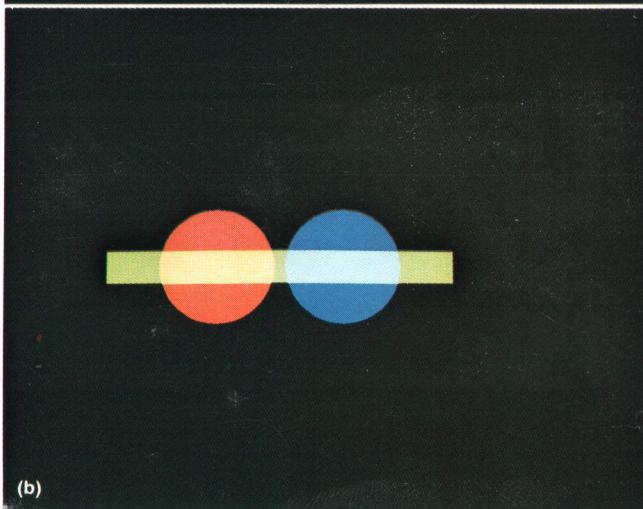


(b)

Fig. 10. Dominant area fill simplifies hidden surface removal for the generation of 3-D images. The bar chart started in (a) uses dominant area fill to achieve the final result shown by (b). As the chart is constructed from the back, the columns in front replace those areas immediately behind the columns.



(a)



(b)

Fig. 11. In (a) dominant area fill gives the result shown when a green rectangle is plotted over the red and blue circles. However, if the area fill is nondominant, the green area is modified by the previous background colors as depicted in (b).

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