Liquid Crystal Display and Technology

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Liquid Crystal Display

Reflective twisted nematic liquid crystal display

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A **liquid crystal display** (**LCD**) is a thin, flat electronic visual display that uses the light modulating properties of liquid crystals (LCs). LCs do not emit light directly.

They are used in a wide range of applications, including computer monitors, television, instrument panels, aircraft cockpit displays, signage, etc. They are common in consumer devices such as video players, gaming devices, clocks, watches, calculators, and telephones. LCDs have displaced cathode ray tube (CRT) displays in most applications. They are usually more compact, lightweight, portable, less expensive, more reliable, and easier on the eyes. They are available in a wider range of screen sizes than CRT and plasma displays, and since they do not use phosphors, they cannot suffer image burn-in.

LCDs are more energy efficient and offer safer disposal than CRTs. Its low electrical power consumption enables it to be used in battery-powered electronic equipment. It is an electronically-modulated optical device made up of any number of pixels filled with liquid crystals and arrayed in front of a light source (backlight) or reflector to produce images in colour or monochrome. The earliest discovery leading to the development of LCD technology, the discovery of liquid crystals, dates from 1888. By 2008, worldwide sales of televisions with LCD screens had surpassed the sale of CRT units.

Overview

LCD alarm clock

Each pixel of an LCD typically consists of a layer of molecules aligned between two transparent electrodes, and two polarizing filters, the axes of transmission of which are (in most of the cases) perpendicular to each other. With no actual liquid crystal between the polarizing filters, light passing through the first filter would be blocked by the second (crossed) polarizer. In most of the cases the liquid crystal has double refraction.

The surface of the electrodes that are in contact with the liquid crystal material are treated so as to align the liquid crystal molecules in a particular direction. This treatment typically consists of a thin polymer layer that is unidirectionally rubbed using, for

example, a cloth. The direction of the liquid crystal alignment is then defined by the direction of rubbing. Electrodes are made of a transparent conductor called Indium Tin Oxide (ITO).

Before applying an electric field, the orientation of the liquid crystal molecules is determined by the alignment at the surfaces of electrodes. In a twisted nematic device (still the most common liquid crystal device), the surface alignment directions at the two electrodes are perpendicular to each other, and so the molecules arrange themselves in a helical structure, or twist. This reduces the rotation of the polarization of the incident light, and the device appears grey. If the applied voltage is large enough, the liquid crystal molecules in the center of the layer are almost completely untwisted and the polarization of the incident light is not rotated as it passes through the liquid crystal layer. This light will then be mainly polarized perpendicular to the second filter, and thus be blocked and the pixel will appear black. By controlling the voltage applied across the liquid crystal layer in each pixel, light can be allowed to pass through in varying amounts thus constituting different levels of gray. This electric field also controls (reduces) the double refraction properties of the liquid crystal.
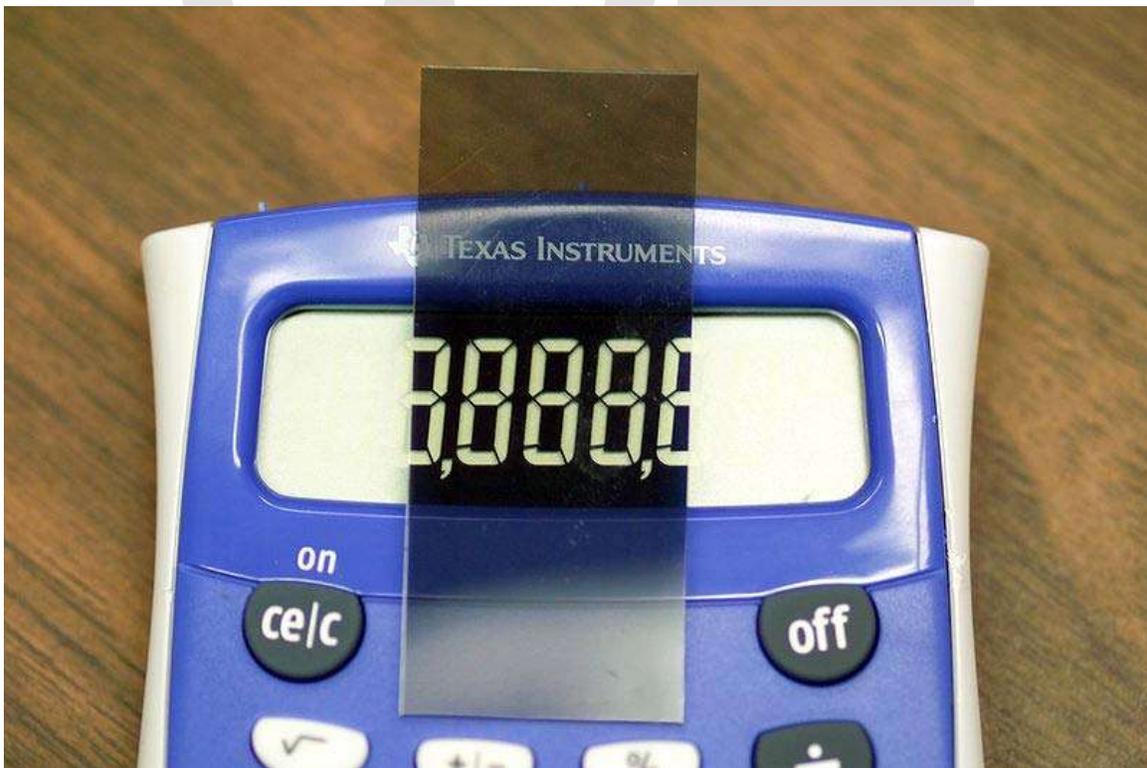
LCD with top polarizer removed from device and placed on top, such that the top and bottom polarizers are parallel.

The optical effect of a twisted nematic device in the voltage-on state is far less dependent on variations in the device thickness than that in the voltage-off state. Because of this, these devices are usually operated between crossed polarizers such that they appear bright with no voltage (the eye is much more sensitive to variations in the dark state than the

bright state). These devices can also be operated between parallel polarizers, in which case the bright and dark states are reversed. The voltage-off dark state in this configuration appears blotchy, however, because of small variations of thickness across the device.

Both the liquid crystal material and the alignment layer material contain ionic compounds. If an electric field of one particular polarity is applied for a long period of time, this ionic material is attracted to the surfaces and degrades the device performance. This is avoided either by applying an alternating current or by reversing the polarity of the electric field as the device is addressed (the response of the liquid crystal layer is identical, regardless of the polarity of the applied field).

When a large number of pixels are needed in a display, it is not technically possible to drive each directly since then each pixel would require independent electrodes. Instead, the display is *multiplexed*. In a multiplexed display, electrodes on one side of the display are grouped and wired together (typically in columns), and each group gets its own voltage source. On the other side, the electrodes are also grouped (typically in rows), with each group getting a voltage sink. The groups are designed so each pixel has a unique, unshared combination of source and sink. The electronics, or the software driving the electronics then turns on sinks in sequence, and drives sources for the pixels of each sink.

Brief history

- 1888: Friedrich Reinitzer (1858–1927) discovers the liquid crystalline nature of cholesterol extracted from carrots (that is, two melting points and generation of colours) and published his findings at a meeting of the Vienna Chemical Society on May 3, 1888 (F. Reinitzer: *Beiträge zur Kenntniss des Cholesterins, Monatshefte für Chemie (Wien) 9, 421-441 (1888)*).

- 1911: Charles Mauguin first experiments of liquids crystals confined between plates in thin layers.

- 1922: Georges Friedel describes the structure and properties of liquid crystals and classified them in 3 types (nematics, smectics and cholesterics).

- 1936: The Marconi Wireless Telegraph company patents the first practical application of the technology, *"The Liquid Crystal Light Valve"*.

- 1962: Richard Williams of RCA found that liquid crystals had some interesting electro-optic characteristics and he realized an electro-optical effect by generating stripe-patterns in a thin layer of liquid crystal material by the application of a voltage. This effect is based on an electro-hydrodynamic instability forming what is now called "Williams domains" inside the liquid crystal.

- 1964: George H. Heilmeier, then working in the RCA laboratories on the effect discovered by Williams achieved the switching of colours by field-induced

realignment of dichroic dyes in a homeotropically oriented liquid crystal. Practical problems with this new electro-optical effect made Heilmeier continue to work on scattering effects in liquid crystals and finally the achievement of the first operational liquid crystal display based on what he called the *dynamic scattering mode* (DSM). Application of a voltage to a DSM display switches the initially clear transparent liquid crystal layer into a milky turbid state. DSM displays could be operated in transmissive and in reflective mode but they required a considerable current to flow for their operation. George H. Heilmeier was inducted in the National Inventors Hall of Fame and credited with the invention of LCD.

- 1960s: Pioneering work on liquid crystals was undertaken in the late 1960s by the UK's Royal Radar Establishment at Malvern, England. The team at RRE supported ongoing work by George Gray and his team at the University of Hull who ultimately discovered the cyanobiphenyl liquid crystals (which had correct stability and temperature properties for application in LCDs).

- 1970: On December 4, 1970, the twisted nematic field effect in liquid crystals was filed for patent by Hoffmann-LaRoche in Switzerland, (Swiss patent No. 532 261) with Wolfgang Helfrich and Martin Schadt (then working for the Central Research Laboratories) listed as inventors. Hoffmann-La Roche then licensed the invention to the Swiss manufacturer Brown, Boveri & Cie who produced displays for wrist watches during the 1970s and also to Japanese electronics industry which soon produced the first digital quartz wrist watches with TN-LCDs and numerous other products. James Fergason while working with Sardari Arora and Alfred Saupe at Kent State University Liquid Crystal Institute filed an identical patent in the USA on April 22, 1971. In 1971 the company of Fergason ILIXCO (now LXD Incorporated) produced the first LCDs based on the TN-effect, which soon superseded the poor-quality DSM types due to improvements of lower operating voltages and lower power consumption.

- 1972: The first active-matrix liquid crystal display panel was produced in the United States by Westinghouse, in Pittsburgh, PA.

- 1996 Samsung develops the optical patterning technique that enables multi-domain LCD. Multi-domain and In Plane Switching subsequently remain the dominant LCD designs through 2010.

- 1997 Hitachi resurrects the In Plane Switching (IPS) technology producing the first LCD to have the visual quality acceptable for TV application.

- 2001 Jean Paul Gaultier uses LCD technology at his 2001 fall collection fashionshow which brings LCD to mainstream.

- 2007: In the 4Q of 2007 for the first time LCD televisions surpassed CRT units in worldwide sales.

- 2008: LCD TVs become the majority with a 50% market share of the 200 million TVs forecast to ship globally in 2008 according to Display Bank.

A detailed description of the origins and the complex history of liquid crystal displays from the perspective of an insider during the early days has been published by Joseph A. Castellano in *Liquid Gold: The Story of Liquid Crystal Displays and the Creation of an Industry*. Another report on the origins and history of LCD from a different perspective has been published by Hiroshi Kawamoto, available at the IEEE History Center.

Illumination

As LCD panels produce no light of their own, they require an external lighting mechanism to be easily visible. On most displays, this consists of a cold cathode fluorescent lamp that is situated behind the LCD panel. Passive-matrix displays are usually not backlit, but active-matrix displays almost always are, with a few exceptions such as the display in the original Gameboy Advance.

Recently, two types of LED backlit LCD displays have appeared in some televisions as an alternative to conventional backlit LCDs. In one scheme, the LEDs are used to backlight the entire LCD panel. In another scheme, a set of red, green and blue LEDs is used to illuminate a small cluster of pixels, which can improve contrast and black level in some situations. For example, the LEDs in one section of the screen can be dimmed to produce a dark section of the image while the LEDs in another section are kept bright. Both schemes also allows for a slimmer panel than on conventional displays.

Passive-matrix and active-matrix addressed LCDs

A general purpose alphanumeric LCD, with two lines of 16 characters

LCDs with a small number of segments, such as those used in digital watches and pocket calculators, have individual electrical contacts for each segment. An external dedicated circuit supplies an electric charge to control each segment. This display structure is unwieldy for more than a few display elements.

Small monochrome displays such as those found in personal organizers, electronic weighing scales, older laptop screens, and the original Gameboy have a passive-matrix structure employing super-twisted nematic (STN) or double-layer STN (DSTN) technology (the latter of which addresses a colour-shifting problem with the former), and colour-STN (CSTN) in which colour is added by using an internal filter. Each row or column of the display has a single electrical circuit. The pixels are addressed one at a time by row and column addresses. This type of display is called *passive-matrix addressed* because the pixel must retain its state between refreshes without the benefit of a steady electrical charge. As the number of pixels (and, correspondingly, columns and rows) increases, this type of display becomes less feasible. Very slow response times and poor contrast are typical of passive-matrix addressed LCDs.

Monochrome passive-matrix LCDs were standard in most early laptops (although a few used plasma displays). The commercially unsuccessful Macintosh Portable (released in 1989) was one of the first to use an active-matrix display (though still monochrome), but passive-matrix was the norm until the mid-1990s, when colour active-matrix became standard on all laptops.

High-resolution colour displays such as modern LCD computer monitors and televisions use an active matrix structure. A matrix of thin-film transistors (TFTs) is added to the polarizing and colour filters. Each pixel has its own dedicated transistor, allowing each column line to access one pixel. When a row line is activated, all of the column lines are connected to a row of pixels and the correct voltage is driven onto all of the column lines. The row line is then deactivated and the next row line is activated. All of the row lines are activated in sequence during a refresh operation. Active-matrix addressed displays look "brighter" and "sharper" than passive-matrix addressed displays of the same size, and generally have quicker response times, producing much better images.

Active matrix technologies
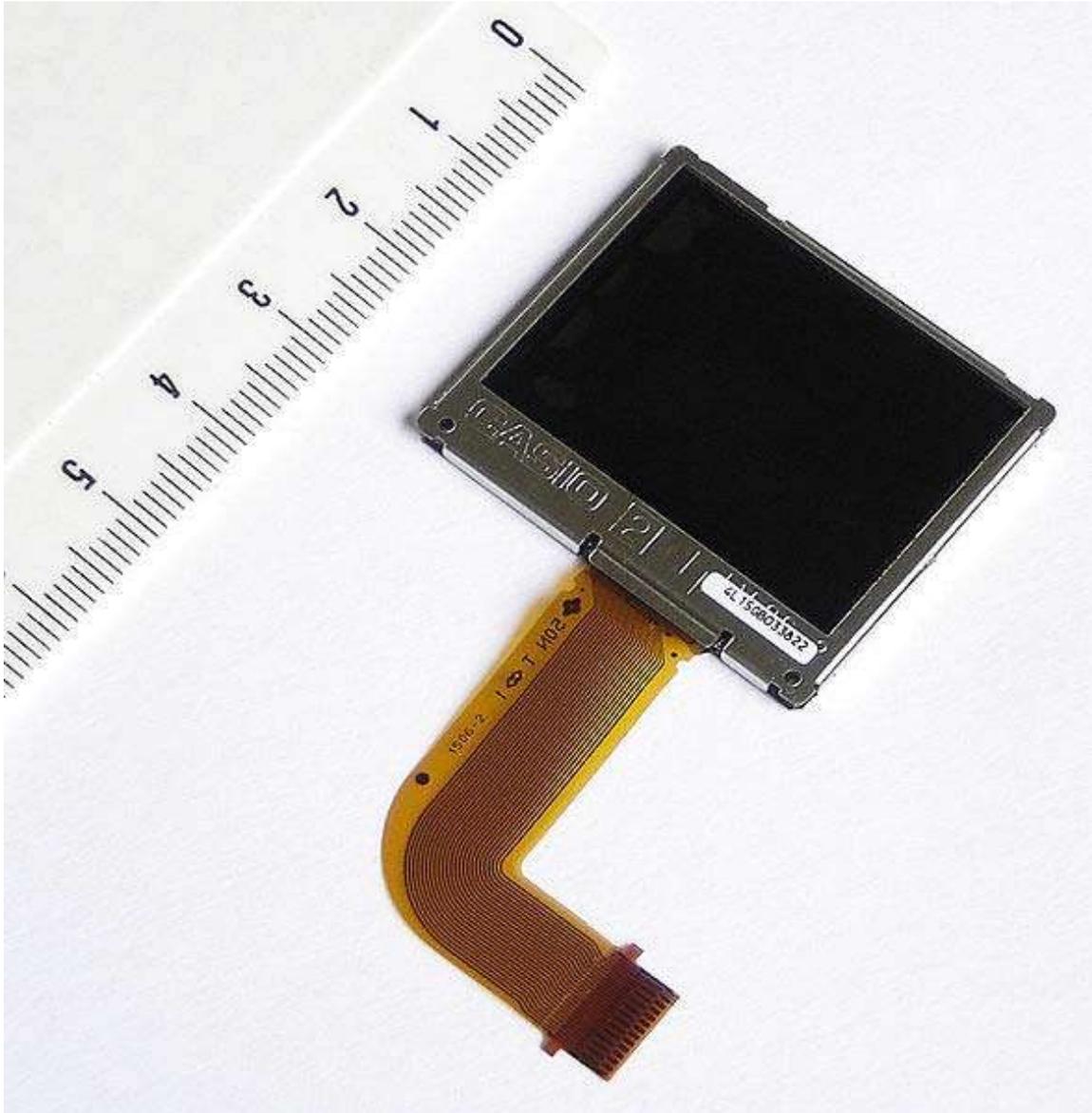
A Casio 1.8 in colour TFT LCD which equips the Sony Cyber-shot DSC-P93A digital compact cameras

Twisted nematic (TN)

Twisted nematic displays contain liquid crystal elements which twist and untwist at varying degrees to allow light to pass through. When no voltage is applied to a TN liquid crystal cell, the light is polarized to pass through the cell. In proportion to the voltage applied, the LC cells twist up to 90 degrees changing the polarization and blocking the light's path. By properly adjusting the level of the voltage almost any grey level or transmission can be achieved.

In-plane switching (IPS)

In-plane switching is an LCD technology which aligns the liquid crystal cells in a horizontal direction. In this method, the electrical field is applied through each end of the crystal, but this requires two transistors for each pixel instead of the single transistor needed for a standard thin-film transistor (TFT) display. Before LG Enhanced IPS was introduced in 2009, the additional transistors resulted in blocking more transmission area, thus requiring a brighter backlight, which consumed more power, and made this type of display less desirable for notebook computers. This newer, lower power technology can be found in the Apple iMac, iPad, and iPhone 4, as well as the Hewlett-Packard EliteBook 8740w. Currently Panasonic is using an enhanced version eIPS for their large size LCD-TV products.

Advanced fringe field switching (AFFS)

Known as fringe field switching (FFS) until 2003, advanced fringe field switching is a technology similar to IPS or S-IPS offering superior performance and colour gamut with high luminosity. AFFS is developed by Hydis Technologies Co.,Ltd, Korea (formally Hyundai Electronics, LCD Task Force).

AFFS-applied notebook applications minimize colour distortion while maintaining its superior wide viewing angle for a professional display. Colour shift and deviation caused by light leakage is corrected by optimizing the white gamut which also enhances white/grey reproduction.

In 2004, Hydis Technologies Co.,Ltd licenses AFFS patent to Japan's Hitachi Displays. Hitachi is using AFFS to manufacture high end panels in their product line. In 2006, HYDIS also licenses AFFS to Sanyo Epson Imaging Devices Corporation.

Hydis introduced AFFS+ which improved outdoor readability in 2007.

Vertical alignment (VA)

Vertical alignment displays are a form of LCDs in which the liquid crystal material naturally exists in a vertical state removing the need for extra transistors (as in IPS). When no voltage is applied, the liquid crystal cell remains perpendicular to the substrate creating a black display. When voltage is applied, the liquid crystal cells shift to a horizontal position, parallel to the substrate, allowing light to pass through and create a white display. VA liquid crystal displays provide some of the same advantages as IPS panels, particularly an improved viewing angle and improved black level.

Blue Phase mode

Blue phase LCDs do not require a liquid crystal top layer. Blue phase LCDs are relatively new to the market, and very expensive because of the low volume of production. They

provide a higher refresh rate than normal LCDs, but normal LCDs are still cheaper to make and actually provide better colours and a sharper image.

Quality control

Some LCD panels have defective transistors, causing permanently lit or unlit pixels which are commonly referred to as stuck pixels or dead pixels respectively. Unlike integrated circuits (ICs), LCD panels with a few defective transistors are usually still usable. It is claimed that it is economically prohibitive to discard a panel with just a few defective pixels because LCD panels are much larger than ICs, but this has never been proven. Manufacturers' policies for the acceptable number of defective pixels vary greatly. At one point, Samsung held a zero-tolerance policy for LCD monitors sold in Korea. As of 2005, though, Samsung adheres to the less restrictive ISO 13406-2 standard. Other companies have been known to tolerate as many as 11 dead pixels in their policies. Dead pixel policies are often hotly debated between manufacturers and customers. To regulate the acceptability of defects and to protect the end user, ISO released the ISO 13406-2 standard. However, not every LCD manufacturer conforms to the ISO standard and the ISO standard is quite often interpreted in different ways.

LCD panels are more likely to have defects than most ICs due to their larger size. For example, a 300 mm SVGA LCD has 8 defects and a 150 mm wafer has only 3 defects. However, 134 of the 137 dies on the wafer will be acceptable, whereas rejection of the LCD panel would be a 0% yield. Due to competition between manufacturers quality control has been improved. An SVGA LCD panel with 4 defective pixels is usually considered defective and customers can request an exchange for a new one. Some manufacturers, notably in South Korea where some of the largest LCD panel manufacturers, such as LG, are located, now have "zero defective pixel guarantee", which is an extra screening process which can then determine "A" and "B" grade panels. Many manufacturers would replace a product even with one defective pixel. Even where such guarantees do not exist, the location of defective pixels is important. A display with only a few defective pixels may be unacceptable if the defective pixels are near each other. Manufacturers may also relax their replacement criteria when defective pixels are in the center of the viewing area.

LCD panels also have defects known as *clouding* (or less commonly *mura*), which describes the uneven patches of changes in luminance. It is most visible in dark or black areas of displayed scenes.

Zero-power (bistable) displays

The zenithal bistable device (ZBD), developed by QinetiQ (formerly DERA), can retain an image without power. The crystals may exist in one of two stable orientations ("Black" and "White") and power is only required to change the image. ZBD Displays is a spin-off company from QinetiQ who manufacture both grayscale and colour ZBD devices.

A French company, Nemoptic, has developed the BiNem zero-power, paper-like LCD technology which has been mass-produced in partnership with Seiko since 2007. This technology is intended for use in applications such as Electronic Shelf Labels, E-books, E-documents, E-newspapers, E-dictionaries, Industrial sensors, Ultra-Mobile PCs, etc.

Kent Displays has also developed a "no power" display that uses Polymer Stabilized Cholesteric Liquid Crystals (ChLCD). A major drawback of ChLCD screens are their slow refresh rate, especially at low temperatures. Kent has recently demonstrated the use of a ChLCD to cover the entire surface of a mobile phone, allowing it to change colours, and keep that colour even when power is cut off.

In 2004 researchers at the University of Oxford demonstrated two new types of zero-power bistable LCDs based on Zenithal bistable techniques.

Several bistable technologies, like the 360° BTN and the bistable cholesteric, depend mainly on the bulk properties of the liquid crystal (LC) and use standard strong anchoring, with alignment films and LC mixtures similar to the traditional monostable materials. Other bistable technologies (i.e. Binem Technology) are based mainly on the surface properties and need specific weak anchoring materials.

Specifications

Important factors to consider when evaluating a Liquid Crystal Display (LCD):

- Resolution versus Range: Fundamentally resolution is the granularity (or number of levels) with which a performance feature of the display is divided. Resolution is often confused with range or the total end-to-end output of the display. Each of the major features of a display has both a resolution and a range that are tied to each other but very different. Frequently the range is an inherent limitation of the display while the resolution is a function of the electronics that make the display work.

- Spatial Performance LCDs come in only one size for a variety of applications and a variety of resolutions within each of those applications. LCD spatial performance is also sometimes described in terms of a "dot pitch". The size (or spatial range) of an LCD is always described in terms of the diagonal distance from one corner to its opposite. This is a historical aspect from the early days of CRT TV when CRT screens were manufactured on the bottoms of a glass bottle. The diameter of the bottle determined the size of the screen. Later, when TVs went to a more square format, the square screens were measured diagonally to compare with the older round screens.

The spatial resolution of an LCD is expressed in terms of the number of columns and rows of pixels (e.g., 1024×768). This had been one of the few features of LCD performance that was easily understood and not subject to interpretation. Each pixel is usually composed of a red, green, and blue sub pixel. However there are newer schemes

to share sub-pixels among pixels and to add additional colours of sub-pixels. So going forward, spatial resolution may be more subject to interpretation.

One external factor to consider in evaluating display resolution is the resolution of your own eyes. For a normal person with 20/20 vision, the resolution of your eyes is about one minute of arc. In practical terms that means for an older standard definition TV set the ideal viewing distance was about 8 times the height (not diagonal) of the screen away. At that distance the individual rows of pixels merge into a solid. If you were closer to the screen than that, you would be able to see the individual rows of pixels. If you are further away, the image of the rows of pixels still merge, but the total image becomes smaller as you get further away. For an HDTV set with slightly more than twice the number of rows of pixels, the ideal viewing distance is about half what it is for a standard definition set. The higher the resolution, the closer you can sit to the set or the larger the set can usefully be sitting at the same distance as an older standard definition display.

For a computer monitor or some other LCD that is being viewed from a very close distance, resolution is often expressed in terms of dot pitch or pixels per inch. This is consistent with the printing industry (another form of a display). Magazines, and other premium printed media are often at 300 dots per inch. As with the distance discussion above, this provides a very solid looking and detailed image. LCDs, particularly on mobile devices, are frequently much less than this as the higher the dot pitch, the more optically inefficient the display and the more power it burns. Running the LCD is frequently half, or more, of the power consumed by a mobile device.

An additional consideration in spatial performance are viewing cone and aspect ratio. The Aspect ratio is the ratio of the width to the height (for example, 4:3, 5:4, 16:9 or 16:10). Older, standard definition TVs were 4:3. Newer, HDTV's are 16:9 as are most new notebook computers. Movies are often filmed in much different (wider) aspect ratios which is why there will frequently still be black bars at the top and bottom of a HDTV screen.

The Viewing Angle of an LCD may be important depending on its use or location. The viewing angle is usually measured as the angle where the contrast of the LCD falls below 10:1. At this point, the colours usually start to change and can even invert, red becoming green and so forth. Viewing angles for LCDs used to be very restrictive however, improved optical films have been developed that give almost 180 degree viewing angles from left to right. Top to bottom viewing angles may still be restrictive, by design, as looking at an LCD from an extreme up or down angle is not a common usage model and these photons are wasted. Manufacturers commonly focus the light in a left to right plane to obtain a brighter image here.

- Temporal/Timing Performance: Contrary to spatial performance, temporal performance is a feature where smaller is better. Specifically, the range is the pixel response time of an LCD, or how quickly you can change a sub-pixel's brightness from one level to another. For LCD monitors, this is measured in btb (black to black) or gtg (gray to gray). These different types of measurements

make comparison difficult. Further, this number is almost never published in sales advertising.

Refresh rate or the temporal resolution of an LCD is the number of times per second in which the display draws the data it is being given. Since activated LCD pixels do not flash on/off between frames, LCD monitors exhibit no refresh-induced flicker, no matter how low the refresh. rate. High-end LCD televisions now feature up to 240 Hz refresh rate, which requires advanced digital processing to insert additional interpolated frames between the real images to smooth the image motion. However, such high refresh rates may not be actually supported by pixel response times and the result can be visual artifacts that distort the image in unpleasant ways.

Temporal performance can be further taxed if it is a 3D display. 3D displays work by showing a different series of images to each eye, alternating from eye to eye. For a 3D display it must display twice as many images in the same period of time as a conventional display and consequently the response time of the LCD becomes more important. 3D LCDs with marginal response times, will exhibit image smearing.

The temporal resolution of human perception is about 1/100th of a second. It is actually greater in your black and white vision (rod cells) than in colour vision (cone cells). You are more able to see flicker or any sort of temporal distortion in a display image by not looking directly at it as your rods are mostly grouped at the periphery of your vision.

- Colour Performance There are many terms to describe colour performance of an LCD. They include colour gamut which is the range of colours that can be displayed and colour depth which is the colour resolution or the resolution or fineness with which the colour range is divided. Although colour gamut can be expressed as three pairs of numbers, the XY coordinates within colour space of the reddest red, greenest green, and bluest blue, it is usually expressed as a ratio of the total area within colour space that a display can show relative to some standard such as saying that a display was "120% of NTSC". NTSC is the National Television Standards Committee, the old standard definition TV specification. Colour gamut is a relatively straight forward feature. However with clever optical techniques that are based on the way humans see colour, termed colour stretch ., colours can be shown that are outside of the nominal range of the display. In any case, colour range is rarely discussed as a feature of the display as LCDs are designed to match the colour ranges of the content that they are intended to show. Having a colour range that exceeds the content is a useless feature.

Colour Depth or colour support is sometimes expressed in bits, either as the number of bits per sub-pixel or the number of bits per pixel. This can be ambiguous as an 8-bit colour LCD can be 8 total bits spread between red, green, and blue or 8 bits each for each colour in a different display. Further, LCDs sometimes use a technique called dithering which is time averaging colours to get intermediate colours such as alternating between two different colours to get a colour in between. This doubles the number of colours that

can be displayed; however this is done at the expense of the temporal performance of the display. Dithering is commonly used on computer displays where the images are mostly static and the temporal performance is unimportant.

When colour depth is reported as colour support, it is usually stated in terms of number of colours the LCD can show. The number of colours is the translation from the base 2-bit numbers into common base-10. For example, s 8-bit, in common terms means 2 to the 8th power or 256 colours. 8-bits per colour or 24-bits would be 256 x 256 x 256 or over 16 Million colours. The colour resolution of the human eye depends on both the range of colours being sliced and the number of slices; but for most common displays the limit is about 28-bit colour. LCD TVs commonly display more than that as the digital processing can introduce colour distortions and the additional levels of colour are needed to ensure true colours.

There are additional aspects to LCD colour and colour management such as white point and gamma correction which basically describe what colour white is and how the other colours are displayed relative to white. LCD televisions also frequently have facial recognition software which recognizes that an image on the screen is a face and both adjust the colour and the focus differently from the rest of the image. These adjustments can have important impact to the consumer but are not easily quantifiable; people like what they like and everyone does not like the same thing. There is no substitute for looking at the LCD you are going to buy before buying it. Portrait film, another form of display, has similar adjustments built in to it. Many years ago, Kodak had to overcome initial rejection of its portrait film in Japan because of these adjustments. In the US, people generally prefer a more colour facial image than is reality (higher colour saturation). In Japan, consumers generally prefer a less saturated image. The film that Kodak initially sent to Japan was biased in exactly the wrong direction for Japanese consumers. TV sets have their built in biases as well.

- Brightness and Contrast ratio: Contrast Ratio is the ratio of the brightness of a full-on pixel to a full-off pixel and, as such, would be directly tied to brightness if not for the invention of the blinking backlight (or burst dimming). The LCD itself is only a light valve, it does not generate light; the light comes from a backlight that is either a florescent tube or a set of LEDs. The blinking backlight was developed to improve the motion performance of LCDs by turning the backlight off while the liquid crystals were in transition from one image to another. However, a side benefit of the blinking backlight was infinite contrast. The contrast reported on most LCDs is what the LCD is qualified at, not its actual performance. In any case, there are two large caveats to contrast ratio as a measure of LCD performance.

The first caveat is that contrast ratios are measured in a completely dark room. In actual use, the room is never completely dark as you will always have the light from the LCD itself. Beyond that, there may be sunlight coming in through a window or other room lights that reflect off of the surface of the LCD and degrade the contrast. As a practical

matter, the contrast of an LCD, or any display, is governed by the amount of surface reflections not by the performance of the display.

The second caveat is that the human eye can only image a contrast ratio of a maximum of about 200:1. Black print on a white paper is about 15-20:1. That is why viewing angles are specified to the point where the fall below 10:1. A 10:1 image is not great, but is discernable.

Brightness is usually stated as the maximum output of the LCD. In the CRT era, Trinitron CRTs had a brightness advantage over the competition so brightness was commonly discussed in TV advertising. With current LCD technology, brightness, though important, is usually the same from maker to maker and is consequently not discussed much except for notebook LCDs and other displays that will be viewed in bright sunlight. In general, brighter is better but there is always a trade-off between brightness and battery life in a mobile device.

Military use of LCD monitors

LCD monitors have been adopted by the United States of America military instead of CRT displays because they are smaller, lighter and more efficient, although monochrome plasma displays are also used, notably for their M1 Abrams tanks. For use with night vision imaging systems a US military LCD monitor must be compliant with MIL-L-3009 (formerly MIL-L-85762A). These LCD monitors go through extensive certification so that they pass the standards for the military. These include MIL-STD-901D - High Shock (Sea Vessels), MIL-STD-167B - Vibration (Sea Vessels), MIL-STD-810F – Field Environmental Conditions (Ground Vehicles and Systems), MIL-STD-461E/F – EMI/RFI (Electromagnetic Interference/Radio Frequency Interference), MIL-STD-740B – Airborne/Structureborne Noise, and TEMPEST - Telecommunications Electronics Material Protected from Emanating Spurious Transmissions.

Chapter- 2

TFT LCD

A 19" LG flat panel computer display

Thin film transistor liquid crystal display (**TFT-LCD**) is a variant of liquid crystal display (LCD) which uses thin-film transistor (TFT) technology to improve image quality (e.g., addressability, contrast). TFT LCD is one type of *active matrix* LCD, though all LCD-screens are based on TFT active matrix addressing. TFT LCDs are used in television sets, computer monitors, mobile phones, handheld video game systems, personal digital assistants, navigation systems, projectors, etc.

Construction
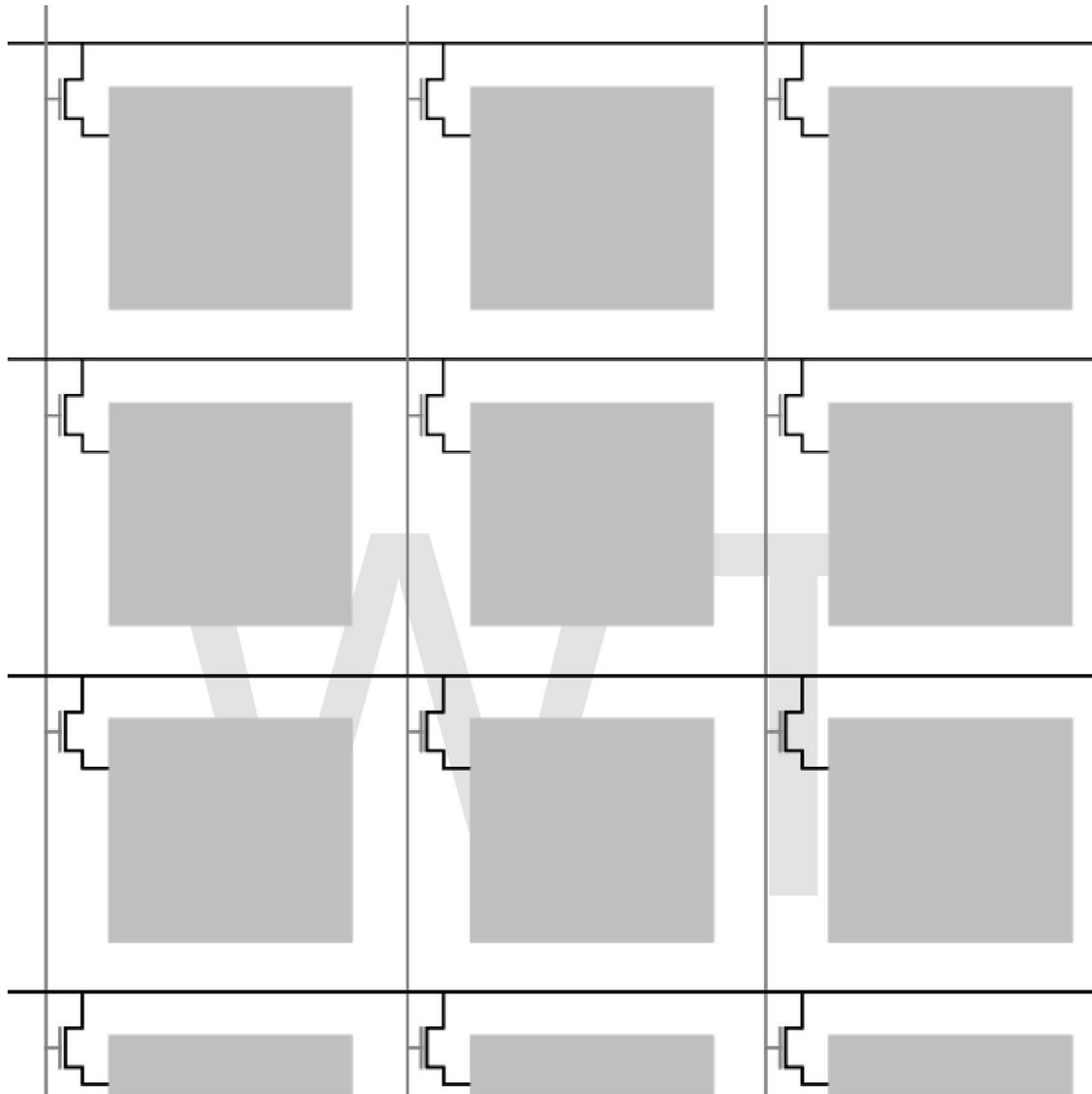
A diagram of the pixel layout

Small liquid crystal displays as used in calculators and other devices have direct driven image elements – a voltage can be applied across one segment without interfering with other segments of the display. This is impractical for a large display with a large number of picture elements (pixels), since it would require millions of connections – top and bottom connections for each one of the three colors (red, green and blue) of every pixel. To avoid this issue, the pixels are addressed in rows and columns, reducing the connection count from millions to thousands. The column and row wires attach to transistor switches, one for each pixel. The one-way current passing characteristic of the transistor prevents the charge applied to the pixel from draining between refreshes to the

display image. Each pixel is a small capacitor with a layer of insulating liquid crystal sandwiched between transparent conductive ITO layers.

The circuit layout process of a TFT-LCD is very similar to that of semiconductor products. However, rather than fabricating the transistors from silicon formed into a crystalline silicon wafer, they are made from a thin film of amorphous silicon deposited on a glass panel. The **silicon** layer for TFT-LCDs is typically deposited using the PECVD process. Transistors take up only a small fraction of the area of each pixel; the rest of the silicon film is etched away to allow light to pass through.

Polycrystalline silicon is sometimes used in displays requiring higher TFT performance. Examples include small high-resolution displays such as those found in projectors or view finders. Amorphous silicon-based TFTs are by far the most common due to their lower production cost, whereas polycrystalline silicon TFTs are more costly and difficult to produce.

Types

Twisted nematic (TN)
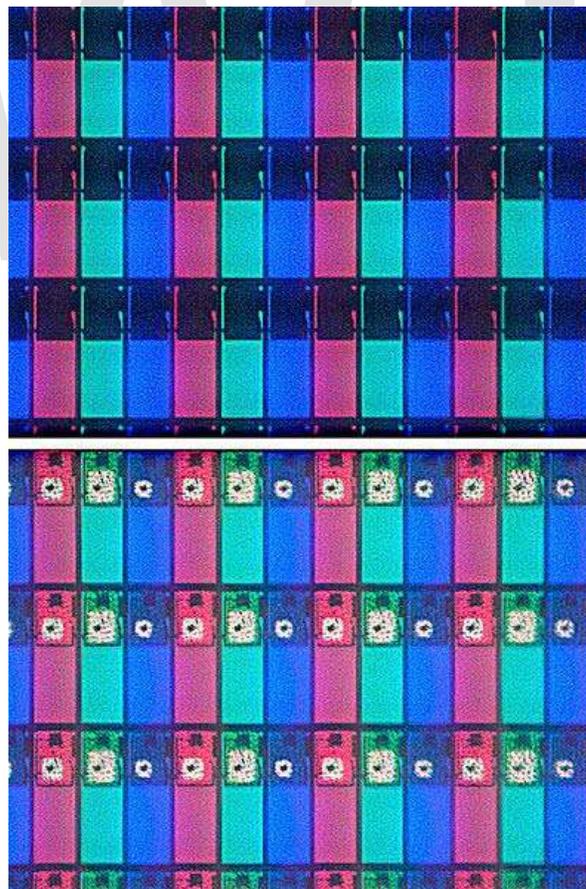
TN display under a microscope, with the transistors visible at the bottom

The inexpensive twisted nematic display is the most common consumer display type. The pixel response time on modern TN panels is sufficiently fast to avoid the shadow-trail and ghosting artifacts of earlier production. The fast response time has been emphasised in advertising TN displays, although in most cases this number does not reflect performance across the entire range of possible color transitions. More recent use of RTC (Response Time Compensation / Overdrive) technologies has allowed manufacturers to significantly reduce grey-to-grey (G2G) transitions, without significantly improving the ISO response time. Response times are now quoted in G2G figures, with 4ms and 2ms now being commonplace for TN-based models. The good response time and low cost has led to the dominance of TN in the consumer market.

TN displays suffer from limited viewing angles, especially in the vertical direction. Colors will shift when viewed off-perpendicular. In the vertical direction, colors will shift so much that they will invert past a certain angle.

Also, most TN panels represent colors using only 6 bits per RGB color, or 18 bit in total, and are unable to display the 16.7 million color shades (24-bit truecolor) that are available from graphics cards. Instead, these panels display interpolated 24-bit color using a dithering method that combines adjacent pixels to simulate the desired shade. They can also use a form of temporal dithering called Frame Rate Control (FRC), which cycles between different shades with each new frame to simulate an intermediate shade. Such 18 bit panels with dithering are sometimes advertised as having "16.2 million colors". These color simulation methods are noticeable to many people and highly bothersome to some. FRC tends to be most noticeable in darker tones, while dithering appears to make the individual pixels of the LCD visible. Overall, color reproduction and linearity on TN panels is poor. Shortcomings in display color gamut (often referred to as a percentage of the NTSC 1953 color gamut) are also due to backlighting technology. It is not uncommon for displays with simple LED or CCFL-based lighting to range from 10% to 26% of the NTSC color gamut, whereas other kind of displays, utilizing more complicated CCFL or LED phosphor formulations or RGB LED backlights, may extend past 100% of the NTSC color gamut, a difference quite perceivable by the human eye.

The transmittance of a pixel of an LCD panel typically does not change linearly with the applied voltage, and the sRGB standard for computer monitors requires a specific nonlinear dependence of the amount of emitted light as a function of the RGB value.

In-plane switching (IPS)

In-plane switching was developed by Hitachi Ltd. in 1996 to improve on the poor viewing angle and the poor color reproduction of TN panels at that time. Its name comes from the main difference from TN panels, that *the crystal molecules move parallel to the panel plane instead of perpendicular to it*. This change reduces the amount of light scattering in the matrix, which gives IPS its characteristic wide viewing angles and good color reproduction.

Initial iterations of IPS technology were plagued with slow response time and a low contrast ratio but later evolutions have made marked improvements to these shortcomings. Because of its wide viewing angle and accurate color reproduction (with almost no off-angle color shift), IPS is widely employed in high-end monitors aimed at professional graphic artists, although with the recent fall in price it has been seen in the mainstream market as well.

Hitachi IPS evolving technology

Name	Nickname	Year	Advantage	Transmittance/ contrast ratio	Remarks
Super TFT	IPS	1996	Wide viewing angle	100/100 Base level	Most panels also support true 8-bit per channel color. These improvements came at the cost of a slower response time, initially about 50 ms. IPS panels were also extremely expensive.
Super-IPS	S-IPS	1998	Color shift free	100/137	IPS has since been superseded by **S-IPS** (Super-IPS, Hitachi Ltd. in 1998), which has all the benefits of IPS technology with the addition of improved pixel refresh timing.
Advanced Super-IPS	AS-IPS	2002	High transmittance	130/250	AS-IPS, also developed by Hitachi Ltd. in 2002, improves substantially on the contrast ratio of traditional S-IPS panels to the point where they are second only to some S-PVAs.
IPS-Provectus	IPS-Pro	2004	High contrast ratio	137/313	The latest panel from IPS Alpha Technology with a wider color gamut and contrast ratio matching PVA and ASV displays without off-angle glowing.
IPS alpha	IPS-Pro	2008	High contrast ratio		Next generation of IPS-Pro
IPS alpha next gen	IPS-Pro	2010	High contrast ratio		Technology transfer from Hitachi to Panasonic

			LG IPS evolving technology
Name	**Nickname**	**Year**	**Remarks**
Super-IPS	S-IPS	2001	LG Display remains as one of the main manufacturers of panels based on Hitachi Super-IPS.
Advanced Super-IPS	AS-IPS	2005	Increased contrast ratio with better color gamut.
Horizontal IPS	H-IPS	2007	Improves contrast ratio by twisting electrode plane layout. Also introduces an optional Advanced True White polarizing film from NEC, to make white look more natural. This is used in professional/photography LCDs.
Enhanced IPS	E-IPS	2009	Wider aperture for light transmission, enabling the use of lower-power, cheaper backlights. Improves diagonal viewing angle and further reduce response time to 5ms.
Professional IPS	P-IPS	2010	Offer 1.07 billion colours (30-bit colour depth). More possible orientations per sub-pixel (1024 as opposed to 256) and produces a better true colour depth.

Advanced fringe field switching (AFFS)

This is an LCD technology derived from the IPS by Boe-Hydis of Korea. Known as fringe field switching (FFS) until 2003, advanced fringe field switching is a technology similar to IPS or S-IPS offering superior performance and colour gamut with high luminosity. AFFS is developed by HYDIS TECHNOLOGIES CO.,LTD, Korea (formally Hyundai Electronics, LCD Task Force).

AFFS-applied notebook applications minimize colour distortion while maintaining its superior wide viewing angle for a professional display. Colour shift and deviation caused by light leakage is corrected by optimizing the white gamut which also enhances white/grey reproduction.

In 2004, HYDIS TECHNOLOGIES CO.,LTD licensed its AFFS patent to Japan's Hitachi Displays. Hitachi is using AFFS to manufacture high end panels in their product line. In 2006, HYDIS also licensed its AFFS to Sanyo Epson Imaging Devices Corporation.

HYDIS introduced AFFS+ which improved outdoor readability in 2007.

Multi-domain vertical alignment (MVA)

Multi-domain vertical alignment was originally developed in 1998 by Fujitsu as a compromise between TN and IPS. It achieved pixel response which was fast for its time, wide viewing angles, and high contrast at the cost of brightness and color reproduction.

Modern MVA panels can offer wide viewing angles (second only to S-IPS technology), good black depth, good color reproduction and depth, and fast response times due to the use of RTC (Response Time Compensation) technologies. When MVA panels are viewed off-perpendicular, colors will shift, but much less than for TN panels.

There are several "next-generation" technologies based on MVA, including AU Optronics' **P-MVA** and **A-MVA**, as well as Chi Mei Optoelectronics' **S-MVA**. Analysts predicted that MVA would dominate the mainstream market, but the less expensive and slightly faster TN overtook it. The pixel response times of MVAs rise dramatically with small changes in brightness. Less expensive MVA panels can use dithering and FRC (Frame Rate Control).

Patterned vertical alignment (PVA)

Patterned vertical alignment and super patterned vertical alignment (**S-PVA**) are alternative versions of MVA technology offered by Samsung's and Sony's joint venture S-LCD. Developed independently, they offer similar features to MVA, but with higher contrast ratios of up to 3000:1. Less expensive PVA panels often use dithering and FRC, while S-PVA panels all use at least 8 bits per color component and do not use color simulation methods. S-PVA also largely eliminated off angle glowing of solid blacks and reduced the off angle gamma shift. Some newer S-PVA panels offered by Eizo offer 16-bit color internally . , which enables gamma and other corrections with reduced color banding. Some high end Sony BRAVIA LCD-TVs offer 10bit and xvYCC color support, for example the Bravia X4500 series. PVA and S-PVA offer the best black depth of any LCD type along with wide viewing angles. S-PVA also offers fast response times using modern RTC technologies.

Advanced super view (ASV)

Advanced super view, also called *axially symmetric vertical alignment* was developed by Sharp. It is a VA mode where liquid crystal molecules orient perpendicular to the substrates in the off state. The bottom sub-pixel has continuously covered electrodes, while the upper one has a smaller area electrode in the center of the subpixel.

When the field is on, the liquid crystal molecules start to tilt towards the center of the sub-pixels because of the electric field; as a result, a continuous pinwheel alignment (CPA) is formed; the azimuthal angle rotates 360 degrees continuously resulting in an excellent viewing angle. The ASV mode is also called CPA mode.

Display industry

Due to the very high cost of building TFT factories, there are few major OEM panel vendors for large display panels. The glass panel suppliers are as follows:

LCD glass panel suppliers

Panel type	Company	Remarks	major TV makers
IPS-Pro	Panasonic	Solely for LCD TV markets and known as IPS Alpha Technology Ltd.	Panasonic, Hitachi, Toshiba
H-IPS	LG Display		LG, Philips
S-IPS	Hannstar Chuangwa Picture Tubes, Ltd.	They also produce other type of TFT panels such as TN for OEM markets such as mobile, monitor, automotive, portable AV and industrial panels.	
A-MVA	AU Optronics		
S-MVA	Chi Mei Optoelectronics		
S-PVA	S-LCD (Samsung/Sony joint venture)		Samsung, Sony
AFFS	Samsung	For small and medium size special projects.	
ASV	Sharp Corporation	Solely for LCD TV markets	Sharp

Raw LCD TFT panels are usually factory-sorted into three categories, with regard to the number of dead pixels, backlight evenness and general product quality. Additionally, there may be up to +/- 2ms maximum response time differences between individual panels that came off the same assembly line on the same day. The poorest-performing screens are then sold to no-name vendors or used in "value" TFT monitors (for example, marked with letter V behind the type number), the medium performers are incorporated in gamer-oriented or home office bound TFT displays (sometimes marked with the capital letter S), and the best screens are usually reserved for use in "professional" grade TFT monitors (often marked with letter P or S after their type number).

Electrical interface

External consumer display devices like a TFT LCD feature one or more analog VGA, DVI, HDMI, or DisplayPort interface, with many featuring a selection of these interfaces. Inside external display devices there is a controller board that will convert CVBS, VGA, DVI, HDMI etc. into digital RGB at the native resolution of the display panel. In a laptop the graphics chip will directly produce a signal suitable for connection to the built-in TFT display. A control mechanism for the backlight is usually included on the same controller board.

The low level interface of STN, DSTN, or TFT display panels use either single ended TTL 5V signal for older displays or TTL 3.3V for slightly newer displays that transmits Pixel clock, Horizontal sync, Vertical sync, Digital red, Digital green, Digital blue in parallel. Some models also feature input/display enable, horizontal scan direction and vertical scan direction signals.

New and large (>15 in) TFT displays often use LVDS signaling that transmits the same contents as the parallel interface (Hsync, Vsync, RGB) but will put control and RGB bits into a number of serial transmission lines synchronized to a clock whose rate is equal to the pixel rate. LVDS transmits seven bits per clock per data line, with six bits being data and one bit used to signal if the other six bits need to be inverted in order to maintain DC balance. Low quality TFT displays often have three data lines and therefore only directly support 18 bits per pixel, while better ones have a fourth data line so they can support 24 bits per pixel, which delivers truecolor. Ultra high end models can support even more colors by adding more lanes, like how 30-bit color can be supported by five data lanes. Panel manufacturers are slowly replacing LVDS with Internal DisplayPort and Embedded DisplayPort, which allow six-fold reduction of the number of differential pairs.

Backlight intensity is usually controlled by varying a few volts DC, or generating a PWM signal, or adjusting a potentiometer or simply fixed. This in turn controls a high-voltage (1.3 kV) DC-AC inverter or a matrix of LEDs.

The bare display panel will only accept a digital video signal at the resolution determined by the panel pixel matrix designed at manufacture. Some screen panels will ignore color LSB bits to present a consistent interface (8bit->6bit/color).

The reason why laptop displays can't be reused directly with an ordinary computer graphics card or as a television, is mainly because they lack a hardware rescaler that can resize the image to fit the native resolution of the display panel. With analogue signals like VGA the display controller also needs to perform a highspeed analog to digital conversion. With digital input signals like DVI or HDMI some simple bit stuffing is needed before feeding it to the rescaler if input resolution doesn't match the display panel resolution. For CVBS (TV) usage a tuner and color decode from a quadrature amplitude modulation (QAM) to Luminance (Y), Blue-Y (U), Red-Y (V) representation which in turn is transformed into Red, Green Blue is needed.

# Twisted Nematic Field Effect
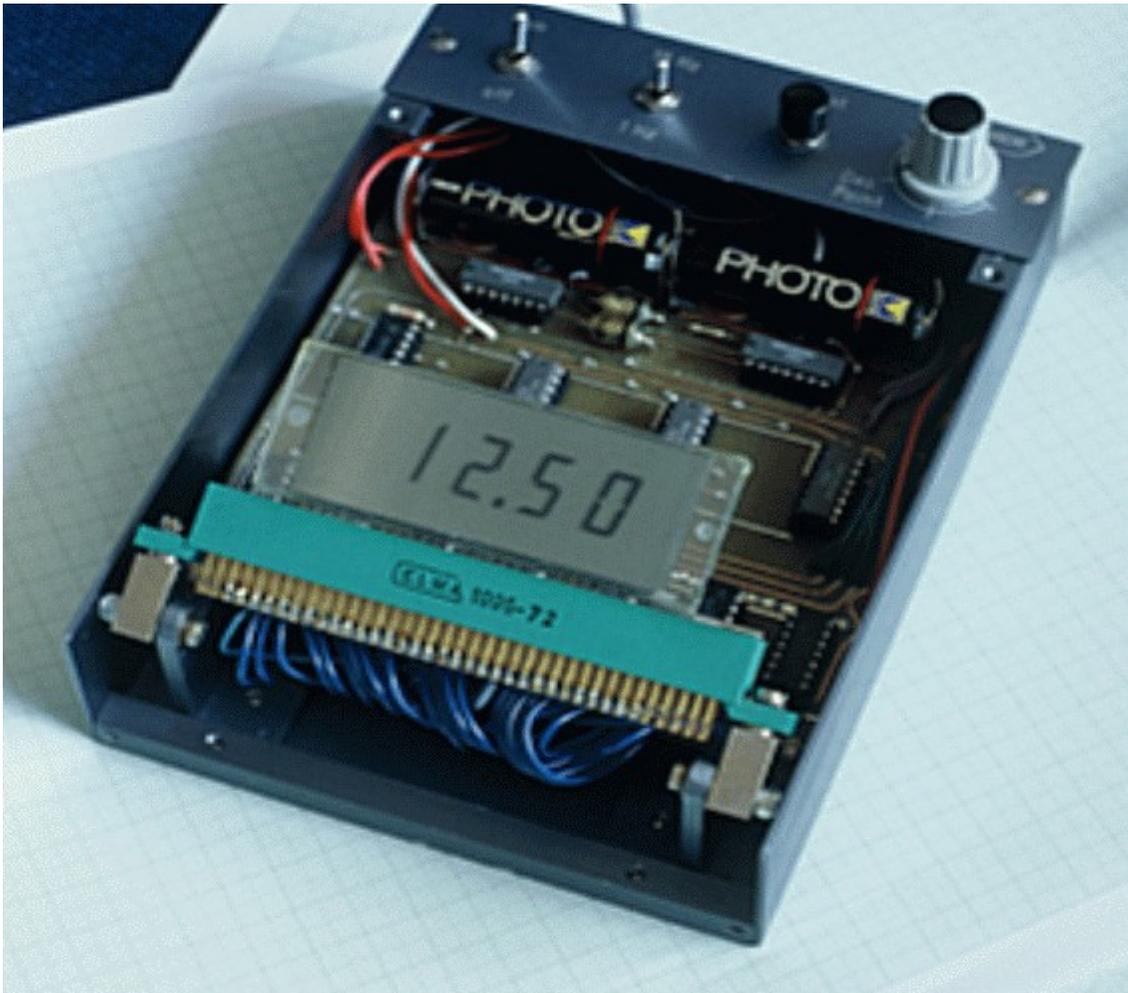
Clock with an early LCD display prototype based on the twisted nematic field-effect

The **twisted nematic effect** (*TN-effect*) is the main technology breakthrough that made liquid crystal displays practical. Unlike earlier displays, TN-cells did not require a current to flow for operation and used low operating voltages suitable for use with batteries. The introduction of TN-effect displays led to their rapid expansion in the display field, quickly pushing out other common technologies like light emitting diodes and

electroluminescence from most electronics. By the 1990s, TN-effect LCDs were largely universal in portable electronics. This electro-optical effect is also called the *Schadt-Helfrich effect*.

Description

The twisted nematic effect is based on the precisely controlled realignment of liquid crystal molecules between different ordered molecular configurations under the action of an applied electric field. This is achieved with little power consumption and at low operating voltages.
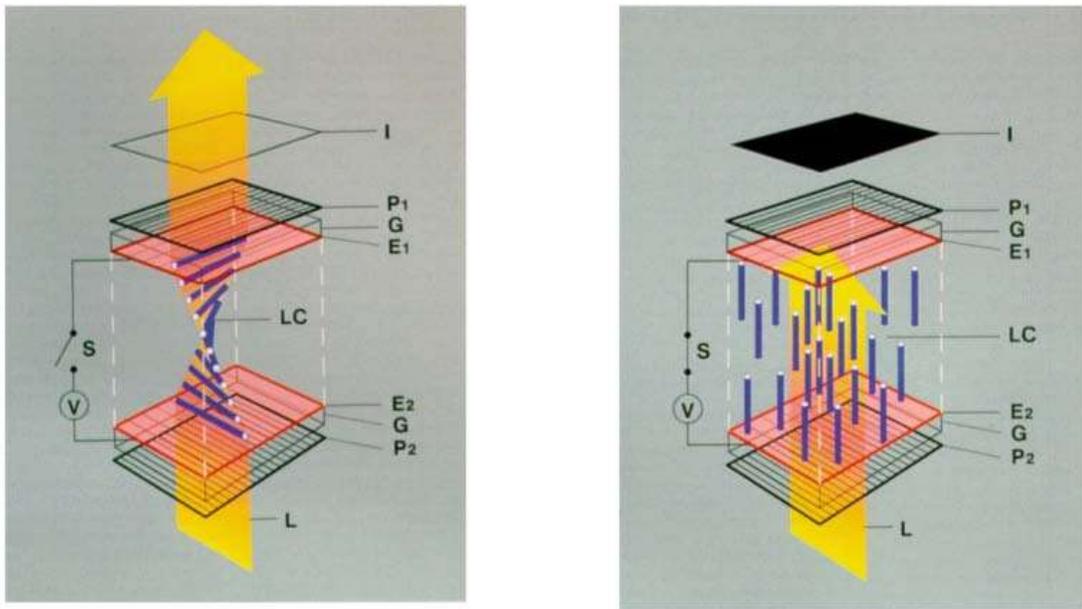
Exploded view of a TN liquid crystal cell showing the states in an OFF state (left), and an ON state with voltage applied (right)

The illustrations to the right show both the OFF and the ON-state of a single picture element (*pixel*) of a twisted nematic light modulator liquid crystal display operating in the "normally white" mode, i.e., a mode in which light is transmitted when no electrical field is applied to the liquid crystal.

In the OFF state, i.e., when no electical field is applied, a twisted configuration (aka helical structure or helix) of nematic liquid crystal molecules is formed between two glass plates, G in the figure, which are separated by several spacers and coated with transparent electrodes, E_1 and E_2. The electrodes themselves are coated with alignment layers (not shown) that precisely twist the liquid crystal by 90° when no external field is present (left diagram). If a light source with the proper polarization (about half) shines on the front of the LCD, the light will pass through the first polarizer, P_2 and into the liquid crystal, where it is rotated by the helical structure. The light is then properly polarized to

pass through the second polarizer, P_1, set at 90° to the first. The light then passes through the back of the cell and the image, I, appears transparent.

In the ON state, i.e., when a field is applied between the two electrodes, the crystal re-aligns itself with the external field (right diagram). This "breaks" the careful twist in the crystal and fails to re-orient the polarized light passing through the crystal. In this case the light is blocked by the rear polarizer, P_1, and the image, I, appears opaque. The amount of opacity can be controlled by varying the voltage. At voltages near the threshold, only some of the crystals will re-align, and the display will be partially transparent. As the voltage is increased, more of the crystals will re-align until it becomes completely "switched". A voltage of about 1- V is required to make the crystal align itself with the field, and no current passes through the crystal itself. Thus the electrical power required for that action is very low.

To display information with a twisted nematic liquid crystal, the transparent electrodes are structured by photo-lithography to form a matrix or other pattern of electrodes. Only one of the electrodes has to be patterned in this way, the other can remain continuous (*common* electrode). For low information content numerical and alpha-numerical TN-LCDs, like digital watches or calculators, segmented electrodes are sufficient. If more complex data or graphics information have to be displayed, a matrix arrangement of electrodes is used. Obviously, the voltage controlled addressing of matrix displays, such as in LCD-screens for computer-monitors or flat television screens, is more complex than with segmented electrodes. These matrix LCDs necessitate integration of additional non-linear electronic elements into each picture element of the display (e.g. thin-film diodes, TFDs, or thin-film transistors, TFTs) in order to allow the addressing of individual picture elements without crosstalk (unintended activation of non-addressed pixels).

History

RCA research

In 1962, Richard Williams, a physical chemist working at RCA Laboratories, started looking for new physical phenomena that might lead to a display technology not involving vacuum tubes. Aware of the long line of research involving nematic liquid crystals, he started experimenting with the compound p-azoxyanisole which has a melting point of 116 °F (47 °C). Williams set up his experiments on a heated microscope stage, placing samples between transparent tin-oxide electrodes on glass plates held at 125 °F (52 °C). He discovered that a very strong electrical field applied across the stack would cause striped patterns to form. These were later termed "Williams domains". The required field was about 1,000 volts per centimeter, far too high for a practical device. Realizing that development would be lengthy, he turned the research over to physicist George Heilmeier and moved on to other work.

In 1964, RCA's Heilmeier along with Louis Zanoni and chemist Lucian Barton discovered that certain liquid crystals could be switched between a transparent state and a highly scattering opaque one with the application of electrical current. The scattering was

primarily forward, into the crystal, as opposed to backscattering towards the light source. By placing a reflector on the far side of the crystal, the incident light could be turned on or off electrically, creating what Heilmeier dubbed *dynamic scattering*. In 1965 Joseph Castellano and Joel Goldmacher, organic chemists, tried to find crystals that remained in the fluid state at room temperature. Within six months they had found a number of candidates, and with further development, RCA was able to announce the first liquid crystal displays in 1968.

Although successful, the dynamic scattering display required constant current flow through the device, as well as relatively high voltages. This made them unattractive for low-power situations, where many of these sorts of displays were being used. Not being self-lit, LCDs also required external lighting if they were going to be used in low-light situations, which made existing display technologies even more attractive in overall power terms. A further limitation was the requirement for a mirror, which limited the viewing angles. The RCA team was aware of these limitations, and continued development of a variety of technologies.

One of these potential effects had been discovered by Heilmeier in 1964. He was able to get organic dyes to attach themselves to the liquid crystals, and they would stay in position when pulled into alignment by an external field. When switched from one alignment to the other, the dye was either visible or hidden, resulting in two colored states called the *guest-host effect*. Work on this approach stopped when the dynamic scattering effect had been demonstrated successfully.

TN-effect

Another potential approach was the twisted-nematic approach, which had first been noticed by French physicist Charles-Victor Mauguin in 1911. Mauguin was experimenting with a variety of semi-solid liquid crystals when he noted that he could align the crystals by pulling a piece of paper across them, causing the crystals to become polarized. He later noticed when he sandwiched the crystal between two aligned polarizers, he could twist them in relation to each other, but the light continued to be transmitted. This was not expected. Normally if two polarizers are aligned at right angles, light will not flow through them. Mauguin concluded that the light was being re-polarized by the twisting of the crystal itself.

Wolfgang Helfrich, a physicist who joined RCA in 1967, became interested in Mauguin's twisted structure and thought it might be used to create an electronic display. However RCA showed little interest because they felt that any effect that used two polarizers would also have a large amount of light absorption, requiring it to be brightly lit. In 1970, Helfrich left RCA and joined the Central Research Laboratories of Hoffmann-LaRoche in Switzerland, where he teamed up with Martin Schadt, a solid-state physicist. Schadt built a sample with electrodes and a twisted version of a liquid-crystal material called PEBAB (p-ethoxybenzylidene-p'-aminobenzonitrile), which Helfrich had reported in prior studies at RCA, as part of their guest-host experiments. When voltage is applied, PEBAB aligns

itself along the field, breaking the twisting structure and the redirection of the polarization, making the cell turn opaque.

Patent battle

At this time Brown, Boveri & Cie (BBC) was also working with the devices as part of a prior joint medical research agreement with Hoffmann-LaRoche. BBC demonstrated their work to a physicist from the US who was associated with James Fergason, an expert in liquid crystals at the Westinghouse Research Laboratories. Fergason was working on the TN-effect for displays, having formed ILIXCO to commercialize developments of the research being carried out in conjunction with Sardari Arora and Alfred Saupe at Kent State University's Liquid Crystal Institute.

When news of the demonstration reached Hoffmann-LaRoche, Helfrich and Schadt immediately pushed for a patent, which was filed on 4 December 1970. Their formal results were published in *Applied Physics Letters* in 15 February 1971. In order to demonstrate the feasibility of the new effect for displays, Schadt fabricated a 4-digit display panel in 1972. This is believed to be the first fully-functional twisted-nematic LCD ever made.

Fergason published a similar patent in the US on either 9 February 1971 or 22 April 1971. This was two months after the Swiss patent was filed and set the stage for a three-year legal confrontation that was settled out of court. In the end, all the parties received a share of what would become many millions of dollars in royalties.

Commercial development

PEBAB was subject to breakdown when exposed to water or alkalines, and required special manufacturing to avoid contamination. In 1972 a team led by George Gray developed a new type of cyanobiphenyls that could be mixed with PEBAB to produce less reactive materials. These additives also made the resulting liquid less viscous, thereby providing faster response times, while at the same time making them more transparent, which produced a pure-white color display.

This work, in turn, led to the discovery of an entirely different class of nematic crystals by Ludwig Pohl, Rudolf Eidenschink and their colleagues at Merck KGaA in Darmstadt, called cyanophenylcyclohexanes. They quickly became the basis of almost all LCDs, and remain a major part of Merck's business today.

Chapter- 4

Active-Matrix Liquid Crystal Display, Blue Phase Mode LCD and Ferro Liquid Display

Active-matrix liquid crystal display

An **active matrix liquid crystal display** (**AMLCD**) is a type of flat panel display, currently the overwhelming choice of notebook computer manufacturers, due to low weight, very good image quality, wide color gamut and response time. The term was first used in 1975 by Dr T. Peter Brody to describe a method of switching individual elements of a flat panel display, using a CdSe TFT for each pixel.

Introduction

These are the most popular type of monitors on the market today. The most common example of an active matrix display contains, besides the polarizing sheets and cells of liquid crystal, a matrix of thin-film transistors (TFTs) to make a TFT-LCD. These devices store the electrical state of each pixel on the display while all the other pixels are being updated. This method provides a much brighter, sharper display than a passive matrix of the same size. An important specification for these displays is their viewing-angle.

Thin film transistors are usually used for constructing an active matrix so that the two terms are often interchanged, even though a thin film transistor is just one component in an active matrix and some designs have used other components such as diodes. Whereas a passive matrix display uses a simple conductive grid to deliver current to the liquid crystals in the target area, an active matrix display uses a grid of transistors and capacitors (which are called the thin film transistors) with the ability to hold a charge for a limited period of time. Because of the switching action of transistors, only the desired pixel receives a charge, and the pixel acts as a capacitor to hold the charge until the next refresh cycle, improving image quality over a passive matrix.

Resolution

There are many different active matrix displays on the market. Each display is associated with a specific physical display resolution. The display resolution signifies the number of

dots (pixels) on the entire screen. The higher the resolution, the more dots or pixels on your display device. The total number of pixels in an active matrix display is fixed. For example, a VGA display has a very low resolution at 640 × 480.

Monitor	Resolution
QVGA (quarter-video graphics array)	320 × 240
VGA (video graphics array)	640 × 480
WVGA (wide video graphics array)	800 × 480
SVGA (super video graphics array)	800 × 600
XGA (extended graphics array)	1024 × 768
WXGA (wide extended graphics array)	1280 × 800
WXGA+	1440 × 900
SXGA (super extended graphics array)	1280 × 1024
SXGA+	1400 × 1050
UXGA (ultra extended graphics array)	1600 × 1200
WSXGA+ (wide super extended graphics array)	1680 × 1050
WUXGA (wide ultra extended graphics array)	1920 × 1200
WQXGA (wide quad extended graphics array)	2560 × 1600

Blue Phase Mode LCD

A **Blue Phase Mode LCD** is a liquid crystal display technology that uses highly twisted cholesteric phases in a blue phase. It was first proposed in 2007 to obtain a better display of moving images with, for example, frame rates of 100–120 Hz to improve the temporal response of liquid crystal displays (LCDs). This operational mode for LCDs also does not require anisotropic alignment layers (e.g., rubbed polyimide) and thus theoretically simplifies the LCD manufacturing process.
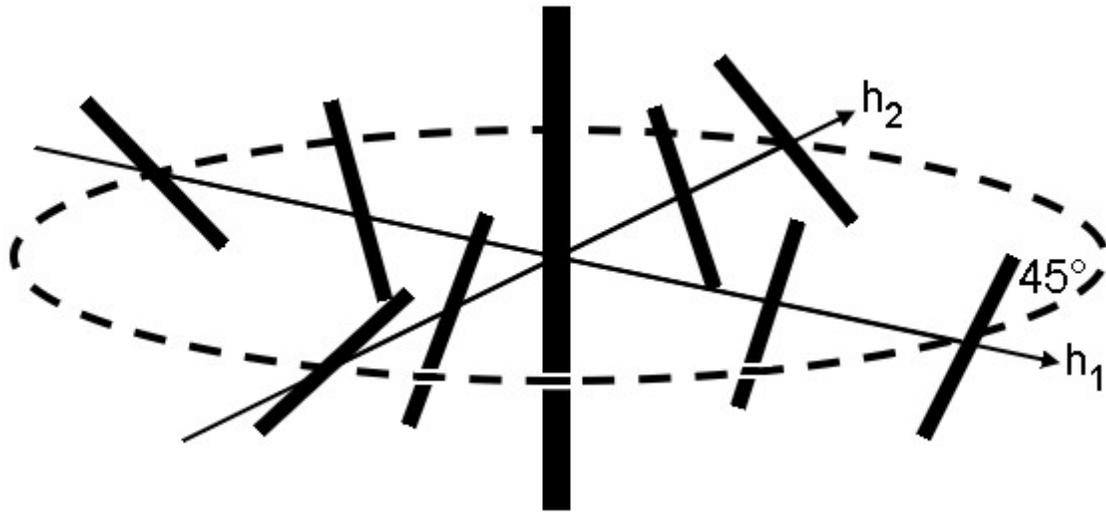
History

Figure 1: Perspective view on a double twisted structure with two helical axes, h_1 and h_2. The directors perform a rotation of 90° across the diameter.

In Reinitzer's reports from 1888 on the melting behaviour of cholesteryl benzoate, there is a note that the substance briefly turned blue as it changed from clear to cloudy upon cooling. This subtle effect however remained unexplored for more than eighty years until some experimental results were published during the late 1960s and early seventies that indicated that the blue color was due to at least two new and very different liquid crystalline phases.

For almost one hundred years, scientists assumed that the most stable cholesteric helical structure could be described by a single helical axis about which the director rotates. It turned out that in the new structure the director rotates in a helical fashion about any axis perpendicular to a line as illustrated in fig. 1. Although an unlimited number of helical axes are actually present, this structure was named *double twist structure*.
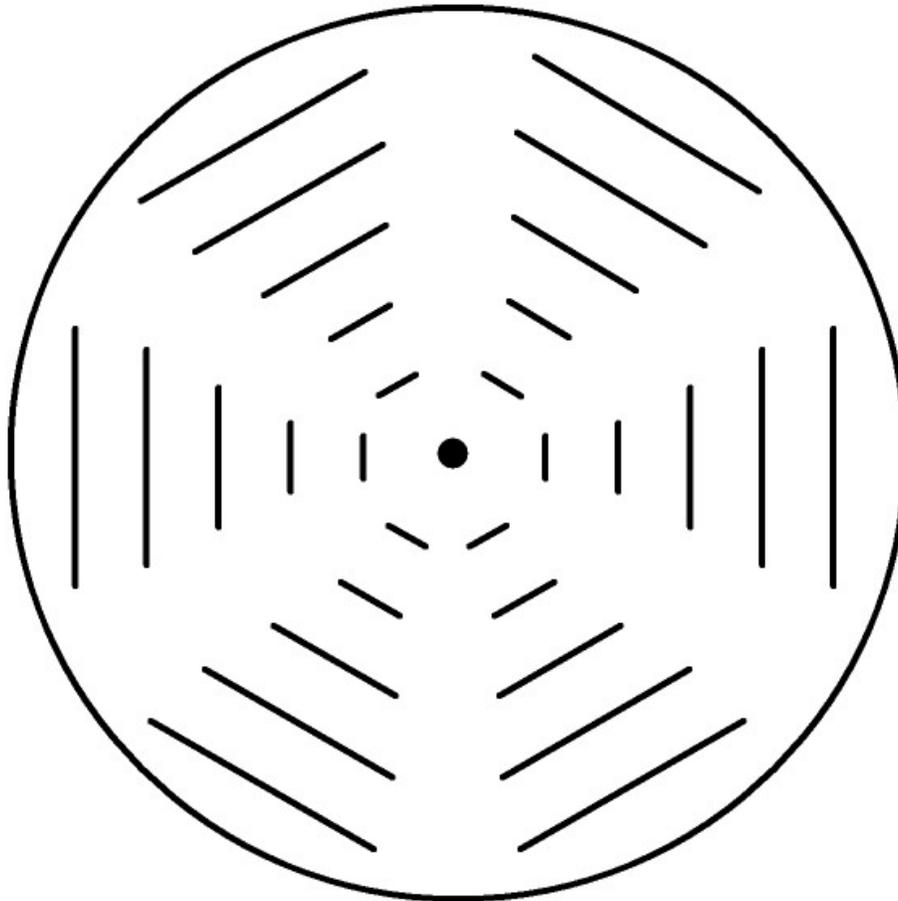
Figure 2: Top view on a double twist cylinder. The plane containing the various helical axes, h, (three of them shown here) is the plane of the figure. The director points out of the plane of the figure in the center and it rotates as you move away from the center.

This *double twist structure* is more stable than the *single twist structure* (i.e., the normal helical structure of chiral nematics) only up to a certain distance from the line at the center. Since this distance is on the order of the pitch of the chiral nematic liquid crystal (typically 100 nm) and since the geometries of usual liquid crystal samples are much larger, the *double twist structure* occurs only rarely.
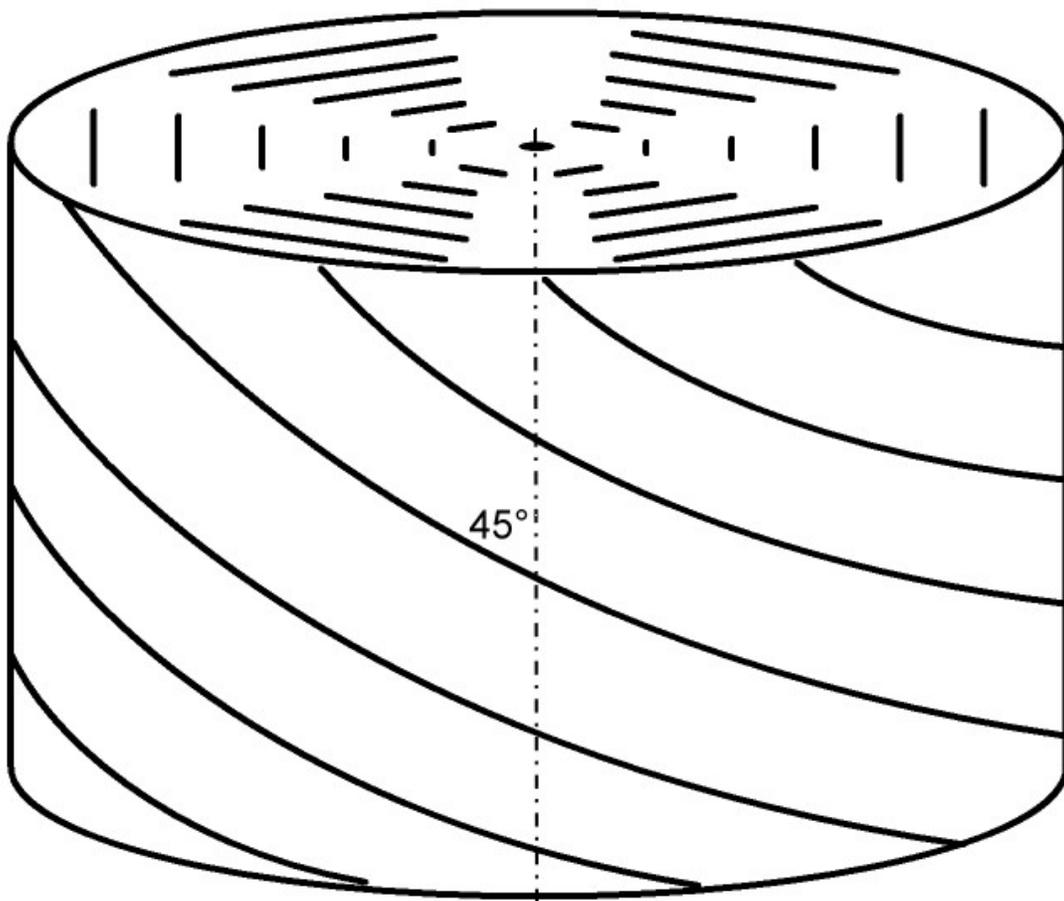
Figure 3: Perspective view on the double twist cylinder. The lines on the outside are supposed to indicate a 45° rotation of the director at that distance from the center line.

Blue phases are special cases when double twist structures fill up large volumes. When double twist structures are limited in all directions to the distance from the center line where the twist amounts to 45° a *double twist cylinder* results. Because of its small radius, such a cylinder is more stable than the same volume filled with a single twist chiral nematic liquid crystal.
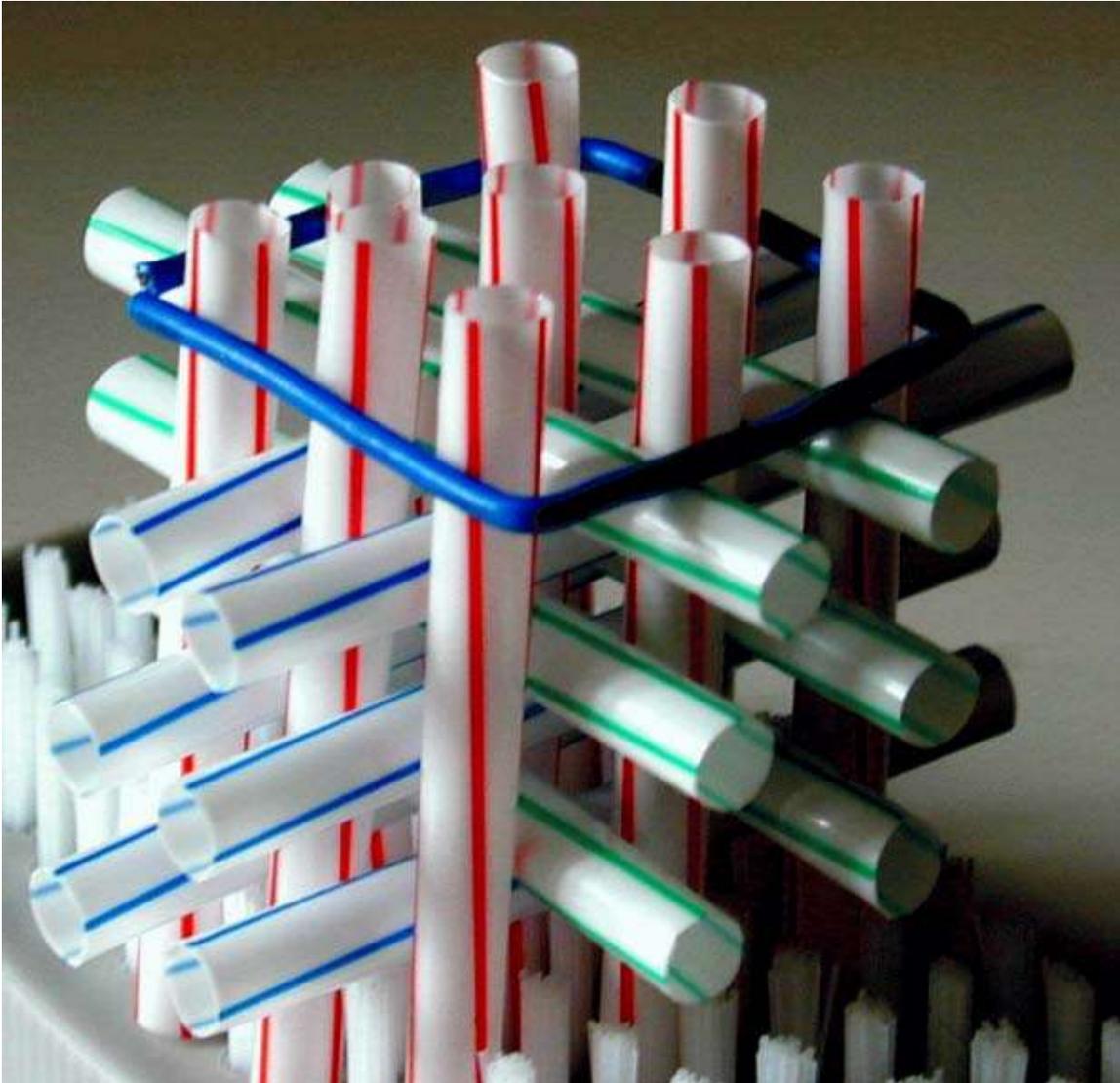
Figure 4: Illustration of a cubic lattice formed by double twist cylinders. All angles are supposed to be right angles.

A large structure can be composed from these *double twist cylinders*, but defects occur at the points where the cylinders are in contact as illustrated in fig. 5. These defects occur at regular distances and tend to make the structure less stable, but it is still slightly more stable than the single twist structure without defects, at least within a temperature range of about 1 K below the transition from the chiral nematic phase to an isotropic liquid.

The defects that occur at regular distances in three spatial dimensions form a cubic lattice just as we know it from solid crystals. Blue phases are thus formed by a regular three-dimensional lattice of defects within a chiral liquid crystal. Since the spacings between the defects of a blue phase are in the range of the wavelength of light (several hundred nanometers), for certain wavelength ranges of the light reflected from the lattice

constructive interference occurs (Bragg reflection) and the blue phase reflects colored light (note that only some of the blue phases actually reflect blue light).
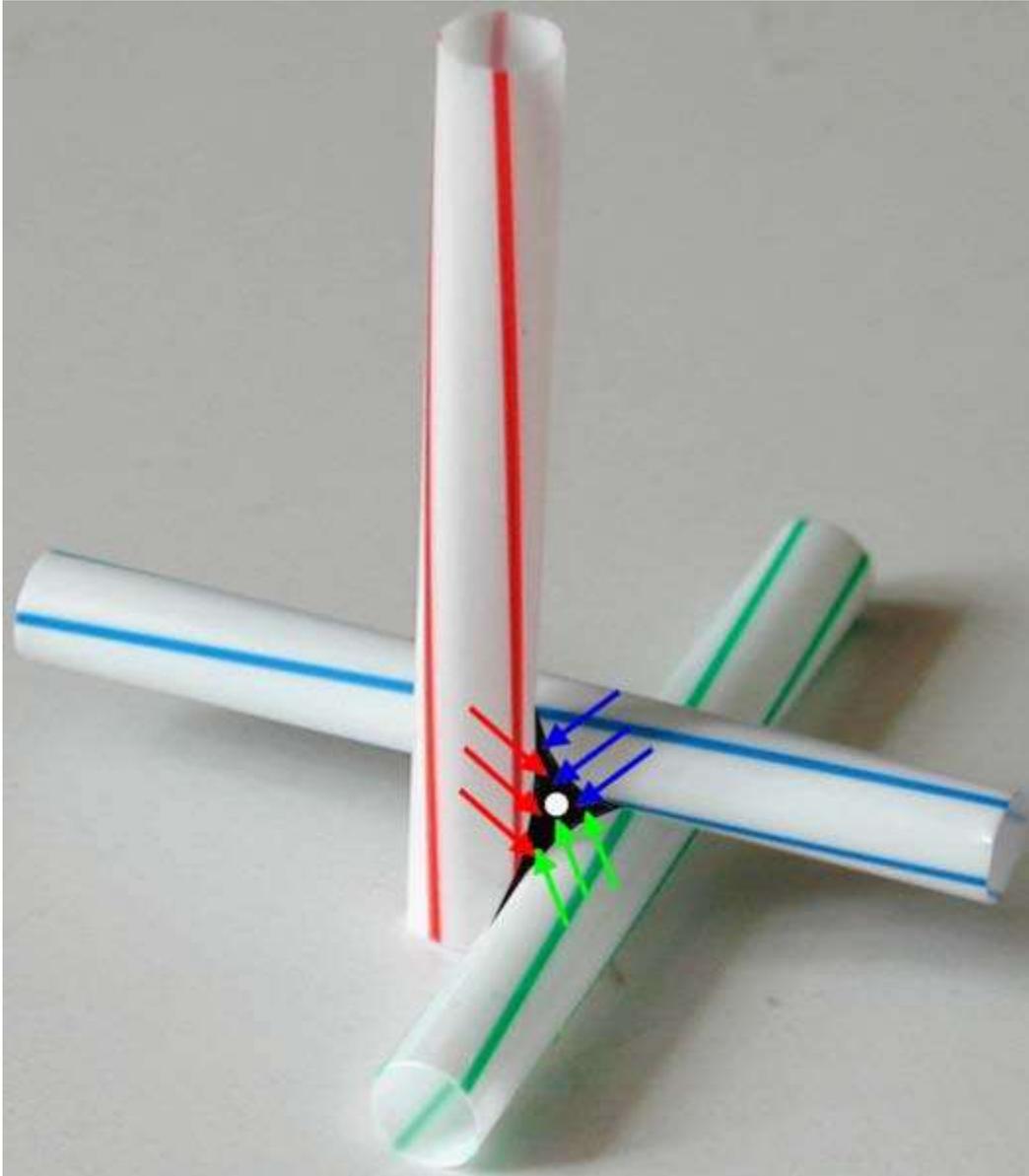

Figure 5: Disclinations form where the double twist cylinders are in contact. The core of the disclination as it crosses the triangular area is shown as a white dot.

Wide temperature range blue phases

In 2005, researchers from the Centre of Molecular Materials for Photonics and Electronics at the University of Cambridge reported their discovery of a class of blue-phase liquid crystals that remain stable over a range of temperatures as wide as 16-60 °C. The researchers showed that their ultrastable blue phases could be used to switch the

color of the reflected light by applying an electric field to the material, and that this could eventually be used to produce three-color (red, green, and blue) pixels for full-color displays. The new blue phases are made from molecules in which two stiff, rod-like segments are linked by a flexible chain, and are believed to be stabilized due to flexoelectricity.

Furthermore, electro-optical switching with response times of the order of 10^{-4} s for the stabilized *blue phases* at room temperature has been shown.

First blue phase LC-display

In May, 2008 Samsung Electronics announced that it has developed the world's first *Blue Phase LCD panel* which can be operated at an unprecedented refresh rate of 240 Hz. Samsung unveiled a 15 inch prototype model of its *Blue Phase LCD* panel at the SID (Society for Information Display) 2008 international Symposium, Seminar and Exhibition, which was held in Los Angeles from May 18 to 23, 2008 .

Developed with a look at cost-efficiency, Samsung's *Blue Phase mode* does not require liquid crystal alignment layers, unlike today's most widely used TFT LCD modes such as Twisted Nematic (TN), In-Plane Switching (IPS) or Vertical Alignment (VA). The *Blue Phase mode* can make its own alignment layers, eliminating the need for any mechanical alignment and rubbing processes. This reduces the number of required manufacturing steps, resulting in savings on production costs. Additionally it has been claimed that *Blue Phase panels* would reduce the sensitivity of the liquid crystal layer to mechanical pressure which could impair the lateral uniformity of display (e.g. luminance, chromaticity).

In a blue phase based LC-display for TV applications it is not the selective reflection of light according to the lattice pitch (Bragg reflection) that is used for display of visual information, but an external electric field induces a birefringence in the liquid crystal via the Kerr effect . That field induced birefringence becomes apparent as a change of transmission when the *Blue Phase Mode LC* layer is placed between crossed polarizers.

Response time compensation by voltage overdriving as currently applied in many LCD panels with 120 Hz frame frequency for improvement of the display of moving images in LCD TVs could become obsolete since the Blue Phase mode features a superior response speed, allowing images to be reproduced at 240 Hz frame rate or higher without the need for any overdrive circuit.

With an isotropic dark state, blue phase LCDs show many interesting electro-optic performances. Presently, the driving voltage of blue phase LCs in IPS structures is still a little bit too high. To reduce the voltage, material engineering for developing high Kerr constant mixtures is critically important.

Ferro Liquid Display

Ferro Liquid Display or Ferro-electric Liquid Display (FLD) or Ferro Fluid Display (FFD) is based on Ferro electric properties of certain liquids. Not all such fluids are crystal but they are generically referred to as Ferro Liquid Crystal Display (FLCD) also.

Description
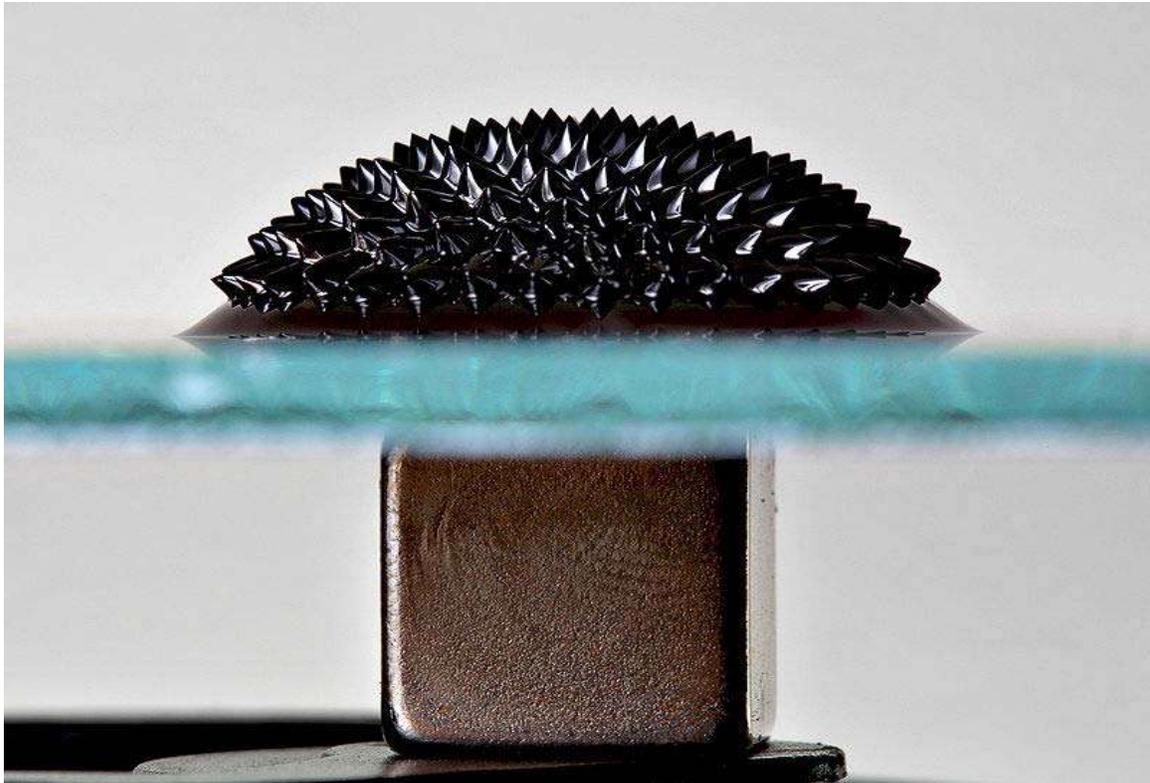
Ferrofluid on glass, with a magnet underneath

These fluids have bistable properties that can be switched with a magnetic field. The switching time is much shorter than that of a typical LCD that twist/untwist due to electric rather than magnetic interactions.

Also see Ferrofluid for how some liquids behave in presence of a magnetic field. Practically the switching time is just the same as the time it takes for the electric signal to switch (the magnetic field). The ferro liquid reacts almost instantly when used in µg quantities (thin layer) as in a typical LCD's crystal layer.

The dot pitch of such displays can be as low as 10 µm giving a very dense high resolution display on a small area. These might find applications in 3D displays and head mounted displays (HMD) where typical LCDs have failed to provide anything better than a 640x480 (RGB pixel) resolution on a sq.cm display area.

Displays based on these are still experimental or of less commercial value only due to the costs. Gradual adoption in consumer electronics is expected to bring the costs down.

A major drawback is that the angle of twist is not easily controlled by intensity of magnetic field. To produce color scales, time multiplexing might be used exploiting the quick switching time. The materials found so far are sensitive to vibration and shock.

Working of Ferro Electric Crystals
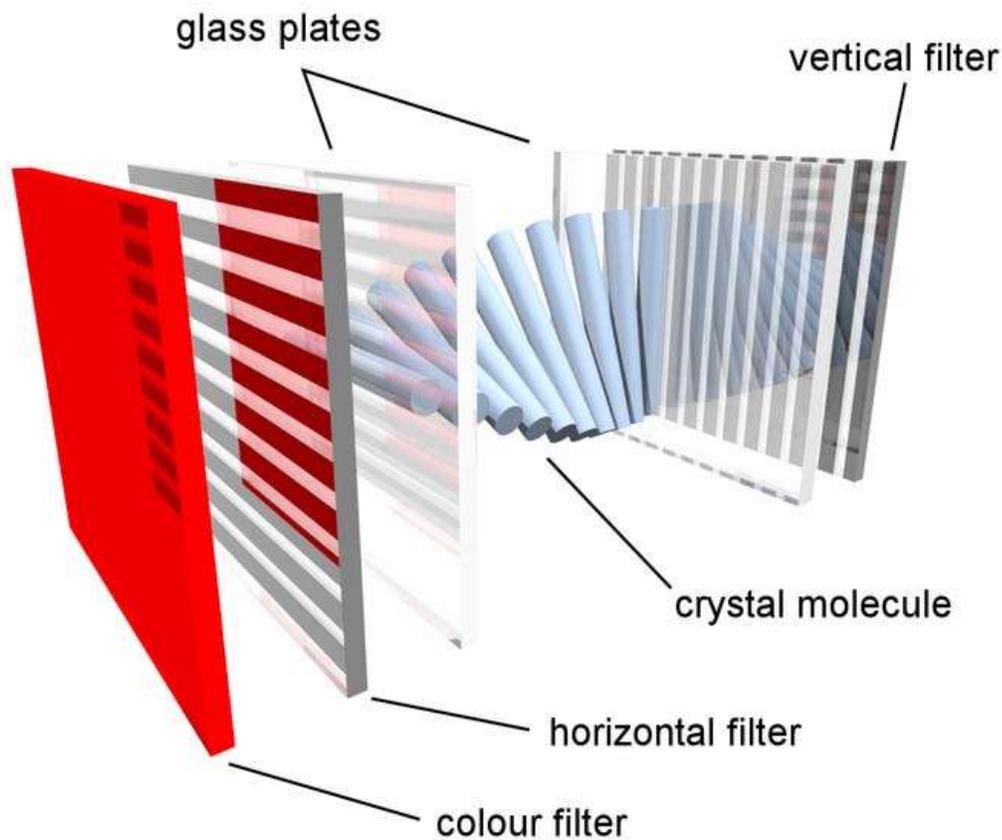
A single pixel

Those based on crystals can retain polarisation permanently. FLCDs are smectic liquid crystals that have a natural layered order. Most FLCDs are

- of the smectic C phase (SmC*)
    - i.e., they are tilted away from the layer normal (90°) and
- possess a chiral behaviour
    - i.e., they have a layered structure with the molecules at some angle (the "cone angle") away from the layer normal, and there is some inherent twist in the structure.

So, an unconstrained system, the azimuthal direction in which the molecules tilt away from the layer normal will differ slightly from one layer to the next.

Typically, the FLCDs are built with cell gaps less than 2 μm for stable molecular alignment. Alignment layer causes perpendicular stacked alignment. The cell's polarisation is determined by the magnetic field applied. That in turn results in opaque or transparent layer when used in combination with polarised layers as in LCD.

Properties and uses

- Very thin layer (less than 2 μm thick) can help produce a 90° polarisation twist.
  - High density displays with small display areas can be produced.
  - DisplayTECH claims that a stamp sized FLCD can drive resolutions needed for 50 inch screens.
- Switching time is less than 100 μs
  - High frame rate video displays are possible.
- Magnetic polarisation effect is bistable.
  - Can be used for low frame rate displays that can run on very low power
  - This property can help build display with non-volatile memory with the advantage that the memory can be changed easily.
- Viewing angle is greater than 120°
  - This makes it suitable for commercial TV applications.

Some commercial products do seem to utilize FLCD.

High switching allows building optical switches and shutters in printer heads.

Chapter- 5

Liquid Crystal
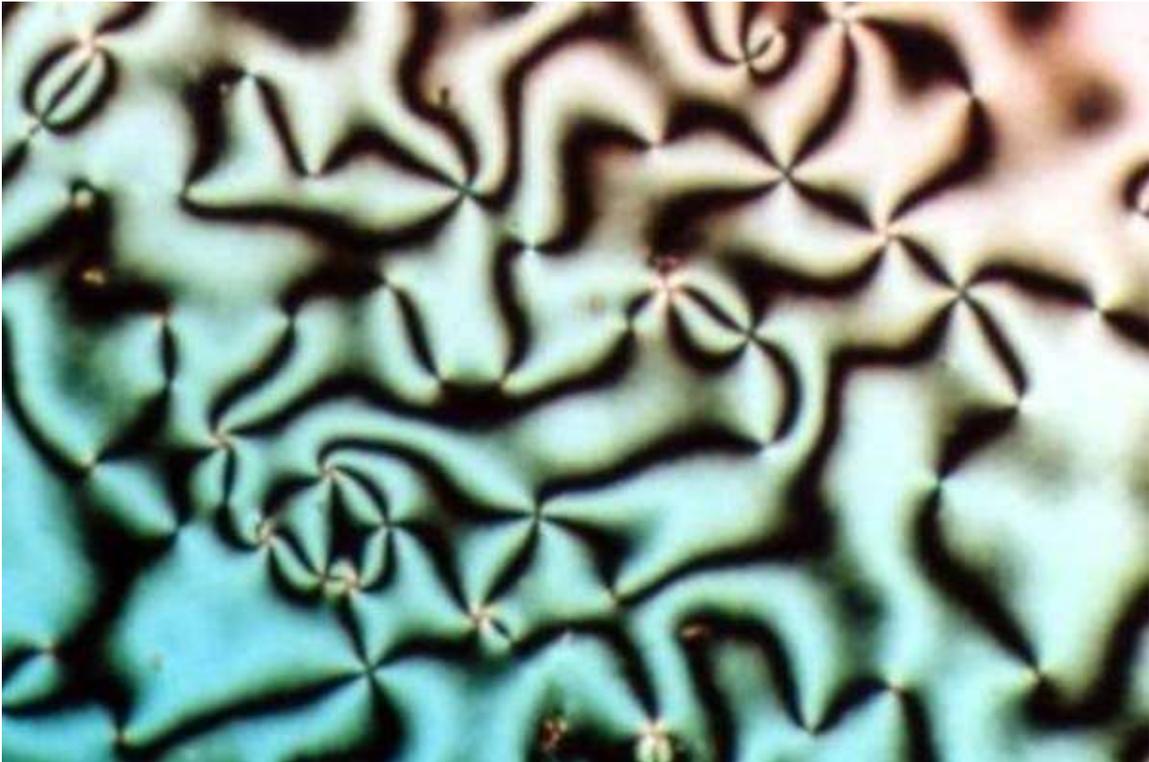
Schlieren texture of liquid crystal nematic phase

Schlieren texture on an LCD screen of a PlayStation Portable viewed through a circular polarizer

Liquid crystals (LCs) are a state of matter that have properties between those of a conventional liquid and those of a solid crystal. For instance, an LC may flow like a liquid, but its molecules may be oriented in a crystal-like way. There are many different types of LC phase, which can be distinguished by their different optical properties (such as birefringence). When viewed under a microscope using a polarized light source, different liquid crystal phases will appear to have distinct textures. The contrasting areas in the textures correspond to domains where the LC molecules are oriented in different directions. Within a domain, however, the molecules are well ordered. LC materials may not always be in an LC phase (just as water may turn into ice or steam).

Liquid crystals can be divided into thermotropic, lyotropic and metallotropic phases. Thermotropic and lyotropic LCs consist of organic molecules. Thermotropic LCs exhibit a phase transition into the LC phase as temperature is changed. Lyotropic LCs exhibit phase transitions as a function of both temperature and concentration of the LC molecules in a solvent (typically water). Metallotropic LCs are composed of both organic and inorganic molecules; their LC transition depends not only on temperature and concentration, but also on the inorganic-organic composition ratio.

Examples of liquid crystals can be found both in the natural world and in technological applications. Most modern electronic displays are liquid crystal based. Lyotropic liquid-crystalline phases are abundant in living systems. For example, many proteins and cell membranes are LCs. Other well-known LC examples are solutions of soap and various related detergents, as well as tobacco mosaic virus.

History

In 1888, Austrian botanical physiologist Friedrich Reinitzer, working at the Charles University in Prague, examined the physico-chemical properties of various derivatives of cholesterol, which are now known as cholesteric liquid crystals. Previously, other researchers had observed distinct color effects when cooling cholesterol derivatives just above the freezing point, but had not associated it with a new phenomenon. Reinitzer perceived that color changes in a derivative cholesteryl benzoate were not the most peculiar feature. He found that cholesteryl benzoate does not melt in the same manner as other compounds, but has two melting points. At 145.5 °C (293.9 °F) it melts into a cloudy liquid, and at 178.5 °C (353.3 °F) it melts again and the cloudy liquid becomes clear. The phenomenon is reversible. Seeking help from a physicist, on March 14, 1888, he wrote to Otto Lehmann, at that time a *Privatdozent* in Aachen. They exchanged letters and samples. Lehmann examined the intermediate cloudy fluid, and reported seeing crystallites. Reinitzer's Viennese colleague von Zepharovich also indicated that the intermediate "fluid" was crystalline. The exchange of letters with Lehmann ended on April 24, with many questions unanswered. Reinitzer presented his results, with credits to Lehmann and von Zepharovich, at a meeting of the Vienna Chemical Society on May 3, 1888.

By that time, Reinitzer had discovered and described three important features of cholesteric liquid crystals (the name coined by Otto Lehman in 1904): the existence of two melting points, the reflection of circularly polarized light, and the ability to rotate the polarization direction of light.

After his accidental discovery, Reinitzer did not pursue studying liquid crystals further. The research was continued by Lehmann, who realized that he had encountered a new phenomenon and was in a position to investigate it: In his postdoctoral years he had acquired expertise in crystallography and microscopy. Lehmann started a systematic study, first of cholesteryl benzoate, and then of related compounds which exhibited the double-melting phenomenon. He was able to make observations in polarized light, and his microscope was equipped with a hot stage (sample holder equipped with a heater)

enabling high temperature observations. The intermediate cloudy phase clearly sustained flow, but other features, particularly the signature under a microscope, convinced Lehmann that he was dealing with a solid. By the end of August 1889 he had published his results in the Zeitschrift für Physikalische Chemie.

Lehmann's work was continued and significantly expanded by the German chemist Daniel Vorländer, who from the beginning of 20th century until his retirement in 1935, had synthesized most of the liquid crystals known. However, liquid crystals were not popular among scientists and the material remained a pure scientific curiosity for about 80 years.
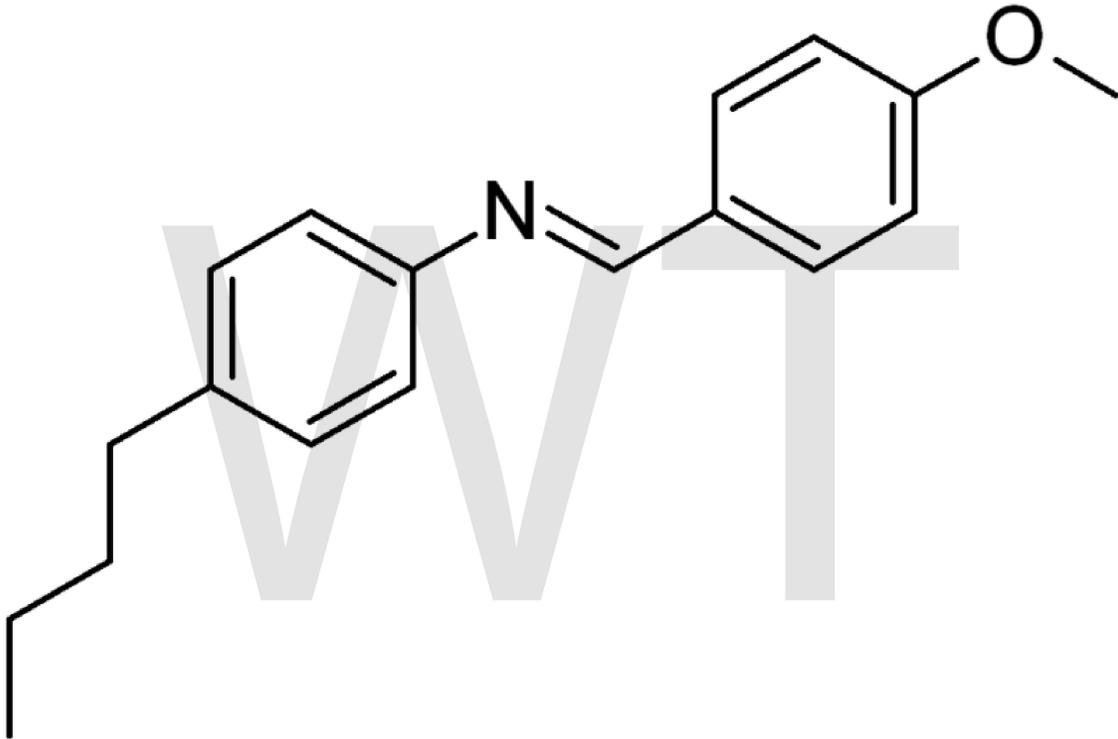
Chemical structure of N-(4-Methoxybenzylidene)-4-butylaniline (MBBA) molecule

In 1969, Hans Kelker succeeded in synthesizing a substance that had a nematic phase at room temperature, MBBA, which is one of the most popular subjects of liquid crystal research. The next step to commercialization of liquid crystal displays was the synthesis of further chemically stable substances (cyanobiphenyls) with low melting temperatures by George Gray.

In 1991, when liquid crystal displays were already well established, Pierre-Gilles de Gennes received the Nobel Prize in physics "for discovering that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers".

Liquid crystal phases

The various LC phases (called *mesophases*) can be characterized by the type of ordering. One can distinguish positional order (whether molecules are arranged in any sort of ordered lattice) and orientational order (whether molecules are mostly pointing in the same direction), and moreover order can be either short-range (only between molecules close to each other) or long-range (extending to larger, sometimes macroscopic, dimensions). Most thermotropic LCs will have an isotropic phase at high temperature. That is that heating will eventually drive them into a conventional liquid phase characterized by random and isotropic molecular ordering (little to no long-range order), and fluid-like flow behavior. Under other conditions (for instance, lower temperature), an LC might inhabit one or more phases with significant anisotropic orientational structure and short-range orientational order while still having an ability to flow.

The ordering of liquid crystalline phases is extensive on the molecular scale. This order extends up to the entire domain size, which may be on the order of micrometers, but usually does not extend to the macroscopic scale as often occurs in classical crystalline solids. However some techniques, such as the use of boundaries or an applied electric field, can be used to enforce a single ordered domain in a macroscopic liquid crystal sample. The ordering in a liquid crystal might extend along only one dimension, with the material being essentially disordered in the other two directions.

Thermotropic liquid crystals

Thermotropic phases are those that occur in a certain temperature range. If the temperature rise is too high, thermal motion will destroy the delicate cooperative ordering of the LC phase, pushing the material into a conventional isotropic liquid phase. At too low temperature, most LC materials will form a conventional crystal. Many thermotropic LCs exhibit a variety of phases as temperature is changed. For instance, a particular type of LC molecule (called mesogen) may exhibit various smectic and nematic (and finally isotropic) phases as temperature is increased. An example of a compound displaying thermotropic LC behavior is para-azoxyanisole.
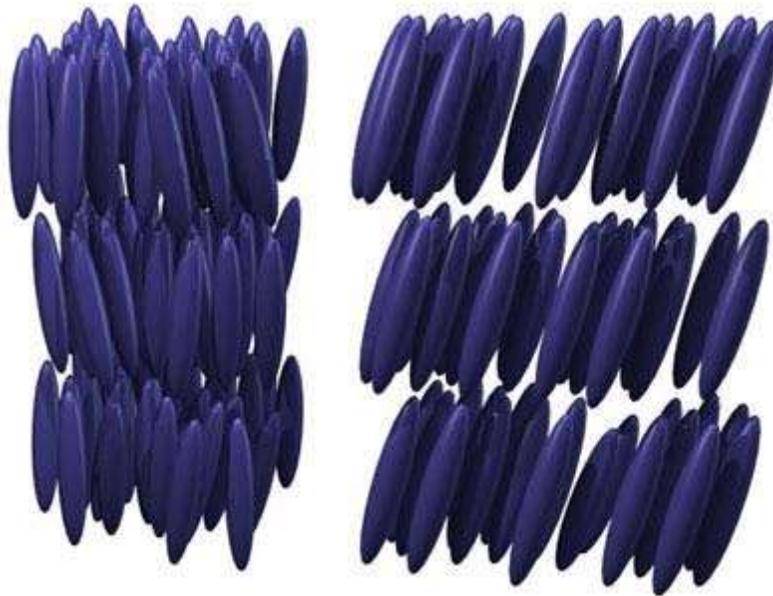
Nematic phase

Alignment in a nematic phase
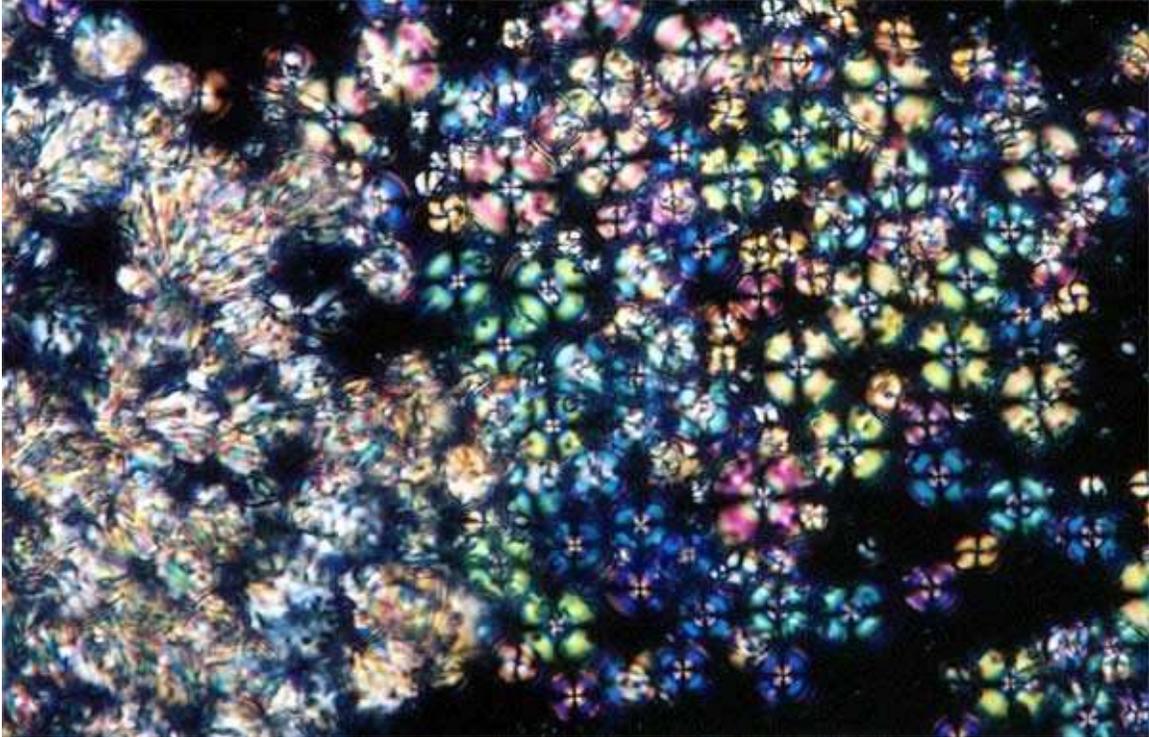
Phase transition between a nematic (left) and smectic A (right) phases observed between crossed polarizers. The black color corresponds to isotropic medium.

One of the most common LC phases is the nematic. The word *nematic* comes from the Greek νημα (*nema*), which means "thread". This term originates from the thread-like topological defects observed in nematics, which are formally called 'disclinations'. Nematics also exhibit so-called hedgehog topological defects. In a nematic phase, the *calamitic* or rod-shaped organic molecules have no positional order, but they self-align to have long-range directional order with their long axes roughly parallel. Thus, the molecules are free to flow and their center of mass positions are randomly distributed as in a liquid, but still maintain their long-range directional order. Most nematics are uniaxial: they have one axis that is longer and preferred, with the other two being equivalent (can be approximated as cylinders or rods). However, some liquid crystals are biaxial nematics, meaning that in addition to orienting their long axis, they also orient along a secondary axis. Nematics have fluidity similar to that of ordinary (isotropic) liquids but they can be easily aligned by an external magnetic or electric field. Aligned nematics have the optical properties of uniaxial crystals and this makes them extremely useful in liquid crystal displays (LCD).

Smectic phases

Schematic of alignment in the smectic phases. The smectic A phase (left) has molecules organized into layers. In the smectic C phase (right), the molecules are tilted inside the layers.

The smectic phases, which are found at lower temperatures than the nematic, form well-defined layers that can slide over one another in a manner similar to that of soap. The smectics are thus positionally ordered along one direction. In the Smectic A phase, the molecules are oriented along the layer normal, while in the Smectic C phase they are tilted away from the layer normal. These phases are liquid-like within the layers. There are many different smectic phases, all characterized by different types and degrees of positional and orientational order.

Chiral phases

Schematic of ordering in chiral liquid crystal phases. The chiral nematic phase (left), also called the cholesteric phase, and the smectic C* phase (right).

The chiral nematic phase exhibits chirality (handedness). This phase is often called the *cholesteric* phase because it was first observed for cholesterol derivatives. Only chiral molecules (i.e., those that lack inversion symmetry) can give rise to such a phase. This phase exhibits a twisting of the molecules perpendicular to the director, with the molecular axis parallel to the director. The finite twist angle between adjacent molecules is due to their asymmetric packing, which results in longer-range chiral order. In the smectic C* phase (an asterisk denotes a chiral phase), the molecules have positional ordering in a layered structure (as in the other smectic phases), with the molecules tilted by a finite angle with respect to the layer normal. The chirality induces a finite azimuthal twist from one layer to the next, producing a spiral twisting of the molecular axis along the layer normal.
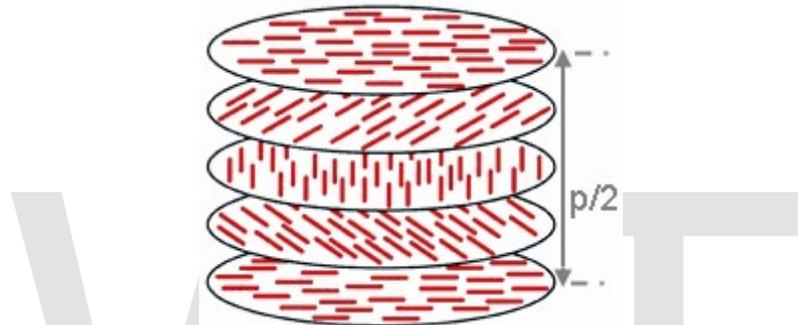
Chiral nematic phase; p refers to the chiral pitch

The *chiral pitch*, p, refers to the distance over which the LC molecules undergo a full 360° twist (but note that the structure of the chiral nematic phase repeats itself every half-pitch, since in this phase directors at 0° and ±180° are equivalent). The pitch, p, typically changes when the temperature is altered or when other molecules are added to the LC host (an achiral LC host material will form a chiral phase if doped with a chiral material), allowing the pitch of a given material to be tuned accordingly. In some liquid crystal systems, the pitch is of the same order as the wavelength of visible light. This causes these systems to exhibit unique optical properties, such as Bragg reflection and low-threshold laser emission, and these properties are exploited in a number of optical applications. For the case of Bragg reflection only the lowest-order reflection is allowed if the light is incident along the helical axis, whereas for oblique incidence higher-order reflections become permitted. Cholesteric liquid crystals also exhibit the unique property that they reflect circularly polarized light when it is incident along the helical axis and elliptically polarized if it comes in obliquely.

Blue phases

Blue phases are special types of liquid crystal phases that appear in the temperature range between a chiral nematic phase and an isotropic liquid phase. *Blue phases* have a regular three-dimensional cubic structure of defects with lattice periods of several hundred nanometers, and thus they exhibit selective Bragg reflections in the wavelength range of light (visible part of electromagnetic radiation) corresponding to the cubic lattice.

Although *blue phases* are of interest for fast light modulators or tunable photonic crystals, the very narrow temperature range within which *blue phases* exist, usually less than a few kelvin, has always been a problem. Recently the stabilization of *blue phases* over a temperature range of more than 60 K including room temperature (260–326 K) could be demonstrated.

Furthermore, electro-optical switching with response times of the order of 10^{-4} s for the stabilized *blue phases* at room temperature has been shown.

In May 2008, it was announced that the first Blue Phase Mode LCD panel had been developed.

Discotic phases

Disk-shaped LC molecules can orient themselves in a layer-like fashion known as the discotic nematic phase. If the disks pack into stacks, the phase is called a discotic columnar. The columns themselves may be organized into rectangular or hexagonal arrays. Chiral discotic phases, similar to the chiral nematic phase, are also known.

Lyotropic liquid crystals
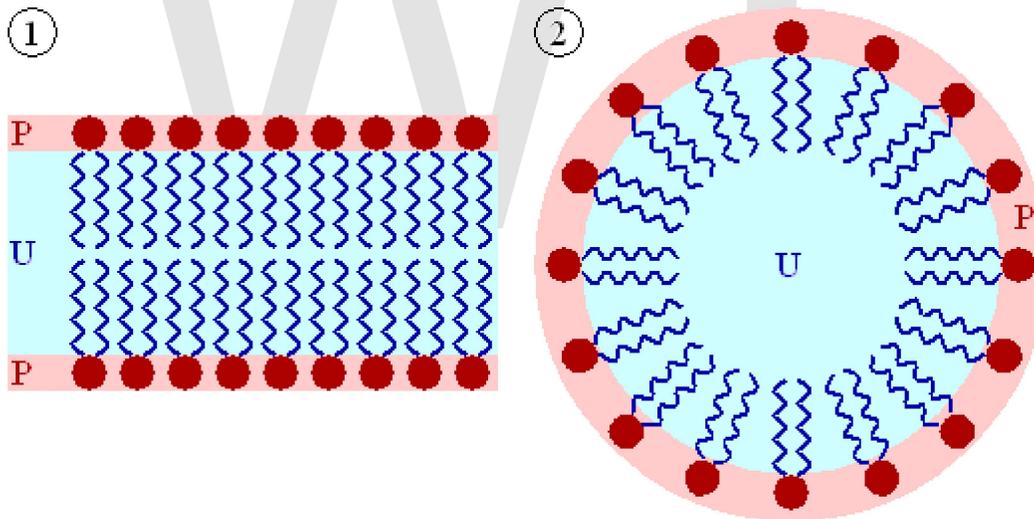
Structure of lyotropic liquid crystal. The red heads of surfactant molecules are in contact with water, whereas the tails are immersed in oil (blue): bilayer (left) and micelle (right)

A lyotropic liquid crystal consists of two or more components that exhibit liquid-crystalline properties in certain concentration ranges. In the lyotropic phases, solvent molecules fill the space around the compounds to provide fluidity to the system. In contrast to thermotropic liquid crystals, these lyotropics have another degree of freedom of concentration that enables them to induce a variety of different phases.

A compound, which has two immiscible hydrophilic and hydrophobic parts within the same molecule, is called an amphiphilic molecule. Many amphiphilic molecules show lyotropic liquid-crystalline phase sequences depending on the volume balances between the hydrophilic part and hydrophobic part. These structures are formed through the micro-phase segregation of two incompatible components on a nanometer scale. Soap is an everyday example of a lyotropic liquid crystal.

The content of water or other solvent molecules changes the self-assembled structures. At very low amphiphile concentration, the molecules will be dispersed randomly without any ordering. At slightly higher (but still low) concentration, amphiphilic molecules will spontaneously assemble into micelles or vesicles. This is done so as to 'hide' the hydrophobic tail of the amphiphile inside the micelle core, exposing a hydrophilic (water-soluble) surface to aqueous solution. These spherical objects do not order themselves in solution, however. At higher concentration, the assemblies will become ordered. A typical phase is a hexagonal columnar phase, where the amphiphiles form long cylinders (again with a hydrophilic surface) that arrange themselves into a roughly hexagonal lattice. This is called the middle soap phase. At still higher concentration, a lamellar phase (neat soap phase) may form, wherein extended sheets of amphiphiles are separated by thin layers of water. For some systems, a cubic (also called viscous isotropic) phase may exist between the hexagonal and lamellar phases, wherein spheres are formed that create a dense cubic lattice. These spheres may also be connected to one another, forming a bicontinuous cubic phase.

The objects created by amphiphiles are usually spherical (as in the case of micelles), but may also be disc-like (bicelles), rod-like, or biaxial (all three micelle axes are distinct). These anisotropic self-assembled nano-structures can then order themselves in much the same way as thermotropic liquid crystals do, forming large-scale versions of all the thermotropic phases (such as a nematic phase of rod-shaped micelles).

For some systems, at high concentrations, inverse phases are observed. That is, one may generate an inverse hexagonal columnar phase (columns of water encapsulated by amphiphiles) or an inverse micellar phase (a bulk liquid crystal sample with spherical water cavities).

A generic progression of phases, going from low to high amphiphile concentration, is:

- Discontinuous cubic phase (micellar cubic phase)
- Hexagonal phase (hexagonal columnar phase) (middle phase)
- Lamellar phase
- Bicontinuous cubic phase
- Reverse hexagonal columnar phase
- Inverse cubic phase (Inverse micellar phase)

Even within the same phases, their self-assembled structures are tunable by the concentration: for example, in lamellar phases, the layer distances increase with the solvent volume. Since lyotropic liquid crystals rely on a subtle balance of intermolecular

interactions, it is more difficult to analyze their structures and properties than those of thermotropic liquid crystals.

Similar phases and characteristics can be observed in immiscible diblock copolymers.

Metallotropic liquid crystals

Liquid crystal phases can also be based on low-melting *inorganic* phases like $ZnCl_2$ that have a structure formed of linked tetrahedra and easily form glasses. The addition of long chain soap-like molecules leads to a series of new phases that show a variety of liquid crystalline behavior both as a function of the inorganic-organic composition ratio and of temperature. This class of materials has been named metallotropic.

Biological liquid crystals

Lyotropic liquid-crystalline phases are abundant in living systems, the study of which is referred to as polymorphism. Accordingly, lyotropic liquid crystals attract particular attention in the field of biomimetic chemistry. In particular, biological membranes and cell membranes are a form of liquid crystal. Their constituent molecules (e.g., phospholipids) are perpendicular to the membrane surface, yet the membrane is flexible. These lipids vary in shape. The constituent molecules can inter-mingle easily, but tend not to leave the membrane due to the high energy requirement of this process. Lipid molecules can flip from one side of the membrane to the other, this process being catalyzed by flippases and floppases (depending on the direction of movement). These liquid crystal membrane phases can also host important proteins such as receptors freely "floating" inside, or partly outside, the membrane, e.g. CCT.

Many other biological structures exhibit LC behavior. For instance, the concentrated protein solution that is extruded by a spider to generate silk is, in fact, a liquid crystal phase. The precise ordering of molecules in silk is critical to its renowned strength. DNA and many polypeptides can also form LC phases and this too forms an important part of current academic research.

Pattern formation in liquid crystals

Anisotropy of liquid crystals is a property not observed in other fluids. This anisotropy makes flows of liquid crystals behave more differentially than those of ordinary fluids. For example, injection of a flux of a liquid crystal between two close parallel plates (viscous fingering), causes orientation of the molecules to couple with the flow, with the resulting emergence of dendritic patterns. This anisotropy is also manifested in the interfacial energy (surface tension) between different liquid crystal phases. This anisotropy determines the equilibrium shape at the coexistence temperature, and is so strong that usually facets appear. When temperature is changed one of the phases grows, forming different morphologies depending on the temperature change. Since growth is

controlled by heat diffusion, anisotropy in thermal conductivity favors growth in specific directions, which has also an effect on the final shape.

Theoretical treatment of liquid crystals

Microscopic theoretical treatment of fluid phases can become quite complicated, owing to the high material density, meaning that strong interactions, hard-core repulsions, and many-body correlations cannot be ignored. In the case of liquid crystals, anisotropy in all of these interactions further complicates analysis. There are a number of fairly simple theories, however, that can at least predict the general behavior of the phase transitions in liquid crystal systems.

Director

As we already saw above, the nematic liquid crystals are composed of rod-like molecules with the long axes of neighboring molecules aligned approximately to one another. To allow this anisotropic structure, a dimensionless unit vector *n* called the *director*, is introduced to represent the direction of preferred orientation of molecules in the neighborhood of any point. Because there is no physical polarity along the director axis, *n* and *-n* are fully equivalent.

Order parameter
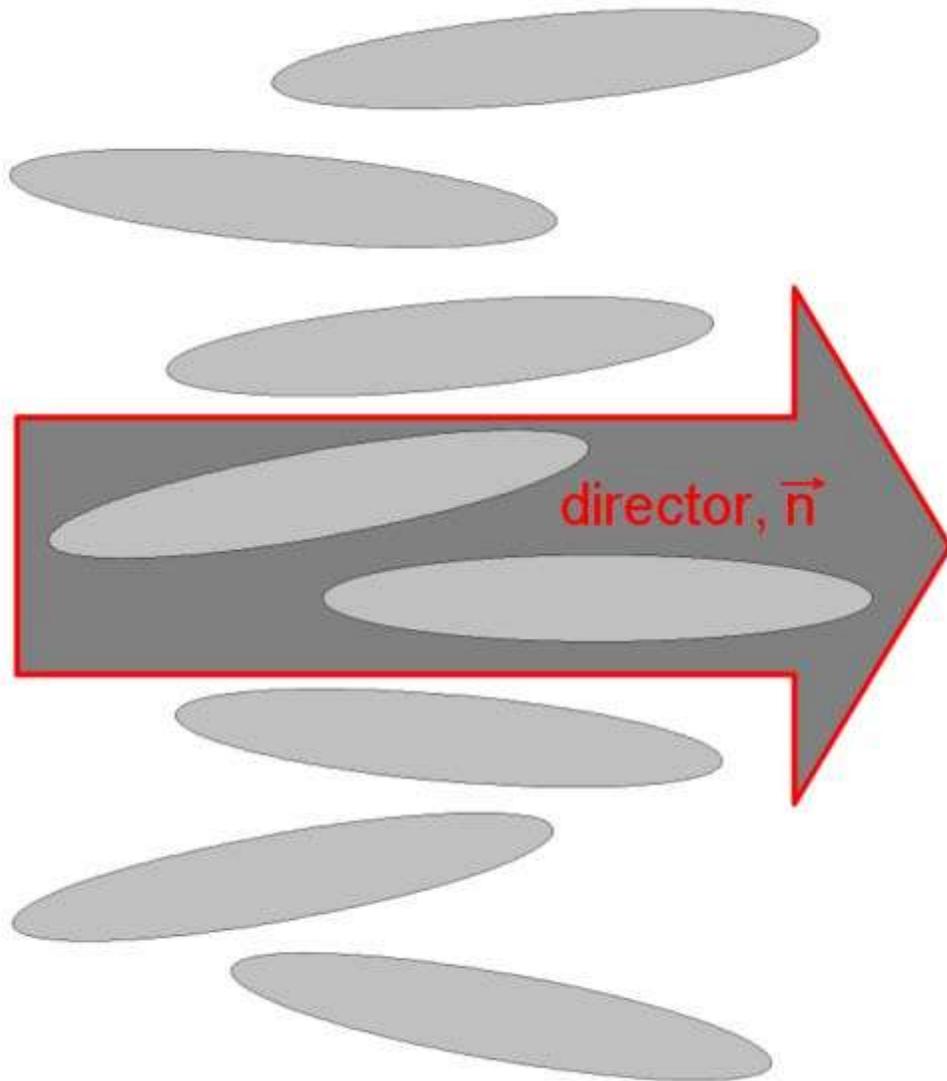
The *local nematic director*, which is also the *local optical axis*, is given by the spatial and temporal average of the long molecular axes

The description of liquid crystals involves an analysis of order. A tensor order parameter is used to describe the orientational order of a liquid crystal, although a scalar order parameter is usually sufficient to describe nematic liquid crystals. To make this quantitative, an orientational order parameter is usually defined based on the average of the second Legendre polynomial:

$$S = \langle P_2(\cos\theta)\rangle = \left\langle \frac{3\cos^2\theta - 1}{2}\right\rangle$$

where θ is the angle between the LC molecular axis and the *local director* (which is the 'preferred direction' in a volume element of a liquid crystal sample, also representing its *local optical axis*). The brackets denote both a temporal and spatial average. This definition is convenient, since for a completely random and isotropic sample, S=0, whereas for a perfectly aligned sample S=1. For a typical liquid crystal sample, S is on the order of 0.3 to 0.8, and generally decreases as the temperature is raised. In particular, a sharp drop of the order parameter to 0 is observed when the system undergoes a phase transition from an LC phase into the isotropic phase. The order parameter can be measured experimentally in a number of ways. For instance, diamagnetism, birefringence, Raman scattering, NMR and EPR can also be used to determine S.

The order of a liquid crystal could also be characterized by using other even Legendre polynomials (all the odd polynomials average to zero since the director can point in either of two antiparallel directions). These higher-order averages are more difficult to measure, but can yield additional information about molecular ordering.

A positional order parameter is also used to describe the ordering of a liquid crystal. It is characterized by the variation of the density of the center of mass of the liquid crystal molecules along a given vector. In the case of positional variation along the z-axis the density ρ(z) is often given by:

$$\rho(\mathbf{r}) = \rho(z) = \rho_0 + \rho_1 \cos(q_s z - \phi) + \cdots$$

The complex positional order parameter is defined as $\psi(\mathbf{r}) = \rho_1(\mathbf{r})e^{i\phi(\mathbf{r})}$ and ρ_0 the average density. Typically only the first two terms are kept and higher order terms are ignored since most phases can be described adequately using sinusoidal functions. For a perfect nematic ψ = 0 and for a smectic phase ψ will take on complex values. The complex nature of this order parameter allows for many parallels between nematic to smectic phase transitions and conductor to superconductor transitions.

Onsager hard-rod model

A simple model which predicts lyotropic phase transitions is the hard-rod model proposed by Lars Onsager. This theory considers the volume excluded from the center-of-mass of one idealized cylinder as it approaches another. Specifically, if the cylinders are oriented parallel to one another, there is very little volume that is excluded from the center-of-mass of the approaching cylinder (it can come quite close to the other cylinder). If, however, the cylinders are at some angle to one another, then there is a large volume surrounding the cylinder which the approaching cylinder's center-of-mass cannot enter (due to the hard-rod repulsion between the two idealized objects). Thus, this angular arrangement sees a *decrease* in the net positional entropy of the approaching cylinder (there are fewer states available to it).

The fundamental insight here is that, whilst parallel arrangements of anisotropic objects lead to a decrease in orientational entropy, there is an increase in positional entropy. Thus in some case greater positional order will be entropically favorable. This theory thus predicts that a solution of rod-shaped objects will undergo a phase transition, at sufficient concentration, into a nematic phase. Although this model is conceptually helpful, its mathematical formulation makes several assumptions that limit its applicability to real systems.

Maier-Saupe mean field theory

This statistical theory, proposed by Alfred Saupe and Wilhelm Maier, includes contributions from an attractive intermolecular potential from an induced dipole moment between adjacent liquid crystal molecules. The anisotropic attraction stabilizes parallel alignment of neighboring molecules, and the theory then considers a mean-field average of the interaction. Solved self-consistently, this theory predicts thermotropic nematic-isotropic phase transitions, consistent with experiment.

McMillan's model

McMillan's model, proposed by William McMillan, is an extension of the Maier-Saupe mean field theory used to describe the phase transition of a liquid crystal from a nematic to a smectic A phase. It predicts that the phase transition can be either continuous or discontinuous depending on the strength of the short-range interaction between the molecules. As a result, it allows for a triple critical point where the nematic, isotropic, and smectic A phase meet. Although it predicts the existence of a triple critical point, it does not successfully predict its value. The model utilizes two order parameters that describe the orientational and positional order of the liquid crystal. The first is simply the average of the second Legendre polynomial and the second order parameter is given by:

$$\sigma = \left\langle \cos\left(\frac{2\pi z_i}{d}\right)\left(\frac{3}{2}\cos^2\theta_i - \frac{1}{2}\right)\right\rangle$$

The values z_i, θ_i, and d are the position of the molecule, the angle between the molecular axis and director, and the layer spacing. The postulated potential energy of a single molecule is given by:

$$U_i(\theta_i, z_i) = -U_0\left(S + \alpha\sigma\cos\left(\frac{2\pi z_i}{d}\right)\right)\left(\frac{3}{2}\cos^2\theta_i - \frac{1}{2}\right)$$

Here constant α quantifies the strength of the interaction between adjacent molecules. The potential is then used to derive the thermodynamic properties of the system assuming thermal equilibrium. It results in two self-consistency equations that must be solved numerically, the solutions of which are the three stable phases of the liquid crystal.

Elastic continuum theory

In this formalism, a liquid crystal material is treated as a continuum; molecular details are entirely ignored. Rather, this theory considers perturbations to a presumed oriented sample. The distortions of the liquid crystal are commonly described by the Frank free energy density. One can identify three types of distortions that could occur in an oriented sample: (1) **twists** of the material, where neighboring molecules are forced to be angled with respect to one another, rather than aligned; (2) **splay** of the material, where bending occurs perpendicular to the director; and (3) **bend** of the material, where the distortion is parallel to the director and molecular axis. All three of these types of distortions incur an energy penalty. They are distortions that are induced by the boundary conditions at domain walls or the enclosing container. The response of the material can then be decomposed into terms based on the elastic constants corresponding to the three types of distortions. Elastic continuum theory is a particularly powerful tool for modeling liquid crystal devices.

Effect of chirality

As already described, chiral LC molecules usually give rise to chiral mesophases. This means that the molecule must possess some form of asymmetry, usually a stereogenic center. An additional requirement is that the system not be racemic: a mixture of right- and left-handed molecules will cancel the chiral effect. Due to the cooperative nature of liquid crystal ordering, however, a small amount of chiral dopant in an otherwise achiral mesophase is often enough to select out one domain handedness, making the system overall chiral.

Chiral phases usually have a helical twisting of the molecules. If the pitch of this twist is on the order of the wavelength of visible light, then interesting optical interference effects can be observed. The chiral twisting that occurs in chiral LC phases also makes the system respond differently from right- and left-handed circularly polarized light. These materials can thus be used as polarization filters.

It is possible for chiral LC molecules to produce essentially achiral mesophases. For instance, in certain ranges of concentration and molecular weight, DNA will form an achiral line hexatic phase. An interesting recent observation is of the formation of chiral mesophases from achiral LC molecules. Specifically, bent-core molecules (sometimes called banana liquid crystals) have been shown to form liquid crystal phases that are chiral. In any particular sample, various domains will have opposite handedness, but within any given domain, strong chiral ordering will be present. The appearance mechanism of this macroscopic chirality is not yet entirely clear. It appears that the molecules stack in layers and orient themselves in a tilted fashion inside the layers. These liquid crystals phases may be ferroelectric or anti-ferroelectric, both of which are of interest for applications.

Chirality can also be incorporated into a phase by adding a chiral dopant, which may not form LCs itself. Twisted-nematic or super-twisted nematic mixtures often contain a small amount of such dopants.

Applications of liquid crystals
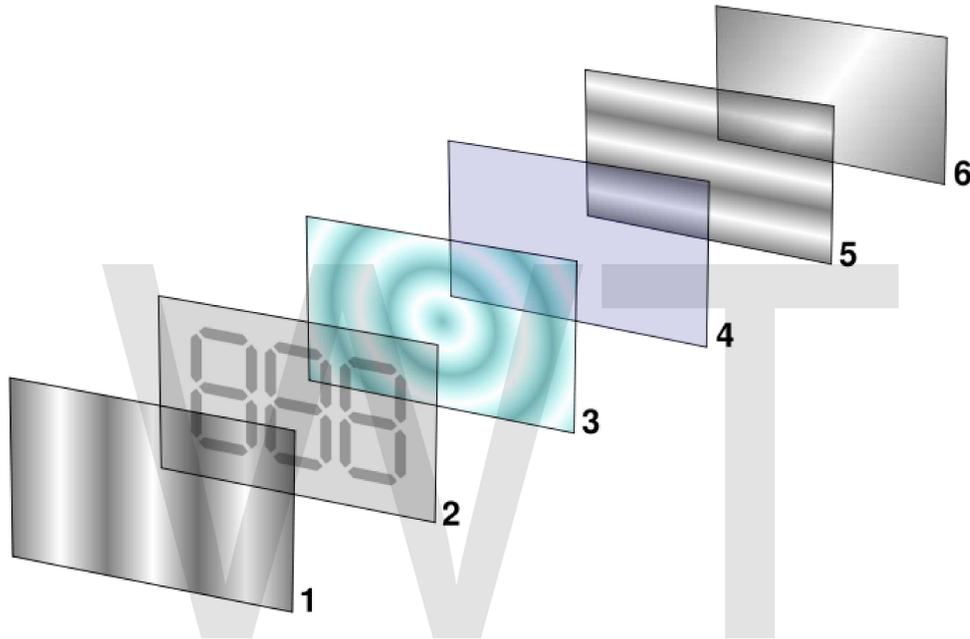
Structure of liquid crystal display: 1 – vertical polarization filter, 2,4 – glass with electrodes, 3 – liquid crystals, 5 – horizontal polarization filter, 6 – reflector

Liquid crystals find wide use in liquid crystal displays, which rely on the optical properties of certain liquid crystalline substances in the presence or absence of an electric field. In a typical device, a liquid crystal layer (typically 10 μm thick) sits between two polarizers that are crossed (oriented at 90° to one another). The liquid crystal alignment is chosen so that its relaxed phase is a twisted one. This twisted phase reorients light that has passed through the first polarizer, allowing its transmission through the second polarizer (and reflected back to the observer if a reflector is provided). The device thus appears transparent. When an electric field is applied to the LC layer, the long molecular axes tend to align parallel to the electric field thus gradually untwisting in the center of the liquid crystal layer. In this state, the LC molecules do not reorient light, so the light polarized at the first polarizer is absorbed at the second polarizer, and the device loses transparency with increasing voltage. In this way, the electric field can be used to make a pixel switch between transparent or opaque on command. Color LCD systems use the

same technique, with color filters used to generate red, green, and blue pixels. Similar principles can be used to make other liquid crystal based optical devices.

Thermotropic chiral LCs whose pitch varies strongly with temperature can be used as crude thermometers, since the color of the material will change as the pitch is changed. Liquid crystal color transitions are used on many aquarium and pool thermometers as well as on thermometers for infants or baths. Other liquid crystal materials change color when stretched or stressed. Thus, liquid crystal sheets are often used in industry to look for hot spots, map heat flow, measure stress distribution patterns, and so on. Liquid crystal in fluid form is used to detect electrically generated hot spots for failure analysis in the semiconductor industry. Liquid crystal memory units with extensive capacity were used in Space Shuttle navigation equipment.

Many common fluids, such as soap, are in fact liquid crystals. Soap forms a variety of LC phases depending on its concentration in water.

Anisotropic Conductive Film and Backlight

Anisotropic conductive film

Anisotropic Conductive Film (ACF), is a lead-free and environmentally friendly interconnect system that is commonly used in Liquid Crystal Display manufacturing to make the electrical and mechanical connections from the driver electronics to the glass substrates of the LCD. The material is also available in a paste form referred to as Anisotropic Conductive Paste (ACP), and both are grouped together as Anisotropic Conductive Adhesives (ACAs). ACAs have more recently been used to perform the flex-to-board or flex-to-flex connections used in handheld electronic devices such as mobile phones, MP3 players, or in the assembly of CMOS camera modules.

History

ACAs developed in the late 1970s and early 1980s, with heat seal connectors by Nippon Graphite Industries, and ACFs by Hitachi Chemicals and Sony Chemicals & Information Devices. Currently there are many manufacturers of heat seal connectors and ACAs, but Hitachi and Sony continue to dominate the industry in terms of market share. Other manufacturers of ACAs include 3m, Loctite, and Delo among others.

In the very early years, ACAs were made from rubber, acrylic, and other adhesive compounds, but they rapidly converged on several different variations of thermoset biphenyl type epoxy resins. The temperatures required were relatively high at 170-180C, however, and the market leaders Sony and Hitachi developed and released acrylic-based materials in the early 2000s that brought the curing temperatures down below 150C while keeping the curing times in the 10-12 second range. Further advances in the acrylic compounds used decreased the curing cycle times to below 5 seconds in many cases, which is where they remain as of this writing. Specification sheets are available at all of the manufacturers' sites listed above.

Current Market

ACF continues to be the most popular form factor for ACAs, largely due to the ability to precisely control the volume of material, density of the particles in any sample, and the distribution of those particles within the sample. This is particularly true in the traditional

ACF stronghold of display interconnects, but ACF has also seen strong growth out of the display industry and into areas long dominated by SMT technologies. The ability to make interconnections in a very small XYZ space has been the key driver in this expansion, helped by the ability under certain conditions to greatly lower cost either by the reduction of component counts or total material used.

ACPs are widely used in lower-end applications, primarily in the assembly of chips on to RFID antenna substrates. They are also used in some board or flex assembly applications, but at a much lower level than ACFs. While ACPs are generally lower cost than ACFs, they cannot provide the same level of control in adhesive quantity and particle dispersion as ACF. For this reason it is very difficult to use them for high-density applications.

Technology Overview

ACF technology is used in chip-on-glass (COG), flex-on-glass (FOG), flex-on-board (FOB), flex-on-flex (FOF), chip-on-flex (COF), chip-on-board (COB), and similar applications for higher signal densities and smaller overall packages. ACPs are typically used only in chip-on-flex (COF) applications with low densities and cost requirements, such as for RFID antennas, or in FOF and FOB assemblies in handheld electronics.

In all cases the anisotropic material is first deposited on the base substrate. This may be done using a lamination process for ACF, or either a dispense or printing process for ACP. The device or secondary substrate is then placed in position over the base substrate and the two sides are pressed together to mount the secondary substrate or device to the base substrate. In many cases this mounting process is done with no heat or a minimal amount of heat that is just sufficient to cause the anisotropic material to become slightly tacky. In some cases this mounting step is skipped and the two sides go directly to the bonding portion of the process. In high volume manufacturing, however, this would lead to inefficiencies in the manufacturing process, so direct bonding is usually done only in the lab or in small scale manufacturing.

Bonding is the third and final process required to complete an ACF assembly. In the first two processes the temperatures can range from ambient to 100°C, with the heat applied for 1 second or less. For bonding, the amount of thermal energy required is higher due to the need to first flow the adhesive and allow the two sides to come together into electrical contact, and then to cure the adhesive and create a lasting reliable bond. The temperatures, times, and pressure required for these processes can vary as shown in the following table.

Table 1: Common ACF Assembly Conditions

Assembly Type	Adhesive Type	Time(Sec)	Temp (°C)	Pressure
Flex-on-Glass (FOG)	Epoxy	10-12	170-200	2-4MPa▲
Chip-on-Glass(COG)	Epoxy	5-7	190-220	50-150MPa※

Chip-on-Flex (COF)	Epoxy	5-10	190-220	30-150MPa※
Flex-on-Board (FOB)	Epoxy	10-12	170-190	1-4MPa▲
Flex-on-Board (FOB)	Acryl	5-10	130-170	1-4MPa▲
Flex-on-Flex (FOF)	Epoxy	10-12	170-190	1-4MPa▲
Flex-on-Flex (FOF)	Acryl	5-10	130-170	1-4MPa▲

▲ Pressures for flex assemblies (FOG, FOB, FOF) are measured across the entire area under the bondhead.

※Pressures for chip assemblies (COG, COF) are calculated on the cumulative surface area of the bumps on the chip.

Backlight

Both unlit and with electroluminescent backlight switched on

A **backlight** is a form of illumination used in liquid crystal displays (LCDs). As LCDs do not produce light themselves (unlike for example Cathode ray tube (CRT) displays), they need illumination (ambient light or a special light source) to produce a visible image. Backlights illuminate the LCD from the side or back of the display panel, unlike frontlights, which are placed in front of the LCD. Backlights are used in small displays to increase readability in low light conditions, and in computer displays and LCD televisions to produce light in a manner similar to a CRT display.

Simple types of LCD displays are built without an internal light source, requiring external light sources to convey the display image to the user. Modern LCD screens, however, are built with an internal light source. Such LCD screens consist of several layers. The backlight is usually the first layer from the back. But in order to create screen images, a mechanism is needed to regulate the light intensity of the screen's pixels. For this, light

valves are used that vary the amount of light reaching the target by blocking its passage in some way. The most common element is a polarizing filter to polarize the light from the source in one of two transverse directions and then passing it through a switching polarizing filter, to block the path of undesirable light.

LCD Back Light

Light source types

The light source can be made up of:

- Incandescent light bulbs
- light-emitting diodes (LEDs)
- An electroluminescent panel (ELP)
- One or more Cold Cathode Fluorescent Lamps (CCFL)
- One or more Hot Cathode Fluorescent Lamps (HCFL)

An ELP gives off uniform light over its entire surface, but other backlights usually employ a diffuser to provide even lighting from an uneven source.

Backlights can be any color. Monochrome LCDs usually have yellow, green, blue or white backlights, while color displays use white backlights that cover most of the color spectrum.

Usage
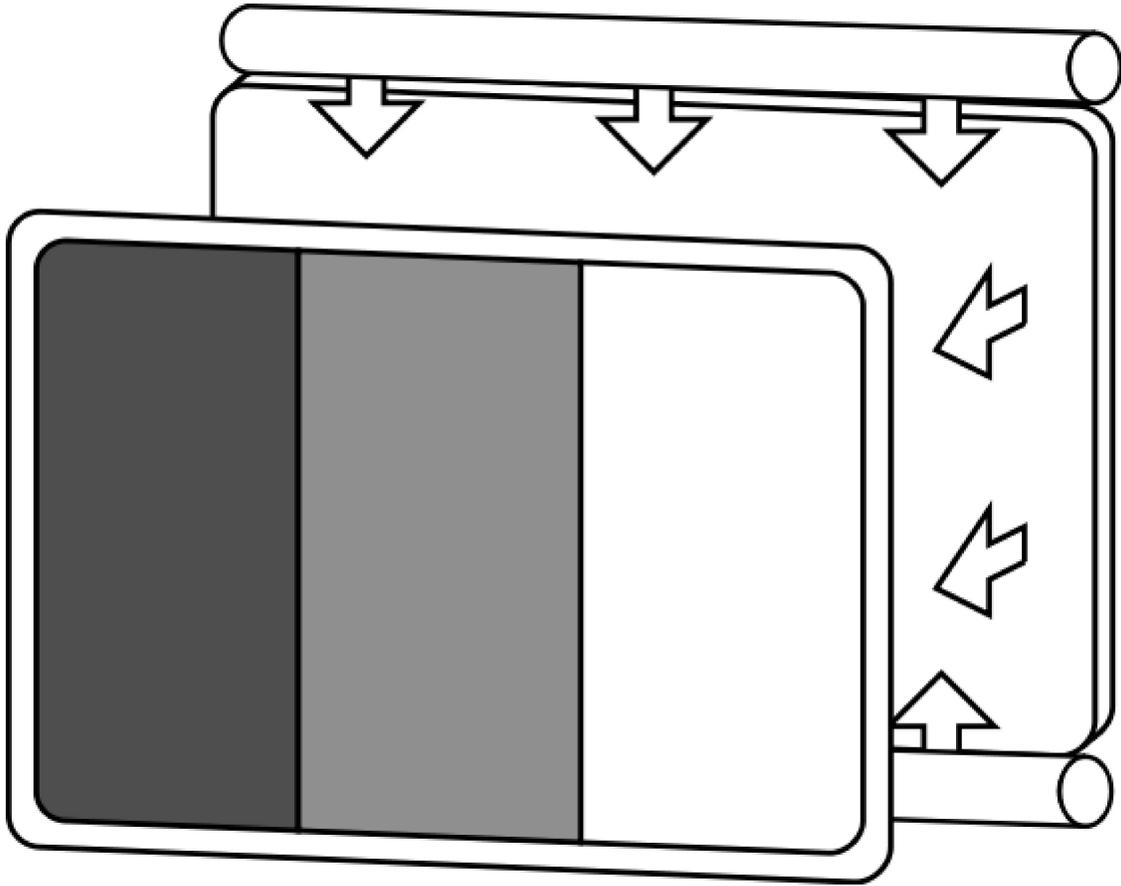
LCD with CCFL backlight

Colored LED backlighting is most commonly used in small, inexpensive LCD panels. White LED backlighting is becoming more common. ELP backlighting is often used for larger displays or when even backlighting is important; it can also be either colored or white. An ELP must be driven by relatively high voltage AC power, which is provided by an inverter circuit. CCFL backlights are used on large displays like computer monitors, and are usually white in color. These also require the use of an inverter and diffuser. Incandescent backlighting can be used when very high brightness is desired, but a drawback is the limited life of incandescent bulbs, and the amount of heat generated, which often means that the bulb needs to be mounted away from the display.

LED backlights
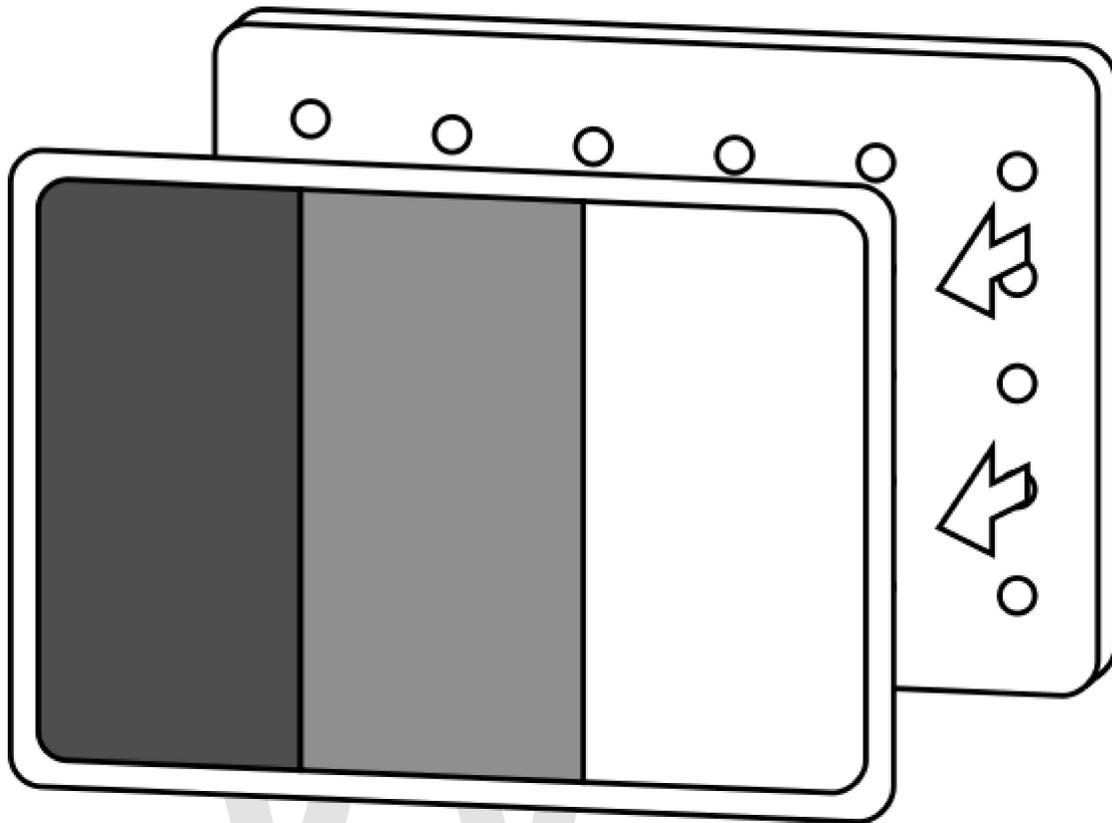
LCD with LED matrix backlight

LED backlighting in color screens comes in two flavors: white LED backlights and RGB LED backlights. White LEDs are used most often in notebooks and desktop screens, and in virtually all mobile LCD screens. A white LED is actually a blue LED with yellow phosphor to give the impression of white light. The spectral curve has big gaps in the green and red parts. RGB LEDs consist of a red, a blue, and a green LED and can be controlled to produce different temperatures of white. RGB LEDs for backlighting are found in high end color proofing displays such as HP DreamColor LP2480zx monitor or selected HP EliteBook notebooks, as well as newer consumer grade displays such as Dell's Studio series laptops which have an optional RGB LED display.

RGB LEDs can deliver an enormous color gamut to screens. When using three separate LEDs (additive color) the backlight can produce a color spectrum that closely matches the color filters in the LCD pixels themselves. In this way, the filter passband can be narrowed so that each color component lets only a very narrow band of spectrum through the LCD. This improves the efficiency of the display since little light is blocked when white is displayed. Also, the actual red, green, and blue points can be moved farther out so that the display is capable of reproducing more vivid colors. CCFL backlighting has also improved in this respect. Many current LCD models, from cheap TN-displays to

color proofing S-IPS or S-PVA panels, have wide gamut CCFLs representing more than 95% of the NTSC color specification.

There are several challenges with LED backlights. Good uniformity is harder to achieve, especially as the LEDs age, with each LED possibly aging at a different rate. Also, the use of three separate light sources for red, green, and blue means that the white point of the display can move as the LEDs age at different rates. Aging also occurs with White LEDs, with changes of several 100K being recorded. White LEDs also suffer from blue shifts at higher temperatures varying from 3141K to 3222K for 10°C to 80°C respectively. Power efficiency also can be a challenge. First generation implementations could use the same or more power as their CCFL counterparts, though it is possible for an LED display to be more power efficient. In 2010, current generation LED displays can have significant power consumption advantages. For example, the non-LED version of the 24" Benq G2420HBD consumer display has a 49W consumption compared to the 24W of the LED version of the same display (G2420HBDL).

The use of LED backlights in notebook computers has been growing. Sony has used LED backlights in some of its higher-end slim VAIO notebooks since 2005. Fujitsu introduced notebooks with LED backlights in 2006. In 2007, Asus, Dell, and Apple introduced LED backlights into some of their notebook models. As of 2008, Lenovo has also announced LED-backlit notebooks, and other companies like HP will also be marketing LED-backlit notebooks in the near future. In October 2008, Apple announced it will be using LED backlights for all its notebook and its new 24-inch Apple Cinema Display, and one year later it introduced a new LED iMac, meaning all of Apple's computer screens, except the 30-inch Cinema HD Display, are now LED. Almost every laptop with 16:9 display introduced since September 2009 uses LED-backlit panels.

Flicker due to backlight dimming

LED backlights are often dimmed by applying pulse-width modulation to the supply current, switching the backlight off and on again like a fast strobe light. If the frequency of the pulse-width modulation is too low and or the user is very sensitive to flicker, this may cause discomfort and eye-strain, similar to the flicker of CRT displays. This can be tested by a user simply by waving a hand or object in front of the screen. If the object appears to have sharply-defined edges as it moves, the backlight is strobing on and off at a fairly low frequency. If the object appears blurry, the display either has a continuously-illuminated backlight or it is operating at a frequency that is too high for the brain to perceive. The flicker can be reduced or eliminated by setting the display to full brightness, though this has a negative impact on image quality and battery life due to increased power consumption.

Backlight diffusers

In order for a non-ELP backlight to produce even lighting (which is critical for LCDs), the light is first passed through a lightguide - a specially-designed layer of plastic that diffuses the light through a series of evenly-spaced bumps. The density of bumps

increases further away from the light source according to a diffusion equation. The diffused light then travels to either side of the diffuser; the front faces the actual LCD panel, the back has a reflector to guide otherwise wasted light back towards the LCD panel. The reflector is sometimes made of aluminum foil, sometimes merely a white-pigmented surface or, as in the 3M Vikuiti ESR, consisting of hundreds of polymer layers of alternating low and high index. Between the lightguide and the LCD panel is usually placed a reflective polarizer film which vastly increases efficiency by repeatedly reflecting any unpolarized light back, which would otherwise be absorbed by the LCD's rear polarizer.

Chapter- 7

LCD Television

A generic LCD TV, with speakers on either side of the screen.

Liquid-crystal display televisions (**LCD TV**) are television sets that use LCD technology to produce images. LCD televisions are thinner and lighter than CRTs of similar display size, and are available in much larger sizes. When manufacturing costs fell, this combination of features made LCDs practical for television receivers.

In 2007, LCD televisions surpassed sales of CRT-based televisions worldwide for the first time, and their sales figures relative to other technologies are accelerating. LCD TVs are quickly displacing the only major competitors in the large-screen market, the plasma display panel and rear-projection television. LCDs are, by far, the most widely produced and sold television display type.

LCDs also have a variety of disadvantages. Other technologies address these weaknesses, including organic light-emitting diodes (OLED), FED and SED, but as of 2010 none of these have entered widespread production.

Description

Basic LCD concepts

LCD television at home together with PlayStation 3 and some other equipment

LCD televisions produced a black and colored image by selectively filtering a white light. The light is typically provided by a series of cold cathode fluorescent lamps (CCFLs) at the back of the screen, although some displays use white or colored LEDs instead. Millions of individual LCD shutters, arranged in a grid, open and close to allow a metered amount of the white light through. Each shutter is paired with a colored filter to remove all but the red, green or blue (RGB) portion of the light from the original white source. Each shutter–filter pair forms a single *sub-pixel*. The sub-pixels are so small that when the display is viewed from even a short distance, the individual colors blend together to produce a single spot of color, a *pixel*. The shade of color is controlled by changing the relative intensity of the light passing through the sub-pixels.

Liquid crystals encompass a wide range of (typically) rod-shaped polymers that naturally form into thin layers, as opposed to the more random alignment of a normal liquid. Some of these, the *nematic liquid crystals*, also show an alignment effect between the layers. The particular direction of the alignment of a nematic liquid crystal can be set by placing

it in contact with an *alignment layer* or *director*, which is essentially a material with microscopic grooves in it. When placed on a director, the layer in contact will align itself with the grooves, and the layers above will subsequently align themselves with the layers below, the bulk material taking on the director's alignment. In the case of an LCD, this effect is utilized by using two directors arranged at right angles and placed close together with the liquid crystal between them. This forces the layers to align themselves in two directions, creating a twisted structure with each layer aligned at a slightly different angle to the ones on either side.

LCD shutters consist of a stack of three primary elements. On the bottom and top of the shutter are polarizer plates set at right angles. Normally light cannot travel through a pair of polarizers arranged in this fashion, and the display would be black. The polarizers also carry the directors to create the twisted structure aligned with the polarizers on either side. As the light flows out of the rear polarizer, it will naturally follow the liquid crystal's twist, exiting the front of the liquid crystal having been rotated through the correct angle, that allows it to pass through the front polarizer. LCDs are normally transparent.

To turn a shutter off, a voltage is applied across it from front to back. the rod-shaped molecules align themselves with the electric field instead of the directors, destroying the twisted structure. The light no longer changes polarization as it flows through the liquid crystal, and can no longer pass through the front polarizer. By controlling the voltage applied across the crystal, the amount of remaining twist can be selected. This allows the transparency of the shutter to be controlled. To improve switching time, the cells are placed under pressure, which increases the force to re-align themselves with the directors when the field is turned off.

Several other variations and modifications have been used in order to improve performance in certain applications. In-Plane Switching displays (IPS and S-IPS) offer wider viewing angles and better color reproduction, but are more difficult to construct and have slightly slower response times. IPS displays are used primarily for computer monitors. Vertical Alignment (VA, S-PVA and MVA) offer higher contrast ratios and good response times, but suffer from color shifting when viewed from the side. In general, all of these displays work in a similar fashion by controlling the polarization of the light source.

Addressing sub-pixels
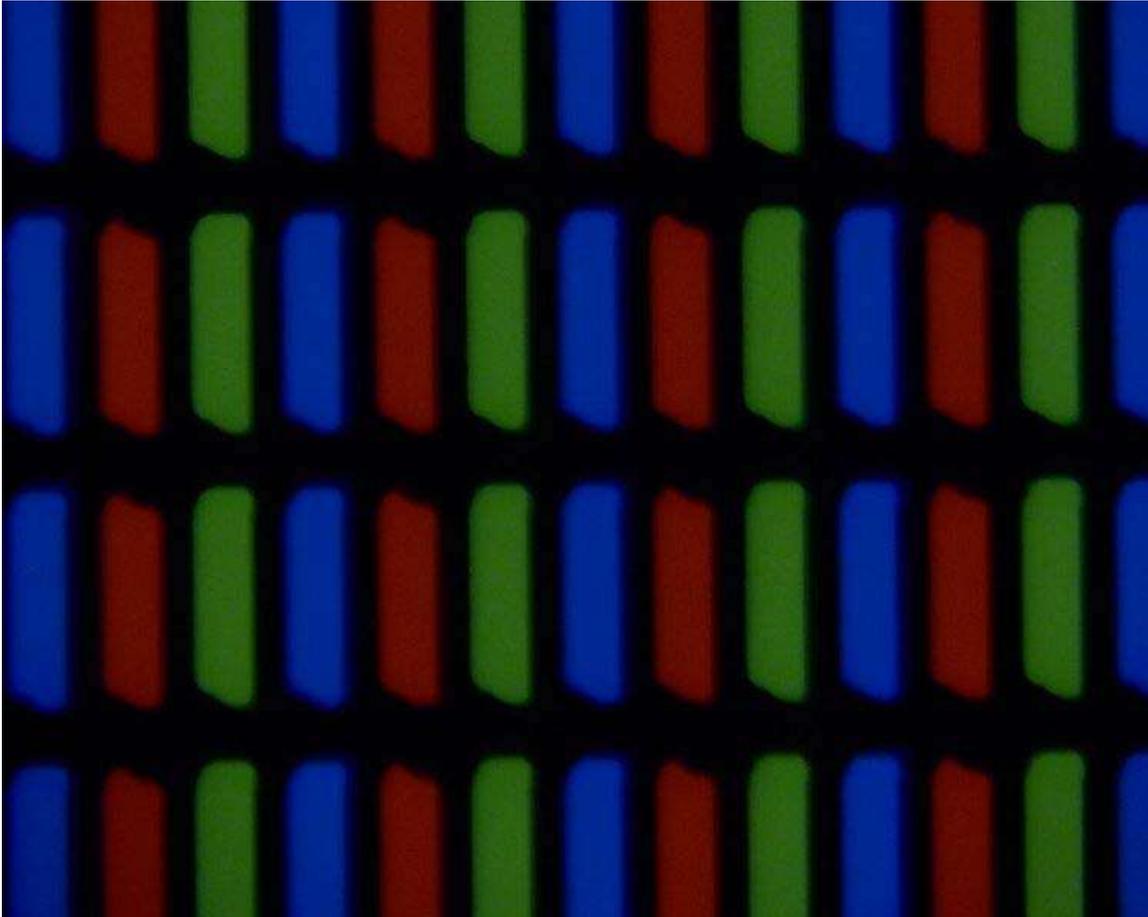
A close-up (300×) view of a typical LCD display, clearly showing the sub-pixel structure. The "notch" at the lower left of each sub-pixel is the thin-film transistor. The associated capacitors and addressing lines are located around the shutter, in the dark areas.

In order to address a single shutter on the display, a series of electrodes is deposited on the plates on either side of the liquid crystal. One side has horizontal stripes that form rows, the other has vertical stripes that form columns. By supplying voltage to one row and one column, a field will be generated at the point where they cross. Since a metal electrode would be opaque, LCDs use electrodes made of a transparent conductor, typically indium tin oxide.

Since addressing a single shutter requires power to be supplied to an entire row and column, some of the field always leaks out into the surrounding shutters. Liquid crystals are quite sensitive, and even small amounts of leaked field will cause some level of switching to occur. This partial switching of the surrounding shutters blurs the resulting image. Another problem in early LCD systems was the voltages needed to set the shutters to a particular twist was very low, but that voltage was too low to make the crystals re-align with reasonable performance. This resulted in slow response times and led to easily

visible "ghosting" on these displays on fast-moving images, like a mouse cursor on a computer screen. Even scrolling text often rendered as an unreadable blur, and the switching speed was far too slow to use as a useful television display.

In order to attack these problems, modern LCDs use an active matrix design. Instead of powering both electrodes, one set, typically the front, is attached to a common ground. On the rear, each shutter is paired with a thin-film transistor that switches on in response to widely separated voltage levels, say 0 and +5 volts. A new addressing line, the *gate line*, is added as a separate switch for the transistors. The rows and columns are addressed as before, but the transistors ensure that only the single shutter at the crossing point is addressed; any leaked field is too small to switch the surrounding transistors. When switched on, a constant and relatively high amount of charge flows from the *source line* through the transistor and into an associated capacitor. The capacitor is charged up until it holds the correct control voltage, slowly leaking this through the crystal to the common ground. The current is very fast and not suitable for fine control of the resulting store charge, so pulse code modulation is used to accurately control the overall flow. Not only does this allow for very accurate control over the shutters, since the capacitor can be filled or drained quickly, but the response time of the shutter is dramatically improved as well.

Building a display

A typical shutter assembly consists of a sandwich of several layers deposited on two thin glass sheets forming the front and back of the display. For smaller display sizes (under 30 inches), the glass sheets can be replaced with plastic.

The rear sheet starts with a polarizing film, the glass sheet, the active matrix components and addressing electrodes, and then the director. The front sheet is similar, but lacks the active matrix components, replacing those with the patterned color filters. Using a multi-step construction process, both sheets can be produced on the same assembly line. The liquid crystal is placed between the two sheets in a patterned plastic sheet that divides the liquid into individual shutters and keeps the sheets at a precise distance from each other.

The critical step in the manufacturing process is the deposition of the active matrix components. These have a relatively high failure rate, which renders those pixels on the screen "always on". If there are enough broken pixels, the screen has to be discarded. The number of discarded panels has a strong effect on the price of the resulting television sets, and the major downward fall in pricing between 2006 and 2008 was due mostly to improved processes.

To produce a complete television, the shutter assembly is combined with control electronics and backlight. The backlight for small sets can be provided by a single lamp using a diffuser or frosted mirror to spread out the light, but for larger displays a single lamp is not bright enough and the rear surface is instead covered with a number of separate lamps. Achieving even lighting over the front of an entire display remains a challenge, and bright and dark spots are not uncommon.

Comparison

A 19" Sony LCD TV

Packaging

In a CRT the electron beam is produced by heating a metal filament, which "boils" electrons off its surface. The electrons are then accelerated and focused in an electron gun, and aimed at the proper location on the screen using electromagnets. The majority of the power budget of a CRT goes into heating the filament, which is why the back of a CRT-based television is hot. Since the electrons are easily deflected by gas molecules, the entire tube has to be held in vacuum. The atmospheric force on the front face of the tube grows with the area, which requires ever-thicker glass. This limits practical CRTs to sizes around 30 inches; displays up to 40 inches were produced but weighed several hundred pounds, and televisions larger than this had to turn to other technologies like rear-projection.

The lack of vacuum in an LCD television is one of its advantages; there is a small amount of vacuum in sets using CCFL backlights, but this is arranged in cylinders which are naturally stronger than large flat plates. Removing the need for heavy glass faces allows

LCDs to be much lighter than other technologies. For instance, the Sharp LC-42D65, a fairly typical 42-inch LCD television, weighs 55 lbs including a stand, while the late-model Sony KV-40XBR800, a 40" 4:3 CRT weighs a massive 304 lbs without a stand, almost six times the weight.

LCD panels, like other flat panel displays, are also much thinner than CRTs. Since the CRT can only bend the electron beam through a critical angle while still maintaining focus, the electron gun has to be located some distance from the front face of the television. In early sets from the 1950s the angle was often as small as 35 degrees off-axis, but improvements, especially computer assisted convergence, allowed that to be dramatically improved and, late in their evolution, folded. Nevertheless, even the best CRTs are much deeper than an LCD; the KV-40XBR800 is 26 inches deep, while the LC-42D65U is less than 4 inches thick – its stand is much deeper than the screen in order to provide stability.

LCDs can, in theory, be built at any size, with production yields being the primary constraint. As yields increased, common LCD screen sizes grew, from 14 to 30", to 42", then 52", and 65" sets are now widely available. This allowed LCDs to compete directly with most in-home projection television sets, and in comparison to those technologies direct-view LCDs have a better image quality. Experimental and limited run sets are available with sizes over 100 inches.

Efficiency

LCDs are relatively inefficient in terms of power use per display size, because the vast majority of light that is being produced at the back of the screen is blocked before it reaches the viewer. To start with, the rear polarizer filters out over half of the original un-polarized light. Examining the image above, you can see that a good portion of the screen area is covered by the cell structure around the shutters, which removes another portion. After that, each sub-pixel's color filter removes the majority of what is left to leave only the desired color. Finally, to control the color and luminance of a pixel as a whole, the light has to be further absorbed in the shutters. 3M suggests that, on average, only 8 to 10% of the light being generated at the back of the set reaches the viewer.

For these reasons the backlighting system has to be *extremely* powerful. In spite of using highly efficient CCFLs, most sets use several hundred watts of power, more than would be required to light an entire house with the same technology. As a result, LCD televisions end up with overall power usage similar to a CRT of the same size. Using the same examples, the KV-40XBR800 dissipates 245 W, while the LC-42D65 dissipates 235 W. Plasma displays are worse; the best are on par with LCDs, but typical sets draw much more.

Modern LCD sets have attempted to address the power use through a process known as "dynamic lighting". This system examines the image to find areas that are darker, and reduces the backlighting in those areas. CCFLs are long cylinders that run the length of the screen, so this change can only be used to control the brightness of the screen as a

whole, or at least wide horizontal bands of it. This makes the technique suitable only for particular types of images, like the credits at the end of a movie. In 2009 some manufacturers made some TVs using HCFL (more power efficient than CCFL). Sets using LEDs are more distributed, with each LED lighting only a small number of pixels, typically a 16 by 16 patch. This allows them to dynamically adjust brightness of much smaller areas, which is suitable for a much wider set of images.

Another ongoing area of research is to use materials that optically route light in order to re-use as much of the signal as possible. One potential improvement is to use microprisms or dichromic mirrors to *split* the light into R, G and B, instead of absorbing the unwanted colors in a filter. A successful system would improve efficiency by three times. Another would be to direct the light that would normally fall on opaque elements back into the transparent portion of the shutters. A number of companies are actively researching a variety of approaches, and 3M currently sells several products that route leaked light back toward the front of the screen.

Several newer technologies, OLED, FED and SED, have lower power use as one of their primary advantages. All of these technologies directly produce light on a sub-pixel basis, and use only as much power as that light level requires. Sony has demonstrated 36" FED units displaying very bright images drawing only 14 W, less than 1/10 as much as a similarly sized LCD. OLEDs and SEDs are similar to FEDs in power terms. The dramatically lower power requirements make these technologies particularly interesting in low-power uses like laptop computers and mobile phones. These sorts of devices were the market that originally bootstrapped LCD technology, due to its light weight and thinness.

Image quality

A traveler pocket-size LCD TV

Early LCD sets were widely derided for their poor overall image quality, most notably the ghosting on fast-moving images, poor contrast ratio, and muddy colors. In spite of many predictions that other technologies would always beat LCDs, massive investment in LCD production, manufacturing, and electronic image processing has addressed many of these concerns.

Response time

For 60 frames per second video, common in North America, each pixel is lit for 17 ms before it has to be re-drawn (20 ms in Europe). Early LCD displays had response times on the order of hundreds of milliseconds, which made them useless for television. A combination of improvements in materials technology since the 1970s greatly improved this, as did the active matrix techniques. By 2000, LCD panels with response times around 20 ms were relatively common in computer roles. This was still not fast enough for television use.

A major improvement, pioneered by NEC, led to the first practical LCD televisions. NEC noticed that liquid crystals take some time to start moving into their new orientation, but stop rapidly. If the initial movement could be accelerated, the overall performance would be increased. NEC's solution was to boost the voltage during the "spin up period" when the capacitor is initially being charged, and then dropping back to normal levels to fill it to the required voltage. A common method is to double the voltage, but halve the pulse width, delivering the same total amount of power. Named "Overdrive" by NEC, the technique is now widely used on almost all LCDs.

Another major improvement in response time was achieved by adding memory to hold the contents of the display – something that a television needs to do anyway, but was not originally required in the computer monitor role that bootstrapped the LCD industry. In older displays the active matrix capacitors were first drained, and then recharged to the new value with every refresh. But in most cases, the vast majority of the screen's image does not change from frame to frame. By holding the before and after values in computer memory, comparing them, and only resetting those sub-pixels that actually changed, the amount of time spent charging and discharging the capacitors was reduced. Moreover the capacitors are not drained completely; instead, their existing charge level is either increased or decreased to match the new value, which typically requires fewer charging pulses. This change, which was isolated to the driver electronics and inexpensive to implement, improved response times by about two times.

Together, along with continued improvements in the liquid crystals themselves, and by increasing refresh rates from 60 Hz to 120 and 240 Hz, response times fell from 20 ms in 2000 to about 2 ms in the best modern displays. But even this is not really fast enough because the pixel will still be switching while the frame is being displayed. Conventional CRTs are well under 1 ms, and plasma and OLED displays boast times on the order of 0.001 ms.

One way to further improve the *effective* refresh rate is to use "super-sampling", and it is becoming increasingly common on high-end sets. Since the blurring of the motion occurs during the transition from one state to another, this can be reduced by doubling the refresh rate of the LCD panel, and building intermediate frames using various motion compensation techniques. This smooths out the transitions, and means the backlighting is turned on only when the transitions are settled. A number of high-end sets offer 120 Hz (in North America) or 100 Hz (in Europe) refresh rates using this technique. Another solution is to only turn the backlighting on once the shutter has fully switched. In order to ensure that the display does not flicker, these systems fire the backlighting several times per refresh, in a fashion similar to movie projection where the shutter opens and closes several times per frame.

Contrast ratio

Even in a fully switched-off state, liquid crystals allow some light to leak through the shutters. This limits their contrast ratios to about 1600:1 on the best modern sets, when measured using the ANSI measurement (ANSI IT7.215-1992). Manufacturers often

quote the "Full On/Off" contrast ratio instead, which is about 25% greater for any given set.

This lack of contrast is most noticeable in darker scenes; in order to display a color close to black, the LCD shutters have to be turned to almost full opacity, limiting the number of discrete colors they can display. This leads to "posterizing" effects and bands of discrete colors that become visible in shadows. which is why many reviews of LCD TV's mention the "shadow detail". For contrast, the highest-end LCD TVs offer regular contrast ratios of 2,000,000:1.

Since the total amount of light reaching the viewer is a combination of the backlighting and shuttering, modern sets can use "dynamic backlighting" to improve the contrast ratio and shadow detail. If a particular area of the screen is dark, a conventional set will have to set its shutters close to opaque to cut down the light. However, if the backlighting is reduced by half in that area, the shuttering can be reduced by half, and the number of available shuttering levels in the sub-pixels doubles. This is the main reason high-end sets offer dynamic lighting (as opposed to power savings, mentioned earlier), allowing the contrast ratio across the screen to be dramatically improved. While the LCD shutters are capable of producing about 1000:1 contrast ratio, by adding 30 levels of dynamic backlighting this is improved to 30,000:1.

However, the area of the screen that can be dynamically adjusted is a function of the backlighting source. CCFLs are thin tubes that light up many rows (or columns) across the entire screen at once, and that light is spread out with diffusers. The CCFL must be driven with enough power to light the brightest area of the portion of the image in front of it, so if the image is light on one side and dark on the other, this technique cannot be used successfully. Displays backlit by full arrays of LEDs have an advantage, because each LED lights only a small patch of the screen. This allows the dynamic backlighting to be used on a much wider variety of images. Edge-lit displays do not enjoy this advantage. These displays have LEDs only along the edges and use a light guide plate covered with thousands of convex bumps that reflect light from the side-firing LEDs out through the LCD matrix and filters. LEDs on edge-lit displays can be dimmed only globally, not individually.

The massive on-paper boost this method provides is the reason many sets now place the "dynamic contrast ratio" in their specifications sheets. There is widespread debate in the audio-visual world as to whether or not dynamic contrast ratios are real, or simply marketing speak. Reviewers commonly note that even the best LCD displays cannot match the contrast ratios or deep blacks of plasma displays, in spite of being rated, on paper, as having much higher ratios.

Color gamut

Color on an LCD television is produced by filtering down a white source and then selectively shuttering the three primary colors relative to each other. The accuracy and quality of the resulting colors are thus dependent on the backlighting source and its

ability to evenly produce white light. The CCFLs used in early LCD televisions were not particularly white, and tended to be strongest in greens. Modern backlighting has improved this, and sets commonly quote a color space covering about 75% of the NTSC 1953 color gamut. Using white LEDs as the backlight improves this further.

In September 2009 Nanoco Group announced that it had signed a joint development agreement with a major Japanese electronics company under which it will design and develop quantum dots for use in LED backlights in LCD televisions. Quantum dots are valued for displays, because they emit light in very specific Gaussian distributions. This can result in a display that more accurately renders the colors that the human eye can perceive. Quantum dots also require very little power since they are not color filtered.

History

An LCD TV hanging on a wall in the Taipei World Trade Center during the Computex Taipei show in 2008.

Early efforts

Passive matrix LCDs first became common in the 1980s for various portable computer roles. At the time they competed with plasma displays in the same market space. The LCDs had very slow refresh rates that blurred the screen even with scrolling text, but their light weight and low cost were major benefits. Screens using reflective LCDs required no internal light source, making them particularly well suited to laptop computers.

Refresh rates were far too slow to be useful for television, but at the time there was no pressing need for new television technologies. Resolutions were limited to standard definition, although a number of technologies were pushing displays towards the limits of that standard; Super VHS offered improved color saturation, and DVDs added higher resolutions as well. Even with these advances, screen sizes over 30" were rare as these formats would start to appear blocky at normal seating distances when viewed on larger screens. Projection systems were generally limited to situations where the image had to be viewed by a larger audience.

Nevertheless, some experimentation with LCD televisions took place during this period. In 1988, Sharp Corporation introduced the first commercial LCD television, a 14" model. These were offered primarily as boutique items for discerning customers, and were not aimed at the general market. At the same time, plasma displays could easily offer the performance needed to make a high quality display, but suffered from low brightness and very high power consumption. However, a series of advances led to plasma displays outpacing LCDs in performance improvements, starting with Fujitsu's improved construction techniques in 1979, Hitachi's improved phosphors in 1984, and AT&Ts elimination of the black areas between the sub-pixels in the mid-1980s. By the late 1980s, plasma displays were far in advance of LCDs.

High-definition

It was the slow standardization of high definition television that first produced a market for new television technologies. In particular, the wider 16:9 aspect ratio of the new material was difficult to build using CRTs; ideally a CRT should be perfectly circular in order to best contain its internal vacuum, and as the aspect ratio becomes more rectangular it becomes more difficult to make the tubes. At the same time, the much higher resolutions these new formats offered were lost at smaller screen sizes, so CRTs faced the twin problems of becoming larger and more rectangular at the same time. LCDs of the era were still not able to cope with fast-moving images, especially at higher resolutions, and from the mid-1990s the plasma display was the only real offering in the high resolution space.

Through the halting introduction of HDTV in the mid-1990s into the early 2000s, plasma displays were the primary high-definition display technology. However, their high cost, both manufacturing and on the street, meant that older technologies like CRTs maintained a footprint in spite of their disadvantages. LCD, however, was widely considered to be unable to scale into the same space, and it was widely believed that the move to high-definition would push it from the market entirely.

This situation changed rapidly. Contrary to early optimism, plasma displays never saw the massive economies of scale that were expected, and remained expensive. Meanwhile, LCD technologies like Overdrive started to address their ability to work at television speeds. Initially produced at smaller sizes, fitting into the low-end space that plasmas could not fill, LCDs started to experience the economies of scale that plasmas failed to

achieve. By 2004, 32" models were widely available, 42" sets were becoming common, and much larger prototypes were being demonstrated.

Market takeover

LCD TV for public viewing in a Hong Kong bus

Although plasmas continued to hold an arguable picture quality edge over LCDs, and even a price advantage for sets at the critical 42" size and larger, LCD prices started falling rapidly in 2006 while their screen sizes were increasing at a similarly rapid rate. By late 2006, several vendors were offering 42" LCDs, albeit at a price premium, encroaching on plasma's only stronghold. More critically, LCDs offer higher resolutions and true 1080p support, while plasmas were stuck at 720p, which made up for the price difference.

Predictions that prices for LCDs would drop rapidly through 2007 led to a "wait and see" attitude in the market, and sales of all large-screen televisions stagnated while customers watched to see if this would happen. Plasmas and LCDs reached price parity in 2007, at which point the LCD's higher resolution was a winning point for many sales. By late 2007, it was clear that LCDs were going to outsell plasmas during the critical Christmas sales season. This was in spite of the fact that plasmas continued to hold an image quality advantage, but as the president of Chunghwa Picture Tubes noted after shutting down

their plasma production line, "Globally, so many companies, so many investments, so many people have been working in this area, on this product. So they can improve so quickly."

When the sales figures for the 2007 Christmas season were finally tallied, pundits were surprised to find that LCDs had not only outsold plasma, but also outsold CRTs during the same period. This evolution drove competing large-screen systems from the market almost overnight. Plasma had overtaken rear-projection systems in 2005. The same was true for CRTs, which lasted only a few months longer; Sony ended sales of their famous Trinitron in most markets in 2007, and shut down the final plant in March 2008. The February 2009 announcement that Pioneer Electronics was ending production of the plasma screens was widely considered the tipping point in that technology's history as well.

LCD's dominance in the television market accelerated rapidly. It was the only technology that could scale both up and down in size, covering both the high-end market for large screens in the 40 to 50" class, as well as customers looking to replace their existing smaller CRT sets in the 14 to 30" range. Building across these wide scales quickly pushed the prices down across the board.

Current sixth-generation panels by major manufacturers such as Sony, Sharp Corporation, LG Display, Panasonic and the Samsung have announced larger sized models:

- In October 2004, Sharp announced the successful manufacture of a 65" panel.
- In March 2005, Samsung announced an 82" LCD panel.
- In August 2006, LG Display Consumer Electronics announced a 100" LCD television
- In January 2007, Sharp displayed a 108" LCD panel under the AQUOS brand name at CES in Las Vegas.

Recent research

Some manufacturers are also experimenting with extending color reproduction of LCD televisions. Although current LCD panels are able to deliver all sRGB colors using an appropriate combination of backlight's spectrum and optical filters, manufacturers want to display even more colors. One of the approaches is to use a fourth, or even fifth and sixth color in the optical color filter array. Another approach is to use two sets of suitably narrowband backlights (e.g. LEDs), with slightly differing colors, in combination with broadband optical filters in the panel, and alternating backlights each consecutive frame. Fully using the extended color gamut will naturally require an appropriately captured material and some modifications to the distribution channel. Otherwise, the only use of the extra colors would be to let the looker boost the color saturation of the TV picture beyond what was intended by the producer, but avoiding the otherwise unavoidable loss of detail ("burnout") in saturated areas.

Competing systems

In spite of LCD's current dominance of the television field, there are several other technologies being developed that address its shortcomings. Whereas LCDs produce an image by selectively blocking a backlight OLED, FED and SED all produce light directly on the front face of the display. In comparison to LCDs, all of these technologies offer better viewing angles, much higher brightness and contrast ratio (as much as 5,000,000:1), and better color saturation and accuracy, and use less than 1/10 as much power. In theory, they are less complex and less expensive to build.

Actually manufacturing these screens has proved more difficult than originally imagined. Sony abandoned their FED project in March 2009, but continue work on their OLED sets. Canon continues development of their SED technology, but announced that they will not attempt to introduce sets to market for the foreseeable future.

Samsung has been displaying OLED sets at 14.1, 31 and 40 inch sizes for some time, and at the SID 2009 trade show in San Antonio they announced that the 14.1 and 31 inch sets are "production ready".

Environmental effects

The production of LCD screens uses nitrogen trifluoride (NF_3) as an etching fluid during the production of the thin-film components. NF_3 is a potent greenhouse gas, and its extensive half-life may make it a potentially harmful contributor to global warming. A report in *Geophysical Research Letters* suggested that its effects were theoretically much greater than better-known sources of greenhouse gasses like carbon dioxide. As NF_3 was not in widespread use at the time, it was not made part of the Kyoto Protocols and has been deemed "the missing greenhouse gas".

Critics of the report point out that it assumes that all of the NF_3 produced would be released to the atmosphere. In reality, the vast majority of NF_3 is broken down during the cleaning processes; two earlier studies found that only 2% to 3% of the gas escapes destruction after its use. Furthermore, the report failed to compare NF_3's effects with what it replaced, perfluorocarbon, another powerful greenhouse gas, of which anywhere from 30% to 70% escapes to the atmosphere in typical use.

Chapter- 8

Computer Monitor

A 19-inch LG flat-panel LCD monitor

A **monitor** or **display** (sometimes called a **visual display unit**) is an electronic visual display for computers. The monitor comprises the display device, circuitry, and an enclosure. The display device in modern monitors is typically a thin film transistor liquid crystal display (TFT-LCD) thin panel, while older monitors use a cathode ray tube about as deep as the screen size.Originally computer monitors were used for data processing

and television receivers for entertainment; increasingly computers are being used both for data processing and entertainment. Displays exclusively for data use tend to have an aspect ratio of 4:3; those used also (or solely) for entertainment are usually 16:9 widescreen, Sometimes a compromise is used, e.g. 16:10.

Screen size
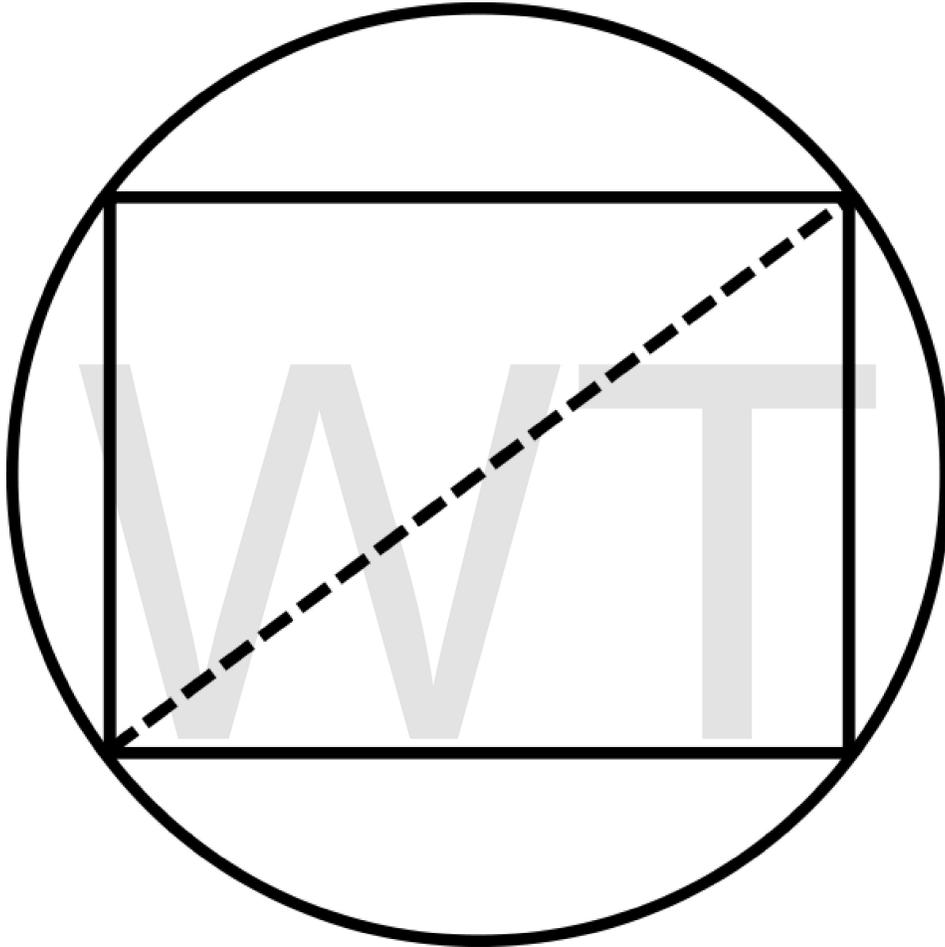
For any rectangular section on a round tube, the diagonal measurement is also the diameter of the tube
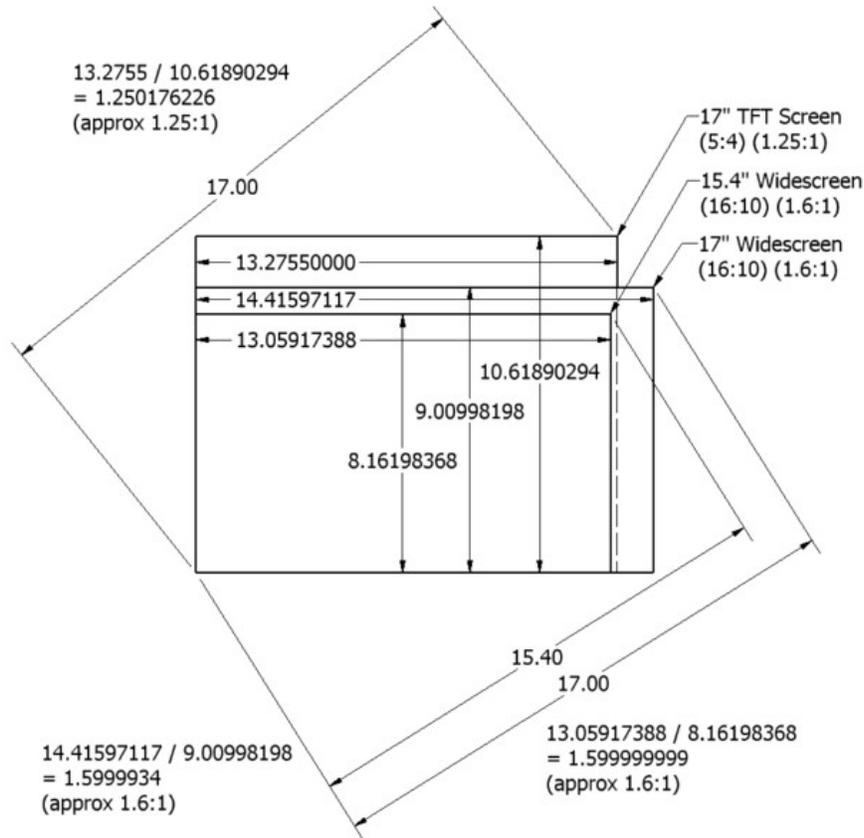
The area of displays with identical diagonal measurements can vary substantially

The size of an approximately rectangular display is usually given as the distance between two opposite screen corners, that is, the diagonal of the rectangle. One problem with this method is that it does not take into account the display aspect ratio, so that for example a 16:9 21 in (53 cm) widescreen display is far less high, and has less area, than a 21 in (53 cm) 4:3 screen. The 4:3 screen has dimensions of 16.8 × 12.6 in (43 × 32 cm) and area 211 sq in (1,360 cm^2), while the widescreen is 18.3 × 10.3 in (46 × 26 cm), 188 sq in (1,210 cm^2). For many purposes the height of the display is the main parameter; a 16:9 display needs a diagonal 22% larger than a 4:3 display for the same height.

This method of measurement is inherited from the method used for the first generation of CRT television, when picture tubes with circular faces were in common use. Being circular, only their diameter was needed to describe their size. Since these circular tubes were used to display rectangular images, the diagonal measurement of the rectangle was equivalent to the diameter of the tube's face. This method continued even when cathode ray tubes were manufactured as rounded rectangles; it had the advantage of being a single number specifying the size, and was not confusing when the aspect ratio was universally 4:3.

A problematic practice was the use of the size of a monitor's imaging element, rather than the size of its viewable image, when describing its size in publicity and advertising

materials. On CRT displays a substantial portion of the CRT's screen is concealed behind the case's bezel or shroud in order to hide areas outside the monitor's "safe area" due to overscan. These practices were seen as deceptive, and widespread consumer objection and lawsuits eventually forced most manufacturers to instead measure viewable size.

Performance measurements

The performance of a monitor is measured by the following parameters:

- Luminance is measured in candelas per square meter (cd/m2 also called a Nit).
- Viewable image size is measured diagonally. For CRTs, the viewable size is typically 1 in (25 mm) smaller than the tube itself.
- Aspect ratios is the ratio of the horizontal length to the vertical length. 4:3 is the standard aspect ratio, for example, so that a screen with a width of 1024 pixels will have a height of 768 pixels. If a widescreen display has an aspect ratio of 16:9, a display that is 1024 pixels wide will have a height of 576 pixels.
- Display resolution is the number of distinct pixels in each dimension that can be displayed. Maximum resolution is limited by dot pitch.
- Dot pitch is the distance between subpixels of the same color in millimeters. In general, the smaller the dot pitch, the sharper the picture will appear.
- Refresh rate is the number of times in a second that a display is illuminated. Maximum refresh rate is limited by response time.
- Response time is the time a pixel in a monitor takes to go from active (black) to inactive (white) and back to active (black) again, measured in milliseconds. Lower numbers mean faster transitions and therefore fewer visible image artifacts.
- Contrast ratio is the ratio of the luminosity of the brightest color (white) to that of the darkest color (black) that the monitor is capable of producing.
- Power consumption is measured in watts.
- Viewing angle is the maximum angle at which images on the monitor can be viewed, without excessive degradation to the image. It is measured in degrees horizontally and vertically.

Comparison

CRT

Pros:

- High dynamic range (up to around 15,000:1), excellent color, wide gamut and low black level. The color range of CRTs is unmatched by any display type except OLED.
- Can display natively in almost any resolution and refresh rate
- No input lag
- Sub-millisecond response times

- Near zero color, saturation, contrast or brightness distortion. Excellent viewing angle.
- Usually much cheaper than LCD or Plasma screens.
- Allows the use of light guns/pens

Cons:

- Large size and weight, especially for bigger screens (a 20-inch unit weighs about 50 lb (23 kg))
- High power consumption
- Generates a considerable amount of heat when running
- Geometric distortion caused by variable beam travel distances
- Can suffer screen burn-in
- Produces noticeable flicker at low refresh rates
- Normally only produced in 4:3 aspect ratio (though some widescreen ones, notably Sony's FW900, do exist)
- Hazardous to repair/service
- Effective vertical resolution limited to 1024 scan lines.
- Color displays cannot be made in sizes smaller than 7 inches (5 inches for monochrome). Maximum size is around 24 inches (for computer monitors; televisions run up to 40 inches).

LCD

Pros:

- Very compact and light
- Low power consumption
- No geometric distortion
- Little or no flicker depending on backlight technology
- Not affected by screen burn-in
- No high voltage or other hazards present during repair/service
- More reliable than CRTs
- Can be made in almost any size or shape
- No theoretical resolution limit

Cons:

- Limited viewing angle, causing color, saturation, contrast and brightness to vary, even within the intended viewing angle, by variations in posture.
- Bleeding and uneven backlighting in some monitors, causing brightness distortion, especially toward the edges.
- Slow response times, which cause smearing and ghosting artifacts. However, this is mainly a problem with passive-matrix displays. Current generation active-matrix LCDs have response times of 6 ms for TFT panels and 8 ms for S-IPS.

- Only one native resolution. Displaying resolutions either requires a video scaler, lowering perceptual quality, or display at 1:1 pixel mapping, in which images will be physically too large or won't fill the whole screen.
- Fixed bit depth, many cheaper LCDs are only able to display 262,000 colors. 8-bit S-IPS panels can display 16 million colors and have significantly better black level, but are expensive and have slower response time
- Input lag
- Dead pixels may occur either during manufacturing or through use.
- In a constant on situation, thermalization may occur, which is when only part of the screen has overheated and therefore looks discolored compared to the rest of the screen.
- Not all LCD displays are designed to allow easy replacement of the backlight
- Cannot be used with light guns/pens

Plasma

Pros:

- High contrast ratios (10,000:1 or greater,) excellent color, and low black level.
- Virtually no response time
- Near zero color, saturation, contrast or brightness distortion. Excellent viewing angle.
- No geometric distortion.
- Softer and less blocky-looking picture than LCDs
- Highly scalable, with less weight gain per increase in size (from less than 30 in (760 mm) wide to the world's largest at 150 in (3,800 mm)).

Cons:

- Large pixel pitch, meaning either low resolution or a large screen. As such, color plasma displays are only produced in sizes over 32 inches.
- Image flicker due to being phosphor-based
- Heavy weight
- Glass screen can induce glare and reflections
- High operating temperature and power consumption
- Only has one native resolution. Displaying other resolutions requires a video scaler, which degrades image quality at lower resolutions.
- Fixed bit depth. Plasma cells can only be on or off, resulting in a more limited color range than LCDs or CRTs.
- Can suffer image burn-in. This was a severe problem on early plasma displays, but much less on newer ones
- Cannot be used with light guns/pens
- Dead pixels are possible during manufacturing

Problems

Phosphor burn-in

Phosphor burn-in is localized aging of the phosphor layer of a CRT screen where it has displayed a static image for long periods of time. This results in a faint permanent image on the screen, even when turned off. In severe cases, it can even be possible to read some of the text, though this only occurs where the displayed text remained the same for years.

Burn-in is most commonly seen in the following applications:

- Point-of-service applications
- Arcade games
- Security monitors

Screensavers were developed as a means to avoid burn-in, which was a widespread problem on IBM Personal Computer monochrome monitors in the 1980s. Monochrome displays are generally more vulnerable to burn-in because the phosphor is directly exposed to the electron beam while in color displays, the shadow mask provides some protection. Although still found on newer computers, screen savers are not necessary on LCD monitors.

Phosphor burn-in can be "fixed" by running a CRT with the brightness at 100% for several hours, but this merely hides the damage by burning all the phosphor evenly. CRT rebuilders can repair monochrome displays by cutting the front of the picture tube off, scraping out the damaged phosphor, replacing it, and resealing the tube. Color displays can theoretically be repaired, but it is a difficult, expensive process and is normally only done on professional broadcasting monitors (which can cost up to $10,000).

Plasma burn-in

Burn-in re-emerged as an issue with early plasma displays, which are more vulnerable to this than CRTs. Screen savers with moving images may be used with these to minimize localized burn. Periodic change of the color scheme in use also helps.

Glare

Glare is a problem caused by the relationship between lighting and screen or by using monitors in bright sunlight. Matte finish LCDs and flat screen CRTs are less prone to reflected glare than conventional curved CRTs or glossy LCDs, and aperture grille CRTs, which are curved on one axis only and are less prone to it than other CRTs curved on both axes.

If the problem persists despite moving the monitor or adjusting lighting, a filter using a mesh of very fine black wires may be placed on the screen to reduce glare and improve contrast. These filters were popular in the late 1980s. They do also reduce light output.

A filter above will only work against reflective glare; direct glare (such as sunlight) will completely wash out most monitors' internal lighting, and can only be dealt with by use of a hood or transreflective LCD.

Color misregistration

With exceptions of correctly aligned video projectors and stacked LEDs, most display technologies, especially LCD, have an inherent misregistration of the color channels, that is, the centers of the red, green, and blue dots do not line up perfectly. Sub-pixel rendering depends on this misalignment; technologies making use of this include the Apple II from 1976, and more recently Microsoft (ClearType, 1998) and XFree86 (X Rendering Extension).

Incomplete spectrum

RGB displays produce most of the visible color spectrum, but not all. This can be a problem where good color matching to non-RGB images is needed. This issue is common to all monitor technologies that use the RGB model. Recently, Sharp introduced a four-color TV (red, green, blue, and yellow) to improve on this.

Display interfaces

Computer terminals

Early CRT-based VDUs (Visual Display Units) such as the DEC VT05 without graphics capabilities gained the label *glass teletypes*, because of the functional similarity to their electromechanical predecessors.

Some historic computers had no screen display, using a teletype, modified electric typewriter, or printer instead.

Composite signal

Early home computers such as the Apple II and the Commodore 64 used a composite signal output to drive a TV or color composite monitor (a TV with no tuner). This resulted in degraded resolution due to compromises in the broadcast TV standards used. This method is still used with video game consoles. The Commodore monitor had S-Video input to improve resolution, but this was not common on televisions until the advent of HDTV.

Digital displays

Early digital monitors are sometimes known as TTLs because the voltages on the red, green, and blue inputs are compatible with TTL logic chips. Later digital monitors support LVDS, or TMDS protocols.

TTL monitors

IBM PC with green monochrome display.

Monitors used with the MDA, Hercules, CGA, and EGA graphics adapters used in early IBM PC's (Personal Computer) and clones were controlled via TTL logic. Such monitors can usually be identified by a male DE-9 (often incorrectly called DB-9) connector used on the video cable. The disadvantage of TTL monitors was the limited number of colors available due to the low number of digital bits used for video signaling.

Modern monochrome monitors use the same 15-pin SVGA connector as standard color monitors. They are capable of displaying 32-bit grayscale at 1024x768 resolution, making them able to interface with modern computers.

TTL Monochrome monitors only made use of five out of the nine pins. One pin was used as a ground, and two pins were used for horizontal/vertical synchronization. The electron gun was controlled by two separate digital signals, a video bit, and an intensity bit to control the brightness of the drawn pixels. Only four shades were possible; black, dim, medium or bright.

CGA monitors used four digital signals to control the three electron guns used in color CRTs, in a signaling method known as **RGBI**, or *Red Green and Blue, plus Intensity*. Each of the three RGB colors can be switched on or off independently. The intensity bit increases the brightness of all guns that are switched on, or if no colors are switched on the intensity bit will switch on all guns at a very low brightness to produce a dark grey. A CGA monitor is only capable of rendering 16 colors. The CGA monitor was not exclusively used by PC based hardware. The Commodore 128 could also utilize CGA monitors. Many CGA monitors were capable of displaying composite video via a separate jack.

EGA monitors used six digital signals to control the three electron guns in a signaling method known as **RrGgBb**. Unlike CGA, each gun is allocated its own intensity bit. This allowed each of the three primary colors to have four different states (off, soft, medium, and bright) resulting in 64 colors.

Although not supported in the original IBM specification, many vendors of clone graphics adapters have implemented backwards monitor compatibility and auto detection. For example, EGA cards produced by Paradise could operate as an MDA, or CGA adapter if a monochrome or CGA monitor was used in place of an EGA monitor. Many CGA cards were also capable of operating as MDA or Hercules card if a monochrome monitor was used.

Single color screens

Green and amber phosphors were used on most monochrome displays in the 1970s and 1980s. White was uncommon because it was more expensive to manufacture, although Apple used it on the Lisa and early Macintoshes.

Modern technology

Analog monitors

Most modern computer displays can show the various colors of the RGB color space by changing red, green, and blue analog video signals in continuously variable intensities. These are almost exclusively progressive scan. Although televisions used an interlaced picture, this was too flickery for computer use. In the late 1980s and early 1990s, some VGA-compatible video cards in PCs used interlacing to achieve higher resolution, but the event of SVGA quickly put an end to them. While many early plasma and liquid crystal displays have exclusively analog connections, all signals in such monitors pass through a completely digital section prior to display.

While many similar connectors (13W3, BNC, etc.) were used on other platforms, the IBM PC and compatible systems standardized on the VGA connector in 1987.

CRTs remained the standard for computer monitors through the 1990s. The first standalone LCD displays appeared in the early 2000s and over the next few years, they

gradually displaced CRTs for most applications. First-generation LCD monitors were only produced in 4:3 aspect ratios, but current models are generally 16:9. The older 4:3 monitors have been largely relegated to point-of-service and some other applications where widescreen is not required.

Digital and analog combination

The first popular external digital monitor connectors, such as DVI-I and the various breakout connectors based on it, included both analog signals compatible with VGA and digital signals compatible with new flat-screen displays in the same connector. Low end older LCD monitors had only VGA inputs with higher end monitors having DVI (once it became available) though LCD monitors without a digital input are uncommon now.

Digital monitors

Monitors are being made which have only a digital video interface. Some digital display standards, such as HDMI and DisplayPort, also specify integrated audio and data connections. Many of these standards enforce DRM, a system intended to deter copying of entertainment content.

Configuration and usage

Multiple monitors

More than one monitor can be attached to the same device. Each display can operate in two basic configurations:

- The simpler of the two is **mirroring** (sometimes **cloning**,) in which at least two displays are showing the same image. It is commonly used for presentations. Hardware with only one video output can be tricked into doing this with an external splitter device, commonly built into many video projectors as a pass through connection.
- The more sophisticated of the two, **extension** allows each monitor to display a different image, so as to form a contiguous area of arbitrary shape. This requires software support and extra hardware, and may be locked out on "low end" products by crippleware.
- Primitive software is incapable of recognizing multiple displays, so **spanning** must be used, in which case a very large virtual display is created, and then pieces are split into multiple video outputs for separate monitors. Hardware with only one video output can be made to do this with an expensive external splitter device, this is most often used for very large composite displays made from many smaller monitors placed edge to edge.

Multiple video sources

Multiple devices can be connected to the same monitor using a video switch. In the case of computers, this usually takes the form of a "Keyboard Video Mouse switch" (KVM) switch, which is designed to switch all of the user interface devices for a workstation between different computers at once.

Virtual displays
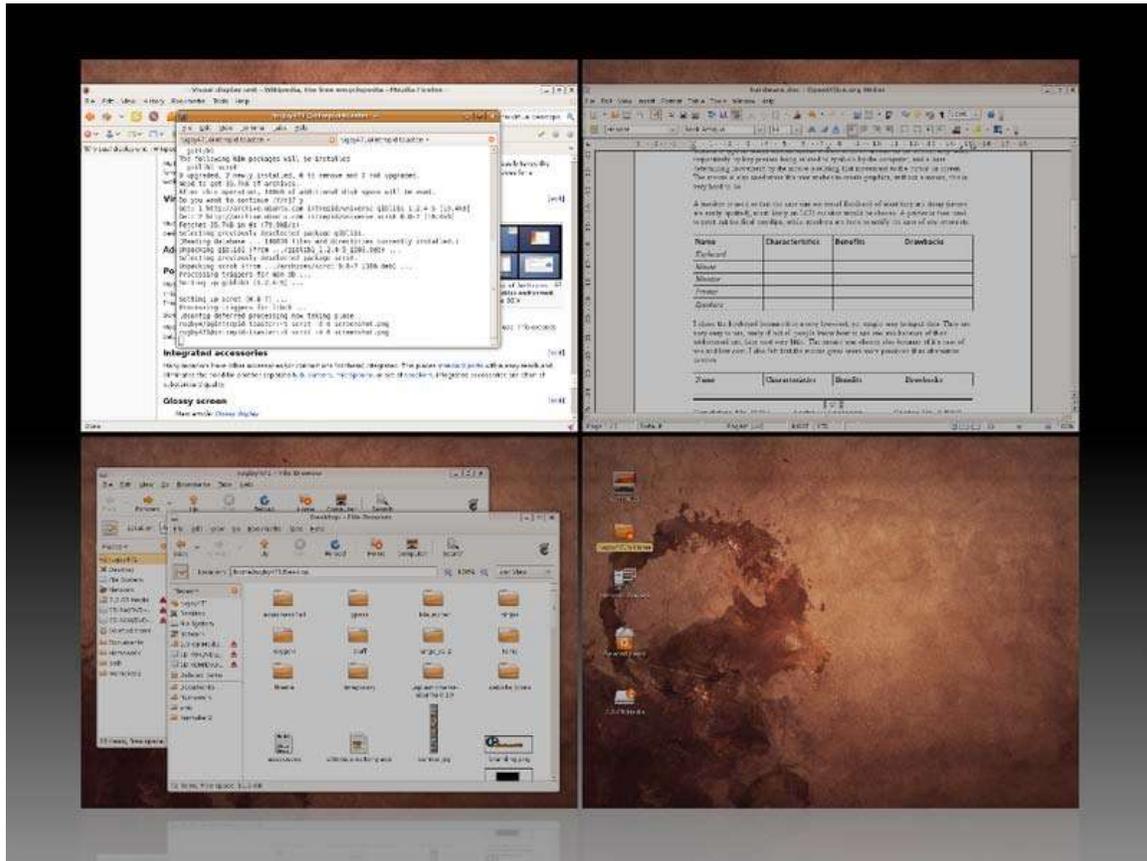
Screenshot of workspaces laid out by Compiz

Much software and video hardware supports the ability to create additional, virtual pieces of desktop, commonly known as **workspaces**. Spaces is Apple's implementation of virtual displays.

Additional features

Power saving

Most modern monitors will switch to a power-saving mode if no video-input signal is received. This allows modern operating systems to turn off a monitor after a specified period of inactivity. This also extends the monitor's service life.

Some monitors will also switch themselves off after a time period on standby.

Most modern laptops provide a method of screen dimming after periods of inactivity or when the battery is in use. This extends battery life and reduces wear.

Integrated accessories

Many monitors have other accessories (or connections for them) integrated. This places standard ports within easy reach and eliminates the need for another separate hub, camera, microphone, or set of speakers.

Glossy screen

Some displays, especially newer LCD monitors, replace the traditional anti-glare matte finish with a glossy one. This increases saturation and sharpness but reflections from lights and windows are very visible.

Directional screen

Narrow viewing angle screens are used in some security conscious applications.

Autopolyscopic screen

A directional screen which generates 3D images without headgear.

Touch screen

These monitors use touching of the screen as an input method. Items can be selected or moved with a finger, and finger gestures may be used to convey commands. The screen will need frequent cleaning due to image degradation from fingerprints.

Tablet screens

A combination of a monitor with a graphics tablet. Such devices are typically unresponsive to touch without the use of one or more special tools' pressure. Newer models however are now able to detect touch from any pressure and often have the ability to detect tilt and rotation as well.

Touch and tablet screens are used on LCD displays as a substitute for the light pen, which can only work on CRTs.

Chapter- 9

LCD Projector and HD44780 Character LCD

LCD projector

An **LCD projector** is a type of video projector for displaying video, images or computer data on a screen or other flat surface. It is a modern analog of the slide projector or overhead projector. To display images, LCD (liquid crystal display) projectors typically send light from a Metal halide lamp through a prism that separates light to three poly silicon panels – one each for the red, green, and blue components of the video signal. As polarized light passes through the panels (combination of polarizer, LCD panel and analyzer), individual pixels can be opened to allow light to pass or closed to block the light. The combination of open and closed pixels can produce a wide range of colors and shades in the projected image.

Metal Halide lamps are used because they output an ideal color temperature and a broad spectrum of color. These lamps also have the ability to produce an extremely large amount of light within a small area: current projectors average about 2,000-15,000 ANSI lumens.

Other technologies, such as DLP and LCOS are also becoming more popular in modestly priced video projection.

Projection surfaces

Because they use small Metal Halide lamps and the ability to project an image on any flat surface, LCD projectors tend to be smaller and more portable than some other types of projection systems. Even so, the best image quality is found using a blank white, grey, or black (which blocks reflected ambient light) surface, so dedicated projection screens are often used.

Perceived color in a projected image is a factor of both projection surface and projector quality. Since white is more of a neutral color, white surfaces are best suited for natural color tones; as such, white projection surfaces are more common in most business and school presentation environments.

However, darkest black in a projected image is dependent on how dark the screen is. Because of this, some presenters and presentation space planners prefer gray screens, which create higher perceived contrast. The trade-off is that darker backgrounds can throw off color tones. Color problems can sometimes be adjusted through the projector settings, but may not be as accurate as they would on a white background.

Throw

A projector's throw ratio is used when installing projectors to control the size of the projected display.

For example, if the throw ratio is 2.0 and the projector is 14' away from the screen, then the display width will be 7'.

History

The LCD projector was invented by New York inventor Gene Dolgoff. He began working on it in college in 1968 as a way to produce a video projector that would be brighter than the then-available 3-CRT projectors. The idea was to use an element referred to as a "light valve" to regulate the amount of light that passes through it. This would allow the use of a very powerful external light source. After trying many different materials, he settled on liquid crystals to modulate the light in 1971. It took him until 1984 to get an addressable liquid crystal display (LCD), which is when he built the world's first LCD projector. After building it, he saw many problems that had to be corrected including major light losses and very noticeable pixels. He then invented new optical methods to create a high efficiency and high-brightness projector and invented depixelization to eliminate the appearance of the pixels. With patents all around the world, he started Projectavision, Inc. in 1988, the world's first LCD projector company, which he took public on Nasdaq in 1990. He licensed the technology to other companies such as Panasonic and Samsung. This technology and company started the digital projection industry. In 1989 he was awarded the first Darpa contract ($1 million) for proposing that the US HDTV standard should use digital processing and projection. As a member of the National Association of Photographic Manufacturers (NAPM) Standards Subcommittee, IT7-3, he along with Leon Shapiro, co-developed the worldwide ANSI standard for measurement of brightness, contrast, and resolution of electronic projectors.

Currently the only remaining manufacturers of the LCDs for LCD projectors are Japanese imaging companies Epson and Sony. Epson owns the technology and has branded it as "3LCD". To market 3LCD projector technology, Epson also set up a consortium called the "3LCD Group" in 2005 with other projector manufacturer licensees of 3LCD technology that use it in their projector models.

Early LCD systems were used with existing overhead projectors. The LCD system did not have a light source of its own: it was built on a large "plate" that sat on top of the projector in place of the transparencies. This provided a stop-gap solution in the era when

the computer was not yet the universal display medium, creating a market for LCD projectors before their current main use became popular.

This technology is employed in some sizes of rear projection television consoles, as there are cost advantages when employed in mid size sets (40 to 50 inch diagonal). This is not expected to have much longevity in the "home theater" marketplace due to expected improvements cost/performance of competing technologies, particularly in direct-view LCD panels at the lower range of sizes and DLP projection in the larger sizes. Another advantage of using this LCD projection system in large television sets is to allow better image quality as opposed to a single 60 inch television, although currently an equal of an LCD projector is the LG 100 inch LCD TV, still in prototype stages this TV is a huge advancement towards projector sized televisions. A common rule of thumb is that an LCD's image quality will decrease with a size increase. A workaround is to use a small LCD panel (or panels) and project them through a lens onto a rear projection screen to give a larger screen size with a decreased contrast ratio, but without the quality loss.

In 2004 and 2005, LCD front projection has been enjoying a come-back because of the addition of the dynamic iris which has improved perceived contrast up to the levels of DLP.

The basic design of an LCD projector is frequently used by hobbyists who build their own DIY projection systems. The basic technique is to combine a high CRI HID lamp and ballast with a condenser and collector fresnel, an LCD removed from a common computer display and a triplet.

HD44780 Character LCD

An **HD44780 Character LCD** is a *de facto* industry standard liquid crystal display (LCD) display device designed for interfacing with embedded systems. These screens come in a variety of configurations including 8x1, which is one row of eight characters, 16x2, and 20x4. The most commonly manufactured configuration is 40x4 characters, which requires two individually addressable HD44780 controllers with expansion chips as the HD44780 can only address up to 80 characters

These LCD screens are limited to text only and are often used in copiers, fax machines, laser printers, industrial test equipment, networking equipment such as routers and storage devices.

Character LCDs can come with or without backlights, which may be LED, fluorescent, or electroluminescent.

Character LCDs use a standard 14-pin interface and those with backlights have 16 pins. The pinouts are as follows:

1. Ground
2. VCC (+3.3 to +5V)
3. Contrast adjustment (VO)
4. Register Select (RS). RS=0: Command, RS=1: Data
5. Read/Write (R/W). R/W=0: Write, R/W=1: Read

6. Clock (Enable). Falling edge triggered
7. Bit 0 (Not used in 4-bit operation)
8. Bit 1 (Not used in 4-bit operation)
9. Bit 2 (Not used in 4-bit operation)
10. Bit 3 (Not used in 4-bit operation)
11. Bit 4
12. Bit 5
13. Bit 6
14. Bit 7
15. Backlight Anode (+)
16. Backlight Cathode (-)

There may also be a single backlight pin, with the other connection via Ground or VCC pin. The two backlight pins may precede the pin 1.

The nominal backlight voltage is around 4.2V at 25˚C using a VDD 5V capable model.

Character LCDs can operate in 4-bit or 8-bit mode. In 4 bit mode, pins 7 through 10 are unused and the entire byte is sent to the screen using pins 11 through 14 by sending 4-bits (nibble) at a time.

Font

The character generator ROM contains 208 characters in a 5x8 dot matrix, and 32 characters in a 5x10 dot matrix.

There is a Japanese version of the ROM which includes kana characters, and a European version which includes Cyrillic and Western European characters.

The 7-bit ASCII subset for the Japanese version is non-standard: it supplies a Yen symbol where the backslash character is normally found, and left and right arrow symbols in place of tilde and the rub-out character.

A limited number of custom characters can be programmed into the device in the form of a bitmap using special commands. These characters have to be written to the device each time it is switched on, as they are stored in volatile memory.

Chapter- 10

LCD Classification

There are various **classifications** of the electro-optical modes of **liquid crystal displays** (LCDs).

LCD operation in a nutshell

The operation of TN, VA and IPS-LCDs can be summarized as follows:

- a well aligned LC configuration is deformed by an applied electric field,
- this deformation changes the orientation of the local LC optical axis with respect to the direction of light propagation through the LC layer,
- this change of orientation changes the polarization state of the light propagating through the LC layer,
- this change of the polarization state is converted into a change of intensity by dichroic absorption, usually by external dichroic polarizers.

Activation

Liquid crystals can be aligned by both magnetic and electric fields. The strength of the required magnetic field is too high to be feasible for display applications.

One electro-optical effect with LCs requires a current through the LC-cell; all other practiced electro-optical effects only require an electric field (without current) for alignment of the LC.

Electro-optical effects in Liquid Crystals

LCs can be aligned by electric and magnetic fields

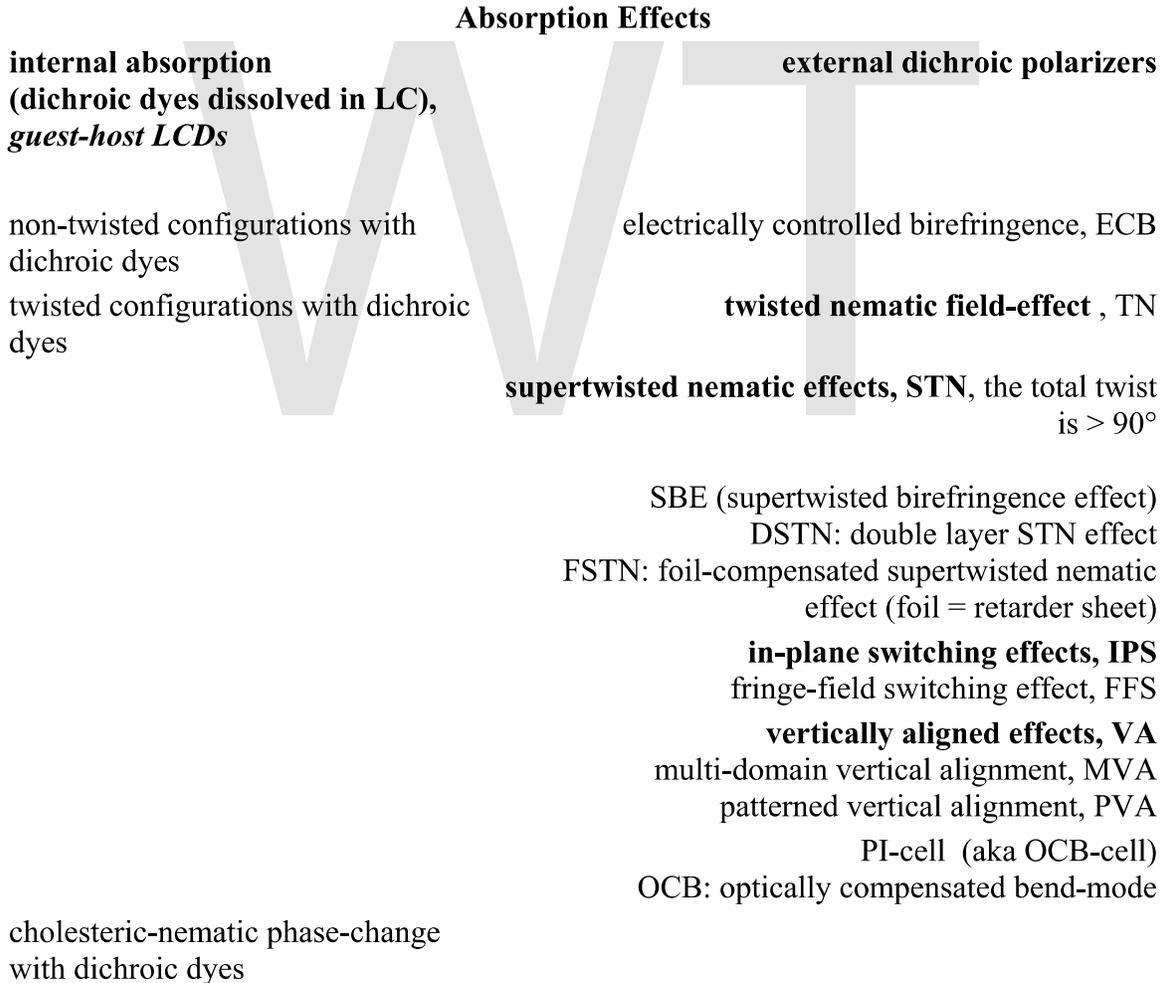| electric field effects	electro-hydrodynamic effects
the electrical field aligns the liquid crystal no current is necessary (very low power required for operation).	current induced domain formation and scattering requires current for activation.
twisted nematic field effect	dynamic scattering mode, DMS

Visual information can be generated by the processes of

- absorption (either by dichroic dyes in the LC or by external dichroic polarizers),
- scattering,
- index matching (e.g. holographic PDLCs).

Absorption Effects

The state of polarization of the light traveling through the LC layer cannot be perceived by human observers, it must be converted into intensity (e.g. luminance) in order to become perceivable. This is achieved with absorption by dichroic dyes and dichroic polarizers.

<div align="center">Absorption Effects</div>

internal absorption (dichroic dyes dissolved in LC), *guest-host LCDs*	external dichroic polarizers
non-twisted configurations with dichroic dyes	electrically controlled birefringence, ECB
twisted configurations with dichroic dyes	**twisted nematic field-effect** , TN
	supertwisted nematic effects, STN, the total twist is > 90°
	SBE (supertwisted birefringence effect) DSTN: double layer STN effect FSTN: foil-compensated supertwisted nematic effect (foil = retarder sheet)
	in-plane switching effects, IPS fringe-field switching effect, FFS
	vertically aligned effects, VA multi-domain vertical alignment, MVA patterned vertical alignment, PVA
	PI-cell (aka OCB-cell) OCB: optically compensated bend-mode
cholesteric-nematic phase-change with dichroic dyes	

Polymer Dispersed Liquid Crystals

Liquid crystals with low molecular weight can be mixed with high molecular weight polymers, followed by phase-separation to form a kind of spongy matrix filled with LC droplets. An external electric field can align the LC to match its index with that of the polymer matrix, switching that cell from a milky (scattering) state to a clear transparent state. When dichroic dyes are dissolved in the LC an electric field can switch the PDLC from an absorbing state to a fairly transparent state.

When the amount of polymer is small compared to that of the LC there will be no separation of both components, but the polymer forms an anisotropic fiber-like network within the LC that stabilizes the state in which it has been formed. In such a way, certain physical properties (e.g. elasticities, viscosities, and thus threshold voltages and response times, respectively) can be controlled.

Polymer Dispersed Liquid Crystals
PDLCs

• absorptive dye-doped PDLCs	• scattering PDLCs
	• holographic PCLCs
	• polymer stabilized LCDs

Bistable LCDs

For some applications bistability of electro-optical effects is highly advantageous, since the optical response (visual information) is maintained even after removal of the electrical activation, thus saving battery charge. These effects are beneficial when the displayed visual information is changed only in extended intervals (e.g. electronic paper, electronic price tags, etc.).

Bistable LCDs

ferroelectric LCs	cholesteric LCs	nematic LCs
bistable ferroelectric LCDs	bistable cholesteric phase-change LCDs	bistable nematic displays
		• twisted-untwisted bistabilities (180°/360° twist)
		• bistable twisted nematic effects, BTN
		• zenithal bistabilities
		• azimutal bistabilities

Reduction of Variations with Viewing Direction in LCDs

With the direction of light propagation in the LC layer also the state of polarization of the light changes, and, as a consequence, the intensity and the spectral distribution of transmitted light changes too. In order to reduce such unwanted variations to a minimum, two approaches are used in actual LC displays: multi-domain approaches and application of external birefringent layers (retarder sheets).

Reduction of Variations with Viewing Direction in LCDs	
multidomain approaches	**(birefringent) retarder sheet compensation**
visual averaging of microscopic regions with different viewing-direction properties	correction of unwanted effects in LC by external birefringent (polymeric) layers.