Liquid Crystal Displays: An overview

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This document describes the origin and developments of LCD technology, with emphasis on the underlying materials science, comparisons with other popular display technologies and practical considerations for their design and implementation. Originally discovered in a carrot extract (cholesteryl benzoate), liquid crystals have become a multi-billion dollar international industry with uses in fields ranging from mechanical engineering to optoelectronics, applications from pocket calculators to holographic optical tweezers. Liquid crystals are found in many diverse applications nowadays, such as automatic clutches, stress detection, digital memory, switchable glass and can be used to alter several basic properties of light including intensity and polarisation via the variable nature of transmissivity, retardation and polarisation rotation in these materials.

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1. Introduction

Liquid crystal displays (LCDs) have become a part of everyday life in most developed countries during the past two decades. Although one of the original intents of liquid crystal displays was television[1], they found many other uses in the half-century before this application was realised, and enabled the existence of some devices that would not have been possible (or as feasible) otherwise at that time. Pocket-calculators may be regarded as a good example of this – while part of their sudden popularity may have been due to the lack of any similar competitor, the LCD allows them to operate for long amounts of time without the need for bulky or external power supplies.

Nowadays, almost all televisions and computer monitors use liquid-crystal displays[2], along with many other technologies including image projectors, mobile phones and portable media/entertainment devices*. This

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* In some portable entertainment devices (particularly in the middle of the 2000-2009 decade), organic-LED screens were also used in portable media players and mobile phones.

LCD "explosion" may be attributed to improvements in design and production methods, which in turn arise from an improved knowledge of the physics of liquid crystals.

Three main technologies for displaying two-dimensional images are liquid crystal displays (LCDs), cathode-ray tube displays (CRTs) and plasma displays. Other display technologies are available including AMOLED and ePaper, however these will not be discussed in depth due to their present limitations. The size of a rectangular display refers to the length of its diagonal, corner to (opposite) corner.

1.1. Cathode-ray tube (CRT) displays

CRTs scan a beam of electrons (the cathode ray) through a deep cavity containing a vacuum (the tube), where planar electrodes apply electric fields to control the direction of (i.e. scan) the beam. The electrons eventually impact on phosphor dots on the back of the glass display screen, causing them to glow. The input requires (at minimum) some intensity waveform to modulate the intensity of the electron beam, and synchronisation signals to instruct the display to begin scanning a new column/row/frame. Colour CRTs use three different types of phosphors, arranged in triangles or strips of triplets – red, green and blue emitters. These are referred to as "subpixels", and each triplet forms a "pixel".

The input to the display may contain a separate signal for each colour (as the RGB format and VGA standard do); the colours may be encoded in a different colour space (for example, YUV[*]); or may be multiplexed as is done by "composite video". Hence, decoding the input analogue signal generally results in a phase displacement from the synchronisation signal[†]. Therefore, in order to guarantee that electrons intended for a certain colour of phosphor only illuminate that type of phosphor, three electron guns are used – one for each colour. A "shadow mask" – that is, a thin, electrically grounded sheet of metal with a fine pattern of holes is used to ensure that a certain beam may only hit its associated phosphor type. As the individual physical pixels are not addressed individually, a beam pulse intended for one subpixel may instead spread over several adjacent subpixels of the same colour. This causes spatial blurring of images, particularly as the pixel count of the signal and the luminous intensity of the display are increased[‡].

The cathode rays also emit X-ray radiation, which poses health risks for long-term use of CRTs. The modulation of the beams and the electric fields that direct them may also cause RF interference in the vicinity of the display. As the phosphors fade between scans, the intensity of a region of the screen may oscillate with the refresh rate, causing a noticeable flickering of the display. Other risks include toxicity from substances such as cadmium (in some phosphors) and implosions due to degradation or damage to the vacuum tube.

The display units themselves are typically large due to the vacuum tube and heavy as they contain high-voltage electronics to direct and produce the electron beams.

Modern CRT displays are capable of displaying a wide gamut[§] (colour-range), encompassing a large amount of the colours that humans can perceive, and are *emissive* devices in that they produce their own light rather than transmitting or reflecting external light, as *transmissive* displays do. This allows them to be used in dark environments, and reduces the effect of ambient light on the perceived gamut. CRTs can also typically produce strong contrasts (bright whites and dark blacks), due to being able to completely turn off individual pixels.

CRT phosphors degrade with usage, resulting in a loss of brightness over time. If static images are displayed for extended periods, this degradation will affect some phosphors more than others, resulting in "burn-in", where images are permanently retained in the phosphors due to the variable degradation.

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[*] In this colour space, *Y* (the "luminance") encodes the brightness of the pixel, while *U* and *V* (the "chrominance") represent co-ordinates in a colour-plane, which becomes greyer nearer the origin. This grey gradient in the UV plane results in the saturation and hue being encoded in each of the *U* and *V* coefficients.

[†] In S-video and Composite standards, the synchronisation signal is encoded in the other components. In VGA, they may be encoded with the colours (commonly the green component), or provided via separate lines.

[‡] An interesting (and now, rare) subclass of CRTs is the *Vector* display. Rather than scanning a modulated beam over every physical pixel to draw a frame, the beam is scanned along polygonal paths. This allows simple vector line images to be displayed at high update rates, reducing flicker, and removes the need for the vector images to first be rendered to raster format, reducing the computational and memory requirements of the image source.

[§] See "CIE 1931" for more information regarding gamut and colour science.

1.2. Plasma displays

Plasma displays have similarities to both CRT displays and LCDs. Also relying on phosphors to produce coloured light, the phosphors are located on the front of small subpixel cells, filled with mercury vapour. When an electrical current is passed through a cell, mercury atoms are excited by incident electrons resulting in fluorescence of ultra-violet. These are absorbed by the phosphors, causing them to emit visible light. An exploded diagram of such a configuration is shown below in Fig. A:

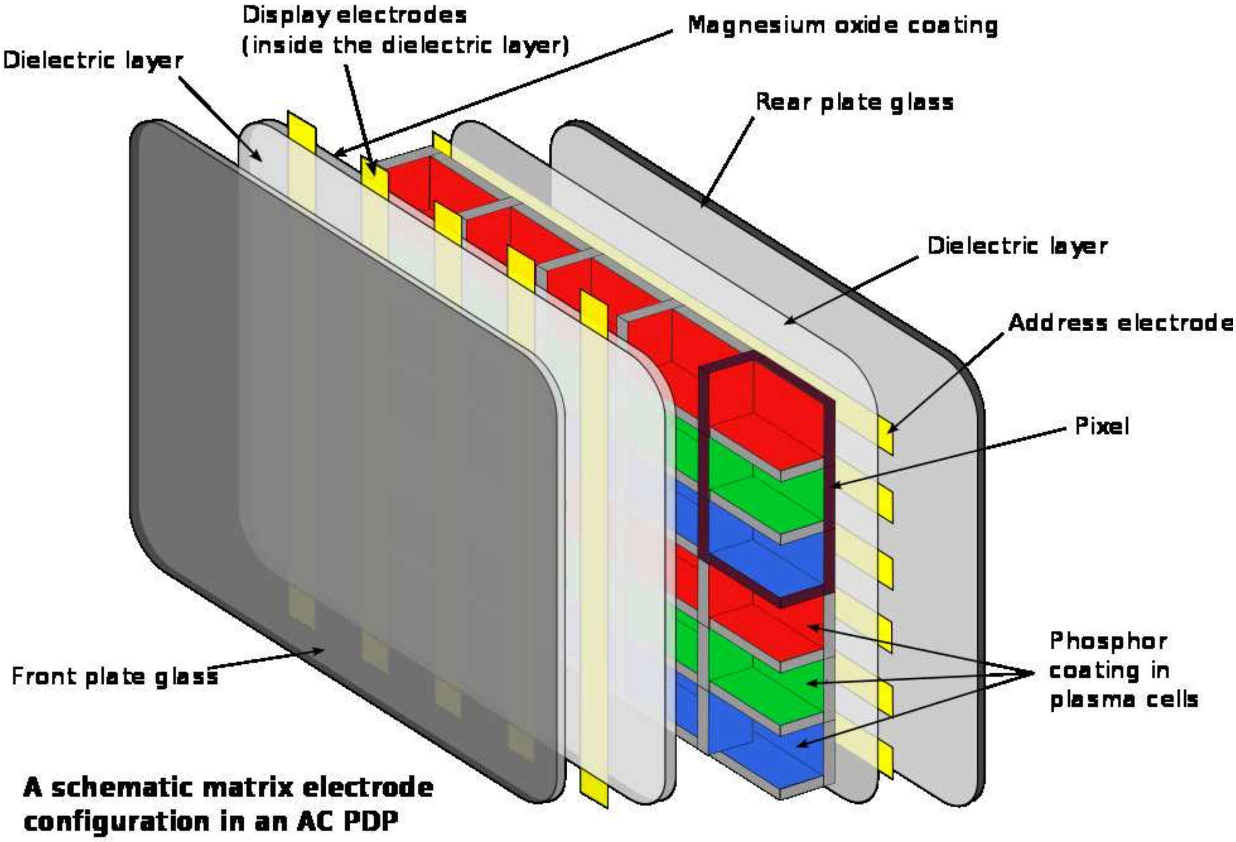

Fig. A. Structure of a typical plasma display
Obtained from Wikimedia Commons on 02-Jan-2011,
http://en.wikipedia.org/wiki/File:Plasma-display-composition.svg#globalusage

The cells are individually addressed by column and row, allowing sharp images and geometries to be displayed. The discrete nature of the pixels makes the panel size of such displays very scalable[*], while the lack of vacuum tube and high-voltage electronics allows plasma displays to be considerably thinner than CRTs. Plasma displays have been produced with sizes in excess of 100 inches. They also exhibit strong contrasts, for the same reasons as for CRTs. Since each pixel may be individually addressed electronically, rather than the physical scanning method used by CRTs, the entire grid may be refreshed/updated at much higher rates than CRTs resulting in smoother video. The ability to address each pixel accurately and individually means that plasma displays can natively handle digital input signals. The conversion to analogue need only happen between the controller circuitry and the pixels themselves, via a high-speed DAC[†].

As modulated high voltages are still needed to quickly trigger fluorescence in the mercury cells, plasma displays may cause RF interference; they also experience burn-in and lose brightness over their lifetime. The gamut of a plasma display is comparable to that of a CRT, owing to the similarities between how they produce colours.

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[*] Due to the high cost of producing plasma displays, most plasma displays are very large; other technologies are more cost-effective for smaller display sizes.

[†] DAC: Digital-to-analogue converter, a device that converts digital signals to analogue signals.

2. From carrots to circular-polarisation filters

In 1888, an Austrian biologist, Reinitzer, noticed that a carrot extract, *cholesteryl benzoate*, appeared to have two melting points[3]. He sent samples to a physicist, Lehmann. Lehmann noticed that above its first "melting point", to a cloudy substance, it exhibited some crystalline properties (when viewed under a microscope) such as long-range ordering and the ability to alter the polarisation of light - yet it still flowed like a liquid. Following its second melt, a clear liquid was formed which behaved more like a typical liquid. Reinitzer was not the first to discover this strange region between the solid and liquid phases, but Lehmann (with Reinitzer's samples) was the first[5]p3 to recognise this as a new type of matter, neither solid nor liquid.

As described by Lehmann (in an English translation of his 1889 paper[5]p52):

> *"If the present interpretation of the observations is to be believed, a unique phenomenon is reported here for the first time. A crystalline and strongly birefringent substance has been observed which possesses such low physical strength that it cannot resist the effect of its own weight."*

2.1. Nematic mesophase

Following this discovery, other scientists began identifying liquid-crystal phases in other materials. Most of these discoveries were accidental, as little was known about the reasons for the existence of the liquid-crystal phase. At the start of the 20th century, Daniel Vörlander began attempting to synthesize liquid crystals in an attempt to understand the relationship between molecular structure and the presence of a liquid-crystal phase[6]. Vörlander found that for a liquid-crystal phase to exist, the molecules must exhibit a linear shape[6] (needle-like)*. From considering how matchsticks in a matchbox behave when the box is tilted or shaken, one can see how with this molecular shape, fluidity may be possible while preserving long-range directional ordering. George Friedel[13] later suggested the term "mesophase" for describing liquid crystal phases and names for different mesophases, including the *nematic* and *smectic*.

While the molecules aren't all necessarily orientated in the same direction (see Fig. B), the average direction of orientation over microscopic volumes is consistent over macroscopic distances (analogous to temperature, or the "velocity field" in aero/fluid dynamics). Directional ordering of needle-like molecules, without positional ordering† is a defining characteristic of the *nematic*‡ phase. The average deviation from this direction at a molecular level is measured by the *order parameter*, which may be regarded as a measure of the amount of orientational order, from completely random (isotropic) molecular orientations to a single constant orientation for all molecules.

Light travelling parallel to the *director* – the average orientational direction of the molecules – experiences large (long) sections of matter, whereas light travelling perpendicular to the director experiences small sections of matter, due to the anisotropic shapes of the molecules, hence strong birefringence is typical of nematic liquid crystals.

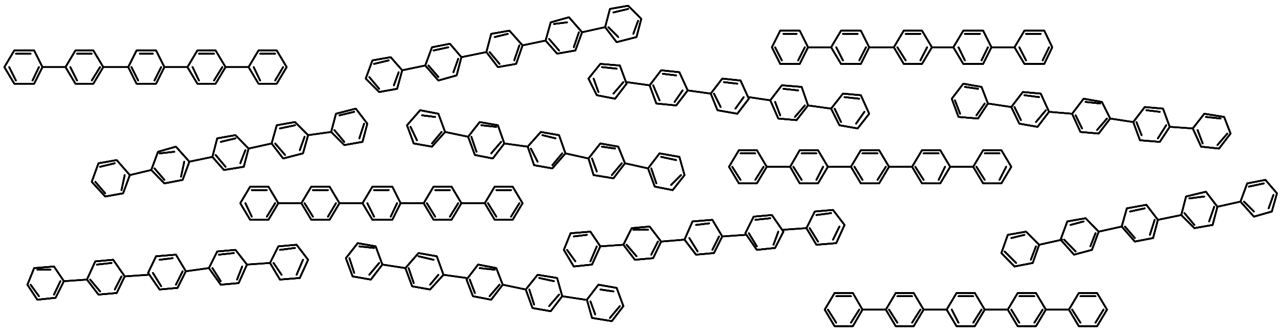

Fig. B. p-Quinquephenyl molecules demonstrating the nematic phase, like matchsticks in a box. The molecules aren't all oriented in the same direction, however the average orientation is consistent at a microscopic scale. For this substance, the nematic phase occurs between 118.2°C and 135.3°C[8]p15.

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[*] It is now known that any extremely anisotropic shape (where the molecules' size along one axis differs greatly from the size along another two) can present liquid-crystal phases. "Flat" molecules may result in "discotic" liquid crystal phases.

[†] When positional ordering is present in a liquid crystal, the material will be in a "smectic" phase ("soap-like", as soapy solutions often exhibit smectic phases).

[‡] Nematic: from the Greek *nema*, meaning "thread"

2.2. Twisted-nematic (cholesteric) mesophase

A few years later, Charles Mauguin documented the *twisted-nematic* or *cholesteric*[*] liquid-crystal structure[7]p1. In this structure, individual planes (cross-sections) display a typical nematic arrangement, but with the lack of axial symmetry due to chirality, the director is rotated slightly between adjacent planes, usually forming a helical superstructure[8]p5 with the helical axis normal to the directors (see Fig. C). This variation of director is usually periodic, with its "pitch" being double the period of the angle of the director[†]. Light circularly polarised with the same handedness as a cholesteric material, travelling parallel the helical axis will generally experience more matter than light of the opposite handedness would, resulting in very different refractive indices, reflectivities and transmissivities[‡] for light of different circular polarisations. Due to electrodynamic interactions, linearly polarised light will have its plane of polarisation rotated when passing along a cholesteric helix, being rotated as the director rotates[26].

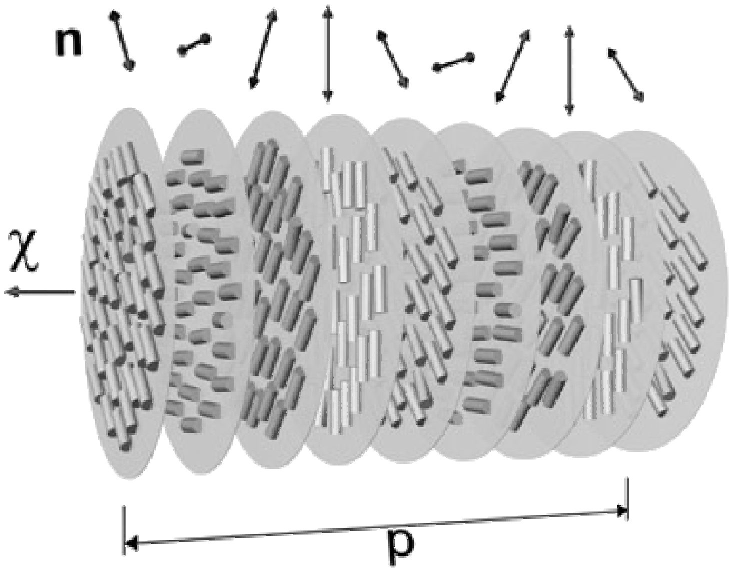

Fig. C. Structure of cholesteric liquid crystals:
- ***p** is pitch*
- ***n** is director*
- *χ is helical axis direction*

Image and caption adapted from [9]

If the molecules mostly have the same handedness[§][12], incident light with wavelength close to (within a few percent of) the pitch of a cholesteric liquid crystal, and with circular polarisation of the same handedness as the helix will be reflected[10]. Due to thermal expansion causing stretching and tightening of the helix, the pitch of a cholesteric liquid crystal can be controlled by altering the temperature, resulting in part of the reflectivity spectrum being shifted with temperature changes. This effect is used in some flexible strip thermometers[**], allowing the temperature at the surface of the strip to be measured by the (reflected) colour of the strip[10] – without requiring any power source or exerting uncomfortable physical pressure (as would be necessary with solid state probe-style thermometers).

The centre of this reflective band varies with the angle of the incident rays[8]p213 relative to the helical axis. This is a consequence of Bragg's law[8][12], causing colours to "appear" and "vanish" on a surface of aligned cholesteric molecules as the angle between the surface and the observer is varied.

A useful feature of cholesteric liquid crystals in for the creation of LCDs is their ability to rotate the polarisation of light passing through them[14][26]. Under certain conditions, some materials exhibit a transition from the cholesteric to nematic mesophase[††]; one such condition is the presence of an externally applied electric or magnetic field[12]. This allows such materials to be used to rotate the plane of polarisation of linearly polarised light *on demand*, in response to an externally applied field.

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[*] Due to its early association with cholesterols

[†] As the sign of the director is undefined, the period of repetition is equal to half of the helical pitch. The pitch represents a *cumulative* rotation of the director around a full-circle – by comparing the directors in pairs of layers, one may (incorrectly) deduce a pitch of half this, due to the sign invariance of the director, i.e. $\boldsymbol{n} \equiv -\boldsymbol{n}$.

[‡] Of particular current interest to cinema, is the ability to completely reflect one circular polarisation, while transmitting most of the other – resulting in a "handedness filter".

[§] This may be ensured by small addition of a chiral dopant, resulting in one twist direction being favoured over the other.

[**] Such as those often seen in large fish-tanks and those used in childcare. The are also used for the "mysterious gem" in so-called "mood-rings" [10]

[††] In the context of liquid crystal displays, this un-twisting is normal to the helical axis so that the director of the nematic phase is oriented parallel to the axis of the previous cholesteric phase – not simply an un-twisting of a helix (until the pitch becomes very large).

3. Design and development

3.1. Light-valves

A simple design for a “light valve” is a twisted-nematic material trapped between two surfaces containing linear polarisation filters, with transparent electrodes in or on the outside of each surface. When in the twisted-nematic phase (with directors parallel to the filters), the sandwiched liquid crystal will rotate the plane of polarisation of any light that passed through the first polariser, whereas when the electric field is applied (causing a transition to the nematic phase), the polarisation of light will be unaffected by the liquid crystal[15]. This design originates from the paradigmatic investigation in [15], which related changes in how a cholesteric affected light to changes in an applied electric field, in order to describe the effect that an applied electric field has on the structure of the liquid crystal.

To understand the application of this to display technology, assume the cholesteric phase rotates light by 90° from surface to surface and the polarisers are crossed (aligned at 90° to each other). Light will pass through the cell normally, as it is rotated by 90° through the twisted-nematic material, until the electric field is applied – then the second polariser will block the light.

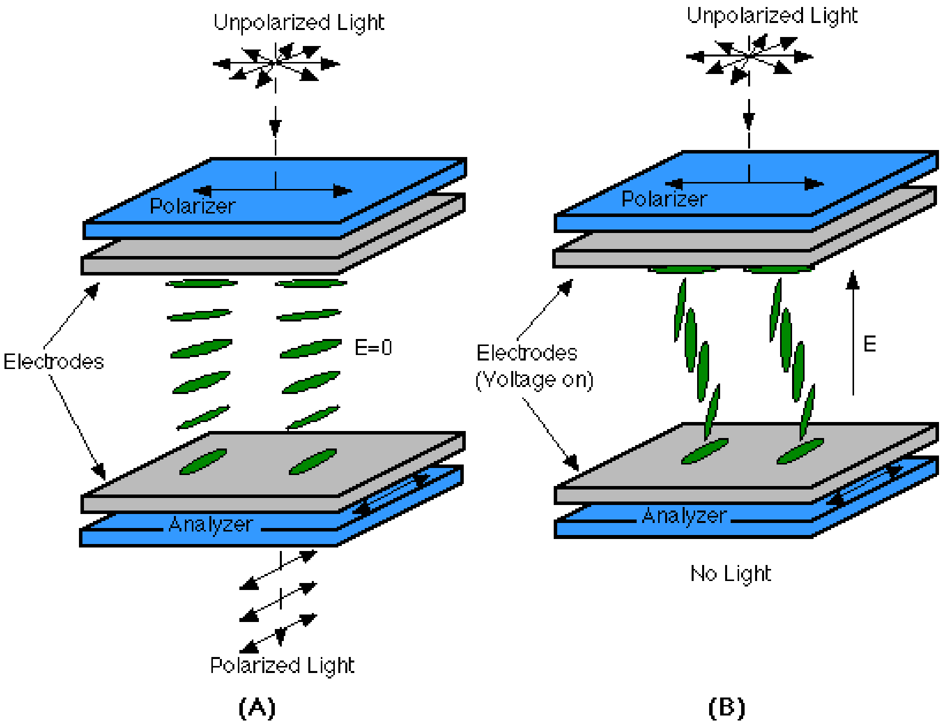

Fig. D. Twisted-nematic material sandwiched between a crossed polarisers and a pair of electrodes, without (A) an electric field applied, with (B) an electric field being applied.
Image obtained from [27]

In order to ensure that the light is rotated by 90°, the inside of the surfaces may be “brushed” along one direction[27], forming small grooves in the surfaces – encouraging the directors at that interface to line up with the brushing direction. The surfaces are then oriented at right angles (with respect to their brushing direction), ensuring that the directors at each interface are at right angles. Thus, light entering at one linear polarisation will leave at a perpendicular one, as the polarisation angle changes to follow the rotation of the directors[16].

If one surface is kept at ground (zero-volts) and shaped electrodes are etched on the other surface, then the shapes may be made to appear and disappear (as opaque or transparent regions) as a voltage is applied and removed from the shaped electrodes[27]. An example of this is the display in a typical digital wristwatch, where a reflector is located behind the display to reflect the transmitted light back to the user. This was the basis of the displays in early digital wristwatches produced by the Swiss and Japanese during the 1970s.

3.2. Pixels: Modern mosaics

A rectangular matrix of such “light-valve” cells is the basis for a monochrome graphic display. With each individual cell becoming an independent “pixel” in the display, complex graphics may be produced (Fig. E, Fig. F).

Fig. E. Monochrome graphic displayed on the liquid crystal display of a Nokia 3310. This display is in the form of a grid, 84 pixels wide and 48 tall.
”By Discostu (Own work) [Public domain], via Wikimedia Commons”, obtained at 09-Jan-2011

Fig. F. Animated game “Space Impact”, featured on Nokia 3410 LCD display.
Obtained at 09-Jan-2011 from http://www.ngagegaming.com/news.cgi?id=EpyZkkVAllHvjIcREP5988/tmpl/nxt_features/prof/feat

The time that a pixel requires to change from opaque to clear (for most early 1990s screens) is typically on the order of tens of milliseconds*[28]. Hence, animation is physically limited to low frame rates by motion blur and “ghosting”†, as shown in Fig. G.

Fig. G. Ghosting (on a colour LCD)
Obtained from http://easyhdtv.blogspot.com/2007/04/hdtv-ghosting.html at 07-Jan-2011

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* In comparison, the response of typical plasma displays is a few milliseconds, and the response of AMOLED displays is nearer to microseconds than milliseconds.

† Both ghosting and motion blur are similar, if not the same. They are the result of previous frames not completely fading out before new ones are drawn, causing a superposition of the previous frames to appear faintly on the display.

3.3. LCD colour range

As with CRTs and plasma displays, individual light-valves may be grouped into triplets and dyed, in order to produce colour-capable displays. LCDs, owing to their use of light-valves, rather than light-sources to create the physical image, are transmissive – and hence require a backlight or a mirror to be located behind the rear polariser in order to illuminate the image visible. Mirrors are generally used in monochrome low-power displays including those found in wristwatches, portable digital thermometers and electrical multi-meters, where gamut is unimportant. Backlit displays (including most all colour displays) incorporate a diffuser in front of one or more CCFLs[*]. As the gamut of a transmissive display is limited by the spectral shape of the light used to illuminate it, the typical gamut of an LCD screen is significantly lower than that of a CRT or plasma display[29], due to the emissive spectra of CCFLs (Fig. H). LED-illuminated LCD displays have recently become available, which can cover a much larger gamut than their CCFL counterparts (or CRT/plasma) do[30].

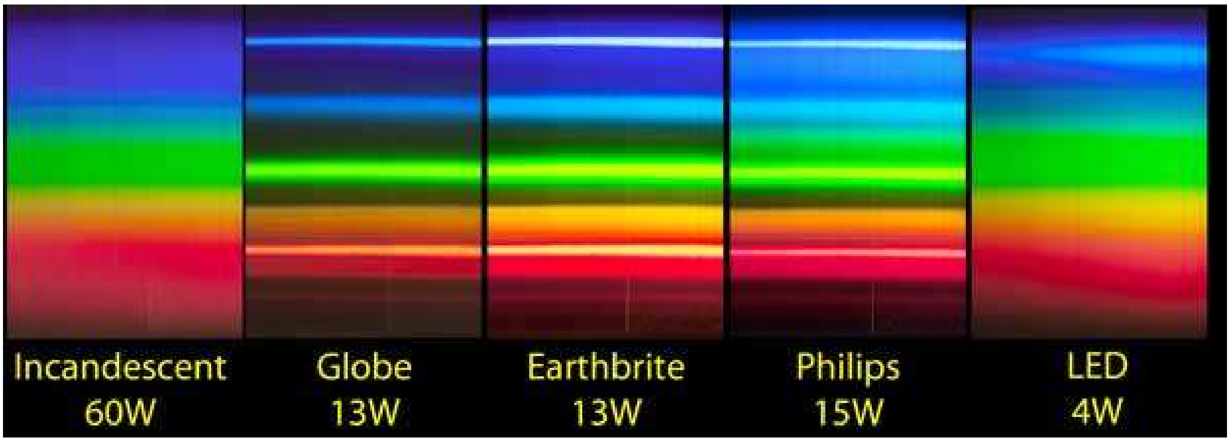

Fig. H. Emission spectra of various room light sources. The middle three spectra correspond to CCFLs. While these room lights are not necessarily required to produce a full range of the visible colours, the large dark bands in the spectral response are immediately noticeable in comparison to the smoother response of LED and incandescent sources. Obtained at 10-Jan-2011 from http://web.ncf.ca/jim/misc/cfl/

Colour LCD screens, much like plasma screens, can display images very sharply (in comparison to CRTs), due to their ability to address each subpixel individually. This subpixel addressing allows images of higher pixel density (dpi/ppi – dots/pixels per inch) than the display to be shown, via subpixel-rendering techniques[17], while maintaining image sharpness.

3.4. Technological improvements

The rising popularity of LCD televisions and monitors over the past decade has encouraged research to solve to the various pitfalls of the technology.

Ghosting and the poor contrast may be considerably reduced by use of an *active-matrix* (more commonly: *TFT*) design. The original *passive-matrix* and *active-matrix* designs both electronically address individual subpixels by their column and row number as shown in Fig. I:

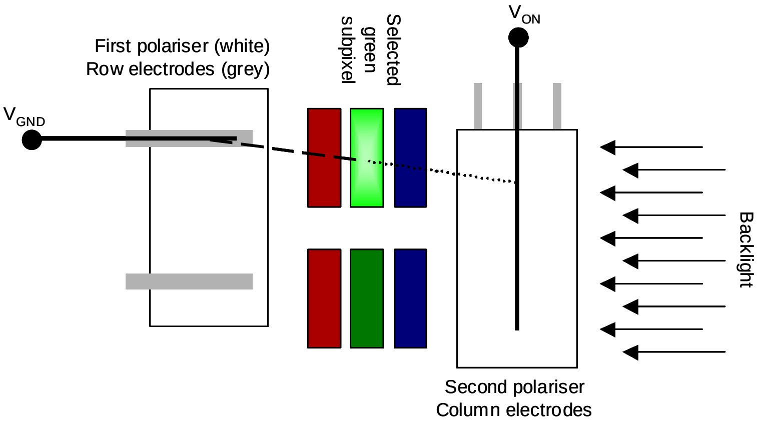

Fig. I. Controlling and selecting a subpixel by the intersection of its column and row electrodes (passive-matrix)

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[*] Cold-cathode fluorescent lamp – a compact light source that relies on secondary emissions or field emissions rather than the thermionic emission used in typical fluorescent (and incandescent) lighting.

In passive-matrix designs, each subpixel is individually scanned, given a momentary electric field that decays while the other subpixels are being scanned. As the pixel count of a display increases, the fraction of time that each subpixel can be controlled for decreases, as more subpixels must be scanned. Hence, passive-matrix displays are impractical for large pixel densities and counts[25].

The key improvement in active-matrix designs is that a field-effect transistor (FET) is incorporated into each subpixel (Fig. J), to "trap" charge and maintain the electric field on the transistor's associated subpixel while others are being scanned. The electrode on one side of the cells is now fixed at ground voltage, while the other side contains both column and row electrodes. One set (lets assume, the column electrodes) are connected to the gates of the transistors in that column, while the other set are connected to sources[*] of transistors in their row. When the gate voltage is at V_{OFF}, the resistance between source and drain becomes very high, effectively disconnecting the cell's capacitor from the other set of electrodes. When the gate voltage is set to V_{ON}, the source-drain resistance becomes minimal, allowing the voltage across the capacitor to be set to the voltage of the data line[25].

Instead of the subpixel being given short pulses during each refresh cycle, a controllable amount of charge is retained on each subpixel, creating a permanent electric field across the liquid crystal cell. This permanent field results in the cells responding (twisting/untwisting) much quicker, due to the field persisting after the cell has been scanned – reducing ghosting and motion blur. Due to this ability to retain charge and produce a permanent field, a pulse of lower voltage may be used to set a pixel (than would be needed in a passive-matrix design).

The proximity of adjacent electrodes of liquid crystal results in capacitance between electrodes and cells in adjacent columns/rows. This causes *crosstalk*, where adjacent subpixels interfere with each other, resulting in a slight blurring of images due to signals intended for one subpixel reaching adjacent subpixels too[24]. The lower voltages used in active-matrix LCDs, combined with the complete "connection" and "disconnection" of individual pixels via FET gate voltages results in less crosstalk and consequently, sharper images[31] are possible than would be on passive matrix displays of similar pixel count and brightness.

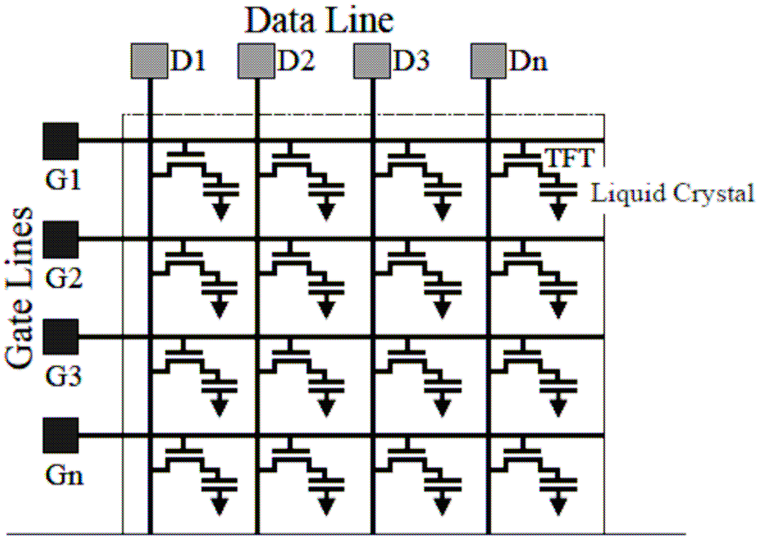

Fig. J. Active-matrix design: Each pixel has one grounded electrode and another that is isolated by a FET. When the gate line activates the FETs in one row, they store some charge due to the voltages on the data lines.

Disadvantages of active-matrix technology include higher price (due to the need for a thin film of transistors) and "dead pixels"[32]. Mechanical stress, thermal damage and production defects may result in some transistors "breaking". This will cause their associated subpixel to "stick" at a certain value, resulting in spots of unwanted colour in the displayed image, known as a "dead pixel"[23].

Another interesting solution to ghosting, often used in conjunction with active-matrix designs is *Overdrive*: NEC realised that the twisting and untwisting of the liquid crystal in response to electric fields starts slowly, but stops rapidly. *Overdrive* involves applying a stronger initial electric field to the subpixel, to accelerate the twisting/untwisting, and then reduce it to the intended value in order to achieve the desired amount of "twist"[18]. This technology is incorporated in most modern LCD controller circuitry.

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[*] The source and drain may be interchangeable in simplistic FET designs.

4. Summary

Despite the numerous disadvantages of LCD when compared with plasma and CRT display technology, LCD has been replacing CRT in all but a few specialist applications[20]. The practicality of LCDs, in conjunction with improved production methods (notably: the “one drop filling process”[21]) enabled LCDs to sell worldwide in high numbers – becoming the market leader in 2008. This global success funded the research and development of newer LCD technologies (including “vertical-alignment” and “in-plane switching”) that overcame some of the previous generations’ limitations. Now, for sizes below forty-two inches, LCD displays are the cheaper, more compact, lighter and energy efficient than plasma and CRT technologies. Plasma displays are generally cheaper for larger sizes; however incur higher lifetime costs due to much lower efficiency and phosphor degradation. For very small displays, AMOLED (active-matrix organic LED) based technologies are becoming more popular[22] due to their low power consumption, high contrast and robustness however large AMOLED displays are expensive and uncommon. For rooms with low ambient light, an LCD backlit by a bright point source may be used in the form of a projector, to display images with size in excess of two hundred inches[*]. The polarisation and phase controlling properties of LCDs, in conjunction with their ability to attenuate passing light, have allowed some exotic applications. One such application is holographic optical trapping[†], where an LCD is used to produce optical phase and polarisation vortices, allowing several independent optical traps to be created simultaneously from one laser source, and manipulated by a computer-controlled liquid-crystal matrix[18].

Owing to the low cost of LCDs and the versatility of the technology, they are likely to remain the dominant 2-D display technology for the near future, enjoying a large and growing market share. Rather than being superseded and replaced by future technologies (e.g. stereoscopic 3D video), LCDs are versatile enough to provide the base platform from which those technologies will be built on. For example, by controlling the refractive index of a liquid crystal layer and creating a spatial refractive index gradient, a “liquid crystal lens” with variable “shape” and focal properties has been demonstrated[33].

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[*] Limited only by the brightness of the projector lamp, the projector’s ability to cool the surrounding electronics (especially the LCD) and the size of the projection surface. The 200-inch claim is from personal experience.

[†] An description of optical tweezers may be found on my website, http://www.battlesnake.co.uk/_uni/tweezers.html

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