SiliconGraphics
Computer Systems

Silicon Graphics 1600SW™ Flat Panel Monitor

White Paper

Contents

Silicon Graphics 1600SW Flat Panel Monitor

—by Dan Evanicky

Welcome to the world of precise color. The Silicon Graphics 1600SW™ flat panel monitor is a full color, digital display with a screen resolution of 1600 x RGB x 1024 pixels. It offers the user uncompromising value in a visual display for the viewing of high information content text and graphic images in a wide-aspect ratio format. In addition, it provides hardware and software to control the color of those images accurately in regard to their viewing environment.

This document details the technology, quality, and science that make Silicon Graphics 1600SW the ultimate flat panel monitor. In engineering this product, our overriding design goal is to offer the user a no-compromise flat panel display that captures the best features of a CRT, enhancing them when possible, by providing the controls and features that only a digital flat panel monitor can offer. The following sections of this document examine how Silicon Graphics achieves this goal.

Part 1, Liquid Crystal Display Construction, describes the basic liquid crystal display (LCD) device and how it is designed and manufactured. Liquid crystal materials and optical components such as polarizers, color filters, and backlight subassembly are defined and their functions explained. This part of the paper also describes how these components are assembled into a working module, and how driver electronics are attached to the display cell.

Part 2, Liquid Crystal Display Operation, explains the various electronic devices used to address the liquid crystal material and the way it in turn manipulates light to form images. Two types of modules are used as examples: the type that addresses LCD pixels in an indirect manner (passive matrix, xy), and the type that addresses LCD pixels in a direct manner (active matrix).

In Part 3, Silicon Graphics Technology, the paper expands on flat panel technology areas in which Silicon Graphics has concentrated its development efforts, leading to improvements in performance and utility. These include display subsystems such as adjustable white balance, backlighting, optical compensation, fast response for video streams, and data transmission from the host computer. Wherever applicable, Silicon Graphics flat panel technologies are contrasted with CRT technology and compared to other more conventional flat panel monitors. These and other advanced features help to differentiate and highlight the value that the Silicon Graphics 1600SW monitor offers users in demanding, color-critical applications.

Building on the basis provided by this paper, a companion Silicon Graphics white paper, "Silicon Graphics ColorLock™ System" by Tom Lianza [to be published], describes the role of color management in all aspects of the imaging process. This paper also describes Silicon Graphics' embedded measuring device and how it is used in white point matching and color calibration. The independently adjustable white balance system is detailed along with the positive impact it has on display luminance and color lookup tables.

Part 1. LIQUID CRYSTAL DISPLAY CONSTRUCTION

Liquid crystal displays (LCDs) typically have three groups of assembly components: the cell, the module, and the monitor. The cell comprises the glass plates that contain the liquid crystal material and the front and back polarizer filters. The module comprises the cell plus display drivers that control light and deliver host computer data to the cell, and a backlight assembly consisting of fluorescent lamps, light pipes, and associated diffusers and reflectors; all contained within a rigid sheet-metal structure. The monitor consists of the module plus an inverter to power the lamps, a display interface to the CPU, a plastic bezel and stand, and a power supply.

1.1 Liquid Crystal Chemistry

Liquid crystals are a set of complex organic compounds composed of elongated, rod-shaped molecules that in their natural state are arranged in a loosely ordered fashion with their long axes parallel. They exist in many phases, with the most common being smectic (gel-like), nematic (most common for computer displays), and cholesteric (naturally rotating liquid crystal structures). There are hundreds of liquid crystal types from which to choose, depending on the physical, electrical, and optical properties the user desires in a display. Typically, a flat panel display will contain a mixture of 10 or more of these compounds.

Liquid crystal materials have two important features that make them useful in display applications: their molecules are "polar," with one end being more electrically positive or negative than the other, much like a compass needle, to use a magnetic analogy; and they are able to conduct, bend, or twist rays of light along their axes depending on their orientation. More on this property will be discussed in Part 2, Liquid Crystal Display Operation. Simply put, we use electronic devices to control liquid crystals to make them manipulate light. Figure 1 shows the structure of a typical biphenyl type of liquid crystal molecule.

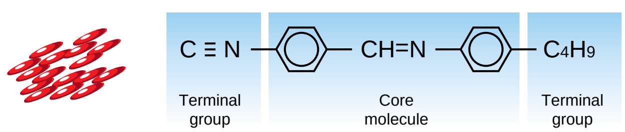


Figure 1. A Typical Liquid Crystal Molecule.

1.2 LCD Cell Construction

1.2.1 Substrates with Patterned Electrodes

An LCD cell is composed of two glass plates that are commonly coated with a very thin, metallic oxide layer known as indium tin oxide (ITO). Because the layer coating each glass substrate is so thin (only a few hundred angstroms), it is transparent; because it is made of an oxide of two metals, it is conductive.

Using conventional semiconductor photoimaging and etching techniques, these layers can be patterned to form electrode structures. The electrodes may be patterned into 7-segmented numeric designs, as those commonly found in liquid crystal watches, or into a series of lines arranged along an x-y grid. In passive matrix-addressed cells, the two layers of ITO are patterned into tightly spaced parallel vertical traces on the front glass (columns) and horizontal traces on the back glass (rows). Figure 11 shows the construction of a 6 row x 7 column passive matrix cell, and its operation is described in section 2.2.1, Passive Matrix LCDs.

1.2.2 Molecular Alignment Layers

After patterning of the ITO layer, the surface of each glass plate is coated with an alignment layer, usually polyimide. That alignment layer is first baked and then polished or buffed to create microscopic parallel grooves on the surface of each plate. Although the grooves are all parallel, it is important to note that each plate has its grooves oriented in a different direction. In subsequent processing, these grooves will cause the molecules of the liquid crystal material not only to "sheet" or wet the surfaces, but to line up parallel along the buffing direction as shown in Figure 2. What is not shown in Figure 2 is that the molecules do not lie exactly flat on the alignment layer but point up slightly from the surface at an angle of 2° to 5°. This "pretilt angle" is critical to the proper function of the display, but is also the cause of certain optical inconsistencies, as will be discussed in section 3.3.1, Viewing Angle. The plates are now ready for spacer application and assembly.

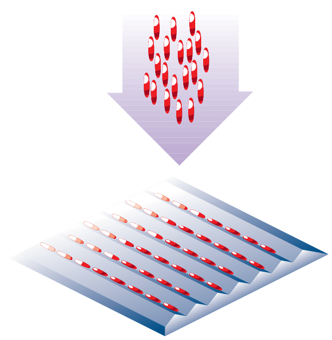


Figure 2. Molecular Alignment to a Buffed Surface. In their natural state, liquid crystal molecules are arranged in a loosely ordered fashion with their long axes parallel. The alignment layer surface can be finely grooved by a polishing or buffing operation. When liquid crystals are flowed onto this layer, their molecules line up parallel along the grooves.

1.3 LCD Cell Assembly

During assembly, a sealing material is applied along the perimeter of one of the glass substrates, leaving a gap of a few millimeters at one corner, and then pre-baked. Cell gap spacers, usually glass or plastic beads, are then applied by dry or wet spraying techniques. These beads are critical to the ultimate function of the display because they must maintain the spacing of the gap separating the two glass substrates at an optimum thickness of 4 to 5 microns, about 1/15 the thickness of a human hair. (In the Silicon Graphics 1600SW monitor display, the gap must be uniform across a 17.3-inch diagonal width!) The two glass plates are then oriented as shown in Figure 3 so that their respective buffing directions are at right angles to one another; they are then clamped and baked or exposed to ultraviolet radiation to set the sealant. This forms an empty package with an open port at one corner that is ready for the injection of the liquid crystal material.

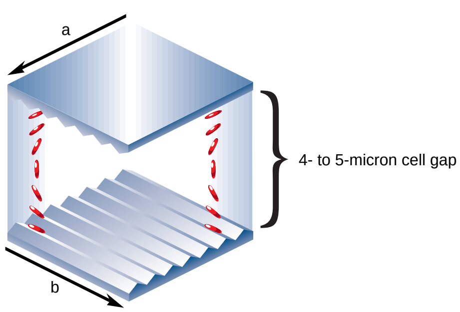


Figure 3. Twisted-Nematic Alignment. A cell can be constructed so that liquid crystals are sandwiched between upper and lower plates with grooves pointing in directions "a" and "b," respectively. The molecules along the upper plate point in direction "a," and those along the lower plate point in direction "b." This forces the liquid crystals into an overall 90° twisted-nematic state.

1.3.1 Filling and Sealing

Several cells are placed in a vacuum chamber in a fixture that suspends them on edge over a container of liquid crystal material. Air is exhausted from the chamber and the cells equilibrate to the surrounding vacuum through their fill ports. After the cells and the liquid crystal (LC) material in the reservoir have outgassed sufficiently, the plates are remotely lowered so that the fill ports are submerged. The LC material is injected by backfill pressure between the glass plates through the gap in the perimeter seal, which is then plugged with epoxy or more UV-cured adhesive. The filled and sealed cells are now ready for the addition of external optical elements and display drivers.

1.3.2 Polarizer Function and Attachment

An important liquid crystal display component is the linear polarizer, which is a film of organic material that has been impregnated with a dichroic material, such as iodine or dye, and then stretched. This stretching causes the film to become an optical filter, able to block out certain orientations of light, exactly in the manner in which an ordinary pair of Polaroid sunglasses screens out unwanted glare. This polarizing film filters out all light except that oriented in the direction parallel to its polarizing axis. Light not parallel to this axis is absorbed, as shown below in Figure 4. The polarizer films are coated with a pressure-sensitive acrylic adhesive common to many label systems and attached to the front and back plates of the LCD cell using conventional lamination techniques. The orientation of these films to the LCD cell and to each other is discussed in Part 2, Liquid Crystal Display Operation. The LCD is now ready to be interfaced to its electronic controlling circuitry.

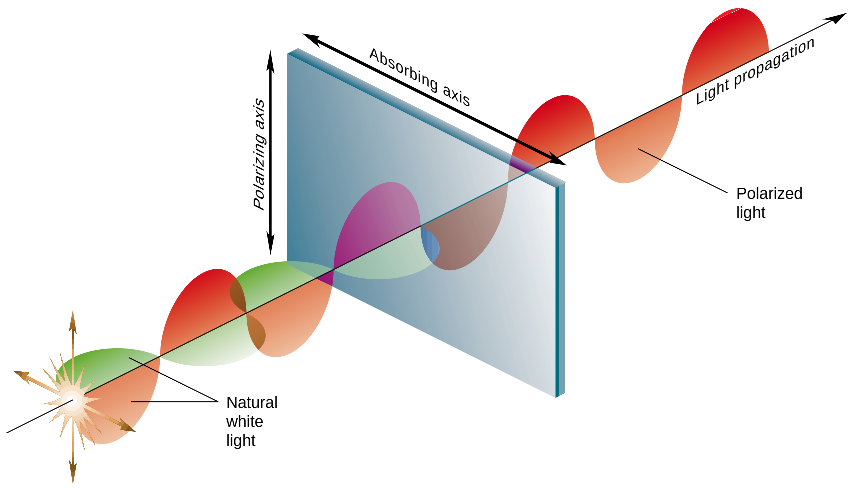


Figure 4. Interaction of Light with a Linear Polarizer.

1.4 LCD Module Construction

1.4.1 Display Drivers

To display images, data from the host computer must somehow be delivered to the inside of the cell and to the liquid crystal material. This data is usually generated by a device known as a display controller, which resides on the motherboard or in a card slot inside the computer, and passed through a high-speed interface along a cable to the row and column display driver integrated circuits (ICs) within the flat panel module. (Please refer to the flat panel module block diagram in Figure 14.) The display driver ICs make possible the palette of displayable gray shades on the LCD screen by using very fine incremental voltages to control the number of luminous levels of light passing through the display to the user. But how to connect these drivers so as to get their voltage signals inside the display?

1.4.2 Driver Attachment

Attaching these drivers to the flat panel cell is no small task. (See Figure 5.) Whether the display is to be a passive or active matrix type, the method used is the same, although the relative scales of the two tasks are quite different. The current, more mature technology used by Silicon Graphics has the display driver ICs arrayed on printed circuit boards positioned along one end and one side of the LCD glass cell.

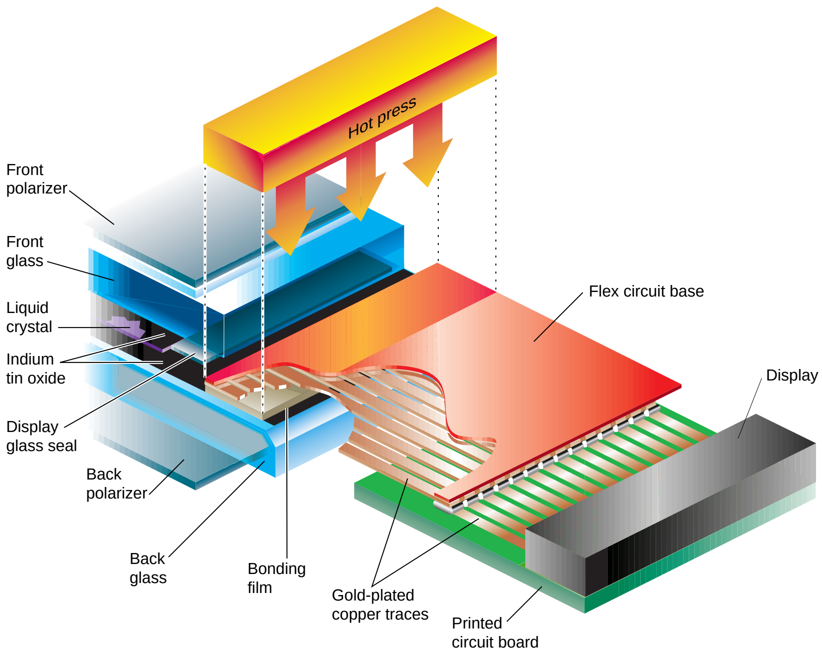


Figure 5. Attachment of Drivers to the Flat Panel Cell.

The outputs of all the driver ICs are connected via tape automated bonding (TAB) to gold-plated copper circuit traces. These traces are in turn connected to a circuit pattern on a flexible polyimide sheet. (The pitch of the circuitry can be on the order of the width of a human hair.) The flexible circuit is connected to the display cell through an anisotropic conductive film (ACF). Signals from the IC travel over the copper traces through the ACF to the ITO data (columns) and scan lines (rows) that emerge along the offset edges of the cell. These ITO traces extend through the seal area on each glass to supply the appropriate electrical voltages to energize the liquid crystal material inside the display. These rows and columns sandwiching the liquid crystal layer form a pixel at each of their interstices, as shown in Figure 11.

The most difficult and critical step by far in manufacturing this circuit is the joining of the gold-plated leads of the flex circuit to the glasslike ITO traces on the display substrates. Over a decade of development in the display industry has gone into making this ACF bonding process capable of maintaining thousands of microscopic connections with 100 percent integrity for an indefinite span of time. In Silicon Graphics 1600SW, there are 5,824 connections that must be perfectly made and must maintain their bond over the life of the monitor. If only one of the almost 6,000 bonds loses its integrity, over 1,000 pixels will cease to function.

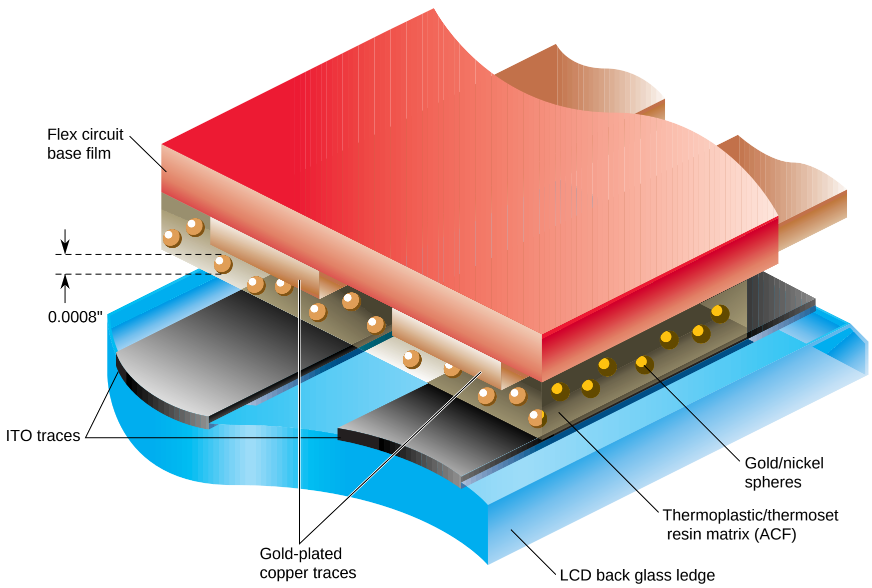


Figure 6a. Anisotropic Conductive Film (ACF) Applied before Bonding.

At the heart of ACF technology are thousands of conductive nickel spheres coated with gold and dispersed in a thermoset (epoxy) resin matrix. A thin strip of this material is applied to the flexible circuit film that is connected to the display driver board. (See Figure 6a.) Sections of this flexible circuit are positioned precisely over the corresponding ITO pads along the display's glass ledge. Heat and pressure in the form of a hot anvil are used at the contact point to bond the ACF to the display electrodes, much like how a design is affixed with a hot iron to a T-shirt. (See Figure 6b.) As the ACF is compressed, the raised gold-plated circuit traces are brought into close proximity with their corresponding ITO electrodes. Any of the metal spheres that are trapped between these relatively high gold/copper traces and the ITO leads are flattened and extruded through the surrounding resin, forming a conductive path connecting the driver IC chip and the ITO traces leading to the LCD. As shown in Figure 6b, the spheres between the flex circuit traces are not compressed, so conductive contact occurs only in the vertical and never the horizontal axis.

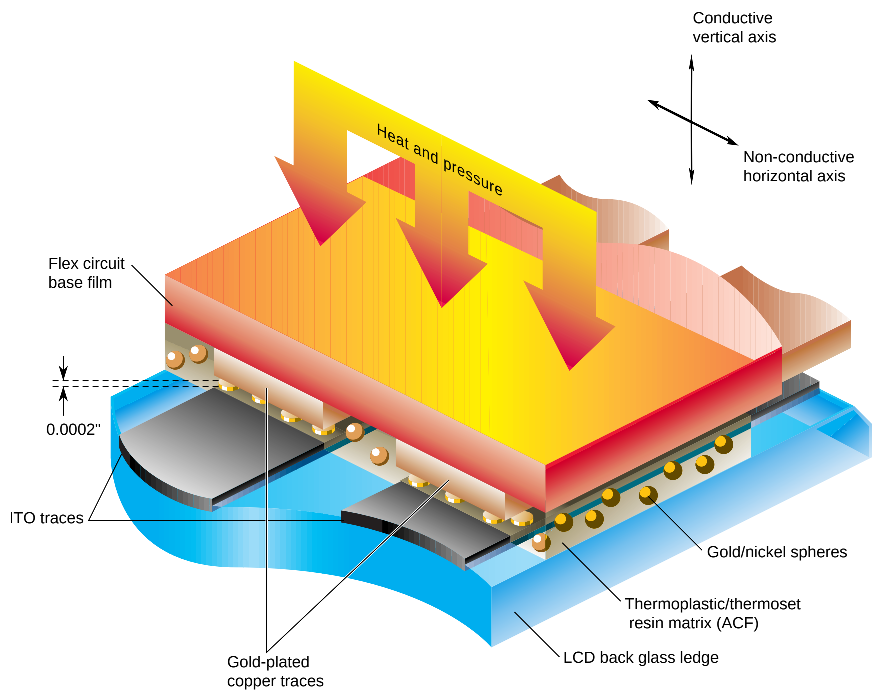


Figure 6b. ACF after Driver Flex Circuit Bonding.

An important consideration is that the metal spheres form their conductive path only as long as they are held in place by the resin. Any relaxation, expansion, or swelling of the epoxy or the beads will cause the bond to become “unglued” and the electrical connection to break. To protect these components, a stamped metal bezel is used to hold the display module assembly together.

1.4.3 Backlighting Technology

The Silicon Graphics 1600SW flat panel monitor uses four 15-inch-long glass tubes about half the diameter of a pencil to backlight its display. These miniature cold cathode fluorescent (CCF) lamps are coated on the inside with a special mixture of rare-earth phosphor materials and filled with mercury, argon, and neon gasses. When activated by a high-voltage source, the atoms of mercury within the tubes begin giving off electrons and a plasma is “struck.” The high-energy electrons emit intense ultraviolet radiation which bombards the phosphor mixture on the walls of the tubes, causing them to fluoresce with a white light too intense to look at directly. The light is transmitted down a clear, acrylic sheet or “pipe” (See Figure 13), on whose underside is printed an array of tiny white dots. (See Figure 7.) Any light striking these dots is scattered and diffused, or “extracted,” and reflected up through the liquid crystal display toward the viewer. Dot size and density increase proportionately with their distance from the CCF lamps. The size and patterning of this extraction array are determined by a special computer program that ensures that the light extracted from this system will be extremely uniform in brightness and color.

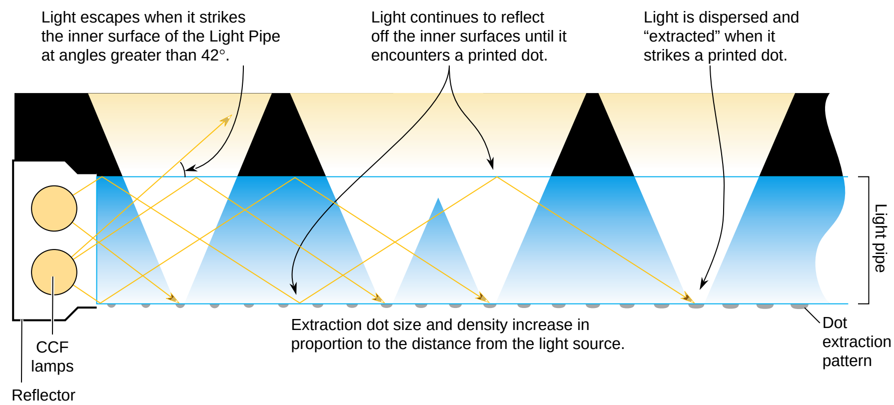


Figure 7. Light Extraction System.

It takes about one or two minutes for flat panel monitors to warm up to full brightness from a cold start. The output from the fluorescent lamps strongly depends on the minimum bulb wall temperature, because this temperature determines the mercury vapor pressure inside the tubes. The colder the temperature, the more mercury condenses on the inside of the bulb, resulting in decreased light output. At 25°C the initial light output is approximately 80 percent of optimum, but at 10°C the light output could easily be at 30 percent of its peak brightness for the first couple of minutes.

Figure 8 is a block diagram for a typical LCD module; Figure 14 indicates how this module is integrated into the Silicon Graphics flat panel monitor and shows the inverter that drives the CCF lamps. The inverter's function is to draw AC current from a wall outlet, convert it to DC current, and power each of the four lamps with .006 Amps of current at approximately 750 volts DC. Figure 13 illustrates the display backlight portion of the module represented in Figure 8.

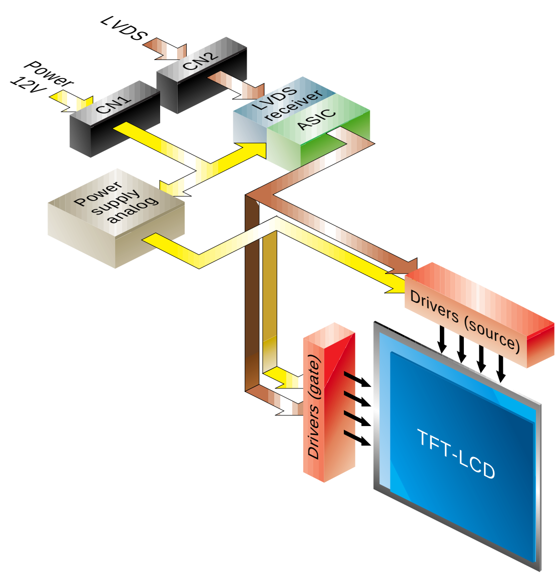
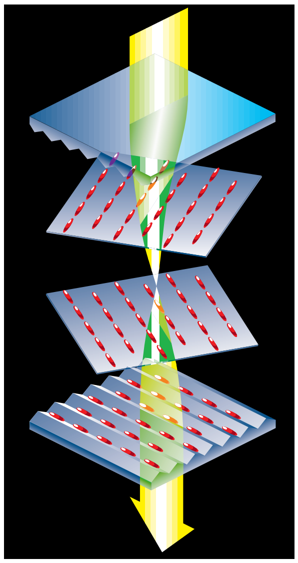


Figure 8. LCD Module Block Diagram.

Part 2. LIQUID CRYSTAL DISPLAY OPERATION

2.1 Twisted-Nematic Display

When the cell's upper and lower glass plates are assembled and the directions of their grooving are arranged at right angles (90°) to one another, the liquid crystal molecules are forced into an overall helix or "twisted-nematic" state as in Figure 9.



2.1.1 Light Control

Any light passing through such a construction follows the direction in which the molecules are arranged. When the molecular alignment is twisted 90°, the light also twists 90° as it passes through the several hundred liquid crystal layers in a cell. Since they are electrically polar, the molecules can be rearranged easily by applying an electrical voltage to either the entire cell or selected portions of it. In the following sections, we will see how these voltage sources can be used to make the liquid crystal molecules control light and form images.

As described in section 1.3.2, Polarizer Function and Attachment, when two polarizing filters are arranged with their axes parallel, light passes through them; but when they are arranged in a "crossed" orientation, the light is blocked. As Figure 10 shows, light that passes through the first polarizer also passes through the second—but not if the bottom polarizer has its optical axis at right angles to the first.

Figure 9. Light Propagation in Step with a Twisted Structure. Light passes through liquid crystals, following the direction in which the molecules are arranged. When the molecular arrangement is twisted 90˚, as shown above, the light also twists 90˚ as it passes through the liquid crystal layers.

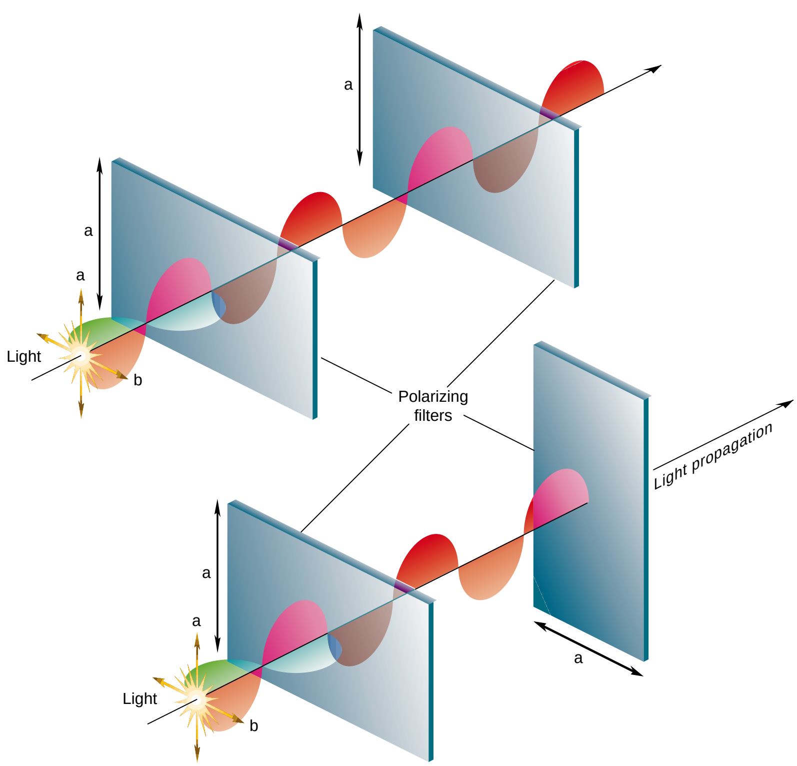


Figure 10. Interaction of Light with Linear Polarizers.

Combining polarizers with a liquid crystal display produces the interesting system shown in Figure 11. When two polarizing filters are arranged with their polarizing axes perpendicular, light entering from above is redirected 90° along the helixical arrangement of the liquid crystal molecules so that it passes through the lower polarizer. When voltage is applied to the liquid crystal layer, the polarity bias that exists in the molecules causes them to turn parallel to the direction of the electric field, straightening out of their twisted state to line up perpendicular to the glass substrates. By rearranging themselves vertically, they can no longer rotate the phase angle of the light so that it is blocked by the lower polarizing filter. (Some early display manufacturers neglected to take into account the fact that many of their customers might also use other optically active devices. For instance, if the front polarizer of their LCD watch were not oriented correctly, someone reading the watch while wearing Polaroid sunglasses would be met with only a black rectangle when trying to tell the time.)

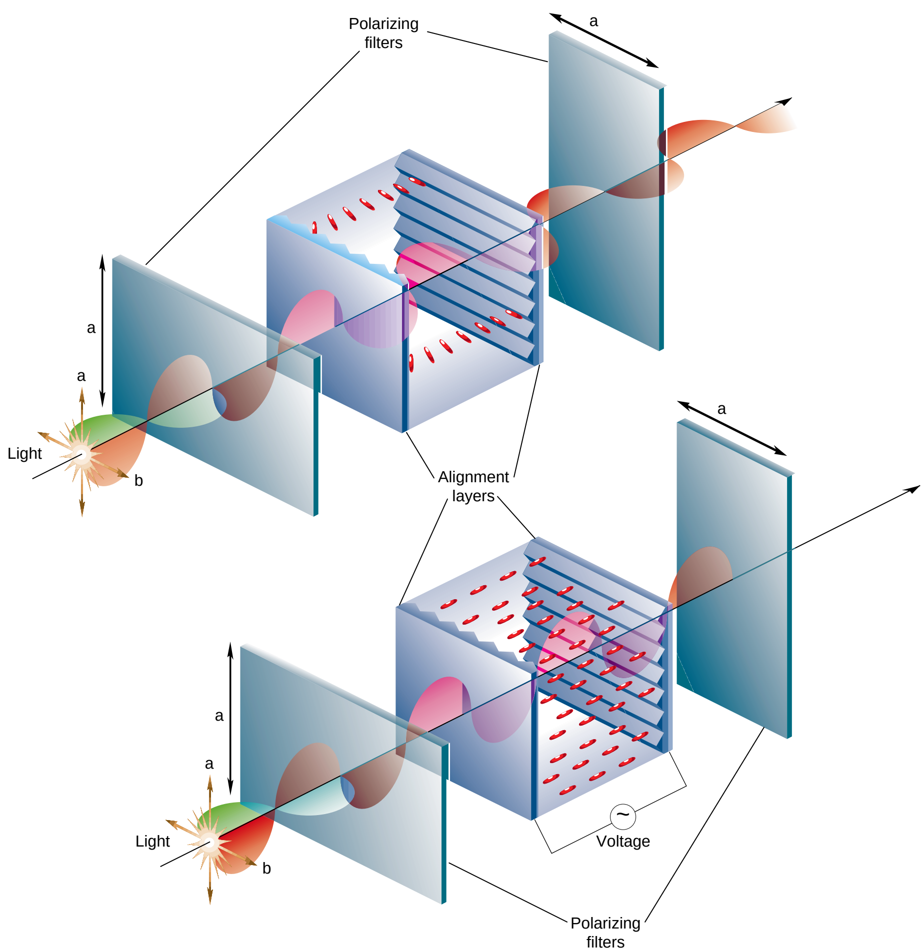


Figure 11. Twisted-Nematic Alignment with Polarizing Filters. When two polarizing filters are arranged with polarizing axes perpendicular ("a" axis), light entering from above is redirected 90˚ along the helixical arrangement of the liquid crystal molecules so that it passes through the lower filter. When voltage is applied, the liquid crystal molecules snap out of their helixical pattern and no longer redirect the angle of the light passing through them, causing the light to be blocked at the lower filter ("b" axis).

Another important effect is that if only a partial amount of voltage is applied to the liquid crystal, the area so addressed will acquire a tone somewhere between light and dark. This tone is known as a “gray scale,” and the number of resolvable gray levels is an important metric by which to judge the performance of a particular display, since the total number of colors available depends on the number of resolvable gray levels and their interaction with color filters.

2.1.2 Color Filters

In order to achieve a color LCD screen, the solution is analogous to the red (R), green (G), and blue (B) phosphors that make up the primary color components in a CRT. It involves the use of vertical stripes of alternating red, green, and blue colored filters (non-polarizing) made of organic dyes, dispersed pigments, or dichroic metal oxides. These are applied by various printing techniques and located on the front glass substrate under a transparent ITO electrode. Any light passing through one of these filters will take on the color characteristics of that primary, or subpixel. The challenge for flat panel makers is to design a system that maximizes the number of gray levels in order to be able to display the greatest number of different colors. Silicon Graphics’ implementation is discussed in section 3.2, Optical Features.

2.1.3 Polarizing Modes and Color Displays

Part of achieving a color LCD screen also involves the orientation of the polarizing elements. There are two types of viewing modes possible depending on the polarizer orientation: “normally white” and “normally dark.” In the normally white orientation in the twisted-nematic, unselected state, the RGB pixel components transmit the backlight as white light. Images are created by selecting pixels to restrict the transmission of certain colors or shades. This is the preferred mode for flat panel monitors and watch displays. (In the normally dark orientation, images are formed by selecting pixels to allow different frequencies of light through the display panel. The dark mode is used in automobile clock and instrument displays.)

2.2 Addressing Technologies

LCDs can be subdivided into two basic types depending on how the individual pixels are addressed: active matrix and passive matrix. The main difference between them is that active matrix-addressed displays have a clear edge in performance, but this performance comes at a correspondingly higher cost both in materials and capital equipment.

2.2.1 Passive Matrix LCDs

As indicated in section 1.2.1, Substrates with Patterned Electrodes, passive matrix displays are simply constructed of only row and column electrodes that overlap to define the pixels. Because liquid crystal molecules respond to the root mean square (rms) voltage they receive, there is a fundamental limit to the number of display rows that can be addressed with this scheme. As the number of rows increases, the actual time that the energizing voltage pulse can spend addressing them grows proportionately shorter. Eventually, a point is reached where the contrast ratio (the difference between the light and dark display pixels) drops to an objectionable minimum. Other constructions, such as those used in super-twisted nematic displays, can extend this point, but they too have their limits.

Very simplistically, Figure 12 shows a selecting voltage applied to the intersection of the second row and the third column of such a monochromatic display. The liquid crystal molecules that are contained within the volume bounded by that row and column respond to the selecting voltage by snapping out of their twisted-nematic state. This creates a pixel that contrasts to the area surrounding it: depending on the polarizer orientation, it can be white on black or black on white.

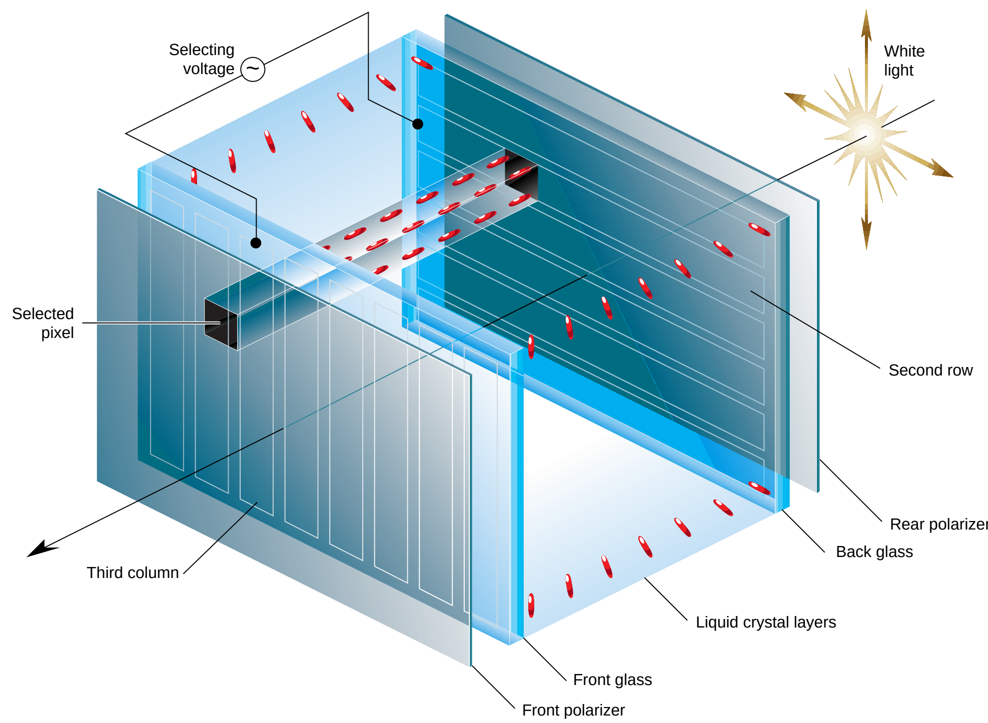


Figure 12. Passive Matrix Cell Addressing.

2.2.2 Active Matrix Liquid Crystal Displays (AMLCDs)

In the flat panel displays developed by Silicon Graphics, the method of driving the cell is taken to a higher level through the use of active matrix-addressing techniques. Instead of a pixel being formed by opposing column and row electrodes, the vertical traces become data or source lines, and the horizontal rows become scan or gate lines, which address a switching element known as a thin film transistor (TFT). Because of the lower processing temperature of this semiconductor material and the low current requirements of LCDs, the material most commonly used for TFTs is amorphous silicon. As shown in Figure 13, the TFT occupies but a small portion of the area of a subpixel element.

The effect of the scan line voltage is to close the switch on the TFT connecting the data line to a subpixel, allowing the voltages at the data lines to be applied to that electrode. The scan line voltage is then reduced to open the switch, thus maintaining the preselected voltage (corresponding to a specific gray level) across the subpixel for the length of one frame time. So for the entire time the scanning pulse is not physically at the pixel, it still has a uniform, uninterrupted driving voltage as though it were a matrix of one-by-one. Therefore, AMLCDs can provide five times the switching speed and an order of magnitude higher contrast ratio than passive matrix displays.

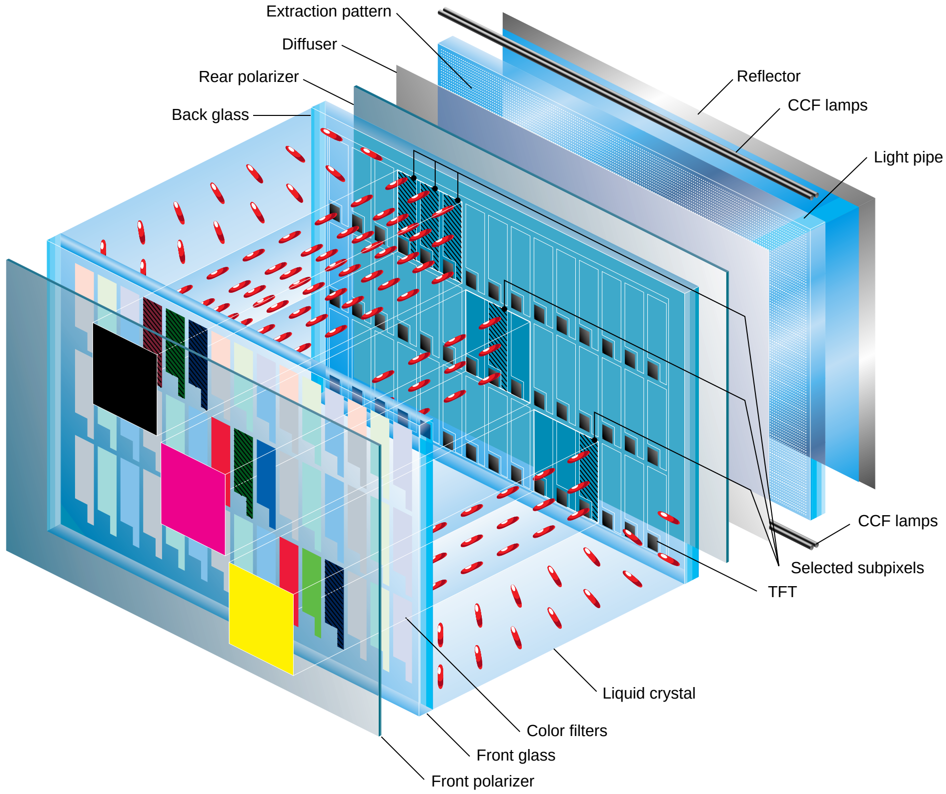


Figure 13. Active Matrix LCD Addressing.

Part 3. SILICON GRAPHICS TECHNOLOGY

3.1 Differences between LCD and CRT Technology

Users accustomed to using CRT monitors will notice that a flat panel monitor that employs liquid crystal display technology is remarkably different in several ways. The differences have to do with the manner in which the flat panel is addressed, the way it is designed, how color is achieved, and how it receives data information. See Figure 14 for a block diagram of Silicon Graphics 1600SW.

3.1.1 Addressing

In an LCD, one of the first things a user notices is the crispness of the text. A CRT pixel is formed by a beam of electrons that scans across the screen. Thus pixels "bloom" at the fuzzy edge of the electron beam and smear into each other as the beam moves. The flat panel monitor's pixels are formed by a combination of light valve and color filters that produce an extremely crisp edge for each subpixel. You can actually see these red, green, and blue subpixels with a small magnifying lens, and verify that each is of the same hue and saturation across its entire area.

3.1.2 Flicker-Free Refresh

Another difference is the lack of flicker on an LCD flat panel monitor. CRTs flicker because the electron beam for a primary color can be in only one place at a time. The phosphor's appearance depends on a property known as "persistence," which causes the phosphor to emit light for a few milliseconds after the energizing beam has moved on. (Persistence is what makes CRT technology possible.) Nevertheless, the light begins to decay almost immediately, resulting in flicker. In an active matrix flat panel, all pixels are being driven all the time. Thus pixels that are not changing in value look perfectly stable.

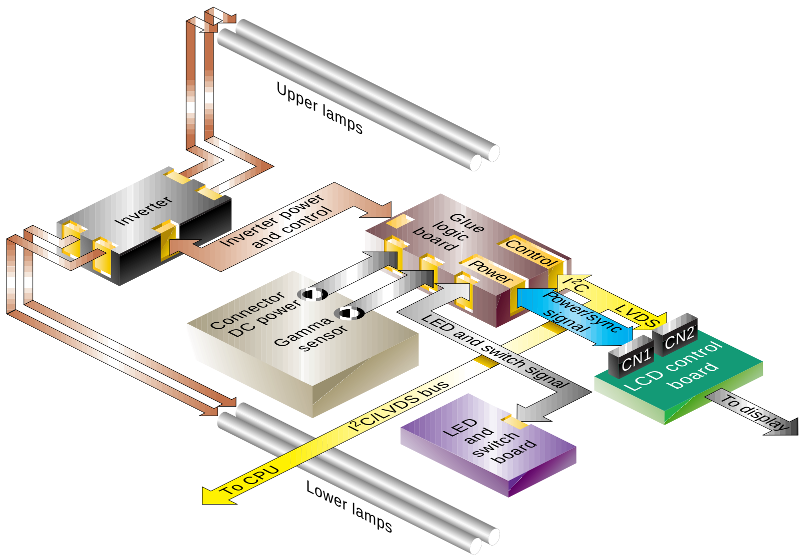


Figure 14. Silicon Graphics 1600SW Flat Panel Monitor Block Diagram.

In a CRT, these millions of subpixels must be updated many times a second with, at the most, three electron beams that are available for this task. After a beam strikes a phosphor dot, it has only a few thousandths of a second to return to this same dot ("refresh it") before its brightness begins to decay drastically. The more often the electron beam can strike a dot in a second, the more stable or more precise the image appears. For a CRT, a refresh rate of 72Hz is acceptable, while at 60Hz or less the image begins to suffer in sharpness.

As we have seen in a previous section, LCD pixels are not addressed directly but rather by voltage from individual capacitors that are charged from a row-at-a-time scan. The liquid crystal molecules see this voltage during the entire time of a refresh cycle and never get a chance to "decay." So rather than a CRT beam, which has typically to land on 1.3 million phosphor dots 60 or 70 times a second, the scan signal in an LCD is responsible for only a thousand or so rows. Practically speaking, there is little difference in an LCD image addressed at 40Hz versus one addressed at 60Hz or 70Hz.

3.1.3 Flat and Spatially Fixed Construction

There is a noticeable lack of distortion and movement in the image displayed by the flat panel monitor. There are two reasons a CRT cannot achieve this: the physics of creating glass tubes makes it almost impossible to make them flat; and the mechanics of controlling an electron beam over a large screen make it almost impossible to get straight lines everywhere on the CRT.

Also contributing to the flat panel's stability is the fact that the display format, and subsequently the image it displays, is fixed. This is unlike a CRT, where the image can be in one spot during one frame and then shifted over a pixel in the next, depending on outside interference or addressing signal stability.

3.1.4 Digital-to-Digital Data Transfer

Silicon Graphics' especially high-resolution 1600 x 1024 display is capable of displaying 8 bits of color resolution per subpixel for a total of 16.7 million colors. To manage the higher resolution and greater number of colors, the pixel "clock" rate (or the speed at which the image data is transferred from the computer to the display) must increase along with the accuracy of timing and sampling the information.

CRTs (and even many other flat panel monitors) use an analog method to transfer data, while Silicon Graphics 1600SW uses a digital one. With an analog interface, the image data being transferred to the monitor is represented by the varying shape of an electrical signal, or "waveform," which guides the electron beam(s) as they write across the face of the CRT. The drawback to this method occurs in the sampling and clocking of data when CRTs attempt to move to higher pixel resolutions, because analog interfaces suffer from poor or unstable timing information. This in turn can cause misalignment of the screen image from frame to frame.

In a digital interface, however, the information is encoded by Silicon Graphics' graphics controller as a series of numerical values, usually evenly spaced in time. These numerical values are sent to individual pixels to set them to specific color values. This digital interface is especially suitable for flat panel monitors where the format is spatially fixed, that is, a digital interface to a digital display. The result is a screen image that is steady and flicker free—and that can be looked at for hours at a time without causing eye fatigue. (For a more complete explanation of Silicon Graphics' flat panel interface, please refer to "Flat Panel Display Interface Technologies" by Joshua Larson-Mogal, at *http://www.sgi.com/peripherals/flatpanel/whitepapers.html*.)

3.1.5 Magnetic Field Immunity

The stream of electrons that scan the face of the CRT is controlled by the precise magnetic field of a beam deflection yoke. Minute fluctuations in the yoke's field can wreak havoc with the screen image. By contrast, even though the molecules in an LCD are controlled by extremely small voltage fields, they are impervious to magnetic fields. The sensitivity threshold for Silicon Graphics 1600SW, for example, has been tested in all three axes by the Helmholtz Coil method and found to exceed an H-field value of 44.61 µTesla (~35Amps/meter): an amount 70 times the tolerance level of most CRTs. (In fact, a CRT must be recalibrated if it is moved from one hemisphere to another, owing to changes in the polarity of the Earth's magnetic field.)

3.2 Optical Features

This section reviews several key engineering and design innovations in the Silicon Graphics 1600SW monitor that successfully solve current display industry problems. The engineering aim has been to let the user work with less fatigue, greater accuracy, and more efficiency. And in implementing these technologies, which include wide-aspect ratio, superior color and spatial resolution, and adjustable white balance, the goal was to arrive at a "no compromise" solution for replacing a CRT with a digital LCD.

3.2.1 Color Saturation

Color saturation is proportional to the thickness of the color filter layers; however, overall light transmission of the display is decreased as color saturation increases. Poorly saturated colors make for a reduced color palette or gamut-which is expressed as a percentage of the National Television System Committee (NTSC) standard. Color gamuts for laptop displays and many flat panel monitors typically range from a low of about 40 percent to a high in the mid-50 percent area.

Silicon Graphics has always strived to maintain the highest color saturation in the industry, offsetting the impact on luminous efficiency through the use of special brightness-enhancing films and backlight structures. These films are specially selected and applied to enable the display to maintain its chromaticity coordinates in varying ambient lighting situations. For example, Silicon Graphics 1600SW has a color reproduction gamut of 62 percent of the NTSC standard, a value higher than that of other flat panel monitor manufacturers and equal to or better than many CRTs.

3.2.2 Gray Scale Levels

The number of gray scale levels that an LCD can display is a measure of how well it is electrically addressed. Each subpixel in Silicon Graphics' flat panel is addressed by 8 bits of data, applied by a digital voltage amplitude modulation method, yielding 256 gray levels for each primary color. Therefore, the monitor is capable of displaying 256 (R) x 256 (G) x 256 (B), or over 16,700,000 colors, all with only 4mV of data pixel voltage control for each subpixel!

Although the pure digital addressing method used by Silicon Graphics is technically challenging, it offers a more precise control over the gray shades being displayed. Other flat panel monitor manufacturers may use analog voltage drivers or combine a digital driver having lower output levels with a frame-rate control method to display an acceptable number of gray shades. However, an analog driver capable of modulating the amplitude of signal voltages at the speed required for the high-definition level of Silicon Graphics 1600SW may well be too large to fit in the display panel! Also, an LCD monitor manufacturer seeking to bypass the technical hurdles of high-level digital drivers by adding one or two bits through the use of frame-rate modulation will likely encounter some screen flicker.

3.2.3 Contrast Ratio

The contrasting areas of light and dark on the LCD screen can be used as a measure of performance. The luminance of a bright, unselected area divided by the luminance of that area while in a dark, selected state is known as the contrast ratio. The contrast ratio achieved by Silicon Graphics 1600SW, when measured by a photopically corrected instrument, is typically about 350:1, a value many times that of most CRTs in office lighting conditions. This photopically corrected instrument allows for the fact that the human eye is more sensitive to the wavelength of green light than it is to the spectrum of red light, and more sensitive to the wavelength of red light than it is to the spectrum of blue light. This is known as the tri-stimulus response. Any instrumentation that seeks to represent actual contrast ratios must emulate this response curve. (See Figure 15.)

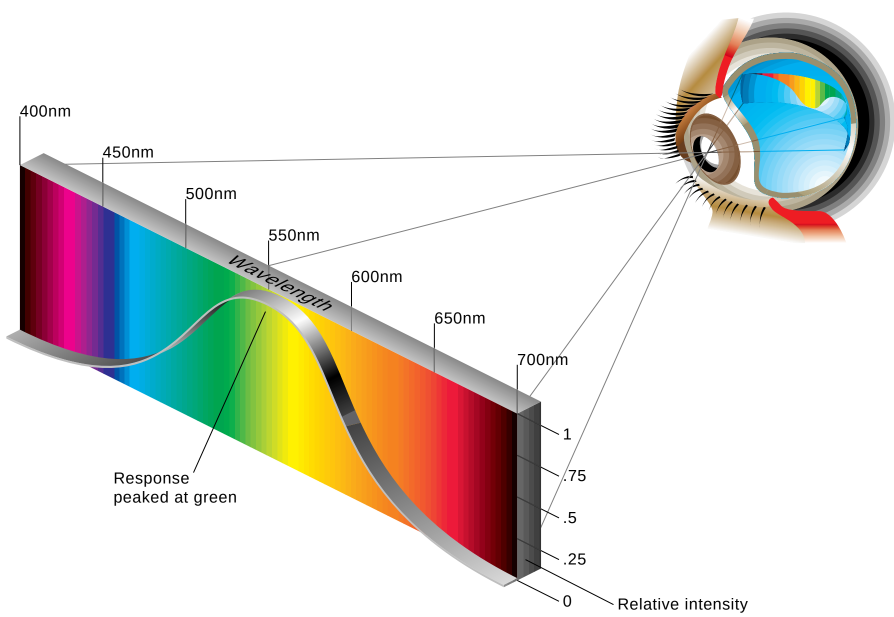


Figure 15. CIE Photopic Curve (Spectral Sensitivity of the Human Eye).

3.2.4 Adjustable White Balance

As part of Silicon Graphics' intellectual property, Silicon Graphics 1600SW uses a separate system to adjust the white balance in a minimal range from 5000° Kelvin to 7000° Kelvin. This system works by adjusting the color temperature of the backlight without reducing the dynamic range of the gray scale levels for any of the color primaries. The benefit to the user is an entirely new dimension of color control over the viewing environment. Of all the flat panel LCDs currently on the market, only Silicon Graphics provides this unique type of user-adjustable white balance. Driven from an on-screen panel or by color calibration software and hardware, the adjustment is accurate to within 25°K. (See the companion white paper by Tom Lianza, "Silicon Graphics ColorLock System," http: [*to be published*] for a more in-depth discussion of adjustable white balance.) Figure 16 shows that this utility adheres closely to the daylight white locus.

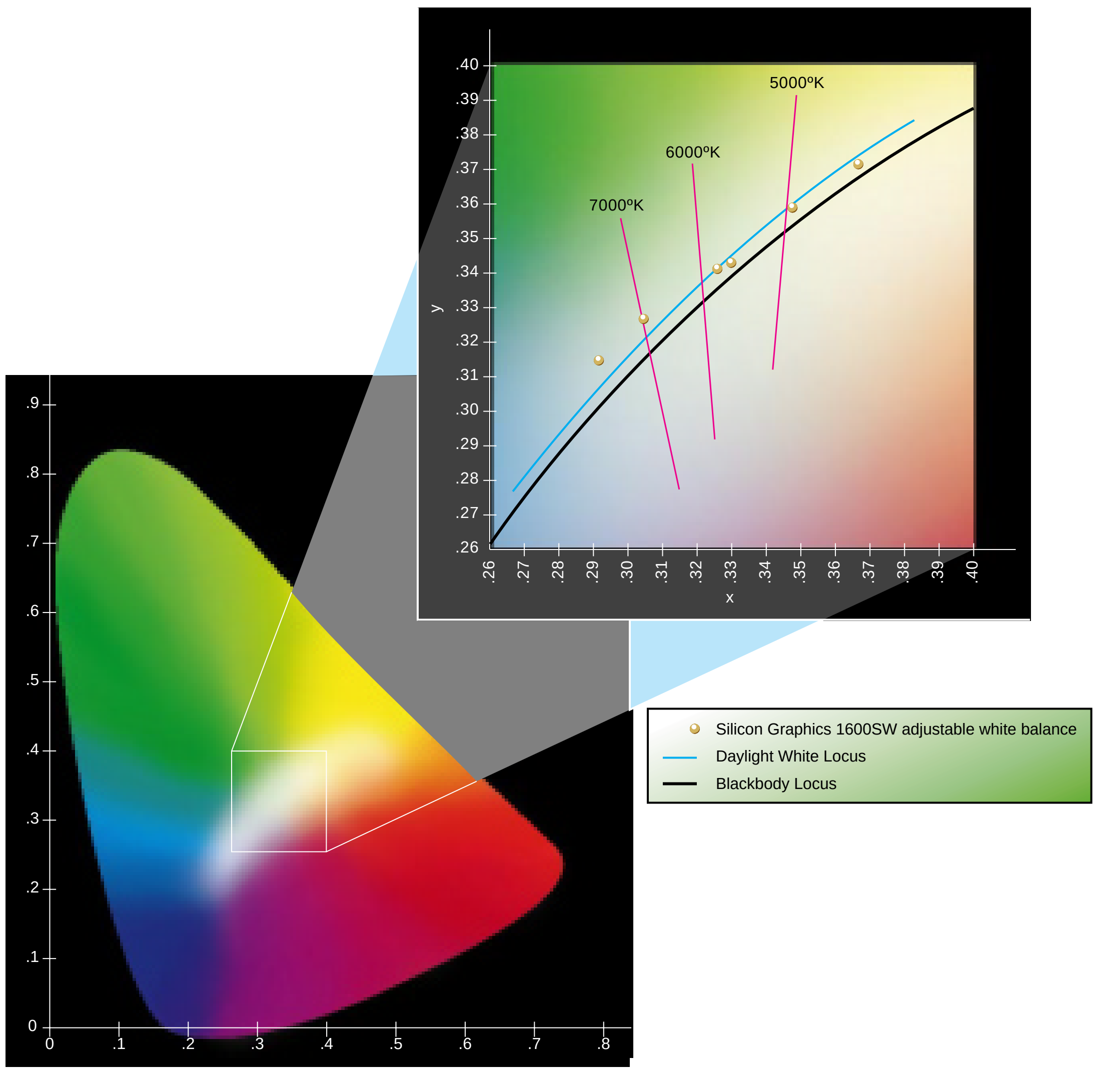


Figure 16. Adjustable White Balance Locus, C.I.E. Chromaticity Diagram.

3.2.5 Colorimetric Profile

The Silicon Graphics 1600SW flat panel monitor complies with the Display Data Channel standard, version 2.0 level B (DDC2B), which defines the communications channel between the display and host system. The monitor also transmits an Extended Display Identification Data (EDID) structure. Encoded within the display's onboard memory are its manufacturing serial number, week and year of manufacture, and important parameters such as display size, power management, gamma, and timing. These data are accessible to the user either directly from the CPU or over a local or wide area network.

Additionally, the Silicon Graphics 1600SW flat panels are carefully characterized at the factory and their colorimetry profiles are stored within the onboard memory of each monitor. This characterization is performed using a very expensive colorimeter, specifically designed for this task, and provides the user with specific color characteristic references from which very accurate calibrations can be achieved.

3.2.6 Colorlock Calibrator

When it is to be used with a Silicon Graphics workstation, the Silicon Graphics 1600SW includes the ColorLock Calibrator, a light-intensity calibration device with photopic responsivity. The ColorLock calibrator is optimized for extremely wide dynamic range operation and exhibits better linearity than measurement instruments costing many times more. It is a completely self-contained, epoxy-encapsulated sensing element that is unaffected by long-term exposure to the environment, showing no degradation over a two-year period. The calibration device uses the colorimetric profile data previously described (see Figure 15) to self-correct the panel to which it is attached and to track aging and changes in the panel.

3.2.7 Native Gamma

The Silicon Graphics 1600SW flat panel monitor has a native gamma value of 1.8; this is lower than gamma values for CRTs, which range from 2.2 to 2.8. The lower gamma in Silicon Graphics 1600SW, together with its much higher contrast ratio, enhances viewability of shadow and mid-tone regions so that the panel may be more effectively used in relatively high-ambient illumination. For lower illumination levels, the calibrator and software supplied with the panel can be used to adjust the gamma from lookup tables.

3.3 Optical Challenges

As the name “liquid crystal” implies, these materials exhibit many of the characteristics of crystalline solids, while being able to move and flow like a liquid. In a crystalline material, the speed of light traveling through it can vary depending on the direction the light is traveling and the orientation of the material's polarization relative to its crystalline axes. This property gives rise to several challenges to the flat panel monitor developer, which are described below.

3.3.1 Viewing Angle

About the only area in which CRTs have a natural advantage over LCD screens is in their superior viewing angle. Light is emitted from a CRT when the electron beam strikes a phosphor pixel, which is a collection of granular crystals on the inside face of the CRT rather loosely deposited by electrophoretic (selective plating) deposition techniques and sintered (fired by high temperatures) to the glass. From the viewing side, the phosphor layer has a diffuse texture, causing it to become a Lambertian (perfectly scattering) light emitter when struck by an energizing electron beam. So images look the same regardless of the angle from which they are viewed.

Twisted-nematic liquid crystal displays, on the other hand, do not emit light but must obtain it from a backlight source and conduct it along their molecular axes. It is in an examination of this molecular structure that several shortcomings are observed. These shortcomings arise from the three-dimensional characteristics of the refractive index of twisted-nematic flat panel displays. Changes in the refractive index of a material that depend on the direction in which light travels through that material are known as "birefringence." Specifically, light accumulates a positive birefringence as it passes through the thickness of the liquid crystal layer. This results in a significant dependence of the contrast ratio on the viewing angle. Various methods for correcting this effect, and their merits, are discussed in the section below on optical solutions.

3.3.2 Off-State Pixel Leakage

There are some issues with flat panels having to do with luminous "crosstalk" from adjacent primary color channels and chromaticity shifts at low-luminance gray scale levels. These problems are caused by light leakage from pixels in the "off" state. Silicon Graphics' flat panel design successfully deals with the first instance of stray light by incorporating a Cr/CrOx black shadow mask deposited on the front color filter plate in the areas between the red, blue, and green subpixel color filters. This mask hides the effect of the liquid crystal molecules as they orient themselves over the uneven topology of the TFT devices and the Gate and Source lines. This is known as a "disclination" effect, which can result in loss of contrast due to scattered light at the pixel edges.

A potentially more serious problem can be caused by very small amounts of light that still can be emitted from "off" pixels, and by the impact this light might have on the colorimetry of adjacent pixels that are in the "on" state but at low gray scale levels. In the "off" state, the luminance of "black" pixels, although very low, is still approximately 0.6 cd/m2, which may be detected in darkened room environments. Silicon Graphics' countermeasures for both these problems are discussed in the following section.

3.4 Optical Solutions

3.4.1 In-Plane Switching

In-Plane Switching (IPS) is an LCD construction that is commonly employed by monitor manufacturers to achieve a broader viewing angle. In this application, the molecules of the liquid crystal are switched between electrodes located "in the plane" of the cell rather than between electrodes on two opposing glass plates. In general, this is a good countermeasure for birefringence effects; however, the application of the IPS method causes problems in other areas of LCD technology. These areas are as follows:

1) Response time. Response time is described in the industry as the time (usually in milliseconds or microseconds) that it takes for a group of liquid crystal molecules to respond to a selection voltage for the duration of one frame and then return to within 10 percent of their relaxed state. Response time for IPS display devices is characteristically slower than for twisted-nematic structures, considerably limiting the LCD's ability to show artifact-free video. The typical response time for Silicon Graphics 1600SW is less than 40mS, while the early IPS monitors were at 100 to 120mS and have only recently improved to 70 to 80mS.

2) Transmissivity. Transmissivity is the percentage of the total luminance from the backlight that is transmitted through the LCD to the user. The Silicon Graphics 1600SW flat panel monitor, with its twisted-nematic construction, has a transmissivity of 4.1 percent. This means that in order to achieve a front-of-screen brightness of 235 Nits, the monitor's 4-CCF lamp backlight must generate a raw brightness of over 5700 Nits. Panels with similar pixel densities but with IPS constructions, however, can have transmissivities of less than half that value. So to achieve the brightness level of the Silicon Graphics

1600SW, an IPS panel might require as many as 10 CCF lamps generating over 11,000 Nits of raw brightness and drawing twice as much power.

In order to improve the viewing angle characteristics of Silicon Graphics 1600SW without compromising switching speeds, Silicon Graphics settled on the following method, which employs stretched optical compensation films.

3.4.2 Stretched Optical Compensation Films

For moving images, using stretched films to compensate for the positive birefringence not only increases the viewing angle but also enables display of moving images at 30 frames per second. By contrast, the IPS technology deployed in some of the earlier generations of display hardware actually restricted the video rate required for non-blurring movement to as slow as 10 frames per second.

As seen in section 2.1, Twisted-Nematic Display, when an addressing voltage is applied to a pixel or group of pixels, the affected molecules snap out of their twisted helixical state. In this fully “on” state, all the molecules should be aligned perfectly perpendicular to the field electrodes. (As previously described, this state is dark in a normally white twisted-nematic cell.) In practice, the molecules are at an angle less than perpendicular, especially when only receiving a portion of the available voltage in order to display a gray shade. This causes light propagation along the molecular chain to “see” a different birefringence and emerge from the display at different viewing angles, detectable by the user as changes in contrast or shifts in the color of a displayed image.

Because the compensation film is optically negative, with its axis also perpendicular to the substrate, it can effectively undo the distortions that light undergoes due to traveling through the stackup of LCD layers at an angle. As illustrated in Figure 17, a film is stretched along two axes to produce a negative birefringent film where nx = ny > nz. When added to the positively birefringent twisted-nematic liquid crystal cell, the differences in retardations are canceled, producing a display where nx = ny = nz. This technique greatly improves the display’s viewing characteristics; it is used in the Silicon Graphics 1600SW flat panel monitor.

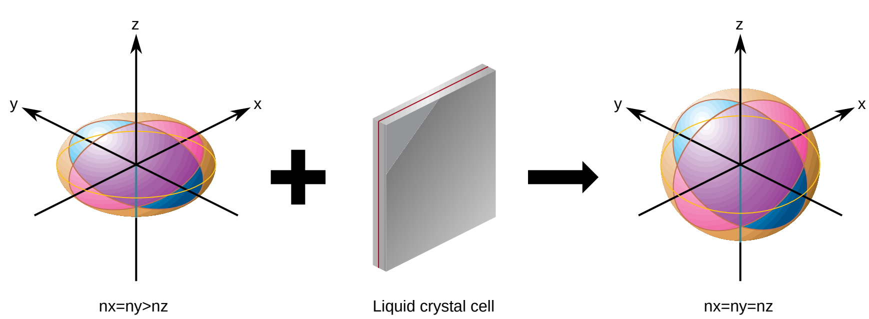


Figure 17. Stretched Optical Films Compensate for Birefringence.

The stretched optical compensation film complements the LCD's birefringence and corrects the distorted light as it exits the cell, (see Figure 18).

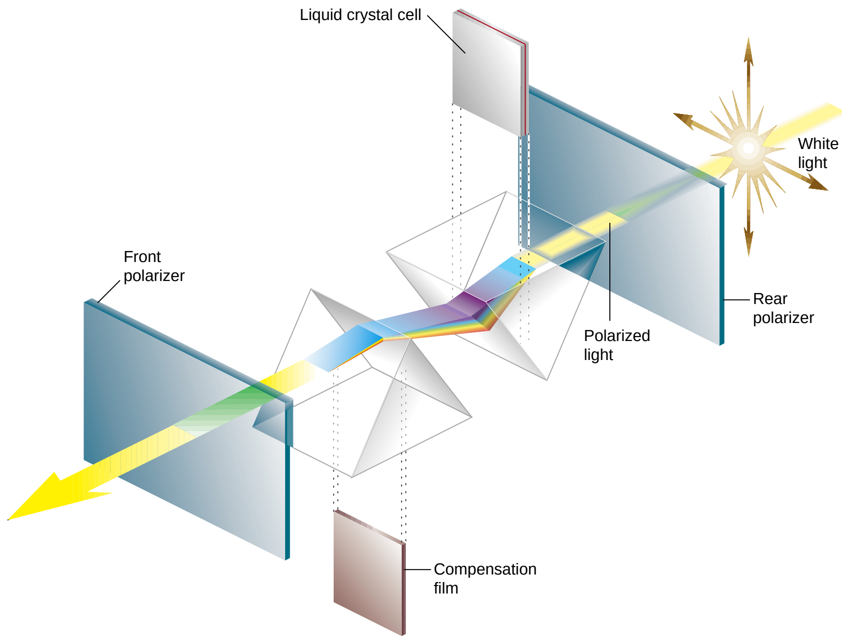


Figure 18. Compensating for Birefringence to Improve Viewing Angle.

3.4.3 Pixel Leakage Countermeasures

Silicon Graphics' countermeasures for this leakage effect are twofold:

1) As previously described in section 3.4.2, negative birefringence compensation films will correct for light distortions traveling through the liquid crystal layers to produce a greater extinction level in "off" pixels.

2) As described in section 3.2.1, Color Saturation, Silicon Graphics uses very thick color filter layers in order to maintain high saturation levels in the primary color subpixels. This high saturation minimizes the impact of the colorimetry component of any stray leakage from adjacent subpixels.

As it turns out, even at moderate light levels, pixel leakage is not an issue because Silicon Graphics' brilliant colors have sufficient luminance to overcome the color influence of adjacent "off" pixels. Color performance is the same for all RGB triads versus a single primary, although some color variation (~10 percent) is measurable for gray levels as they shift from white to black.

3.5 Ergonomics

With its full-color digital display, sleek form factor, 1600 x 1024 resolution, and high-density dot pitch, Silicon Graphics 1600SW provides substantial and important improvements in image quality for all kinds of visual computing environments, satisfying the most demanding high-information applications for content creation, desktop publishing, CAD, and imaging. Several key ergonomic innovations have also been engineered into this new monitor that are aimed at letting the user work with less fatigue, greater precision, and reduced cost. In implementing these ergonomic features, again Silicon Graphics' goal is to bring together and improve on all the best aspects of digital LCDs, giving users advantages that are beyond what is achievable on a CRT.

3.5.1 Wide Aspect Ratio

Most important and immediately apparent is the wide-aspect ratio of the Silicon Graphics 1600SW monitor. Most CRTs present an aspect ratio of 1.25:1, width to height, at 1280 horizontal x 1024 vertical pixels. At 1600H x 1024V pixels and an aspect ratio of 1.6:1, Silicon Graphics 1600SW lets programmers allocate much more real estate to applications, and provides a wider view into the working environment. In fact, the monitor's 17.3-inch SuperWide™ diagonal format accommodates two full 8 1/2-inch by 11-inch pages side-by-side, with room left over for control panels or icons. The wide format has no impact on the way applications are run; its extra screen real estate simply lets the user see and have access to more information while working.

But beyond these very evident benefits, Silicon Graphics elected a wide design because it creates a machine interface that more closely allies with the way the human cerebral cortex "reads" information: from left to right, right to left, horizontally instead of vertically. Humans owe this tendency to the fact that for our ancestors, the ability to scan the horizontally composed vistas of the African plains quickly often meant the difference between life and death. This basic survival skill became hardwired into the human cerebral cortex.

You can test this today by noticing your reaction to complex visual information presented on a horizontal axis, then comparing it to your response to a sweeping vertical scene. To take in the horizontal scene, you quickly move your eyes back and forth with very little movement of your head. To take in a complex vertical scene your reaction is quite likely to step back and move your entire head and upper body, perhaps even tilting your head. So in effect, gathering information that is arranged vertically requires considerably more time and effort than does reading information that is arranged horizontally. In other words, an extended vertical read involves a fundamentally inefficient process.

And using a flat panel LCD, Silicon Graphics provides this horizontal wide-aspect ratio advantage without any compromise to image quality. By contrast, CRTs cannot achieve the same wide-aspect ratio without sacrificing consistency of line and graphical information, particularly in corner pixels. This is because the scanning beams in a CRT emanate from a single point and have to fire at very oblique angles to reach the outermost areas of the screen. Some CRT monitor manufacturers compensate for this deficiency by increasing pixel pitch at the corners, thereby affecting the linearity of straight lines and resulting in images with non-uniform pixel densities. With a flat panel, the corner pixel is just as easy to reach as the center pixel.

3.5.2 Pixel Pitch

For Silicon Graphics, the medium is a significant part of our message; therefore, the 110 dpi resolution of Silicon Graphics 1600SW is a key feature for the display of high-information content images. This is especially valuable in areas such as medicine, satellite imagery, military, or film—all of which require finely rendered text and graphics. The Silicon Graphics 1600SW flat panel monitor's 0.231mm pixel pitch smoothes out the visible stair-step or "jaggy" appearance of curved lines and text characters, providing the monitor with a built-in anti-aliasing capability. For a CRT, duplicating this dot pitch comes at the price of lower yields, less accurate convergence of its electron beams, and the possibility of more eye strain and fatigue for the user.

3.5.3 Flat Screen

Also tied to aspect ratio is the Silicon Graphics monitor's inherent advantage in using a flat surface to eliminate image distortion. Most CRTs are curved to help resist the compressive effect of thousands of pounds of air against the hard vacuum in the CRT bulb. Attempting the same wide-aspect ratio for this curved surface would again create distorted text, line, and graphic images. As the user tries to position the CRT to find the optimum viewing position for a specific area of the monitor, other parts of the monitor's curved faceplate catch room reflections or glare. By contrast, once the user adjusts the viewing angle of Silicon Graphics 1600SW, the entire surface of the panel becomes the "sweet spot." Additionally, to soften both glare and non-glare reflections, Silicon Graphics also provides a protective anti-glare hard coating on the Silicon Graphics 1600SW flat panel screen.

3.5.4 Emissions

By their nature, CRTs must produce radiation to function. Although considerably lower in energy and penetrating ability than x-rays (or gamma radiation), the CRT scanning guns produce streams of electrons (or beta radiation) at tens of thousands of volts of potential energy. As a countermeasure against any damaging biological effects, CRT bulb manufacturers employ heavily leaded glass to screen harmful rays from the user—glass that drastically reduces visible light transmission as well. Silicon Graphics 1600SW does not emit harmful radiation and can work in magnetic and other environments that would destabilize a CRT.

3.5.5 Power Management

Power management for the Silicon Graphics 1600SW flat panel monitor is controlled from an 8-bit bi-directional register within the display monitor through the Philips Inter-Integrated Circuit (I2C) bus and protocol, including power-on initialization and various adjustment functions. This implementation of the I2C architecture assumes that the host computer interfacing to the flat panel is the only master device driving the I2C bus.

The front panel of the monitor is equipped with a manual power button and a status LED. At any time the power to the panel may be disabled for energy savings or privacy. The user may analyze the condition and status of the monitor and system by examining the various screen, LED, and system states listed below.

STATE 0

- LED: OFF
- Screen is OFF
- I2C Functioning

STATE 1

- LED: Flashing yellow
- Screen is OFF
- I2C Functioning

STATE 2

- LED: SOLID GREEN
- Backlight is ENABLED
- Screen is ACTIVE
- I2C Functioning

STATE 3

- LED: SOLID YELLOW
- Backlight is DISABLED
- Screen is INACTIVE
- I2C Functioning

3.6 Notes on Quality

3.6.1 Pixel Defects

Occasionally, the user can notice several brightly colored dots on the monitor that remain in the same place regardless of the image displayed on the screen. An anomaly of flat panel technology, these dots result from microscopic flaws in the panel, which can cause one of the red, blue, or green components of a pixel to be stuck in the "on" mode. Although they can be any of the primary colors, bright green dots are more noticeable because the human eye is more sensitive to that color. If the bright defects are displayed against the background of a dark image, they may seem large when in actuality they are no wider than the diameter of a single human hair.

3.6.2 The CIE Photopic Curve

The CIE photopic curve was developed to show the spectral (color) sensitivity of the average human eye, which is predominantly peaked in the yellow-green region. (See Figure 15.) The eye tends to focus first on the middle wavelengths: those producing a green sensation. Longer (red) and shorter (blue) wavelengths fall behind or in front of the imaging plane. Additionally, the human lens does not transmit all wavelengths equally, absorbing almost twice as much in the blue region of the spectrum as in the yellow and red regions.

The resolution of the Silicon Graphics flat panel monitor is 1600 x 1024 pixels. Therefore, there are
1600 x RGB x 1024, or 4,915,200, subpixels in your display—all in an area equivalent to 2.6 times that of an 8-inch silicon wafer. Although the current level of flat panel technology is not capable of producing a 100 percent defect-free active matrix display at reasonable costs, yields are improving steadily. The Silicon Graphics display's strict quality standards allow no more than 5 green defects per monitor (and no more than a total of 8 bright defects of all colors combined). This amount represents only about 0.0001 percent of the total number of pixels in the panel.

3.6.3 Backlight

CCF lamps decay most quickly in brightness during their first few hundred hours of operation, then gradually the rate of decay tapers off. The curve is somewhat logarithmic, but there are capacitive coupling issues at play. Affecting the lamp lifetime are factors such as lamp current and gas pressure, the shape of the driving waveform, and duty cycles.

As lamps degrade, it becomes increasingly more difficult to strike the plasma at colder temperatures because the mercury dopant in the gas condenses on the walls of the tubes at the lower end of the operating range. However, Silicon Graphics has allowed for that change in our inverter design by specifying the striking voltage for the tubes to be rated at their end-of-life. And even after end-of-life, the flat panel does not "fail" and will still be about 50 percent brighter than a conventional CRT.

Without instrumentation, the user likely will not be aware of any change even over a span of several months. Silicon Graphics' target time to half brightness is 20,000 hours (about 2 years, 3 months, with 24-hour usage). By using a dimming feature with the onset of a screen-saver application and a PowerSave shutdown after some time of inactivity, Silicon Graphics 1600SW should be able to extend its half-life by several years beyond that time. In fact, our lamp supplier has data that shows our backlight will last 10 years before it degrades to 50 percent brightness.

GLOSSARY

Active Matrix	Also known as AMLCD (active matrix liquid crystal display). A liquid crystal display structure in which switching transistors or diodes are attached to each pixel to switch each pixel on or off. Also see TFT (thin film transistor).
Alignment Layer	An organic thin film layer applied by spin-coating techniques and then baked at high temperature. This film (about 400A thick) is then treated to impart a direction to which the liquid crystal molecules may align. See also Buffing.
Amorphous Silicon	The semiconductor material that is used to make the thin film transistors (TFTs) of an active matrix LCD; similar to the material used in the construction of solar cells. Its low deposition temperature (<300˚C) makes it well suited for the production of larger area displays. An important consideration in the design of the AMLCD is that the a-Si must be protected from exposure to light, which can cause spontaneous switching triggered by photovoltaic response.
Anisotropic Conductive Film	(ACF) A thermoset (epoxy) resin matrix containing thousands of tiny (<20um) conductive metal spheres. Strips of this material are used to connect the tape automated bonding (TAB) integrated circuit (IC) display drivers to the liquid crystal display. In the attachment process, a heated anvil is used to pressure-bond the IC driver circuit leads to their respective indium tin oxide (ITO) display traces. Because the compressing is in the vertical “z” axis, the bond is made from circuit trace to ITO lead without danger of horizontal lead-to-lead or trace-to-trace shorting.
Aperture Ratio	(or Fill Factor) The ratio between the transmissive portion of a pixel and its surrounding electronics.
Backlight	The light source for a transmissive LCD; usually an acrylic light pipe edge lit by one or more CCFTs (cold cathode fluorescent tubes). See also Light Pipe.
Biaxially Stretched Films	Films of polycarbonate material that are specially prepared by stretching to alter their optical properties. By stretching along one (unilateral) axis, the molecules first become oriented in that direction. By stretching a second time at 90° to the first axis, the film shrinks in the first direction, causing the molecules to rise slightly slanted out of the plane of the film. This results in a material having a different optical retardation in the vertical axis, which makes it effective in compensating for the positive birefringence in a twisted-nematic LCD, thus producing a flat panel with a wider viewing angle.
Birefringence	The phenomenon of light traveling with different velocities in crystalline materials, depending on the propagation direction and the orientation of light polarization relative to the crystalline axes.
Black Body	A theoretically perfect radiator in the form of a spherical cavity that can be heated to a known temperature and having a small exit port through which energy emissions can be observed and measured. This object absorbs all incident radiation and re-radiates that energy with complete efficiency.

Black Matrix	The dark border surrounding a subpixel, used to enhance contrast and protect the thin film transistor (TFT) from bright light. Black Matrix is also used to mask disclination effects that occur as the molecules align themselves to the topology of the TFT and Gate and Source Bus structures. See Disclination.
Brightness	The luminosity of color, which can be expressed as luminous flux (lumen), luminous intensity (candela), luminance (candelas per square meter), and illuminance (lux).
Buffing	The method whereby the alignment layer on an LCD substrate is rubbed in parallel strokes using a soft cloth or ordinary paint roller. Although not entirely understood, the process is thought to align molecules with their long axes parallel to the buffing direction, thereby inducing the liquid crystal molecules that wet the buffed surface to follow suit. Somewhat of a "black art," the factors controlling this operation are the pressure, speed, and number of strokes as well as the type, size, and direction of the fibers in the buffing cloth.
Candela	The luminous intensity of color. See also Brightness and Nit.
CCFTs	(Cold Cathode Fluorescent Tubes) Tubes that furnish the light for the display. Approximately 2mm in diameter and 375mm in length, CCFTs are filled with neon, argon, and mercury, and their walls are coated with phosphors that emit a mixture of red, green, and blue light, depending on the desired color temperature (white balance). In operation, an electrical potential is applied across each lamp, causing the gasses inside to strike a plasma. The plasma emits UV radiation, which excites the phosphor coating on the lamp walls into emitting visible light.
Cell	An assembly consisting of two glass substrates, a perimeter seal, and a liquid crystal layer. The front substrate usually contains a color filter layer. If the cell is an active matrix construction, its back substrate contains thin film transistor switching elements and their associated circuitry.
Cell Gap	The distance between the two LCD glass substrates. Typical twisted-nematic gaps, which are determined by the molecular twist pitch, are 4 to 6 micrometers.
Cholesteric	A reference to the class of optically active liquid crystals that are similar in structure to cholesterol. These naturally rotating compounds are used as additives in LCDs to impart a common twist direction to the molecules in twisted-nematic displays.
Chromaticity Diagram	A graph on which chromaticity coordinates (r, g, b) of each monochromatic color are plotted.
CIE Photopic Curve	A chart developed to show the spectral (color) sensitivity of the average human eye, which is predominantly peaked in the yellow-green region.
Color Calibration	The process of adjusting a display's output characteristics so as to modify its appearance to conform to predetermined standards or settings. Usually accomplished through the use of a color or luminance measuring device and a lookup table (LUT) of values accessible to the computer's graphics controller. See Gamma.

Color Filter A red-, green-, or blue-dyed gelatin or pigment placed above each LCD subpixel. Combinations of various light levels passing through these color elements can produce all the visible spectral colors.

Color Resolution The colors that can be represented on a display depending on the number of gray scales resolved by the LCD element.

Color Temperature The definition of a monitor's white point, whose chromaticity coordinates can be somewhat arbitrary, existing in color space from red-white to blue-white. Expressed in degrees Kelvin (˚K), color temperature refers to the amount of light radiated by a perfect thermal radiator (see Black Body). Values at or below 5000˚K appear reddish; higher numbers, for example 7000˚K, appear bluish.

Column Drivers Micro electronic circuits that provide the correct voltages to the individual subpixel through the source lines. For example, 8-bit drivers provide 256 gray shades, or 256 distinct colors per subpixel.

Contrast Ratio The ratio between the amount of light transmitted by a pixel in its unselected OFF state and its selected ON state. In an active matrix liquid crystal display (AMLCD), this ratio is usually greater than 200:1.

Dielectric Properties The resistivity of the liquid crystal material is 10^{11} to 10^{13} ohm-cm. Contamination of this material by just a few molecules can set up "screening fields" or "double layers" which block effective voltages and degrade contrast ratios.

K11: Splay K22: Twist K33: Bend

The object is to maximize K33/K11. Any such contamination will decrease this ration.

Disclination Analogous to parallel slippages in crystal lattice structures, these are defects that arise out of the twisted nature of liquid crystals. The three forces that affect an LCD are splay, twist, and bend; which are responsible for the molecules' returning to their original aligned state after a selecting voltage is removed. Any electrical or mechanical influence causing an imbalance in these forces can result in a disclination. See also Dielectric Properties and Black Matrix.

Display Controller A digital signal source that orders data correctly for display. It provides H and V sync, Data enable, Clock, and 8-bits each of R, G, and B information.

Double Domain A method of achieving an enhanced viewing angle where multiple alignment directions are produced on the same subpixel. Vertical viewing angles can increase from +35°/-10° to ±40°.

EL (Electroluminescent Display) A display produced by an electric field that is applied across a polycrystalline phosphor, stimulating the phosphor and emitting light. Two types of ELs are DC Powder, which provides a good appearance but limited life, and AC thin-film, which affords good efficiency, gray scale, and color. Overlaid phosphors are used for multi-color.

FED (Field Emitter Display) A display consisting of an array of micro tips, at a density of 1000s beneath each pixel, each of which is essentially a miniature CRT in a vacuum envelope. Can be operated at very high-current densities with low-drive voltages.

Frame Rate The number of times in one second, measured in Hertz (Hz), that a display's system hardware redraws pixels to the monitor screen. With CRT monitors, a series of scanning electron beams (one for each primary color) "write" to their assigned subpixels in a left-to-right, top-to-bottom rasterized scan. In active matrix displays, frame rate is the time period in which all gate electrodes are scanned sequentially from top to bottom until the entire screen is energized. Normally for LCDs, one frame is 1/60 of a second; however, CRT monitors prefer higher values of around 72Hz because the persistence of the phosphor coating on the inside of the monitor decays unless refreshed quickly. This can result in eye fatigue, either perceived or subliminal, caused by the resulting flicker associated with slower rates. The computer system's graphics rendering rate is usually related to the frame rate.

Gamma The relationship between the video input signal and the light output or luminance (see Gray Scale). A goal of all image reproduction systems is to reflect and reproduce accurately the tone of the original scene. Display systems generally have inherent nonlinearities in how they reproduce this tone data; these nonlinearities are called natural or "native" gamma. Computer system hardware permits an adjustment or correction of native gamma through the use of LUTs, whose values are collectively called the correction gamma.

Gate Electrode The "row" electrode in an AMLCD that controls whether a voltage is applied to a liquid crystal subpixel.

Gray Scale An intermediate luminous level of light, between "full on" and "full off," that penetrates a color filter primary. This level, in multiple graduations, is controlled by the magnitude of the voltage that is used to address an LCD subpixel. See Source Electrode.s

Hue Colors such as red, orange, yellow, green, blue, purple-blue, purple, and red-purple; but not white, gray, or black.

IPS (In-Plane Switching) Another method of achieving an enhanced viewing angle where the liquid crystal molecules are switched in the plane of the LCD layer rather than orthogonal to it. This method results in excellent viewing angles but negatively impacts aperture ratio and response time, resulting in slower, dimmer displays.

Light Pipe A rectangular plate cut from acrylic stock extruded in huge sheets from a melt and located behind the LCD. Used in conjunction with a printed dot extraction pattern to distribute uniformly the light coming from cold cathode fluorescent tubes (CCFTs) located at its edge(s). See also Backlight.

Luminance The amount of light emitted or scattered by a surface. Luminance is the weighted average of red, green, and blue color values that provide the perceived brightness of the combination. The English unit of measure for luminance is a "foot-lambert" (fL) and is defined as one foot-candle falling upon a perfectly diffusing white surface.

Module An assembly that comprises the cell plus display drivers that control light and deliver host computer data to the cell, as well as a backlight assembly consisting of fluorescent lamps, light pipes, and associated diffusers and reflectors, all contained within a rigid sheet-metal structure. See Cell.

Monitor An assembly that consists of the module plus an inverter to power the lamps, a display interface to the CPU, a plastic bezel and stand, and a power supply. See Cell and Module.

Nematic That phase of liquid crystal materials where the molecules are linked together at the ends of their long axes like beads on a string (nematic is Greek for “string”). In this state, the liquid crystal molecules can move freely parallel to the “string,” but not in a perpendicular direction. See Smectic.

Nematic-to-Isotropic Temperature at which LCDs change phases from a liquid crystal to a liquid.

Nit A unit of photometric luminance equal to one candela per square meter (cd/m2). 1 Nit = Cd/m2 = 0.292 fL. See also Candela and Luminance.

Normally Black The twisted-nematic LCD structure in which light is blocked when pixels are in an unselected state. Characteristically, polarizers applied to a twisted-nematic display are arranged with their polarizing axes parallel.

Normally White The mode of a twisted-nematic LCD structure with crossed polarization axes, in which light is transmitted in the absence of an electric field. This is the preferred construction for laptop and monitor displays because the selected “on” state produces a pure black that is free from any wavelength dependency effects.

NTSC A color television standard or timing format encoding all of the color, brightness, and synchronizing information into one signal.

Passive Matrix LCDs that are addressed by a multiplexed-drive time-sharing system using a voltage equalization method. As the number of scan lines increases, the viewing angle narrows and the contrast ratio is reduced.

Photopic Luminance The photometric curves which represents the average weighted response of the human eye, as defined by Comission Internationale de l’Eclairage (CIE). A fixed amount of power in the green spectral region will appear to the human eye and brain as much “brighter” than the same amount of power in the red or blue regions.

Pixel A collection of granular crystals on the inside face of the CRT rather loosely deposited by electrophoretic deposition techniques and sintered to the glass.

Pixel Pitch The distance from the edge of one pixel to the similar edge on an adjacent pixel.

Pixel Resolution The number of addressable pixels in a display. Several standard display sizes are:

VGA	640 x 480
SVGA	800 x 600
XGA	1024 x 768
SXGA	1280 x 1024
SXGA-Wide	1600 x 1024
UXGA	1600 x 1200
HDTV	1920 x 1080
UXGA-Wide	1920 x 1200
QXGA	2048 x 1536

Plasma A type of display where an ionizing electric field is applied across a gas contained in a glass envelope with row and column electrodes. Photons are emitted when the atoms return to the ground state. The two types of plasma displays are DC plasma, offering good uniformity, color, and gray scale but drivers that are high voltage and lifetime limited; and AC plasma, available in large 42-inch full-color sizes.

Polarizer A dye- or iodine-impregnated polymer film that is drawn or stretched in one axis, orienting both the film and the optical dopants in the same direction. This causes an optical polarization that allows passage of light components oriented only in a certain direction.

Primary Colors The colors (red, green, and blue) that cannot be produced by any combination of other colors. Conversely, any color can be produced by mixing the three RGB primary colors.

Response Time The speed at which the orientation of a liquid crystal material can change in response to a charging/discharging cycle. Typically noted as "rise plus fall," for twisted-nematic structures, this time ranges from 20 to 50ms and depends mainly on the viscosity of the liquid crystal material.

Pretilt The angle the molecules make with the surface of the display glass plates. Pretilt is controlled by the type, amount, and pressure used in buffing the alignment layer to form the molecular orientation and is the source of the angular dependence of the viewing angle.

Row Driver Or "gate driver." The switch for turning the thin film transistor (TFT) on or off.

Saturation The vividness of a color.

Smectic The phase of liquid crystal materials in which molecules are linked together along their short axes like layers of logs (smectic is Greek for "grease"). In this state, the molecules can move freely within the layer structure. See Nematic.

Spacer A glass fiber rod or resin sphere used to set the minimum distance between the front and back glass substrates to control the thickness, or cell gap, of the liquid crystal layer of an LCD panel. Typical concentrations of these spacer beads are a few hundred per square millimeter. With typical cell gaps at 4 to 5um, the diameter of these spacers is six times below the perceptual range of the human eye at a viewing distance of 12 inches.

Source Electrode The "column" electrode in an AMLCD that determines the amount of voltage to be applied to an LCD subpixel. The magnitude of this voltage determines the gray level to which that subpixel transmits light to its respective color filter primary. See Gray Scale.

Tape Automated Bonding (TAB) A flexible substrate upon which the display driver ICs are mounted through a heat/pressure process.

TFT (Thin Film Transistor) A device that can be made from a-Si, p-Si, or CdSe used as a switch to a charge storage device beneath each subpixel of an active matrix liquid crystal display (AMLCD).

Transmissivity The amount of light that passes through the display, expressed as a percentage of total light available from the backlight. The factors that affect this total are the incremental transmissivities of the various optical components: polarizers, color filters, and ITO films; factored by the aperture ratio of individual subpixels. See Aperture Ratio.

Uniaxial Describes materials that possess one unique axis or optic axis that is parallel to the liquid crystal director.

Vacuum Filling A process by which empty display cells are placed in a vacuum chamber and lowered into contact with the liquid crystal material, which is then injected into the display as the chamber is gradually returned to atmospheric pressure.

Viewing Angle The bounding angles generated from a point normal to the display surface within which can be found acceptable contrast ratios and linear gray scales.

VFD (Vacuum Fluorescent Display) A cathodoluminescent display constructed similar to a triode electron tube whose anodes can be viewed from the electron beam side. A heated filament provides electrons that are drawn to the acceleration grid and anodes to impact low-voltage phosphors. This display is widely used in car and VCR clocks. VFD pixel resolutions greater than VGA are very difficult, and VFD color units are limited by phosphor lifetimes.

Dan Evanicky is Principal Scientist at Silicon Graphics and has over 28 years' experience in flat panel technology. Beginning at Texas Instruments with some of the earliest research and development on liquid crystals for watches and calculators, Dan subsequently worked on display technologies at Micro Display Systems (Seiko), Kylex (Exxon Enterprises), 3M Company, Greyhawk, Dynabook Technologies, and Momenta. Several inventions for liquid crystal devices and manufacturing techniques he helped develop remain in worldwide use today.

For the past ten years his focus has been on system-side solutions, engineering displays for projection light valves, laptops, pen computers, and desktop monitors. His work at Silicon Graphics includes Indy Presenter™, the Presenter 1280, and currently the Silicon Graphics 1600SW™ flat panel monitor. He has published numerous papers and holds five patents with twelve more pending.