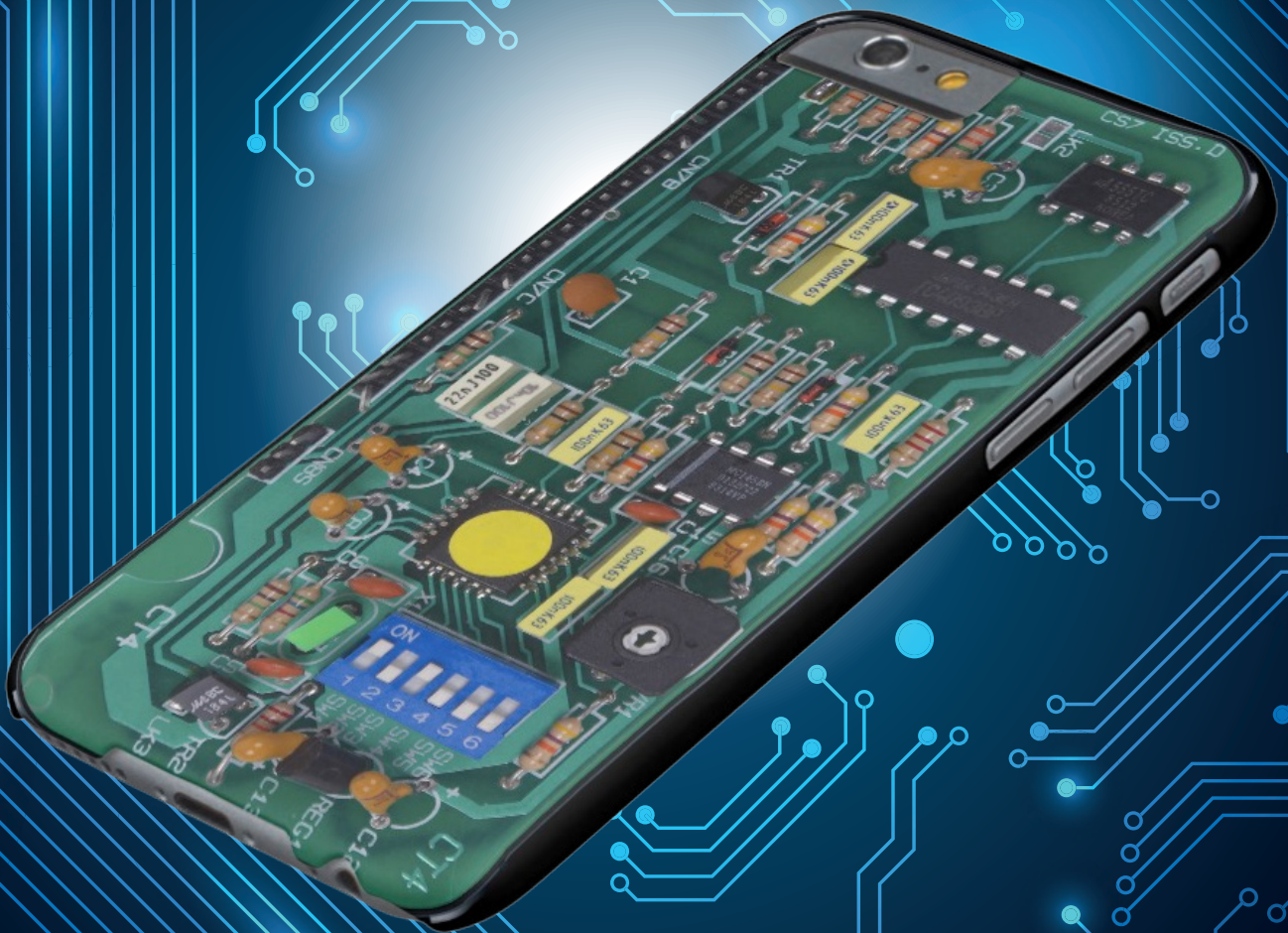


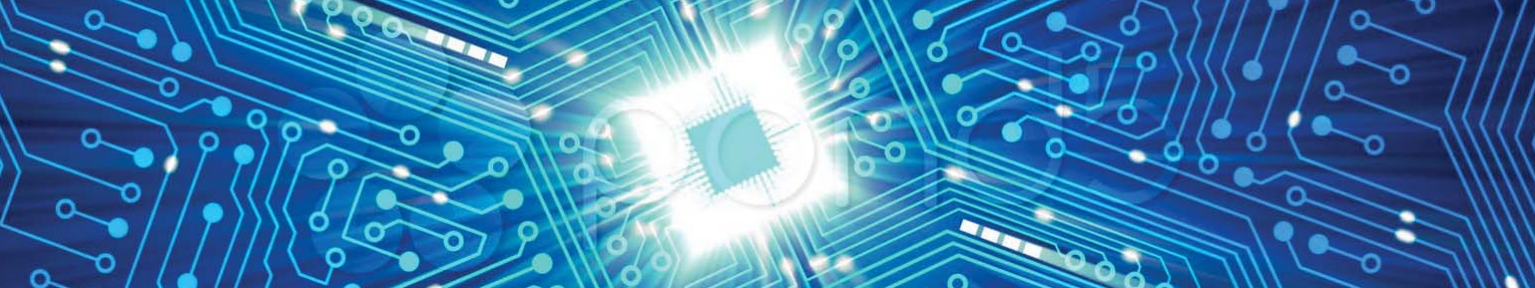
CIRCUIT ANALYSIS AND DESIGN

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CIRCUIT ANALYSIS AND DESIGN

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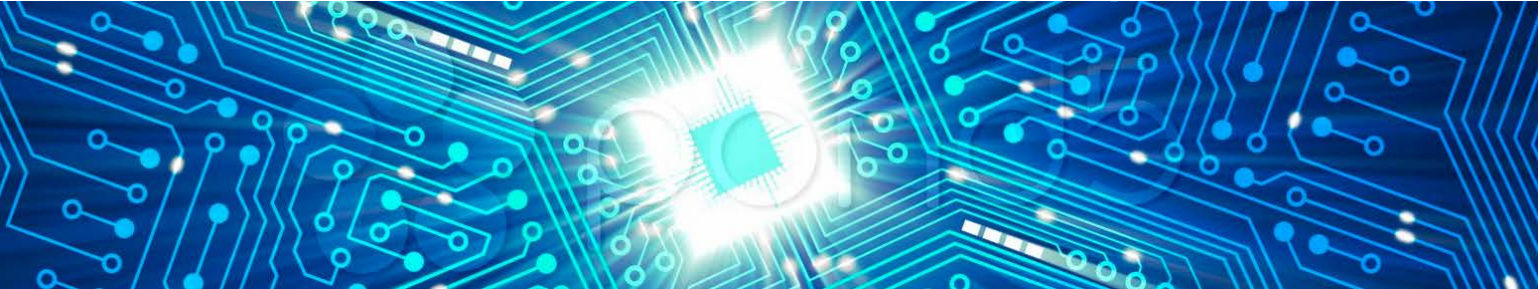
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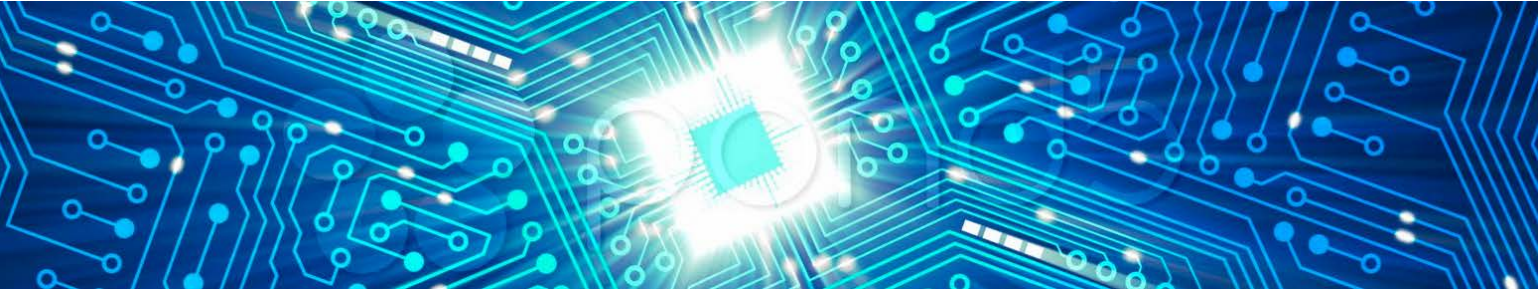
To an academic, writing a book is an endeavor of love.

We dedicate this book to Jean, Anissa, and Katie.



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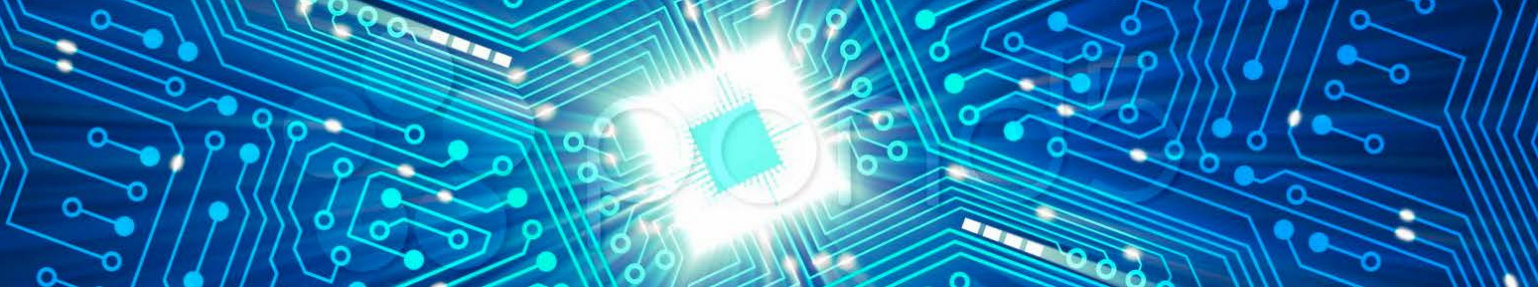
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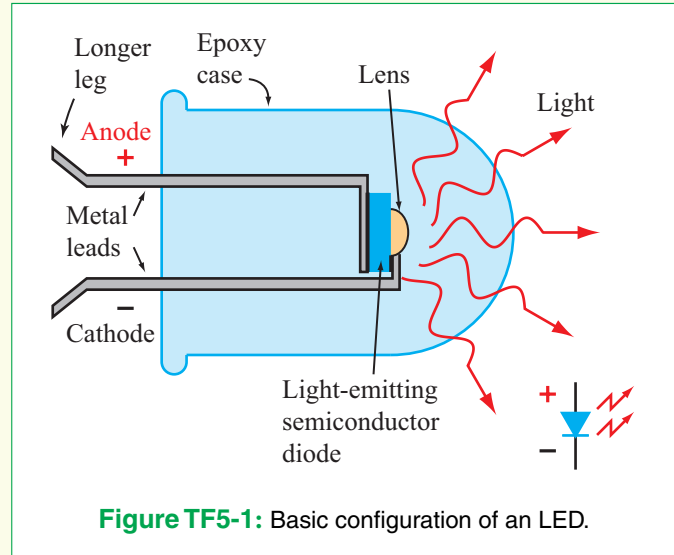
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Technology Brief 5 Light-Emitting Diodes (LEDs)

How LEDs Are Made

LEDs are a specific type of the much larger family of semiconductor diodes, whose basic behavior we discussed earlier in Section 2-6. When a voltage is applied in the forward-biased direction across an LED, current flows and photons are emitted (**Fig. TF5-1**). This occurs because as electrons surge through the diode material, they recombine with charge carriers in the material and release energy in the form of photons (quanta of light). The energy of the emitted photon (and hence the wavelength/color) depends on the type of material used to make the diode. For example, a diode made of indium gallium aluminum phosphide (InGaAlP) emits red light, while a diode made from gallium nitride (GaN) emits bluish light. Extensive research over many decades has yielded materials that can emit photons at practically any wavelength from the infrared through ultraviolet (**Fig. TF5-2**). Various “tricks” have also been employed to modify the emitted light after emission. To make white light diodes, for example, certain blue light diodes can be coated with crystal powders which convert the blue light into a broad-spectrum “white” light. Other coatings such as **quantum dots** are still the subject of today’s research. In a traditional package, the LED transmits light in a hemispherical pattern, but numerous other light-focused packaging methods are available that can focus the light in virtually any way imaginable. LEDs can be focused using highly reflective coatings to intensify their light for higher power applications.



In addition to semiconductor LEDs, a newer class of devices called **organic light emitting diodes** (OLEDs) are the subject of intense research efforts. OLEDs operate in a manner that is analogous to conventional LEDs, but are made from organic molecules (often polymers). Because OLEDs are lighter weight than conventional LEDs and can be made to be flexible, they have the potential to revolutionize handheld and lightweight displays, such as those used in phones, PDAs and flexible screens. Imagine a flexible contact lens that could allow you to see a heads-up display or augmented reality!

LED Advantages

LEDs have several major attributes that have made them a key element of many applications. First, they can be

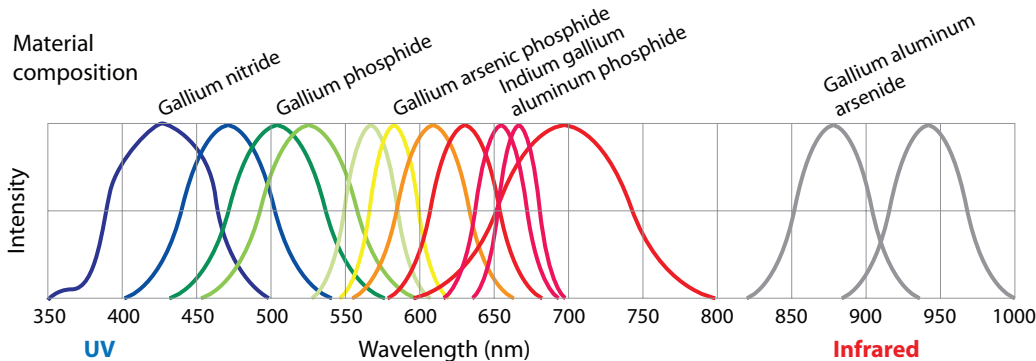




Figure TF5-3: LED-lit building.

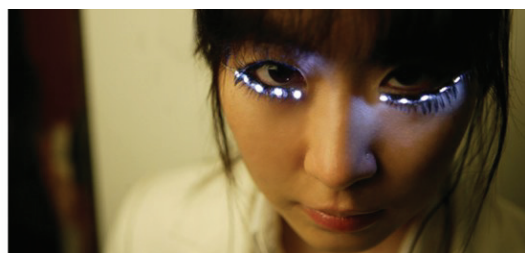


Figure TF5-4: LED eyelashes can be worn in many colors, and can be made to turn on or off with a tip of the head. (Credit: Soomi Park.)

produced in a wide variety of wavelengths from infrared through ultraviolet. Targeted or broad spectra can also be produced, making them applicable to virtually any optical application. Second, they are energy efficient. An incandescent lightbulb uses 80% of its energy for heat and 20% to produce light. LEDs use only about 20% of their energy for heat and 80% for light. This also makes them cool, requiring less energy to remove the excess heat. Third, they are manufactured in a huge array of colors, sizes, shapes, designs, and more. They are affordable (not yet less expensive than incandescent bulbs in the initial purchase price, but definitely less expensive over the lifetime of the bulb). Fourth, they last longer (often > 100k hours) than incandescent bulbs, which is particularly important in hard-to-reach applications. Fifth, they can be integrated directly into semiconductor circuits, printed circuit boards, and light-focusing packages. Various combinations of these advantages are key to the following broad range of applications of LEDs.

LEDs for Lighting

In an era where energy efficiency matters financially, environmentally, and practically, LEDs have become a popular mainstay in home and office lighting, street lighting and consumer products from home appliances and toys to high-efficiency tail lights for cars and flashlights. Of growing importance is the replacement of traditional incandescent bulbs with LEDs in homes and buildings (**Fig. TF5-3**), because of their energy efficiency.

But lighting is more than just enabling us to see at night. LEDs can be used in horticulture to efficiently target ideal wavelengths for plant growth, and exposing produce to certain wavelengths of light can help it ripen on demand, or can extend its ripened shelf life. UV LEDs are being explored to enhance development of polyphenol, which are believed to have antioxidant qualities, in growth of green, leafy vegetables. LEDs provide high visibility bike lights, safety vests, tennis shoes, and more. They are also used artistically for decoration and advertising on buildings and signs, woven into clothes often augmented by plastic fiber optic threads (e.g., Philips Research Lumalive textiles), or even worn with LED eyelashes (see **Fig. TF5-4**)!

LEDs for Medical Applications

LEDs are used for a variety of medical applications. One particularly important application is the pulse oximeter (**Fig. TF5-5**), which measures blood oxygen level and pulse rate. Oxygenated blood absorbs light at 660 nm (red light), whereas deoxygenated blood absorbs light at 940 nm (infrared). Pulse oximeters use two LEDs, one at 600 nm and another at 940 nm, which are arranged to transmit through a translucent section of the body such as the finger or ear lobe. Two associated light collecting sensors are placed on the opposite side to measure the amount of each wavelength that is transmitted through the body. The ratio of the red and infrared light indicates how much oxygen is in the blood. To insure that the received light signals are actually from the blood, the measurement is made over several seconds (several pulses), focusing in on the pulsing blood rather than the static surrounding tissues.



Figure TF5-5: Pulse oximeter used to measure blood oxygen content.

LEDs are also used to treat many superficial (skin) conditions. Red light in the range of 600–950 nm can be used to treat acne, rosacea, and wrinkles. The red light works by stimulating the mitochondria in the skin to make older cells behave like younger cells. Blue-light therapy in the 405–420 nm range is used for acne treatments and “anti-aging” skin therapies because of its ability to stimulate collagen in the skin. Green to yellow light (532–595 nm) can reduce skin redness (rosacea). Combining LED light sources with topical drug treatments that are **photoactivated** may be used to treat a variety of skin conditions including skin cancer and pre-cancer.

LEDs are also used extensively in dentistry. Blue LEDs can be used to cure (harden) polymer composite materials used for fillings. The rate at which the filling material cures is proportional to the power carried by the LED light, so high power LEDs are used to speed up the curing process.

Ultraviolet (UV) LEDs

The UV range provides a wealth of applications, and low-cost high-power UV LEDs are enabling many of these applications. Inks (printing), adhesives and coatings are often cured with LEDs in the UV range (primarily 395 nm, 385 nm or 365 nm). UV LED flashlights are used to detect fraudulent identification (at the airport, for example) and currency. UV-LEDs are used extensively in forensic analysis and drug discovery. In the lower UV spectral range (100–280 nm) LEDs sterilize air and water by breaking up the DNA and RNA of



Figure TF5-6: Large LED display.

microorganisms and preventing their reproduction. For example, 275 nm is believed to be the most effective wavelength for eradicating pathogens such as E-coli in water. LEDs in this range are also used for spectroscopic and fluorescence measurements and for chemical and biological detectors.

LED Displays

LEDs, with their wide range of colors, efficiency, low cost, flexibility, low profile and light weight, are ideal for both handheld displays and much larger displays (such as billboards and signage, as shown in **Fig. TF5-6**). Some LED displays use edge lighting where LEDs shine light across the screen (allowing the display to be thinner than traditional screens but not improving picture quality). Others use RGB LEDs. These LEDs use a common anode but have separate cathodes for red, green and blue LEDs (making the composite a 4-pin LED). They can be made to generate light with almost any color, depending on the voltages applied across the combination of RGB pins. This greatly enhances picture color. RGB LEDs can also be dimmed independently and instantly (giving a more dynamic picture, especially great “black” levels for dark scenes). The flexibility and bendability of OLEDs promise new, creative options for the next generation of TVs and smart phones—can you imagine rolling your TV up like a poster and carrying it with you anywhere? Or wearing it? Or ...?

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.

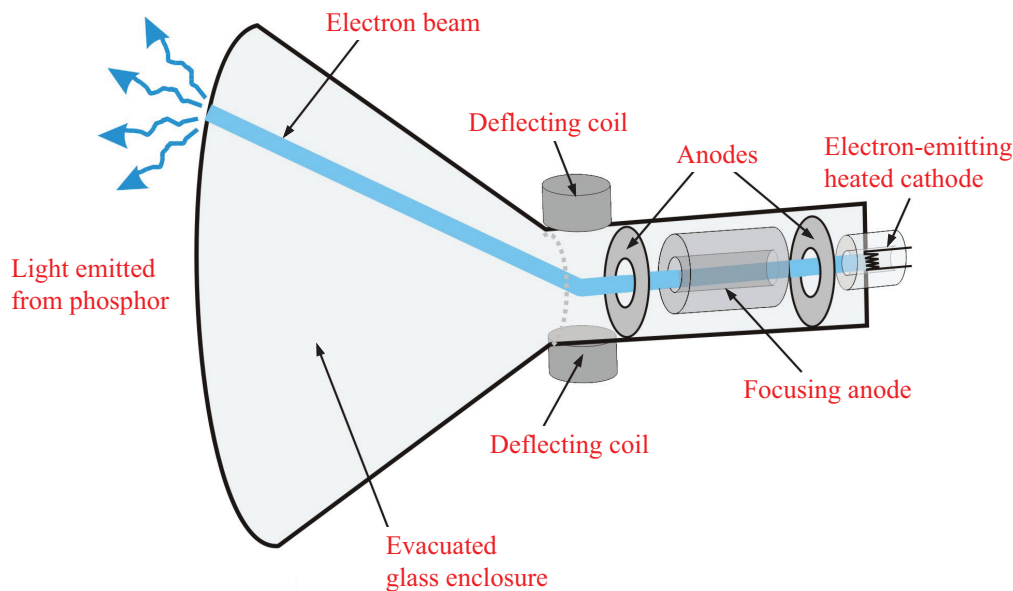


Figure TF9-1: Schematic of CRT operation.

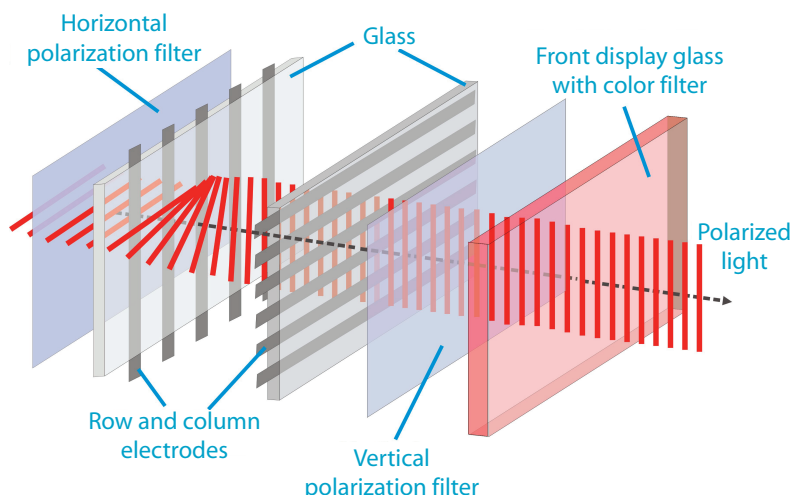


Figure TF9-2: Schematic of LCD operation.

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**).

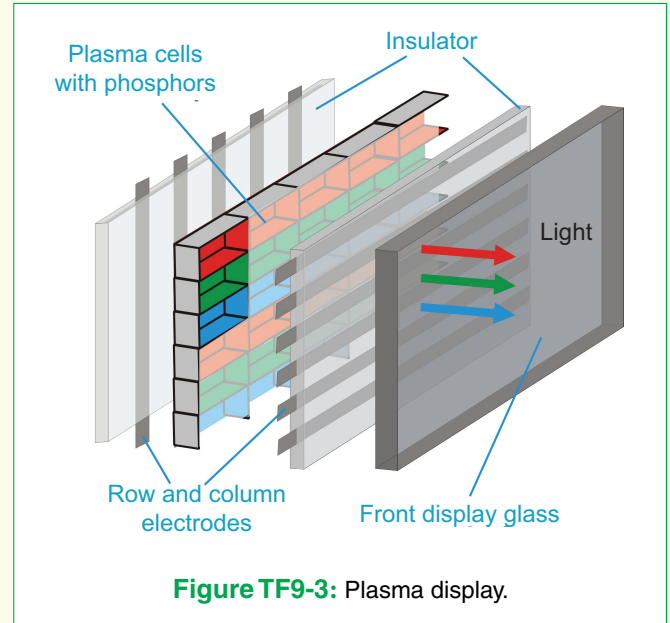


Figure TF9-3: Plasma display.

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

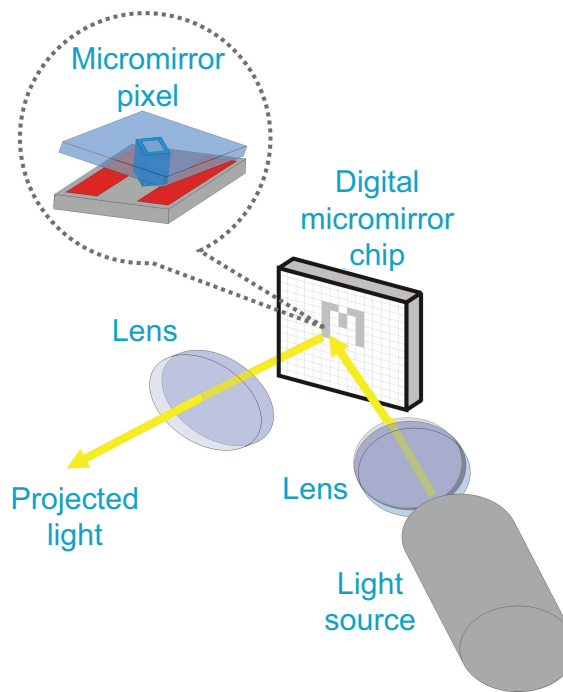


Figure TF9-4: A typical digital light processor (DLP) arrangement includes a light source, lenses, and a micromirror array that steers the light to create projected pixels.

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

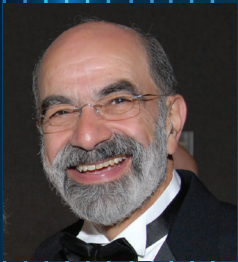
Digital Light Processing (DLP)

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!

CIRCUIT ANALYSIS AND DESIGN

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