How LCDs Work

by Jeff Tyson

You probably use items containing an **LCD** (**liquid crystal display**) every day. They are all around us -- in laptop computers, digital clocks and watches, microwave ovens, CD players and many other electronic devices. LCDs are common because they offer some real advantages over other display technologies. They are thinner and lighter and draw much less power than cathode ray tubes (CRTs), for example.

A simple LCD display from a calculator

But just what are these things called liquid crystals? The name "liquid crystal" sounds like a contradiction. We think of a crystal as a solid material like quartz, usually as hard as rock, and a liquid is obviously different. How could any material combine the two?

In this article, you'll find out how liquid crystals pull off this amazing trick, and we will look at the underlying technology that makes LCDs work. You'll also learn how the strange characteristics of liquid crystals have been used to create a new kind of shutter and how grids of these tiny shutters open and close to make patterns that represent numbers, words or images!

LCD History

Today, LCDs are everywhere we look, but they didn't sprout up overnight. It took a long time to get from the discovery of liquid crystals to the multitude of LCD applications we now enjoy. Liquid crystals were first discovered in 1888, by Austrian botanist **Friedrich Reinitzer**. Reinitzer observed that when he melted a curious cholesterol-like substance (**cholesteryl benzoate**), it first became a cloudy liquid and then cleared up as its temperature rose. Upon cooling, the liquid turned blue before finally crystallizing. Eighty years passed before **RCA** made the first experimental LCD in 1968. Since then, LCD manufacturers have steadily developed ingenious variations and improvements on the technology, taking the LCD to amazing levels of technical complexity. And there is every indication that we will continue to enjoy new LCD developments in the future!

Liquid Crystals

We learned in school that there are three common states of matter: solid, liquid or gaseous. **Solids** act the way they do because their molecules always maintain their orientation and stay in the same position with respect to one another. The molecules in **liquids** are just the opposite: They can change their orientation and move anywhere in the liquid. But there are some substances that can exist in an odd state that is sort of like a liquid and sort of like a solid. When they are in this state, their molecules tend to maintain their orientation, like the molecules in a solid, but also move around to different positions, like the molecules in a liquid. This means that liquid crystals are neither a solid nor a liquid. That's how they ended up with their seemingly contradictory name.

So, do liquid crystals act like solids or liquids or something else? It turns out that liquid crystals are closer to a liquid state than a solid. It takes a fair amount of heat to change a suitable substance from a solid into a liquid crystal, and it only takes a little more heat to turn that same liquid crystal into a real liquid. This explains why liquid crystals are very sensitive to **temperature** and why they are used to make thermometers and mood rings. It also explains why a laptop computer display may act funny in cold weather or during a hot day at the beach!

Just as there are many varieties of solids and liquids, there is also a variety of liquid crystal substances. Depending on the temperature and particular nature of a substance, liquid crystals can be in one of several distinct phases (see below). In this article, we will discuss liquid crystals in the **nematic phase**, the liquid crystals that make LCDs possible.

One feature of liquid crystals is that they're affected by **electric current**. A particular sort of nematic liquid crystal, called **twisted nematics** (TN), is naturally twisted. Applying an electric current to these liquid crystals will untwist them to varying degrees, depending on the current's voltage. LCDs use these liquid crystals because they react predictably to electric current in such a way as to control light passage.

Liquid Crystal Types

Most liquid crystal molecules are rod-shaped and are broadly categorized as either **thermotropic** or **lyotropic**.

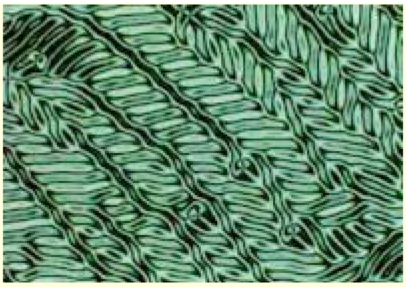


Image courtesy Dr. Oleg Lavrentovich, Liquid Crystal Institute

Thermotropic liquid crystals will react to changes in temperature or, in some cases, pressure. The reaction of lyotropic liquid crystals, which are used in the manufacture of soaps and detergents, depends on the type of solvent they are mixed with. Thermotropic liquid crystals are either **isotropic** or **nematic**. The key difference is that the molecules in isotropic liquid crystal substances are random in their arrangement, while nematics have a definite order or pattern.

The orientation of the molecules in the nematic phase is based on the **director**. The director can be anything from a magnetic field to a surface that has microscopic grooves in it. In the nematic phase, liquid crystals can be further classified by the way molecules orient themselves in respect to one another. **Smectic**, the most common arrangement, creates layers of molecules. There are many variations of the smectic phase, such as smectic C, in which the molecules in each layer tilt at an angle from the previous layer. Another common phase is **cholesteric**, also known as **chiral nematic**. In this phase, the molecules twist slightly from one layer to the next, resulting in a spiral formation.

Ferroelectric liquid crystals (FLCs) use liquid crystal substances that have chiral molecules in a smectic C type of arrangement because the spiral nature of these molecules allows the microsecond switching response time that make FLCs particularly suited to advanced displays. **Surface-stabilized ferroelectric liquid crystals** (SSFLCs) apply controlled pressure through the use of a glass plate, suppressing the spiral of the molecules to make the switching even more rapid.

Building a Simple LCD

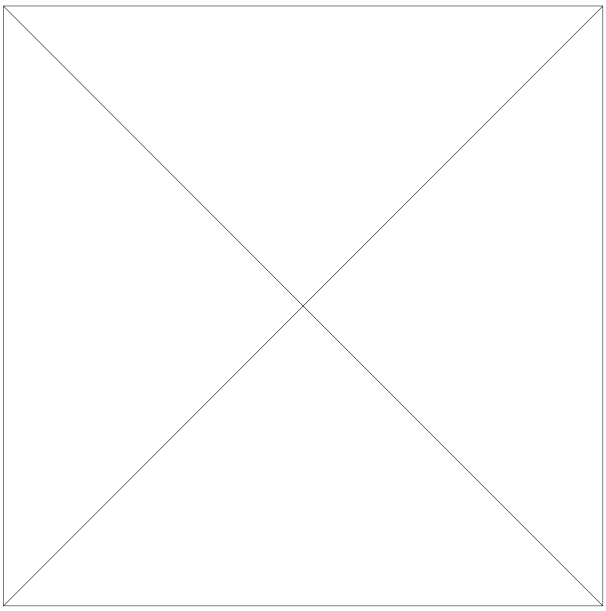
There's far more to building an LCD than simply creating a sheet of liquid crystals. The combination of four facts makes LCDs possible:

- Light can be polarized. (See How Sunglasses Work for some fascinating information on polarization!)
- Liquid crystals can transmit and change polarized light.
- The structure of liquid crystals can be changed by electric current.
- There are transparent substances that can conduct electricity.

An LCD is a device that uses these four facts in a surprising way!

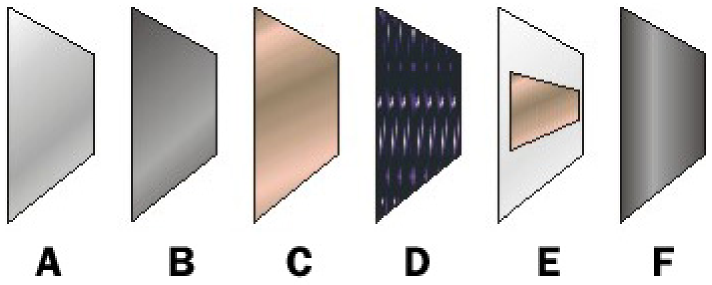
To create an LCD, you take **two pieces of polarized glass**. A special polymer that creates microscopic grooves in the surface is rubbed on the side of the glass that does not have the polarizing film on it. The grooves must be in the same direction as the polarizing film. You then add a **coating of nematic liquid crystals** to one of the filters. The grooves will cause the first layer of molecules to align with the filter's orientation. Then add the second piece of glass with the **polarizing film at a right angle** to the first piece. Each successive layer of TN molecules will gradually twist until the uppermost layer is at a 90-degree angle to the bottom, matching the polarized glass filters.

As light strikes the first filter, it is polarized. The molecules in each layer then guide the light they receive to the next layer. As the light passes through the liquid crystal layers, the molecules also change the light's plane of vibration to match their own angle. When the light reaches the far side of the liquid crystal substance, it vibrates at the same angle as the final layer of molecules. If the final layer is matched up with the second polarized glass filter, then the light will pass through.



If we apply an **electric charge** to liquid crystal molecules, they untwist! When they straighten out, they change the angle of the light passing through them so that it no longer matches the angle of the top polarizing filter. Consequently, no light can pass through that area of the LCD, which makes that area darker than the surrounding areas.

Building a simple LCD is easier than you think. Your start with the sandwich of glass and liquid crystals described above and add two transparent electrodes to it. For example, imagine that you want to create the simplest possible LCD with just a single rectangular electrode on it. The layers would look like this:

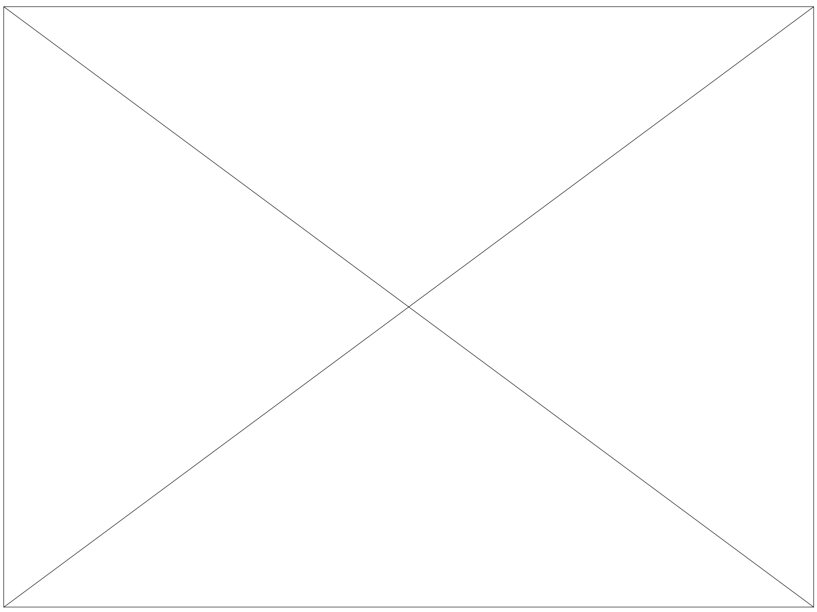


The LCD needed to do this job is very basic. It has a mirror (**A**) in back, which makes it reflective. Then, we add a piece of glass (**B**) with a polarizing film on the bottom side, and a common electrode plane (**C**) made of indium-tin oxide on top. A common electrode plane covers the entire area of the LCD. Above that is the layer of liquid crystal substance (**D**). Next comes another piece of glass (**E**) with an electrode in the shape of the rectangle on the bottom and, on top, another polarizing film (**F**), at a right angle to the first one.

The electrode is hooked up to a power source like a battery. When there is no current, light entering through the front of the LCD will simply hit the mirror and bounce right back out. But when the battery supplies current to the electrodes, the liquid crystals between the common-plane electrode and the electrode shaped like a rectangle untwist and block the light in that region from passing through. That makes the LCD show the rectangle as a black area.

Backlit vs. Reflective

Note that our simple LCD required an **external light source**. Liquid crystal materials emit no light of their own. Small and inexpensive LCDs are often **reflective**, which means to display anything they must reflect light from external light sources. Look at an LCD watch: The numbers appear where small electrodes charge the liquid crystals and make the layers untwist so that light is not transmitting through the polarized film.



Most computer displays are lit with built-in **fluorescent tubes** above, beside and sometimes behind the LCD. A white diffusion panel behind the LCD redirects and scatters the light evenly to ensure a uniform display. On its way through filters, liquid crystal layers and electrode layers, a lot of this light is lost -- often more than half!

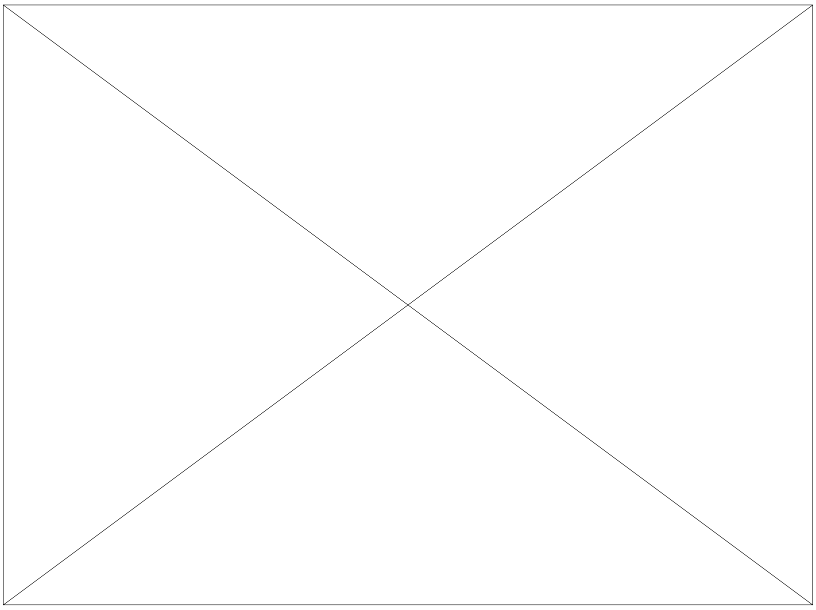
In our example, we had a common electrode plane and a single electrode bar that controlled which liquid crystals responded to an electric charge. If you take the layer that contains the single electrode and add a few more, you can begin to build more sophisticated displays.

LCD Systems

Common-plane-based LCDs are good for simple displays that need to show the same information over and over again. Watches and microwave timers fall into this category. Although the hexagonal bar shape illustrated previously is the most common form of electrode arrangement in such devices, almost any shape is possible. Just take a look at some inexpensive handheld games: Playing cards, aliens, fish and slot machines are just some of the electrode shapes you'll see!

There are two main types of LCDs used in computers, **passive matrix** and **active matrix**.

Passive-matrix LCDs use a simple grid to supply the charge to a particular pixel on the display. Creating the grid is quite a process! It starts with two glass layers called **substrates**. One substrate is given columns and the other is given rows made from a transparent conductive material. This is usually **indium-tin oxide**. The rows or columns are connected to **integrated circuits** that control when a charge is sent down a particular column or row. The liquid crystal material is sandwiched between the two glass substrates, and a polarizing film is added to the outer side of each substrate. To turn on a pixel, the integrated circuit sends a charge down the correct column of one substrate and a ground activated on the correct row of the other. The row and column **intersect** at the designated pixel, and that delivers the voltage to untwist the liquid crystals at that pixel.



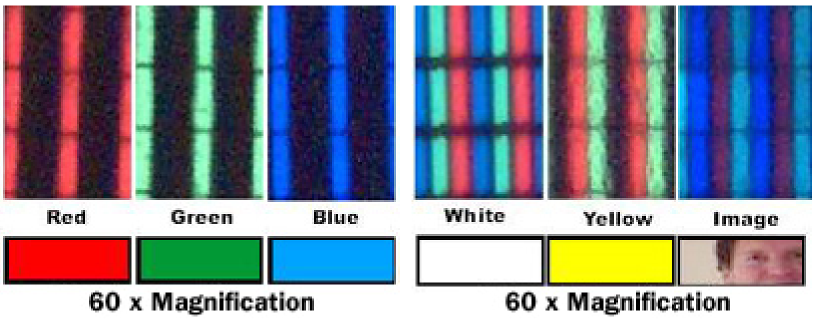
The simplicity of the passive-matrix system is beautiful, but it has significant drawbacks, notably **slow response time** and **imprecise voltage control**. Response time refers to the LCD's ability to refresh the image displayed. The easiest way to observe slow response time in a passive-matrix LCD is to move the mouse pointer quickly from one side of the screen to the other. You will notice a series of "ghosts" following the pointer. Imprecise voltage control hinders the passive matrix's ability to influence only one pixel at a time. When voltage is applied to untwist one pixel, the pixels around it also partially untwist, which makes images appear fuzzy and lacking in contrast.

Active-matrix LCDs depend on **thin film transistors** (TFT). Basically, TFTs are tiny switching transistors and capacitors. They are arranged in a matrix on a glass substrate. To address a particular pixel, the proper row is switched on, and then a charge is sent down the correct column. Since all of the other rows that the column intersects are turned off, only the capacitor at the designated pixel receives a charge. The capacitor is able to hold the charge until the next refresh cycle. And if we carefully control the amount of voltage supplied to a crystal, we can make it untwist only enough to allow some light through. By doing this in very exact, very small increments, LCDs can create a **gray scale**. Most displays today offer 256 levels of brightness per pixel.

Color

An LCD that can show colors must have **three subpixels** with red, green and blue color filters to create each color pixel.

Through the careful control and variation of the voltage applied, the intensity of each subpixel can range over **256 shades**. Combining the subpixels produces a possible palette of **16.8 million colors** (256 shades of red x 256 shades of green x 256 shades of blue), as shown below. These color displays take an enormous number of transistors. For example, a typical laptop computer supports resolutions up to 1,024x768. If we multiply 1,024 columns by 768 rows by 3 subpixels, we get 2,359,296 transistors etched onto the glass! If there is a problem with any of these transistors, it creates a "bad pixel" on the display. Most active matrix displays have a few bad pixels scattered across the screen.



LCD Advances

LCD technology is constantly evolving. LCDs today employ several variations of liquid crystal technology, including super twisted nematics (STN), dual scan twisted nematics (DSTN), ferroelectric liquid crystal (FLC) and surface stabilized ferroelectric liquid crystal (SSFLC). For an in-depth (and pretty technical) article that addresses all of technologies, see Liquid Crystal Materials.

Display size is limited by the quality-control problems faced by manufacturers. Simply put, to increase display size, manufacturers must add more pixels and transistors. As they increase the number of pixels and transistors, they also increase the chance of including a bad transistor in a display. Manufacturers of existing large LCDs often reject about 40 percent of the panels that come off the assembly line. The level of rejection directly affects LCD price since the sales of the good LCDs must cover the cost of manufacturing both the good and bad ones. Only advances in manufacturing can lead to affordable displays in bigger sizes.