ROYAL SCHOOL OF ARTILLERY

BASIC SCIENCE & TECHNOLOGY SECTION

Optical Systems

INTRODUCTION

The performance of the 'Mark One Eyeball 'can be considerably enhanced with binoculars, telescopes, periscopes and the like. All these instruments use lenses, prisms and mirrors to collect more light, magnify a view of a scene or enable viewing from a more secure location. Such devices are not limited to simple eyeball enhancement - they can equally well be used when it is a television or thermal camera that is producing the picture.

Other forms of optical devices operate in the reverse mode - they take a small light source (e.g. the laser used to guide HVM darts) and project it outwards, to convey guidance information or other data.

This handout describes the basic operating techniques of optical systems that use mirrors, lenses and prisms either to collect light from a distant scene or to project light to a distant point.

REFLECTION FROM A PLANE SURFACE

In this context, plane means a flat surface - an ordinary mirror. This might seem to be a simple device, but plane mirrors perform essential functions in ADAD, TICM II Thermal Camera and the HVM Aiming Unit, for example. The terms used to describe the geometry of simple reflection are as follows:

- **Normal**: a line at right-angles to the surface where the reflection takes place.
- **Angle of Incidence**: the angle between the ray of light that is approaching the surface. Its usual symbol is 'i'.
- **Angle of Reflection**: the angle between the reflected ray of light and the normal. Its usual symbol is 'r'

The law of reflection states that the angle of reflection is equal to the angle of incidence. This is illustrated in Figure One. This law applies to curved surfaces as well as to plane surfaces, provided that the normal used to determine the angles is normal (i.e. at right angles) to the surface at the point of reflection.

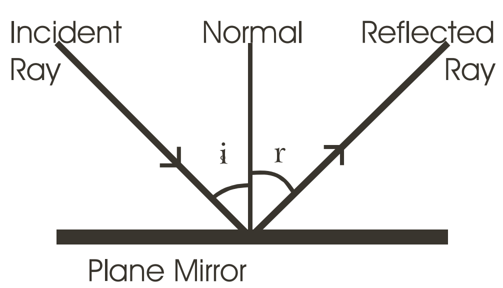


Figure 1: Reflection at a Plane Surface

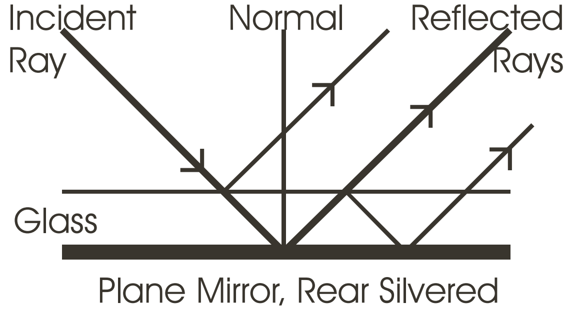


Figure 2: Reflection at a Mirror with Rear Silvering

CONSTRUCTING A MIRROR

There are two main ways of making a plane mirror and the most common method uses a piece of flat glass with a reflective coating applied to the back surface. A protective layer of paint, or similar, is applied to the coating and the light to be reflected must pass through the glass to the reflecting surface and then, after reflection, back through the glass again. Unfortunately, some light is reflected at the interface between glass and air and this type of mirror, although cheap, gives multiple images. This is illustrated in FIgure Two.

A front-silvered mirror has the reflective coating on the front surface of the glass (it can also be made of an opaque material) and this has reflection at only one surface so there are no multiple reflections. However, the reflective coating is vulnerable to wear and contamination. Front-silvered mirrors must always be treated with great care. Reflection from a front-silvered mirror is the same as the reflection illustrated in Figure One.

This type of reflection, from a very smooth surface is called 'specular' reflection. Many natural surfaces are not smooth enough for specular reflection and their roughness causes light to reflect in all directions in a 'diffuse' reflection.

REFLECTIONS FROM A PIVOTING MIRROR

When a mirror is pivoted, say by 5°, then the normal turns with it by the same number of degrees. The angle of incidence changes by 5° and, according to the law of reflection, the angle of reflection changes by the same amount (by 5° in this example). When we consider the total change in the direction of the beam of light then the result is that it has changed by 10° - twice the angle through which the mirror moved.

The field of view of the ADAD is about twelve degrees in elevation and this is achieved by pivoting a mirror, situated behind the rotating lens, by six degrees. The change in beam direction as the mirror is tilted is

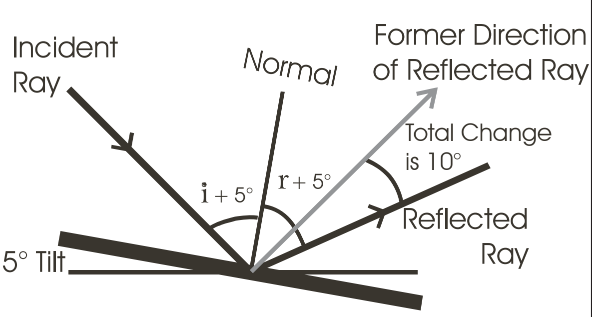


Figure 3: Reflection from a Tilted Mirror

illustrated in Figure Three. To deviate a beam of light by a right-angle (90°), the mirror is placed at 45° to the beam.

IMAGE FORMATION IN A PLANE MIRROR

When you look in a mirror then you can see your own reflection - in the mirror. The geometry of this reflection is shown in Figure Four. Each point on the object (the man) reflects the ambient light and this light is reflected in all directions. The light from the man is reflected in all directions because his surface is not very smooth and shiny as the surface of a mirror would be.

Any of this light that reaches the mirror will reflect according to the rules of reflection. The paths of some simple rays of light are illustrated in Figure Four. This represents a man looking at his own image in a mirror. From the diagram you should note that:

- The image is located at the apparent point of origin of the light rays that are reflected from the mirror. This is found by tracing back along the path of the rays of light that reach the eye of the viewer, to determine where they meet. (These trace-back rays are shown using dotted lines.)
- The light rays do not actually come from, or go to, the image. This type of image is called a ‘virtual’ image.
- The image is laterally inverted (left & right swapped over) but not upside down.
- The image is a far behind the mirror as the man is in front of the mirror. It also appears to be the same size as the man.

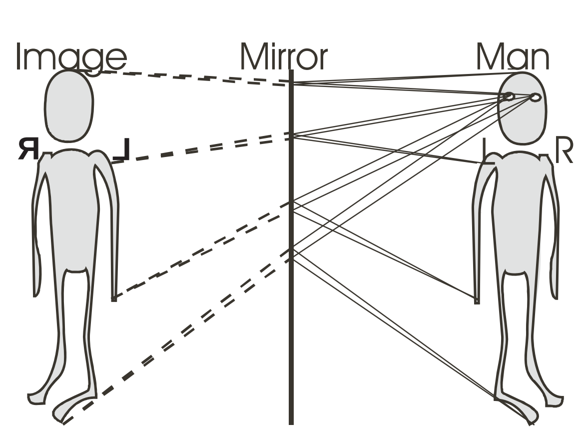


Figure 4: Image formation in a Plane Mirror

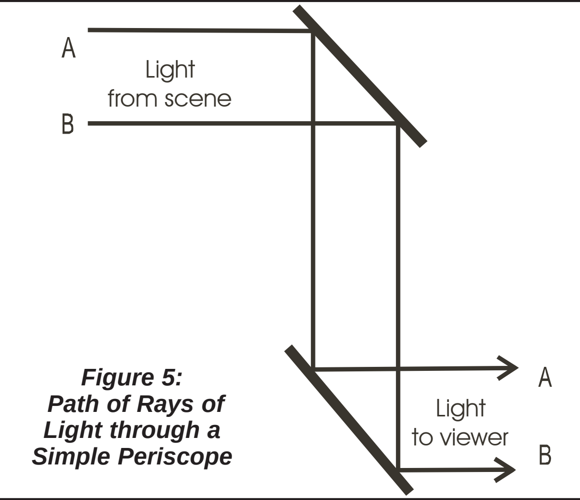


Figure 5: Path of Rays of Light through a Simple Periscope

THE PERISCOPE

To see out of a submarine, or other enclosed space, a periscope might be used. The basic periscope consists of two mirrors, set at 45°, and gives a forward view, as illustrated in Figure Five. The double reflection that occurs as the light passes through the periscope results in an image that is the correct way around for normal viewing. You might have noticed, perhaps when viewing film dramas about submarines, that the submarine captain walks around in a circle, with the periscope, when he scans the horizon. This is necessary when using a simple periscope, for reasons that are explained below.

In Figure Five, rays from the top of the object are labeled ‘A’ and rays from the bottom are labeled ‘B’. You can see that, when they emerge from the periscope, the rays maintain their relative position, so the image is the right way up.

In Figure Six, the top mirror has been rotated by 180° so that anyone looking into the bottom mirror would be able to see things behind him. Unfortunately, if you look at the way that the rays of light are reflected in this configuration then you will see that ray ‘A’ now emerges from the periscope at the bottom whilst ray ‘B’ emerges at the top. This means that the view through the periscope is upside down. If the submarine captain did not walk around his periscope, but had the top mirror rotated to look astern (submarine captains would never

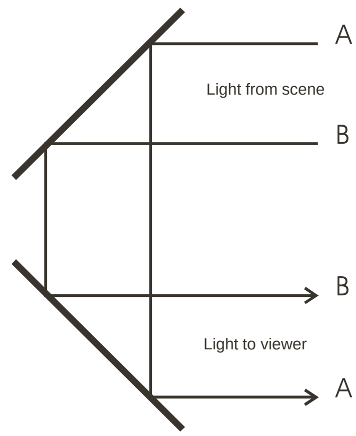


Figure 6: Viewing Objects Behind, with a Periscope

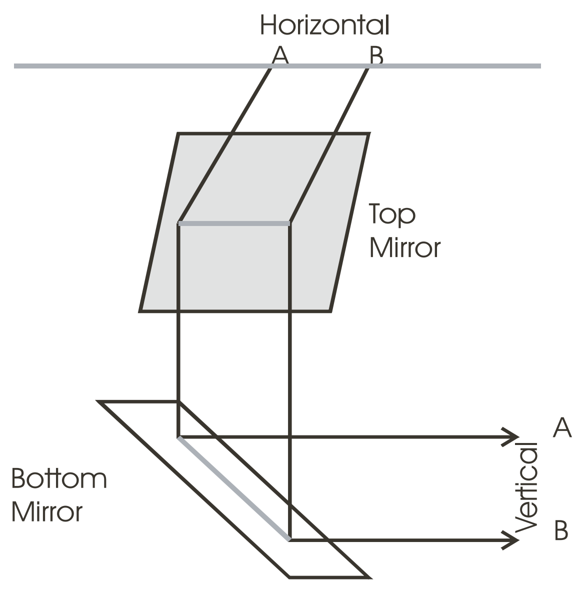


Figure 7: Viewing to One Side through a Periscope

say *backwards*!) then he would see the sky at the bottom and the sea at the top of his view through the periscope. This would be somewhat disconcerting and not very practical.

When attempting to look to one side then the situation is even stranger as the horizon would be vertical - not its usual horizontal. This is illustrated in Figure Seven, where a distant horizon to the right of the observer, has been brought into view by rotating the top mirror of the periscope to the right by 90°. The ray ‘A’, which enters the periscope to the left of ray ‘B’, now emerges above ray ‘B’. When viewed by the observer,

The effect described above is called rotation of the image, or image rotation. Any periscope-like device, that can turn to see around the horizon, will suffer from this problem. This includes the periscopes (sometimes called ‘panoramic sights’) found in armoured vehicles (the vehicle commander does not have room to walk around his periscope) and in ADAD. Such periscopes require additional optical devices to counter this rotation of the image and these are covered later in this handout.

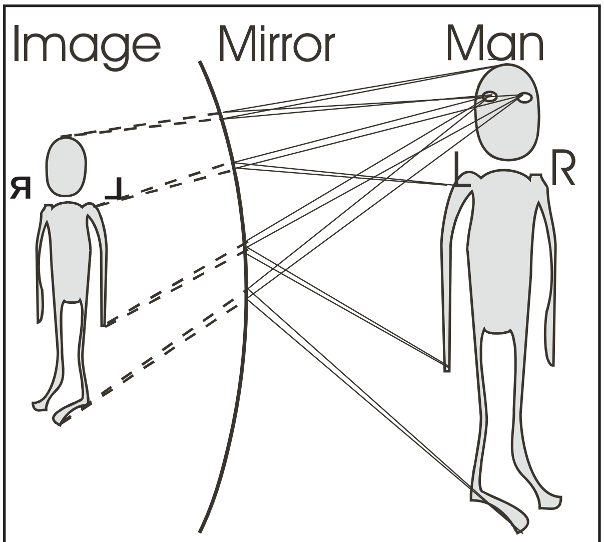


Figure 8: Reflection in a Convex Mirror. The Image is Smaller than the Object. Used for Driving Mirror, Security Mirror

REFLECTION FROM CONVEX SURFACES

A curved mirror that bulges out, towards the source of light, is called a convex mirror. When rays of light reflect from a convex mirror then they spread out (diverge). More specifically, their amount of divergence is increased. If traced back to their apparent source, then rays of light that have been reflected from a convex mirror will appear to have originated from a point behind the mirror. This is illustrated in Figure Eight.

The image is always smaller than the object and this gives a wider field of view. Convex mirrors are used for the wing mirrors of vehicles to exploit this wide field of view. As with the plane mirror, the image is virtual as no rays of light actually originate from the image. The apparent location of the image is found by back-tracking along the rays of light (dotted lines in the Figure).

Since the rays of light do not converge then this type of mirror cannot be used to take a photograph - unless it is used in conjunction with other mirrors and lenses that can converge the light.

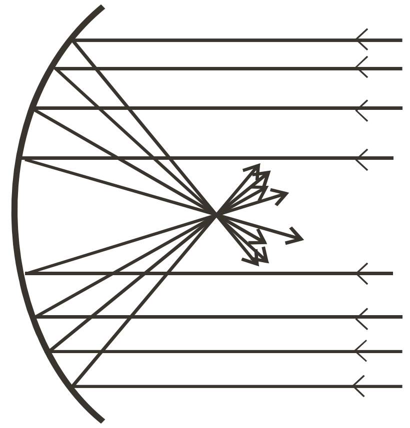


Figure 9: Focusing Effect of Concave Mirror

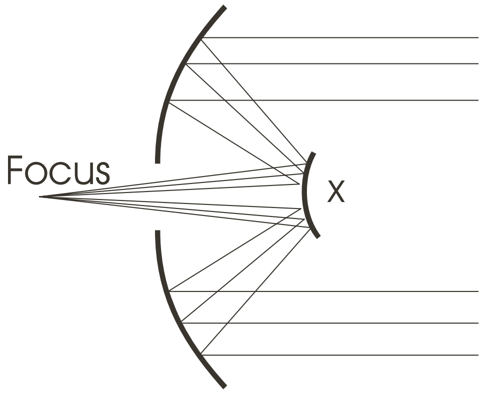


Figure 11: Cassegrain Mirror System

REFLECTIONS FROM CONCAVE SURFACES

The shape of a typical satellite receiving dish is concave, the centre of the reflector is further away than its edges. When rays of light (or radio waves) reflect from a concave surface then they come together (converge) and might come to a focus. This is illustrated in Figure Nine. Here, the rays of light have arrived at the mirror as parrallel lines, because they originated from a great distance. When such rays arrive from a direction at right-angles to the centre of the mirror then the are focused at the 'Principal Focus' of the mirror. In the case of a satellite dish, the radio waves from the satellite form an 'image' at the focal point and there is an antenna at that point to receive the waves

Whenever the object is farther away from the mirror than the principal focus then a real image is formed, as illustrated in Figure Ten. It is a real image (not a virtual image) because the rays of light actually pass through the location of the image. If a sheet of white paper were placed at that point then a visible image would be seen, projected onto the paper by the mirror.

Convex mirrors can be difficult to use in this way as anything placed so as to detect the image will tend to obstruct light approaching the mirror. This problem can be alleviated by offsetting the mirror or by using a second mirror to place the image elsewhere, as illustrated in the Cassegrain System, shown in Figure Eleven. The secondary mirror is convex - but is less curved than the main mirror so that its effect is to re-locate the focus to a more convenient point. Some light is blocked by the secondary mirror but this is not usually important.

When an object is place closer to a concave mirror than the principal focus then an enlarged virtual image is formed, as shown in Figure Twelve. This is what happens with a shaving mirror. The person's face is placed close to the mirror and the eyes can see thing s more clearly in the enlarged image. It is a virtual image and it cannot be captured on a screen. For this magnification to occur, the object must be closer to the mirror than the principal focus of the mirror.

REAL IMAGES

When the image is to be detected using a camera and film, an electronic thermal detector or a TV camera then a real image must be projected onto the surface of whatever detector is being used. The light actually arrives at a real image whereas it only appears to come from a virtual image. Consequently, lenses and mirrors used in photography and television (including thermal) must use combinations of lenses and mirrors that produce a real image on the film or detector chip.

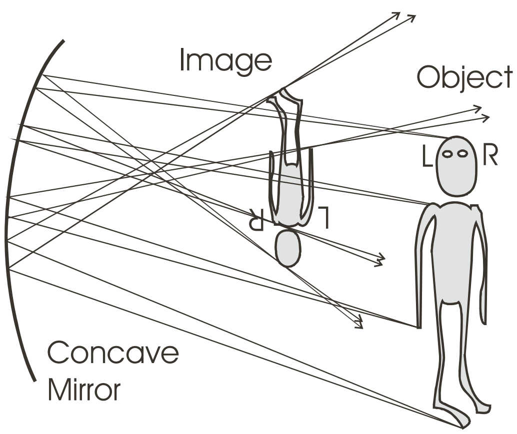


Figure 10: Reflection in a Concave Mirror
Rays from Relatively Distant Objects are focused in front of the Mirror.
Used for radar / satellite dish antenna

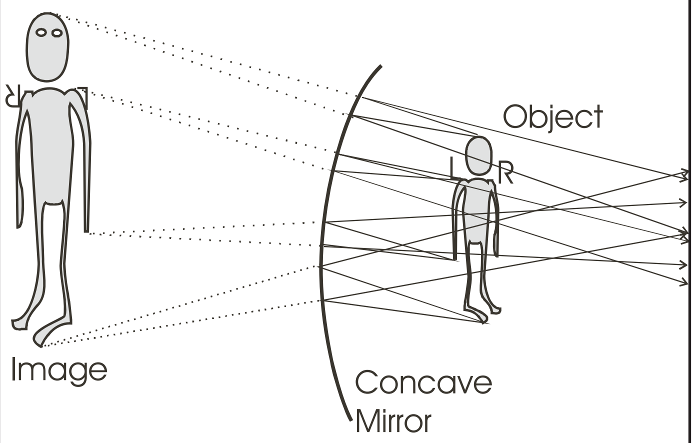


Figure 12: Reflection in a Concave Mirror
Rays from Relatively Close Objects Form a Virtual, Magnified Image in the Mirror.
Used for Shaving / Make-up mirror

REVERSIBLE PATHS

All rays of light are reversible - so the object and the image can be interchanged. In Figure Ten, if the man stood where the image currently is located then an image of him would be projected at the point where he was formerly located. This image would be bigger than the man. Clearly this could not work for the situation where there is a virtual image in a mirror, as in Figure Eight because the virtual image is located on the other side of the mirror - the light would not be able to pass through the mirror.

If a source of light is placed at the focus of the mirror in Figure Nine then all light from that source that reaches the mirror will be reflected in a narrow beam. This is how searchlight, headlamp and torch beams are produced. The source of light could also be placed at point ‘X’ if the secondary mirror were removed.

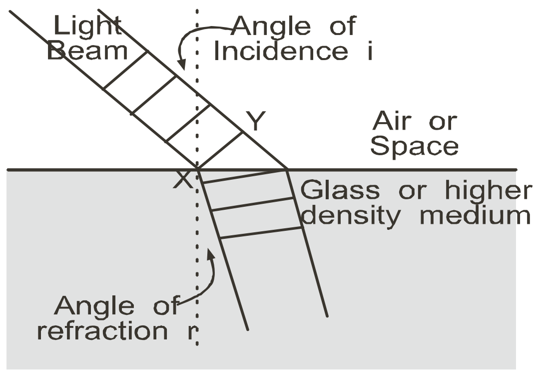


Figure 13: A Beam of Light Passing from Air to Glass

REFRACTION

When visible light passes through a vacuum then its velocity is, of course, the speed of light, 3×10^8 ms^{-1}. When light passes through most transparent media, such as glass, plastic and water, then its velocity is reduced (never increased – since nothing can travel faster than light). In some types of glass, the velocity of light is about one-half of its value in a vacuum. One consequence of the change of velocity is that a ray of light that crosses a boundary between two different media will change direction unless its angle of incidence is zero (i.e. the ray crosses the boundary at right-angles to its surface.

Figure Thirteen shows the bending that occurs when a beam of light passes from the air into glass. The ray always bends towards the normal when it slows down and vice-versa. The ray bends as it enters the glass in Figure Eleven because the part labeled ‘X’ enters the glass first, before ‘Y’. As one side of the beam is then travelling more slowly than the other then the beam is skewed. Tracked vehicles are steered in a similar way - the track on one side of the vehicle is slowed down compared to the track on the other side.

When passing through the glass of a window, because the two surfaces of the glass are parallel then the same amount of bending occurs on the way out of the glass as occurred on the way into the glass. However, since the bending on the way out is in the opposite direction to that on the way in then the beam is bent back to its original direction, having passed through a zig-zag. (See Figure Twelve.) The amount of displacement is very small for window glass because the glass is thin.

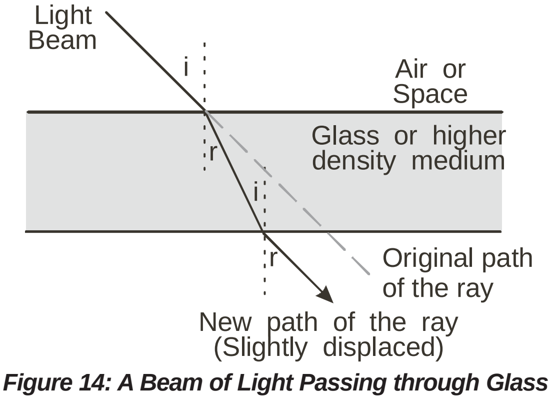


Figure 14: A Beam of Light Passing through Glass

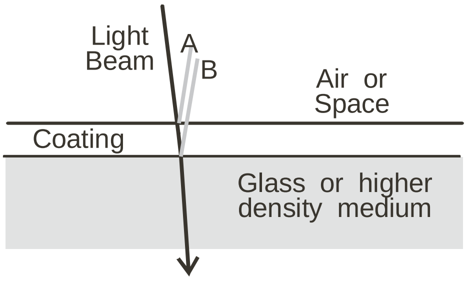


Figure 15: A Beam of Light Passing into Glass, with a Quarter-Wavelength Coating to Raduce Reflections

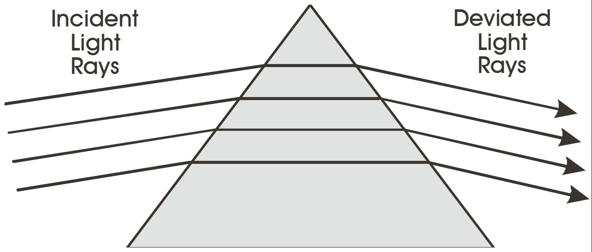


Figure 16: Deviation of a Beam of Light by an Equilateral Prism (60° angles)

Optical Coating: whenever any wave passes through a boundary where there is a change of velocity then some of the wave will be reflected at the boundary. The amount that is reflected varies with the angle of incidence, being greatest as it approaches 90° and less at zero degrees. This reflected wave can sometimes adversely affect the performance of optical equipment so many optical surfaces have a special coating that is designed to reduce this. The special layer is usually one-quarter of a wavelength in thickness and it is constituted to reflect an equal amount of energy from the light that passes in and the light that passes out of it. This is illustrated in Figure Fifteen.

The two reflections result in rays 'A' and 'B' and these have equal intensities. However, the ray 'B' has travelled an additional half-wavelength, compared to ray 'A' so it is in anti-phase. Thus, the two rays, 'A' and 'B' cancel each other and there is no reflection. This coating gives optical surfaces a characteristic blue, green or purple colour. Although it can produce exact cancellation at only one particular wavelength, by selecting the chosen wavelength to be in the centre of the operating range then the reflections, in general, are reduced by a significant amount. Vigorous cleaning of such coatings will, of course, reduce their effectiveness by changing the thickness of the coating.

In practice, better performance is obtained when a series of coating is applied to the glass surface. Without a coating, up to 10% of the light might be reflected - not entering the glass. WIth a coating, more than 99% of the light will enter the glass and a much brighter image will be produced by the optical system.

THE BASIC PRISM

The common prism is a piece of glass with a triangular cross-section. Unlike a piece of window glass, the surfaces of the prism are not parallel and the refraction on exit does not usually cancel the refraction on entrance - the two refractions are cumulative and the ray of light is deviated. This is illustrated in Figure Sixteen.

Dispersion: the velocity of light in most media varies with the colour of the light and in glass, blue light travels slightly more slowly than red light so the blue light is refracted through a greater angle. This effect produces the spectrum of light – showing all the colours. When the refraction occurs in the water of falling rain then we see a rainbow. Most optical equipment is designed to eliminate this effect as it causes coloured edges and/or blurring to occur in the image as the different colours are focused at different places.

CRITICAL ANGLE AND INTERNAL REFLECTION

When light approaches the boundary between a dense medium, such as glass, and air then there is a 'critical angle' of incidence. If the light approaches at a greater angle than the ciritcal angle then it is totally reflected at the boundary and does not leave the glass. For optical glass, this critical angle is about 42°, so any ray of light with a greater angle of incidence is totally reflected from the inside surface of the glass. 'Total Internal Reflection', as it is called, occurs at the inside surface - this cannot be contaminated by dust and fingerprints.

Critical Angle is illustrated in Figure Seventeen. From left-to-right the illustrations represent four rays of light each trying to leave the glass at different angles of incidence, as follows:

- **Ray 'a'**: has an angle of incidence of zero degrees. It passes straight out of the glass. There is no refraction at this angle.
- **Ray 'b'**: has an angle of incidence of 30°. This ray exits at an angle of 49°. (See Page Thirteen for calculation method.) Note that as the angle of incidence increases then the angle of refraction increases at a greater rate.
- **Ray 'c'**: this illustrates the critical angle, 42° (for ordinary glass). This ray leaves the glass along its surface, with an angle of refraction of 90°.
- **Ray 'd'**: this ray approaches the boundary with an angle of incidence of 43° - greater than the critical angle - and cannot get out of the glass. It is internally reflected. Any ray that has an angle greater than the critical angle is totally internally reflected.

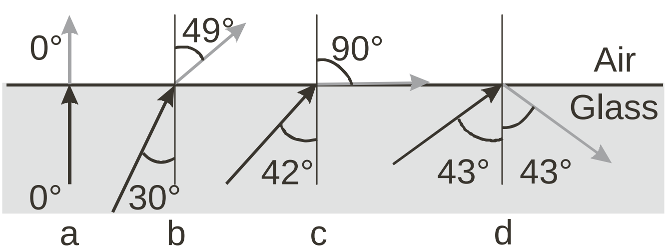


Figure 17: Illustrating the Refraction of a Ray of Light that is attmpting to Pass from Glass to Air. Illustration 'c' Represents the Critical Angle (42°)

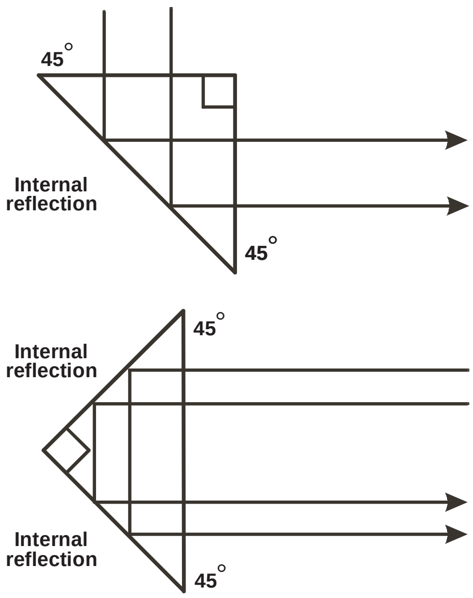


Figure 15: Use of a 45° Isosceles Prism to Reflect a Beam of Light

Many uses of prisms, e.g. in binoculars, exploit this internal reflection. Glass prisms are often made with a triangular cross-section, as shown in Figure Sixteen. When a 60° prism is used, as in the Figure, then the beam of light usually passes through the prism and a spectrum is produced by dispersion. When a 45° prism is used then it is easy to arrange for light to arrive at an internal surface at an angle greater than the critical angle of 42°. Two, simple applications of 45°, or isosceles, prisms are shown in Figure Fifteen:

- **Bending by 90°**: use a pair of these to make a periscope without mirrors. Reflection is internal and the reflecting surface is unaffected by dust, etc. Light enters and leaves at 90° so there is no refraction and, therefore, no dispersion.
- **Reversing direction**: use four of these in a pair of binoculars so that the path of light is folded up inside the binoculars.

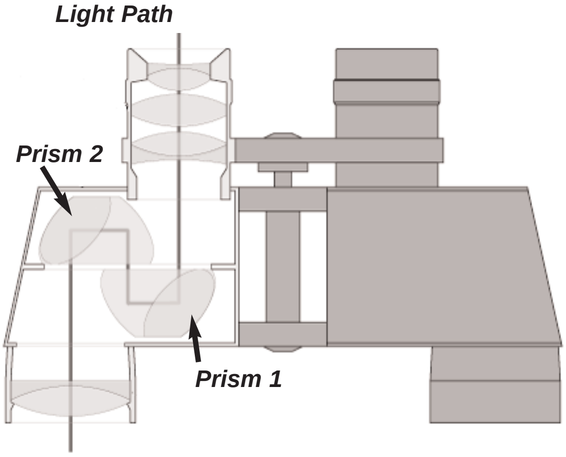


Figure 16: Prisms and Lenses in Binoculars

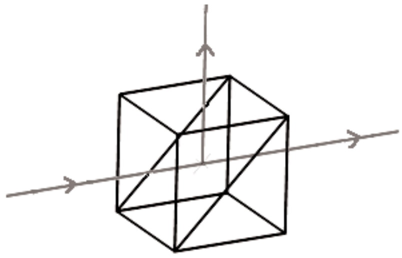


Figure 18: Illustrating a Beam-Splitter Cube

BINOCULARS

The simple arrangement of lenses used in binoculars produces an upside-down image. Using two prisms, as shown in Figure Sixteen, inverts the image and has the added advantage that the light-path is folded and, therefore, the device is shorter in length and easier to hold. To save space and weight, the corners of the prisms, which are not used to look through, are cut away. The prisms are shown in more detail in Figure Seventeen. The 'crossed' prisms put the image the right way around and the right way up.

BEAM-SPLITTER CUBE

This is built using two prisms, glued together to form a cube of glass, as illustrated in Figure Seventeen. The two prisms have very flat faces and are very closely spaced together, with a very thin layer of transparent glue used to bind them together. The space between the prisms has a thickness that is comparable to the wavelength of the light that is being split. Under these conditions, some of the light, which would normally be internally reflected at the boundary, passes straight through.

Depending on the design of the cube, the light energy might be split 50/50 or in any other desired proportion. This type of beam-splitter may also be used in reverse - to combine two beams of light into one. This is used in the HVM Laser Grid to combine the beams from two lasers that are used to guide the missile to its target. (One beam controls the missile in pitch, the other controls it in yaw).

The cube is designed to operate at one particular wavelength, according to the spacing between the two prisms.

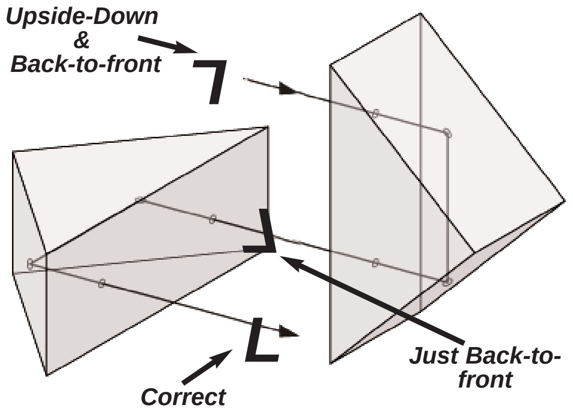


Figure 17: Use of Porro Prism to Correct an Image

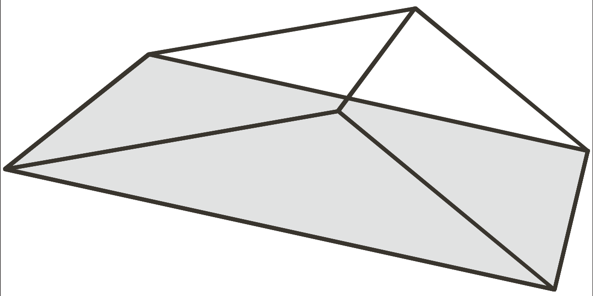


Figure 19: The Dove Prism

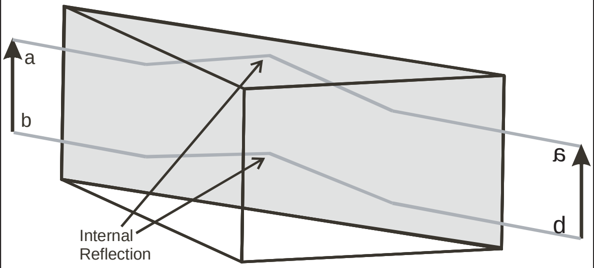


Figure 20: The Dove Prism - Not Rotating an Image

Figure 20a: Looking through a Dove Prism, oriented to give no rotation of the image

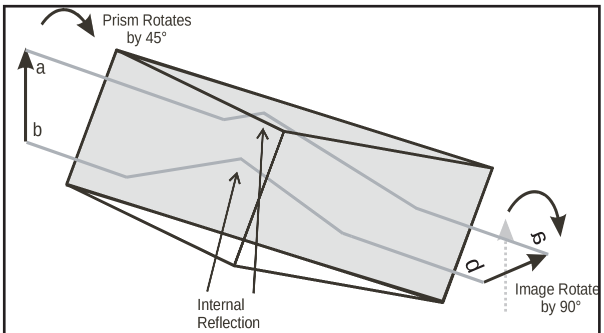


Figure 21: The Dove Prism - Rotating an Image 90°

Figure 21a: Looking through a Dove Prism that has been rotated by 45° The image has rotated by 90°

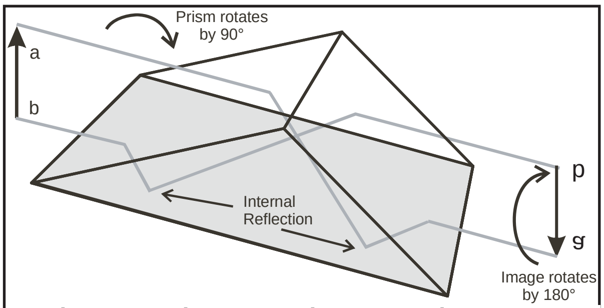


Figure 22: The Dove Prism - Inverting an Image

Figure 22a: Looking through a Dove Prism that has been rotated by 90°. The image has rotated by 180°

DOVE PRISM

The Dove Prism can be used to rotate an image by any number of degrees, from zero to 360°. The prism is shown in Figure Nineteen. The prism does not have a right-angle – the angle is chosen so that the beam of light passes symmetrically through the prism, as this is necessary to ensure that the dispersion (into red/blue light) that occurs on entry is exactly cancelled by the dispersion that occurs on exit. (Note that the direction of dispersion on entry is reversed during the internal reflection. This is why the second dispersion cancels it.)

If the Dove Prism is viewed as shown in Figure Twenty then the internally-reflecting surface is vertical and it acts as a simple mirror (the image is laterally inverted, as with all single reflections). The rays of light follow parallel paths through the prism. This can be seen in the photograph in Figure Twenty (a) where the numbers '5' and '6' are the right-way up but laterally inverted.

Rotating the Dove Prism by 45° causes the same rays of light to take an aysmmetric path through the prism, with the result that the image rotates by 90°, in the same direction. This is illustrated in Figure Twenty-One and there is a photograph in FIgure Twenty-One (a). The prism can be seen to have rotated 45° but the image that you can see through the prism has turned by 90°.

When the prism has been rotated by 90° then the image seen through it will have rotated by 180°, as shown in Figure Twenty-Two. A photograph of this is shown in Figure Twenty-Two (a) where you can see that the '7' and 'Y' keys appear to be upside-down.

When the top part of a periscope turns then the image that is seen through the periscope tumbles - at the same rate.When a Dove Prism is turned then the image turns twice as fast. If the Dove Prism is placed in a perisope and geared to turn at half the rotation rate of the top mirror, in the same direction, then the image does not rotate at all, because the two rotations cancel. Thus, the Dove prism compensates for the image tumbling that occurs in this type of periscope. This use is illustrated in Figure Twenty-Three.

The reflection in the Dove Prism will, of course, produce lateral inversion of the image. In most optical systems, there will be a number of other prisms, mirrors or lenses that also produce lateral inversion. By arranging things so that the number of lateral inversions is even then the image will appear to be correct when viewed by the observer.

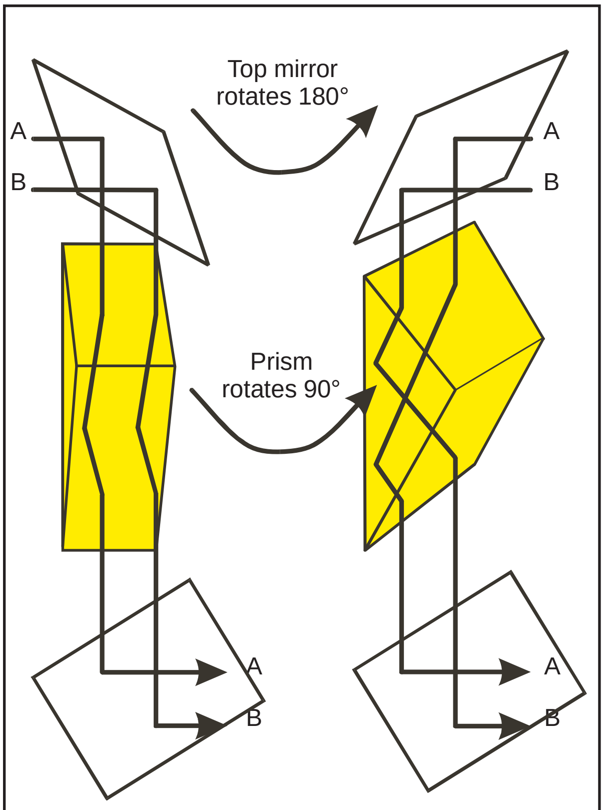


Figure 23: A Dove Prism in a Panoramic Periscope

Two drawbacks of this prism are that it is asymmetirc (therefore: not balanced for rotation) and that the light enters and leaves the glass at glancing angles (therefore: light is reflected into other parts of the device). These drawbacks can be overcome using another design of prism - the Pechan Prism.

PECHAN PRISM

This is a development of the Dove Prism so that the light always enters and leaves the glass at right-angles to the surface. It is formed from two, separate prisms and there are five reflections compared to just a single reflection for the Dove Prism. The Pechan Prism is illustrated in Figure Twenty-Four. The two halves of the prism are normally in close contact – the diagram shown them apart so that the path of the light is more easily seen. You should observe that the ray of light marked ‘A’ emerges on the opposite side of ray ‘B’: the rays are rotated by 180°.

All rays enter and leave the glass at right-angles to the surface. Internal reflection occurs where the angle of incidence exceeds about 42° and you can probably work out that the angle of incidence at the sloping, outer sides will only be 22.5°. These two surfaces are silvered, like an ordinary mirror, otherwise the light would pass out of the prism. As this prism is rotated then the rotation of the image changes, in the same manner as that which occured in the Dove Prism, except that the path of the rays is more complicated.

Three useful features of the Pechan Prism are:

- **Symmetry**, relative to its optical axis, unlike the Dove Prism. This symmetry means that it is mechanically balanced and can be rotated without undue vibration.
- **Normal Entry/Exit**:the rays of light always enter and leave the prism normal (i.e. at 90°) to its surface. This differs greatly from the Dove Prism, where the rays enter and leave at a glancing angle - which causes stray reflections.
- **Large Entry/Exit Area**: the Pechan Prism can accommodate fairly wide beams of light.

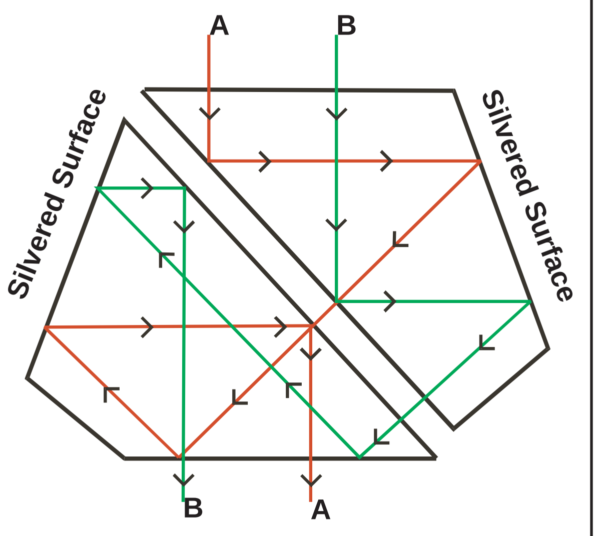


Figure 24: A Pechan Prism Being Used to Invert a Beam of Light (180° Rotation)

The Pechan Prism is used in the Panoramic Sight of HVM/Stormer and in ADAD. BST has a Pechan Prism that you can place on a piece of paper and rotate - to see the effect.

FORMATION OF IMAGES BY LENSES

Lenses are used much more than mirrors to produce images in optical equipment for the simple reason that the viewer can be on the opposite side of the lens to the object. Consequently, there is no obstruction to the light and the viewing can take place in a light-tight box (e.g. camera) at the back of the lens.

There are two basic types of lens, called concave (diverging) and convex (converging).

To form a real image, the lens must be converging. Many practical lenses are made from several pieces of glass (or other refracting material) and, in that case, the total converging strength must exceed the total diverging strength in order to form a real image. A real image is necessary when the image is to be viewed using a detector (e.g. themal camera, TV camera) of photgraphic film (e.g. ordinary camera).

CONVERGING LENSES

The convex lens can be thought of as a series of prisms, similar to those shown in Figure Twenty-Five. The angle of the prisms reduces with distance from the centre of the lens. In practice, a lens would be made using a smooth curve rather than the stepped form shown in the Figure. The light entering the lens of Figure Twenty-Five is parallel to the 'Principal Axis' of the lens (a line through its centre, at right-angles). This light has come from a distant source and the point where the rays of light converge is called the 'Principal Focus'. The distance from the lens to the focus is called the 'Focal Length'. Standard lenses, used in 35 mm cameras, have focal lengths of 50 mm.

If the point of origin of the rays of light is moved upwards then the focus will move downwards and vice-versa. The surface where the focus appears is called the 'Focal Plane'. If the object is moved closer to the lens then the image is formed farther away from the lens. When a camera is 'focused' then either the film or the lens must be moved, so that the focused image falls on the film (or electronic detector).

When a real object if placed some distance in front of a lens then light reflected from the object will reach the lens and be converged to a focus. The light from each individual point on the object will come to a focus at a different point, forming a real image. This is illustrated in Figure Twenty-Six. All the light from the donkey's ear is focused by the lens to one point on the image whilst the light from its hoof is focused at a different point.

Since rays of light are reversible, the object and image may be interchanged. In that case, the object is small (e.g. a viewfoil) and close to the lens whilst the image is large

If the distance between the object and the lens is reduced then light that reaches the lens will become more divergent until it is beyond the ability of the lens to converge it to form a real image. This occurs when the distance to the object is less than the focal length of the

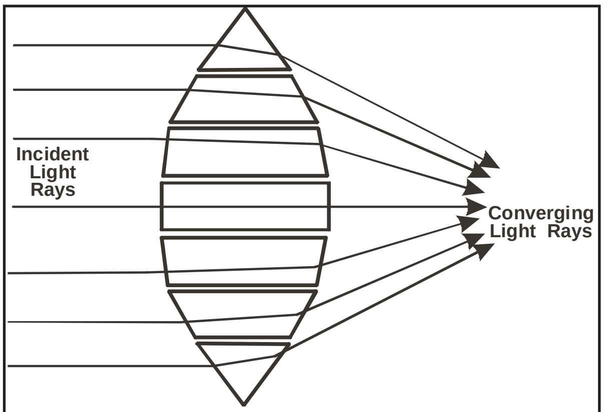


Figure 25: Converging Lens Made from Prisms

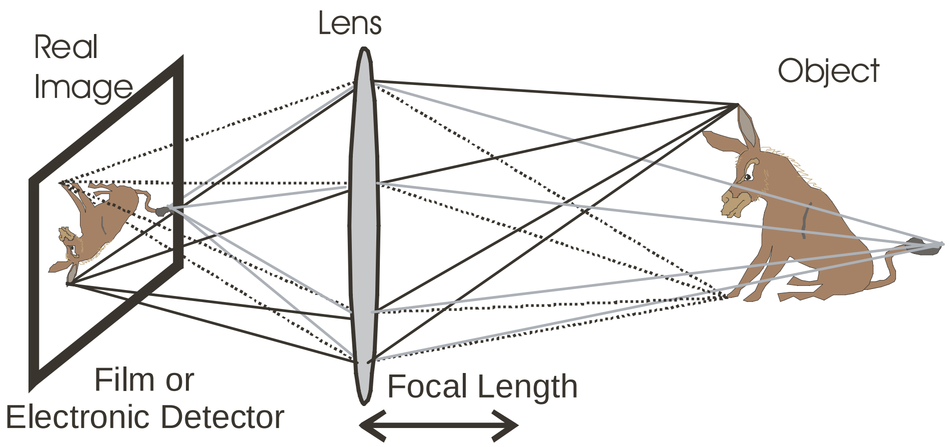


Figure 26: Formation of a Real Image by a Convex Lens, DIstant Object
Typical Use: Form an Image on a Camera's Photographic Film or Electronic sensor

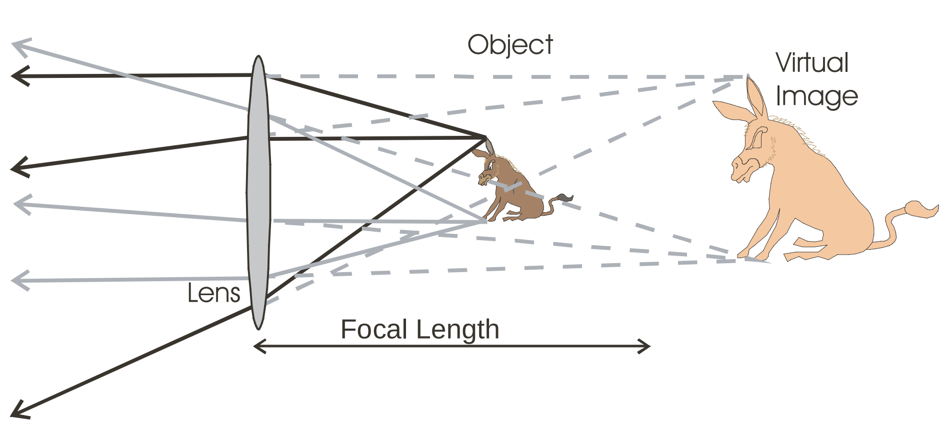


Figure 27: Formation of a Virtual Image by a Convex Lens, Close Object
Example of Use: Magnifying Glass

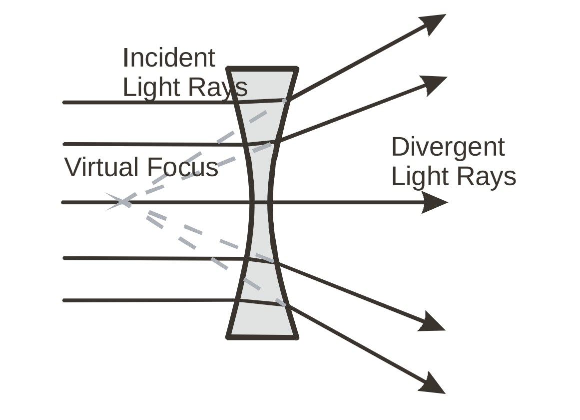


Figure 28: Concave Lens and Virtual Focus

Figure 29: A Catadioptic Lens

lens. The situation is illustrated in Figure Twenty-Seven. A virtual image is formed which is magnified and the correct way around. This is the ray diagram for a convex lens used as a magnifying glass.

CONCAVE (DIVERGING)LENSES

A lens that is thinner in the middle than it is at the edges will cause light to diverge, as indicated in Figure Twenty-Eight. The light appears to have come from the virtual focus and a virtual image is formed that is smaller than the object. Concave lenses are used in conjunction with convex lenses to build practical lenses for optical systems.

Figure Twenty-Five illustrated that a convex lens can be thought of as a series of prisms - a concave lens can also be thought of as being comprised of many prisms – the opposite way around to those of a convex lens.

However, prisms split light into its component colours (the process is called 'Dispersion' and it produces a 'Spectrum' of colours). Consequently, all simple lenses will produce images with coloured edges caused by this dispersion.

A compound lens can be designed, using a pair of convex and concave lenses so that the dispersion effects cancel whilst the overall effect of the lens remains convergent - therefore an image is formed without colour-fringes. This type of lens is called an 'Achromatic Doublet' Most practical lenses consists of several elements that have been carefully designed so that their faults cancel and high performance is obtained. Camera lenses usually contain at least six lenses, sometimes as many as twelve.

ZOOM LENSES

When a convex lens is combined with a concave lens then the focal length of the combination varies when the separation of the two lenses is changed. This differs from the movement of the lens that is used to focus a camera (or other optical system) because, when moving a lens to focus it then the whole lens generally moves as one and the size of the image remains fixed. When some of the elements that make up a lens are moved, whilst others remain fixed then the effect is to change the focal length and, hence, the size of the image. This is the basis of the 'Zoom Lens'.

Zoom lenses are complex - because it is difficult to achieve the required change in image size whilst maintaining the position where the image comes to a focus. This position must be maintained because the film or electronic detector is at that position. Many designs for zoom lenses use two groups of moving elements that move in opposite directions: one group to change the focal length and the other to maintain focus. Some designs use as many as five groups of moving elements. Early zoom lenses were able to vary their magnification (and focal length) by a factor of around 2.5 times (e.g. focal length 40 mm - 100 mm for a camera using 35 mm film). Modern designs can provide a zoom-range of ten times and more (at a price).

Zoom lenses are useful for surveillance because they can be 'zoomed-out', to provide a wide field of view and then, when something of interest is seen, they can be 'zoomed-in' to obtain a closer look at the object. For more information on zoom lenses, try searching the Internet (e.g. Google.com).

CATADIOPTIC LENSES

These are hybrids, using both lenses and mirrors to produce an image. The construction is similar to the Cassegrain arrangement (shown in Figure Eleven) with extra lenses in the light path. Their advantages include short length, compared to ordinary tele-photo lenses and greather light-gathering ability. An example of a Catadiptic lens is shown in Figure Twenty-Nine. All such lenses have an annular (ring-shaped) aperture, due to the presence of the small mirror in the centre of the aperture. Photographs taken through such lenses sometimes have circles of light, around the sun or other bright source of light in the picture - ordinary lenses usually produce star-shaped highlights under such circumstances. The Night Observer's Device (NOD-A/B), now obsolete, contained a catadioptic system.

LENS & MIRROR CALCULATIONS

The position and magnification of an image formed in a lens can be calculate using standard formulae as follows:

- The distance from the lens to the object is ‘u’.
- The distance from the lens to the image is ‘v’.
- The focal length of the lens is ‘f’.

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

- Distances to real images are positive, distances to virtual images are negative.
- Converging lenses have positive focal lengths, diverging lenses have negative focal lengths.
- The magnification is ‘m’.

$$m = \frac{\text{Height of image}}{\text{Height of object}} = \frac{v}{u}$$

Applying the above rules to the situation in Figure Twenty-Six, the focal length is 50 cm and the object is 150 cm from the lens.

$$\begin{aligned} 1/50 &= 1/150 + 1/v \\ 0.02 &= 0.00667 + 1/v \\ 1/v &= 0.02 - 0.00667 \\ 1/v &= 0.0133 \\ v &= 1/0.0133 \\ v &= 75 \text{ cm} \end{aligned}$$

The real image is 75 cm from the lens.
The magnification is one half (75 ÷ 150)

Applying them to the situation in Figure Twenty-Seven, the focal length is still 50 cm but the object is at a distance of 30 cm from the lens.

$$\begin{aligned} 1/50 &= 1/30 + 1/v \\ 0.02 &= 0.0333 + 1/v \\ 1/v &= 0.02 - 0.0333 \\ 1/v &= -0.0133 \\ v &= -75 \text{ cm} \end{aligned}$$

The virtual image is 75 cm from the lens.
The magnification is 2.5 (75 ÷ 30)

The same set of rules applies to mirrors when a converging mirror (concave) has a positive focal length and a diverging mirror (convex) has a negative focal length.

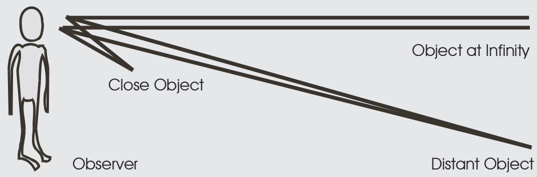
When a mirror is made from part of a sphere then its focal length is always one half of the radius of the sphere from which it was made.

To find the focal length of a simple convex lens, hold it away from a white wall or piece of card until you see a real image of a distant scene on the wall. The distance from the wall to the lens is approximately equal to the focal length.

VISUAL PERCEPTION OF DISTANCE AND SIZE

When light from a scene enters the human eye then the brain interprets the information as an image. Amongst other features of the image, the brain interprets distance to and size of objects in view. Optical illusions can arise when adjacent features in a scene cause conflicting interpretations.

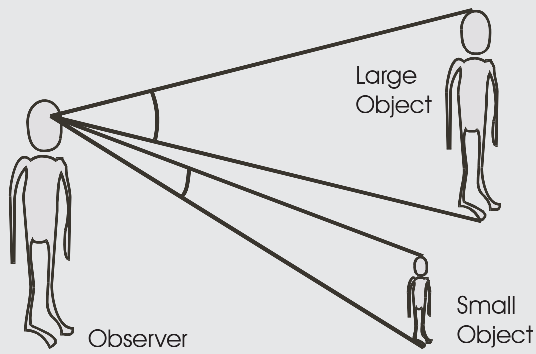
The distance to an object determines the amount of divergence of the rays of light that reach the eye from the object. The closer the object is to the eye then the more the rays of light diverge. Rays of light from a very distant object, for example, the sun, are effectively parallel when they arrive on Earth.



Divergence of Rays from Different Distances

The normal human eye can focus light from objects at distances from about 25 cm to infinity: to focus on close objects requires more effort from the eye muscles than focussing at infinity. Consequently many optical instruments are designed to present a virtual image for viewing that is formed from parallel light, effectively placing the image at an infinite distance from the eye that causes minimum eye-strain when view.

The height of an object determines the angular extent of that object in the field of view. An object of height one metre at a distance of one kilo-metre will subtend an angle of 1m/ in the scene. An object will appear magnified in an optical instrument if the angle that it subtends is greater when it is viewed through the instrument than when it is viewed through the unaided eye.



Angle Subtended by Objects of Different Sizes

The unaided human eye can also sense the distance to an object by the effort needed to turn both eyes to give the same image. For close images, the eyes turn inwards more than they do for distant images. (Observe someone who is trying to focus his eyes on the tip of his nose to see this in action.) Night vision devices seldom allow this ‘binocular vision’ and, consequently, you can walk into trees, etc. whilst using them.

REFRACTIVE INDEX OF A MATERIAL

This is found by dividing the two velocities of light, the velocity in a vacuum and the velocity in the material. For water, the refractive index, μ, has a value of 1.33; for glass, the value may be between about 1.5 and 2.0. Ordinary air has a refractive index of approximately 1.0, as the speed of light in air is almost the same as in a vacuum. The formula for refractive index is:

$$\mu = \frac{\text{velocity of light in a vacuum}}{\text{velocity of light in the medium}}$$

The refractive index also appears in a formula that links the angle of incidence, i, with the angle of refraction, r:

$$\mu = \frac{\text{Sin } i}{\text{Sin } r}$$

When light passes from glass back into air then the refractive index in the inverse of its value from air into glass.

Finally, the critical angle, θ_c, which determines whether light is internally reflected, is given by:

$$\theta_c = \text{Sin}^{-1}\left({}^{1}/_{\mu}\right)$$

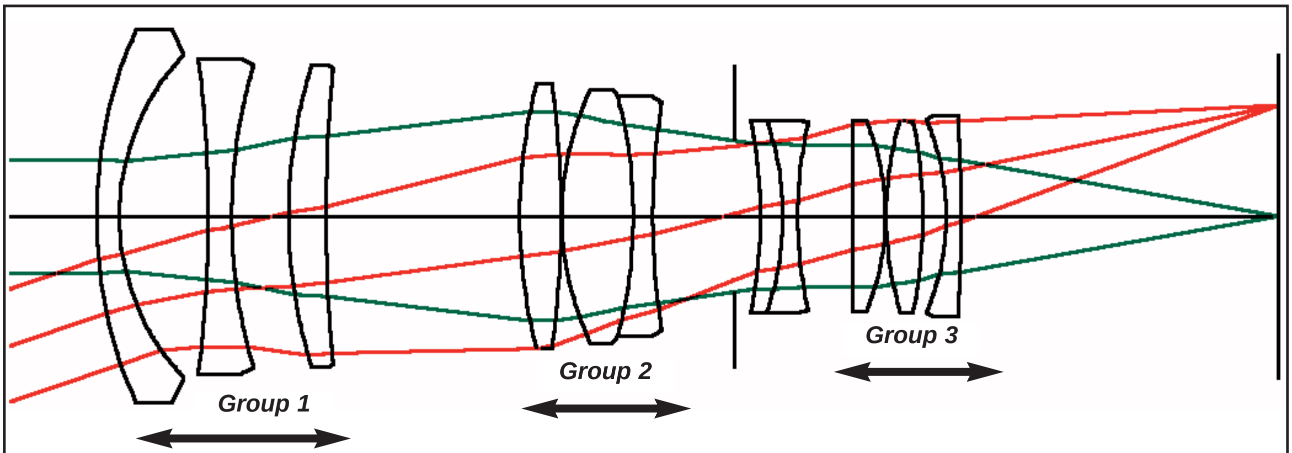
A Dismantled 'Leica' Zoom Lens

LIGHT COLLECTING POWER OF A LENS

The brightness of the image is the important factor here, not the size of the lens. If one lens collects more light than another but also produces an image that is larger by the same factor then the brightness of the two images would appear to be the same. The 'figure of merit' for any lens is found by dividing its focal length by its diameter. This is called the 'f-number' of the lens and the lower the 'f-number' then the brighter the image. Typical camera lenses are designated 'f 2.8' or 'f 3.5' to indicate that their diameters are, respectively, 1/2.8 and 1/3.5 of the focal length. (For example, a camera lens of focal length 50 mm with a diameter of 25 mm would have an f'number of 50/25 or 2 - it would be designated f 2.)

Lenses with longer focal lengths produce bigger images (greater magnification) and so require large diameters – look at the telecopic lenses used by press photographers.

The light passing through a lens will also vary according to the illumination of the scene. From dawn to noon the ilumination might easily vary by several orders of magnitude. To control the amount of light that passes through the lens, a lens is fitted with an 'iris' that can be opened to allow through more light (e.g. on a dull day) or 'stopped-down' to reduce the amount of light (e.g. on a sunny day). Many modern optical devices have automatic irises that operate without user intervention.



A Representation of a Practical Zoom Lens, Showing the Paths of the Light-Rays and Zoom-Groups

SELF-TEST QUESTIONS

1. When light is reflected from a smooth surface then the angle of incidence is equal to the angle of:

   a. dispersion.
   b. reflection.
   c. refraction.
   d. diffraction.

2. The top mirror of a periscope is tilted upwards by 6°. The line of sight of the periscope will change by:

   a. 6° upwards.
   b. 6° downwards.
   c. 12° upwards.
   d. 12° downwards.

3. When an image is formed by reflection in a plane mirror then the image is:

   a. as far behind the mirror as the object is in front of the mirror.
   b. a real image.
   c. upside down.
   d. the point where the rays of light meet in a focus.

4. When an image is formed by reflection from a convex mirror then the image is:

   a. a real image.
   b. a virtual image.
   c. magnified.
   d. upside down.

5. When an image of a distant object is formed in a concave mirror then the image is:

   a. a real image.
   b. a virtual image.
   c. magnified.
   d. the right way up.

6. When a beam of light passes from air into glass then it is refracted:

   a. away from the normal.
   b. by internal reflection.
   c. because it travels faster in glass than in air.
   d. towards the normal.

7. When a beam of light approaches the inside surface of a prism at an angle greater than the critical angle then it is:

   a. refracted as it leaves the glass.
   b. split into a spectrum of colours as it leaves the glass.
   c. rotated through 90° as it leaves the glass.
   d. internally reflected at the surface.

8. A pechan prism, used in a panoramic periscope, would be used to:

   a. magnify the image.
   b. produce a real image.
   c. keep the horizon horizontal as the periscope turns to different azimuths.
   d. tilt the angle of view to enable the periscope to see objects at different elevations.

9. To produce a real image using a single lens, it is necessary to have a:

   a. concave lens.
   b. convex lens.
   c. short focal length.
   d. long focal length.

10. A complex lens, with many elements, would have one group of elements that could be moved in order to adjust the:

   a. amount of light passing through the lens.
   b. magnification of the image (zoom).
   c. orientation of the image.
   d. brightness of the image.

Answers

1. Angle of incidence = angle of reflection. Fig 1. (b)
2. 12° up. Deviation is twice angle of tilt. Fig 3 (c)
3. Equal distance: object/image. Fig 4 (a)
4. Convex mirror has a virtual image. Fig 8 (b)
5. Concave mirror & dist. object = real image. Fig 9. (a)
6. Towards the Normal. Fig 11 (d)
7. Internal reflection. Figs 15/16. (d)
8. Keeps the image horizontal. Fig 17. (c)
9. Convex lens & dist object = real image. Fig 20. (b)
10. Moveable groups for zooming the lens. (b)

Teaching Objectives		Comments
G.03.01 Describe the properties of reflection by a plane mirror		
G.03.01.01	Describe the terms incidence, reflection and normal.	
G.03.01.02	State the law of reflection.	
G.03.01.03	Explain how a beam of light is deviated by a moveable mirror.	Doubling of the angle of movement.
G.03.01.04	Describe the formation of a virtual image by reflection in a plane mirror.	Define virtual image.
G.03.01.05	State that the distance from the mirror to the image equals the distance from the mirror to the object.	Same size image, laterally inverted but not upside down.
G.03.01.06	Describe the path of light rays through a simple periscope consisting of two mirrors.	
G.03.02 Describe the properties of reflection by a convex mirror		
G.03.02.01	Describe the formation of a virtual image by reflection in a convex mirror	Basic ray diagram.
G.03.02.02	State that the image is smaller than the object, giving a wide angle of view	Visible in the ray diagram. Security mirrors, vehicle mirrors.
G.03.03 Describe the properties of reflection in a concave mirror		
G.03.03.01	Describe the formation of a real image by reflection of a relatively distant object in a concave mirror.	Concept of focus, similarities with satellite dish. Define real image, contrast with virtual.
G.03.03.02	Describe the production of a beam from a light source at the focus of a concave mirror.	Searchlight, OHP lamp, etc.
G.03.03.03	State that the paths of rays of light are almost always reversible.	
G.03.03.04	Describe the formation of a virtual image by reflection of a close object in a concave mirror.	Shaving mirror example.
G.03.03.05	State that the final image must be real when it is to be viewed via film, electronic detector, TV or thermal camera.	
G.03.04 Describe the basic properties of refraction		
G.03.04.01	Describe refraction as the bending of light (or any wave) as it crosses any boundary between two media with a different velocity.	e.g. passing from air into water or glass.
G.03.04.02	Describe the path of a ray of light through a transparent, rectangular block in a range of directions.	No calculations, bent towards the normal when velocity reduces, away when velocity increases.
G.03.04.03	Describe the concept of critical angle.	State that it is about 42° for glass.
G.03.04.04	Describe the path of a ray of light through a simple prism without internal reflection.	Mention dispersion.
G.03.04.05	Describe the path of a ray of light through a simple prism with internal reflection.	

Teaching Objectives		Comments
G.03.05 Describe the basic properties of a concave lens		
G.03.05.01	Describe the formation of a virtual image by refraction in a concave lens	
G.03.05.02	State that the image is smaller than the object, giving a wide angle of view	
G.03.06 Describe the basic properties of a convex lens.		
G.03.06.01	Describe the formation of a real image by refraction of a relatively distant object in a convex lens.	Concept of focus. Image on opposite side of lens to object, can be inside a box (camera).
G.03.06.02	Describe the production of a beam from a light source at the focus of a convex lens.	
G.03.06.03	Describe the formation of a virtual image by refraction of a close object in a convex lens.	Magnifying glass.
G.03.07 Describe the basic features of practical lenses.		
G.03.07.01	State that practical lenses are made using many individual elements to give better performance	Often six elements in a camera lens.
G.03.07.02	Describe the operation of lens coatings to reduce reflection (blooming).	
G.03.07.03	Describe the purpose of a lens iris.	
G.03.07.04	State that a zoom lens contains moveable elements inside that vary its magnification.	Over ten elements in a zoom lens.
G.03.08 Describe the basic features of prisms using internal reflection.		
G.03.08.01	Describe the advantages of using internal reflection in prisms compared to external refection in mirrors.	
G.03.08.02	Describe the use of an isosceles prism to turn a beam of light through 90°	Applications include periscope.
G.03.08.03	Describe the use of a prism to turn a beam of light through 180° (porro prism)	Example: binoculars, folding the light path to give a short, overall length.
G.03.08.04	Describe the use of a prism to rotate a beam of light by 180° without change of direction (dove prism).	Example: to produce a telescope image that it the right way up.
G.03.08.05	Describe the use of a high-performance pecan prism to rotate a beam of light (similar to dove prism).	Better performance because the angles of incidence are all 90° when entering/leaving the prism.
G.03.09 Describe the basic features of rotating periscopes.		
G.03.09.01	Describe the rotation of the image seen through a periscope when the top mirror is turned relative to the bottom mirror.	Compare submarine periscopes, where the captain walks around the periscope, to the ADAD or HVM type, where only the top turns.
G.03.09.02	Describe how the pecan or dove prism can be used to counter the rotation.	
G.03.09.03	State that the counter-rotation prism must turn at one-half the speed of the periscope, due to the doubling of the angle of deviation during reflection.	