Increasing electronic display information content: An introduction

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This paper is an introduction to a group of eighteen papers on electronic display research and development within IBM. Displays in the computer industry and some of the directions display research is taking are discussed. A motivation for the IBM work on increasing the spatial resolution and image content of various liquid crystal displays is offered. Finally, the significant progress in IBM's display technology over the last decade is discussed.

Introduction

Electronic displays provide a strong visual connection between human and computer, starting with the display providing visual stimuli to the eye. Photons impinging on the cornea of the eye and then being imaged onto the retina are just the first of several steps in the visual cognition process. Significant processing of the visual stimuli occurs before the information leaves the primary visual cortex for interpretation by the rest of the brain. The visual channel to the brain has a very high information bandwidth; it can distinguish approximately ten million colors [1], accepts either steady images for reading or rapidly changing frames of information, which it fuses into smooth motion, and conveys scenes that may be perceived as either flat (2D) or having apparent depth (3D).

One goal of display research is to match the information output of the display to the information capacity of the human visual system (HVS). Too little information from the display slows down the human–computer interaction, while sending more information from the display than the HVS can absorb is, at best, poor engineering. No single parameter can describe the HVS capacity completely; hence, evaluating the match between a display and the HVS is complicated. Display engineers consider various individual measures such as the display picture element (pixel) size compared to that which can be resolved by the eye, or the number of visually distinguishable colors the display can present, or the number of pixels the display can show in a single frame. Although the HVS continues to be superior, in the area of spatial resolution displays are gaining rapidly.

Modern displays provide an additional mode of communication with the user. Their display surfaces can be touched or written upon with a stylus to communicate with the computer. This feature is especially useful with

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flat-panel displays, making electronic pen-and-paper possible. There is another dimension to this visual human–computer interaction, a psychological one. A user develops a "feeling" about the computer that is based upon the quality of the display—a good feeling if the display is bright, crisp, steady and has depth of color. A dim, fuzzy, jittering display with faint colors, on the other hand, may not only generate unjustified negativism about the computer system, but actually cause the user discomfort or fatigue.

It is not surprising, then, that computer makers spend considerable effort to provide users with a high-quality, cost-effective display to complement their computer systems. This issue of the *IBM Journal of Research and Development* describes some of the research and development efforts on high-resolution displays within IBM to create displays that are easy to read, are comfortable to use, and extend the visual human–computer interaction beyond what has been the norm.

Display technology and market

The dominant computer display today is the cathode ray tube (CRT) monitor. The CRT is just over a hundred years old and in its modern form represents a magnificent piece of engineering capable of producing high-quality images. Previous generations of some CRT monitors were criticized because they flickered and had poor contrast, line jitter, and other problems. Worldwide ergonomic standards were developed in response, and the vast majority of today's CRT monitors deliver solid display performance. Most display predictions suggest that CRT technology will continue to be important.

IBM develops engineering specifications for its CRT monitors and markets them for all of its computing systems. In terms of research, development, and manufacturing of displays, however, IBM's focus is on liquid crystal displays (LCDs) [2]. LCDs offer significant reductions in weight, volume, power, and emissions, while simultaneously having crisper picture elements, higher spatial resolutions, geometrically accurate and stable placement of pixels, and a wider range of colors. LCDs, the *sine qua non* of the mobile computer market, are now appearing as monitors connected to personal computers, workstations, and mainframes. In 1997 approximately 400000 LCD monitors were sold worldwide. The first announcement of an LCD monitor under $1000 was made by Viewsonic, Inc., in April 1998. Indeed, we are now witnessing the first steps of a major change in computer display technology. Since cost, not visual performance, has limited the penetration of LCD monitors into the desktop market, the recent declines in LCD prices will fuel their emergence.

IBM participates in this technology revolution in several ways. The IBM Display Business Unit, headquartered in Yamato, Japan, develops active-matrix liquid crystal displays and manufactures them through its manufacturing subsidiary, Display Technology Inc., a joint venture with Toshiba Corporation. Active-matrix liquid crystal displays, known more specifically as thin-film-transistor/liquid crystal displays (TFT/LCDs) and classified as direct-view displays, have the highest image quality of any LCD manufactured today. Numerous other types of LCDs are produced in the industry at lower costs, but with poorer image quality and less image content [3]. In 1997, IBM manufactured approximately a million TFT/LCDs for its Thinkpad and desktop products and for some original equipment manufacturers (OEMs). Research and development in IBM support this manufacturing activity. Eleven papers in this issue describe some of the work on TFT/LCD technology in IBM.

The IBM Display Business Unit also manufactures a new type of liquid crystal display designated as a projection display. Such displays use a small element, often called a light valve, to produce the image. This image is optically magnified and projected onto a screen for viewing. The image can be projected from behind a screen the user is viewing (rear projection), or from the front, as in a movie theater (front projection). Projection systems cost less than direct-view systems for producing images that may be many meters measured diagonally. IBM's projection display technology uses a liquid crystal layer over a CMOS silicon chip containing an array of highly reflective electrodes, or "pixels," that form the image. Depending on the application, some or all of the display-addressing circuitry is integrated in the chip, simplifying the packaging and reducing costs. Complete light engines consisting of three light valves (one each for red, green, and blue channels), the optics, illumination, and control electronics are sold by the IBM Display Business Unit to OEMs. IBM's current offerings have the highest information content in the LC projection industry, with announced light valves having formats of 1280×1024 pixels and 1600×1280 pixels.

Seven papers in this issue discuss various aspects of this multidisciplined projection technology and describe a unique four-million-pixel prototype optical monitor. This same liquid-crystal-on-silicon technology can be used to create microdisplays for mobile applications, such as cellular phones, personal digital assistants, fax viewers, and head-mounted displays. These displays are classified as virtual displays, since an optical element, similar to a magnifying glass, forms an enlarged view of the image produced by the light valve on the viewer's retina, creating a virtual image. Virtual displays are characterized by very small dimensions (less than half an inch), low power, low weight, and low cost. The information content, however,

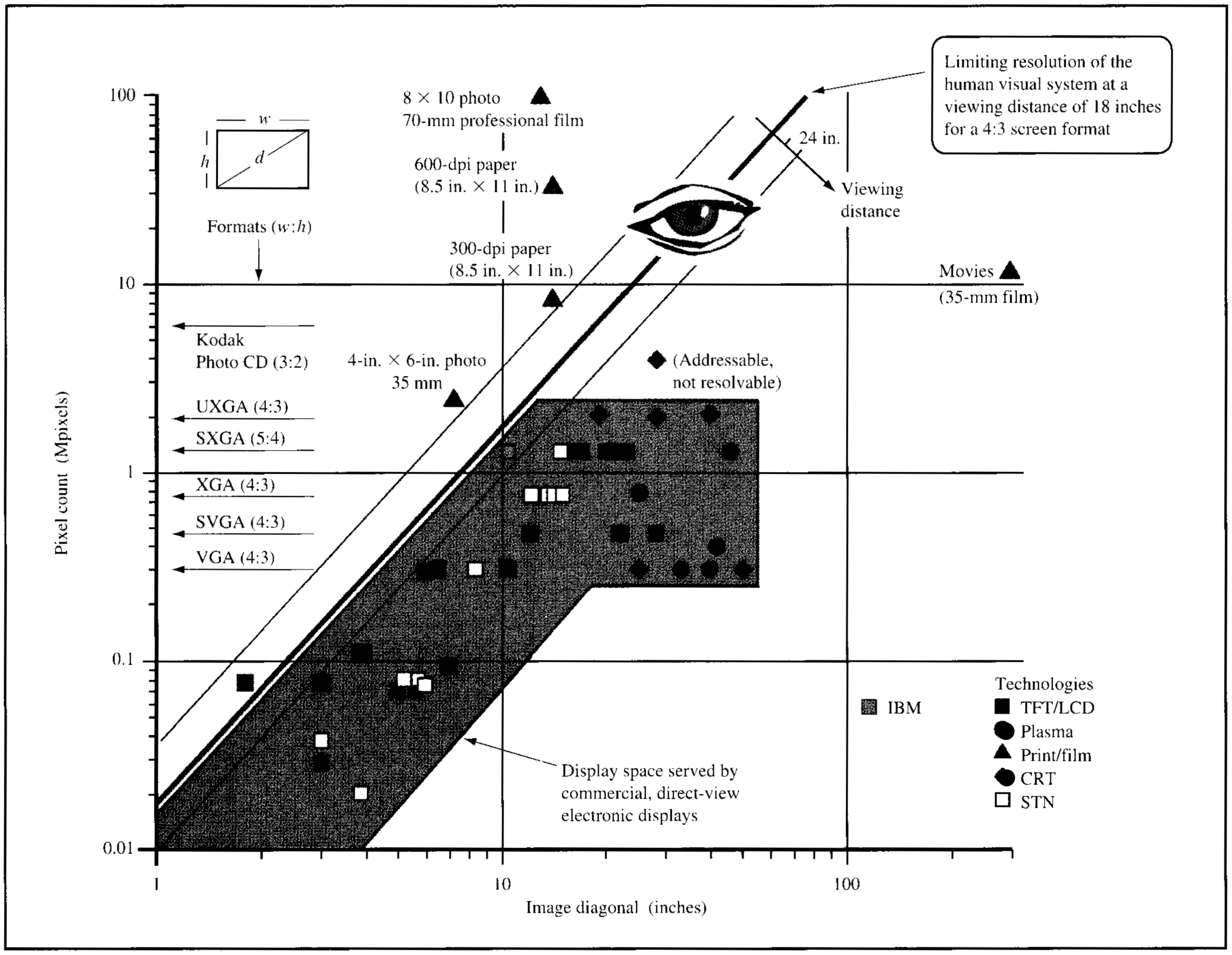

Figure 1

A view of display space showing existing electronic, paper, and film displays.

can be quite high, in some cases matching that found on desktop monitors. Finally, liquid-crystal-on-silicon technology is useful for writing information into holographic storage systems, which are currently in the research stage; a paper on this topic is included.

Display information content

Having mentioned three display types (direct-view, projection, and virtual), we now provide a brief but more detailed discussion about display information content as measured by total pixel count. The intent is to show how direct-view electronic displays compare with other information displays, such as paper and film, and to discuss the relationships among these display types. This discussion should also serve to create a perspective of the directions display research is taking.

Consider a two-dimensional display space in which the axes are the image pixel count and the image diagonal. Note that the term *image diagonal* refers to the viewed image size, which for projection and virtual displays is larger (by some magnification) than the light valve creating the image. Data representing commercially available displays are plotted in this display space in **Figure 1**. The approximate area served by direct-view electronic displays is outlined and colored. One quickly sees that only a small portion of display space is served by direct-view electronic displays, that pixel count increases with image diagonal, and that familiar examples of print and film displays are beyond the capabilities of today's electronic displays. One particular deficiency is that no electronic display exists to show full photo CD images, which are modern, digital compressed images having

3000 × 2000 pixels. Thus, total pixel content is one measure of display improvement.

There are good reasons for some of the "white space" in Figure 1. Very large images having few pixels, for example, are of little use, especially in the computer industry. Similarly, very small images with millions of pixels have no commercial interest, since information this spatially dense cannot be resolved by the human visual system. The resolving power of the eye defines the slope of the colored region showing electronic displays in Figure 1. The red lines in the figure are the calculated pixel resolution limits of the eye for different viewing distances. This calculation uses the generally accepted value of one minute of arc as the limiting resolution of the eye. This limitation is derived from the finite spacing between photoreceptor cells (rods and cones) on the retina of the eye. One minute of arc is the angle subtended by the strokes of each letter in the bottom line of a standard (Snellen) eye chart when viewed from a distance of 20 feet. In a specialized task, detecting misalignment of two lines laid end to end, humans exhibit an acuity that is five times better than the one minute of arc mentioned above. However, this relates to an ability to localize objects rather than resolving them and does not enter into reading acuity tests.

For a fixed-image diagonal, going above the appropriate (for the application) red line by adding more pixels to a display has rapidly diminishing returns, since such an "improved" display is generally expensive to fabricate and the user cannot resolve the pixels (that is, the user cannot appreciate the improvement). Not surprisingly, most display manufacturers have stayed below the appropriate eye-limiting resolution line. Also, each application has a range of acceptable viewing distances; many workstation users prefer viewing distances between 20 and 24 inches, and older workers use larger viewing distances. Consider a future display, however, about the size and weight of your favorite magazine, which you hold at a distance where reading is comfortable. In this scenario, viewing distances of 12 inches or less are likely, and resolutions of 200–300 pixels per inch will be needed. A good CRT today provides 100 pixels per inch.

Figure 1 shows a region between about 15 and 50 inches in image diagonal in which the pixel count is far below what the eye can resolve. In simple terms, this is because it has been technically difficult to fabricate such displays. Note, for example, the 28-inch-diagonal CRT with four million addressable, *but not resolvable*, pixels. This data point represents the Sony DDM CRT monitor. In this case, the CRT technology has been pushed to the practical limits and still comes up short. Similarly, direct-view displays larger than about 50 inches are not produced, either because they are very expensive or because they have technical problems at these sizes.

How displays will evolve is speculative, but current work suggests that the following developments may occur. Projection displays will fill the display space with image diagonals larger than about thirty inches and with pixel content above a million and probably less than 20 million. Mobile computer displays and desktop monitors will have image diagonals of 10–30 inches and information content ranging from XGA to perhaps six million pixels. A full range of spatial resolutions will be available, each suited to specific applications. Numerous new mobile applications will generate requirements for displays in the 1–10-inch-diagonal range, with pixel count dictated by the application and limited on the high side by eye resolution. This is the area of display space in which new display technologies are most likely to evolve. Virtual displays with pixel counts up to one million pixels will probably become available.

Two prototypes are described in this issue, each representing a new data point in the display space of Figure 1. A paper describes a 10.5-inch SXGA display fabricated with TFT/LCD technology, shown as the yellow data point in Figure 1. This prototype display has 157 color pixels per inch, equivalent to the color printing resolution found in high-quality magazines, and represents one step toward making electronic displays more paperlike. The term *paperlike* in this case means having spatial resolution approaching that of print media. One might expect such a display to provide the ease and speed of reading we experience with paper, and studies are under way to explore this. If this display were used in an application in which the user is typically 24 inches from the screen, Figure 1 suggests that the display would be overdesigned, being above the 24-inch viewing resolution line. At a working distance of 18 inches, however, say for use in an IBM Thinkpad,* the display design is appropriate and approaches the eye resolution limit.

The second prototype, a 2048 × 2048-pixel LCD rear-projection LC monitor, is also discussed in this issue. This display has a 28-inch-diagonal screen and the same coordinates in Figure 1 as the Sony CRT mentioned above. The LCD projection monitor, however, has all four million pixels resolvable, is brighter, and is usable in normal room lighting. A comparison between the Sony CRT and the LCD optical monitor is included. The potential for various high-information-content projection monitors is suggested by this work.

Two primary directions for display research are to increase image content and to increase the spatial resolution of displays. In both categories, LCD technology has the ability to outperform CRT displays. Other areas of research are also important, however, such as reducing display module size and power, improving viewing characteristics (brightness, contrast, viewing angle), and developing materials and processes to reduce cost. Papers describing such work are included in this issue.

Recent progress

Progress in direct-view TFT/LC displays has been substantial during the current decade, suggesting that 1) the technology is extendible; 2) the customer demand has been significant; and 3) the industry has responded with research and development investments. As an example, consider the progress in IBM's displays. Pixel count is often used as a metric, as in Figure 1, though by ignoring color it underestimates the ability of the display to convey visual information. If each pixel can produce a thousand different colors, for example, and there are a million display pixels, the display may be said to have the capacity to produce a billion elements of visual stimulation. The product of pixel count times the number of colors per pixel is the metric we use to measure recent progress. This measure allows comparisons of the relative ability of displays to produce rich and complex information. It is independent of display diagonal and, being a pixel-based measurement, ignores approaches such as dithering and error diffusion to achieve more apparent colors at the expense of spatial resolution. The time line of increase in IBM's TFT/LCD display information capacity is plotted in **Figure 2**. The data are for product-level displays only and do not include experimental prototypes.

On average, progress has been approximately a 10× increase in billions of addressable retinal stimuli (BARS) every two years. It should be mentioned that in the same interval during which this remarkable progress occurred, the IBM Thinkpad TFT/LC display power was reduced from 15 watts (VGA) to 2.7 watts (XGA), and weight was reduced from 1500 grams to 470 grams.

Additional improvements are required by the industry. In addition to increasing information content and spatial resolution, a common focus for both direct-view and projection LC displays is reduction of costs. Demanding applications require additional gray-scale capability as well as wider viewing angles. The growth of display information content increases the demands on the system supporting the display—bandwidth, memory, rendering cycles, and power are examples. Display subsystem architectures that economically support very large images are needed, and efficient digital interfaces between system and display must evolve to preserve the high image quality inherent in digital images. New interfaces must also allow connections at convenient distances between system and display. Operating systems and application programs will have to recognize and accommodate high-spatial-resolution displays to ensure that menu items and other frequently used icons and informational text are automatically rendered at sizes that are easily visible at comfortable distances. Today, variable resolution is only partially accommodated.

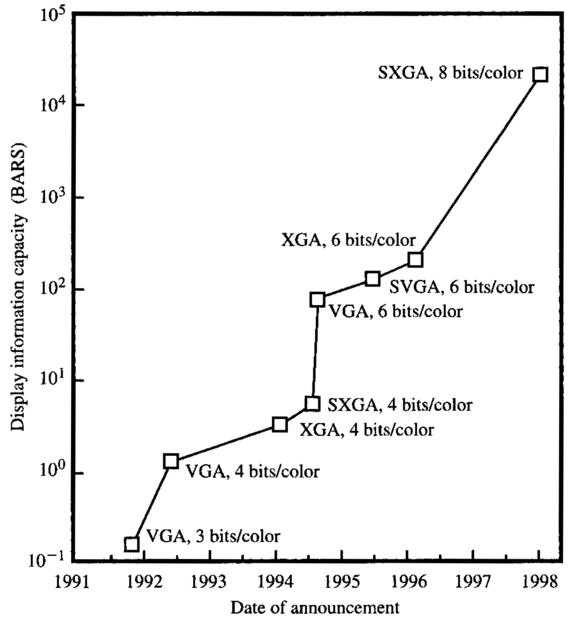

Figure 2

Information capacity increase of IBM TFT/LC displays with time. Information capacity is in units of pixel count times number of colors (billions of addressable retinal stimuli, or BARS).

IBM strives to conform to the 1997 Kyoto Agreement[1] to reduce energy consumption. Liquid crystal displays today consume less power than other types of computer displays, and additional power reductions in LCDs are possible. LCDs with high information content, high spatial resolution, good contrast, and portability have the exciting potential of replacing paper in some applications. Progress toward a paperless office is desirable for energy reduction as well for obvious ecological reasons. Future LC displays, especially those having high spatial resolution and a size and shape matching that of a magazine, are well within reach. We expect that the emergence of such high-resolution displays may finally allow for an office having less hardware on the desk and less paper in the files. Projection displays with millions of pixels and image sizes appropriate for groups of people will speed the analysis of ever more complex information and foster collaborative work. This will improve productivity as well as quality of life in the workplace.

[1] Kyoto protocol to the United Nations framework convention on climate change, December 1997.

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