

Electronic displays for information technology

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The principal channel of interactive communication from a computer to a person is an electronic display. The amount of information shown and the way in which it can be exhibited depend on successfully matching the capabilities of the display to the human visual system. Making this channel as wide, as fast, and as effective as possible has been the goal of electronic display development for the last fifty years. The cathode ray tube (CRT), which has been the dominant display device used in offices and homes, is the display device on which the personal computer and the graphical user interface were developed. Today, the capabilities of information technology are brought to new environments by new display technologies. Active-matrix liquid crystal displays (AMLCDs) have freed the personal computer from the desktop, projection displays bring the power of information technology into meetings, small liquid crystal displays have allowed the development of hand-held computers, and head-mounted displays are bringing wearable computer technology onto the factory and warehouse floor.

Introduction

In July 1945, at the end of the Second World War, the Director of the Office of Scientific Research and

Development, Vannevar Bush, wrote an article entitled "As We May Think" for the *Atlantic Monthly* [1]. The article exhorted the scientific and technical communities which were ending their work on weapons to develop new technologies to "give man access to and command over the inherited knowledge of the ages." In the article Bush describes the Memex, "a device in which an individual stores all his books, records and communications." The Memex would allow its operator to link together pieces of information and to send sets of this linked information to other people. This is now widely recognized as an early description of hypertext. The information displayed by the Memex would be visible on "slanting translucent screens, on which material can be projected for convenient reading." Bush based his prognostication on the use of microfiche for data storage and envisioned that memos, letters, drawings, photographs, magazines, and newspapers would be stored in the Memex.

Today the Memex exists as the combination of the personal computer and the Internet. Over the last fifty years the development of the digital computer, magnetic storage, and communication technologies have allowed the Memex to become smaller and more powerful than Vannevar Bush had envisioned. However, all of the original goals for the Memex have not been fully met; the displays that are used on personal computers today do not allow a full page of printed text to be shown and easily read. Instead, the display shows a smaller region of the page, and the viewer can move around the page by panning and zooming. Reading a page from a newspaper in this manner on a current personal computer is tedious.

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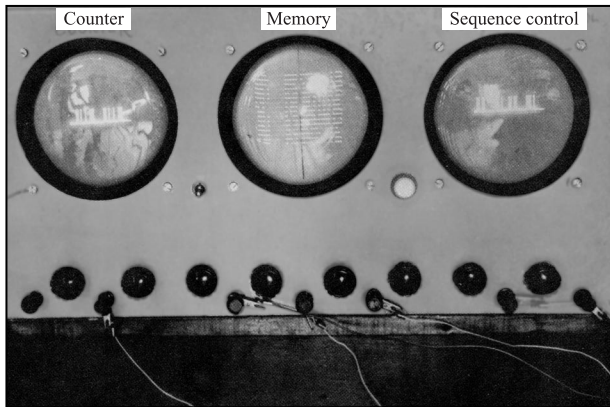


Figure 1

EDSAC display. Built at Cambridge University in 1949, the EDSAC digital computer was the first to use cathode ray tubes to display information. The center display shows the contents of the memory.

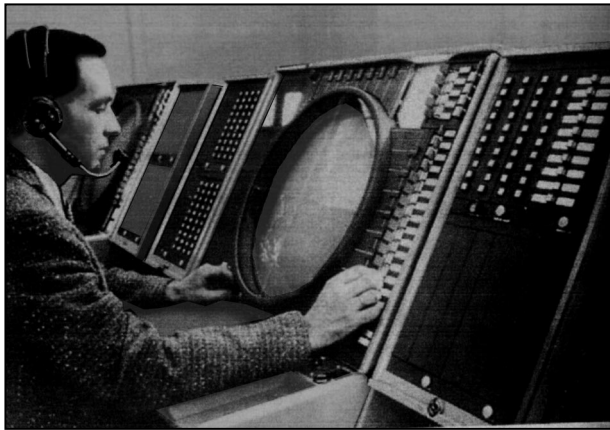


Figure 2

SAGE operator console. Project SAGE, sponsored by the U.S. Air Force, was designed to provide air defense for North America. The system used cathode ray tubes in the operator consoles to show aircraft flight paths and other radar data and to provide for operator input. The computer supplied the data to the display and interacted with the operator, who used a “light gun” containing a photosensor that detected when the desired point on the screen was being refreshed by the drive electronics. This permitted the operator to designate a single flight path from among many and to perform operations on that flight path such as naming it.

The first use of an electronic display on a digital computer was the Electronic Delay Storage Automatic Calculator, EDSAC, built by Maurice V. Wilkes at Cambridge University in May 1949 [2]. The machine utilized cathode ray tubes to display the contents of the memory of the machine (**Figure 1**). Previously, early computers used

mechanical dials or printers to display their results. For a significant period after this, computers operated with punched cards and printouts to communicate with users. In the 1950s the SemiAutomatic Ground Environment (SAGE) [3] computer system operated by the U.S. Air Force to provide air defense for North America utilized monochrome CRTs to display airplane flight paths (**Figure 2**). The paths on the CRT screen were drawn using vector graphics. Only endpoint locations of line segments were stored and then used by the display’s electronics in drawing the line segment. This approach minimized the amount of memory required. The user could select an individual flight path with a “light gun.” The light gun used a photodetector to sense when an area of the display was being refreshed in order to select a flight path and to perform a variety of functions such as displaying the name and location of an aircraft on the screen. It was one of the first applications in which a large computer system allowed users to interact dynamically with the system’s collected data. This represented an expanded role for electronic information systems, since a user could access the computer and interact with large databases in collaboration with many other users. Telephone lines were used to connect remote stations into the network. The displays in the SAGE system served as a medium through which collaboration could occur. This electronic interaction with information led to the time-sharing systems of the 1960s. Engineering design and commercial applications dominated the early use of these computers.

In April 1964 IBM announced the 2250 Display Unit (**Figure 3**), on which much of the development of computer-aided design applications took place [3]. The IBM 2250 system used a monochrome CRT display with a working area of approximately 12 inches $\times$ 12 inches and a resolution of 85 pixels per inch (ppi). Bit-mapped graphics were used. In this architecture each pixel on the display was represented by a location in the computer’s memory. By changing the value in the memory locations in which the video data was stored, the image on the display could be altered. The 1024 $\times$ 1024 addressable pixels, requiring one million memory locations to represent them, were refreshed at a frequency of 40 Hz. A “light pen” based on the “light gun” in the SAGE system was included. The high cost of producing such a display system in the mid-1960s limited the application of the technology to high-end systems.

Interactive computer systems led to the development of the CRT-based terminal, which has been extensively employed in business applications such as accounting and word processing. The IBM 2260 Display Station, announced in 1965 (**Figure 4**), used a monochrome CRT to display up to 12 rows of 80 characters. A character generator was used to reduce the cost and communication bandwidth of the system. The pattern used to create each

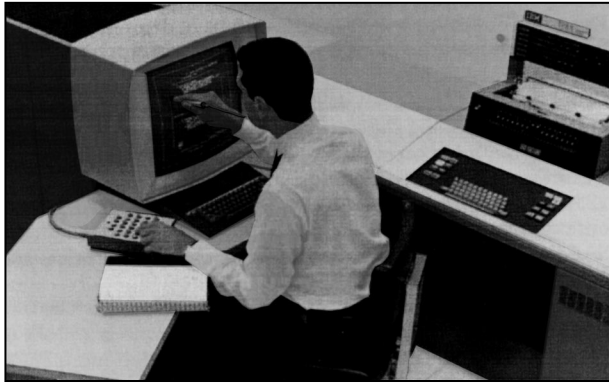


Figure 3

The IBM 2250 Display Unit, announced in April 1964, utilized a monochrome cathode ray tube with 1024×1024 -pixel addressability which was refreshed at 40 Hz. Like the SAGE operator console, the system included a "light pen" which could detect screen position. This display system was used to develop many of the techniques that are used in computer-aided design (CAD) systems. The working area of the display was approximately 12 in. $\times$ 12 in., giving the display a resolution of 85 ppi.

character was stored in read-only memory in the display. Character codes were sent to the display from the host computer, and the local pattern in the display memory was used to display the character. These initially text-based monochrome CRT terminals have been transformed into the personal computer, using a color CRT display. (Since user buying preference clearly favors color over monochrome displays, color displays dominate the marketplace, even though they have not achieved as low a price as monochrome displays.) The IBM 2260 systems displayed both text and graphics using a bit-mapped image of the screen in the computer memory, an arrangement similar to the method used in the 2250 Display Unit.

In the early 1970s, the Xerox Corporation set up a laboratory in Palo Alto, California, to perform research and development on the technologies that would make possible a "paperless office" [4]. By 1982, "What You See Is What You Get" (WYSIWYG) graphics on a computer was being reported by the press, the concept being that a document should appear the same on the computer screen as it would in its printed form. Intriguingly, from 1980 to 1993, even though the personal computer was revolutionizing the workplace, the consumption of paper in the United States rose from 67 million tons to 91 million tons. Although the personal computer had made possible word processing, people still preferred reading word-processed documents from paper to scrolling through a document on a computer display.

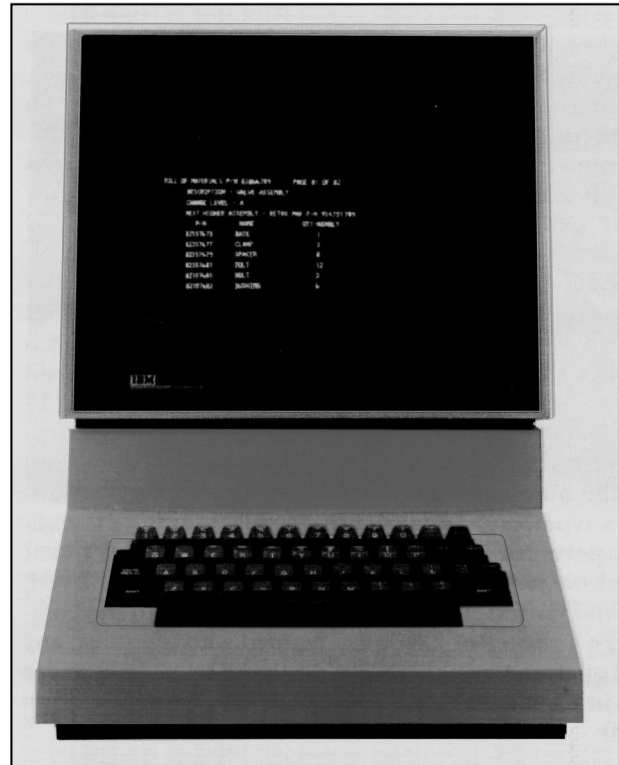


Figure 4

The IBM 2260 Display Station was a monochrome cathode-ray-tube-based text display which could display 960 characters in twelve rows of 80 characters. Announced in March 1965, this display was used in many early business applications.

The advantage of electronic displays has been their interactivity, despite the fact that their performance has not been equivalent to that of the printed page. In applications from air traffic to inventory control, the electronic display provides a means for interaction with the underlying data. Over time, electronic displays have improved: As the total number of pixels in the display has increased, and as those pixels have been made smaller, the quality of electronic text and graphics has approached that of the printed page. But this is not expected to eliminate paper from the office; instead, better screen renditions of information increase the performance efficiency of many office automation tasks. For example, design applications can benefit from the user seeing more of the design, thus reducing the time spent looking for the region that requires modification.

Display characteristics

The key characteristics of an electronic display which are of greatest importance to the user are screen size,

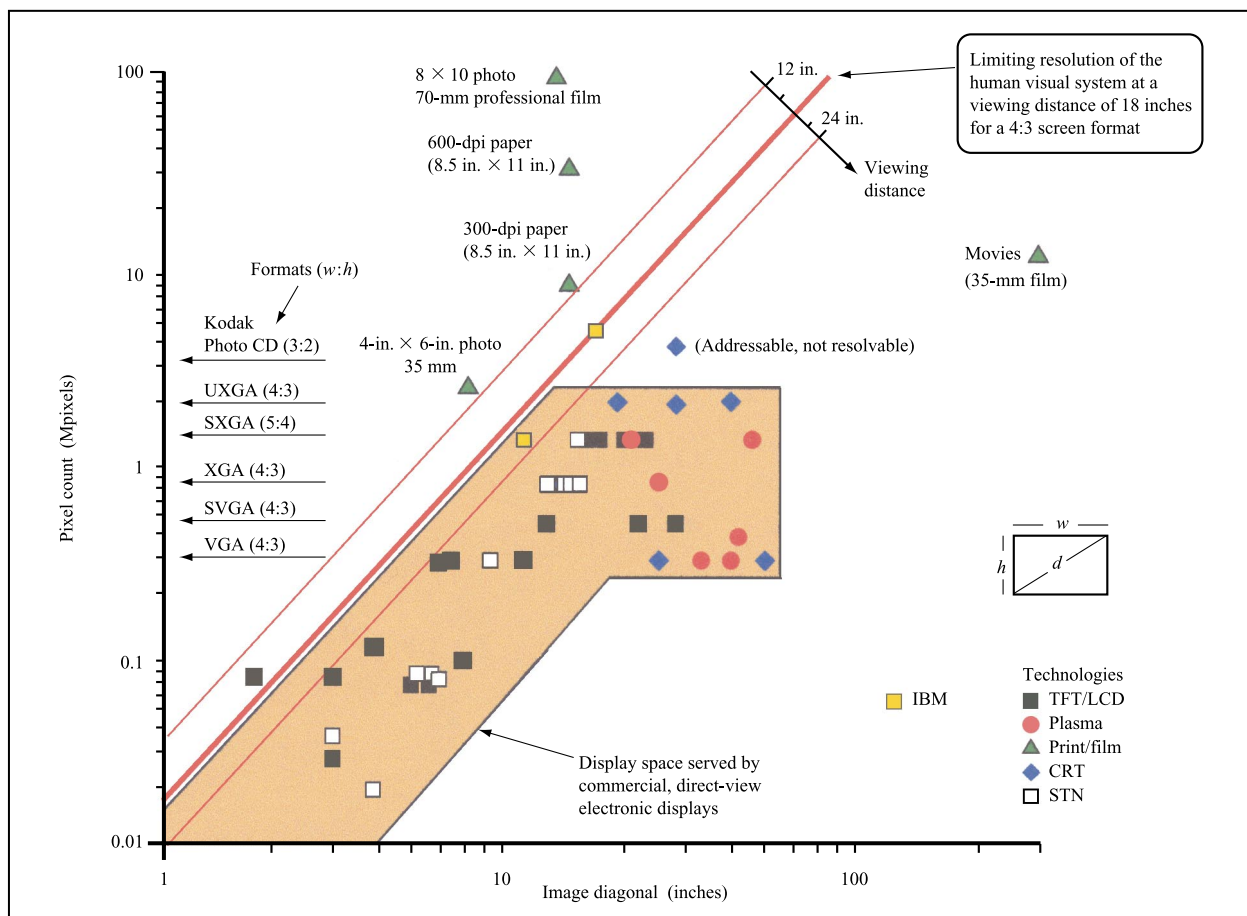


Figure 5

Display content versus display diagonal [5].

Table 1 Display formats and information content.

Format	Columns of pixels	Rows of pixels	Million pixels
CGA	320	200	0.06
EGA	640	400	0.26
VGA	640	480	0.31
SVGA	800	600	0.48
XGA	1,024	768	0.79
SXGA	1,280	1,024	1.31
UXGA	1,600	1,200	1.92
HDTV	1,920	1,080	2.07
QXGA	2,048	1,536	3.15
SONY DDM	2,048	2,048	4.19
QSXGA	2,560	2,048	5.24
Kodak CD	3,072	2,048	6.29

information content (total number of pixels), resolution (pixel size), color (degree of saturation and number of

levels of luminance), brightness, contrast, dependence of the image on viewing angle, and moving picture quality.

The range of currently available electronic displays with respect to screen size and information content (in megapixels) is shown in **Figure 5** for various technologies such as CRTs, liquid crystal displays, and plasma displays [5]. Also shown for comparison are photographs, print on paper, and movies (35-mm film). While electronic displays span a large range of sizes, current commercially available displays contain less than 2 megapixels of information content, while photographs, movies, and print on paper contain much more information. The information content of an electronic display is described by its format, as shown in **Table 1**.

The most common desktop monitor displays today use XGA format, although SXGA monitors are growing in popularity, and monitors with UXGA are available and are used in applications such as prepress, engineering design,

and other applications in which maximum information is required.

Figure 5 also shows the limit of resolution of the human visual system. Since the vast majority of electronic displays lie below the limit of human ocular resolution, people can actually see and perceive the individual pixels. This is not the case with printed characters or photographs and is one of the reasons that electronic displays are not as comfortable for reading and as pleasing for images as newspapers or photographs. One of the key challenges of display technology is to reduce pixel size to below the point at which humans can perceive individual pixels; accomplishing this is a goal for the future.

Electronic displays create colored pixels by combining red, green, and blue subpixels in close proximity. The degree of saturation of each primary color is determined by the mechanism for creating the color. Thus, CRTs use different colored phosphors and liquid crystal displays use different color filters. The range of possible colors, known as the color gamut of the display, can be plotted by using the 1931 CIE (Commission Internationale de l'Eclairage) chromaticity diagram shown in **Figure 6**. In this plot, the range of colors possible for a given display is represented by the area of the triangle whose corners are the red, green, and blue primary colors. The number of actual colors which can be shown is determined by the number of luminance levels (also known as gray scale) of each primary. The gray scale is determined by the electronics which drive the display. Today most new desktop monitors (CRT or LCD) are capable of an 8-bit (256-level) gray scale, resulting in more than 16 million possible colors. Most notebook computers use only 6-bit gray scale for cost reasons, although 8-bit drivers are available. A palette of 16 million colors with a large-area CIE plot for a given display is enough to satisfy most users, but further improvements in gamut and gray scale are possible.

The desirable brightness and contrast of the display depend on the ambient light level. In typical office or home lighting, a brightness of 150–250 cd/m^2 is adequate and is achieved by most new displays. For viewing in darkened conditions (such as watching television or movies), the darkness of the black state of the display is important; emissive displays such as CRTs and plasma displays are currently superior to liquid crystal displays with respect to the darkness of the black state. The contrast ratio is the ratio of the luminance of the white state to the luminance of the black state under ambient lighting conditions. Most good displays today achieve contrast ratios of 100 or more, and in the future this will also improve.

The performance of an electronic display can vary with viewing angle. While emissive displays such as CRTs can be viewed well at all angles, common liquid crystal displays lose contrast when viewed at non-normal angles.

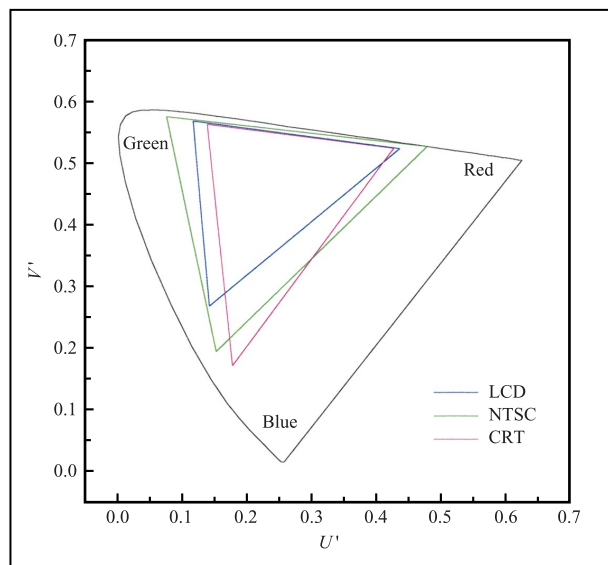


Figure 6

International CIE color diagrams with color coordinates V' , U' for typical CRT monitors and liquid crystal displays compared with the National Television Standards Committee (NTSC) specifications for color space.

In many LCDs the contrast ratio falls from more than 100:1 when viewed perpendicular to the display surface to less than 10:1 when viewed at $\pm 20^\circ$ in the vertical direction. Several new technologies have been developed for LCDs which increase their viewing angle to $\pm 70^\circ$ in all directions, so that viewing angle is much less of a concern for electronic displays today than it was several years ago [6–10].

The image quality of moving pictures also varies in electronic displays. Humans perceive continuous motion if they are presented with a series of still images in rapid succession. The quality of the perceived motion depends on there being a blank or black image between each of the still images. In a movie theater this is accomplished by a shutter which blocks the light while the film is advanced to the next frame. CRTs render motion well because the phosphor emits light for only a small fraction of the frame time. Because liquid crystals have more persistence, they typically show rapidly moving images with “ghosts” or other motion artifacts. This effect can be largely eliminated by pulsing the backlight of the LCD [11], but further work using different liquid crystals is continuing to improve video performance.

Given the above display characteristics, it is interesting to create a rough estimate of the display requirements for an electronic display to match the capabilities of the printed page. With this in mind, a

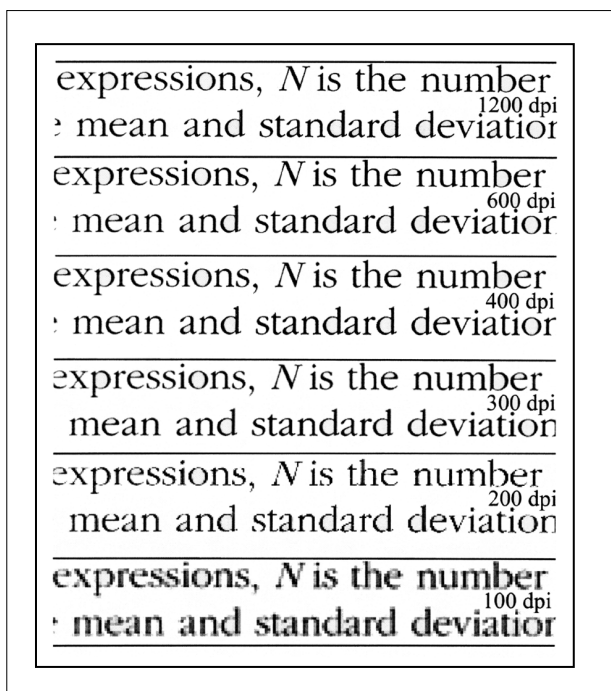


Figure 7

Effect of resolution on displayed text.

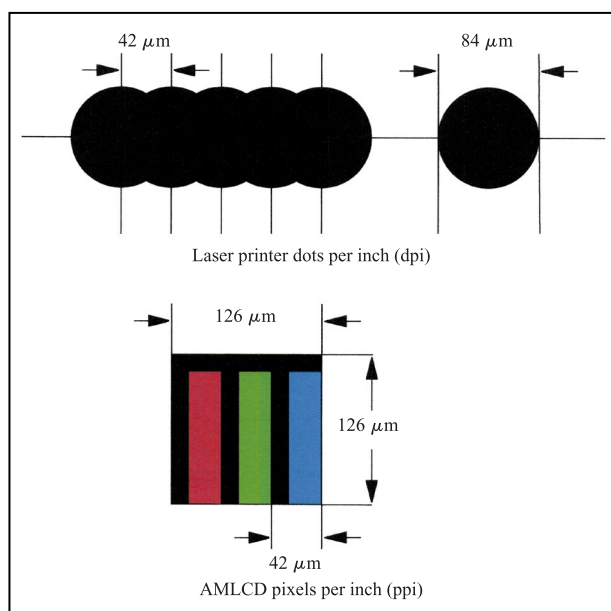


Figure 8

Laser printer dots and AMLCD pixels.

simple experiment was performed using a conventional desktop scanner (**Figure 7**). Text from a printed book was scanned in at different scanning resolutions, as indicated in the figure, printed on paper at 300 dots per inch (dpi), and then magnified so that the details of the shapes of the scanned characters could be discerned. In the examples shown in Figure 7, the capital letter N was originally 2.5 mm high and the lowercase letter S was 2.0 mm high. Scanning in at 100 dpi produces a very poor reproduction of the text. At 200 dpi jagged features are noticeable, but at 300 dpi and above the letters are rendered quite well. While this simple experiment hints that 300 dpi should be sufficient for electronic display of text, more complete analyses of the electronic display requirements have been performed by Larimer et al. [12, 13]. These analyses have indicated that by using suitable software to vary the gray levels of the pixels making up the characters, resolutions as low as 140 ppi could be used to display text with performance effectively equivalent to that of the printed page.

Laser printers generate images of letters by writing black dots on the page (**Figure 8**). A 600-dpi laser printer can locate the position of a dot within 1/600 of an inch (42 μm). The diameter of each of these dots is approximately 84 μm . Each dot overlaps its neighbors, thereby producing a smoother edge on the lines that make up a character. Laser printers with resolutions of 1200 dpi and 2400 dpi are also available. These printers use smaller dot sizes and finer dot position control to create smoother character edges and finer details. A typical 2.3-mm-high letter printed on a 600-dpi laser printer is made up of a vertical line of overlapping dots. Since the size, shape, and gray level of dots used in laser printers are so different from those of the pixels of electronic displays, it does not make sense to directly compare printed dots per inch (dpi) with pixels per inch (ppi). The proper comparison involves an understanding of the limits of human visual acuity, as indicated in Figure 5.

Cathode ray tubes

Cathode ray tubes (CRTs) are the most common electronic display in use in information technology. The CRT consists of an electron gun, electrostatic or magnetic fields to direct the electron beam, and a phosphor screen. When the electron beam strikes the phosphor screen, the phosphor generates light. A color display is made by using three electron guns and three different color phosphors to produce a broad range of colors. The profile of the electron beam is Gaussian, so that the dot of light on the screen is brighter in the center than at the edge. The brightness of the dot is controlled by the intensity of the electron beam. Color CRTs are typically manufactured with resolutions of approximately 100 ppi.

CRTs have been manufactured for more than fifty years. The tooling and techniques used were developed

specifically for the CRT and were designed for low-cost manufacturing. Although CRT technology is considered mature, advances in performance and cost reduction continue [14]. CRTs are being manufactured with higher brightness and contrast and with flatter tube faces, taking up less overall space. Flatter tube faces have required the development of thicker faceplates and new flatter shadow masks, leading to greater tube weight for a display of a given size. Although the luminous efficiency of phosphors has been constant for some time, the contrast and brightness of the display have been improved by reducing the reflectivity of the phosphor screen; this decreases the contrast of the display, allowing the faceplate of the display to be made less light-absorbing. (The faceplate is typically made light-absorbing to reduce the reflection of ambient light from the phosphor screen.) Tube length has been decreased by increasing the deflection angle of the electron beam. This has required a reduction in the aberrations that are introduced with larger deflection angles. To accomplish this, more sophisticated electron guns have been designed and built. Over the last decade, the CRT used with PCs has progressed from the EGA to the XGA format with an overall price decrease. CRT display technology is inherently able to handle multiple display formats on a single device, since the number of scan lines is determined by the drive waveforms that are applied to the display. Thus, a CRT display capable of XGA content is capable of lower-content modes as well.

In summary, cathode ray tube technology has continued to advance. Over time, the length of the neck of the tube for a given screen size has decreased. The face of the tube has become flatter, and the price has decreased. CRTs continue to have price/performance superior to those of other display technologies.

Flat-panel displays

Alternative display technologies were not in significant use until the 1990s. In the past ten years, however, active-matrix liquid crystal displays (AMLCDs) and other display technologies have seen increased application. Initially the driving force was thin, lightweight, low-power displays for mobile computing that could match the resolution and content of desktop CRTs. The decreasing price, larger screen sizes, and increased information content of AMLCD technology are increasing their acceptance in desktop applications.

In the 1980s, several manufacturers [15] applied AMLCD technology to pocket television screens. The success of such devices spurred development to increase the capability of the technology to produce displays for notebook computers. The primary obstacles to such development were the manufacturing yield and power efficiency of the display. The pocket television typically contained fewer than 100 000 transistors, with each



Figure 9

The IBM ThinkPad 700C notebook computer was announced in 1991. It utilized a 10.4-in.-diagonal VGA (640 × 480-pixel) active-matrix liquid crystal display.

transistor used to address a single subpixel; a VGA-content AMLCD requires almost a million transistors distributed over a much larger area. The increased area and complexity of the notebook computer displays required greater attention to many aspects of their fabrication. For example, during display fabrication, foreign material such as dust can cause defects in a display, reducing manufacturing yield and increasing cost. Such foreign material can have many sources in a factory, since it can be generated by every moving part on every tool. Close cooperation between tooling vendors and display manufacturers was required in order to improve tool reliability and reduce dust. Electrostatic discharge also poses a significant threat in the factory, since the displays are built on an insulating substrate (glass) and moving or sliding the plate can induce electric charge on it. Strategies to discover and control these problems required significant development time.

Reducing the display power required improving the aperture ratio of the display. (Aperture ratio is the ratio of the display area that transmits light to the total display area.) Early displays had aperture ratios of roughly 30 percent; today aperture ratios exceed 60 percent. By 1991 factories had come on line which could produce 10.4-in.-diagonal VGA displays. In that year, IBM announced the Thinkpad® 700C notebook computer (**Figure 9**), which

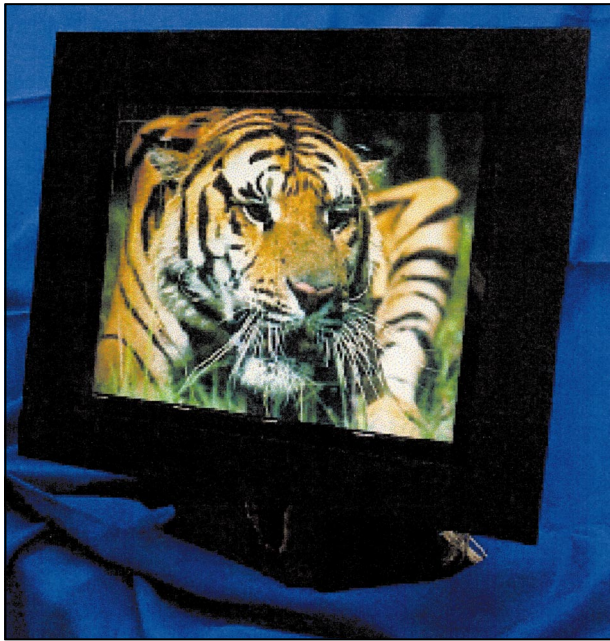


Figure 10

The Roentgen AMLCD prototype is a 16.3-in.-diagonal display with a resolution of 200 ppi and a content of more than five million pixels. The display can portray text and graphics in the desktop environment with fidelity comparable to that of traditional hard-copy output such as photographs and the output from laser printers.

utilized the new AMLCD display. As the technology has progressed, the glass substrate size used in the factory and the size of the display have increased. Today a typical AMLCD factory uses a 650-mm $\times$ 720-mm substrate on which six 13.3-in.-diagonal XGA displays are fabricated simultaneously. The performance goal of these notebook computer displays was to match the capabilities of the CRTs used for personal computers. They are designed with the same pixel content and resolution used in desktop displays.

A recent trend is the application of AMLCDs to large desktop monitors. This initially occurred in situations in which space and power were of significant concern, as for example in financial trading rooms. With continued price reductions, AMLCDs are appearing in the office environment. The display requirements for these applications are different from those of notebook computers; a wider viewing angle, higher luminance, and larger-size viewing area are required in these products. An advantage of flat-panel displays is that a large-viewing-area display does not consume much desk space. In addition, flat displays allow the width of the panel to be much larger than the height with no penalty in depth. This

is not the case with the CRT, making it more difficult to fabricate CRTs which are wide enough to display the equivalent of two pages of information side by side. Over time the flat-panel display may include more of the system function of the personal computer, allowing new form factors in desktop systems.

Recently, AMLCDs have been developed which significantly exceed the resolution of a typical shadow-mask color cathode ray tube. Color CRTs achieve a pixel resolution of approximately 100 ppi [16]. At the 18-in. viewing distance typical for desktop work, the normally corrected human eye can resolve features that are 1/200 of an inch in size. Recently a prototype 200-ppi color AMLCD has been built (**Figure 10**) that approaches the acuity of the eye [17]. This 16.3-in.-diagonal display contains more than five million pixels and more than 15 million subpixels. On this display, text has the appearance of laser printer output; photographic images look like positive prints. **Figure 11** shows examples of magnified text images on a typical CRT, a common notebook computer display, and prototype LCDs at 150 ppi [18] and 200 ppi. The characters on the CRT appear smooth but somewhat fuzzy because of the diffuse shape of the electron beam. The pixels on the LCDs are sharp, but the low resolution of the notebook computer display shows jagged, poorly defined characters. At 150 ppi the jaggedness of the characters is much reduced, and this is further improved in the 200-ppi display. At 200 ppi the individual pixels are not resolved by the eyes of a normal person at a normal viewing distance, as shown in Figure 5, so the characters appear to be very smooth. At 200 ppi the individual letters, such as the "g" in the word "gives," have all the characteristics of a printed letter, with different thicknesses for different parts of the letter.

While 200-ppi displays have a greatly improved appearance, there are still some image defects that remain. Even higher resolution will be required to improve the quality further, and this will be the subject of future technology development. Such high-resolution displays will allow users to view drawings, text, and images with full detail. Initially, high-resolution display technology will be useful in applications in which high-information-content media are currently used. These include medical applications, CAD, graphic arts, and publishing. The technology is well suited to displaying scanned information. Whether the image source is a medical X-ray, a digital photograph, or a scan of a rare book, the appearance of the image in the display gives an excellent rendition of the original. Such displays are also useful as true WYSIWYG displays, since the screen image truly resembles the hard-copy output. Ultimately the technology will serve as a method for delivering a digital rendition of books, photographs, and art into the home. This will turn

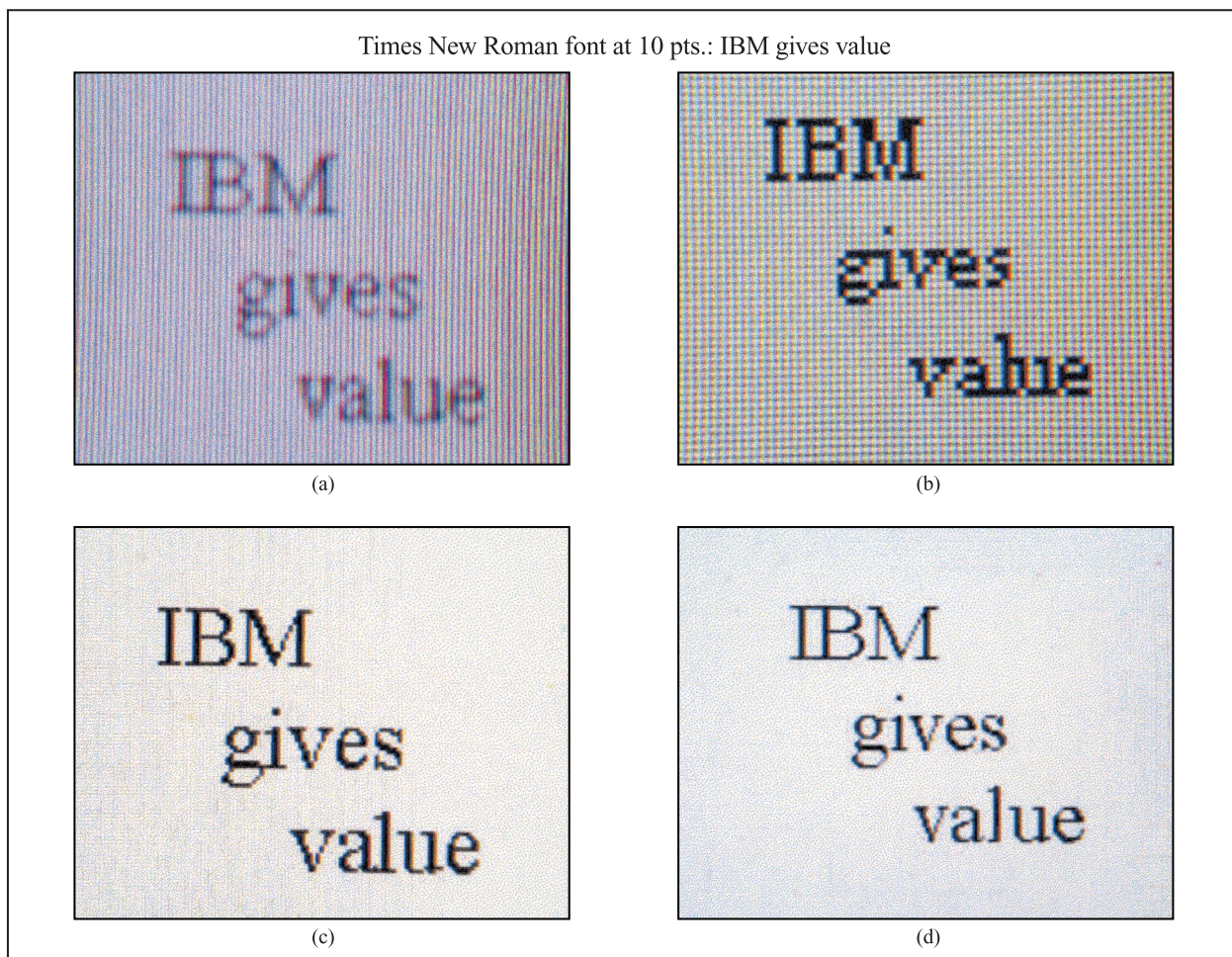


Figure 11

The screen image of a 0.25-mm shadow-mask cathode ray tube (a) is compared with an 83-ppi active-matrix liquid crystal display (b), a 150-ppi AMLCD (c), and the Roentgen 200-ppi AMLCD (d). The CRT screen image shows the diffuse edge of the Gaussian spot of the electron beam. The 83-ppi commercial AMLCD shows the sharp edges of the characters but has a boxy appearance; as the resolution is increased, image fidelity improves.

the display into an on-line catalog with photographic-quality images of the products.

Initially, very high-resolution liquid crystal displays will be designed for desktop applications. The aperture ratio of the initial displays will be too low for battery-powered operation. Further development will be required to increase the aperture ratio. Higher-resolution portable or hand-held displays have increased readability, which is generally recognized as a requirement for improving current displays, but at present this is very difficult to achieve because of the low power requirements of portable hand-held devices.

Significantly, high-resolution displays can make practical use of existing amorphous silicon technology

manufacturing lines to fabricate new types of products.

Amorphous silicon technology is very extendable [19].

However, displays having higher resolution and higher content place a much greater demand on the ability of the manufacturing process to consistently yield fine structures. The metal lines that distribute electrical signals over the display must be deposited with low-resistance aluminum or copper. The color filters must be fabricated with tighter tolerances to accurately overlay the subpixels of higher-resolution displays. Additional manufacturing experience will be required to produce such devices with high yield. High-resolution displays also place new demands on the graphics system of the computer. The QSXGA (Table 1) prototype display shown in Figure 10 requires data rates

of almost 1 GB/s between the frame buffer and the display when the display is refreshed at 60 Hz [17]. Four SXGA display adapters are used to render this display, and the display is split into four virtual displays for rendering purposes [17]. Such parallel approaches significantly reduce the operating frequency required. New approaches to reduce the bandwidth of the graphics system must be explored and developed.

Although application software and operating systems have been developed using CRTs, some aspects must be modified in order to add support for high-resolution displays. Currently the software of the graphical interface takes account of the information content of the display format, as indicated in Table 1. The software does not independently take account of the resolution of the display or adjust for it. Thus, if the software presents its data to the display in a VGA format, it will occupy only 1/16th of the area of a QSXGA display. The high-resolution displays of the future will go well beyond the capability of CRTs in terms of information content and resolution, and the systems and software will have to take this capability into account. This is similar to the situation that arose when laser printers became widely available for personal computers.

Current-generation AMLCD factories have been designed to fabricate several notebook computer screens on a single sheet of glass. These factories are capable of building single displays with up to a 30-in. diagonal. It is likely that the desktop display of the future will have an aspect ratio that is significantly wider than the current 4:3 aspect ratios of CRTs. Instead, an aspect ratio of 16:9, such as that used in HDTV, will become more popular. These displays can show two pages of text on the screen simultaneously, can contain more than 10 million pixels, and will go beyond the QSXGA format that has been prototyped.

Displays have traditionally been oriented vertically in the office environment. Flat-panel displays allow the display to be tilted at any angle, creating the electronic equivalent of the drafting table or artist's sketch pad. These displays will require touch and pen input capability. The goal is to have AMLCDs match the size, resolution, and color fidelity of currently used drafting tables or artists' tablets.

Large-area displays

Enabling groups of people to work together requires building devices with very large displays. The most widely used large-area display is the CRT-based projector. For color, three CRTs are typically used, with one tube producing the red image, another the green, and the third the blue. The images are combined on the screen to produce a full-color image. Alternative technologies which are becoming important in large-area displays include a

display developed by Texas Instruments which is based on small mirrors built on top of a silicon chip and moved under electrical control. Several companies have developed liquid-crystal-on-silicon displays, which use liquid crystal effects similar to those used in notebook computers to modulate light [20–22]. Polysilicon-based liquid crystal displays have been applied to conference-room projectors. The Hughes JVC Corporation has developed a liquid crystal display which is addressed using a small CRT [23, 24]. A number of display producers are also working on plasma display technology; flat displays up to 60 in. diagonal have been fabricated [25, 26]. Plasma technology displays are manufactured using screen printing to define the pixel structure. Although this is a limitation for high-resolution applications, it works well for fabricating large-area displays. These displays are used for presentations using a notebook computer and for situations in which groups of people, some of whom may be located at a distance, desire to work together. Large-area displays can then function as an electronic chalkboard on which people may draw their ideas and notes, as a screen for presentations, and as a window into a distant room to see who is speaking. The requirements for this kind of display are different from those of desktop displays. The users will in general be located farther away, so that less than 50 ppi may be sufficient, whereas the size of the display will range from 30 inches to 100 inches in the office environment. The content of these displays would range from 1 to 12 million pixels.

Small hand-held devices

Small portable devices present special requirements for displays [27], since power and allowable thickness are limited. The earliest hand-held displays, which appeared in wristwatches and calculators, were seven-segment liquid crystal displays—the simplest liquid crystal display devices. Each segment was hard-wired directly to the switchable power source. If there were N segments, $N + 1$ connections were needed (the additional one is for the common electrode) to drive such a display. To reduce the number of connections as the information content was increased, the simple matrix method was developed. A simple matrix consists of rows and columns of transparent electrodes in which the pixels are formed at the electrode crossings. The one-row-at-a-time driving method is typically used to address the simple matrix display. If a simple matrix display has M rows and N columns, the number of connectors is $M + N$, and the number of addressable pixels is $M \times N$. For a reasonably large number of M and N , say more than 10, the number of connectors is substantially reduced for the simple matrix display in comparison to the seven-segment display, having a number of segments equal to the number of addressable pixels of the simple matrix display.

Twisted nematic (TN) liquid crystal material was first used for simple matrix display. Because the transmission versus voltage (T-V) curve is not sharp enough, the maximum number of rows is limited to 30 or less [28]. To raise the number of addressable rows, the super-twisted nematic (STN) material, which has a much steeper transition in the T-V curve, was developed. Using STN material, VGA and XGA formats are achievable with a double-scan driving method (two sets of data drivers located on the top and bottom of the panel, with each set driving half of the display).

Today, a simple matrix-twisted nematic reflective display is typically used in hand-held devices such as pagers, personal digital assistants, and some palm-top computers. Such displays utilize a reflective liquid crystal mode to save power. Liquid crystal displays in notebook computers are backlit using cold-cathode fluorescent lamps. For a smaller display, the length of the cold-cathode fluorescent lamp is reduced. The efficiency of the cold-cathode fluorescent lamp drops off significantly as the length of the tube is reduced, increasing the amount of power that would be dissipated in the backlight. If the application environment lacks adequate light to use a reflective liquid crystal display, a transfective display is used. This display works as both a reflective and a backlit display. When the external light becomes too dim, a powdered electroluminescent backlight is used to illuminate the display. Performance compromises are made to obtain both backlit and reflective performance.

New materials are being developed which may improve the performance of monochrome reflective displays [29]. Microencapsulated electrophoretic materials offer a high-reflectivity transducer that has a long lifetime. Obtaining a bright, high-contrast reflective display is important; newspaper has a reflectance of 60%, and most small reflective displays have only half this reflectivity, which reduces the legibility of the device.

Reflective color displays have been extensively studied [30]. As with reflective monochrome displays, reflective color displays have low reflectance, rendering operation more difficult in dim lighting situations.

Head-mounted and virtual displays

In hand-held applications in which higher information content is desired, displays that are viewed through magnifying optics offer an attractive solution. Displays with up to 1.2 million pixels of content (SXGA) have been demonstrated [31]. These displays are low-cost because of the small area of semiconductor used to create the display. They are low-power, since all of the light that leaves the display enters the user's eye. Such displays may be used in a number of different form factors—for example, small devices such as pagers or cell phones

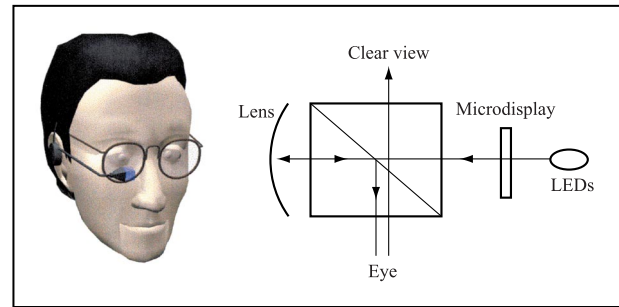


Figure 12

Design of head-mounted display.



Figure 13

Head-mounted wearable display.

which are held to the user's eye for viewing faxes or maps. Alternatively, a head-mounted display is a well-known example of a display separate from the rest of the system (**Figures 12 and 13**). Systems which display images to both eyes are used in virtual-reality applications, and systems which provide an image to only one eye are used to provide information for applications such as inventory control, maintenance, and the construction industry.

Several types of display are used to build head-mounted and virtual displays [32, 33]. The most common is the monochrome CRT used in many camcorder viewfinders. Polysilicon liquid crystal displays that employ color filters to construct a small color viewfinder have also been used. The Kopin Corporation has pioneered a technology which builds a conventional integrated circuit on a decal that can be applied to a glass surface. This allows the fabrication of

Table 2 Calculations of head-mounted display design (courtesy of Russell Budd, IBM Research).

<i>Screen content</i>	<i>Screen diagonal size (in.)</i>	<i>Viewing distance (in.)</i>	<i>Diagonal field of view (degrees)</i>	<i>Pixel angular resolution (pixels/degree)</i>
VGA 640 × 480	10.4	18	32.2	24.8
	10.4	24	24.5	32.7
SVGA 800 × 600	10.4	18	32.2	31
	10.4	24	24.5	40.9
	12.1	18	37.2	26.9
	12.1	24	28.3	35.3
XGA 1024 × 768	13.3	18	40.6	31.6
	13.3	24	31	41.3

a display with more of the control circuitry built into a very small area. Several groups have built reflective liquid crystal cells on top of silicon wafers. This also has the advantage of a high degree of integration without the need to fabricate a decal. The drawback of the technique for head-mounted and virtual applications is the more restrictive illumination requirements of the reflective cell. Organic light-emitting diodes (OLEDs) can also be built on top of silicon wafers. The FED Corporation has prototyped a VGA display that is nearly ideal. Because the OLED material produces light directly, no additional light source is needed, just a lens to image the display; this allows for a very compact head-mounted display. The optical design of a head-mounted display is shown in Figure 12. **Table 2** shows the diagonal field of view measured in degrees for typical notebook computer displays at 18-in. and 24-in. viewing distances.

In these calculations, the diameter of a typical exit pupil used to design head-mounted displays is 6 to 8 mm. For eye relief, or the distance from the user's eye to the lens that images the display, typical values are 25 to 35 mm. The object is the display itself. The diagonal field of view ranges from 24 to 40 degrees, with a pixel angular resolution of 24 to 40 pixels per degree, well below the visual acuity limit of the eye, which is one minute of arc.

A prototype head-mounted display has been made which houses the lens and display within a half-inch cube; with 25 mm of eye relief and an exit pupil of 4–6 mm, the device has a resolution of 21 pixels per degree. The device is comfortably small (Figure 13). The device content could be tripled before reaching the acuity limit of the eye, allowing it to reach XGA content.

Stereoscopic displays

Over the last ten years, virtual reality has become an area of intense research. The goal of such systems is to present to the viewer an interactive three-dimensional space that is generated within the computer. The viewer can move within the space and interact with objects or other users

in the space. The systems are typically immersive; that is, the viewer's entire visual field of view is covered by the display system. When the objects within the space are close to the viewer, typically within an arm's length, the human visual system detects the binocular disparity of the scene (the difference between the right-eye and left-eye views of the scene). The human visual system merges these two images into a three-dimensional view of the scene. Applications in the design and synthesis of new chemical compounds; interaction with a designed system not yet built, such as an aircraft, to determine how easily the machine may be operated and serviced; linking of a human being to a remote system while providing a sense of "telepresence"; all have been exploited in industrial settings. In the home, head-mounted three-dimensional displays will first be applied to computer-based games.

Head-mounted displays are typically associated with virtual reality systems. Although the earliest stereoscopic head-mounted displays utilized CRTs, these have been superseded by polysilicon liquid crystal displays and other systems which make possible a lighter head-mounted device. Each eye looks into a separate display, and each of the displays is connected to a separate rendering engine to produce two views of the scene. As with head-mounted displays that provide two-dimensional imagery, the weight of the display is crucial for ease of use.

In 1992 the University of Illinois Electronic Visualization Laboratory demonstrated the CAVE, a 10 × 10 × 9 cubic foot space in which three of the walls are screens with rear-projected imagery, with an additional projector that places imagery on the floor of the space. All of the imagery is stereoscopic and time-multiplexed; viewers wear glasses which contain shutters that open when the imagery for that eye is being displayed. One of the users has a head tracker, and the imagery is generated from that user's viewpoint. Several users can be immersed in the virtual environment. This is advantageous for situations requiring collaboration in a virtual environment. Newer designs have reduced the form factor of this sort of

environment and have developed systems in which two viewers can each see their viewpoints correctly displayed.

Although these systems can generate the sensation of three dimensions within the human visual system, they do so without using all of the cues that humans use in actual environments. In particular, the three-dimensional imagery in these systems does not allow the user to shift the focal point of the eye when looking at a part of the three-dimensional object that is nearby.

Holographic displays

Holography is an image-generation technique which can correctly display all of the visual depth cues employed by the human visual system. Electronic holography uses an electronic transducer to create a holographic fringe pattern which generates the desired image. As with stereoscopic displays, holographic displays are most useful for situations in which three-dimensional objects are within arm's reach of the viewer. Holographic displays also provide a path to a collaborative environment in which each viewer will have the scene correctly displayed without wearing any additional hardware. In the past ten years, prototype interactive electronic holographic display systems have been fabricated by the MIT Media Laboratory [34].

The principal requirements of an interactive electronic holography system are the ability to calculate and display the correct holographic fringe pattern in real time. Calculating the fringe pattern for a holographic display is hundreds of times more difficult than rendering a two-dimensional display image. It is estimated that off-the-shelf hardware capable of rendering holograms in real time is still years away.

The computing requirement for a cubic centimeter of holographic video is roughly one billion operations per second. Rendering a holographic apple requires roughly a cubic liter, or 1000 times more computing capacity. The desired transducer for holographic video is a phase-modulating device with 256 output levels and a quarter-micron pitch. Current liquid-crystal-on-silicon spatial light modulators have a pitch around 10 μm , or 40 times larger than is required.

Conclusions

Tremendous progress has been made over the last forty years in electronic information display. Technological developments now underway will lead to information-display capabilities that will exceed Vannevar Bush's 1945 vision of the Memex; the ability to see the full content of hard-copy documents and video, the ability to see multiple documents simultaneously, and the ability to create and modify documents instantly will allow people to learn and work more easily.

Electronic displays are playing a vital role today in opening up new types of information devices and enhancing the functions of traditional devices. CRT displays for desktop computers are becoming smaller and brighter, with increased resolution and content. Active-matrix liquid crystal displays are bringing the legibility typically associated with hard copy to desktop and portable applications, resulting in new products and dramatically enhancing some existing applications. Projection display technology is allowing information technology to connect collaborating groups. Further out in time, head-mounted displays will bring information technology to many manufacturing and service applications. Eventually technological improvements will permit the economical construction of holographic displays.

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References

1. Vannevar Bush, "As We May Think," *The Atlantic Monthly* **176**, No. 1, 101–108 (July 1945).
2. Charles Eames and Ray Eames, *A Computer Perspective*, Harvard University Press, Cambridge, MA, 1973.
3. Emerson W. Pugh, Lyle R. Johnson, and John H. Palmer, *IBM's 360 and Early 370 Systems*, The MIT Press, Cambridge, MA, 1991.
4. John Seely Brown, "PostModern PARC," *The Red Herring* magazine, pp. 28–32 (June 1997).
5. P. M. Alt and K. Noda, "Increasing Electronic Display Information Content: An Introduction," *IBM J. Res. Develop.* **42**, No. 3/4, 315–320 (1998).
6. S.-C. Lien, C. Cai, R. W. Nunes, R. A. John, E. A. Galligan, E. Colgan, and J. Wilson, "Multi-Domain Homeotropic Liquid Crystal Display Based on Fringe Field Structure," *Jpn. J. Appl. Phys.* **37**, 597 (1998).
7. A. Lien, R. Nunes, R. A. John, E. Galligan, E. Colgan, J. Wilson, and C. Cai, "Ridge and Fringe-Field Multi-Domain Homeotropic LCD," *1998 SID International Symposium Digest of Technical Papers*, Society for Information Display, 1998, pp. 1123–1126.
8. R. Kiefer, B. Weber, F. Windscheid, and G. Baur, "In-Plane Switching of Nematic Liquid Crystals," *Proceedings of Japan Display'92*, 1992, p. 547; M. Ohta, M. Oh-e, and K. Kondo, "Development of Super-TFT-LCDs with In-Plane Switching Display Mode," *Proceedings of Asia Display'95*, 1995, p. 707.
9. Y. Koike, S. Kataoka, T. Sasaki, H. Tsuda, A. Takeda, and K. Ohmuro, "A Vertical Aligned LCD Providing Super-High Image Quality," *Technical Digest, International Display Workshops (IDW'97)*, 1997, p. 159.
10. Y. Tanaka, Y. Taniguchi, T. Sasaki, A. Takeda, Y. Koibe, and K. Okamoto, "A New Design to Improve Performance and Simplify the Manufacturing Process of High-Quality MVA TFT-LCD Panels," *1999 SID International Symposium Digest of Technical Papers*, Society for Information Display, 1999, p. 206.
11. K. Sueoka, H. Nakamura, and Y. Taira, "Improving the Moving Image Quality of TFT LCDs," *Conference Record of the 1997 International Display Research Conference and International Workshops on LCD Technology and Emissive Technology*, 1997, pp. 203–206.
12. J. Gille, R. Samadani, R. Martin, and J. Larimer, "A Human Visual Discrimination Model Analysis of the Gray Scale/Resolution Tradeoff: Displays with 150 dpi or Less

- Resolution [LCDs]," *1994 SID International Symposium Digest of Technical Papers*, Society for Information Display, 1994, pp. 494–497.
13. J. Larimer, J. Gille, and J. Luszcz, "Display Resolution Tradeoffs: Grayscale Spacing," *Conference Record of the 1997 International Display Research Conference and International Workshops on LCD Technology and Emissive Technology*, 1997, pp. 262–265.
 14. M. Maeda, "Trends in CRTs," *Proceedings of the 19th International Display Research Conference Workshop*, Berlin, 1999, p. 177.
 15. S. Morizumi, K. Oguchi, T. Misaya, and H. Ohshima, "B/W and Full Color LC Video Displays Addressed by Poly-Si TFTs," *SID Symposium Digest*, 1984, pp. 316–319.
 16. Larry Tanas, Jr., *Flat Panel Displays and CRTs*, Van Nostrand Reinhold Co., New York, 1985.
 17. K. Schleupen, P. Alt, P. Andry, S. Asaad, E. Colgan, P. Fryer, E. Galligan, W. Graha, P. Greier, R. Horton, H. Ifill, R. John, R. Kaufman, A. Lanzetta, K. Latzko, S. Libertini, F. Libsch, A. Lien, M. Mastro, S. Millman, R. Nunes, R. Nywening, R. Polastre, J. Ritsko, M. Rothwell, K. Warren, J. Wilson, R. Wisnieff, S. Wright, C. Yue, M. Kodate, S. Takasugi, H. Kinoshita, and H. Kitahara, "High-Information-Content Color 16.3" Desktop-AMLCD with 15.7 Million a-Si:H TFTs," *Proceedings of the 18th International Display Research Conference*, Seoul, 1998, p. 187.
 18. E. G. Colgan, P. M. Alt, R. L. Wisnieff, P. M. Fryer, E. A. Galligan, W. S. Graham, P. F. Greier, R. R. Horton, H. Ifill, L. C. Jenkins, R. A. John, R. I. Kaufman, Y. Kuo, A. P. Lanzetta, K. F. Latzko, F. R. Libsch, S.-C. A. Lien, S. E. Millman, R. W. Nywening, R. J. Polastre, C. G. Powell, R. A. Rand, J. J. Ritsko, M. B. Rothwell, J. L. Staples, K. W. Warren, J. S. Wilson, and S. L. Wright, "A 10.5-Inch-Diagonal SXGA Active Matrix Display," *IBM J. Res. Develop.* **42**, No. 3/4, 427–444 (1998).
 19. W. E. Howard, "Limitations and Prospects of a-Si TFTs," *J. SID* **3**, No. 3, 127–132 (1995).
 20. P. M. Alt, "Single Crystal Silicon for High Resolution Displays," *Proceedings of the 17th International Display Research Conference*, Toronto, 1997, pp. M19–M28.
 21. R. L. Melcher, P. M. Alt, D. B. Dove, T. M. Cipolla, E. G. Colgan, F. E. Doany, K. Enami, K. C. Ho, I. Lovas, C. Narayan, R. S. Olyha, Jr., C. G. Powell, A. E. Rosenbluth, J. L. Sanford, E. S. Schlig, R. N. Singh, T. Tomooka, M. Uda, and K. H. Yang, "Design and Fabrication of a Prototype Projection Data Monitor with High Information Content," *IBM J. Res. Develop.* **42**, No. 3/4, 321–338 (1998).
 22. R. L. Melcher, "Projection Television," *Proceedings of the 19th International Display Research Conference Workshop*, Berlin, 1999, pp. 81–117.
 23. W. P. Bleha, "Development of ILA(R) Projectors for Large Screen Display," *Proceedings of the 15th International Display Research Conference*, 1995, pp. 91–93.
 24. W. P. Bleha, "Image Light Amplifier (ILA) Technology for Large Screen Projection," *J. Soc. Motion Picture & Television Eng. (USA)* **106**, No. 10, 710–717 (October 1997).
 25. L. F. Weber, "Plasma Display Device Challenges," *Proceedings of the 18th International Display Research Conference*, Seoul, 1998, pp. 15–27.
 26. J. Deschamps, "Large Emissive Flat Displays," *Proceedings of the 19th International Display Research Conference Workshop*, Berlin, 1999, pp. 137–176.
 27. R. Akins, "Displays for Hand-Held Portable Electronic Products," *1999 SID International Symposium Digest of Technical Papers*, 1999, pp. 872–875.
 28. P. M. Alt and P. Pleshko, "Scanning Limitations of Liquid Crystal Displays," *IEEE Trans. Electron Devices* **ED-21**, 146–155 (1974).
 29. B. Comiskey, J. D. Albert, H. Yoshizawa, and J. Jacobson, "An Electrophoretic Ink for All-Printed Reflective Electronic Displays," *Nature* **394**, No. 6690, 253–255 (July 16, 1998).
 30. Y. Taira, "Reflective Color LC Displays," *Proceedings of the Eurodisplay '99 Workshop*, Berlin, September 6, 1999, pp. 63–80.
 31. David Lieberman, "Heads-Up Display Shows Way to Wearable LCD," *EE Times*, Issue No. 1066, p. 16, June 21, 1999.
 32. Frank J. Ferrin, "Update on Optical Systems for Military Head-Mounted Displays," *Helmet- and Head-Mounted Displays IV, Proc. SPIE* **3689**, 178–185 (1999).
 33. K. Keller and D. Colucci, "Perception in HMDs: What Is It in Head-Mounted Displays (HMDs) That Really Make Them All So Terrible?" *Proc. SPIE* **3362**, 46–53 (1998).
 34. M. Lucente, "Computational Holographic Bandwidth Compression," *IBM Syst. J.* **35**, No. 3&4, 349–365 (1996).

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