Introduction to Liquid Crystals: Chapter 1

Liquid Crystal Displays: Manipulating light with molecules.

by

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INTRODUCTION

Liquid crystals are materials which have unusual, fascinating and often beautiful properties. Their discovery was credited to an Austrian biologist almost 110 years ago when he noticed that the solid phase of a derivative of cholesterol melted to form an iridescent fluid before becoming a clear liquid. He realised that the classification of materials into solids, liquids and gases was not adequate and the term 'liquid crystal' was coined. Many thousands of materials are now known to be liquid crystalline, including synthetic systems (e.g. materials for displays, Kevlar, detergents and antiasthmatic drugs) and naturally occurring materials (e.g. beetles' wings, DNA, spiders' webs, and even budgerigar droppings).

Liquid crystals are best known for their use in displays which became common in the early 1980s and are now used extensively. Liquid crystal displays (LCDs) can be found in objects as diverse as watches, calculators, information display boards, aeroplane

They cockpits and lap top computers. operate by modulating light and simple optics and an understanding of what liquid crystals are is all that is necessary to understand how a liquid crystal light valve works. LCDs were invented in the 1950s, but only became common in the late 1970s. The main reason for this marketing delay was the lack of good stable chemicals that form liquid crystals. The materials that were available in the 1950s degraded on exposure light, something that is clearly to unacceptable in a device that manipulates light! Professor George Gray from Hull University's Chemistry Department in the U.K. solved the materials problem in the early 1970s by inventing a new series of light stable molecules which formed liquid crystal phases over a very wide temperature range. It didn't take long for industry to take advantage of this windfall of materials and by the late 1970s liquid crystal displays were all the rage.

WHAT ARE LIQUID CRYSTALS?

To understand how liquid crystal devices work, it is necessary to explain what a liquid crystal actually is. As the name suggests, liquid crystals are materials which have properties intermediate to the solid and liquid states of matter. They are true fluids (i.e. they flow readily), but they retain orientational order on melting from the solid to the liquid crystal state. This is shown schematically in Figure 1 where a solid in the form of a hexagonal crystal lattice melts to form a liquid crystal before finally melting to the 'normal' liquid state.



Figure 1.

On heating a crystal structure the molecules can form an oriented liquid crystal structure before finally becoming totally disordered in the high temperature liquid phase.

One of the prerequisites for a material to form a liquid crystalline state is that the molecules are *geometrically anisotropic*. Put more simply, they must be different in different directions (e.g. cigar shaped as shown here). As the crystal melts, there is a state where the molecules are free to move, but still retain some order - the liquid crystal state. In this case they all point in the same direction and posses ORIENTATIONAL ORDER, but no positional order. A spherical molecule cannot form a liquid crystal state as there is no preferred orientation which it can adopt. It is this orientational order which is characteristic of the liquid crystal state. When the temperature is increased further, the molecules eventually have sufficient energy to move completely randomly and no longer possess even orientational order.

There are several ways in which fluid, ordered states can form. The simplest is the one shown in figure 1, and is known as a 'nematic' phase. The name comes from the Greek word *nematos* meaning thread-like and is due to the rather beautiful thread-like appearance of these materials when viewed using a polarising microscope. The only type of order that occurs in nematic liquid crystals is *orientational*. All of the common liquid crystal devices employ nematic liquid crystals.

More ordered liquid crystal states can exist where, in addition to pointing in a preferred direction, the molecules form a layered structure. Such materials are known as 'smectic' and their structure is shown schematically in figure 2. Smectic phases occur at lower temperatures than nematic phases (they have more order) and are far more viscous as the easiest mode of flow is for the layers to slip over one another.



A cartoon of a smectic phase where the cigar shaped molecules have orientational order and form a layered structure.

Molecular structure can be very complex and molecular engineers find new methods of adding different functionality to molecules all the time. One of the most common methods of making a molecular structure more complex is to introduce *chirality*. Chirality describes the lack of mirror symmetry in a molecule, i.e. the fact that for some molecules the mirror image can not be superimposed on the original, something best shown in a diagram (figure 3). Chirality is often referred to as handedness the left and right hands are chiral as one is the mirror image of the other, but they cannot be superimposed on one another (try it!). The addition of chirality to molecules is very important in liquid crystals and can result in some fascinating fluids. Here, only the simplest liquid crystal phase that can be formed from chiral molecules is described, known as the cholesteric phase.

The name 'cholesteric' was adopted because many of the materials first discovered that showed chiral liquid crystal structures derived from cholesterol. In fact, many naturally occurring liquid crystals are chiral and these are discussed later.



Figure 3. *Chirality and handedness.*

The structure of the cholesteric phase is shown schematically in figure 4. A slice of this structure is identical to the nematic phase, i.e. all the molecules point in the same direction. However, successive slices point in different directions and the overall structure is helical - this can be seen by tracing out the positions tips of the molecules on progressing from one slice to the next throughout the structure in the diagram



Figure 4. The arrangement of molecules in a cholesteric liquid crystal.

. The helicoidal structure has fascinating optical properties which are described in the next chapter.

THE CONSTRUCTION AND OPTICS OF AN LCD.

Having described liquid crystal phases, it is now possible to explain how a liquid crystal device works. The device has a simple construction - it is a sandwich of nematic liquid crystal between glass. The liquid crystal layer is extremely thin - only about 10 μ m thick, which is less than the thickness of a human hair. Although the nematic liquid crystal has a structure in which the molecules all point in a preferred direction, this direction must be defined in the device in order for it to operate.

The method of doing this is surprisingly simple. The glass surfaces are treated with a rubbed polymer layer which forces the liquid crystal molecules to lie in a specific



Figure 5. Alignment of nematic liquid crystals by grooved surfaces.

direction. The rubbing forms micro-grooves in the polymer surface and the liquid crystal molecules prefer to lie along rather than across the grooves, see figure 5. The other important element in the device are the transparent electrodes on the inner surfaces of the glass. These allows a voltage to be applied across the device, taking advantage of another property of liquid crystals, their response to an electric field. Nematic liquid crystal molecules possess a small electronic dipole (a small positive charge at one end of the molecule and a small negative one at the other). The dipole ensures that the molecule responds to an electric field, as shown in figure 6. On application of the field the molecules rotate to minimise their energy - this is achieved by the positive ends of the molecules rotating to point in the direction of the negative electrode and vice versa. The idea is identical to magnetic dipoles rotating in a magnetic field.

The elements needed to form a liquid crystal device are almost all there. The molecules can be made to lie pointing in a preferred direction within the device, and, when a voltage is applied, that direction is changed. As the voltage is removed, the molecules will return to their original position lying flat against the glass plates. Now the way in which such a device interacts with light must be considered. The construction of the most common device, the TWISTED NEMATIC



Figure 6. *The re-orientation of nematic liquid crystal molecules on application of a voltage.*

(TN) device is shown in figure 7.Notice in figure 7(a) that the glass surfaces of the device have been treated so that the molecules on the top surface lie at right angles to those on the bottom. Because the liquid crystal used is nematic, the molecules try to all point in the same direction, though the surface treatment prevents them from doing so. The molecular orientation in the device has to reach a compromise and the molecules are twisted through 90° (a quarter turn) between the top and bottom glass surfaces, as shown in the figure. It is this twist which gives the device its name and it is extremely important in the operation of the device.



Figure 7

The operation of a twisted nematic device in (a) the light state and (b) the dark state. The glass surfaces are coated with alignment layers which allow the molecules to become preferentially oriented in specific directions on the surfaces. The glass is also coated with transparent Indium Tin Oxide electrodes which allows a voltage to be applied across the liquid crystal layer.

The optical properties of this twisted nematic device rely on the use of polarised light (notice that in figure 7 it is placed between crossed polarisers). Two pieces of crossed polariser alone they do not transmit light. However, if the twisted nematic device is placed between crossed polarisers, light is transmitted. This is because the twisted structure guides the direction of polarisation of the light so that it is rotated by 90° on passing through the device. Light passing through the first polariser has the direction of polarisation rotated by the TN device such that it can pass through the second (crossed) polariser; the device appears light. The effect can be demonstrated by taking a glass microscope slide and building up a twist (quarter turn) by placing a few strips of sellotape one on top of another. The glass alone will not allow light through crossed polarisers, but the twist built up of sellotape strips will. Both the sellotape and the liquid crystal are examples of birefringent (or doubly refracting) materials and it is this property which allows the polarised light to be guided.

The operation of the device is now clear. In the absence of a voltage, the liquid crystal adopts a twisted structure that guides light and therefore appears light when placed between crossed polarisers. However when a sufficiently large voltage (usually about 1.5V) is applied across the device the molecules rotate to point in the direction of the electric field and the twist is destroyed. In the absence of the twist light is not guided through the crossed polarisers and the device appears dark. When the voltage is removed, the molecules relax back to the original twisted state under the influence of the

WHAT ABOUT COLOUR?

In many cases, especially computer terminals and television sets, the display must be coloured, not just black and white. Colour is achieved by putting small colour filters in front of the device. The colours which are chosen are the primary colours (red, green and blue) from which any other colour can be made. The filters are placed on extremely small picture elements known as pixels next surface forces and the device again transmits light.

The device is a light valve which transmits light when no voltage is applied to the device, and appears dark when the voltage is applied. Notice that all that liquid crystals can do is allow light to be transmitted or not - they are known as *passive* devices, as opposed to active devices such as light emitting diodes or electroluminescent displays which actually create light in some (Light emitting diodes work by way. electrons an holes combining in the semiconductor material which makes up the diode, producing a photon, whilst an electroluminescent material is a phosphor which emits light when it is subjected to an alternating electric field.) In the completed liquid crystal display device, a mirror is often placed behind the TN display and ambient light (from the room lights, sunlight) is used for windows or illumination. In more complex displays such as computer screens, a flat electroluminescent back light is placed behind the TN device to provide the light.

By the way, because the device relies on polarized light, several different effects can easily be observed, all of which rely on basic optics. For example, if you look at a liquid crystal display whilst wearing Polaroid sun glasses, you will be able to see that the device uses polarised light by rotating the display or turning your head. Alternatively, by using parallel polarisers in the device rather than crossed ones, you can make the display appear bright when the voltage is applied and dark with the voltage off (the opposite to that described above).

to one another so that the coloured picture can be built up - the eye is tricked into combining the colours from a small area of the display to give the composite colour. This technique is used in all colour TV sets and if you look closely at one you will be able to see the colour filters on the front of the display.

WHAT ABOUT COMPLEXITY AND SPEED?

The most common example of a TN device is probably in the digital watch. All that is necessary in such an application is the ability to display the digits from 0 - 9 and change between them faster than the eye response time (about 25ms). The electrode design is typically one such as that shown in figure 8(a) as all the required digits can be made up from this pattern. The response time of the liquid crystal changing from the light to dark state is approximately 10ms.





(b) Figure 8

Electrode patterns for (a) a 7 segment alphanumeric display (front and rear surface electrodes shown), and (b) a dot-matrix display for more complex graphics. The electrode connections are always made along the edges.

In order to make more complex displays, arrays of electrodes are arranged in a crisscross pattern (vertical electrodes on the top surface, say, and horizontal ones on the bottom surface), figure 8(b). As this device is just a complex arrangement of the twisted nematic device described, the whole device will transmit light if it is placed between crossed polarisers. A picture, graph or message can be made up of dark dots if the pixels (picture elements or dots) at the crossover points of the top and bottom electrodes can be switched to the dark state individually. A liquid crystal device requires a certain voltage to be applied to the electrodes in order to rotate the molecules and cause the display to appear dark. If half the voltage which is required to switch the liquid crystal is supplied along the bottom surface electrode, and the other half to the top surface electrodes, only the crossover point will have a sufficiently large potential difference across it to turn it dark. The remainder of the liquid crystal will not be affected.

Graphics may be built up from these dots in much the same way as newspaper print makes up pictures. This type of display is known as 'dot matrix' as the picture is made up of a matrix of dark dots. The whole picture is built up dynamically by scanning the voltage applied to one set of electrodes as shown. Very simple graphics such as those on programmable calculators can be successfully displayed in this way.

Of course, life is rarely as simple as it might be. The response time of the liquid crystal is actually the major restriction in making displays increasingly more complex. Even to make up a picture with very basic resolution typically 100x100 pixels (or 100 horizontal and 100 vertical lines) are needed. The speed with which the picture can be built up is a severe restriction. If a display has only 10 lines and liquid crystal a response time of 10ms, the picture will take 100ms (= 0.1s) to build up - this is slow enough for the eye to see it. What is more, the first rows will have relaxed back by the time the scan is back round to re-address them. There are some electronic tricks which can be played to make this scan time for a picture faster, but the basic problem remains. Because the liquid crystal will relax back to the original state soon after the electric field is removed, the refresh rate must be much faster than a simple scan will allow.

The problem is far worse if a high resolution colour display is required, because three separate pixels are needed to make up one 'dot' of the display (one red, one green and one blue). In some black and white flat panel liquid crystal displays (such as are used in some computer games and lap top computers), the display is indeed rather slow and the information update can be seen easily. In fact, the technology is really being pushed to its limits in these cases and full colour complex displays cannot be made in this simple way.

A SOLUTION: THIN FILM TRANSISTOR DISPLAYS.

The problem of combining speed and complexity which was discussed above is overcome in a very ingenious way by the use of high technology. For full colour flat panel, highly complex displays, silicon transistors are fabricated directly onto the glass at the corner of each pixel, as shown in figure 10. The technology needed to do this is both advanced and expensive since for a high resolution colour display ~1,500,000 transistors must be fabricated onto the glass. However, having individual transistors on each pixel means that each pixel can essentially be addressed individually rather than having to scan the display line by line. As a result the whole display is much faster

and high resolution can readily be achieved. The resulting displays are superb and some of the top class lap tops now sport this technology. In fact, in Japan, where the technical engineering expertise was developed to produce these displays on a large scale, small, full colour, flat panel TV sets can be bought. These are really high quality devices - their only drawback is their price. The production of silicon chips on glass is difficult and expensive, and in some cases the devices have cost more to produce than they can actually be sold for $(\sim \$1,000)!$ technological Clearly, though the achievement was amazing, something else is needed.



Figure 10. A diagram showing the construction of a thin film transitor device (redrawn from 'Liquid Crystals: applications and uses, Edited by B Bahadur)

THE FUTURE!

Liquid crystals are extremely versatile materials. Over the last few years materials known as ferroelectric liquid crystals have been developed which look set to take over from the TN device which has really reached its technological and economic limits. (A *ferroelectric* material is one which not only switches between two states extremely quickly when an electric field is applied across it, but will remain stable in one of the states until a reverse field is applied to switch it back.) Ferroelectric liquid crystals have response times of only 10µs - 1,000 times faster than nematic materials. Further, they don't need expensive deposition technology to switch each pixel individually. The ferroelectric materials have the property that they are as stable in the light state as the dark state. Because they will automatically stay in one state there is no need to re-address them the nematic materials. as often as Ferroelectric liquid crystal devices should be in the market place within the next few years as the next generation of liquid crystal devices.

Just as a final comment, you might be surprised that one state of matter, the liquid crystal state, is responsible for all of the technology described above. However, it is even more far reaching than that. There are more than 25 different ways in which liquid crystal phases can be formed and only one has been considered here. Each different liquid crystal is a fluid state of matter in which the molecules can move freely, but where there is some orientational or positional order. Liquid crystalline materials can also change colour with temperature, form optical data storage media and detect pressure and heat. In all cases the system is fluid, ordered and may have some explicit functionality which may be a property which changes in response to electrical, optical, or thermal stimulus. Liquid crystals are actually of fundamental importance to life itself and cell membranes form liquid DNA crystal phases. Even the brain is approximately 70% liquid crystalline, so crystal they really are important to our lives! The next chapter describes how the cholesteric liquid crystals are responsible for some amazing optical effects in nature.

Introduction to Liquid Crystals: Chapter 2

Interference in nature and spiralling liquid crystals.

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INTRODUCTION.

The last chapter discussed the nature of liquid crystals, described their structures and considered the application of nematic phases in devices. In this chapter only the cholesteric phase (with the helical structure) is considered and particular emphasis is placed on how it is responsible for some spectacular optical effects in nature.

We begin with a description of interference of light caused by periodic (repeating) structures. Interference is a term that refers to a consequence of the addition of waves and, as light is an electromagnetic wave, applies to light in the same way as it applies to any other sort of wave.



Figure 1 *Waves adding resulting in interference.*

There are two limiting cases of interference: *constructive interference*, where the two waves adding up are in phase (i.e. the peaks

of each wave coincide in space and time) resulting in a large amplitude wave, figure 1(a); and destructive interference in which the two waves are out of phase, such that the peak of one coincides with the trough of the other and the amplitudes cancel, figure 1(b).

The interfering waves can be from any source, BUT for constructive interference to occur the waves must be in phase. One of the most common ways in which two light waves combine to give constructive interference is when light is incident on a thin film, as shown in figure 2.



Figure 2. In thin film interference, light reflecting from the upper and lower surfaces interfere.

Part of the incident light wave is reflected from the first boundary and part from the second. If the path difference between these two reflected waves is a whole number of wavelengths, then they will still be in phase and the reflected waves will add to give constructive interference. The condition for constructive interference for light which is incident at right angles to the surface is:

$$m\lambda = 2nd$$

where *m* is an integer (i.e. 0, 1, 2,...), λ is the wavelength of light, n is the refractive index of the film and *d* is its thickness and θ The refractive is the angle of incidence. index must be included in this equation because λ is the wavelength of light in air and this becomes smaller in a medium of refractive index *n* by a factor λ/n . Usually *m* is taken to be 1, and *n* is about 1.5. The key thing to notice about this equation is that it means that the wavelength of light that will be reflected most strongly (i.e. undergo constructive interference) is about the same size as the film thickness. It is easy to see that the soap layer in blue soap bubbles must be thinner than green or red ones because wavelength of blue light is shorter than green or red light. Notice that if the angle of incidence increases (θ in the diagram), the effective thickness of the layer becomes greater so that the colour of the light experiencing constructive interference shifts towards the red end of the spectrum. You can see this on a soap bubble if you move your head around whilst looking at the bubble.

An interesting technological application of thin film interference is in compact disc players. The digital information is read off a CD using light. Because the information is



Figure 3. Thin film interference in a CD. The diagram shows a section through the CD.

stored digitally, it consists only of 0s or 1s and these correspond to the light reflected from the CD undergoing destructive or constructive interference respectively. One form of operation is shown schematically in figure 3. Information is recorded in the track of the CD by forming pits so the film thickness is different at the places corresponding to 0s and 1s on the disc. The incident light has a long wavelength in air (the laser diode emits radiation in the infrared region of the spectrum), but because the polymer film on the CD has a refractive index of about 1.5, the wavelength of the light in the thin film is visible and at the red end of the spectrum (about 7 $\times 10^{-9}$ mThe depth of the pits is half of the wavelength of light, i.e. they are about 3.5×10^{-9} m deep so that the light reflected back from the pits undergoes constructive interference and is recorded as a 1. The thickness of the film away from the pits is designed so that the reflected light undergoes destructive interference and is recorded as a zero. The pits in CD tracks can be seen using a high magnification microscope.

Constructive interference can also take place when waves are reflected off periodic structures, as shown in Figure 4. Part of the incident light is reflected at each layer and again one wavelength is strongly reflected the condition is the same as that described above. Constructive interference of light from periodic structures is often known as Bragg reflection in honour of Sir William Bragg and his son Lawrence, who pioneered the study of crystal structure with x-rays (the wavelengths of x-rays are short enough to be of the same order as the spacing between atoms in crystals).



Figure 4 *Constructive interference from many layers.*

BRAGG REFLECTION FROM CHOLESTERIC LIQUID CRYSTALS.

The structure of the cholesteric phase was described in the last chapter. It is helical with many more turns than was shown in the diagram. Since the helix is repeated throughout the cholesteric liquid crystal structure the structure is periodic and the repeat distance is the *pitch* of the helix (the repeat distance in a screw thread is the pitch of the screw), see figure 5. Most cholesteric liquid crystals have a helical pitch which is about the same size as the wavelength of light, so that constructive interference of light where the wavelength that matches the cholesteric structure will take place. The cholesteric liquid crystal will appear brightly coloured (or iridescent) and the interference phenomenon is known as *selective* or *Bragg* To a first approximation, the reflection. selective reflection of light from cholesteric liquid crystals can be thought of in exactly the same way as the Bragg reflection of light from the much simpler periodic structure shown in figure 4. However, the helical structure in fact has very complex optical properties and the light that is selectively reflected from a cholesteric liquid crystal is circularly polarized. In order to explain what circular polarisation is, it's necessary to introduce a small diversion to recall what is meant by polarisation.



Figure 5. Screw threads and helical pitch.

Polarisation is just a term used to describe the directions in which the electric (and magnetic) fields in an electromagnetic wave are oscillating. Most light sources produce unpolarised light, where. the electric field of the light wave is distributed randomly around, but at right angles, to the direction in which the light is travelling. Linearly polarised light is light in which the electric field has been constrained to oscillate in a single plane. For example, if a light wave was travelling from left to right across this page and the electric field was confined to the plane of the page, it might be described as vertically polarised (provided the page was held upright!), see figure 6(a). The term linear is used to describe such light because the tips of the electric field vectors may be joined using a straight line. Α circularly polarised light wave is shown in figure 6(b). The tip of the electric field traces out a circle as viewed along the ray. Clearly, the circle could be traced out clockwise or anticlockwise, and circularly polarised light is described as being left handed or right handed. In a cholesteric liquid crystal, the helical structure selectively reflects circularly polarised light of the handedness that matches the structure. The other handedness of circular polarisation is transmitted by the structure, even though the wavelength might be correct to experience Bragg reflection, because the handedness of polarisation doesn't match the structure. Thus, a cholesteric structure will selectively reflect light of a particular wavelength (or colour), but only half of the light that falls on the structure will be selectively reflected (that of the correct handedness), and the rest will pass through the cholesteric material unaffected.



Figure 6 (a) Linear and (b) circularly polarised light.

Usually, the fact that the light reflected from a cholesteric material is circularly polarised is unimportant, and the material's iridescence is it's key feature. However, certain beetles

THE THERMOCHROMIC EFFECT.

One of the most noticeable properties of cholesteric liquid crystals is not just that they selectively reflect light of a particular wavelength and are therefore strongly coloured, but that the colour that is reflected depends on temperature. Such a material is known as *thermochromic* (*thermo* means heat and *chromic* means colour). The helical structure of a cholesteric liquid crystals expands and contracts as the temperature changes, so that the repeat distance of the structure and therefore the selectively reflected wavelength is temperature dependent. The typical dependence of the selective reflection wavelength with temperature is shown in figure 7. Lower temperatures correspond to a longer pitch (and reflect red light), whilst at higher temperatures the pitch is shorter and the reflected light is blue. This may seem wrong. Usually materials are thought to expand as the temperature increases so it may be expected that the longer pitch state (red) will occur at higher temperatures. This doesn't happen in these cases because in fluids the density usually stays constant so the desire for molecules to move further apart as they are given more thermal energy cannot be achieved by expansion. In fact, adjacent molecules twist to higher angles in an attempt to move further apart so the structure becomes more highly twisted as the temperature increases. The more highly twisted the structure is, the shorter is its repeat distance and therefore the more the selective reflection colour will move towards the blue end of the spectrum.

The use of cholesteric liquid crystals as thermochromic materials is widespread and they particularly common in medical applications. In the simplest example, liquid crystals are used in forehead thermometers (also known as 'fever indicators'). These devices are based on a strip printed with several different thermochromic materials, each operating at a slightly different temperature around the normal body make use of polarisation to obtain spectacular optical effects so this point is important for discussion later in the chapter.

temperature. The segment that appears bright green is that which displays the correct temperature (green appears brightest to the human eye).



The usual temperature dependence of the colour of a cholesteric liquid crystal.

Thermal mapping of various areas of the body has been used as a diagnostic technique for a wide ranging group of medical conditions in which a temperature differential near the skin surface may be related to the disorder. Medical applications of liquid crystals are widespread; material seems to have been applied to almost every possible area of the body! Examples include the evaluation of deep vein thrombosis and the prediction of foot ulceration in diabetic patients through thermal mapping. The use of liquid crystal thermography to screen for cancer, especially breast cancer, is common. Subcutaneous and intracutaneous malignant tumours are usually between 0.9°C and 3.3°C warmer than the surrounding tissue. making thermography a useful candidate for cancer screening. A thermochromic sheet placed over the affected area will be coloured differently around the tumour site than in the region where the tissue is healthy. Liquid crystals are particularly useful as they provide a safe, non-invasive imaging technique using visible light, in contrast to, say, x-rays, which carry their own risks.

Industrial applications of thermochromic liquid crystals are also well known, from thermometers in refrigerators, cats eyes that change colour in freezing conditions, through to paints which when applied to silicon chips indicate if they are over heating. At the extreme of applications, engineers have been known to paint aircraft wings with thermochromic liquid crystal to image the flow of air in flight!

The less serious uses of thermochromic liquid crystals are very well known. Mood rings change colour as the hand changes temperature, supposedly giving information on the wearer's mood. Stress cards (about the size of a credit card) can be held between the finger tips to give a reading of how stressed the user is. If stress is related to the temperature of the fingertips, then this is a good way to measure it! It is even possible to purchase 'love-o-meters' which, when clutched in the hand or elsewhere indicates whether the holder is frigid, warm, steamy or passionate! Some textiles have been made that incorporate thermochromic liquid crystals which is an interesting idea, but not one which necessarily results in tasteful fashion (liquid crystal covered swimsuits are an example of this!).

CHOLESTERIC LIQUID CRYSTALS IN NATURE.

Almost all living things exhibiting anisotropy in their organic tissues either are or once were liquid crystalline. There are many examples of liquid crystals in living things and a surprisingly large number of them exhibit cholesteric phases.

One of the most striking examples of liquid crystals in biological systems is in beetles and other insects where cholesteric liquid crystals are responsible for the iridescent outer coats. If a collection of beetles is examined with a polariser absorbing left circularly polarized light, the colours of many species appear black. This optical effect occurs because the beetles' backs were formed from cholesteric liquid crystals which selectively reflect left handed Only certain circularly polarised light. brightly coloured beetles have cholesteric liquid crystal films on their backs and others simply use thin film interference to produce their brightly coloured outer coatings. In order to discriminate between selective reflection of light and thin film interference, a poor dead beetle may be immersed in a liquid of refractive index close to that of its outer coating (which is made of a material known as *chitin*). The colours will disappear if the phenomenon responsible for them is thin film interference. This is because if the refractive index of the thin coating of chitin is the same as that of the fluid, light will not distinguish between the two layers - the layers are identical to the probing light. Because the thin chitin layer is now indistinguishable from the fluid, thin

film interference will not occur. In beetles where cholesteric liquid crystals are responsible for the iridescence, they remain coloured when immersed in the liquid.

The colour producing layer in beetles is probably created in the late chrysalis stage from a liquid crystalline glandular secretion which rapidly hardens on their backs. Mixed colours such as bronze are created by changing the pitch throughout the liquid crystal layer. In one beetle, the Plusiotis Gloriana, the optical system is even more sophisticated. The reflecting layer of this scarab beetle has an anticlockwise helicoidal architecture and interferes only with left circularly polarised light. Below the first reflecting layer is another thin, non-twisted layer 1.8µm thick that transforms the transmitted right circularly polarised light to left circular which is reflected by a second cholesteric layer. Thus the reflectivity of this beetle is twice that of beetles with only one cholesteric layer, nearing the optimum 100% value where both right and left circularly polarised light are reflected.

Some liquid crystals phases occur when certain materials are dissolved in water, a very common phenomenon in biological systems. Biological materials that form liquid crystals include bile acid salts, long chain fatty acids, retinols and vitamins A, E and K. The deposits that clog arteries are also in a liquid crystalline state, the main components being cholesteryl esters. Myelin, that forms the sheath around nerve cells and is prominent in the transmission of electrical impulses by the nerve, is also liquid crystalline. Studies show that most of the cholesterol that occurs in myelin and in the brain, is synthesised in situ and forms a liquid crystal phase with water. Another important example of a biological liquid crystal is DNA, the molecule in all cells that contains genetic information. DNA forms a cholesteric liquid crystal in water, and it is interesting that it will form this ordered fluid phase even if the sugar phosphate back bone to which the nucleic acids are connected is removed. The nucleic acids themselves will form an ordered fluid, but the sugar phosphate back bone of the molecule is

SUMMARY

Thin film interference is the cause of some of the most spectacular optical effects that occur in nature. Cholesteric liquid crystals are unique materials which spontaneously adopt a periodic structure in which the repeat distance is correct to selectively reflect light at visible wavelengths. When used by man, their applications span from the important (e.g. medical thermography) to the ridiculous! In nature, liquid crystals play an extremely important role as ordered fluids necessary to get the genetic order right. Blood can in some circumstances form a liquid crystal phase, a situation which is rather dangerous since the viscosity increases, hindering the flow. The condition where this occurs is known as sickle cell anaemia. Indeed it is not surprising that so many biological systems exhibit liquid crystallinity. All require some sort of order and a retention of fluidity. What is perhaps surprising is that it took so long for such systems to be recognised since understanding biological systems clearly requires some understanding of the liquid crystal state.

are the building blocks of cells. It is thought that the liquid crystal state even takes part in the process of cell division where the fluid within the cell must become ordered before the division of the cell into equal halves can take place. The study of liquid crystals allows us to understand ordered fluids and as well as being important with respect to technological applications, it is playing an increasingly important role in understanding many biological processes.

FURTHER READING.

It is difficult to find good descriptions of liquid crystals that aren't at very specialised level. The best is perhaps 'Liquid Crystals: Nature's delicate phase of matter' by P J Collings, which is relatively inexpensive and gives broad coverage of the subject. Articles about liquid crystal devices often appear in magazines such as 'New Scientist'. There is also a virtual liquid crystal textbook on the web site:

http://abalone.cwru.edu/tutorial/enhanced/files/textbook.htm

or look at our web site:

http://reynolds.ph.man.ac.uk