**The Modern Usages of Liquid Crystals**

A diagram of different types of liquid

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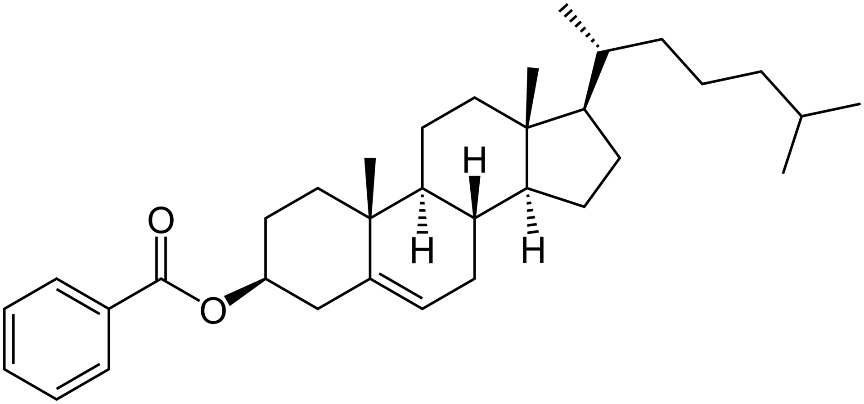
# 1.0 Introduction

In 1964 the first LCD (liquid-crystal display) was developed. At the time this was a huge technological advancement as well as their commercial success in 1968. It marked for the whole new generation of technical devices with LCDs implemented in televisions, watches, and many other displays at the time. This form of display continues to be prominent however is slowly being replaced by other forms of technology. In this essay I hope to investigate the workings of liquid crystals and answer later whether they are still practical even in modern day technology.

# 2.0 What are Liquid Crystals

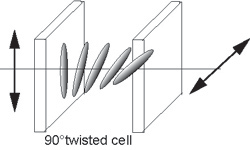
## 2.1 History Behind Liquid Crystals

Liquid Crystals were initially discovered in 1888 by Friedrich Reinitzer (accidentally discovered but discovered nonetheless) during his research at Karl-Ferdinands-Universität (Charles University in Prague) into physio-chemical properties of different cholesterols. Previous researchers had observed changes in colour when cooling certain cholesterols just above the point of freezing, but none recognised this as a new phenomenon. Upon his further research, he found that the cholesteryl benzoate had two distinct melting points. One at 293.9 °F where it melts to a cloudy liquid, and again at 353.3 °F.



Chemical Structure of Cholesteryl Benzoate

This was found to be a reversible phenomenon and so with help of physicist Otto Lehmann they exchanged letters and samples, as well as opinions from Reinitzer’ s colleague who indicated that the “fluid” (or what they presumed a fluid at the time) was crystalline, Reinitzer presented his results at a meeting of the Vienna Chemical Society on May 3rd 1888. By this time Reinitzer had discovered the main standing characteristics of these cholesteric liquid crystals being their existence of two melting points, their ability to reflect circularly polarised light and their ability to rate the polarising direction of light.



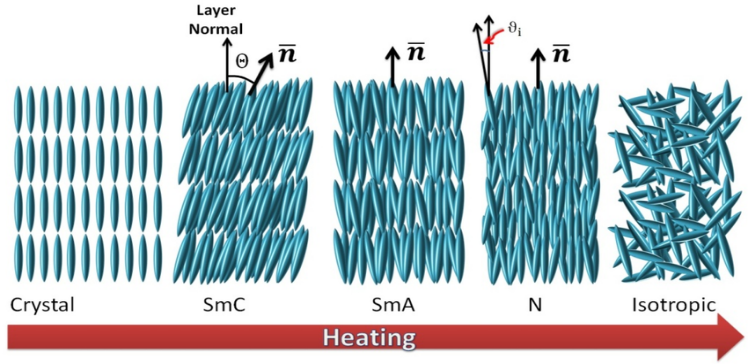
Example of an LC rotating the direction of polarisation



**Photo of Otto Lehman**

After Reinitzer’ s accidental discovery, he did not continue investigating this phenomenon any further (although Reinitzer is usually credited with the discovery of the new phase of matter liquid crystal phase due to his vast early work).

His research was continued by another man named Otto Lehmann. Lehman had expertise in both crystallography and microscopy in his postdoctoral years and so would end up much more useful than Reinitzer’ s botanical expertise. Lehman did research on first cholesteryl benzoate as well as other compounds with similar properties to that of cholesteryl, particularly those with the unique “double melting phenomenon.”



Example of an LC of which its properties change with increasing temperature, demonstrating the “double melting phenomenon.”

In his research, he would use a microscope attached with a hot stage which allowed for him to make high temperature observations of the compounds and hence allowed him to observe changes in polarised light with the compounds in their different states (observe characteristics of the double melting phenomenon). During his research using the microscope became convinced that he was dealing with solid structures and later (August 1889) he published his findings in the Festschrift für Physikalische Chemie (or the International Journal of Research in Physical Chemistry and Chemical Physics) and would be the first to suggest the name liquid crystals.

The first proposition regarding the structure of liquid crystals would be first made after Lehmann, a German chemist by the name of Daniel Vorländer furthered Lehmann’s work rather significantly working from the beginning of the 20th century up to 1935 in which he retired (although before which he would be responsible for synthesising most of the liquid crystals known).

Following this, many different scientists would continue contributing to these discoveries such as Joel E Goldmacher, Joseph A Castellano in 1966 experimenting with techniques involving nematic compounds (a technique still used today) and Hans Keller in 1969 whom synthesized one of the most popular type of liquid crystal that is consistently used in experimentation today (a nematic phase: N-(4-methoxybenzylidene)-4-butylaniline that could exist in a stable state at room temperature).

It would not be until 1991 that Pierre-Gilles de Gennes working at the Université Paris-Sud would win a Nobel Prize for studies related to liquid crystals. He would greatly influence the theoretical and experimental development into liquid crystals from mid 1960s up to (and past) this point.

## 2.2 Liquid Crystal States

Before going into the physics of liquid crystals it is important to acknowledge the different types of liquid crystals. These different types can be described as mesophases and are characterised by different kinds of ordering. They are distinguished through positional order (the regular distance between molecules), orientational order (a scale of the group of molecules that point in the same direction) and bond orientational order (a measure of the alignment of molecular symmetry axes). These order parameters vary between 0 to 1 (intuitively with one being completely ordered and 0 in complete disorder). More in depth into what this means later in [2.3 Physics behind Liquid Crystals](#_2.3_Physics_Behind).

Generally Liquid Crystals can be sorted into two categories: Thermotropic Crystals and Lyotropic Crystals (but this document will mainly focus on Thermotropic Crystals and only briefly touch on Lyotropic Crystals).

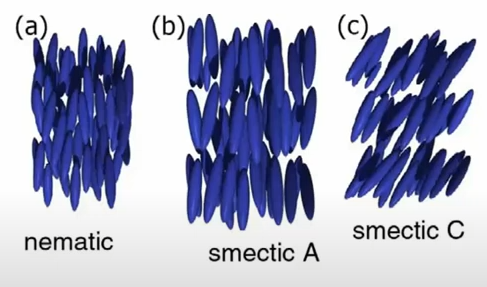
### 2.2.1 Thermotropic Crystals

Thermotropic crystals are liquid crystals of which phases can be caused by change in temperature. If their temperature is too high, the thermal motion will break from their bonds and destroy its ordering that gives it its unique characteristics and become a conventional crystal. These crystals express distinct characteristics with changing temperature but similarly are represented as interacting “rigid rods” to form a structure exhibiting certain properties. **Note:** all the following crystals fall under thermotropic Crystals until lyotropic Crystals so a liquid crystal could start in a smectic state and move to nematic with increasing temperature. Below will also mention principal directors which are explained more in depth in [2.3 Physics behind Liquid Crystals](#_2.3_Physics_Behind).



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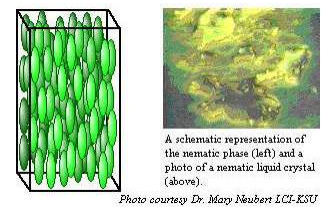
Some sub-states of Thermotropic crystals and an arrow showing increasing temperature (more detailed diagrams in 2.3)



#### 2.2.1.1 Nematic Phase

One of the simplest liquid crystal phases is the nematic. In this phase, molecules lack crystalline positional order, however they do align parallel along their directors maintaining a long range orientational order. The term nematic comes from the Greek “νήμα” (or nema) meaning thread. Hence this namely term given its long and orientated structure alike to a long thread.

A representation of the nematic phase showing they align parallel along their director (orientational order) but lack positional order.

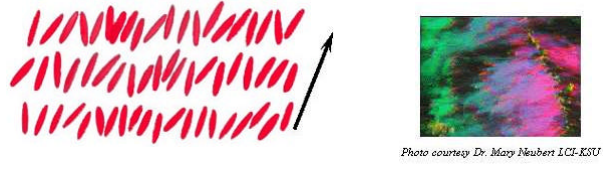
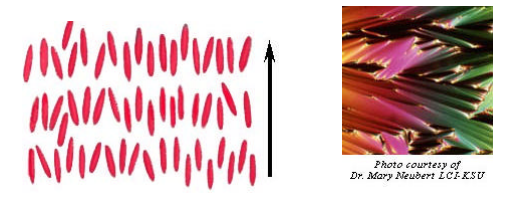


Most nematic phases are uniaxial (meaning they have one axis) that is long as above with a long range orientational order. However, some nematic phases are biaxial, meaning as well as being oriented along their long axis (the principal director) they also orient about a second axis (the secondary director).

The nematic phase existing at the highest temperature over the other phases, occurs just before the isotropic or liquid phase, hence it exhibits similar properties such as the fluidity of isotropic crystals. However, they can be easily aligned along their director using an external magnetic or electric field. These aligned nematic crystals now exhibit new physical properties, in particular optical properties, which make them useful in developing new technologies such as Liquid Crystal Displays (mentioned later).

#### 2.2.1.2 Smectic Phase

Smectic phase crystals are found at a lower temperature than nematic crystals (that can be seen from a couple of the diagram earlier) and form well-defined **layers** that can slide over each other, alike to soap. Its name originates from the Latin “smecticus” meaning cleaning or to have soap-like properties. As well as a fitting name given its structure is also derived from the fact that the slippery substance found at the bottom of a soap dish is a form a smectic liquid crystal. Smectic phase crystals are all positionally ordered along one director/ direction (directional order). This phase splits into smectic A and smectic C phase crystals. In smectic A crystals are orientationally ordered normal to their layers, however in smectic C crystals their orientation tilts away.



Representation of smectic A and smectic C liquid crystals (on top and bottom respectively). The black arrow illustrates the director where the top has the director orientated normal to the plane, and the bottom has the director orientated away from the normal of the smectic plane.

Due to smectic liquid crystals’ property of layering, the smectic phase can be split into many different sub-phases (of which twelve sub-phases have been identified so far) although the above only discusses the two main phase; smectic A and smectic C. The characteristics of these different sub-phases are determined by their different type and degrees of positional and orientational order.

#### 2.2.1.3 Twisted Nematic

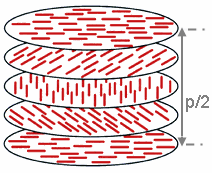
Twisted or chiral nematic liquid crystals, per the name, shows chirality (such it cannot be superposed on its mirror image by any form of transformation). It is also often called the cholesteric phase as it was first observed for cholesterol derivatives. This phase has its molecules twisting perpendicular to its director as show in the diagram below.



A representation of the chiral nematic structure which its molecules (mesogens) twist as you go along perpendicular to the director.

As seen in the above diagram, they keep directional order along their director. About each “sheet” positional order is kept, however over a longer range with the structure’s molecules twisting it doesn’t maintain long range positional order.

The distance over which twisted nematic liquid crystals’ molecules undergo a 360 degree twist is denoted by the chiral pitch, p (although note that the structure repeats itself every half-twist or 180 degrees). This pitch changes generally changes with temperature or if additional molecules are added to its structure, such allowing the chiral pitch of the twisted nematic liquid crystal to be changed and controlled.



Another representation of a chiral nematic structure with half the pitch shown. As seen the structure repeats after a 180 degree rotation or half the pitch

In some chiral nematic liquid crystals, the pitch is of the same order wavelength as visible light. This allows these liquid crystals to exhibit unique optical properties such as triggering low-threshold laser emission and Bragg reflection (effectively selective reflection of the “Bragg reflection” wavelength to be used to control what light is emitted through a liquid crystal) which can be exploited for many modern uses (some of which are mentioned later on in [3.0 Modern (and Future) Uses and Applications](#_3.0_Modern_(and)). The structure of chiral nematic liquid crystals can also be used particularly for its twisting property to rotate polarised light by certain degrees. Hence a vertically polarised light can be very easily rotated to be horizontally polarized.

#### 2.2.1.4 Blue Phases (photonic crystals)

Blue phase liquid crystals appear in the temperature range between chiral nematic phase and isotropic liquid phase. They have a double-twisted columnar arrangement, however given its self-assembling properties it can form many possible three-dimensional structures based on certain conditions of the environment. The double-twisted columnar arrangement means their molecules orient about two axes hence are biaxial (orienting about the axis of the column and its radius).

The lattice structure of blue phase liquid crystals is periodic (with periods of several hundred nanometres). This allows for Bragg reflection to occur leading to the scattering of coherent waves at different angles due to the crystalline lattice, and hence their superposition.

Its three-dimensional cubic lattice of double-twisted cylinders along with its periodic property, results in the material exhibiting photonic crystal properties. This allows the liquid crystals to control the propagation of light.

As will be mentioned later, blue phase liquid crystals can be used for LCD development due to their fast light modulation, however they are generally within a small and low temperature range which makes their application quite difficult.

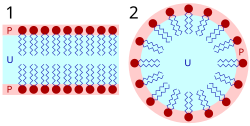
Although blue phase liquid crystals all exist in a low temperature range, they split into sub-phases with differing existing temperatures. Blue phase I liquid crystals have a body-centred cubic structure (a type of cubic structure in which one atom is placed at the centre and one at each corner as well). They exist in a rather narrow temperature range. Blue phase II liquid crystals have a simple cubic structure and exist at a slightly higher temperature than those of blue phase I. A less common third phase namely blue phase III liquid crystals (also referred to as the blue fog) is much less ordered than the former two.

### 2.2.2 Lyotropic Crystals

(**NOTE**: this document will only talk about Lyotropic crystals here and not in the applications, as the focus of this document is towards the application of liquid crystals to further modern technology. Lyotropic liquid crystals do have many uses, but are mostly biological technologies, hence none worth mentioning for the context of this document focussing on the physics and computer science side of application)

Lyotropic crystals are liquid crystals of which phases can be caused by change in solvent. Their structure is not necessarily particularly strict; however, they consist of two or more components that exhibit liquid crystalline properties incertain concentration ranges encompassed withing a solvent. Their structures are typically self-assembled (if assembled at all). In lyotropic phase liquid crystals, the solvent that encompasses the compounds provide its fluidity. Contrary to thermotropic liquid crystals, lyotropic liquid crystals have another degree of freedom (being their concentration of compounds) which enables a greater variety of phases to be accessed.

Many lyotropic liquid crystals (still dependant on the concentration of their compounds due to the encompassing solvent) exhibit amphiphilic properties. This means that the molecule that they form has both hydrophilic (attracted to water) and hydrophobic (repelled by water) parts. This molecule then exhibits ‘both’ properties due to the combination of the contrasting parts with separations in nanometres between them. An everyday example of this kind of lyotropic liquid crystal is soap.



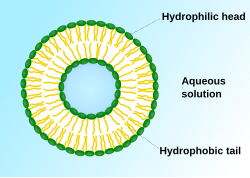
The structure of a lyotropic liquid crystal. The red heads of the molecules (referred to as the polar head group) are the hydrophilic part of the molecule and hence in contact with water. The blue tails are the hydrophobic part of the molecule and so are immersed in oil.

U: Oil P: Water

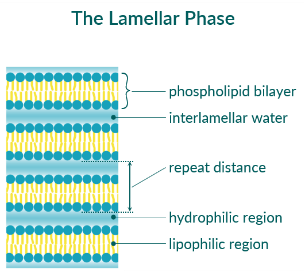
Diagram1: bilayer structure Diagram2: micelle structure

As stated previously, the content of the solvent molecules alters the structure of the lyotropic liquid crystal. At very low amphiphile concentration, the molecules are dispersed randomly without any ordering. At a still low but higher concentration, the amphiphilic molecules assemble into micelle or vesicle structures (micelle and vesicle structures are effectively the same but vesicle structures have a structure embedded within itself typically forming a lipid bilayer). This structure works intuitively by protecting the hydrophobic tail even when surrounded by water or solvent with the hydrophilic surface on the outside.

Example of a vesicle structure like the micelle structure. It forms a bilayer with a hydrophobic layer both on its outer surface and on the inside (hence bilayer)



These spherical (micelle and vesicle) structures do not order themselves in these low concentration solutions, however at higher concentrations their assemblies become ordered. An example of this ordering is a hexagonal columnar phase in which the amphiphiles form long cylinders (with the same idea of a hydrophilic surface and hydrophobic interior) that arrange into, roughly, a hexagonal lattice. At even higher amphiphilic molecular concentration, a lamella phase (also referred to as the neat soap phase) forms. In this phase sheets of amphiphiles are separated by thin layers of water.



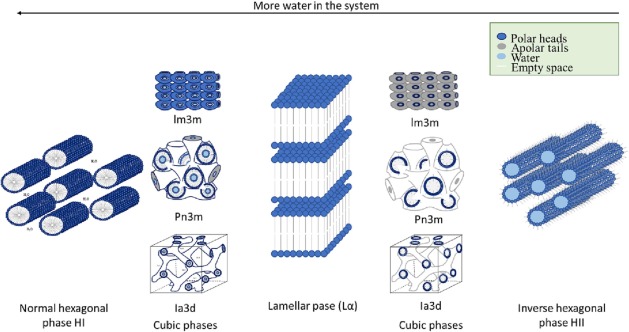
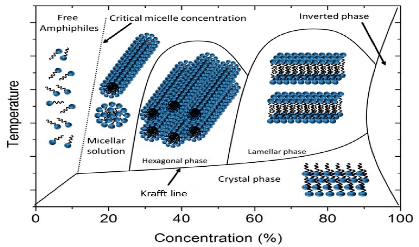
The lamella phase showing an amphiphilic bilayer separated by layers of water (once again with hydrophilic surface on outer edges)

Typically, most objects made by amphiphiles are spherical (such as micelles and vesicles), however other forms such as the previously discussed lamellar phase exist. Others such as disc-like (bicelles), rod-like and biaxial (three distinct micelle axes) can also form. These self-assembled nanostructures can order themselves, alike to thermotropic liquid crystals, and hence form larger structures similar in versions to some thermotropic liquid crystals (for example a nematic phase of rod-shaped micelles).  
With ever increasing concentrations, inverse phases can be observed such as an inverse hexagonal columnar phase or an inverse micellar phase.

A progression of the phases starting from low concentration and increasing would be:

1. Micellar cubic phase
2. Hexagonal (columnar) phase
3. Lamellar phase
4. Reverse hexagonal columnar phase
5. Inverse micellar phase

A representation of the different amphiphilic phases within the group of lyotropic liquid crystals with varying concentration or water in system



Within each layer, these self-assembled structures can be designed with specific parameters. For example, in the lamellar phase the distance between layers can be increased by increasing the solvent volume (by a little as too great an increase would decrease the concentration till self-assembly triggers another phase).

Although also a part of liquid crystal polymers (a section of liquid crystals not talked about here), Kevlar is also a form of lyotropic LCP.

## 2.3 Physics Behind Liquid Crystals

Liquid crystal materials (particularly thermotropic liquid crystals) follow several common characteristics. Among them includes a rod-like molecular structure, a strong dipole and/or easily polarizable substituents.

Liquid crystals given their microscopic fluid phases and anisotropy makes analysis of them quite difficult. However as mentioned previously, liquid crystals can be described in terms of their order parameters and directors as well as the pair distribution function.

The director of a liquid crystal is the line of alignment along its common axis. This axis is generally the molecular direction of the preferred orientation of the liquid crystal. In all order parameters, the director is used to find the mathematically expressed value of its respective ordering.

A previously used diagram (re-used below) shows visually the director of molecules in different liquid crystal phases



A diagram showing the director of mesogens (molecules), in different liquid crystal states.

Order parameters are expressions of “how ordered” a material is. This value varies continuously from 0 to 1 (completely disordered and completely ordered respectively). Some of the different order parameters are the below:

* **Orientational order parameter**: A measure of the tendency of the molecules axes to align along the director
* **Positional/ Translational order**: The extent to which the position of an average molecule or group of molecules shows translational symmetry or periodicity in their molecular positioning
* **Bond orientational order**: The degree of angular alignment between neighbouring molecules
* **Chiral order**: A measure of the helical pitch of a liquid crystal structure (hence this will only apply to twisted nematic liquid crystals)
* **Polarisation order**: The degree of alignment of molecular dipoles

In addition, when analysing liquid crystals, we consider the scale of which the structure is ordered (e.g. whether the relevant ordering is maintained over a short range and/ or a long range).

These order parameters allow us to describe and determine the phase a liquid crystal may be in. Different order parameters however are specific to certain phases (such as the chiral order parameter being specific to twisted nematic and so will only tell you how “twisted” the structure is. Effectively pointless to use on other phases such as a nematic phase liquid crystal).

### 2.3.1 Orientational Order Parameter

The orientational order parameter measures the degree to which the long axes of rod-like molecules in a liquid crystal align along a common direction or director (denoted here by ). The mathematical equation of this orientational order parameter in 3-dimenstions is shown below:

As mentioned above, the director is denoted by . The long axis of the molecule is denoted by , S denoting the orientational order parameter, and the < > brackets is used to denote that the order parameter takes the average calculation (as the dot product of vectors can only be carried for individual mesogens) over the volume/ structure or whatever scale the calculation is being carried out at.

Its important to note that these denoted vectors are specifically unit vectors. Hence by using the equation:

And the fact that the modulus of a unit vector is simple one, this simplifies the equation to:

(Provided that vectors a and b are unit vectors)

Hence going back to our original equation, we can rearrange to:

Where theta () is the angle between the long axis and director.

This equation of orientational order parameter is most generally used to distinguish nematic and smectic phase liquid crystals, as well as their ordering themselves (however the later to be mentioned translational order parameter better describes smectic phase liquid crystals).

Although previously stated that the order parameter of a material ranges between 0 and 1 (which is still true), liquid crystals’ order parameters will be in a range not inclusive of 0 and 1. For example, an orientational order parameter of 0 would suggest an isotropic liquid with complete disordering, and contrastingly an order parameter of 1 would suggest a crystalline or solid state. Hence in the case of liquid crystals such as a nematic liquid crystal, this value will range between 0.3 and 0.9.

The image below shows a graphical way of representing the orientational order parameter within a structure. By plotting the orientation of each of the long axis of these mesogens and comparing to a graph or probability of finding a mesogens to be pointing in a certain direction, we can see how the majority of mesogens will align along the average director in the middle, with some tending away (but at much lower percentage)

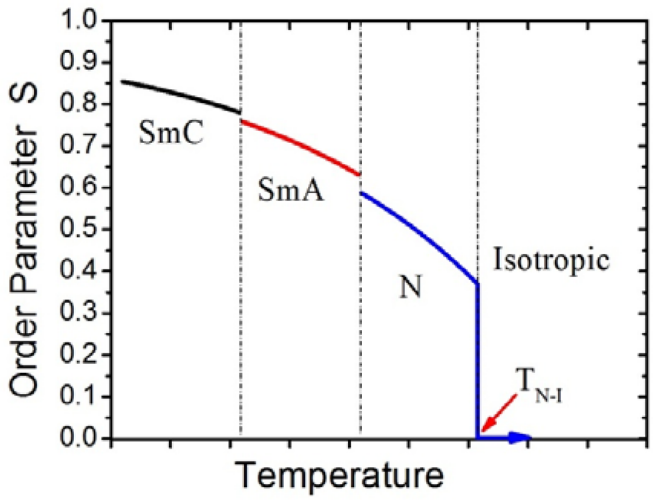
A diagram of a graph

Description automatically generated

Another image below shows how we can observe and see how the orientational order parameter shows how “ordered” a material is.

We can simply observe and see that the ordering of the yellow mesogens is better ordered than the grey mesogens. And this can then be seen from the two different graphs of probability they show. The width of the inner curve of the top graph is greater than that of the bottom graph.

Hence, the smaller width indicates that there’s higher probability of finding mesogens along the average director, otherwise the structure is more ordered.

A diagram of a graph and diagram of a graph

Description automatically generatedThis graph shows how the order parameter varies as a function of temperature. As temperature progresses, the phases of liquid crystal changes from smectic to nematic. After passing the threshold temperature (sometimes for liquid crystals, a phase change occurs to an isotropic liquid. An isotropic liquid is completely disordered hence why the orientational order parameter drops to zero after reaching this temperature. It also follows why the order parameter in each phase decreases with increasing temperature, as by increasing the temperature mesogens have more energy and become “freer to move”. Hence mesogens become more disordered as they are free to point in directions away from the average director.

### 2.3.2 Translational Order Parameter

Translational order parameters are most relevant to smectic phase and columnar liquid crystals (but not nematic phase liquid crystals as they lack translational order, or they lack periodicity with lattice layering hence no translational order). The translational order parameter quantifies the degree at which molecules are arranged in a periodic, lattice structure.

Below shows the mathematical expression for the translation order parameter:

Once again, the brackets denote that the calculation is taken as an average over the volume of the structure. Ssm denotes the translational order parameter for a smectic phase liquid crystal and z denotes the distance of a molecule. The value ***a*** is the periodicity of the layers show in a diagram below. This expression can be expressed as an integral (as shown below) but this document will not go into this derivation.

For the above, P(z) is the probability of finding a mesogens at a certain distance z.

A blue and black line on a white background

Description automatically generated with medium confidenceA graphical example of a smectic phase liquid crystal in which the distance between periodic layers is ***a***

If the value of the translational order parameter is zero, it is likely either a nematic phase liquid crystal or an isotropic liquid. Any other value other than zero suggest that it is a smectic phase liquid crystal.

The other three order parameters: bond orientational order, chiral order and polarization order will not be delved into with greater detail as for the purpose of this document, it is only necessary to talk a little about orientational and translational order parameters which relate closely to nematic and smectic phase liquid crystals (a focus of this document).

# 3.0 Modern (and Future) Uses and Applications

Liquid crystals have a vast many different uses whether that’s now, or in its potential for the future. The following sections will cover different applications.

## 3.1 Quantum Applications

A basic computer is one that work with a bit that can hold two different values (typically either 1 or 0). A quantum computer however works with qubits which can hold the values 1, 0 or a state of superposition which is “both 1 and 0 at the same time”. This third state effectively holds all possible potential states whilst not being any specific one at once. Quantum computers can then take advantage of this third state of superstition along with analogies such as quantum entanglement (the ability for quantum particles to correlate with each other) and quantum interference to solve extremely complex, exponentially large memory intensive and potentially “unsolvable” problems.

Liquid crystals can aid in the development of quantum applications in its ability to produce quantum light. For the usage in quantum computing, this quantum light can be used to generate qubits. As of now producing qubits is extremely difficult, however by taking advantage of the optical properties of liquid crystals and usage of electric fields to alter and control its structure, quantum light of entangled particles can very easily be produced and tuned. This technology can not only be used in quantum computing, but also in quantum communication. Using the tuneable capabilities of liquid crystals to change structure with outside effect (such as the electric field alignment mentioned before) makes it extremely versatile and easier for the transmission of information in quantum communication. Particularly in quantum communication, its “un-hackable” property, stemming from the fact that interference or observation of the transmission disrupts the quantum entanglement and alerts both sender and receiver instantly, is extremely and will prove extremely useful in the future.

## 3.2 LCDs

One of the most common applications of liquid crystals are LCDs (Liquid Crystal Displays). It’s likely that mentioning liquid crystals to someone would cause them to think of LCDs (rather than LCDs causing them to think of liquid crystals). Liquid crystal displays work by controlling the amount of light that passes though the screen. A traditional LCD can be split into four parts:

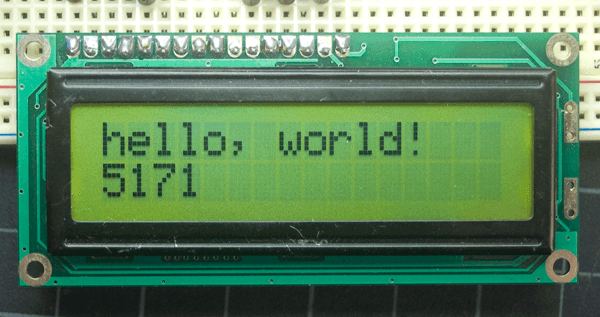
1. Backlighting
2. Polarising filters
3. Liquid crystals
4. Transparent electrodes (glass with electrodes)
5. Screen

First a backlight or initial light source is shone out. This light goes through two polarising filters placed at 90 degree angles to one another (such at its current state no light can pass through). A liquid crystal is then placed or “sandwiched” between the two polarising filters. The light travels through the first filter, is rotated 90 degrees by the liquid crystal and after passing through the second filter (which due to the rotation of the liquid crystal is now in line with) is displayed on the screen producing a pixel. Repeating this thousands of times across the screen eventually leads to displaying an image, or more rather a video. Although a backlit is generally used, in the past (and sometimes even now) a reflective surface, namely a reflector, potentially accompanied with a low power light source is used to produce the image by taking advantage of the light in surroundings.

The commercial LCD will use a twisted nematic liquid crystal. As previously mentioned, this structure in its helical (or twisting) structure is capable of rotating polarisation of light by certain angles based of the length of the liquid crystal. Hence light is allowed to pass in its base state as the twisted nematic liquid crystal rotates the polarisation of light by 90 degrees hence in line with the second polarising filter. To change/ switch the state of the pixel (in the simplest case from light to no light) the twisted nematic liquid crystal is aligned by an electric field generated either side of the liquid crystal. This effectively “untwists” the liquid crystal hence no longer rotates the polarisation of light is then blocked by the second filter.

Diagram of a mirror with different types of glass

Description automatically generated with medium confidence

A diagram summarising the structure of a simple LCD.

Here is an example of an old liquid crystal display from an Arduino kit. Here a backlight shines through and the letters are formed from the blocking of light using liquid crystals.

A black circle with red green and blue squares

Description automatically generatedOf course, this only allows for either light of no light, hence, to generate colours (as you would expect for a video of coloured pixels) each pixel of colour is split into sub-pixels. The number of these sub-pixels can vary across different LCDs such as the basic RGB (three sub-pixels representing red, green blue), or the RGBW approach (four sub-pixels representing red, green blue and white). To produce these actual colours, a colour filter is placed in front of the second polarising filter.

Above shows a close-up example of what the colour filter may look like for an LCD based with RGB pixels. This example shows the colour filter set out in strip-based format; however, they can be arranged in other kinds of order such as below.

A group of colored rectangles

Description automatically generated

(note however that the most common format is the stripe)

By varying the intensity of light that goes through each sub-pixel, we can control the resulting colour of the final pixel. For example, by setting all red, green and blue sub-pixels to their highest intensity, a white colour is produced, and by shining light through the red and green filters at highest intensity, and shining no light through the blue filter, a yellow colour can be produced. Otherwise through simple additive colour synthesis, a range of different colours, effectively up to all the colours the human eye can see, can be produced.

Above has only discussed the TN (twisted nematic) liquid crystal display. However, a few others are bullet pointed below summarising their uses:

1. STN (super twisted nematic): like a standard TN-LCD however it uses instead a super twisted nematic liquid crystal that twists over 90 degrees and less than 360 degrees (typically for displays twisting 270 degrees)
2. IPS (in-plant switching): alternative to TN-LCDs that rotates light in the plane of layer (hence in-plane) such that by default light cannot pass, but when aligned rotates light such that it may pass. Also relies on one electrode to align the liquid crystal opposed to TN-LCDs two electrodes. This alternative creates a wider viewing angle and is generally a better LCD
3. (UB-) FFS (ultra brightness fringe field switching): another alternative to TN-LCDs that works using a nematic liquid crystal and does not allow light to pass in its default state. Instead using a standard electric field, it takes advantage of fringe fields generated by the arrangement of electrodes in the same plane as the liquid crystals.
4. VA (vertical alignment): like FFS-LCDs in that their default state (ideally) no light can pass. VA-LCDs can also split into many other technologies such as PS-VA and SA-VA LCDs.

All the listed above LCDs are based on nematic or twisted nematic liquid crystals. However, a future technology (in development) utilizes blue phase liquid crystals instead.

These displays are namely BPD (blue phase displays) or BMD (blue mode displays). Their main advantage over using a nematic or twisted nematic liquid crystal lies in the extremely fast switching times of blue phase liquid crystals which can me less than a millisecond. In addition, the isotropic property of blue phase liquid crystals means that they don’t require orientation which decreases cost in manufacturing the display, instead they self-align in three dimensions. When an electric field is applied to the liquid crystal, the double-twist cylinders that make up the three-dimensional structure unwind, and the liquid crystals molecules re-orientate as a result to allow light to pass through. Hence in its default state it doesn’t allow light to pass through, and in its “on state” it allows light to pass through.

Its lack of needing alignment brings down the cost of manufacture, and its fast-switching times produce excellent moving picture quality. However, it’s still in an experimental stage because stable blue phase liquid crystals lie withing the narrow and very low temperature range of less than a few kelvins. Some recent experimentation has managed to develop stable blue phase liquid crystals at over 60 kelvin including room temperature ones.

## 3.3 Opacity changing glass (smart glass)

Smart glass or opacity changing glass is (as the name suggests) glass that can switch between transparent, translucent and opaque states. There are several classes of smart glass including: electrochromic glass, suspended particle device (SPD) glass, thermochromic glass and liquid crystal display glass. This document will only discuss LCD glass and thermochromic glass as the rest simply do not use LC technology.

LCD glass work in a similar way to which an LCD does. It is typically arranged in the following layers:

1. Layer of glass
2. Polarising filter
3. Conductive layer (ITO)
4. Liquid crystal layer

And then the same top three on the opposite side to sandwich the LCs.

In the same setup as an LCD, the polarising filters parallel to each other are placed either side of the liquid crystal such that in their default state only scattered light can pass through (this is explained in the next paragraph), and so the glass is “opaque” (or more specifically translucent as it technically does not block/ absorb all light). The conductive layer made from a layer of indium tin oxide (which is also commonly used in the electrode layer of LCDs) that produce an electric field when current is passed through. This electric field aligns the liquid crystal with the polarising filters allowing light to pass thought directly.

Noticeably indifferent to the LCD the polarising filters of this smart glass are not placed perpendicular to each other. This is as the liquid crystal used in smart glass is a PDLC (polymer-dispersed liquid crystal) rather than the nematic or twisted nematic ones used in LCDs. This liquid crystal in its default state scatters light such that when passing through the smart glass ends up “milky” on the other side as light is being passed though however is so in a scattered manner.

LCD glass is typically used in office spaces, meeting rooms or bathrooms for instant privacy. Downsides however include the fact that a constant current is required to maintain its transparent state, and along with the price of LCD glass itself over a simple blind makes this very expensive.

Thermochromic glass is glass that’s properties change with temperature. In its default state it acts as normal glass allowing light to freely pass through. Once the liquid crystals of glass heat up and surpass a critical temperature, the material transitions into a “tinted” state. In this state the amount of visible and infrared light that can pass through is greatly reduced.

Thermotropic glass’ properties of minimising passage of infrared light can be used to prove energy efficiency of many different industries, such as reducing the need for air conditioning by controlling the amount of heat that can enter a building. As thermochromic glass relies purely on its property to transition into a different state based of temperature makes it both more energy efficient and cheaper as no power is required. It’s also just simpler as it works passively rather than any advanced external input needed.

## 3.4 Laser emission

Before understanding how liquid crystals aid in laser emission it’s important to understand the fundamentals of a laser.

A laser consists of the following:

1. Gain medium
2. Laser pumping energy
3. High reflector
4. Output coupler

Until the final laser beam is produced

A laser starts by pumping the gain medium with energy. This energy is typically supplied as an electric current or light of a specific wavelength. Then the gain medium amplifies the light (increases the power) by stimulated emission (the process of exciting an electron to a higher energy state). These electrons “want” to go back to equilibrium and to do so return to their ground state of energy. In doing this they release a photon which is emitted in a random direction. Stimulated emission now occurs with these original “seed” photons that can stimulate excited atoms to release photons if its of the correct energy. This emitted photon is coherent with the stimulating photon. On either side of the gain medium two mirrors are placed (the high reflector and output coupler) forming an optical cavity. Photons bounce between the mirrors passing through the gain medium multiple times, each time stimulating more emissions and amplifying the intensity of it (due to the constructive interference of light within the cavity). Once the light reaches a high enough intensity, the output coupler allows a portion of the light to be released forming what we see as the laser beam. This light is coherent and monochromatic.

A purple tube with a bolt and lightning bolt

Description automatically generated

This shows the workings of a laser with the reflector on the left, output coupler on right and the tube being the gain medium

A liquid crystal laser is one that uses a liquid crystal as the optical cavity. This allows the selection of the emitted wavelength, intensity and polarization from the laser’s gain medium. In this way, we can tune our laser for certain properties making it extremely efficient (and cost effective) in laboratories and experiments that require varying and testing lasers of different properties. They are able to maintain a similar size to a standard laser, but now with the capability of tuning the wavelength of the emitted beam, and all whilst still maintaining a larger area of coherence.

## 3.5 Liquid crystal cored Fiber Array

Fiber arrays are made by taking fibers and embedding them into a substrate which is typically has V-shaped gaps to hold the fibers. These fibres can transmit light over distances with extremely low loss of energy due to noise. The light is transmitted via the process of total internal reflection by setting up a core (traditionally of pure glass or silicon dioxide) and a cladding of lower refractive index than the core. This allows for total internal reflection of the light to occur, hence allowing it to travel across large distances regardless of the topology of the path.

By replacing the core of these fibers with an isotropic liquid crystal (such as a nematic phase liquid crystal), we can take advantage of the tuneable properties of them to precisely control the propagation of light through the fiber array. This also makes wavelength-division multiplexing much easier by selectively choosing the wavelengths that pass using the liquid crystal. WDM is the splitting of light into different wavelengths, sending all at the same time and then combining the wavelengths at the destination to obtain the original message, this allows more light to be sent increasing the data transmission capacity without physically changing the optical fiber. The refractive index of the liquid crystal itself can also be controlled to reduce crosstalk in fiber arrays.

These features making application of fiber arrays to sensing applications, optical communications networks and more extremely useful.

## 3.6 Stealth Technology

The idea of using liquid crystals for stealth technology would be revolutionary, given their extremely low power consumption and would most definitely be cheaper than the other current alternatives. It uses advanced circuitry and the optical properties of liquid crystals to effectively scatter light (specifically using a scattering matrix approach) such that when viewing an object such as a ship, it is disguised from radar, infra-red and some other detection methods. A proof of concept has already been produced by researcher Christopher R Lavers in developing low-cost optical stealth. Further research is being done into this to investigate the possibilities of this technology.

# 4.0 My Analysis and Opinion

From researching the topic of liquid crystals, I have learnt many things besides themselves including research into topology, order parameters and developed a much better understanding of some of workings behind real world innovations. In fact, it’s from smart glass that I was originally inspired to take this project as I continued to wonder what else liquid crystals had and could be implemented into.

Liquid crystals are simply fascinating to me and extremely useful as they open a whole world of possibilities of technologies which are either in development or yet to be thought of. Their unique optical properties that can change in different circumstances, such as enacting an electric field across them or varying the temperature, are incredibly versatile and across the board are much more energy efficient than their current alternatives.

I believe that although LCDs are steadily being replaced with other displays such as OLED, liquid crystals have so much more to offer whether that is in BPDs or in the potential for stealth technologies and even quantum application. They have a long way to go, and their unique usages will continue to thrive in the near future.

# Bibliography

1. **Wikipedia,** Liquid Crystal, July 30 2024, Available at <https://en.wikipedia.org/wiki/Liquid_crystal> (Last Accessed September 17th 2024)
   1. Reinitzer F (1888). ["Beiträge zur Kenntniss des Cholesterins". Monatshefte für Chemie.](https://www.biodiversitylibrary.org/part/232475) 9 (1): 421–441. doi:10.1007/BF01516710. S2CID 97166902. Archived from the original on November 4, 2022.
   2. Lehmann O (1889). "Über fliessende Krystalle". Zeitschrift für Physikalische Chemie. 4: 462–72. doi:10.1515/zpch-1889-0434. S2CID 92908969.
   3. Sluckin TJ, Dunmur DA, Stegemeyer H (2004). [Crystals That Flow – classic papers from the history of liquid crystals](https://books.google.co.uk/books?id=iMEMAuxrhFcC&redir_esc=y). London: Taylor & Francis. ISBN 978-0-415-25789-3.
   4. Gray GW (1962). Molecular Structure and the Properties of Liquid Crystals. Academic Press.
   5. Vertogen, Ger; Jeu, Wim H. de (December 6, 2012). Thermotropic Liquid Crystals, Fundamentals. Springer Science & Business Media. p. 13. ISBN 9783642831331. OCLC 851375789.
2. **Iam-Choon-Khoo, Liquid Crystals,** December 22nd 2021 (Last Accessed October 8th 2024
3. **Introduction to liquid crystals**, October 8 2024, Available at: [https://uh.edu/~chembi/liquidcrystals.pdf](https://uh.edu/~chembi/liquidcrystals.pdf%20) (Last Accessed October 8th 2024)
4. **Vojtech Krcmarsky, Polarization state control using liquid crystals**, 2014 (last Accessed 9th October 2024)
5. The orderly beauty of liquid crystals (2020) YouTube. Available at: [https://www.youtube.com/watch?v=fEPefMCvN60](https://www.youtube.com/watch?v=fEPefMCvN60%20) (Accessed: 10 October 2024).
6. Liquid Crystal Descriptors Order Parameters (2020) YouTube. Available at: [https://www.youtube.com/watch?v=lq6oaIKBfaY](https://www.youtube.com/watch?v=lq6oaIKBfaY%20) (Accessed: 10 October 2024)
7. Liquid Crystals pt1 Definitions (2020) YouTube. Available at: [https://www.youtube.com/watch?v=C7yW6brH7h0](https://www.youtube.com/watch?v=C7yW6brH7h0%20) (Accessed: 23 September 2024).
8. Liquid Crystals pt2 Order Parameters (2020) YouTube. Available at: <https://www.youtube.com/watch?v=F19FJs06ojw&t=609s> (Accessed: 23 September 2024).
9. Liquid Crystals pt3 Application (2020) YouTube. Available at: [https://www.youtube.com/watch?v=SZYVtLVq1Eo](https://www.youtube.com/watch?v=SZYVtLVq1Eo%20) (Accessed: 23 September 2024).
10. Liquid Crystal Applications (2020) YouTube. Available at: [https://www.youtube.com/watch?v=e5MLLpb8y-8](https://www.youtube.com/watch?v=e5MLLpb8y-8%20) (Accessed: 10 October 2024)
11. The billion-dollar race for the perfect display (2023) YouTube. Available at: [https://www.youtube.com/watch?v=TyUA1OmXMXA](https://www.youtube.com/watch?v=TyUA1OmXMXA%20) (Accessed: 08 October 2024).
12. Internal structure of a liquid crystal or LCD TV screen (2022) YouTube. Available at: [https://www.youtube.com/watch?v=Gx-JVoOFYhs](https://www.youtube.com/watch?v=Gx-JVoOFYhs%20) (Accessed: 08 October 2024).
13. Fiber optic cables: How they work (2011) YouTube. Available at: [https://www.youtube.com/watch?v=0MwMkBET\_5I&t=126s](https://www.youtube.com/watch?v=0MwMkBET_5I&t=126s%20) (Accessed: 09 October 2024).
14. Liquid-Crystal Laser (2023) Wikipedia. Available at: [https://en.wikipedia.org/wiki/Liquid-crystal\_laser#Mechanism](https://en.wikipedia.org/wiki/Liquid-crystal_laser%23Mechanism%20) (Accessed: 09 October 2024).
15. Laser (2024) Wikipedia. Available at: [https://en.wikipedia.org/wiki/Laser#Design](https://en.wikipedia.org/wiki/Laser%23Design%20) (Accessed: 09 October 2024).
16. Padavic-Callaghan, K. (2024) Liquid crystals could improve quantum communication devices, New Scientist. Available at: [https://www.newscientist.com/article/2435010-liquid-crystals-could-improve-quantum-communication-devices/?\_ptid=%7Bkpdx%7DAAAAv16GlNHzhAoKcmJhNGYxWmNwZRIQbTB0bjlxOHExZGRkc3VnbxoMRVg1Q1FOVDBDT0tYIiUxODIycDUwMGI4LTAwMDAzNGVodTlzcTdpNmpmOGZycjBqaHM0KhtzaG93VGVtcGxhdGVSWVRQSDA2M0JYMkk1NjgwAToMT1RDTzJDNlc2NEhGQg1PVFZJTENJSlY3TUpLUhJ2LYUA8BZ3b29sZWp3dDFaCzg0LjkyLjM1Ljg3YgNkd29ot4D8tgZwGXgE](https://www.newscientist.com/article/2435010-liquid-crystals-could-improve-quantum-communication-devices/?_ptid=%7Bkpdx%7DAAAAv16GlNHzhAoKcmJhNGYxWmNwZRIQbTB0bjlxOHExZGRkc3VnbxoMRVg1Q1FOVDBDT0tYIiUxODIycDUwMGI4LTAwMDAzNGVodTlzcTdpNmpmOGZycjBqaHM0KhtzaG93VGVtcGxhdGVSWVRQSDA2M0JYMkk1NjgwAToMT1RDTzJDNlc2NEhGQg1PVFZJTENJSlY3TUpLUhJ2LYUA8BZ3b29sZWp3dDFaCzg0LjkyLjM1Ljg3YgNkd29ot4D8tgZwGXgE%20) (Accessed: 13 September 2024).
17. Lavers, C.R. (2021) Theoretical modelling of liquid crystal electro-optical material display elements to achieve optimal low power consumption ship stealth, LIDSEN Publishing Inc. Available at: [https://www.lidsen.com/journals/rpm/rpm-03-02-019#2.TheoreticalApproach](https://www.lidsen.com/journals/rpm/rpm-03-02-019%232.TheoreticalApproach) (Accessed: 09 October 2024).
18. Wavelength-division multiplexing (2024) Wikipedia. Available at: [https://en.wikipedia.org/wiki/Wavelength-division\_multiplexing](https://en.wikipedia.org/wiki/Wavelength-division_multiplexing%20) (Accessed: 09 October 2024).
19. History of LCD displays (2017) History of LCD Displays. Available at: [https://www.merckgroup.com/en/expertise/displays/solutions/liquid-crystals/history-of-lcd-displays.html#:~:text=Liquid%20crystals%20play%20in%20many,new%20generation%20of%20technical%20devices](https://www.merckgroup.com/en/expertise/displays/solutions/liquid-crystals/history-of-lcd-displays.html%23:~:text=Liquid%20crystals%20play%20in%20many,new%20generation%20of%20technical%20devices). (Accessed: 10 October 2024).
20. Blue Phase LCD technology (2017) Merck KGaA, Darmstadt, Germany. Available at: [https://www.merckgroup.com/en/expertise/displays/solutions/liquid-crystals/lcd-technologies/blue-phase0.html#:~:text=The%20key%20advantage%20of%20Blue,need%20for%20this%20technical%20expense](https://www.merckgroup.com/en/expertise/displays/solutions/liquid-crystals/lcd-technologies/blue-phase0.html%23:~:text=The%20key%20advantage%20of%20Blue,need%20for%20this%20technical%20expense). (Accessed: 09 October 2024).
21. (2017) Phase diagram based on measurements as well as simulations performed by... | download scientific diagram. Available at: [https://www.researchgate.net/figure/Phase-diagram-based-on-measurements-as-well-as-simulations-performed-by-Ninet-et-al\_fig5\_242332284](https://www.researchgate.net/figure/Phase-diagram-based-on-measurements-as-well-as-simulations-performed-by-Ninet-et-al_fig5_242332284%20) (Accessed: 13 September 2024).
22. Kim, T., Lu , T.J. and Song, S.J. (2016 ) ‘2.3 Surface flow visualization using thermochromic liquid crystal’, in Application of Thermo-Fluidic Measurement Techniques . Butterworth-Heinemann.
23. Semenza, P. (2024) Making color in lcds, Available at: [http://archive.informationdisplay.org/id-archive/2013/january-february/display-marketplace-making-color-in-lcds#:~:text=LIQUID-CRYSTAL%20DISPLAYS%20(LCDs),any%20color%20can%20be%20generated.](http://archive.informationdisplay.org/id-archive/2013/january-february/display-marketplace-making-color-in-lcds%23:~:text=LIQUID-CRYSTAL%20DISPLAYS%20(LCDs),any%20color%20can%20be%20generated.%20) (Accessed: 10 October 2024).
24. What is PDLC Smart Glass? (2024) Smartglass World. Available at: <https://www.smartglassworld.net/what-is-pdlc-smart-glass> (Accessed: 09 October 2024).
25. Senyuk, B. (2006) Liquid Crystals: a Simple View on a Complex Matter, Liquid crystals: A simple view on a complex matter. Available at: [http://personal.kent.edu/~bisenyuk/liquidcrystals/index.html](http://personal.kent.edu/~bisenyuk/liquidcrystals/index.html%20) (Accessed: 10 September 2024).