L2 REFLECTION AND REFRACTION

OBJECTIVES

General aims

When you have finished studying this chapter you should understand the nature of reflection and refraction of light and the simple laws which govern those processes. You will learn how to use the ray model for describing the behaviour of light and you should be able to apply the model to simple examples. Also, you will learn to describe dispersion, the process responsible for rainbows.

Minimum learning goals

1. Explain, interpret and use the terms:

   wavefront, spherical wavefront, plane wavefront, ray, point source, scattering, reflection, reflectivity, specular reflection, diffuse reflection, refraction, refractive index, Snell's law, internal reflection, total internal reflection, critical angle, grazing incidence, dispersion, spectrum, optical fibre, light pipe.
2. State the laws of reflection and refraction, describe examples and apply the laws to simple examples involving plane boundaries.
3. Describe partial and total reflection. Derive, recall and apply the relation between critical angle and refractive indices.
4. Describe what happens to speed, frequency and wavelength when monochromatic light goes from one medium to another. Apply these descriptions to simple quantitative problems.
5. Describe the phenomenon of dispersion and its explanation in terms of refractive index and the wave model of light. Describe examples which illustrate dispersion by refraction.
6. Remember that the speed of light in air is practically equal to its speed in vacuum.
7. Describe and explain the operation of optical fibres and other examples of total internal reflection.

Extra Goals

8. Describe and explain the formation of mirages and rainbows.

TEXT

2-1 WAVEFRONTS AND RAYS

Imagine a wave moving outwards from a source, like the expanding ripples that appear when the surface of a pond is disturbed by dropping a stone into it. Those ripples constitute a wave. All the points on the crest of a particular ripple are at the same stage, or phase, of the wave's vibration.

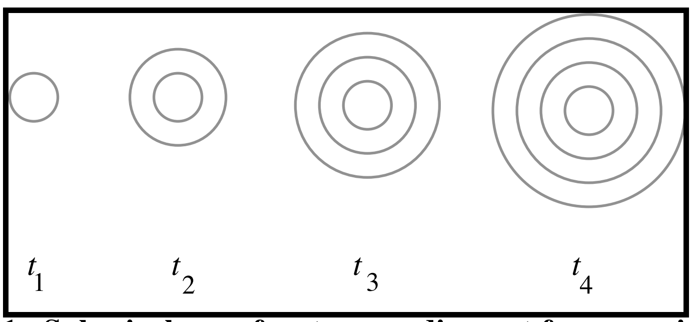


Figure 2.1. Spherical wavefronts spreading out from a point source

A curved line, or a surface for a three dimensional wave, that connects all adjacent points that have the same phase is called a **wavefront**. For the water waves on the pond a wavefront could be one of the expanding circles corresponding to a particular wave crest or trough. For sound waves the wavefront would be a surface containing all adjacent points where the wave pressure is in step. For light the wavefronts are surfaces connecting adjacent points where the oscillating electric fields are in step. Note that for any given wave we can define any number of wavefronts. It is often useful, however, to focus attention on a set of wavefronts separated from one another by one wavelength.

If the light comes from a point source, then the wavefronts are concentric spheres, centred on the source and expanding away from the source at the speed of light; light from a point source has **spherical wavefronts** (see figure 2.2). At a large distance from the source the curvature of a small section of a spherical wavefront is so small that the wavefront is nearly flat and is a good approximation to a **plane wave**.

The ray model of light

If we select a small section on a wavefront and follow its progress as it moves away from the source, the path traced out by this section is called a **ray**. A ray by its nature is always an imaginary directed line perpendicular to the wavefronts.

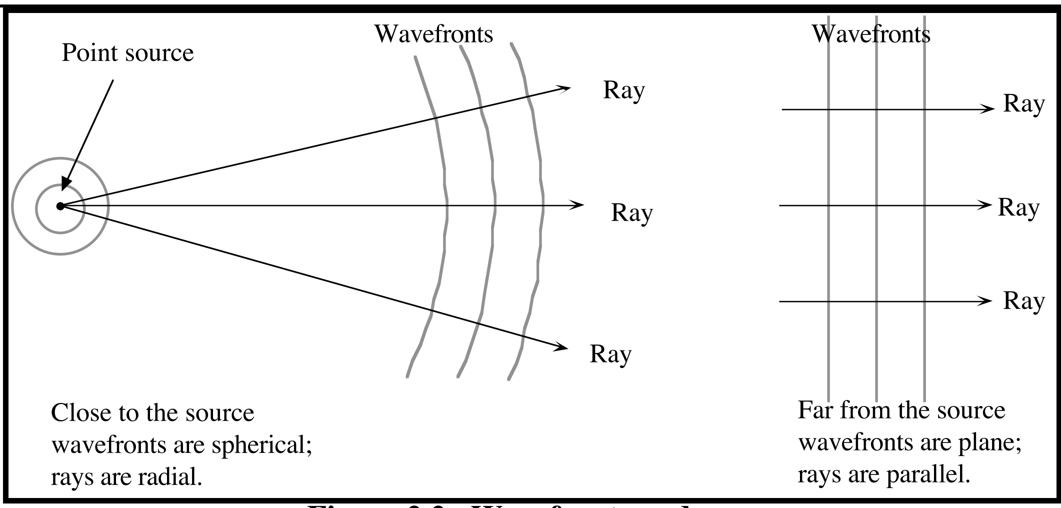


Figure 2.2. Wavefronts and rays

In very general terms rays are lines along which light travels. The direction of a ray at a point in space shows the direction in which the wave's energy is travelling at that place. We can talk about rays even without using the wave model of light.

A **beam** of light is like a tube; unlike a ray it has a non-zero width. In principle we can imagine an infinite number rays within a beam, but in practice we use only a few rays to describe the progress of the light. A narrow beam of light is often called a **pencil**.

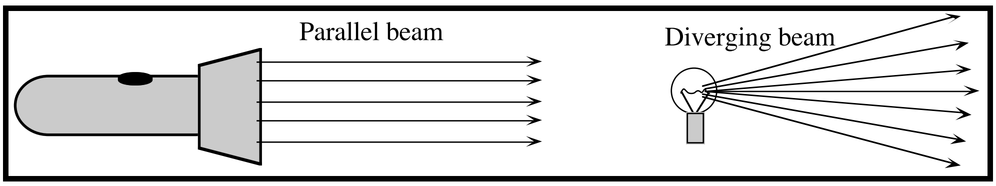


Figure 2.3. Beams of light represented as bundles of rays

2-2 INTERACTIONS OF LIGHT WITH MATTER

This chapter is concerned mostly with what happens to light when it encounters the boundary between two different materials. Before going into details of reflection and refraction we start with an overview of the processes that can happen.

We can represent light travelling through empty space or air using rays which continue straight ahead until the light meets some material object. However when light travels through a material medium the description may not be so simple. Some portion of the light in each beam may be scattered away from its original direction (figure 2.4). This **scattering** is caused by the interaction of light with small particles, even atoms or molecules, within the material. The scattered light goes off in many different directions, and may be scattered again and again before it is finally absorbed somewhere. For monochromatic light the probability of scattering depends on the relative sizes of the particle and the wavelength of the light. So some wavelengths are more susceptible to scattering than others.

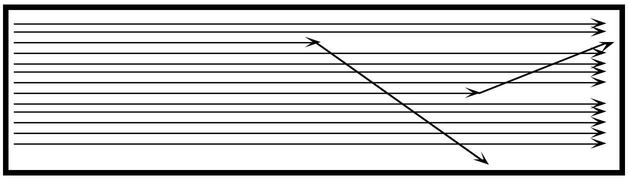


Figure 2.4. Scattering from a beam of light

Scattering is the basis of explanations of why the sky is blue and why the setting sun looks reddish. Light coming through the atmosphere from the sun is scattered by individual air molecules. Since scattering is more likely for shorter wavelengths, some fraction of the short wavelength part of sunlight - blue light - gets scattered out of the direct path from the sun. Multiple scattering spreads the scattered blue light over the whole sky. Since some of the blue light is removed from the direct white-light beam from the sun, the light that still comes through without scattering is somewhat redder than it would be if there were no atmosphere. This explanation is supported by the fact that the sun looks redder at sunset, when the light has to traverse a greater thickness of the atmosphere, than it does at midday.

On a smaller scale, the scattering of a small fraction of the light in a beam by dust or smoke particles in the atmosphere can help in tracing the path of the main beam. This effect is often used in demonstrations which allow us to see the paths of beams of light.

Transmission and absorption of light

The main interest in this chapter is in what happens to light when it comes to the boundary between two different materials. Briefly, several things can happen there: some of the light may be **reflected** back into the material where it came from while some of it may continue to travel through the second medium. You can see an example of this partial reflection when you look obliquely at a window. You can usually see a reflected image of the scene nearby, but most of the light from outside goes in through the window. Light which goes through is said to be **transmitted**. Transmitted light may or may not be **absorbed** significantly along the way. Window glass, for example absorbs very little light but a brown bottle glass absorbs quite strongly.

Light penetrates some materials better than it does others. If light penetrates without much scattering the material is said to be **transparent**. If there is a significant amount of scattering as the light goes through, the material is **translucent**. You can see things clearly through transparent materials but not so well through translucent materials. Materials which let no light through are said to be **opaque**. Light can be gradually absorbed even as it travels through a transparent material, so that a thick piece of a transparent material may appear to be opaque. Furthermore, the rate at which light is absorbed as it travels through the material can depend on the spectral composition of the light, i.e. on the mixture of different frequency components. For example white light, after passing through a slab of coloured glass, will emerge from the other side with a different mixture of frequencies, i.e. it will have a different colour.

When light comes from a transparent medium, or empty space, to the boundary of an opaque material, there may be some reflection but there is no significant transmission; all the absorption takes place in a very thin layer of material near the surface.

An important effect on transmitted light is that its direction of travel can change as it crosses the boundary between materials. This effect is called **refraction** and the light is said to be **refracted**. Refraction will be considered in §2-4.

The **speed of light** in a material is also important. In empty space, a vacuum, all light travels at the same constant speed of 3.0×10^8 m.s^{-1}, which we always denote by the symbol c. However when light travels through a material its speed is always less than c. The actual value of the speed can now depend on a number of factors such as the chemical composition and the density of the material. It also depends on the frequency of the light, so that normal light, which contains a complex mixture of components with different frequencies, travels with a range of different speeds. As you will see at various stages in this course, the dependence of speed on frequency has a number of important consequences. For example some parts of a flash of light can be delayed or left behind when the light goes through a material medium.

2-3 REFLECTION

Diffuse reflection

We see objects when light from them enters our eyes. Apart from self-luminous objects, such as the sun, lamps, flames and television screens, all other objects are seen only because they reflect light. Hence the apparent shape, texture and colour of objects depend upon the light which falls on them, called the **incident light**, and the way it is reflected. Even when the incident light comes mostly from one direction, the reflecting surface can scatter the light so that it travels in many different directions. This scattering process, which occurs at a well-defined boundary, is usually called **diffuse reflection**. The diagram shows what happens to a parallel beam of light when it is reflected diffusely. Although all the incident rays are parallel, the reflected rays go all over the place - in many different directions. This model explains why you can see an object in reflected light by looking at it from many different directions - you don't have to be in a particular place to see it.

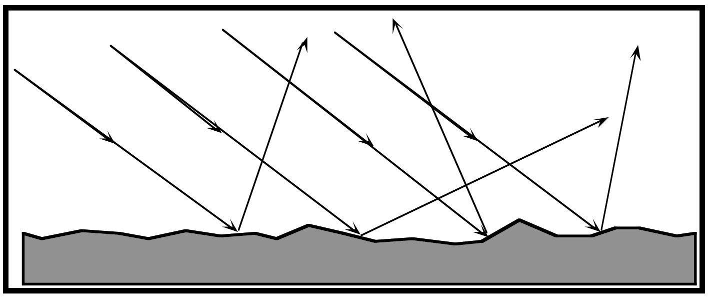


Figure 2.5 Diffuse reflection

The sketch is greatly magnified. On a microscopic scale the reflecting surface is rough,even though it may look smooth to the naked eye.

Reflectivity

When light falls on a surface some of it is absorbed or transmitted and the rest is reflected. The **reflectivity** of the surface is defined as

$$\text{reflectivity} = \frac{\text{total intensity of reflected light}}{\text{total intensity of incident light}} .$$

In this definition the incident and reflected light are each summed over all directions. Reflectivities range from less than 0.5% for black velvet and surfaces covered with powdered carbon to more than 95% for freshly prepared magnesium oxide and polished silver surfaces. White paper has a reflectivity of about 80%.

Colour

Colours of objects can be explained by supposing that their surfaces reflect different proportions of the various frequency (or wavelength) components of the incident light. Different mixes of these components produce the different visual sensations that we call colour.

It is worth noting in passing that there is no one-to-one correspondence between frequency and colour. Although some narrow ranges of light frequencies produce colour sensations such as the colours of the rainbow, red through to violet, there are many colours, such as purple and brown, which do not correspond to any one band of frequencies.

Mirror reflection

Although most examples of reflection in nature are diffuse reflection, the special, regular, kind of reflection exhibited by mirrors and very smooth surfaces plays an important role in the science of optics. This kind of reflection is called **specular reflection** (from the Latin, *speculum*, a mirror) which can be described as reflection without scattering. Some examples of specular reflectors are the surfaces of many types of glass, polished metals and the undisturbed surfaces of liquids. Some of these, such as glass and many liquids, also transmit light, whereas light does not penetrate beyond the surface of a metal. The fact that light is not transmitted through metals can be explained in terms of the interaction between the light and electrons within the metal. An example of a metal reflector is an ordinary mirror - a thin coating of metal is placed on the back surface of a piece of glass and most of the reflection takes place there. In fact the weak reflections at the front surface of the glass are usually a nuisance.

The laws which govern specular reflection can be described most simply in terms of rays. We imagine some incident light, travelling in a well-defined direction, which strikes a flat reflecting surface such as a mirror or a piece of glass. The incident light can be represented by a bundle of parallel rays. The reflected light will also travel in a well-defined direction which can be represented using another bundle of parallel rays. Since there is no scattering, for each incident ray there is only one reflected ray.

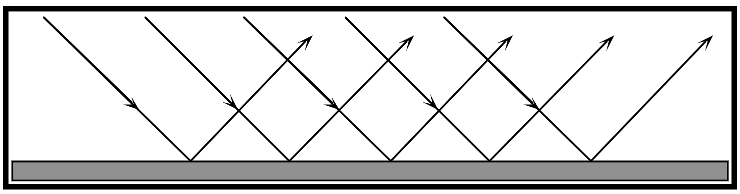


Figure 2.6. Specular or mirror-like reflection

In order to describe the relation between reflected and incident rays we need to look at the point where the incident ray meets the reflecting surface. At that point we imagine a line constructed perpendicular to the surface, in geometrical language called the **normal** to the surface. The reflected ray also departs from the same point. The angle between the incident ray and the normal is called the **angle of incidence** and the angle between the normal and the reflected ray is called the **angle of reflection**. The behaviour of the rays in specular reflection can be described completely by two laws, illustrated in figure 2.7.

- The incident ray, the normal and the reflected ray all lie in one plane.
- The angle of incidence is equal to the angle of reflection.

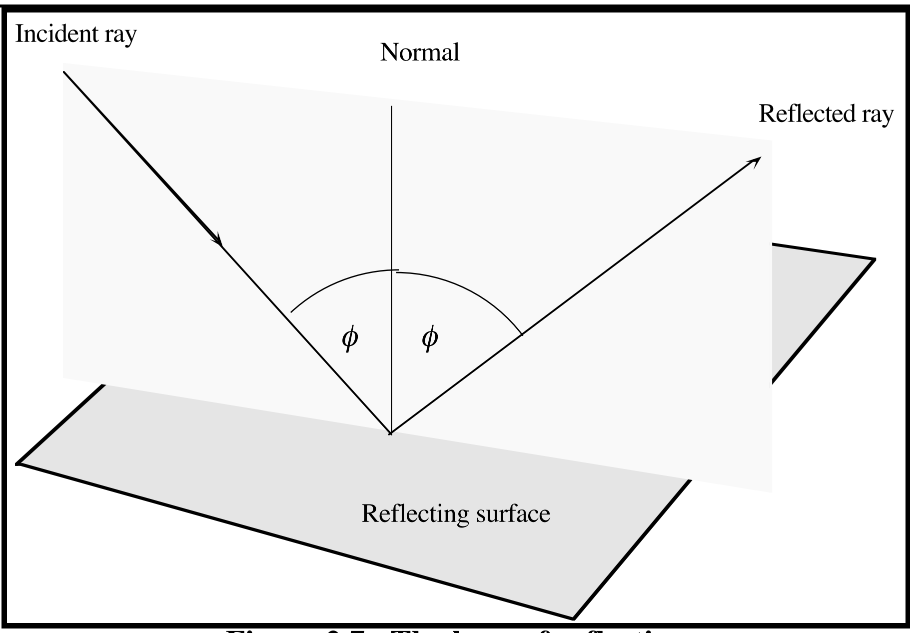


Figure 2.7. The laws of reflection

Notes

- Since any two intersecting lines define a plane, we can draw a plane diagram, like figure 2.8 below, containing the incident ray and the normal. The first of the two laws says that the reflected ray will lie in the same plane, not sticking out of the page at some angle.
- Note that the amount of light reflected cannot be predicted from these laws. That depends on the reflectivity of the surface.

2-4 REFRACTION

We have looked at the laws which govern the paths of specularly reflected light; we now consider what happens to the part of the light which goes into the other material. You already know that it could be partly absorbed, but which direction does it go? Does it go straight ahead or in some other direction or directions. The answer is that if the boundary is smooth enough to be a specular reflector, then the direction of the transmitted light is uniquely determined by the nature of the two materials, the frequency (or the wavelength) of the light and the angle of incidence. Furthermore, the light does not go straight ahead; instead the rays bend at the boundary so that the light goes on in a new direction. The new direction is described by two laws which are almost as simple as the laws of reflection.

- Firstly, the incident ray, the normal, and the refracted ray (as well as the reflected ray) all lie in the same plane. So we can draw all three rays on one plane diagram (figure 2.8).

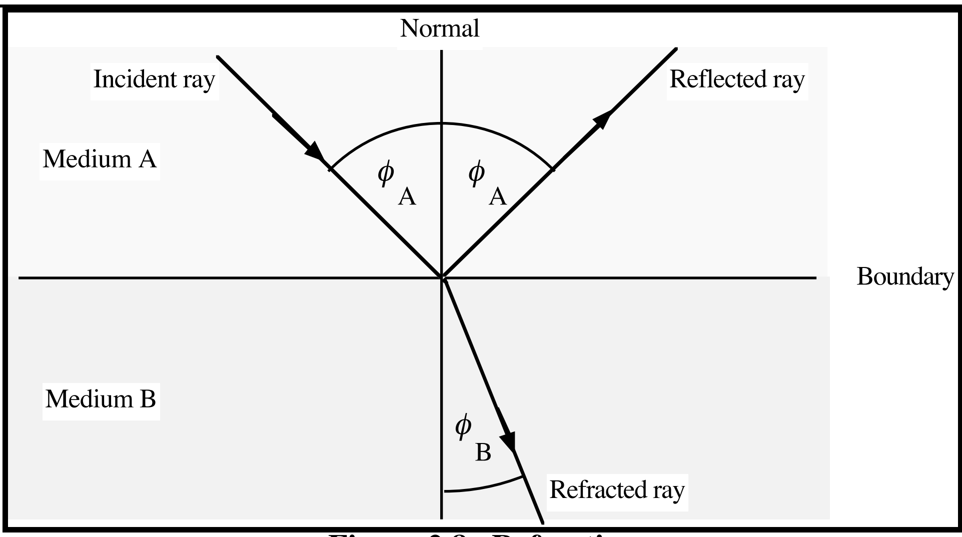


Figure 2.8. Refraction

- Secondly, the direction of the refracted ray is determined by the direction of the incident ray and the ratio of the speeds of light in the two materials:

$$\frac{\sin\phi_A}{\sin\phi_B} = \frac{v_A}{v_B} . \qquad \text{... (2.1)}$$

Note that if the light slows down when it goes into the second medium the rays will bend towards the normal, but if it goes faster then the rays will bend away from the normal. This immediately points to a problem with the equation, because it seems to say that we could get a situation where the sine of the angle of refraction, ϕ_B could have a value greater than 1 - which does not make sense. The proper interpretation of this is that in such a case, the refracted ray cannot exist; i.e. that the light will not penetrate the second medium at all. We return to this point shortly.

The law of refraction is a simple consequence of the wave theory of light. You can see in figure 2.9 how plane wave fronts must change their orientation if the light slows down as the wavefronts go from one material into another.

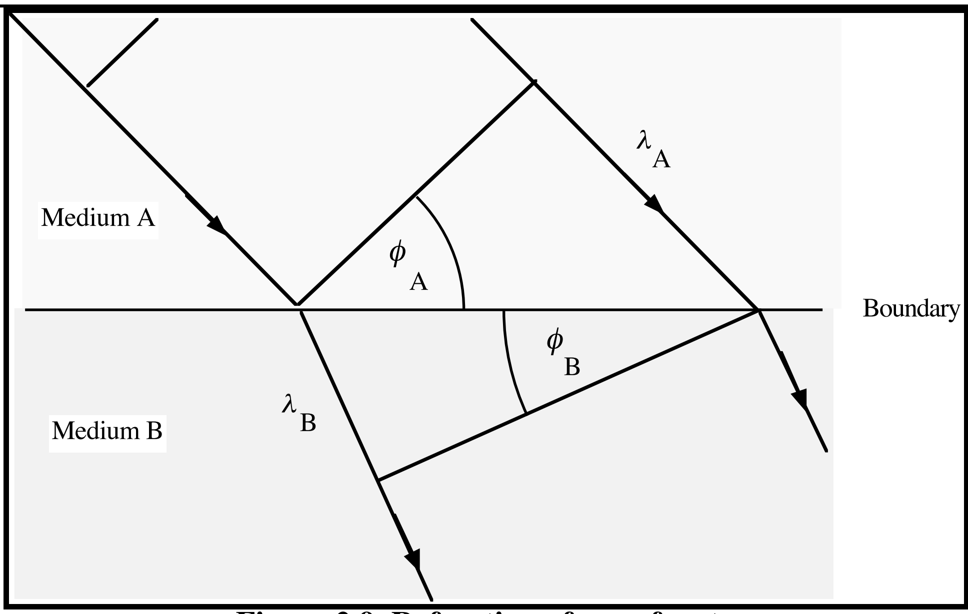


Figure 2.9. Refraction of wavefronts.

The diagram shows two consecutive wavefronts which are one wavelength apart. Since the frequency of the waves remains the same, no matter what medium they travel through, and since the wave speed is equal to the product of frequency and wavelength, the wavelength is proportional to the wave speed. Hence the wavelength in medium B is less than that in medium A. So as each wavefront crosses the boundary, it is pulled around to make a smaller angle with the boundary. Hence the rays of light, which are perpendicular to the wavefronts, must also bend as they enter the new medium.

This law of refraction was known from experiments long before the wave theory of light was invented. In its original form the law was expressed in terms of a property of the two materials called **refractive index** (symbol n) through the equation:

$$n_A\sin\phi_A = n_B\sin\phi_B . \qquad \text{... (2.2)}$$

Clearly, there must be some relation between the refractive index of a material and the speed of light in that material. The refractive index of a material can be defined the ratio of the speed of light in empty space (c) to the speed of light in the material (v):

$$n = \frac{c}{v} \qquad \text{... (2.3)}$$

This definition links the two forms of the refraction equation.

Notes

• The law of refraction expressed in terms of refractive index, $n_A \sin\phi_A = n_B \sin\phi_B$, is known as **Snell's law**.

• The symmetrical form of this equation, in which swapping the labels A and B makes no difference, indicates that the incident and refracted light paths are reversible - light can travel either way along the path defined by the incident and refracted rays. See figure 2.10, which (except for the reflected ray) is similar to figure 2.8 with the ray directions reversed.

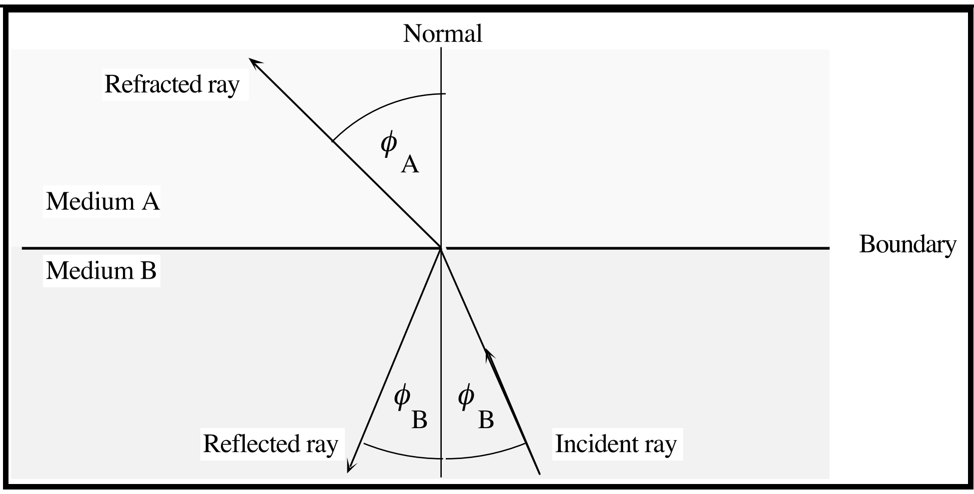


Figure 2.10. Refraction from a medium with high refractive index

• Light always travels slower in a material than it does in a vacuum. Consequently all values of refractive index are greater than one.

• The speed of light in a material depends on the chemical composition of the material, its physical state and also on the frequency of the light. The dependence of speed on frequency has some interesting consequences which we consider in §2-7 under the heading of dispersion. However for many practical applications it is good enough to use a single value of refractive index for each material. The following table shows some measured values of refractive index.

Material	Refractive index
air at STP	1.0003
ice	1.31
liquid water	1.33 to 1.34
olive oil	1.46
optical glasses	1.50 to 1.75
quartz	1.54 to 1.57
diamond	2.42

• You should remember that the speed of light in air differs from its speed in vacuum by less than 0.1%. Therefore in most calculations you can regard air and vacuum as having the same refractive index.

• The frequency of light does *not* depend on the medium.

• It follows that, since the product of wavelength and frequency is equal to the wave speed, the wavelength does depend on the medium. You can see that in figure 2.9.

2-5 REFLECTION AT A BOUNDARY BETWEEN TRANSPARENT MATERIALS

Specular reflection occurs every time light meets a smooth boundary at which the refractive index changes. The reflectivity depends on the refractive indices of the materials on either side of the boundary, the angle of incidence and the polarisation of the incident light. For a given pair of materials it also depends on which way the light goes through the boundary.

Consider first, the case where the incident light comes through the medium with lower refractive index, from air to glass for example. You can easily verify the dependence of reflectivity on angle of incidence by studying the intensity of reflections in a window as you change your angle of view from very small angles of incidence to **grazing incidence** (almost 90°). The reflectivity of glass in air is small for small angles of incidence and increases with increasing angle until it becomes almost 100% at grazing incidence.

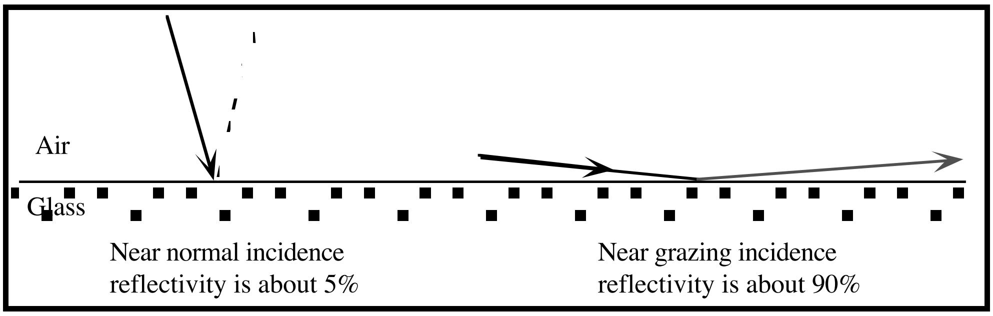


Figure 2.11. Effect of angle of incidence on the reflectivity of plain glass

If the refractive index decreases across the boundary, (e.g. from glass to air), then at small angles of incidence the reflectivity is again low. But this time as the angle of incidence increases the reflectivity reaches 100% well before grazing incidence. Complete reflection happens when the angle of incidence is greater than a value called the **critical angle**, denoted by ϕ_c in figure 2.12.

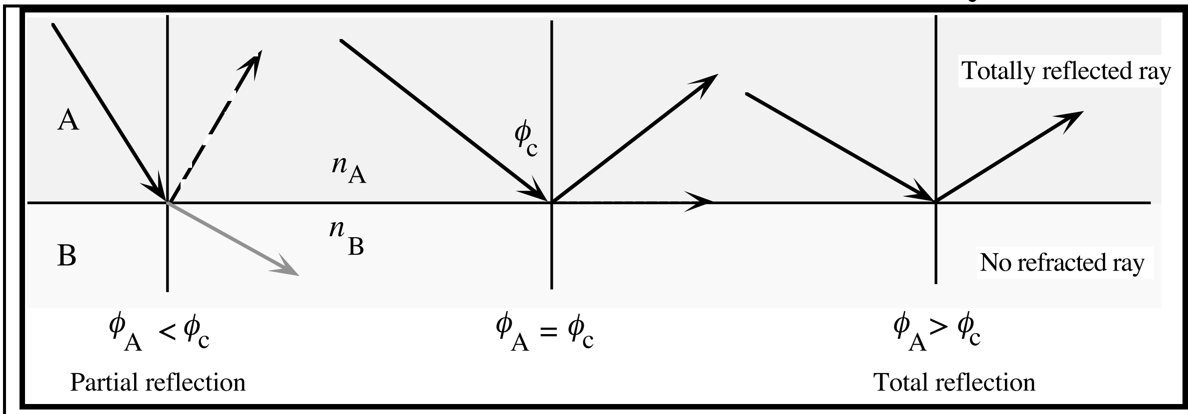


Figure 2.12. Reflection at a boundary where refractive index decreases

Beyond the critical angle all the incident light is reflected and there is no refracted ray, so the phenomenon is called **total internal reflection**. The relation between critical angle and the refractive indices of the two media can be found by inserting the maximum possible value for the angle of refraction, 90°, into Snell's law which gives

$$\sin\phi_c = \frac{n_B}{n_A} \qquad ...(2.4).$$

Remember that total internal reflection can occur only when light strikes a boundary where the refractive index decreases; reflection is back into the medium with the higher refractive index.

2-6 APPLICATIONS OF TOTAL INTERNAL REFLECTION

Prism reflectors

An ordinary glass mirror consists of a reflective metallic coating on the back of a sheet of glass but that is not the only way to make a mirror. Total internal reflection can be exploited to make a perfectly reflecting mirror using only glass, with no metal backing. Figure 2.13 shows how: light enters a prism perpendicular to the first surface so it is not refracted. When the light reaches the next face, the angle of incidence is greater than the critical angle so all the light is reflected. In this example, when the light gets to the third face of the prism it is refracted as it leaves the prism. That final refraction could be a problem because the refractive index is slightly different for different frequencies of light.

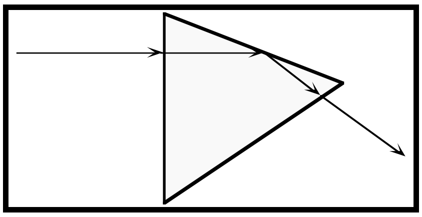


Figure 2.13. Total internal reflection in a prism

However if we use a right-angled prism and a suitable type of glass (figure 2.14) the light can be made to undergo two total reflections with no net refraction before it emerges in a direction which is always exactly opposite to that of the incident light. Such a device is often called a **corner reflector** or retroreflector. Retroreflecting beads are exploited in reflective road signs and "cat's eyes".

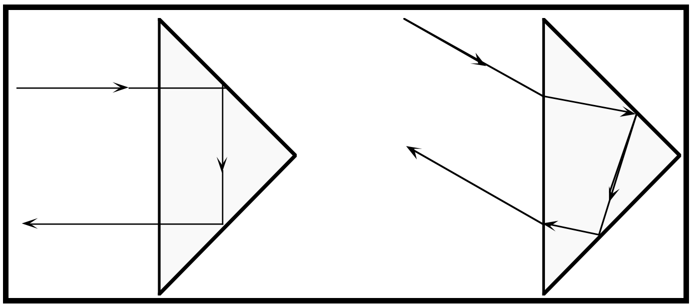


Figure 2.14. A corner reflector

The direction of a reflected ray is always reversed.

A pair of corner reflecting prisms can be used to displace a beam of light sideways without altering its direction of travel or to compress the path of a light beam into a small space. This arrangement, which is often used in binoculars, is an example of a device called an **optical relay** - a device which simply alters a light path without contributing to the formation of an image (see also chapter L7).

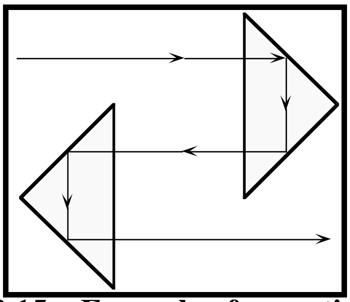


Figure 2.15. Example of an optical relay
In this example the path of the ray is displaced sideways but its final direction is unaltered.

Light pipes

Another important application of total internal reflection is the **optical fibre** or light pipe. Here a light ray enters one end of a transparent rod or fibre and is totally reflected many times, bouncing from side to side until it reaches the other end. This alone is not very useful, but what is important is that when the pipe is bent, the light path can be bent with it, staying within the pipe. The light pipe still works provided that each angle of incidence remains greater than the critical angle, so the light cannot get out until it reaches the flat end of the light pipe. Although there is a high contrast in refractive index between the material of the fibre and air, fibres often need to be coated with a protective medium which reduces the ratio of refractive indices and hence, also, the value of the critical angle. In order to make sure that the angles of incidence remain large enough, the fibre should not be bent too severely.

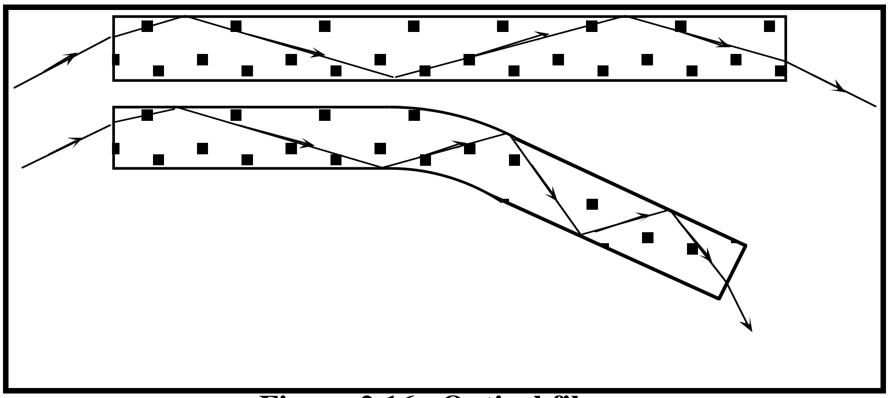


Figure 2.16. Optical fibres
Light is trapped in the fibre by total internal reflection - even when the fibre bends.

Optical fibres have many uses including data transmission, an alternative to sending electrical signals along conducting cables. The advantage of optical fibres here is that the capacity of the medium to carry information is vastly greater. Many different signals can be sent along the same fibre; in more technical terms, optical fibres have large bandwidths.

An important medical application is the fibre-optic **endoscope**, a device for transmitting images of inaccessible internal organs. A typical endoscope contains two bundles of optical fibres - one to carry light to illuminate the object and another bundle to transmit the image. The image is formed by a small lens attached to the end of a collection of thousands of individual fibres. Each fibre carries light from one part of the image, which can be viewed at the other end where the light emerges. In order to get a useful image at the output end, the fibres must be arranged in the same way that they were at the input end. Images seen this way are necessarily grainy, since the final image consists of a collection of light or dark coloured spots, one spot for each fibre.

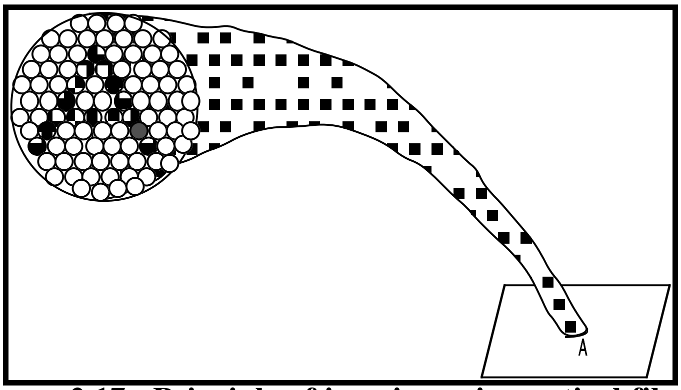


Figure 2.17. Principle of imaging using optical fibres
The resolution is limited by the diameter of each of the fibres.

2-7 DISPERSION

The dependence of refractive index (and wave speed) on the frequency of light produces some important effects which are often very useful and occasionally a nuisance, but nearly always pretty. The beautiful effects can be explained in terms of the notion that the perceived colours of light are related to the mixture of frequency components that the light contains.

The classic example is the production of a **spectrum** of many colours when ordinary white light passes through a prism of clear (colourless) material such as glass. Each ray of light which passes through the prism is refracted twice, once as it enters and again as it leaves. See figure 2.18. The amount of bending or refraction depends on the frequency of the light (as well as the nature of the glass). So white light, which can be described as a continuous distribution of many different frequency components, will bend by many different amounts; one ray of white light becomes a continuous collection of rays with a continuous range of frequencies. Only a few such rays can be shown in the diagram.

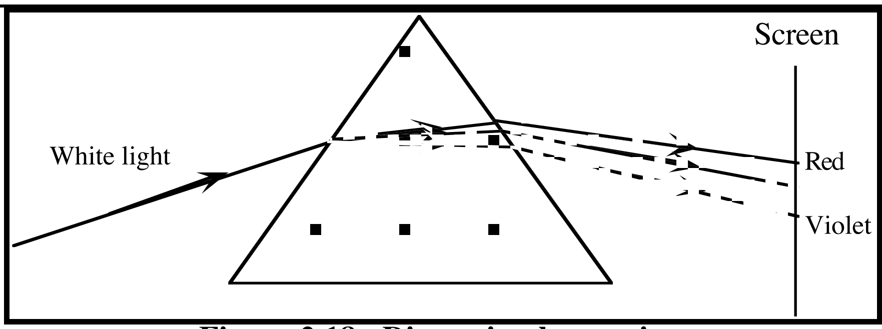


Figure 2.18. Dispersion by a prism
The angular separation between rays is exaggerated.

When a beam of white light is sent into a prism and the refracted light is allowed to strike a diffuse reflector such as a white card, a spectrum of light is formed on the screen. The colours of the spectrum range from red, corresponding to the light which is refracted least, through yellow, green and blue to violet which is refracted the most. Since we know from independent evidence that violet corresponds to high frequency radiation, we can conclude that the refractive index of glass is higher for higher frequency light. The relationship between frequency and refractive index is not, however, a simple linear one, see figure 2.19.

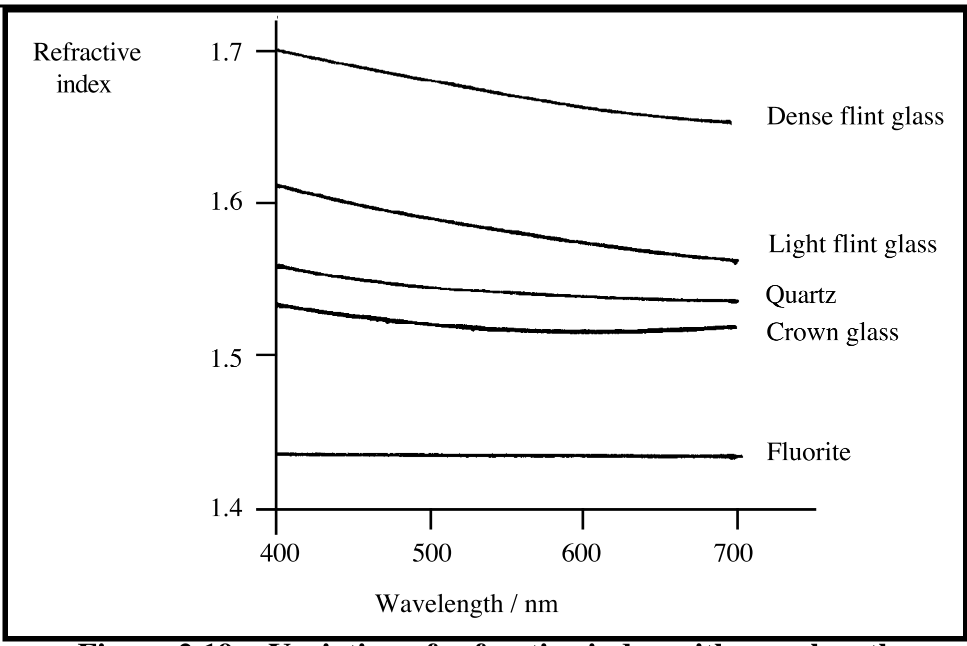


Figure 2.19. Variation of refractive index with wavelength

Since the frequency of light is not easily measured directly, it is traditional to specify properties like refractive index which vary with frequency in terms of the variation with the wavelength instead. (Wavelengths of light can be measured using interference and diffraction techniques described in chapters L4 and L5.) Values of wavelength used in such descriptions are always the wavelength in vacuum corresponding to $\lambda = c/f$. They do *not* refer to the actual wavelengths of the light in the glass.

Glass prisms are used in **spectroscopes** and **spectrographs -** instruments which disperse the spectrum of a light source into components with different frequencies. A simple arrangement is illustrated in figure 2.20.

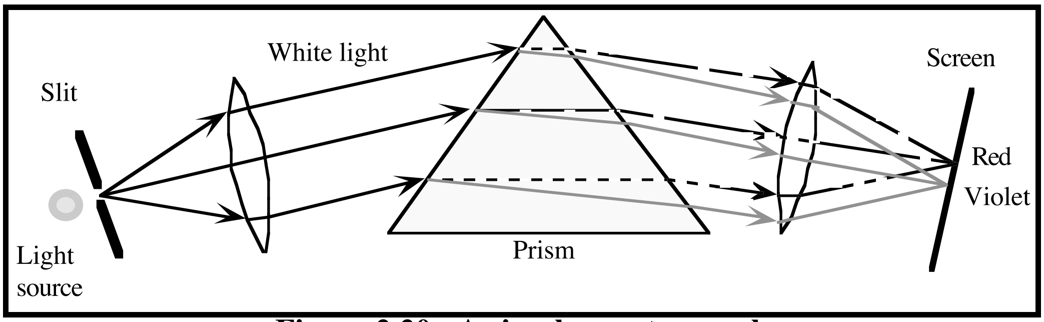


Figure 2.20. A simple spectrograph
Angular separations between rays are exaggerated.

Rainbows

The colours of the rainbow are formed by dispersion in small water droplets. A complete explanation involves some complicated ray tracing, but it is clear that whatever the light paths are, they are different for different frequencies. Figure 2.21 shows how dispersion in a raindrop produces a primary rainbow. (The primary rainbow is the brightest bow, sometimes the only one that you can see.)

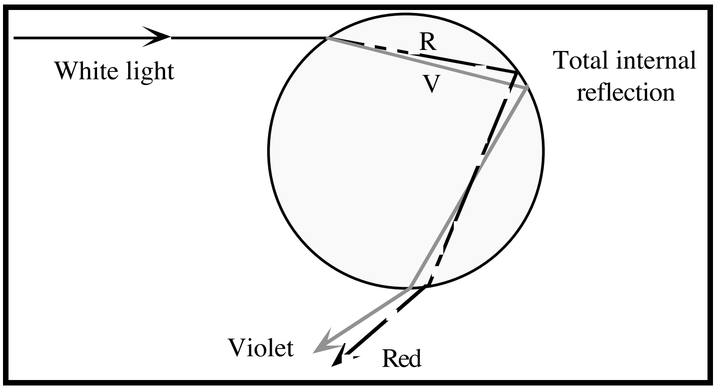


Figure 2.21. Dispersion in a water droplet

A ray of white light from the sun is refracted as it enters a spherical raindrop (figure 2.21) and dispersion occurs. The dispersed light rays are totally internally reflected and are then refracted again as they leave the drop. The dispersed rays which come out are now travelling in different directions, depending on their frequencies, so they appear to come from different parts of the sky. The angles between the incident rays from the sun and the rays from the rainbow are essentially fixed by the refracting properties of water and are on average about 138° for the primary rainbow. This fixed value for the scattering angle accounts for the shape of the rainbow.

2-8 MIRAGES

There are several kinds of mirage. Probably the commonest type is the illusion that light from distant objects is being reflected by a pool of water which is not really there. This kind of mirage is caused by refraction in a hot layer of air close to the ground. Although the refractive index of air is very close to 1.000, it is not exactly 1. Furthermore the refractive index of the air depends on its temperature. Light coming from the sky at an angle not much above the horizon travels into air whose refractive index gets less as the light gets closer to the ground. See figure 2.22. The variation in refractive index makes the light rays bend away from the ground so that eventually they will be totally internally reflected within the air and will travel upwards. You can see this effect most noticeably on a long horizontal bitumen road on a hot day. The black bitumen absorbs a good deal of the sunlight which hits it and it gets very hot. The road surface then heats the air immediately above it, the hottest air being closest to the road, so the refractive index is least near the hot road surface.

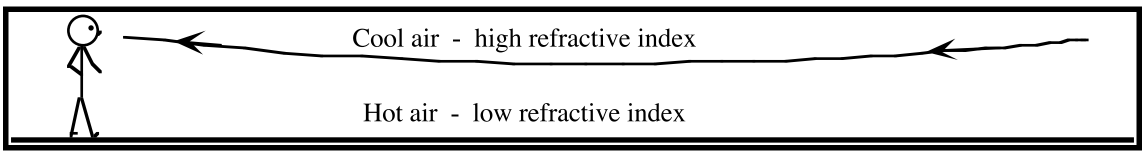
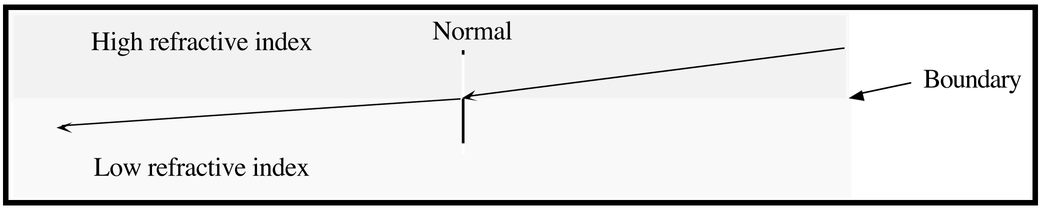
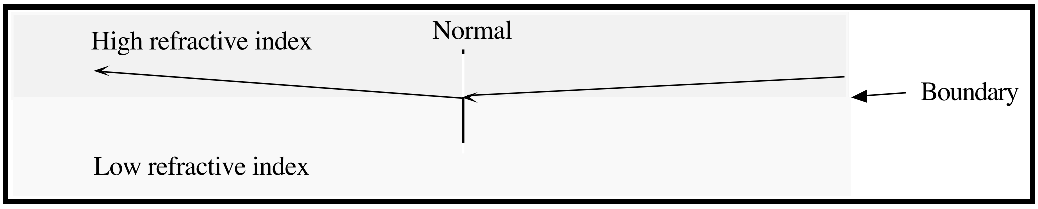


Figure 2.22. Path of a light ray in a common mirage

Although the variation in refractive index is continuous, the process can be understood in terms of many different layers with different refractive indices. Imagine a ray coming to the boundary between two such layers, as in figure 2.23. If the ray is close to horizontal it has a large angle of incidence, so when it goes into the hot air of lower refractive index the angle of refraction is even larger. In the lower part of figure 2.23 an incident ray meets a boundary at an angle greater than the critical angle so it is totally reflected. Then as the ray continues back up through the air the refraction process is reversed and the angle to the horizontal gets larger. A person seeing the refracted light perceives that it is coming up from the ground, but it looks like light from the sky, or some object near the horizon, creating the illusion that the light has been reflected by a pool of water.



Light which is almost horizontal is refracted to be even closer to the horizontal.



When the light is almost horizontal it gets totally reflected.

Figure 2.23. Refraction and total internal reflection in a mirage

Other kinds of mirage are more complex than this but all can be explained in terms of variations in the refractive index of the atmosphere.

2-9 IMAGES

We see things by the light that comes from them into our eyes. Although the process of seeing is a complex one involving both eye and brain, some aspects of seeing can be discussed in terms of ray optics. When you see an object your eye collects light from all over the object. Light rays go out in all directions from each point on the surface of the object, but only some of those rays enter the eye and those that do are contained within a cone. The angle of that diverging cone of rays depends on the distance from the object point to the eye - the further away the object, the smaller is the angle. Although the eye-brain system does not respond directly to that angle, or the degree of divergence of the rays, it does produce perceptions of depth by much more complex mechanisms. We can, however, model or calculate the apparent distances of object points from an eye by considering the diverging cone of rays from each object point to the eye.

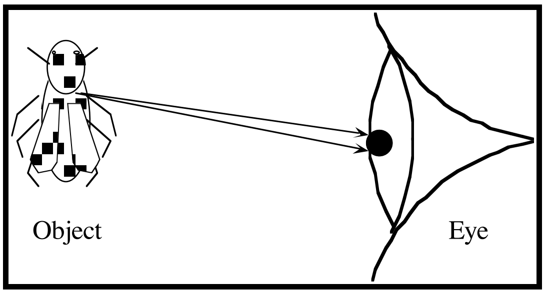


Figure 2.24. Seeing an object
The direction and the divergence of the rays indicate the perceived position of the object point.

The apparent location of an object point can be found by considering rays from the same object point arriving at the eye from different directions. Those rays can be extended back until they meet, in order to find out where they appear to come from. The point where they meet is called an **image point**. When there is no refraction or reflection of the light rays as they travel from the object to the eye, through still air for example, the positions of the object and its image coincide. However if the light is reflected or refracted on its way to the eye, then object and image are in different places.

Specular reflection by a plane mirror

Although many rays of light are involved, the image point corresponding to each object point can be found using any two rays. All other rays from the same object point will, after reflection, appear to come from the same image point. The diagram shows how two rays coming from an object point are reflected in a plane mirror.

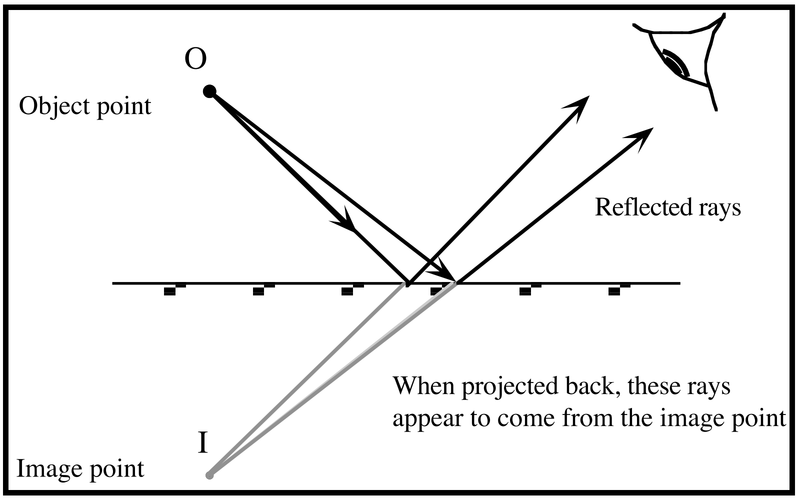


Figure 2.25. Reflection in a plane mirror

When the reflected rays are projected back behind the mirror, they appear to diverge from an image point I which is as far behind the mirror as the object point O is in front. Note that in this and other diagrams the actual rays of light are drawn in black while their projections back into places where the light does not really go (or come from) are shown in grey. Since the light does not actually come from the image in this case, it is called a **virtual image**. This method of locating the image by following the paths of different rays is called **ray tracing**.

Images affected by refraction

Objects located inside a refracting medium, such as water, seem to be in the wrong place and they also look distorted. You can easily observe that by putting an object in a dish of water. The diagram shows how light rays coming from an object point under water are bent as they leave the water so that they seem to be coming from an image point which is not at the position of the object. In this example the image of one object point is actually somewhat spread out - the cone of rays no longer diverges from a unique point after refraction. Since the eye collects only a very narrow cone of rays, the spreading out effect is not noticeable if you keep your eye in one place. But if you move your head, you will see the image move! Contrast that with normal viewing in which the brain perceives that fixed objects stay put when you move your head.

Other examples of virtual images formed by refraction at plane boundaries include the apparent bending of straight objects placed partly underwater and the pair of images of one object seen through adjacent sides of a fish tank.

For more about images see chapter L3.

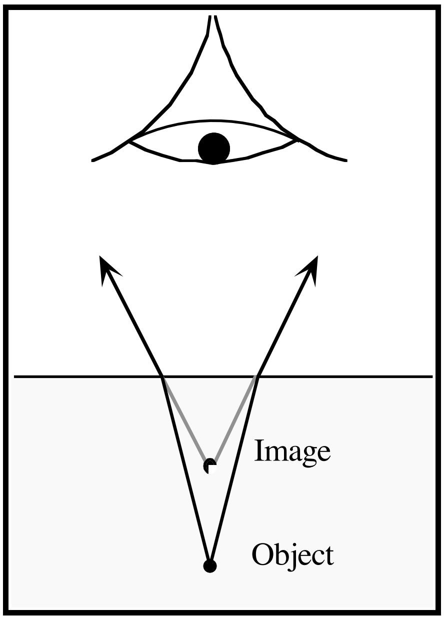


Figure 2.26. Viewing an object under water

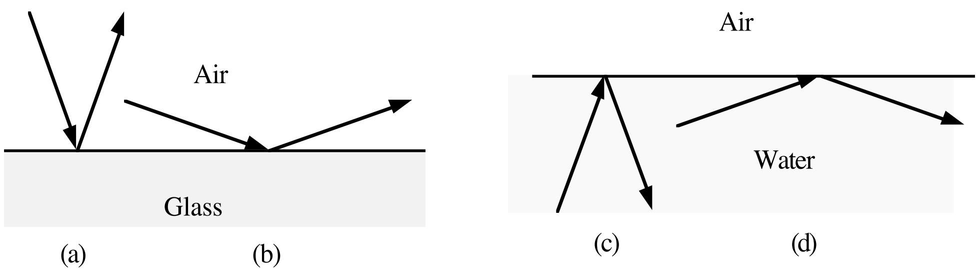
The angular width of the cone of rays is exaggerated. Only a small cone of light enters the eye.

QUESTIONS

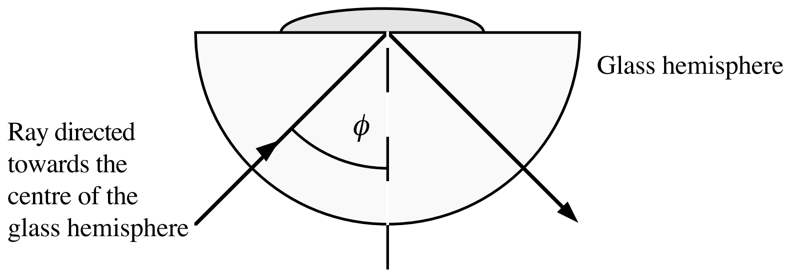
The following questions do not have answers that have to be learned. They are designed to help you to think about the relevance and applications of principles covered in this chapter.

Q2.1 In the corner reflector of figure 2.14, the angles of the prism are 90°, 45° and 45°. What can you say about the refractive index?

Q2.2 Look at the diagrams below and in each case, determine whether little, almost all, or all of the incident light is reflected.



Q2.3 The refractive index of small quantities of liquid can be measured by finding the critical angle of reflection.

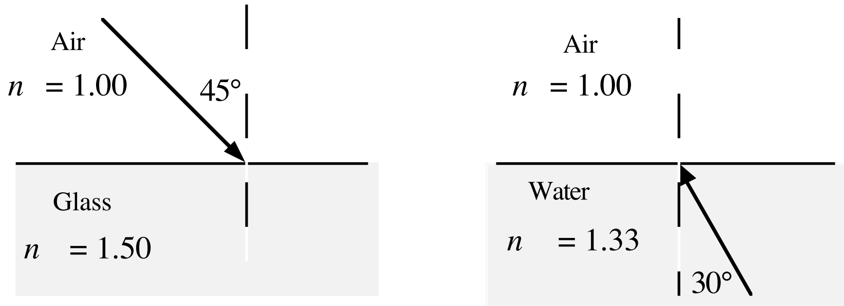


Total internal reflection takes place for all angles of incidence ϕ greater than the critical angle. The critical angle with a drop of liquid present is 59°. The refractive index of the glass is 1.56. Calculate the refractive index of the liquid.

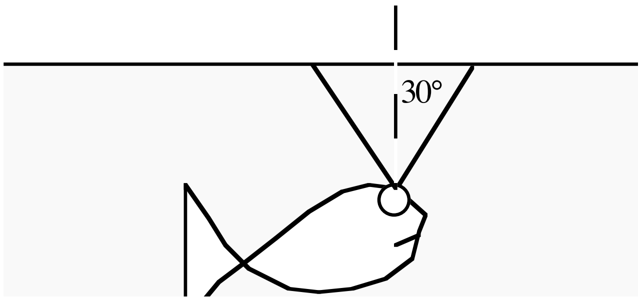
Over what range of values of the refractive index of the liquid can this method be used?

Q2.4 Recently, in one year, eight people in N.S.W. suffered severe spinal injuries caused by diving into shallow water and landing on their heads. In some cases the water was clear and the bottom of the pool was plainly visible. Why is it surprising that people should make that mistake?

Q2.5 Calculate the angle between the refracted ray and the normal and sketch the path of the refracted ray in the two examples below.



Q2.6 A fish views the outside world through a water-air boundary so its view is distorted. Suppose the fish's eye has a field of view in water which is a cone of half angle 30°. When the fish looks straight out of the water how much of the outside does it see? What would the fish see if its field of view in water were a cone of half angle 50°?



Q2.7 Refer to the graph of refractive index as a function of wavelength for various materials (figure 2.19). Which would give a more spread-out spectrum, a prism of dense flint glass or a prism of crown glass?

Q2.8 A book quotes the refractive index of an optical glass as 1.48626 at a wavelength of 587.6 nm. What is the frequency of the light used? What is its actual wavelength in the glass?

Discussion questions

Q2.9 When you look at reflections in a sheet of glass, you can often see a double image. Why?

Q2.10 When you look over the top of hot object, such as a bitumen road on a summer's day, the view of things beyond seems to wobble or shimmer. Explain.

Q2.11 Do you think that sound waves should obey the same laws of reflection and refraction as light waves?

Q2.12 Can you invent an experiment to measure the wavelength of light using specular reflection? Could you do it with refraction?

Q2.13 Can total internal reflection occur when light travels through water to a boundary with glass? How would you specify the kind of material where total reflection of light travelling through water can occur?

Q2.14 Does the value of critical angle for a given pair of materials depend on the frequency of light? Does total internal reflection cause dispersion? Can there be any dispersion in light which has been totally internally reflected?

Q2.15 The usual way to make a spectrum using a slab of glass is to make a prism in which there is an angle (not zero) between the faces where the light goes in and out. Does that mean that you can't get a spectrum from a piece of glass with parallel faces (zero angle) like a window pane? What is the advantage of having the two faces at an angle?

Q2.16 Making a spectrum by just putting a prism into the path of some white light doesn't give the best results. What else should you do to make a really nice spectrum?

FURTHER READING

Katzir, Abraham; **Optical Fibers in Medicine**, *Scientific American,* May 1989, 86 - 91.

Fraser, A.B. & W.H. Mach, **Mirages**, *Scientific American,* January 1976, 102 - 111.

Walker, Jearl, **The Amateur Scientist, How to create and observe a dozen rainbows ...**, *Scientific American,* July 1977, 138 - 144.

Walker, Jearl, **The Amateur Scientist, Mysteries of rainbows ...**, *Scientific American,* June 1980, 147 - 152.