

Discussed are a graphics system and a high-resolution printer that provide scientists with a means of producing camera-ready text and graphics. This paper describes techniques for producing three types of graphics: halftone pictures, line drawings, and solid-filled areas. An overview of the software system is also presented.

A high-resolution computer graphics system

by S. W. Handelman

A graphics system that incorporates an experimental high-resolution, all-points-addressable printer has been in use for several years at the IBM Thomas J. Watson Research Center. This system produces camera-ready copy of printed text and graphics of sufficiently high quality for publication.¹ The combined use of graphics software and hardware provides the Research user community with nearly complete control over the visual quality of their printed work. All the figures in this paper have been produced by this high-resolution computer graphics system. Discussed here are techniques used to produce the three types of graphics included here—halftone imagery, line drawings, and area-filled images.

High-resolution graphics

The high-resolution printer uses a computer-controlled cathode ray tube (CRT) that is capable of projecting an image of 800 dots per inch, both horizontally and vertically, onto photographic film. These dots are uniform in size and intensity. The individually addressable dots are called picture elements or *pixels*.

The printer projects text characters onto the film by referencing appropriate *fonts* (files of prestored character images of the same size and style). Enhancements to the software allow users to send their own raster data to the printer either as fonts of regular characters or as fonts of special characters that contain elements of larger graphic images.

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Computer graphics, in general, greatly aids scientists by making theoretical and abstract concepts more perceptible. A highly practical, labor-saving use for computer graphics is its ability to automatically render precise and detailed drawings. As Benoit Mandelbrot writes, "Hand drawing would have been prohibitive, but I was fortunate in having access to an experimental computer graphics device that produces camera-ready copy."²

Raster graphics

The classification of raster-graphic systems as described by Newman and Sproull³ can be used to characterize the types of graphics described in this paper.

- *Rasters*, or rectangular arrays, for representing variable intensities.
- *Lines and dots* for the representation of line drawings.
- *Solid areas*, as defined by the geometry of their outlines, for representing surfaces or solids.

Television, the most familiar raster display, produces images by a modulated electron beam projecting variable-intensity raster scans onto a screen. The high-resolution printer, as described before, operates in a binary mode; it cannot vary the intensity of a pixel as a TV does. However, it can produce images in shades of gray using methods adapted from the printing industry and known as "halftoning." It combines several adjacent pixels in a very small matrix to form a *halftone point*. When these halftone points are combined, they can form patterns of varying intensities of gray from black to white. (Because the blackness of ink cannot be changed, the same effect is achieved in printing halftone photographs by varying the halftone point size by acid-etching the printing plate.) Since the high-resolution printer has a resolution of 800 pixels per inch, a halftone point 12 pixels wide can be repeated to yield over 500 halftone points across an 8½-inch plot. This is approximately equivalent in quality of resolution to the lower end of newspaper halftone printing.

variable-
intensity
plots

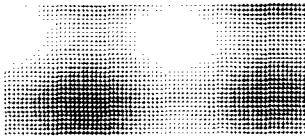
Two methods that have been used at the Research Center to create halftone patterns are:

- Line segments
- Halftone character sets

By the *line-segment method*, each point on a picture is defined as a small line segment with an area proportional to the intensity to be displayed. The large amount of computer time required to compute line segments has led to the more cost-effective technique of producing halftone imagery by halftone characters.

A *halftone character* produced by the high-resolution printer is a pattern or matrix of pixels as previously described. Each halftone character is a halftone point. A *halftone font* is a set of such characters that spans specified levels of a gray scale. A 12 by 12 pixel raster, for example, can produce 145 different gray levels. (White halftone points are produced by no pixels blackened, and black points are produced by all 144 pixels blackened. All other halftone points in the gray scale have numbers of blackened pixels between those extremes.) Since the eye cannot distinguish that many distinct shades of gray, several different halftone font subsets have been created and stored; these cover a variety of ranges and intervals of gray, depending on the application.

Figure 1 Sample characters of a halftone font in which individual raster points are the picture elements



The user creates a picture by transmitting character strings that represent the differing intensities at successive halftone points along raster-scan lines. The printer uses these characters to index into a prestored font; the host computer is not required to calculate the pattern for each intensity over and over again as is the case with the line-segment method.

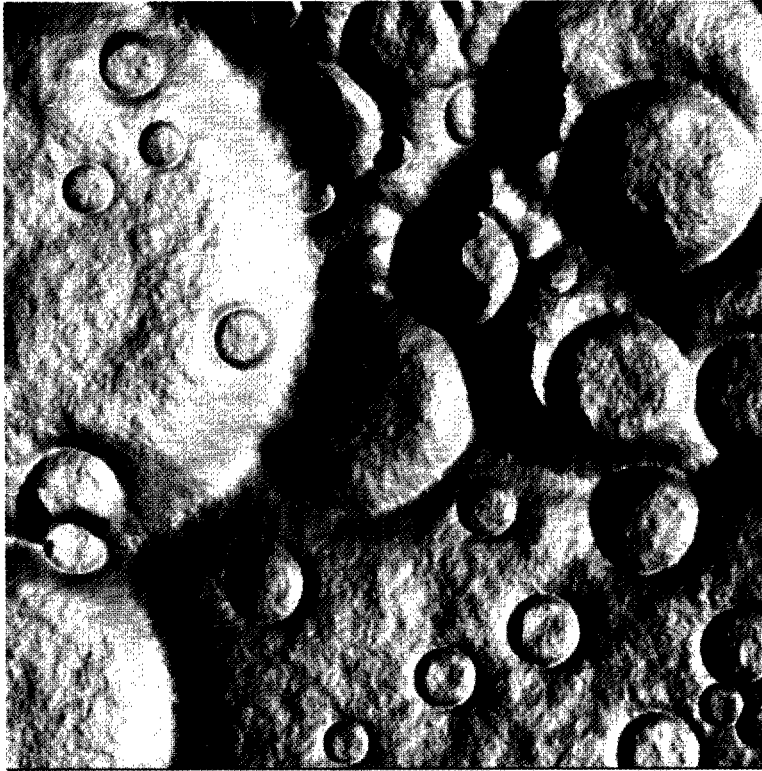
Figure 1 is a representation of several characters of a font of halftone points. Each box in the figure is the space occupied by a 12 by 12 matrix of high-resolution pixels, with many of the pixel positions unused, of course. Figure 2 is an example of halftone imagery. Here the scientist is visualizing the effect of cratering. Figure 2a is a vertical view, and Figure 2b is an oblique view thirty degrees above the horizontal.

line drawings

Line drawings are the most widely used graphics produced by computers and may range from simple x - y data to hidden-line elimination for a complicated mathematical surface. In making line drawings, the printer excels in its ability to print various line thicknesses or weights.

The mathematical concept shown in Figure 3 illustrates this capability. It represents a stylized tree that was created by the methods discussed in Reference 2. (Examples of real space-filling networks are the lung and the blood circulatory system.) Note that there are lines as thin as one raster unit (i.e., one pixel width) and as thick as many raster units. Because of its exceeding fineness, a one-raster line might disappear if not properly copied. This capability, however, is very important because it enables the scientist to show the viewer that the tree branches to infinitesimal capillary-like structures. Such details may not be individually resolvable by the naked eye, yet they are perceived together with the other components as part of a mathematical progression approaching the infinitesimal. By this method, one can also convey an impression of imperfections at a boundary, for example, by drawing items smaller than can normally be seen. In this way, the

Figure 2 Example of halftone imagery illustrating cratering (a) viewed from directly above and (b) from an elevation of thirty degrees above the horizon



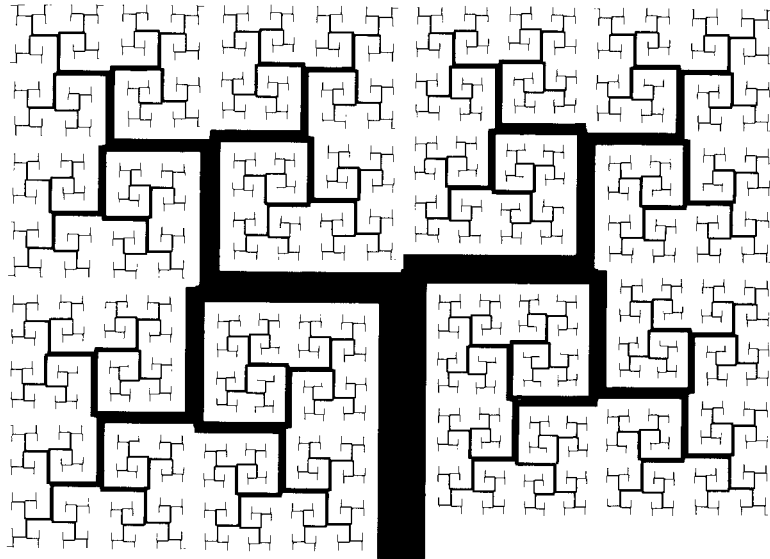
(A)



(B)

high-resolution graphics systems can produce subtle effects that take advantage of the psychological perception of the eye.²

Figure 3 A stylized tree using a hierarchy of line weights to illustrate a space-filling principle analogous to the lungs and the circulatory system (Copyright Benoit B. Mandelbrot, used with permission.)



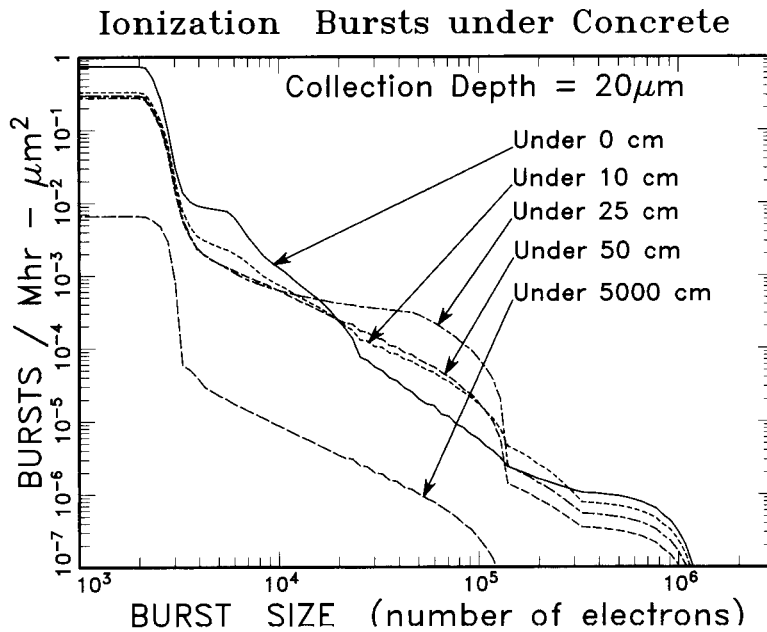
The use of multiple line weights (as illustrated in Figure 4) is also important. It permits a scientist to overlay several traces on a single graph and yet minimize confusion that might occur in the case of a multivalued plot in which all curves have the same line weight. Under magnification, roughness at boundaries in Figure 4 gives visible evidence of raster scan lines as they approximate curves. This is particularly apparent for letters.

**solid-
area-
filling
graphics**

The third method uses shaded-in segments of black and white to fill in an enclosed area, as in the case of coloring the sections of a map. This type of work requires a high-precision printer to prevent voids or gaps at the perimeter of the object from being rendered as a surface or a solid. When performed by hand, such filling-in is often time-consuming and inaccurate. Other graphics devices do not usually have the required high resolution.

The high-resolution experimental printer uses thousands of line segments to fill in each area desired. Since a line can be as fine as one raster, we can fill in all the detail that the eye can see. The printer's exactness makes possible lines of uniform intensity that abut one another to form continuous black areas. If several different masters are produced for one picture and these masters represent color separations or flat color areas, a picture that incorporates several different colors can be produced by overlaying the separations and printing them in different colors. The cover of

Figure 4 A multivalued plot using a range of line weights and styles shown here for a scientific application, but equally useful for business graphs



Scientific American for April 1978 pictures two algorithms of Benoit Mandelbrot that were programmed by the author and Mark Laff and then printed as flat color areas to produce the striking cover design. A hypothetical map created by this method is shown in Figure 5.

Using the high-resolution graphics system

Taking line drawing as an example, the graphics user produces a picture by the following three-step process.

1. The picture is defined as a file of x - y line segments called a PIC file and a file of character strings called a LABEL file.
2. A conversion program, called LBLGRAPH, converts these line segments and text characters into a file called PICTURE.
3. The PICTURE file is sent to the high-resolution printer, or it can be sent to a lower-resolution draft printer, as described later in this paper.

Although it is possible for the user to produce the PIC and LABEL files directly, high-level user support has been developed to make the job easier. Several methods used at the Research Center to provide high-level access are described here. This is neither a definitive nor an exhaustive list, but it demonstrates the imagination and the industriousness of the system users.

Figure 5 Color separations shown in black and white for which color may later be substituted
(Copyright Benoit B. Mandelbrot, used with permission.)



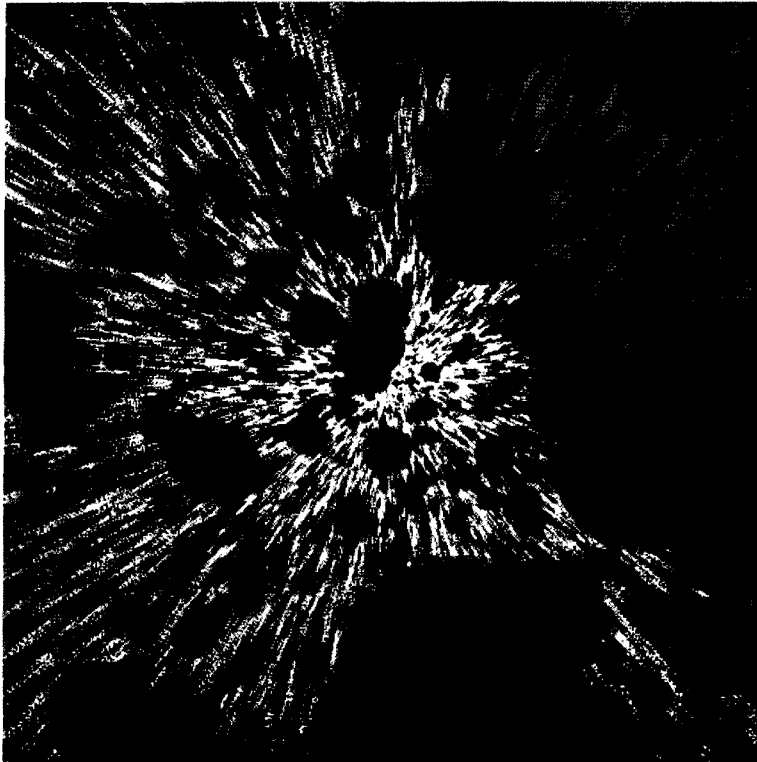
**plotting
from
high-level
languages**

One method uses a plotting program written in both FORTRAN and PL/I that allows a scientist to transmit arrays to be plotted. Options have been set up to specify types of grids, axes, data points, and labels. Scientists have produced simple graphs as well as complex line drawings, such as contour plots, using this method. A similar facility has been constructed along the same lines using APL. Figure 6 is an unusual contour plot showing a contour perspective of an array of cones that we call "explosion." The bases of the cones were shifted outward as the picture was being drawn to produce the explosive effect.

**plotting
from
existing
plotting
packages**

A second method uses add-ons to existing graphics languages. For example, the basic software packages for the CALCOMP plotter¹ and the GCS system⁴ have been modified to output PIC and LABEL files. These files can then be converted to a PICTURE file and sent to be plotted. This method is advantageous because it allows users to take programs that run correctly on one device and with minimal procedural changes rerun them to produce the high-quality output.

Figure 6 A halftone image of an unusual contour plot that was later titled *Explosion* (Copyright Benoit B. Mandelbrot, used with permission.)



The third method uses the interactive graphics terminals available at Research. Start/stop terminals are attached through the Advanced Terminal Subsystem (ATS), an IBM System/7-based front-end processor.⁵ The IBM 3277 Graphics Attachment RPQ⁶ and the IBM 3250 Display System, directly attached to the host systems, provide higher bandwidth and user interactivity. These terminals are supported through a common, device-independent interface. The data stream sent to these terminals can be recorded. Programs have been developed to take this stream and convert it to the PIC and LABEL files. This is a desirable mode of operations because it allows the user to see the picture as it is being drawn. It also eliminates the black-box approach to graphics, which is a condition inherent in batch processing.

Menu-driven programs are available for those who do not write their own programs. These programs guide the user in placing text and graphics on the screen and then produce the files required for hardcopy output.

plotting
from an
interactive
terminal

Graphics front end and host system

The use of the ATS system for graphic hardcopy requires a virtual machine (VM) that is called the Print Plot Machine (PPM). This machine receives plots from the ATS and converts them into the PIC and LABEL files. Figure 7 shows the flow of data from the application program to the terminal and back to PPM for processing.

system software services

The vast majority of the users at the Research Center use the services of the Conversational Monitor System (CMS) and VM/370. One of the most important features in the development of the proper tools to use the high-resolution printer is the EXEC processor. The allocation of the proper work files, the execution of programs, and the spooling of output from machine to machine are controlled mainly by EXECs. (EXECs are special-purpose programs written by and shared among Research Center users to perform special functions.) Often an experimental application can be interfaced with the printer by the creation of the proper EXEC. For example, halftones are produced by processing a LABEL file of halftone characters. Although a user can produce this file directly, EXECs have been set up to do this automatically. A typical application requires the programmer to produce a 512 by 512 array of halftone points. This array is processed by an EXEC that converts them to a LABEL file. The EXEC then runs LBLGRAPH and sends the halftone points (i.e., characters) to be plotted.

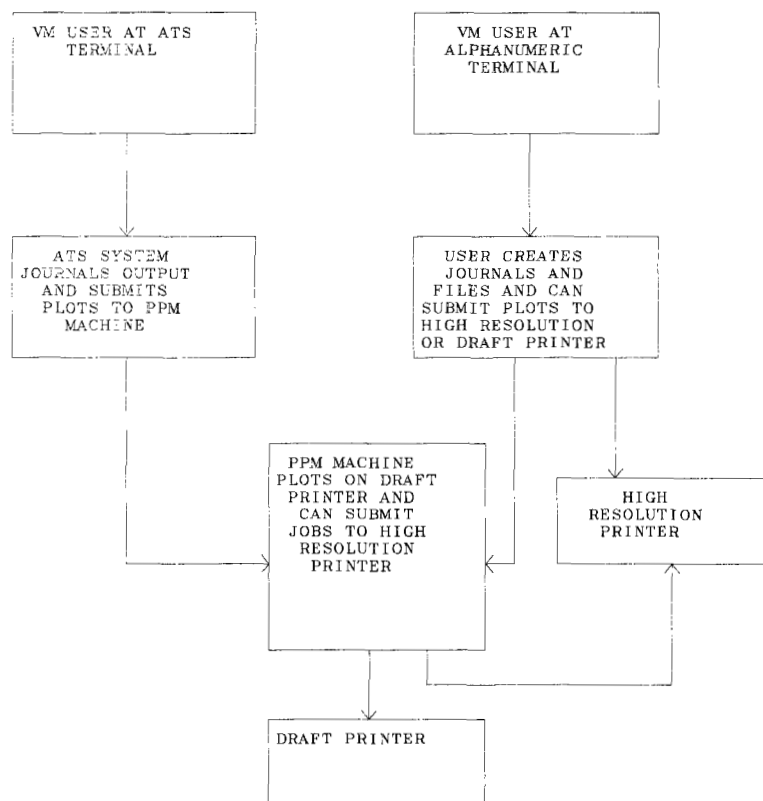
Print Plot Machine (PPM)

The Print Plot Machine (PPM) mentioned previously is a useful resource. In addition to converting ATS data to LBLGRAPH, this machine produces draft-quality output on a lower-resolution printer/plotter at 200 pixels per inch. The draft-quality output is identical in size and format to that of the high-resolution printer, but with only one-quarter the resolution. The lower-resolution machine is used primarily for the drafting of text documents. Many graphics documents bound for the experimental printer are plotted initially in draft form for a quick check. The rapid turnaround and the elimination of the photographic process save both time and money for the user who requires a draft copy. Figure 7, which shows the flow of data to the PPM machine, was produced on the draft printer.

Concluding remarks

The examples of art and text presented in this paper suggest the range of applications that are possible through the use of the high-resolution graphics system at the IBM Research Center. Simplicity provides the users with the freedom and capability for producing high-quality reports and publications. The high-resolution graphics system provides increased potential for creating artwork of heightened scientific and business interest.

Figure 7 Data flow from display station to high-resolution or draft printer output



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