Chapter 20
Display Devices

20.1 CRT:

The cathode ray tube (CRT) remains the traditional monitor device in TV and computer despite the emergence of new devices, such as liquid crystal display (LCD) and plasma display (PD). The CRT consists of an evacuated glass envelope containing an electron gun (or triple gun in color CRT). The e-beam passes through the magnetic fields generated by a deflection yoke. The deflection is arranged in such a way that the electron spot scans the screen line by line. For a color CRT, special care has to be taken in the design of the yoke to ensure that all 3 beams are deflected and focused to the same point (Fig. 20.1). The 3 beams pass through holes in the shadow mask in such a way that each beam strikes only its own phosphor (red, green, blue) (Fig. 20.2). On striking the phosphor, the energy of the electrons is converted into light which then passes through the screen to the user. The primary function of the electron gun is to generate an electron beam and accelerate it by means of a high anode voltage. The power of an electron beam is the product of the anode voltage and the scan current.

When luminance values of the three colors are quantized, 10 bits per color are needed to guarantee a good image. The CRT, however, is unique in requiring fewer bits due to the fact that we do not digitize the luminance of the CRT but the drive voltage of the gun which has a nonlinear relationship with luminance. The luminance of the CRT is proportional to the beam power P_b which is the product of the anode voltage V_a and the beam current I_b. The value of the beam current is controlled by the drive voltage V_d of the gun.

$$I_b = KV_d^{\gamma} \qquad (20-1)$$

Where γ lies between 2.2 and 3. Signal source such as broadcast TV and photo CD are precompensated or γ corrected. For computer generated images, γ (gamma) correction can be achieved by color look up tables in the graphic controller. The result of the nonlinearity of the gun is that fewer bits per pixel are needed. It has been found that 8 bits / color or 24 bits per pixel are adequate for good image quality.

Another important function of the electron gun is to focus all the electrons of one beam into a small spot and then to maintain the spot size over the entire scan. The smaller the details to be resolved or the size of the characters to be displayed on the screen the smaller the spot has to be.

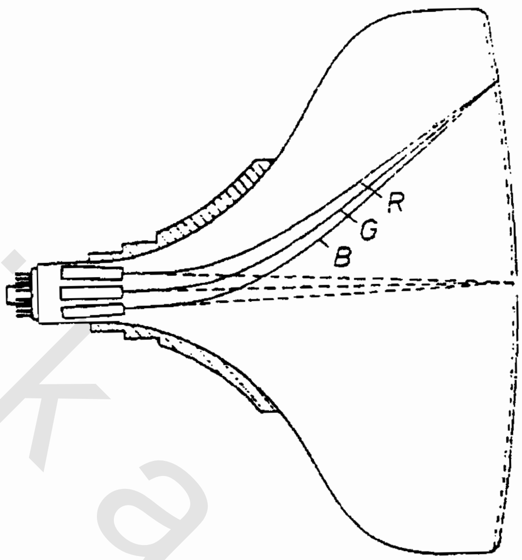


Fig. (20.1) Basic CRT

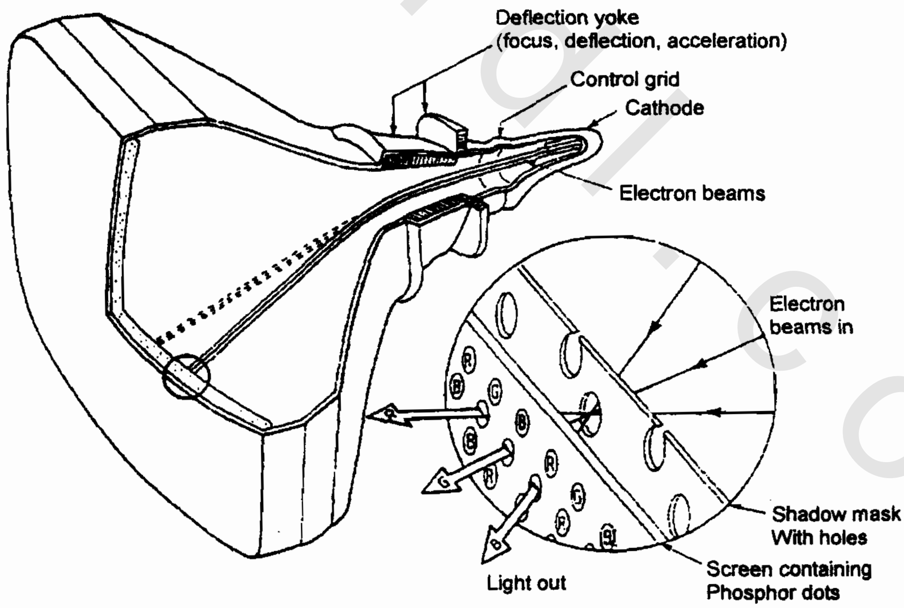


Fig. (20.2) Shadow mask

20.2 Liquid Crystal Cell:

CRT is considered an emissive device. Liquid crystal display (LCD) is not. The molecules in ordinary liquids normally have random orientation. In liquid crystals, the molecules are oriented in a definite crystal pattern. When an electric field is applied to the liquid crystal, the molecules which are approximately cigar shaped tend to align themselves perpendicular to the field. Charge carriers flowing through the liquid disrupt the molecular alignment, and cause turbulence within the liquid (Fig. 20.3). When not activated, the liquid crystal is transparent. When activated, the molecular turbulence causes the light to be scattered in all directions so that the activated areas appear bright. This phenomenon is known as dynamic scattering.

The liquid crystal material may be one of several organic compounds which exhibit the optical properties of a solid, while retaining the fluidity of a liquid. Examples of such compounds are cholesteryl nonanoate and pazoxyanisole.

A liquid crystal cell consists of a layer of liquid crystal (LC) material sandwiched between glass sheets with transparent metal film electrodes deposited on the inside faces (Fig. 20.4). With both glass sheets transparent, the cell is known as transmittive type cell. When only one glass sheet is transparent and the other has a reflective coating the cell is termed reflective type (Fig. 20.5).

When not activated the transmittive type cell will simply transmit rear or edge lighting through the cell in straight lines. In this condition, the cell will not appear bright. When activated, the incident light is diffusely scattered (Fig. 20.5a) and the cell appears quite bright even under high intensity ambient light conditions.

When not activated light in the reflective type is reflected from the mirror surface and the cell does not appear bright. When activated the dynamic scattering phenomenon occurs and the cell appears bright (Fig. 20.5b).

Another version of LC is called field effect LCD and is constructed similarly to the dynamic scattering type (Fig. 20.4) with the exception that two polarizing optical filters are placed at the surface of each glass sheet.

The liquid crystal material employed is known as twisted nematic type and it actually twists the light passing through when the cell is not energized. This twisting allows the light to pass through the polarizing filters.

Thus, in the case of a transmittive type cell the unenergized cell can appear dark against a bright background? When energized, the cell becomes transparent and disappears into the background.

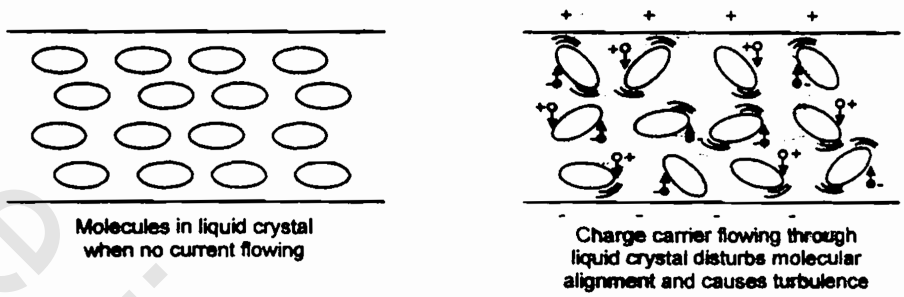


Fig. (20.3) Molecules in a liquid crystal
a) no field *b) under field*

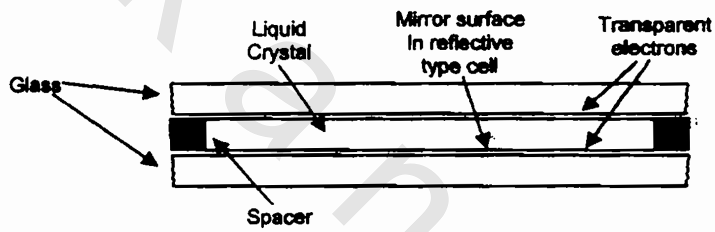


Fig. (20.4) LC Cell

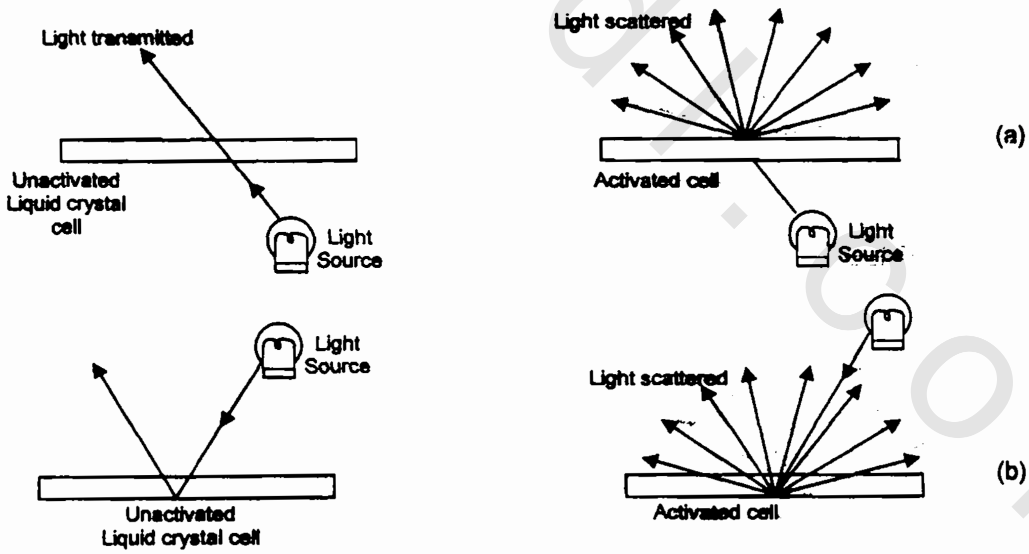


Fig. (20.5) Types of LC cells
a) transmittive. *b) reflective*

20.3 Active Matrix LCD (AMLCD):

Super twisted nematic (STN) liquid crystal displays represent one of the two principal flat panel display technologies, the other being active matrix LCDs (AMLCDs). Active matrix addressing places an electronic switch at each pixel of an LCD, thus, controlling the charging of the pixel capacitor up to the voltage corresponding to the desired grey shade and then holding this voltage until the next video information is written in. The available switches are thin film transistors *TFTs* which are field effect transistors using amorphous silicon $(a-S_i)$ as the semiconductor. Passive addressing does not require a switch at each pixel. However, in contrast to active addressing it suffers from limitations in the number of addressable lines, in the number of grey shades as well as in the time for which it is possible to hold a given grey shade, which results in flicker.

Fig. (20.6), Fig. (20.7) shows the addressing of a pixel by *TFTs*. For all *TFTs* the pixels of one line are made conductive by positive gate pulse upon which the video information is charged through the columns simultaneously in all pixels of the line into the LC capacitors C_{LC} and an additional thin film storage capacitor C_s. The charging of the capacitors to the voltage $V_{LC}(t)$ is governed by nonlinear differential equation as both C_{LC} and the on resistance of the *TFT* are voltage dependent.

As $V_{LC}(t)$ rises, the voltage $V_{DS}(t)$ of the *TFT* drops. This results in a decrease of the drain source current I_{DS} with time. After loading C_{LC}, the voltage must be held during the frame time which is effectively supported by C_s.

20.4 LCD Light Valve Systems:

The liquid crystal material is able to change the polarization of light (Fig. 20.8) not in a fixed but in a variable manner under the influence of an electric field. The molecules are long and rod shaped and when aligned together will polarize light. Unlike a normal polarizer, a liquid crystal has its molecules reoriented by the influence of an electric field.

The twisted nematic (TN) cell (Fig. 20.9) consists of two glass sheets separated by liquid crystal. Each plate has 2 coatings, one is transparent electrode (electrical conductor usually indium tin oxide) and the other is an alignment layer, which helps the liquid crystal to align its molecules in one direction in the manner of spaghetti lining itself on a matched grooved surface.

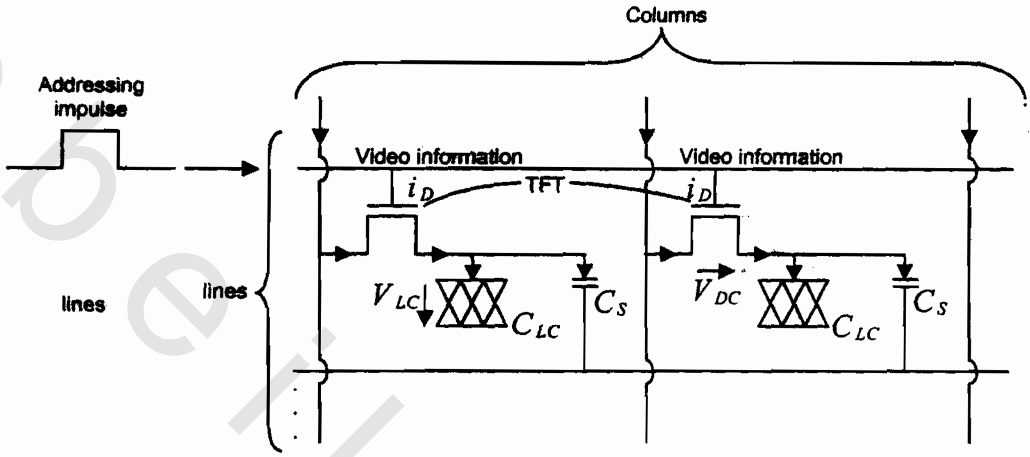


Fig. (20.6) TFT **addressing (operation)**

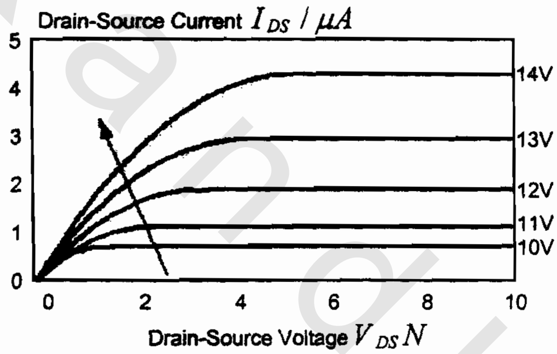


Fig. (20.7) TFT **addressing (**I **–**V **characteristic)**

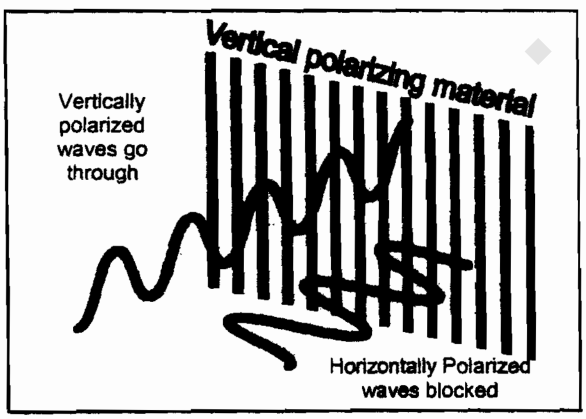


Fig. (20.8) Polarization of light

In the TN cell, the alignment on one plate is 90° different from that of the other. The nature of the liquid crystal material is such that the alignment of its molecules changes through the material. In Fig. (20.10) polarizing filters are added. In (Fig. 20.10a), unpolarized light is represented as two planes of light at right angles to each other. The filter lets light of one plane of polarization through and blocks the rest. On its way through the liquid crystal material, the light has its plane of polarization rotated through 90° following the twist of the liquid crystal. The polarizing filter on the other glass is at 90° to that on the entrance side, and thus, lets the light through. In Fig. (20.8b), an electric field is applied across the liquid crystal cell. This causes the liquid crystal to straighten up, so the polarized light now retains its initial polarization and hence, gets absorbed at the exist filter. This type of cell is a "normally light", all requiring the electric field to go dark. The straightening effect, and hence, light transmission or blocking is proportional to the voltage applied.

The passive matrix LCD (PMLCD) is shown (Fig. 20.11). The complete display still consists of the two glass plates, the polarizing filters and the liquid crystal sandwiched in the middle. The electrode pattern is a set of columns and rows. Each intersection can be regarded as a set of an individual TV cell. If the voltage is applied to one row and one column the intersection will respond.

An image can be built up by selecting a row and applying the required voltage on the column corresponding to the brightness of each cell in that row. Thus, the rows are scanned from top to bottom.

The amount of time allowed for energizing each cell is very short, yet to maintain a display any energized cell must retain its new state until the next time it is scanned. This means using a high viscosity liquid crystal with considerable lag, making it difficult for it to track a fast changing image. Also, in the PMLCD, capacitive coupling causes a control voltage applied to a single cell to influence adjacent cells, hence, reduce contrast. In active matrix liquid crystal display (AMLCD), every pixel in the array has an electronic switch (Fig. 20.12).

When a row is selected, the switch connects the data to the cell in that row. However, when the switch is open circuit, the voltage is maintained across the cell. Thus, the TN cell is held to the required state until the next scan cycle and then there is no dependence on cell lag.

There is no restriction on the overall number of scan lines. The switch is a thin film transistor (*TFT*) made of pure crystalline silicon. Color is achieved by *RGB* additive color mixing. This requires the LCD panel to have three times the number of cells than the required pixel resolution formed as triads. AMLCDs with a backlight are used for LCD monitors for video. LCD monitors for data and graphics are used in portable (laptop) computers.

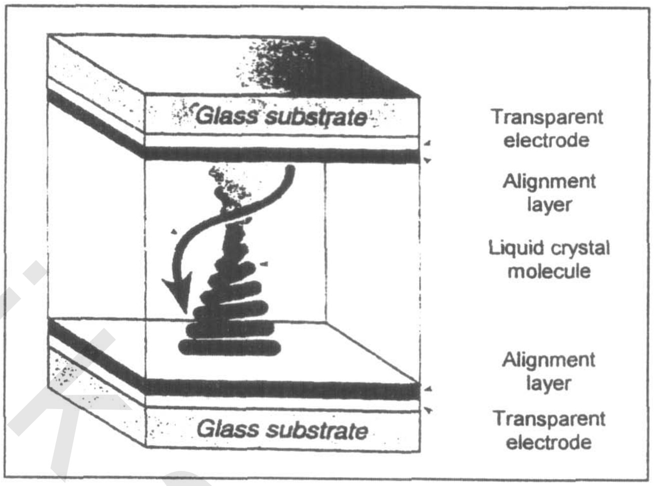


Fig. (20.9) TN cell

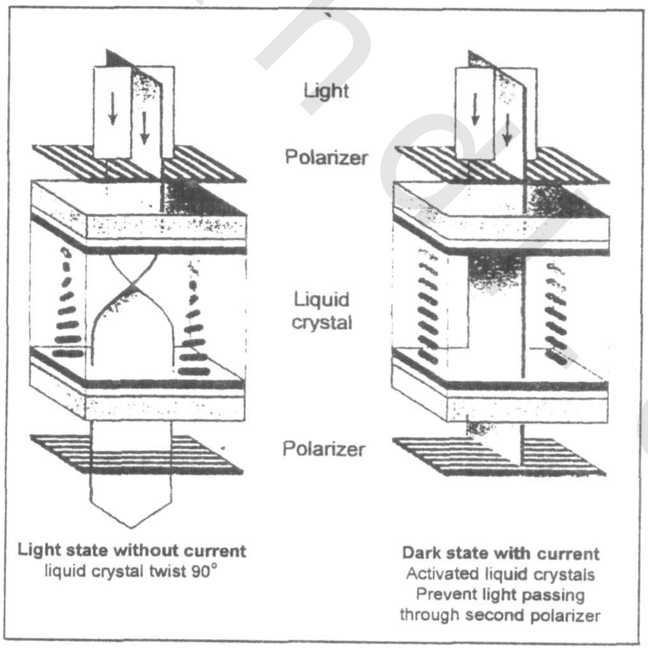


Fig. (20.10) The cell in action

a) light goes through when unactivated

b) light is blocked when activated

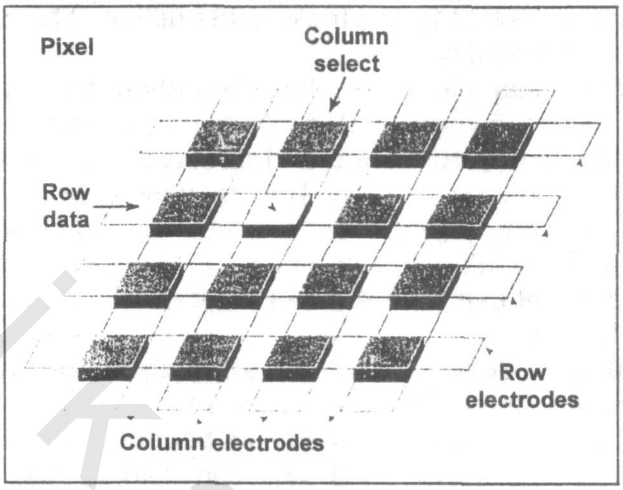


Fig. (20.11) PMLCD

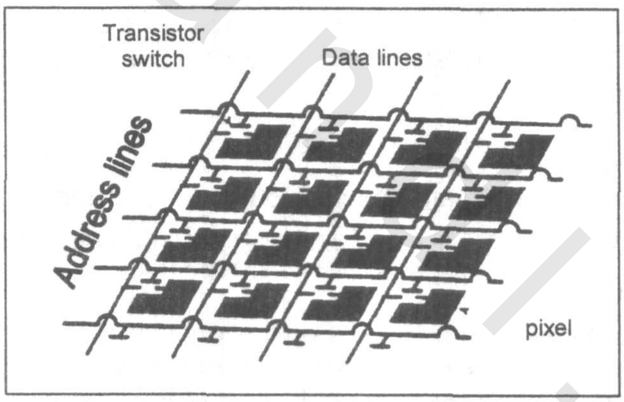


Fig. (20.12) AMLCD

LCDs are now used in tiling as video wall (Fig. 20.13). Video tiles use the optical system shown (Fig. 20.14).

The idea of an LCD projector is to illuminate an LCD as a slide and project the image using an objective lens (Fig. 20.15). The principle of the three panel projector is shown (Fig. 20.16). The separation of the light into RGB is achieved by dichroic mirrors – in mirror box. These are mirrors which reflect light of a particular wavelength and transmit the rest. Thus, a green dichroic reflects green and transmits the red and blue. While 3 panels projectors give the best color and brightest image by virtue of the dichroic color separation, single panel projectors are much cheaper because of their simple construction. This could be done using filters at the cost of color quality.

An alternative uses dichroic color separation with a single LCD panel without color filters. The technique (Fig. 20.17) has interesting similarity to the shadow mask. White light is collimated and directed at a stack of dichroic mirrors each angled with respect to each other. This results in 3 colored beams of light being reflected at different angles. This multicolored illumination is directed at a microlens array. It collects all the incident light and directs it at the individual LCD cells. This makes efficient use of light. The LCD cells are illuminated by only one of red, green or blue beams.

Digital micromirror device (DMD) is another reflective light valve which uses digital light processing (DLP). The device is arranged so that if electric charge is present between the mirror and an electrode beneath, the mirror tips. If such a mirror is illuminated by a beam of light the beam can be swung through 90° (Fig. 20.18).

Unpolarized light is absorbed in a light trap and wanted light is diverted through a projection lens which projects an image on a screen. There is a mirror for every pixel. The mirror is 17 micrometer square. The DMD can be manufactured using chip technology.

20.5 Emissive Displays:

There are three main technologies: alternating current thin film electroluminescent displays (ACTFEL), plasma display panels $(PDPs)$ and field emission displays $(FEDs)$.

In the three cases - with the exception only of monochrome (neon orange) $PDPs$ - light is emitted in a solid state material named a phosphor. The name phosphor is used for photoluminescent (UV excited) powdered materials used in lighting tubes.

The same principle is used in color $PDPs$. The cathode luminescent (e–beam excited) materials which coat the back of the cathode ray tube faceplates are also called phosphors. The same principle is used in $FEDs$.

In ACTFEL panels, the light emitting materials are notably different in the sense that the electrons which induce the emission of light are accelerated in the material. The active material is in the from of a thin film not a powder as is $PDPs$ and $FEDs$

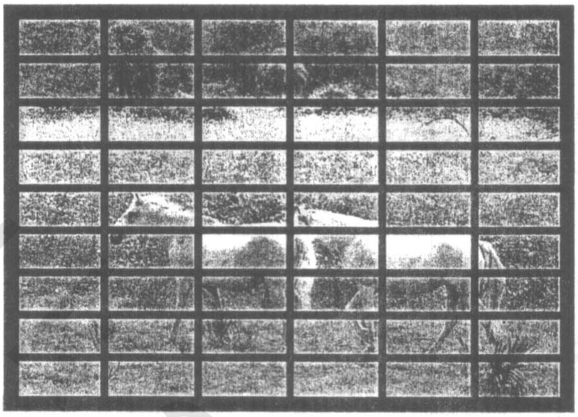


Fig. (20.13) Video wall

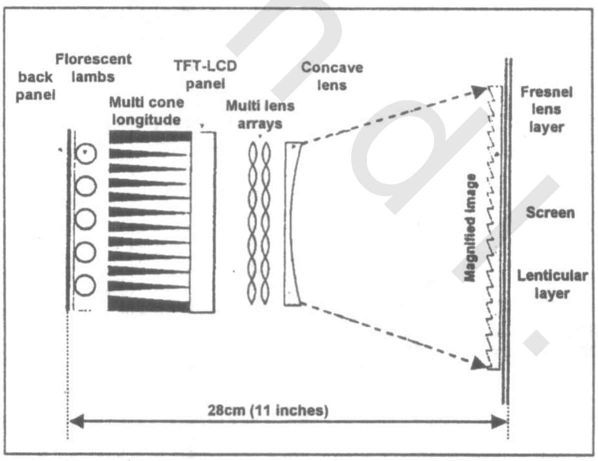
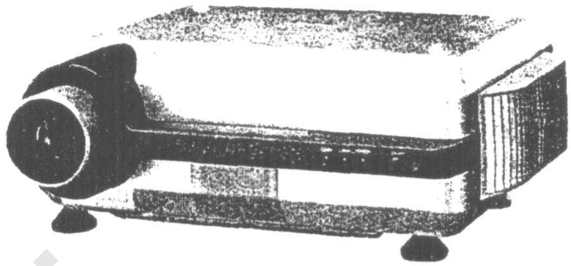


Fig. (20.14) LCD display based on magnification



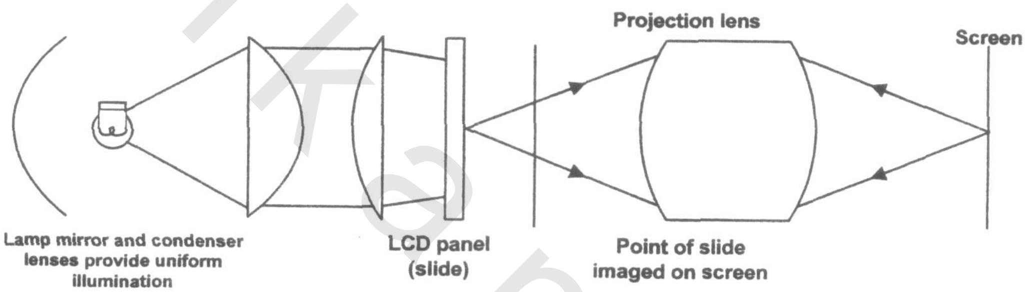


Fig. (20.15) A simple LCD projector

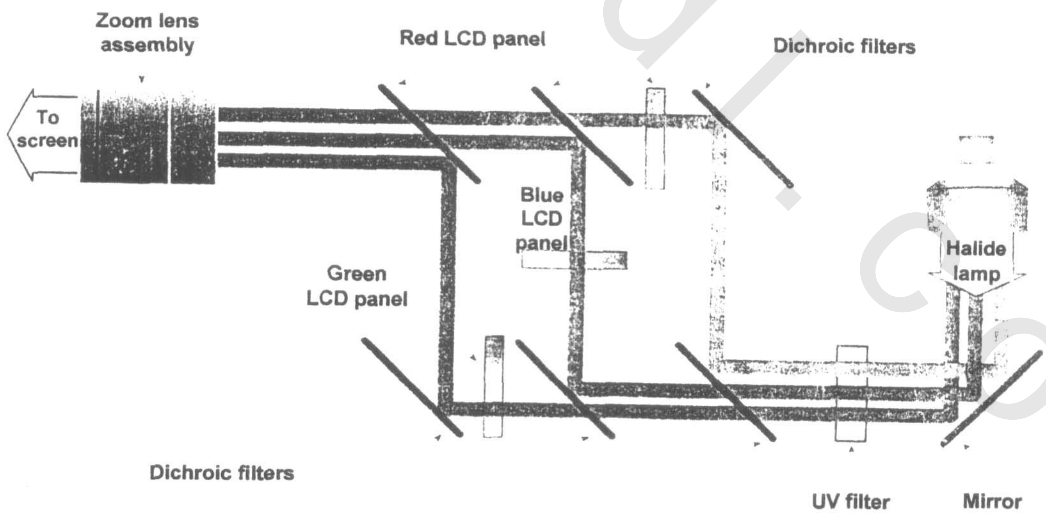


Fig. (20.16) 3 Panel LCD projector

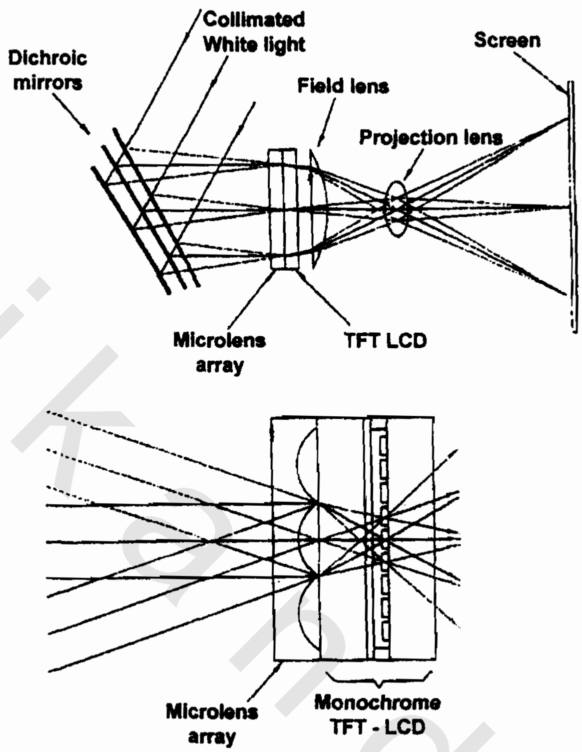


Fig. (20.17) Singe LCD with microlens arrays

Unlike LCDs, all emissive panels have very broad natural viewing angle and can work over a broad temperature range (0-55°C). One difficulty of all emissive panels is a decrease in image contrast and readability due to the diffuse scattering or specular reflection of ambient light by the very structure of the panel. Such scattering may be reduced by using filters or block matrix.

Another point is noticed when the emitting material is in solid state (including $CRTs$), i.e., image burn - in effect. The decrease with time of the luminance of TV panels is more or less uniform and less than in computer monitor. In ACTFEL, the active film $(0.5-1\mu m)$ is sandwiched between two high quality insulating films (Fig. 20.19).

The electrons originate at the film – insulator interfaces. The very sharp voltage threshold above which conduction occurs in the active film is due to the tunnel injection from the interface states into the active layer. The electrons are eventually trapped at the anodic interface. During the conduction, the build up of charges establishes an internal field, which opposes the externally applied voltage so that the current terminates when the resulting field falls below threshold. Light is emitted by the excited activator atoms in the form of a pulse. Upon reversal of the external voltage polarity, the internal field effectively adds to the applied field and lower the conduction threshold for those pixels which have been activated. Once the activator atoms are excited, they can decay to the ground state through a radiative transition, and hence, emit light with a specific emission spectrum.

In monochrome plasma display panel PDP, light is emitted by a gaseous discharge. The TV characteristic of a plasma cell (Fig. 20.20) shows the electron avalanche process (vertical branch) by which an electron ionizes a N_e atom creating a N_e ion and another electron. When this reaction becomes more probable than the loss of one electron, an exponential growth of the current results, and electrical breakdown occurs. Mixture atoms are then excited by electron collision. Relaxation leads ultimately to photoluminscence of phosphor triads which produce the primary colors in full color PDPs .

Field effect displays (FEDs) are vacuum electron devices in which the light source is the cathode luminescence of phosphors. FEDs are not similar to CRTs in that there is no deflection of the electrons, but rather local modulation of the electron current by the application of suitable potentials on anodes and grids with respect to the cathodes. FEDs differ from vacuum fluorescent displays in that electrons are not emitted by a cathode consisting of an oxide heated filament, but by field emission from a cold cathode, thus, saving the heating power in vacuum fluorescent displays (VFDs). The next advantage is that the cathode can be used as an addressing electrode. In VFDs, the electron source cannot be modulated because the thermal response is slow and would be difficult to pattern. Instead, the electron emission is permanent and is modulated by a grid. In FEDs, the field emission cathode can be patterned with a sufficient resolution, and matrix addressing can be performed in X,Y directions.

20.6 Stereoscopic Imaging:

A common feature of 3D or stereoscopic imaging is the provision of two adjacent video cameras which generate twin perspective views necessary for adaptive real time stereoscopic displays.

Fig. (20.21) shows dual camera configuration suitable for stereoscopic imaging. A 3D coordinate system has its origin at the center of the left camera. In this example, the optical axes of the two cameras are parallel and lie in the XZ plane. Under these conditions, the cameras are said to be boresighted. The Z-axis coincides with the optical axis of the left camera. Both camera lenses have focal length f and they are separated by the distance d . Suppose the point $P(X_0 Y_0 Z_0)$ is situated in front of the cameras casting an image on both image planes.

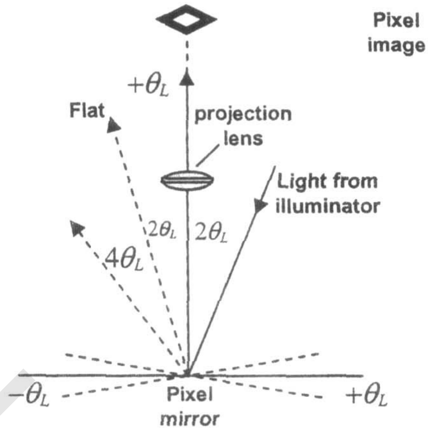


Fig. (20.18) DMD operation

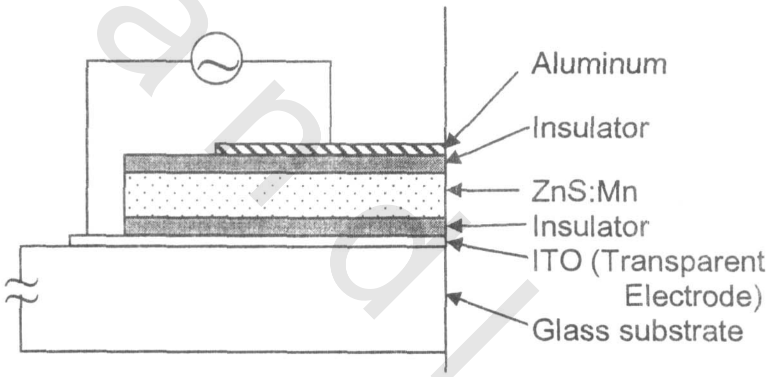


Fig. (20.19) ACTFEL structure

We see that a line from P through the center of the left camera lens will intersect the Z axis at $Z=-f$ image plane (prob. 20.1) at

$$Z_0 = \frac{fd}{x_r - x_l} \qquad (20-1)$$

and

$$R = \frac{d\sqrt{f^2 + x_l^2 + y_l^2}}{x_r - x_l} \qquad (20-2)$$

The closer Z_0, the larger the shift between right and left images. For narrow angle (telephoto) systems $X_0, Y_0 << Z_0$ and x_l and y_l are small compared to f and eqn. (20.2) can be approximated to eqn. (20-1).

A 3D screen can be recreated for a viewer through stereoscopic display. This is the basis for 3D movies and stereoscopic photography. Fig. (20.22) illustrates the viewing geometry for stereoscopic display. The image pair is positioned a distance D in front of the viewer's eyes, which are separated by the interocular distance S. A small feature located at coordinates x_l, y_l in the left image and x_r, y_r in the right image will appear to the observer located at point p. We way show (Prob. 20.3) that

$$X_r = X_l - \frac{DS}{Z} \qquad (20 - 3)$$

This implies that for distant objects $(Z = \infty)$, the right and left eye coordinates are identical. As an object is shifted left in the right eye image, its apparent position moves toward the observer.

Stereoscopic photography is a technique that uses a camera (Fig. 20.21) that produces positive transparences at the image plane. These transparences are rotated 180° about the Z-axis and positioned in front of the observer (Fig. 20.22).

If the relationship

$$DS = fD \qquad (20 - 4)$$

is satisfied, the scene will appear as if the observer had viewed it first hand. Two conditions must be satisfied to obtain accurate reproduction of a 3D scene. First, there should be a converging lens in front of each of the viewer's eyes, so that the viewer can focus his eyes at infinity and still see the two transparences in focus. Positive lenses with focal length D are commonly used. Second, the viewing geometry is exact only when the viewer's line of sight falls along the Z-axis.

20.7 3D Display Types:

Two of the displays under discussion are frame sequential, wherein two views comprising the stereo pair are temporarily multiplexed. One system (Fig. 20.23) uses active spectacles to decode the image by means of liquid crystal shutter device arranged in place of lenses of a pair of spectacles. These shutters can selectively block an image from reaching either eye.

The other system uses passive spectacles (Fig. 20.24) with a large liquid crystal device (stereoscopic modulator) interposed between the monitor and the viewer. This device encodes alternate frames with either clockwise or anti clockwise polarization, subsequently decoded by polarizing spectacles worn by the viewer.

In the anaglyph display (Fig. 20.25), the left and right views are spatially multiplexed and encoded using different colors on the display. These views are subsequently decoded by means of colored (red and green) spectacles worn by the viewer.

The auto stereoscopic display has the left and right views spatially multiplexed but the viewer is not required to wear any special spectacles. The separate images of a stereo pair reside on either the odd or even columns of the display.

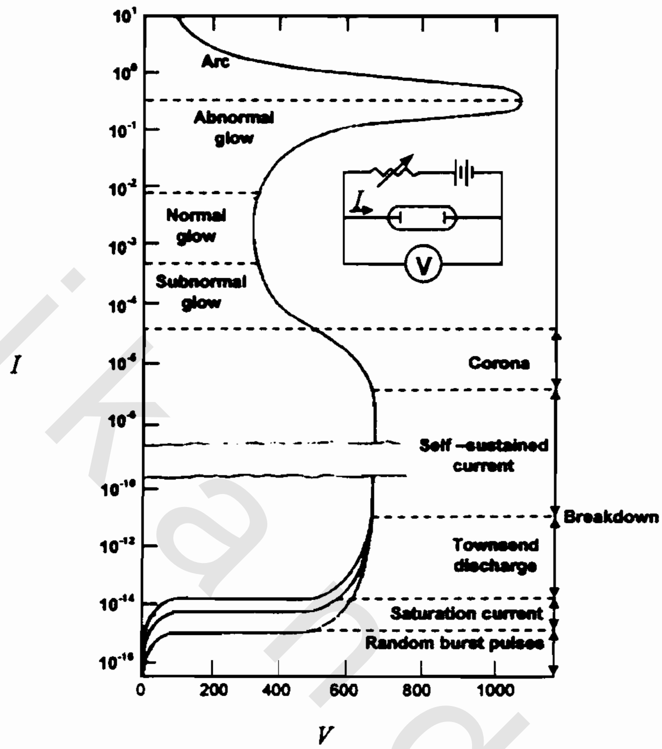


Fig. (20.20) IV characteristic of a plasma cell

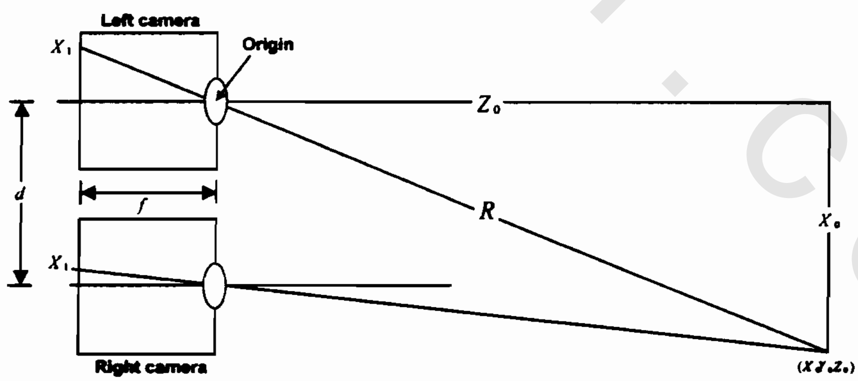


Fig. (20.21) Stereoscopic imaging

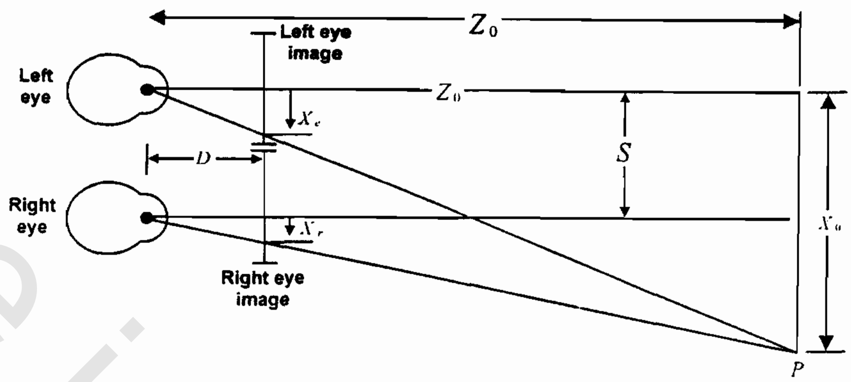


Fig. (20.22) Stereoscopic display

These interleaved pictures are then directed to the observer's eyes by means of a lenticular sheet at the display surface (Fig. 20.26). In this case, the display device is a color *TFT* liquid crystal panel.

A stereo 3D motion picture can be based on anaglyph type, where two versions of the movie one red and one green displaced to each other are imprinted on the film and viewed by anaglyph spectacles.

A new type of color 3D movie (e.g IMAX) is based on running two copies of a film shot at the same time with a stereo 3D camera. Each projector has attached to it a polarizer. The viewer wears glasses made of similar polarizers. The two projectors are synchronized and the viewer is immersed in the movie. Screens may not be flat but may be curved or dome shaped.

A talking head has LCD display inside a spherical screen and used in museums.

20.8 Virtual Reality (VR):

Virtual reality refers to immersive, interactive multi sensory viewer - centered 3D computer generated environments and a combination of technologies required to build these virtual environments. The term telepresence means that at the control station, the operator can perform - through quality sensory feedback-functions possible at the work site. The term cyberspace is associated mostly with entertainment systems and the internet.

In a virtual environment system, a computer generates sensory impressions that are delivered to the human senses. The type and quality of these impressions determine the level of immersion and the feeling of presence in VR.

We can group VR systems according to the level of immersion they offer to the users. Desktop VR (window on world WOW). This is the simplest type of VR applications. It uses a conventional monitor to display monoscopic images (walk thrus). No other sensory output is supported. Fish Tank VR is an improved version of desktop VR. These systems support head tracking, and therefore, improve the feeling

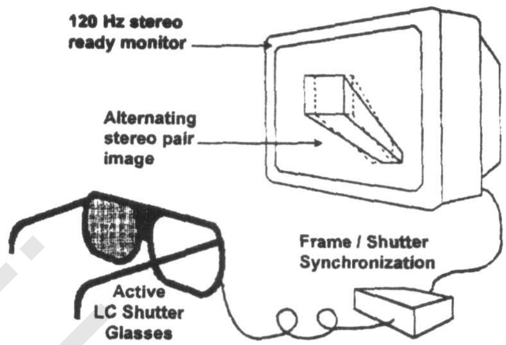


Fig. (20.23) Occluding shutter display

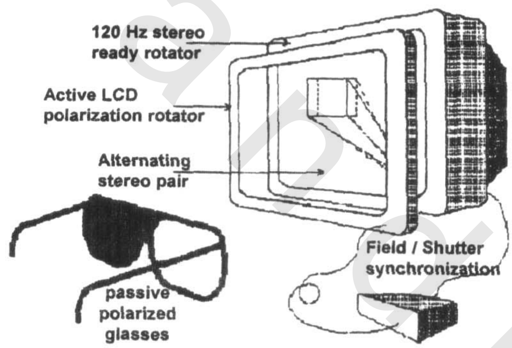


Fig. (20.24) Polarization rotating display

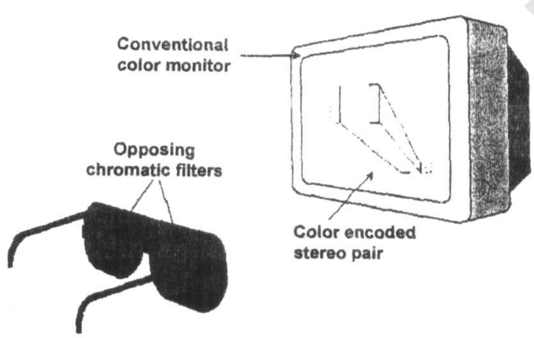


Fig. (20.25) Color anaglyph display

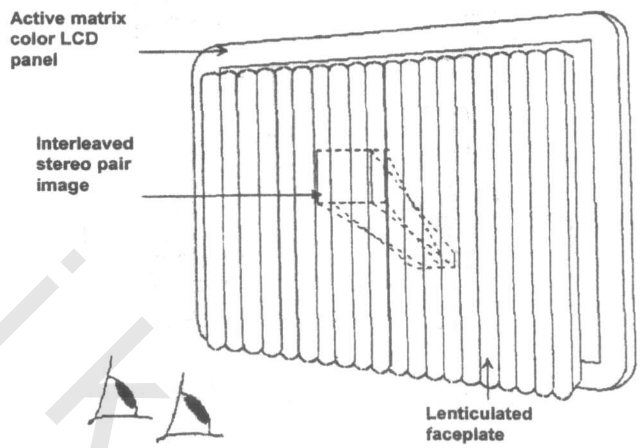


Fig. (20.26) Auto stereoscopic lenticular display

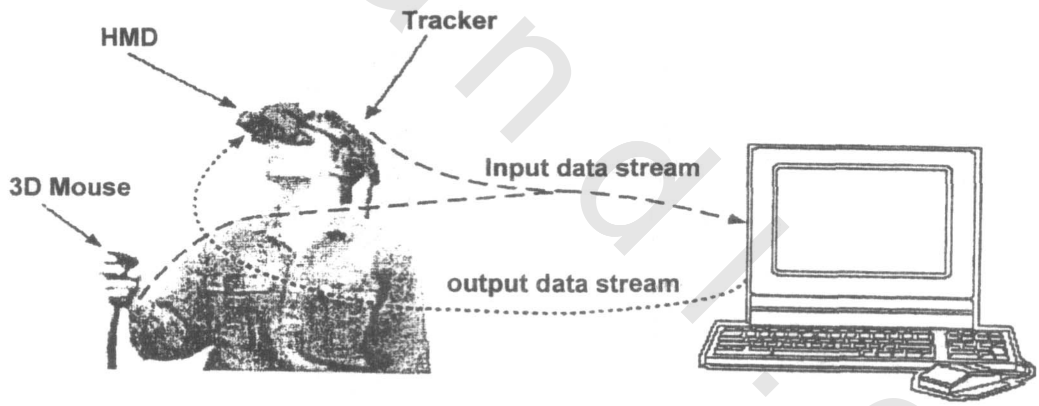


Fig. (20.27) VR components

of being there, thanks to the motion parallax effect. They use a conventional monitor with shutter glasses for stereoscopic viewing. Immersive systems let the user totally immerse in a computer generated world with a headmount display (HMD) that supports a stereoscopic view of the scene according to the user's position and orientation (Fig. 20.27).

Input devices determine the way a user communicates with the computer. These include trackers, 3D mouse and gloves.

Output devices are responsible for the presentation of the virtual environment and its phenomena to the user. These include visual, auditory or haptic (sensory) displays.

Beyond input and output hardware, the underlying software plays an important role in managing I/O devices, analyzing incoming data and generating proper feedback. This software must be real time and must be prompt in order not to destroy the feeling of immersion.

VR is used in designing, vehicle driving simulation, military applications, medicine, training, education and entertainment.

20.9 Tracking:

The primary task in VR is to build the 3D model on the computer then add the texture, lighting and shadow to it. This is called rendering. Then the computer should be able to shift and rotate the view using a S/W camera to be able to look at the scene from all angles and positions. However, coupled to that, there must be a correlation between the viewer's position and the orientation and the view to be viewed depending on the relative position and the angle of the viewer so that he could see the object as if he were going into and around it and from all angles and positions. This is called tracking. 3D objects have 6 degrees of freedom for position and orientation. Each tracker must support this data.

In general, there are two types of trackers, those that deliver absolute data and those that deliver relative data. The most important properties of trackers to be considered for choosing the right device are update rate, latency, accuracy, resolution and range. The update rate defines the number of measurement/s. Higher update values support smoother tracking of movements but require more processing. The latency is the time (measured in ms) between the user's physical action and the beginning of transmission of the report that represents this action. Lower values lead to better performance. Accuracy is the measure of error in the reported position and orientation. Smaller values mean better accuracy. Resolution is the smallest change in position and orientation that can be detected by the tracker. Smaller values mean better resolution. Range is the working volume within which the tracker can measure position and orientation with a specified accuracy, resolution and angular coverage.

There are different types of trackers (Fig. 20.28). The most common type is magnetic trackers. They consist of a static part (emitter or source) which emits DC or AC magnetic field. Different sensors are attached to body parts. Each sensor is a 3D coil one in each coordinate. It picks up magnetic flux, and hence, generates AC current or voltage which is digitized and transmitted to the computer. This is called body tracking and is used to capture motion and impart it to a computer generated graphic (an animal or a bird for example). The location of each sensor is assigned to a position on the computer graphic and a process called calibration must be done first to indicate a reference point or initial position. As the actor wearing the sensors moves his hand or leg, the sensors transmit to the computer data indicating the motion relative to the initial position. This is instantly conveyed to the animal or bird figure. This technique is used in modern 3D animation. Magnetic trackers use small handy and light sensors. They require no line of sight and have relatively high update rates and low latency.

However, the working volume is limited and the resolution gets worse as the emitter – receiver distance is growing. External fields may cause distortion.

Acoustic trackers use ultrasonic waves (above $20kHz$ for determining the position and orientation of an object in space. 3 emitters and 3 multiple receivers are used to determine the position and orientation. Such trackers do not suffer from magnetic interference but suffer from acoustic interference or noise and the restriction of the line of sight and low update rates.

Another tracker called face tracker is concerned with the detection of facial expressions and imparting them to a computer generated graphic representing an animal or a bird for example. With proper lip sync, a cat can be made to speak with life - like pronunciation and expression. This is widely used now in movies. The face tracker (Fig. 20.29) consists of a helmet worn by the actor. It contains infrared (IR) source and a set of detectors on the inner surface of the helmet band. A set of tiny bits of reflective paper is attached to various locations on the face. The IR emitted by the source and reflected off the tiny reflectors falls on the detectors and the signals are transmitted to the computer. At the start, calibration is performed and the set of the reference points where the reflectors are attached are transferred to the head of the animal. As the actor speaks, the expression on his face forces transferred the location of the reflectors to shift positions. This shift is transferred to the head of the animal graphic.

A third type of trackers is associated with the headmount (Fig. 20.30). Here it is required that the position and orientation of the viewer's head be reported to the computer to determine the part of the view to be viewed and its orientation with respect to every possible movement and orientation of the viewers head. Normally this type of tracker uses liquid micro switches where the tilting of a small drop of liquid gives an indication of rotation.

There are also many types of optical trackers, beacons, pattern recognition trackers and laser ranging. Beacon trackers use a group of beacons $(LEDs)$ and a set of cameras capturing images of beacons' pattern (Fig. 20.31). An optic pattern recognition tracker (as the new optical mouse) determines position and orientation by comparing new patterns to previously sensed ones. Laser ranging trackers transmit into the object the laser light that is passed through a diffraction grating.

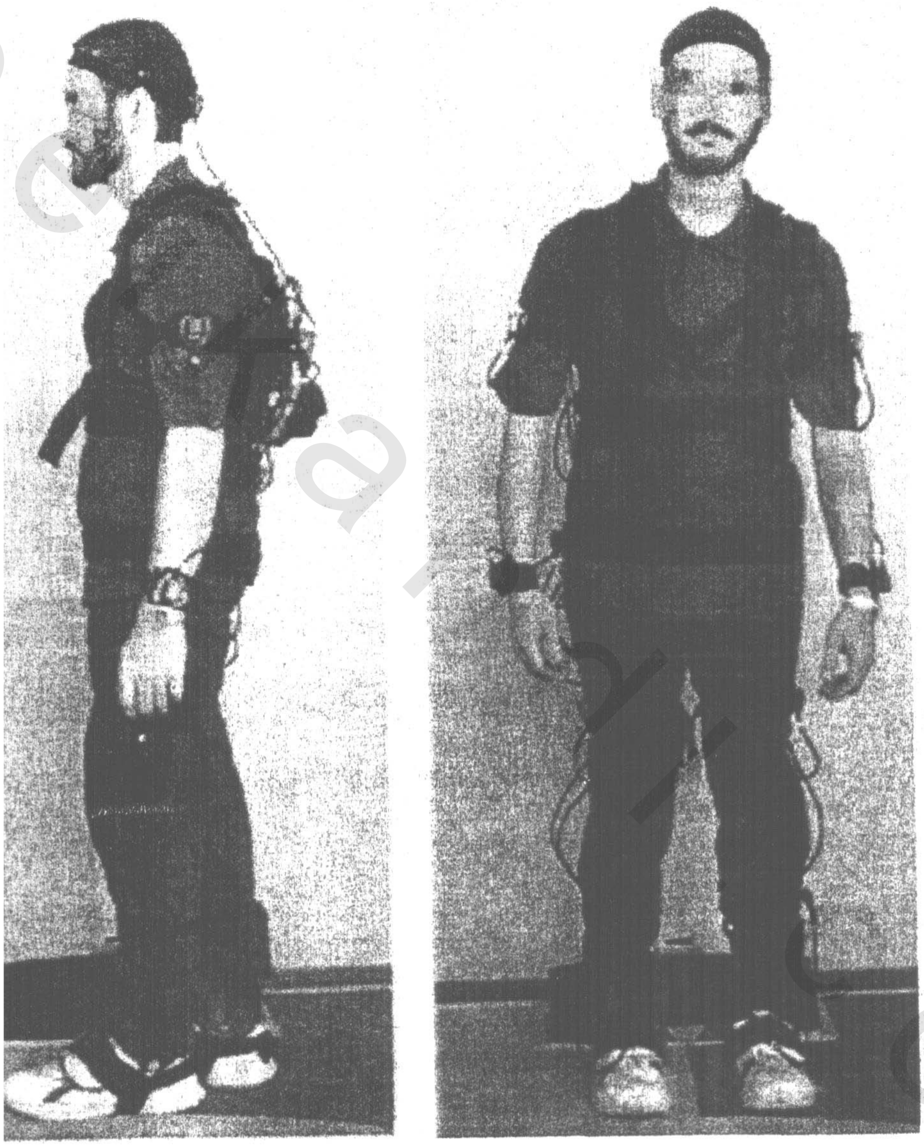


Fig. (20.28) Motion capture

A sensor analyzes the diffraction pattern on the body's surface to calculate the position and orientation.

Eye tracking is used to follow the eye motion. Such trackers vary from limbus tracking which monitors the boundary between iris and sclera or image tracking which uses a video camera and image processing techniques to determine the gaze direction or corneal reflection, which uses phototransistors to analyze the reflection of collimated beam of light from the convex cornea surface.

Input devices also vary in types. The 3D mouse or bat is a simple interaction tool which is joystick like, which can be moved in space by hand. It is equipped with a tracker sensor to determine its position / orientation and has a few buttons that may trigger some actions.

Gloves (Fig. 20.32) are 3D input devices that can detect the joint angles of fingers. The measurement of finger flexion is done with the help of fiber optic sensors, foil strain technology or resistive sensors.

20.10 VR Displays:

We have different types of VR displays. One is large screen with 3 projectors and a blender where the images are projected seamlessly. What is unique about this type of display is the real time rendering. The model with texture and lighting is downloaded on the projection server. But the computer camera and flybox which provide interaction operate in real time. This is done by prestoring images of views from different positions and orientations in a library while the server (super computer) provides the right view according to the manipulation by the flybox. This is done in real time, i.e., the viewer does not notice any lag in the process. The projection could be stereo and the viewer uses polarized glasses.

Another application is called fake space where the viewer is embedded within 4 – 6 walls (including floor and ceiling) which are used to totally immerse the viewer in 6 degrees of freedom environment. A VR capsule also may be used for individualized VR experience.

Another and more common individualized display is the headmounted display (HMD) (Fig. 20.33). It consists of two active LCD displays and the tracker. The viewer monitors on the LCD displays the stereo output of the computer, based on the input data supplied by the input device or tracker. To complete the immersive effect, stereo audio is supplied by speakers in the HMD. This type of display is particularly popular in military applications, training and entertainment.

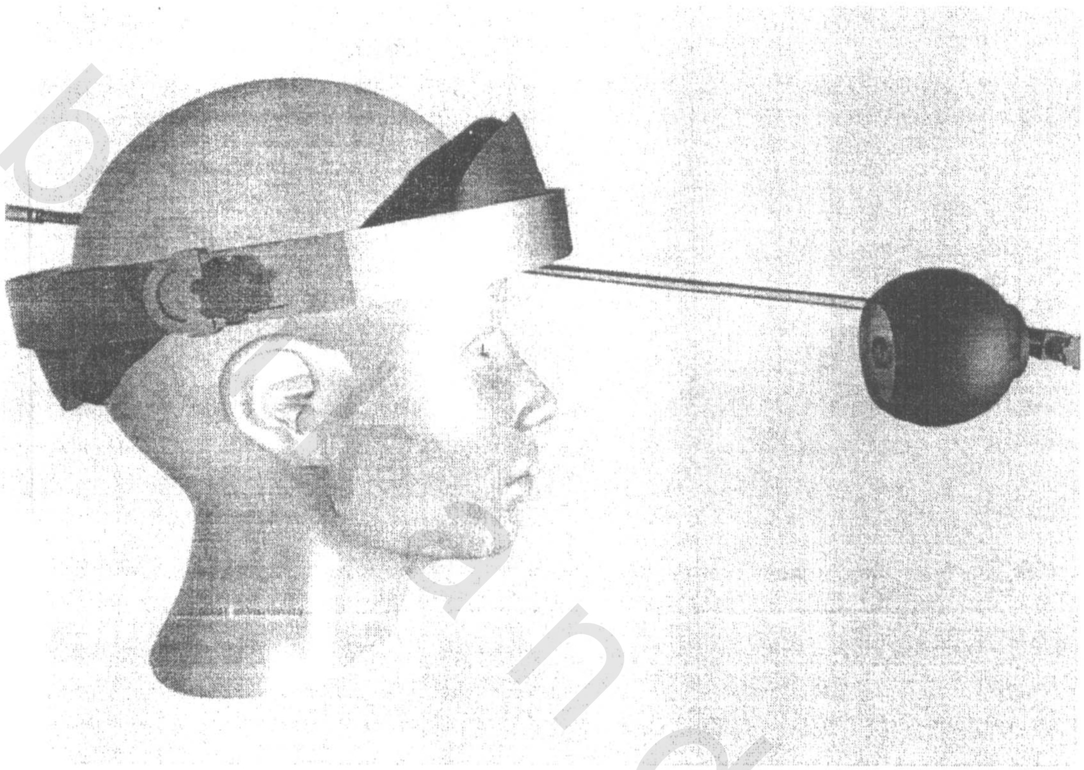


Fig. (20.29) Face tracker

Fig. (20.30) Headmount tracker

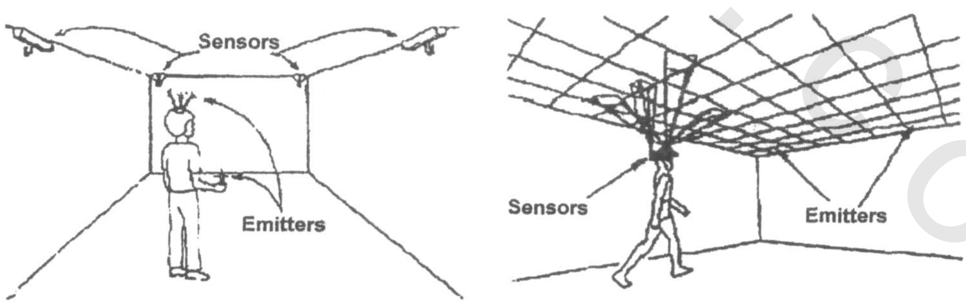


Fig. (20.31) Beacon tracker
a) outside in *b) inside out*

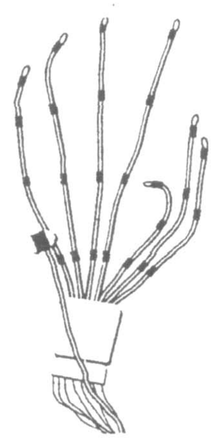


Fig. (20.32) VR gloves

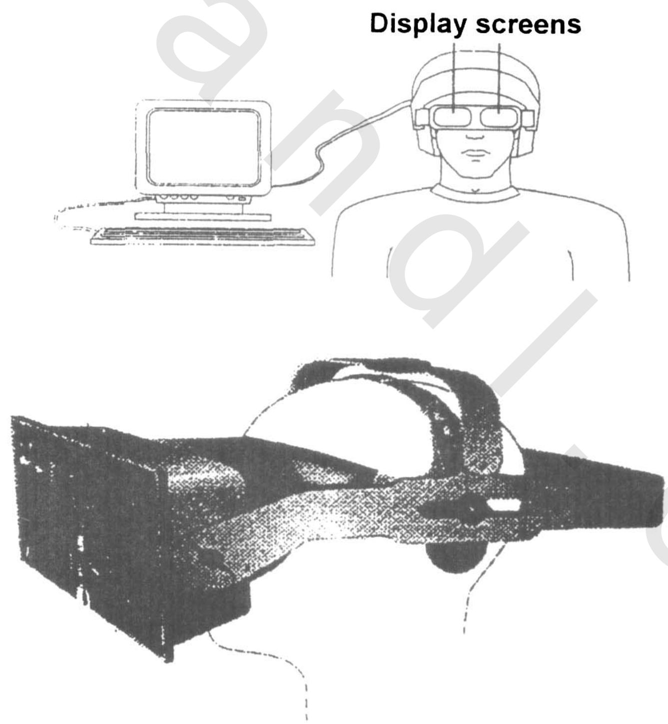


Fig. (20.33) HMD

Problems

1. Verify eqn. (20.1)

2. Verify eqn. (20.2)

3. Verify eqn. (20.3)

4. Verify eqn. (20.4)

5. A stereoscopic camera has 50mm lenses separated by 70mm. Find the location of the image of a small object at $XYZ = 3m, 2m, 6m$. What is the range of the object (Fig. 20.21).?

6. For prob. (20.5), show the requirements on the display system (Fig. 20.22), and verify eqns. (20-3) and (20-4).

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A-1-1 Bounds on the Complementary Error Function

A-1-1 Bounds on the Complementary Error Function:

Substituting $u-x$ for z in eqn.(A-1-4), we get

$$erfc(u)=\frac{2}{\sqrt{\pi}}\exp(-u^2)\int_{-\infty}^{0}\exp(2ux)\exp(-x^2)dx$$

For any real x, the value of $\exp(-x^2)$ lies between the successive partial sums of the power series

$$1-\frac{x^2}{1!}+\frac{(x^2)^2}{2!}-\frac{(x^2)^3}{3!}+\cdots$$

Therefore ,for $u>0$, we find, on using $(n+1)$ terms of this series, that $erfc(u)$ lies between the values taken by

$$\frac{2}{\sqrt{\pi}}\exp(-u^2)\int_{-\infty}^{0}(1-x^2+\frac{x^4}{2}-\cdots\pm\frac{x^{2n}}{n!})\exp(2ux)dx$$

for even n and for add n. Putting $2ux=-v$ and using the integral

$$\int_{0}^{\infty}v^n\exp(-v)dv=n!$$

we obtain the following asymptotic for $erfc(u)$, assuming $u>0$:

$$erfc(u)\cong\frac{\exp(-u^2)}{\sqrt{\pi}u}\left[1-\frac{1}{2u^2}+\frac{1.3}{2^2u^4}-\ldots\pm\frac{1.3.5\ldots(2n-1)}{2^nu^{2n}}\right] \qquad \text{(A-1-6)}$$

For large positive values of u ,the successive terms of the series on the right hand side of eqn. (A-1-6)decrease very rapidly. We thus deduce two simple bounds on $erfc(u)$, one lower and the other upper, as shown by[1]

$$\frac{\exp(-u^2)}{\sqrt{\pi}u}(1-\frac{1}{2u^2})<erfc(u)<\frac{\exp(-u^2)}{\sqrt{\pi}u} \qquad \text{(A-1-7)}$$

For large positive u ,a second bound on the complementary error function $erfc(u)$ is obtained by omitting the multiplying factor $1/u$ in the upper bound of eqn. (A-1-7):

$$erfc(u)<\frac{\exp(-u^2)}{\sqrt{\pi}} \qquad \text{(A-1-8)}$$

In Fig. (A-1-1), we have plotted $erfc(u)$, the two bounds defined by eqn.(A-1-7), and the upper bound of eqn. (A-1-8). We see that for $u\geq 1.5$, the bounds on $erfc(u)$,defined by eqn. (A-1-7),become increasingly tight.

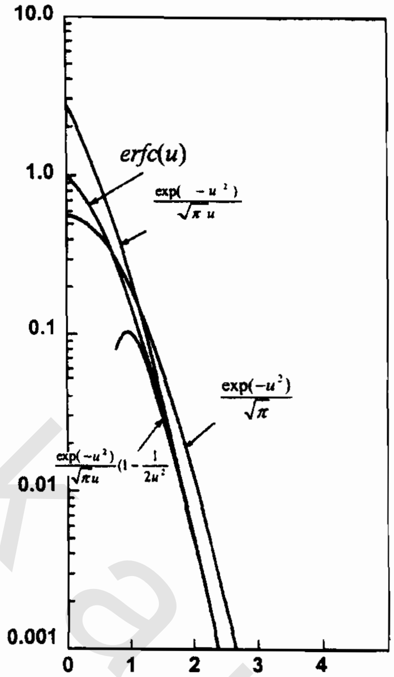

Fig. (A-1-1) The complementary error function and its bounds

A-1-2 Q-Function:

Consider a standardized Gaussian variable X of zero mean and unit variance. The probability that an observed value of the random variable X will be greater than ν is given by the Q-function:

$$Q(\nu) = \frac{1}{\sqrt{2\pi}} \int_{\nu}^{\infty} \exp(-\frac{x^2}{2}) \qquad \text{(A-1-9)}$$

The Q-function defines the area under the standardized Gaussian tail. Inspection of eqns (A-1-4) and (A-1-9) reveals that the Q-function is related to the complementary error function as follows:

$$Q(\nu) = \frac{1}{2} erfc\left(\frac{\nu}{\sqrt{2}}\right) \qquad \text{(A-1-10)}$$

Conversely, putting $u = \nu / \sqrt{2}$,we have

$$erfc(u) = 2Q(\sqrt{2}u) \qquad \text{(A-1-11)}$$

APPENDIX A-2

Schwarz Inequality

Prove the following Schwarz inequality for a pair of real finite energy signals $f(t)$ and $g(t)$:

$$\left[\int_a^b f(t)g(t)dt\right]^2 \leq \left[\int_a^b f^2(t)dt\right]\left[\int_a^b g^2(t)dt\right] \qquad \text{(A-2-1)}$$

with equality only if $g(t) = cf(t)$,where c is an arbitrary constant.

The Schwarz inequality for finite-energy, complex-valued functions $X(\omega)$ and $Y(\omega)$ is given by

$$\left|\int_{-\infty}^{\infty} X(\omega)Y(\omega)d\omega\right|^2 \leq \int_{-\infty}^{\infty}|X(\omega)|^2 d\omega \int_{-\infty}^{\infty}|Y(\omega)|^2 d\omega \qquad \text{(A-2-2)}$$

with equality only if $Y(\omega) = cX^*(\omega)$,where c is an arbitrary constant.

We can prove eqn. (A-2-1) as follows: For any value of λ ,we know that

$$\int_a^b [\lambda f(t) - g(t)]^2 dt \geq 0$$

or

$$\lambda^2 \int_a^b f^2(t)dt - 2\lambda \int_a^b f(t)g(t)dt + \int_a^b g^2(t)dt \geq 0$$

Because this quadratic in λ is nonnegative for any value of λ, its discriminate must be nonpositive, and eqn. (A-2-1) follows. If the discriminate equals zero, then for some value of $\lambda = c$, the quadratic equals zero. This is possible only if $cf(t) - g(t) = 0$, and the result follows.

To prove eqn.(A-2-1), we observe that $|X(\omega)|$ and $|Y(\omega)|$ are real functions and inequality (A-2-1) applies. Hence,

$$\left[\int_a^b |X(\omega)Y(\omega)|d\omega\right]^2 \leq \int_a^b |X(\omega)|^2 d\omega \int_a^b |Y(\omega)|^2 d\omega \qquad \text{(A-2-3)}$$

with equality only if $|Y(\omega)| = c|X(\omega)|$, where c is an arbitrary constant. Now recall that

$$\left|\int_a^b X(\omega)Y(\omega)d\omega\right| \leq \int_a^b |X(\omega)||Y(\omega)|d\omega = \int_a^b |X(\omega)Y(\omega)d\omega| \qquad \text{(A-2-4)}$$

with equality if and only if $Y(\omega) = cX^*(\omega)$,where c is an arbitrary constant. eqn. (A-2-2) immediately follows from eqns. (A-2-3) and (A-2-4).

APPENDIX A-3

Fourier Transforms and Operations

Commonly used Fourier transforms are listed in Table (A-3-1) and Fourier operations in Table (A-3-2)

Table (A-3-1) Fourier transforms

	$x(t)$	$X(f)$
1-	$\delta(t)$	1
2-	1	$\delta(t)$
3-	$\cos 2\pi f_0 t$	$\frac{1}{2}[\delta(f-f_0]+\delta(f+f_0)$
4-	$\sin 2\pi f_0 t$	$\frac{1}{2j}[\delta(f-f_0]-\delta(f+f_0)$
5-	$\delta(t-t_0)$	$\exp(-j2\pi f t_0)$
6-	$\exp(j2\pi f_0 t)$	$\delta(f-f_0)$
7-	$\exp(-a\|t\|), \quad a>0$	$\frac{2a}{a^2+(2\pi f)^2}$
8-	$\exp\left[-\pi\left(\frac{t}{T}\right)^2\right]$	$T\exp\left[-\pi(fT)^2\right]$
9-	$u(t)=\begin{cases}1 & for\ t>0\\ 0 & for\ t<0\end{cases}$	$\frac{1}{2}\delta(f)+\frac{1}{j2\pi f}$
10-	$\exp(-at)u(t), a>0$	$\frac{1}{a+j2\pi f}$
11-	$t\exp(-at)u(t), a>0$	$\frac{1}{(a+j2\pi f)^2}$
12-	$rect(t/T)$	$T\ \mathrm{sinc} fT$
13-	$\cos 2\pi f_0 t[rect(t/T)]$	$\frac{T}{2}[\mathrm{sinc}(f-f_0)T+\mathrm{sinc}(f+f_0)T]$
14-	$W\sin Wt$	$rect(f/W)$
15-	$\begin{cases}1-\frac{\|t\|}{T} & \text{for } \|t\|\le T\\ 0 & \text{for } \|t\|>T\end{cases}$ $for\|t\|\le T$ $for\|t\|>T$	$T\ \mathrm{sinc}^2 fT$
16-	$\sum_{m=-\infty}^{\infty}\delta(t-mT_0)$	$\frac{1}{T_0}\sum_{n=-\infty}^{\infty}\delta\left(f-\frac{n}{T_0}\right)$

Note: $rect(f/2W)=1$ for $-W<f<W$,0 for $\|f\|>W$, and $\mathrm{sinc}\, x=(\sin\pi x)/\pi x$.

Table (A-3-2) Fourier operations

Operation	$x(t)$	$X(f)$
1.Scaling	$x(at)$	$\frac{1}{\|d\|}X(\frac{f}{a})$
2.Time shifting	$x(t-t_0)$	$X(f)\exp(-j2\pi f t_0)$
3.Frequency shifting	$x(t)\exp(j2\pi f_0 t)$	$X(f-f_0)$
4.Time differentiation	$\frac{d^n x}{dt^n}$	$(j2\pi f)^n X(f)$
5.Frequency differentiation	$(-jt)^n(x(t))$	$\frac{d^n X}{df^n}$
6.Time integration	$\int_{-\infty}^{t} x(\tau)dt$	$\frac{1}{j2\pi f}X(f)+\frac{1}{2}X(0)\delta(f)$
7.Time convolution	$x_1(t)*x_2(t)$	$X_1(f)X_2(f)$
8.Frequency convolution	$x_1(t)x_2(t)$	$X_1(f)*X_2(f)$

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