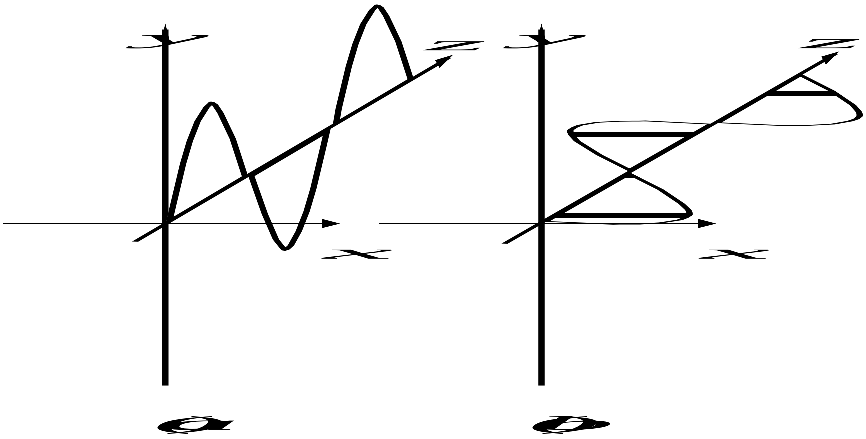
Q1 a) [30%] Monochromatic, light sources such as lasers can be represented in terms of an orthogonal set of propagating eigenwaves which are usually aligned to the *x* and *y* axes in a co-ordinate system with the direction of propagation along the *z* axis . These eigenwaves can be used to describe the propagation of light through complex media. The Jones calculus allows us to describe these waves and their propagation.



If we have an electromagnetic wave propagating in the *z* direction along the *x* axis then the light is classified as linearly polarised in the *x* direction or horizontally polarised. This wave can be represented as a Jones matrix, assuming an amplitude V_x .

$$V = \begin{pmatrix} V_x \\ 0 \end{pmatrix}$$

If the light is polarised in the direction of the *y* axis, then we have linearly polarised light in the *y* direction of amplitude V_y or vertically polarised light.

$$V = \begin{pmatrix} 0 \\ V_y \end{pmatrix}$$

We can now combine these two eigenwaves to make any linear state of polarisation we require. We can also represent more complex states of polarisation such as circular states. So far we have assumed that the eigenwaves are phase (i.e. they start at the same point). We can also introduce a phase difference ϕ between the two eigenwaves, which leads to circularly polarised light. In these examples, the phase difference ϕ is positive in the direction of the z axis and is always measured with reference to the vertically polarised eigenwave (parallel to the *y* axis), hence we can write the Jones matrix.

$$V = \begin{pmatrix} V_x \\ V_y e^{j\phi} \end{pmatrix}$$

For light of wavelength λ passing through a birefringent crystal of thickness t, we define the retardation Γ as.

$$\Gamma = \frac{2\pi\ t}{\lambda}\left(n_f - n_s\right)$$

The effect of this retardation can be expressed as a Jones matrix, assuming that the fast axis is in the same direction as the *y* axis.

$$W_0 = \begin{pmatrix} e^{-j\Gamma/2} & 0 \\ 0 & e^{j\Gamma/2} \end{pmatrix}$$

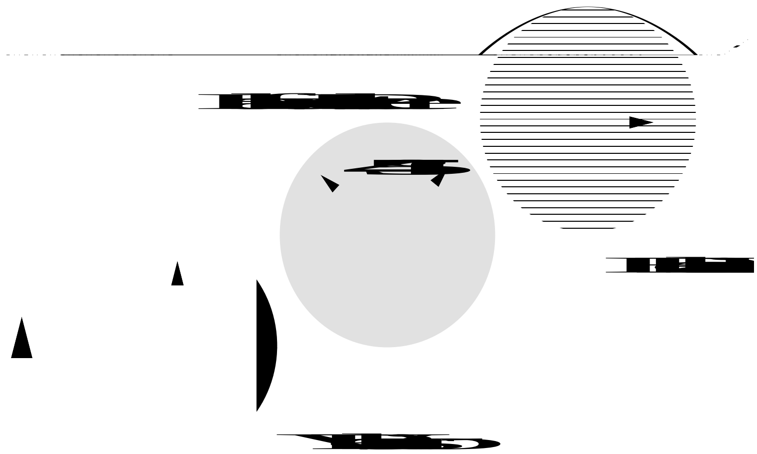
The polarisor can be written as a Jones matrix. If the direction of the polarisor is such that is passes vertically polarised light.

$$P_y = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

b) [25%] We can use Jones calculus to solve the propagation of light through optical systems. A combination of optical elements *starting from left to right*, can be expressed, *starting from right to left,* as a series of matrix multiplications. E.g. If we have a pair of crossed polarisors (vertical and horizontal), then there will be no light propagated through the system. If we place a halfwave plate with its fast axis at 45º to the *y* axis between the two crossed polarisors, and illuminate with vertically polarised light.

$$\begin{pmatrix} V_x' \\ V_y' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} 0 & -j \\ -j & 0 \end{pmatrix}\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 0 \\ V_y \end{pmatrix}$$

$$= \begin{pmatrix} -jV_y \\ 0 \end{pmatrix}$$



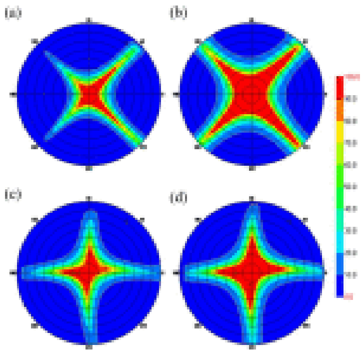
c) [25%] The interpretation of viewing angle is such that we need to calculate the Jones matrix for the light propagating at angle to or about the optical (z) axis. For rotation about the z axis, the calculation is just a rotation matrix applied to the waveplate above. For an arbitrary rotation of the fast axis by an angle ψ about the y axis. Rotation with Jones matrices can be done as with normal matrix rotation. If we define a counter clockwise rotation of angle ψ about the axis y as positive then the rotation matrix is.

$$R(\psi) = \begin{pmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{pmatrix}$$

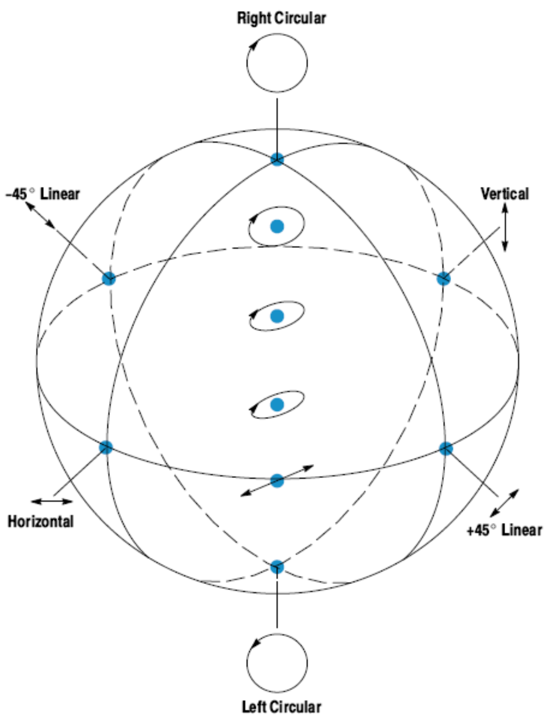
Hence the general form of the retardation plate is.

$$W = R(-\psi)W_0 R(\psi)$$

For light that passes through at an angle to the optical axis we can project each eigenstate directly onto the Jones matrix. This is a basic trigonometric transformation of the axes leading into the from surface of the waveplate. It is quite important to note that the retardance G of the waveplate depends on the thickness of the plate t. If the light enters at an angle to the optical axis, then the apparent thickness will increase, increasing the retardance. This will then take the waveplate away form the half wave criteria. A plot of the intensity of the light at different angles through the waveplate when between crossed polarisors is an iscontrast plot. This is an effective plot of the viewing characteristics of the optical system.



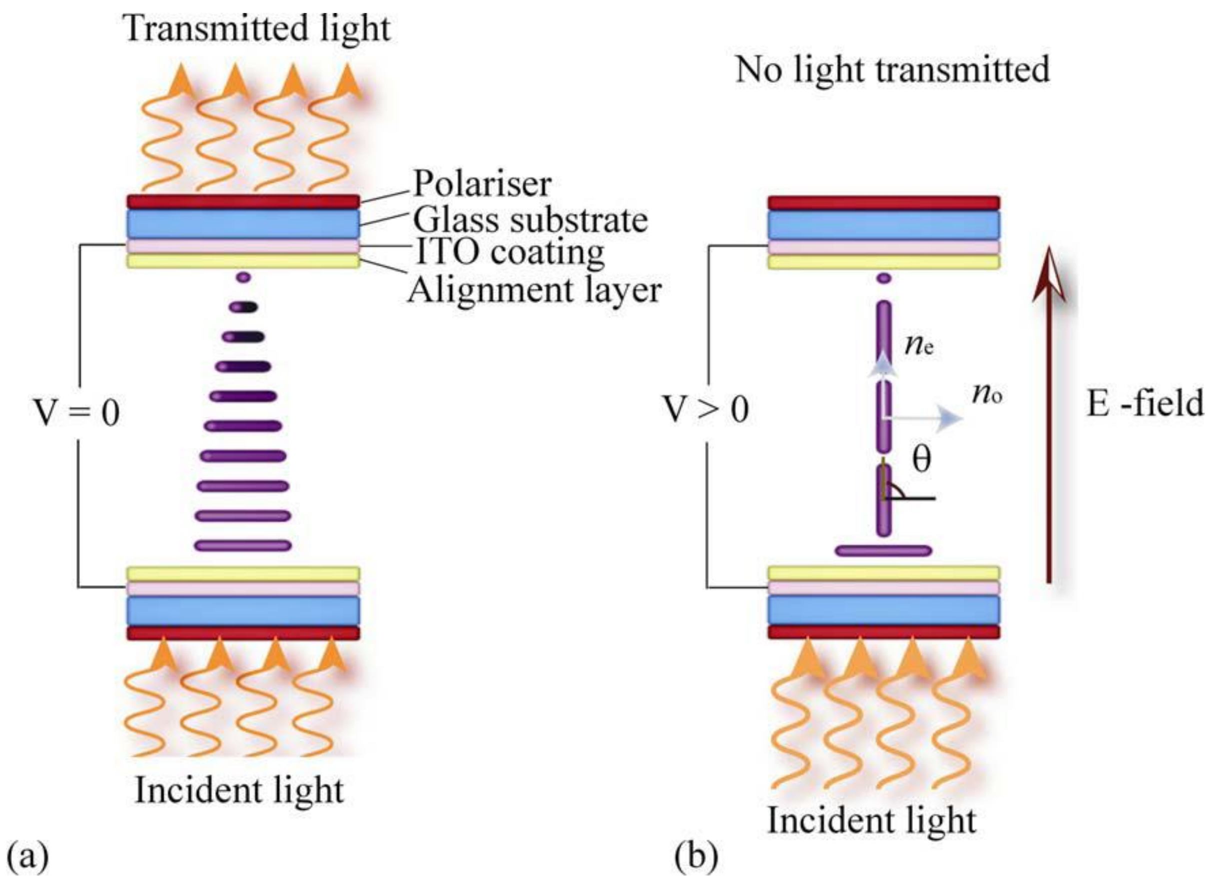
d) [20%] A very useful tool in analysing polarised light is the Poincare sphere which translates the different polarisation states into a 3D space. The co-ordinates of this spaces are defined by Stokes parameters which can be derived from the two eigen states of the original polarisation. The Poincare sphere identifies all of the polarised states recognised by Jones matrices. The viewing chacteristics of a display can be mapped on tot the sphere and a trajectory formed as the light passes through the LCD. This can then be compensated for by plotting a return trajectory to the circumference circle and the anisotropic function of trajectory is the basis of the compensation film.



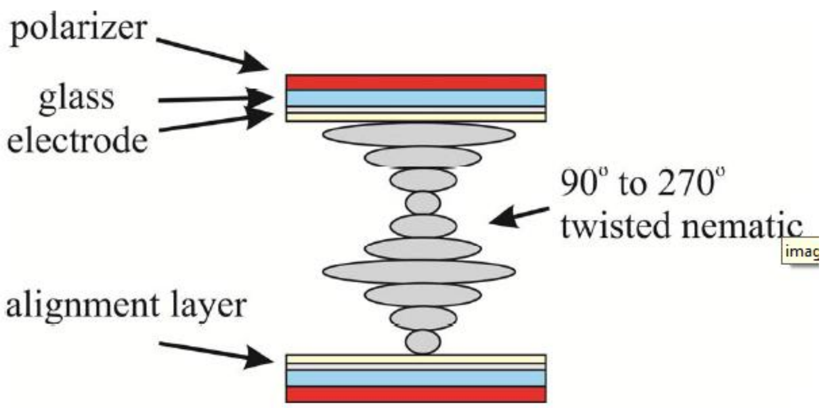
Q2) a) [30%] In the architecture of a TN cell, which corresponds to one picture element (pixel), involves two glass plates that are separated by solid spacers typically of the order of 5 to 10 μm thickness. The inner surfaces are coated with first a conducting layer such as ITO and then an alignment layer whereby the rubbing direction of the top plate is at 90^o to that of the bottom surface. This results in a 90^o twist of the director profile from the top to bottom substrate. On the outer surfaces of the cell a thin film polariser is attached whereby the transmission axis is aligned to the rubbing direction and therefore the nematic director at the surface.

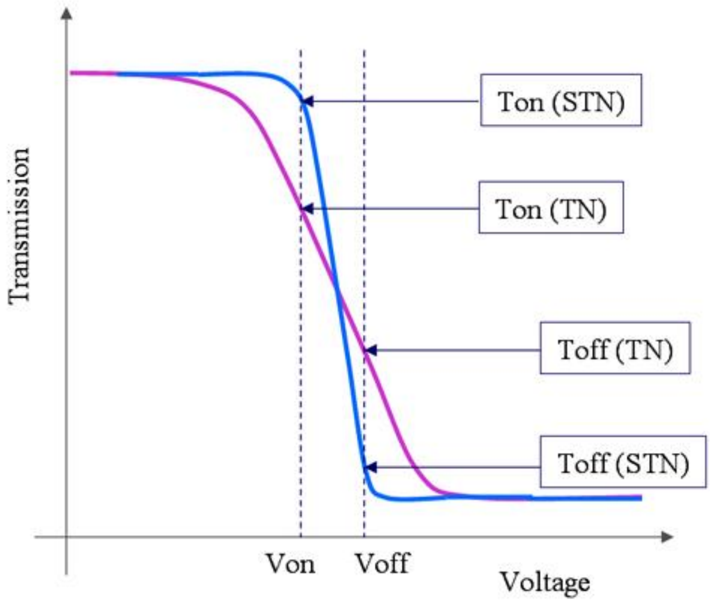
In the 'off' state due to the formation of the 90o twist, the waveguide nature of the medium enables light to be transmitted through the crossed polarisers. Plane polarised light enters the cell from the bottom and follows the twist before passing through the second polariser. With the application of an electric field well above threshold the molecules in the centre of the cell reorient so as to align with the direction of the applied field and the twist is then unwound. At field strengths much greater than the threshold, the effective birefringence is zero and thus the plane of polarization is not rotated through the cell. This is the dark 'on' state. In order to achieve colour, red, green, and blue colour filters are added.

There are three main advantages in going from the planar aligned nematic to the TN structure. The twist is a form of pre-stress which changes the elastic properties of the LC and make it switch a lot faster. The viewing characteristic is much better as the LC director now covers two dimensions. The Maugan waveguide effect can be used over a much wider wavelength range than the planar LC.



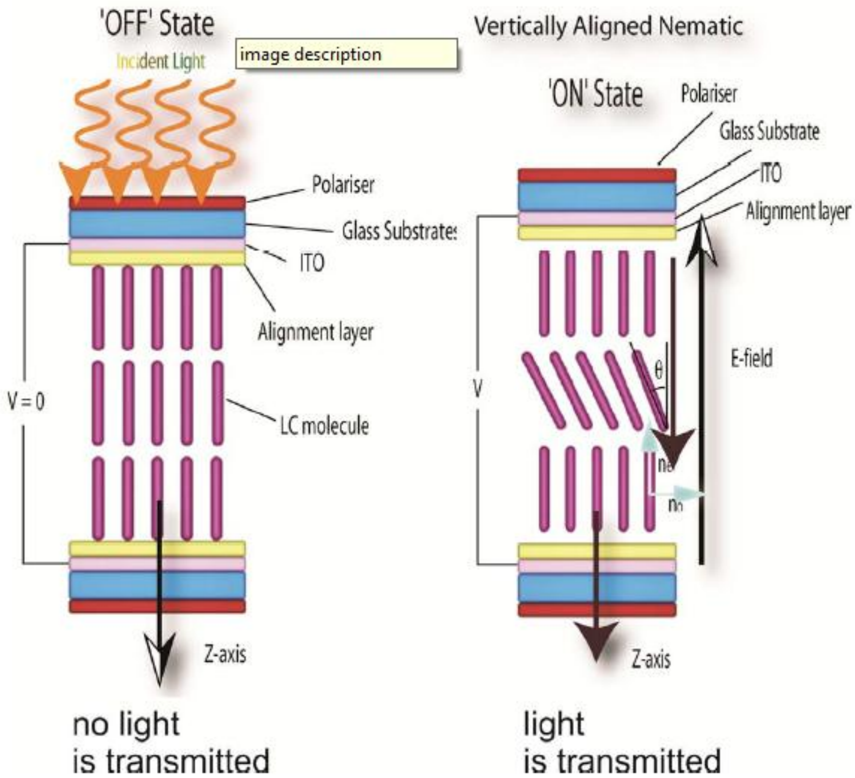
b) [25%] The supertwist LCD adds a further 180 degree twist to the liquid crystal to either 240 or 270 degrees. This has the effect of distorting the LC even further creating a more non-linear electro-optical effect, with faster response times, but we lose the Maugan waveguiding effect.





$$N = \left\{ \frac{(V_{on}/V_{off})^2 + 1}{(V_{on}/V_{off})^2 - 1} \right\}^2$$

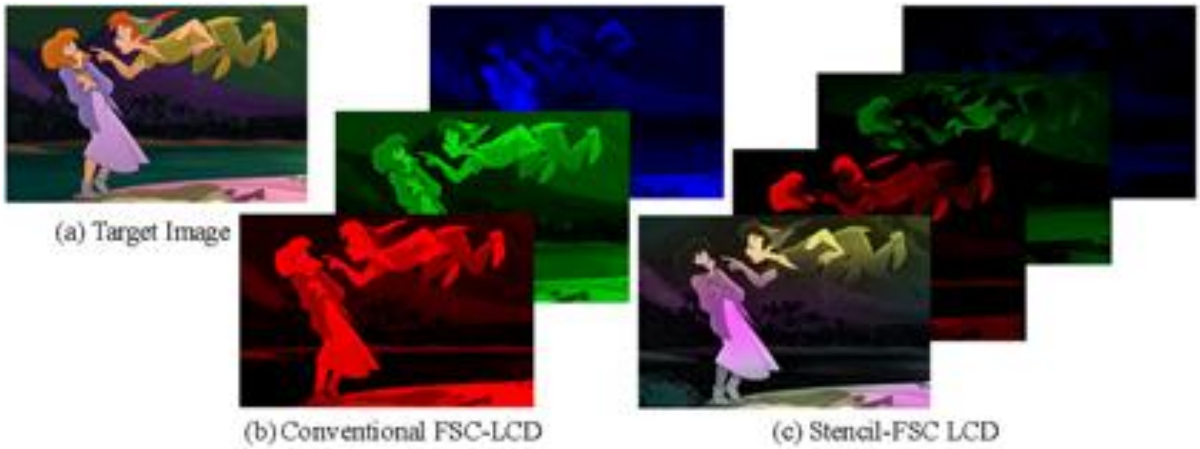
The supertwisted nematic device has a greater twist angle which results in a steeper electro-optic curve. It is more suitable for multiplexing in comparison to the TN device. However, grayscale can be more difficult for the STN mode because of the very steep T-V curve. In order to maximise the number of column and rows that can be addressed using PM addressing it is necessary to make the difference between the on-voltage and off-voltage as small as possible, otherwise known as the Alt-Pleshko criteria. This means increasing the steepness of the transmission-voltage curve. The solution was to increase the helical twist to angles between 90º and 270º. Another drawback of the STN architecture is that the extra twist makes the viewing characteristic much more complicated and harder to compensate for.



c) [25%] The vertically aligned nematic (VAN) consists of a homeotropic alignment of the LC in the absence of an electric field. As a result, there is no optical activity between crossed polarizers. When an electric field is applied the molecules tilt out-of-the plane of the device resulting in a net retardation between crossed polarizers. The advantages of the VA technology are that it requires no rubbing process

and it combines a very good contrast ratio with fast response times. For on-axis viewing the dark state is very good and, unlike the IPS mode, is not limited by the quality of the alignment. The VAN mode has very good response times, although in this case there is no simple analytical solution for the response time. However, to a first approximation, the response time of the VAN mode is governed by the viscosity and bend elastic constant.
The VAN mode requires a negative dielectric anisotropy material as the LC not aligns perpendicular to the applied field. The E field is now in plane which makes the backplane electrode much more complicated to fabricate.

d) [20%] The response time of the LC material dominates the frane rate of the LCD and therefore dictates how fast a video sequence can be displayed. For modern VAN LCDs this is now around 8msec, but this is not fast enough to eliminate unwanted motion artifacts caused by slow frame lag. High frame rate displays can be made more efficient using frame sequential colour techniques.

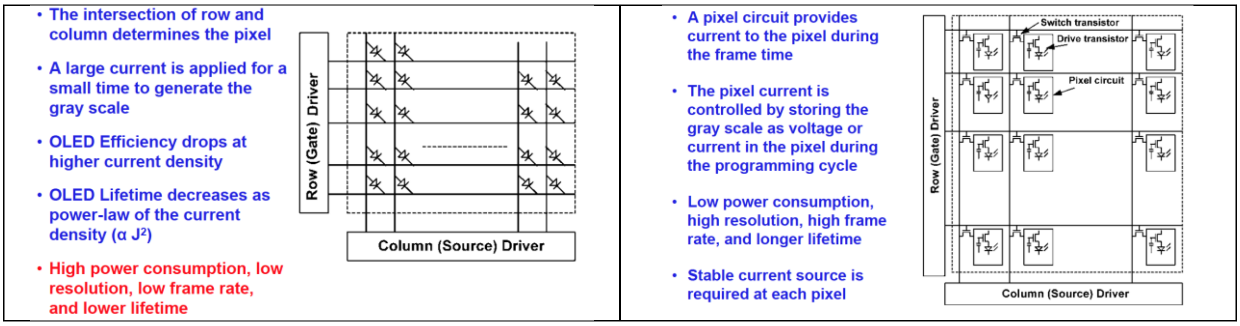


Current displays produce colour through spatial averaging from colour filters. However, it is also possible to obtain colour through time averaging of a sequence of different intensity primary colours. In this case the frame is divided into three sub-fields: one for each primary colour. The backlight flashes red, green, and blue – synchronized with the display addressing. For a 60 Hz refresh rate the primary colour subfield must operate at 180 Hz. As a result, this requires very fast response time liquid crystals modes. LED backlights are well-suited for frame sequential LCD.

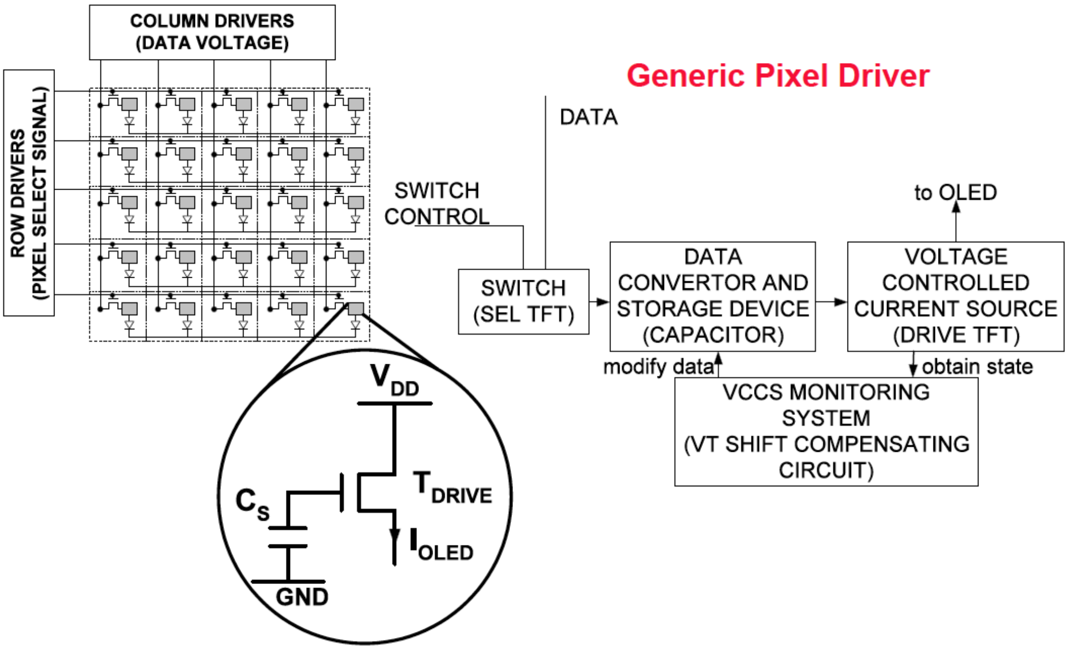
The other main application that would benefit from a fast LC mode is 3D displays or auto stereoscopic displays. They usually display alternate left and right views at high frame rates and a fast LC would help eliminate motion artifacts in the display process.

Q3 Please use illustrations along with design equations where pertinent:
(a) [25%] Addressing schemes for OLED displays are based on passive or active matrix architectures.

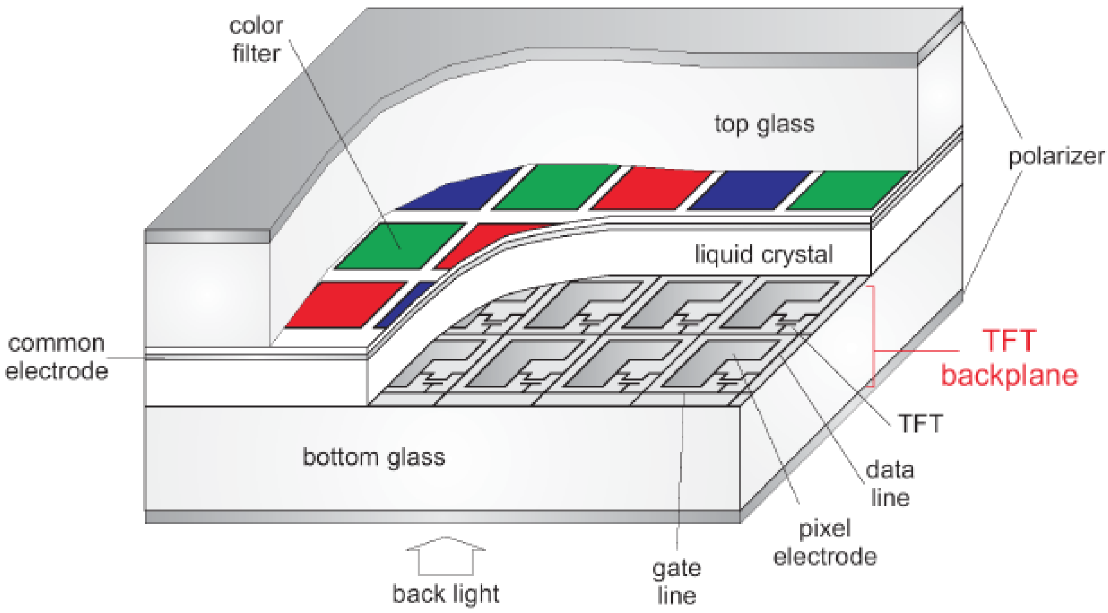
Passive Matrix	Active Matrix



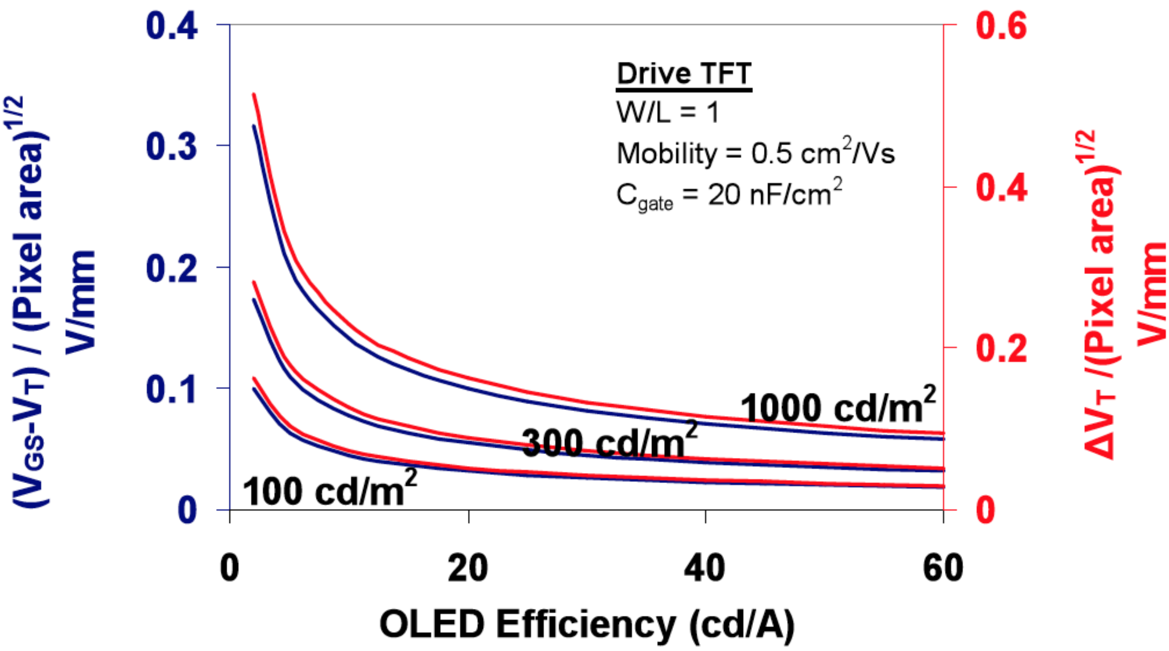
(b) [25%] High resolution pixel architecture for stable OLED display operation has requires the following building blocks comprising pixel switching, data conversion and storage, current source, and threshold voltage shift compensation circuit.



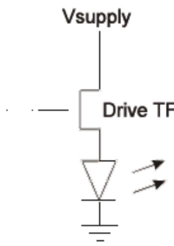
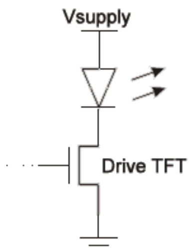
In contrast, the liquid crystal display, as does not require a current source at every pixel (since its voltage driven) nor compensation circuit for threshold voltage shift. The threshold voltage shift is much smaller than in OLED displays and shifts are recovered by holding the off state at negative voltage.



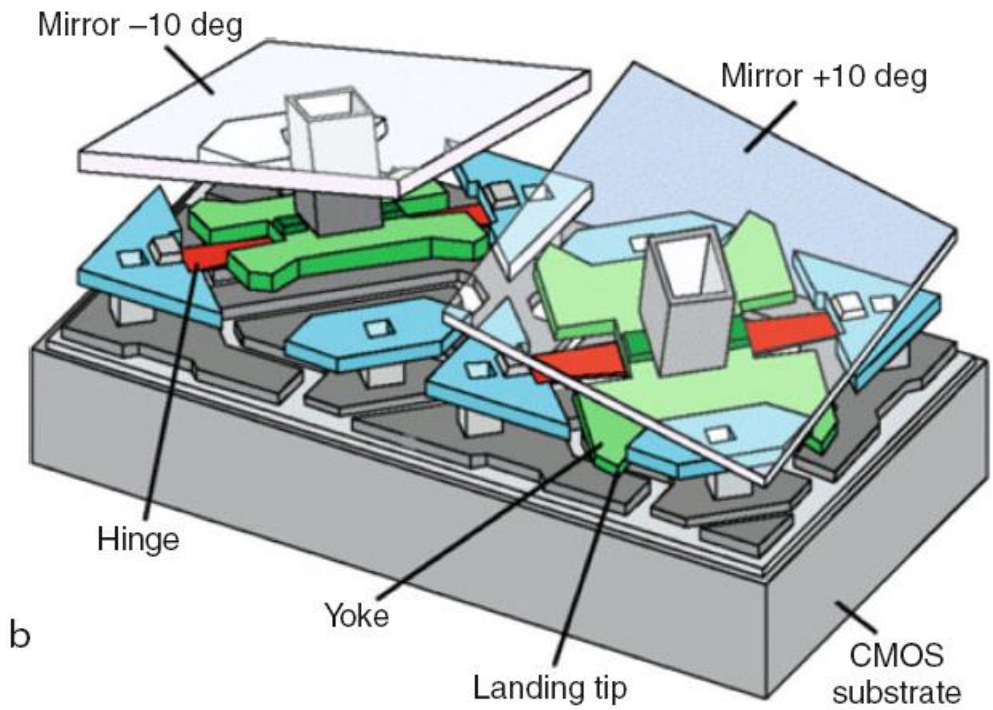
(c) [25 %] The gate overdrive voltage is defined by V_{GS}-V_T where V_T is a function of the TFT's terminal voltages and can change with time depending on the degree of bias stress. The overdrive voltage can also be written as V_{GS}-V_{T0}-ΔV_T. If normalized to the pixel area (since the current through the TFT is a function of the transistor's W/L) we can sketch the overdrive voltage (or correspondingly the threshold voltage) as a function of the OLED efficiency as shown.



(d) [25%] See table below for a comparison of the two main modes

	Bottom Emission	Top Emission
OLED connected at source of drive TFT  	• Reduced aperture ratio • Regular OLED - transparent anode • OLED current depends on OLED voltage which changes with aging – undesirable location! • Safeguards against small variation in drive current by source degeneration	• > 70% aperture ratio • Regular OLED – transparent cathode. • OLED current depends on OLED voltage which changes with aging – undesirable location! • Safeguards against small variation in drive current by source degeneration
OLED connected at drain of drive TFT  	• Reduced aperture ratio • Inverted OLED - transparent cathode • OLED current independent of OLED voltage	• > 70% aperture ratio • Inverted OLED - transparent anode • OLED current independent of OLED voltage

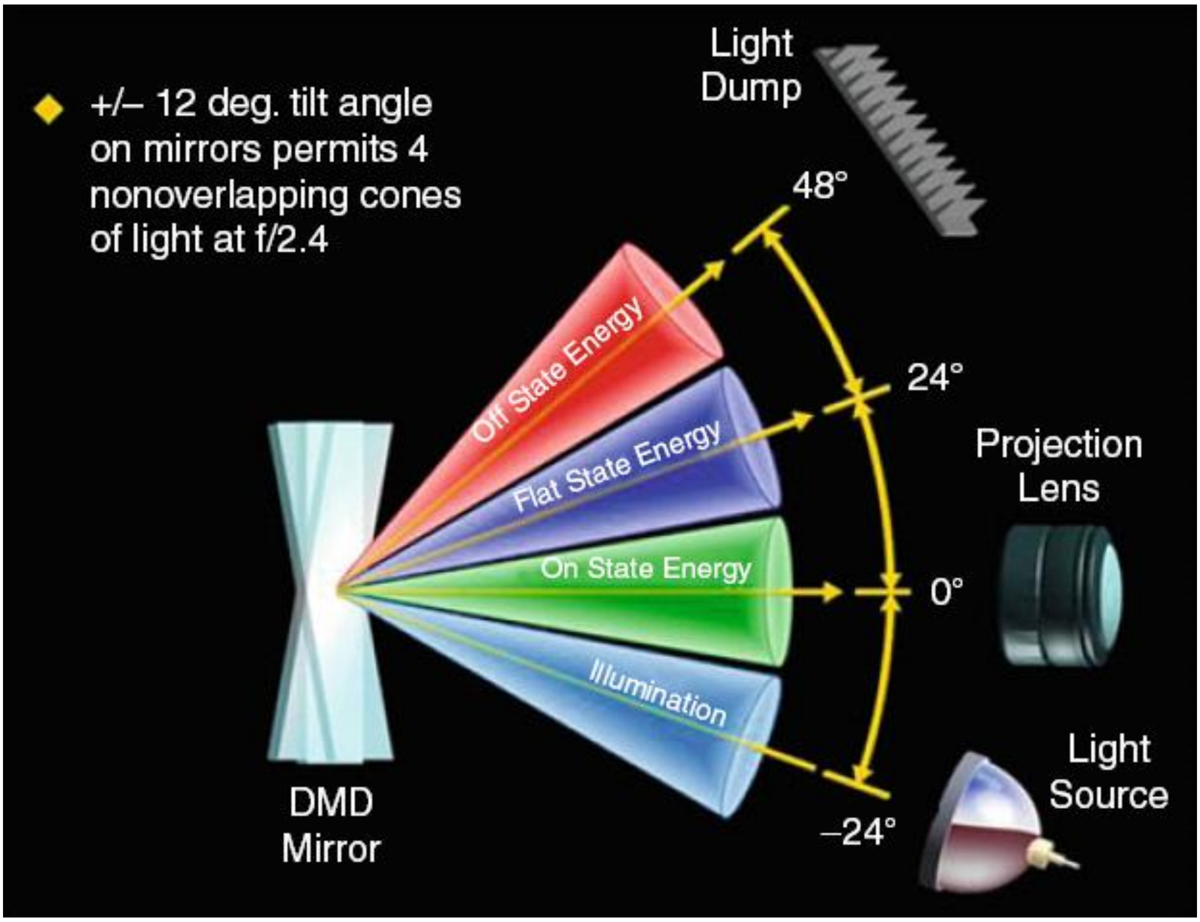
Q4 a) [30%]



The square mirror is suspended between posts with a flat metallic torsion hinge. At rest, the mirror remains horizontal and flat. Underneath the mirror is a silicon memory cell (Static

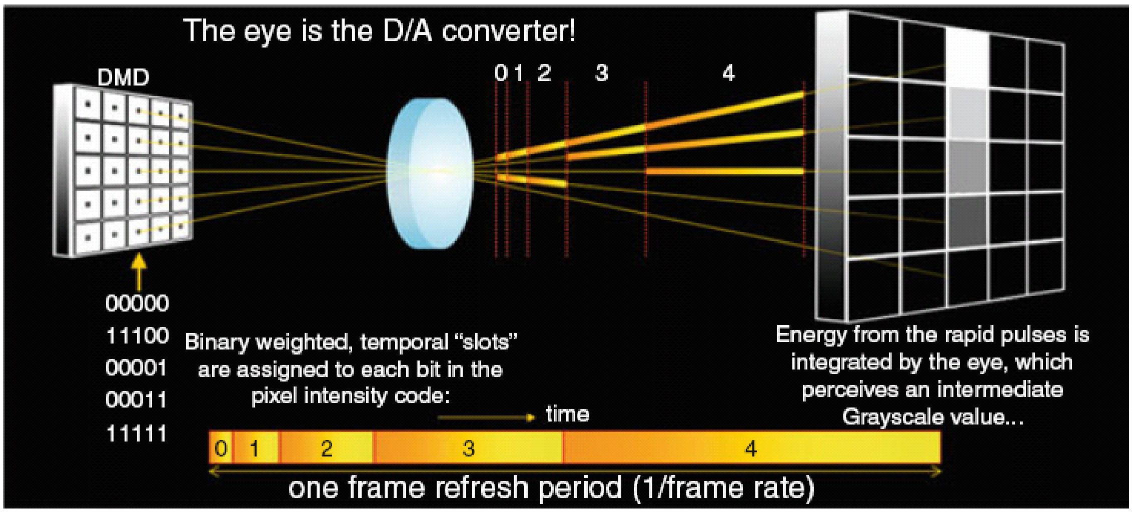
RAM) that stores a digital value (1 or 0) just like any computer memory cell. The difference between this RAM and a normal computer memory is that the outputs of the cell are wired to a pair of offset address electrodes on the surface of the silicon. These electrodes are wired so that a positive voltage appears on one side or the other depending on the memory value.

The differential voltage appearing between the mirror and the address electrodes causes the mirror to be attracted to tilt to one side or the other. The mirror moves all the way so that its tip touches down at a landing surface. The device is thus an electrostatic/torsion balance. The torsion in the hinge creates a restoring force to help the mirror return to its flat state once the mirror is released. The mirror can therefore be switched from tilted left to tilted right. The mirror angle is 12^o from flat (in most versions). Mirror rotation from ‘‘1’’ to ‘‘0’’ is 12 + 12 = 24^o. This movement allows a beam of light to be switched through 48^o.

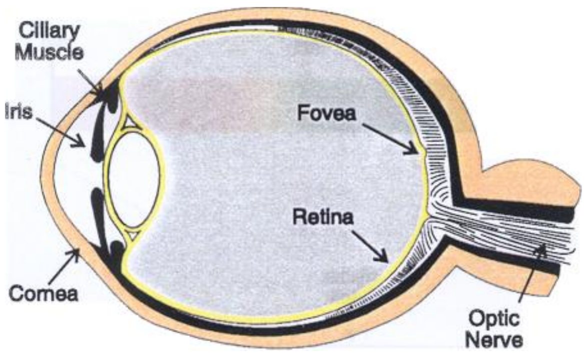


The main limitation of the DMD is that it can only steer light from an ‘‘on’’ to an ‘‘off ’’ condition where we have light or no light for every picture element (pixel). Hnce it is only a binary intensity modulator.

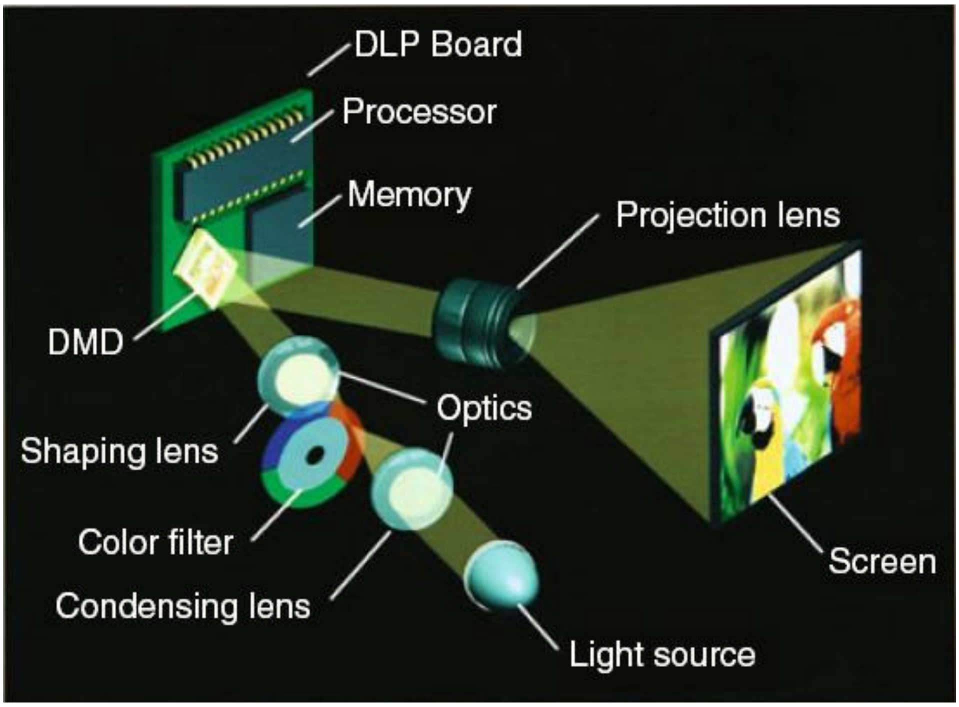
b) [30%] In practice, we need to produce shades of gray that correspond to a digital word or byte for each pixel. Computer graphics typically produce 8bit grayscale values that correspond to 256 brightness levels (2^8). This is produced on DMDs pulse width modulation.



The dithering of grayscales is then combined with the RGB colour components to make full colour image. The problem with this technique is the fact that the eye responds much faster to colour information that it does to intensity. The photo-sensitive layer which covers the inner surface of the eye is the retina. The retina is made up of large numbers of receptors which can be classified into two groups, named by virtue of their shape as rods (colour) and cones (intensity).



c) [20%]



For a RGBRB colour wheel, there will be 5 sectors on the wheel, each 360/5 = 72^{o}

8 bitplanes per grayscale frame, 5 colour per frame = 40 binary frames every 50th of a second for 50 Hz = 2000 frames per second. Every colour sector will illuminate 8 bitplanes for each colour and will have to rotate once every 50th of a second. Hence speed will be 50x60 = 3000rpm.

d) [20%] It is relatively simple to create a 3D projection system using a standard 2D DMD projector. Most 3D auto stereoscopic systems use time multiplexing to project a left and then a right eye view one after another onto a screen. Some form of eyewear is then used to filter each view so that only the correct eye sees the required view. As the DMD is illuminated with un polarized light, all that is needed is a time sequential shutter that switches the polarization of the light every 100th of a second. The polarization state should match one of the two orthogonal states in the passive glasses. Many systems use right and left circular polarization states to encode the views. Note that this will require a polarisation maintaining screen. The colour wheel would have to run at 6000rpm (twice speed).