Technology Brief 9
Display Technologies

From cuneiform-marked clay balls to the abacus to today's digital projection technology, advances in visual displays have accompanied almost every major leap in information technology. While the earliest "modern" computers relied on cathode ray tubes (CRT) to project interactive images, today's computers can access a wide variety of displays ranging from plasma screens and LED arrays to digital micromirror projectors, electronic ink, and virtual reality interfaces. In this Technology Brief, we will review the major technologies currently available for two-dimensional visual displays.

Cathode Ray Tube (CRT)

The earliest computers relied on the same technology that made the television possible. In a CRT television or monitor (**Fig. TF9-1**), an ***electron gun*** is placed behind a positively charged glass screen, and a negatively charged electrode (the ***cathode***) is mounted at the input of the electron gun.

- During operation, the cathode emits streams of electrons into the electron gun.
- The emitted electron stream is steered onto different parts of the positively charged screen by the electron gun; the direction of the electron stream is controlled by the electric field of the deflecting coils through which the beam passes.
- The screen is composed of thousands of tiny dots of phosphorescent material arranged in a two-dimensional array. Every time an electron hits a phosphor dot, it glows a specific color (red, blue, or green). A pixel on the screen is composed of phosphors of these three colors.
- In order to make an image appear to move on the screen, the electron gun constantly steers the electron stream onto different phosphors, lighting them up faster than the eye can detect the changes, and thus, the images appear to move. In modern color CRT displays, three electron guns shoot different electron streams for the three colors.

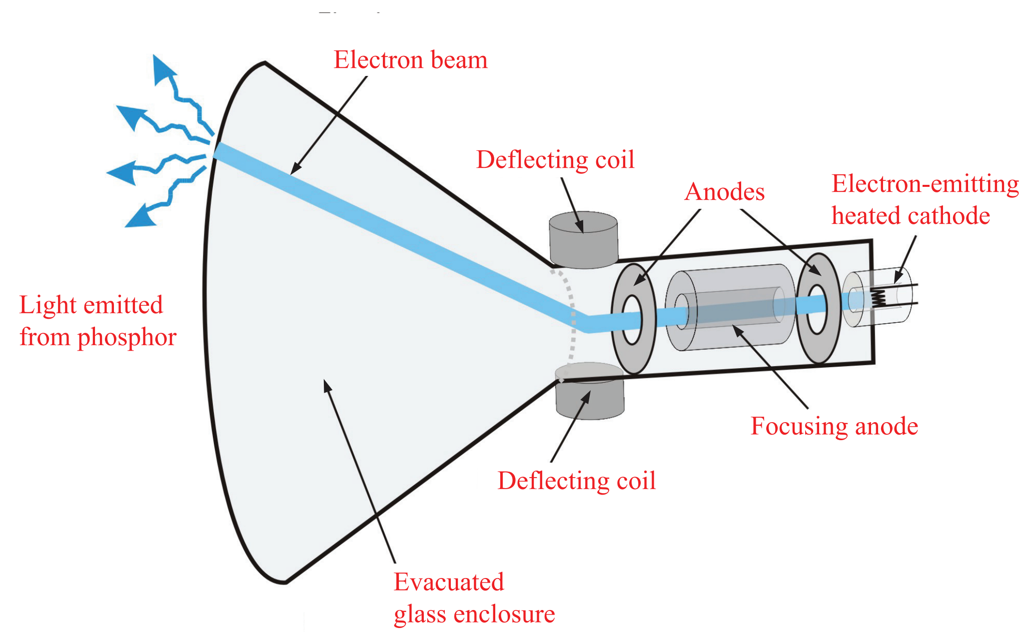

Figure TF9-1: Schematic of CRT operation.

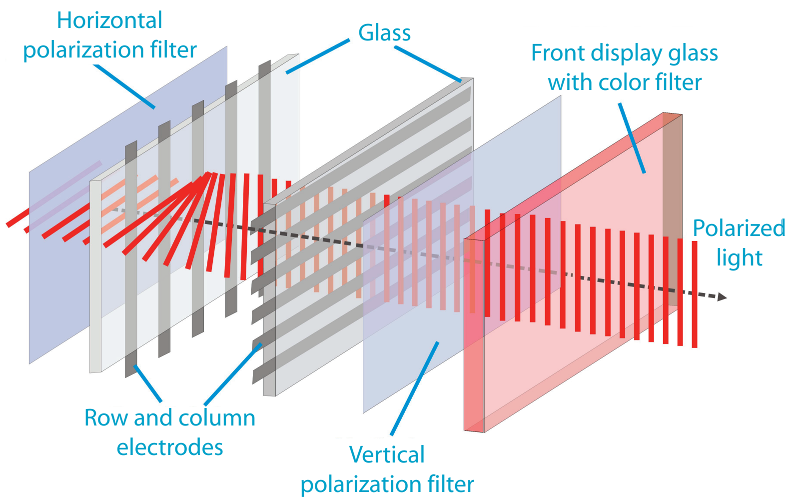

Figure TF9-2: Schematic of LCD operation.

The basic concept behind CRT was explored in the early 2000s in the development of ***field emission displays*** (FED), which used a thin film of atomically sharp electron emitter tips to generate electrons. The electrons emitted by the film collide with phosphor elements just as in the traditional CRT. The primary advantage of this type of "flat-panel" display is that it can provide a wider viewing angle (i.e., one can look at an FED screen at a sharp angle and still see a good image) than possible with conventional LCD or LED technology (discussed next).

Liquid Crystal Displays (LCD)

LCDs are used in digital clocks, cellular phones, desktop and laptop computers, and some televisions and other electronic systems. They offer a decided advantage over other display technologies (such as cathode ray tubes) in that they are lighter and thinner and consume a lot less power to operate. LCD technology relies on special electrical and optical properties of a class of materials known as ***liquid crystals***, first discovered in the 1880s by botanist Friedrich Reinitzer. In the basic LCD display, light shines through a thin stack of layers as shown in **Fig. TF9-2**.

- Each stack consists of layers in the following order (starting from the viewer's eye): color filter, vertical (or horizontal) polarizer filter, glass plate with transparent electrodes, liquid crystal layer, second glass plate with transparent electrodes, horizontal (or vertical) polarizer filter.
- Light is shone from behind the stack (called the ***backlight***). As light crosses through the layer stack, it is polarized along one direction by the first filter.
- If no voltage is applied on any of the electrodes, the liquid crystal molecules align the filtered light so that it can pass through the second filter.
- Once through the second filter, it crosses the color filter (which allows only one color of light through) and the viewer sees light of that color.
- If a voltage is applied between the electrodes on the glass plates (which are on either side of the liquid crystal), the induced electric field causes the liquid crystal molecules to rotate. Once rotated, the crystals no longer align the light coming through the first filter so that it can pass through the second filter plate.
- If light cannot cross, the area with the applied voltage looks dark. This is precisely how simple hand-held calculator displays work; usually the bright background is made dark every time a character is displayed.

Modern monitors, laptops, phones, and tablets use a version of the LCD called ***thin-film transistor*** (TFT) LCD; these also are known as ***active matrix*** displays. In TFT

LCDs, several thin films are deposited on one of the glass substrates and patterned into transistors. Each color component of a pixel has its own microscale transistor that controls the voltage across the liquid crystal; since the transistors only take up a tiny portion of the pixel area, they effectively are invisible. Thus, each pixel has its own electrode driver built directly into it. This specific feature enabled the construction of the flat high-resolution screens now in common use (and made the CRT display increasingly obsolete). Since LCD displays also weigh considerably less than a CRT tube, they enabled the emergence of laptop computers in the 1980s. Early laptops used large, heavy monochrome LCDs; most of today's mobile devices use active-matrix displays.

Light-Emitting Diode (LED) Displays

A different but very popular display technology employs tiny light-emitting diodes (LED) in large pixel arrays on flat screens (see Technology Brief 5 on LEDs). Each pixel in an LED display is composed of three LEDs (one each of red, green, and blue). Whenever a current is made to pass through a particular LED, it emits light at its particular color. In this way, displays can be made flatter (i.e., the LED circuitry takes up less room than an electron gun or LCD) and larger (since making large, flat LED arrays technically is less challenging than giant CRT tubes or LCD displays). Unlike LCDs, LED displays do not need a backlight to function and easily can be made multicolor.

Modern LED research is focused mostly on flexible and ***organic LEDs*** (OLEDs), which are made from polymer light-emitting materials and can be fabricated on flexible substrates (such as an overhead transparency). Flexible displays of this type have been demonstrated by several groups around the world.

Plasma Displays

Plasma displays have been around since 1964 when invented at the University of Illinois. While attractive due to their low profile, large viewing angle, brightness, and large screen size, they largely were displaced in the 1980s in the consumer market by LCD displays for manufacturing-cost reasons. In the late 1990s, plasma displays became popular for ***high-definition television*** (HDTV) systems.

Each pixel in a plasma display contains one or more microscale pocket(s) of trapped noble gas (usually neon or xenon); electrodes patterned on a glass substrate are placed in front and behind each pocket of gas (**Fig. TF9-3**).

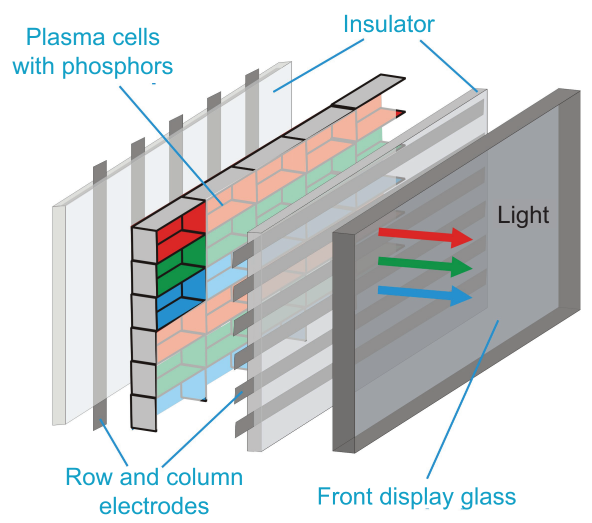

Figure TF9-3: Plasma display.

The back of one of the glass plates is coated with light-emitting phosphors. When a sufficient voltage is applied across the electrodes, a large electric field is generated across the noble gas, and a plasma (ionized gas) is ignited. The plasma emits ultraviolet light which impacts the phosphors; when impacted with UV light, the phosphors emit light of a certain color (blue, green, or red). In this way, each pocket can generate one color.

Electronic Ink

Electronic ink, ***e-paper***, or ***e-ink*** are all names for a set of display technologies made to look like paper with ink on it. In all cases, the display is very thin (almost as thin as real paper), does not use a backlight (ambient light is reflected off the display, just like real paper), and little to no power is consumed when the image is kept constant. The first version of e-paper was invented in the 1970s at Xerox, but it was not until the 1990s that a commercially viable version was developed at MIT. A number of electronic ink technologies are in production or in development.

- Most common electronic ink technologies trap a thin layer of oil between two layers of glass or plastic onto which have been patterned transparent electrodes. The total stack is usually less than a tenth of a millimeter.
- Within the oil are suspended charged particles. In some versions, the oil is colored.

Table TT9-1: A comparison of some characteristics of common display technologies; see also http://en.wikipedia.org/wiki/Comparison_of_CRT,_LCD,_Plasma,_and OLED.

Pros	Cons
Cathode Ray Tube (CRT)	
• Good dynamic range (~15,000 : 1) • Very little distortion • Excellent viewing angle • No inherent pixels	• Large and heavy, limiting maximum practical size • High power consumption and heat generation • Burn-in possible • Produces noticeable flicker at low refresh rates • Minimum size for color limited to 7″ diagonal • Can contain lead, barium, and cadmium, which are toxic
Plasma Displays	
• Excellent contrast ratios (~1,000,000 : 1) • Sub-millisecond response time • Near zero distortion • Excellent viewing angle • Very scalable (easier than other technologies to make large displays)	• Large minimum pixel pitch; suitable for larger displays • High power consumption than LCD • Limited color depth since plasma pixels can only be turned on or off, no grading of emission • Image burn-in possible
Organic Light-Emitting Diode (LED) Displays	
• Excellent viewing angle • Very light • Very fast, so no image distortion during fast motion • Excellent color quality because no backlight is used	• Limited lifetime of organic materials (but progress in this area is rapid) • Burn-in possible • More expensive than other technologies (ca. 2012)
Liquid Crystal Displays (LCD)	
• Small and light • Lower power consumption than plasma or CRT • No geometric distortion • Can be made in almost any size or shape • Liquid crystal has no inherent resolution limit	• Limited viewing angle • Slower response than plasma or CRT can cause image distortion during fast motion • Slow response at low temperatures • Requires a backlight, which can vary across screen
Digital Light Projection (DLP) Displays	
• No burn-in • Cheaper than LCD or plasma displays • DLPs with LED and laser sources do not need light source replacement very often • Excellent for very large screens (theaters) due to possibility of using multiple color sources (color depth) and no inherent size limitation to hardware	• Requires light source replacement • Reduced viewing angle compared with CRT, plasma, and LCD • Some viewers perceive the colors in the projection, producing a rainbow effect
Electronic Ink Displays	
• Very low power consumption • Works with reflected light; excellent for viewing in bright light • Lightweight • Flexible and bendable	• Slow, consumer units not yet suitable for fast video • Ghost images persist without refresh • Color displays are still under development

- Applying a potential across the electrodes on either side of the oil suspension attracts the charged particles to either the top or bottom substrates (depending on the polarity). Some displays use white particles in black fluid. Thus, when the white particles move to the top, they block the black fluid and the display appears white. When they move to the bottom, the display appears dark. Some displays use

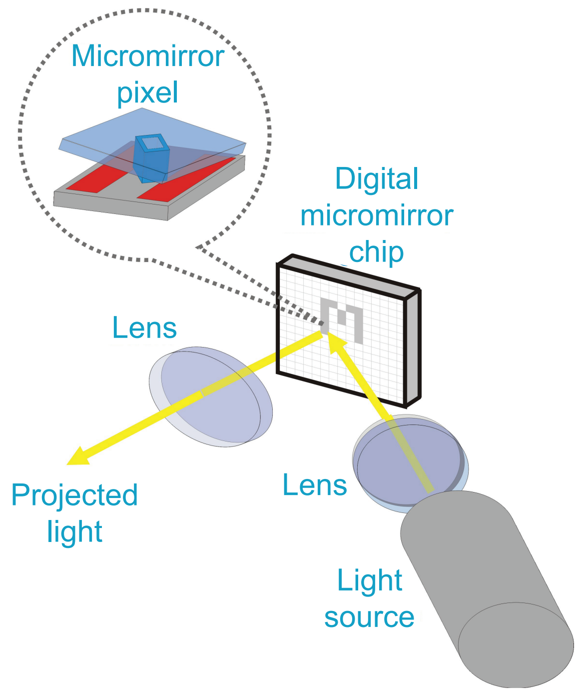

Figure TF9-4: A typical digital light processor (DLP) arrangement includes a light source, lenses, and a micromirror array that steers the light to create projected pixels.

a combination of black and white particles to achieve the same effect.

Digital Light Processing (DLP)

Digital light processing (DLP) is the name given to a technology that uses arrays of individual, micro-mechanical mirrors to manipulate light at each pixel position. Invented in 1987 by Dr. Hornbeck at Texas Instruments, this technology has revolutionized projection technology; many of today's digital projectors are made possible by DLP chips. DLP also was used heavily in large, rear-projection televisions.

- A basic DLP consists of an array of metal micromirrors, each about 100 micrometers on a side (**Fig. TF9-4(inset)**). One micromirror corresponds to one pixel on a digital image.
- Each micromirror is mounted on micromechanical hinges and can be tilted towards or away from a light source several thousand times per second!
- The mirrors are used to reflect light from a light source (housed within the television or projector case) and through a lens to project it either from behind a screen (as is the case in rear-projection televisions) or onto a flat surface (in the case of projectors), as in (**Fig. TF9-4**). If a micromirror is tilted away from the light source, that pixel on the projected image becomes dark (since the mirror is not passing the light onto the lens).
- If it is tilted towards the light source, the pixel lights up. By varying the relative time a given mirror is in each position, grey values can be generated as well.
- Color can be added by using multiple light sources and either one chip (with a filter wheel) or three chips. The three-chip color DLP used in high-resolution cinema systems can purportedly generate 35 trillion different colors!