REFRACTION

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WHAT IS REFRACTION?

When a ray of light in air is incident on the surface of a transparent medium such as glass, some of it is reflected, whilst the remainder is transmitted. The larger the angle of incidence is, the larger the amount of light that is reflected.

No medium is perfectly transparent and some absorption of light always occurs, the energy being converted to heat. This latter effect will be ignored. The direction of the ray inside the medium is different to that of the incident ray unless the incident ray is normal (perpendicular) to the surface. The transmitted ray is bent as it crosses the surface between one medium and another. This *change of direction* of the ray at the surface is called *refraction.*

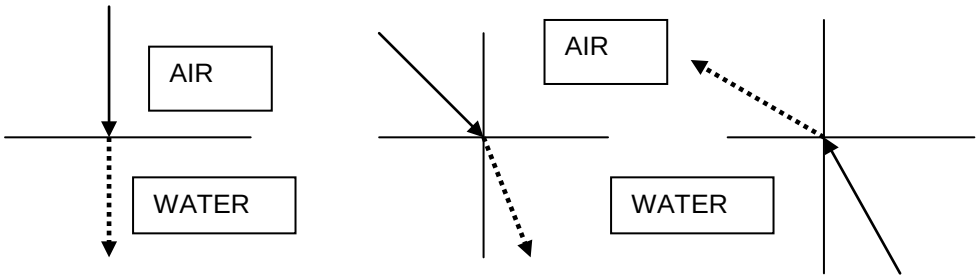


Figure 3.1: *Refraction at the air/water and water/air interfaces*

The preceding diagrams show several important aspects of refraction. When a light beam goes from air into water **along the normal** to the surface between them, it simply continues along the same path.

When it enters the water (an **optically more dense medium**) at any other angle, it is bent **towards the normal**.

The paths are reversible; thus a light beam emerging from the water (into the **optically less dense** air) is bent **away from the normal** as it enters the air. This effect gives rise to the phenomenon of the apparent depths of objects.

REFRACTING MATERIALS

Common refracting materials are glass, (in particular high-grade optical quality glass), quartz, and a variety of plastics. These have been chosen not only for their effect on the direction of light rays passing through them, but also for their transparency, homogeneity, and their resistance to atmospheric corrosion. Optical glass is commonly used in the manufacture of prisms and lenses. Two main types of optical glass are available: these are crown and flint. The former is a compound of silica (sand, SiO_2) and salts of sodium and potassium. In addition, small quantities of other materials such as barium and zinc oxides may be present. Flint glasses, in addition to the constituents above, contain oxides of lead and are denser than crown glasses.

Certain plastics materials are now increasingly being used for ophthalmic lenses. In this category is the **thermosetting** material allyl diglycol carbonate, commonly known as CR-39 (the CR standing for Columbia Resin). These plastics start as linear polymer chains that get cross-linked permanently during molding. Therefore **they cannot be remolded**.

Polyethylene, polystyrene, polyvinyl chloride and polytetrafluoroethylene (PTFE) are examples of **thermoplastic** materials. These plastics do not undergo any chemical change during the molding process and **can** therefore **be remolded** several times without changing their properties.

THE REFRACTIVE INDEX

Refraction occurs because light travels at different speeds in different media. We have previously noted that the speed of light in vacuum, c, equals 3 x 10^8 m/s, which is the maximum speed at which light travels. (We will assume that the light travels with the same speed in air.)

In a material medium, the speed of the light, v, is less. The ratio of these speeds is the *refractive index* (n) of the medium.

$$n = \frac{c}{v}$$

Since v is never greater than c, the index of refraction (which is a dimensionless number) is never less than 1. The index of refraction is sometimes called a measure of the optical density of the material. Materials with larger indices of refraction are said to be *optically denser*. The previous statements about the direction in which light rays are bent in passing into a different medium can now be restated in terms of optical density.

In order to account for the light slowing down as it does, consider the accompanying figure which represents a beam of light entering a piece of glass from the left. Once inside the glass, the light may encounter an electron bound to an atom, indicated as point ***A*** in the figure. Let us assume that light is absorbed by the atom, which causes the electron to oscillate. The oscillating electron then acts as an antenna and radiates the beam of light toward an atom at point ***B,*** where the light is again absorbed by an atom at that point.

(We need not consider the details of these absorptions and emissions.) For now, it is sufficient to think of the process as one in which the light passes from one atom to another through the glass. (The situation is somewhat analogous to a relay race in which a baton is passed between runners on the same team.)

Although light travels from one atom to another with a speed of 3 x 10^8m/s, the processes of absorption and emission of light by the atoms take time. Enough time is required, in fact, to lower the speed of the light in the medium. Once the light emerges into the air again, the absorptions and the emissions cease and its speed returns to the original value.

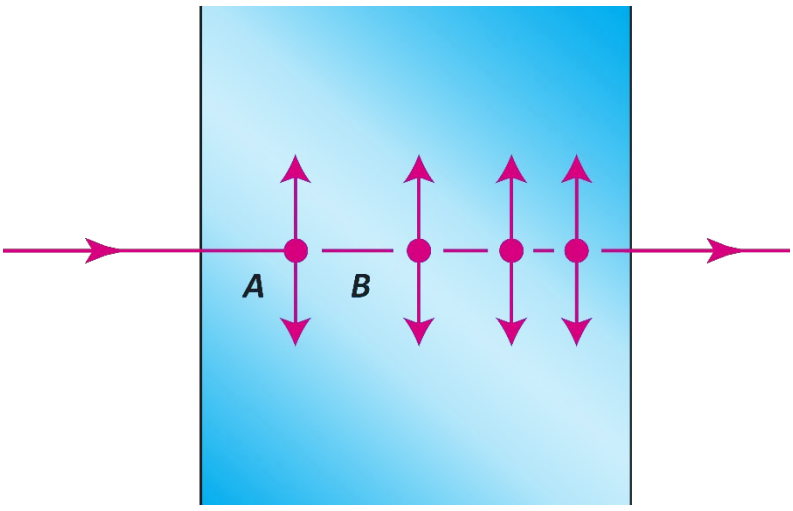


Figure 3.2: *A beam of light entering a piece of glass*

The **frequency** of a light wave is determined by its source and is **unaffected by the medium**. Therefore, since the speed decreases in the medium, the wavelength must also decrease.

In air the light has wavelength λ_{air} and moves at speed c. When it passes into a new medium with refractive index n, its wavelength is λ_n and it moves with speed v. Using the definition of refractive index, we can derive the relationship:

$$\lambda_n = \frac{\lambda_{air}}{n}$$

Summary:

	AIR	OTHER MEDIUM
Refractive Index	1	n
Speed of Light	$c = 3 \times 10^8$ m/s	$v = \frac{c}{n}$
Frequency	$f_{air} = \frac{c}{\lambda_{air}}$	$f_n = \frac{v}{\lambda_n} = f_{air}$
Energy	$E_{air} = hf_{air}$	$E_n = E_{air}$
Wavelength	λ_{air}	$\lambda_n = \frac{\lambda_{air}}{n}$

Table 3.1: *Summary of parameters changing and not changing in a change of medium*

THE REFRACTIVE INDEX VARIES WITH WAVELENGTH

As we have seen in Chapter 1, the index varies with the wavelength of the light (approximately 1 to 2% for the range of visible light.) The range of refractive indices in glass can be seen below in table 3.2

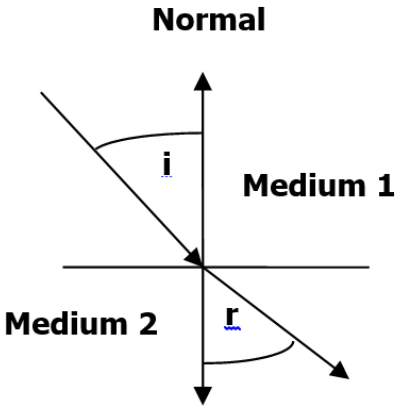
color	Wavelength (nm)	n
Red	660	1.520
orange	610	1.522
yellow	580	1.523
green	550	1.526
blue	470	1.531
violet	410	1.538

Table 3.2: *The refractive index of spectacle crown glass varies with the wavelength of the light*

REFRACTION AT PLANE SURFACES

The following figure shows an incident ray of light being refracted at the plane boundary between two media such as air and glass. **i** is the angle of incidence and **r** is the angle of refraction. Note that both angles are measured between the normal and the appropriate ray.

As mentioned at the start of this chapter, there is also a weak reflected ray that becomes more pronounced as i increases.



Experimental measurements of refraction at a plane surface were made as long ago as the second century A.D. by Ptolemy and others, but no relationship between the angles of incidence and refraction was discovered. Law 1 below was formulated in the 10th Century (Ibn Sahl) and it was not until 1621 that Willebrord Snell, professor of mathematics at the University of Leiden, finally deduced the relationship between the angles of refraction and incidence for various pairs of media. Snell's work was however not published during his lifetime. These laws were first published (1637) by René Descartes who had discovered them independently. This is given below as Law 2.

The laws of refraction can be stated as follows:

Law 1. The incident ray and the refracted ray lie in one plane which is normal to the refracting surface at the point of refraction.

Law 2. Snell's law (or Snell-Descartes laws) states that the ratio of the sines of the angles of incidence and refraction is equivalent to the opposite ratio of the indices of refraction.

$$n_1 \sin i = n_2 \sin r$$

n_1 refers to the medium from which the light is traveling and n_2 refers to the medium the light is entering.

This expression applies strictly only to isotropic media (those where the optical properties do not vary in different directions through the medium) and for light of a single colour (monochromatic light).

REAL AND APPARENT DEPTH

We often see refraction effects when we look at light coming from objects after it passes through a glass of water, for example. We also see the effects when we view objects partially submerged in water. The accompanying figure shows that our optical system can be deceived by refraction effects. Indeed, a fish underwater is not located where our optical system tells us. The figure shows the cone of light leaving a point on the fish that will eventually enter the eye. It is bent away from the normal at the surface and appears to the eye to be diverging from a point displaced both to the right and not quite so deep as the real point. We say we see an image of the fish. As in the case of a mirror, the light is not really diverging from the point our eye tells us it is.

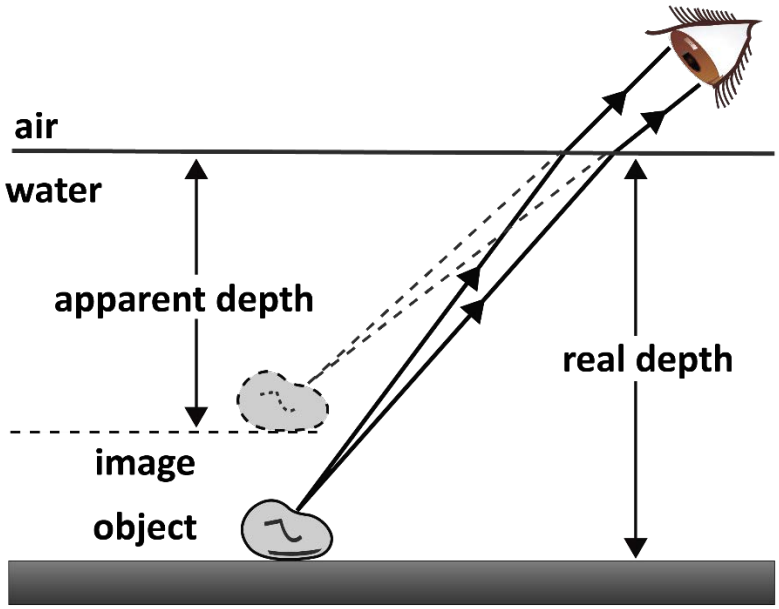


Figure 3.3: *Actual depth and apparent depth*

The perceived depth is referred to as the apparent depth (**h'**) and the actual depth (**h**) as the real depth. It can be shown that these distances are related by:

$$h = nh'$$

The image must then be displaced a distance (**h-h'**) away from the object. It follows from the above relationship that the ratio of real depth to apparent depth is equal to the refractive index of the medium:

$$n = h/h'$$

TOTAL INTERNAL REFLECTION

When light originates in an optically denser medium, the angle of refraction is larger than the angle of incidence. This gives rise to a very interesting and useful phenomenon. Consider the rays in figure 3.4. One can see that the rays striking the surface at larger and larger angles of incidence are refracted more and more until the refracted ray barely skims the surface of the water. This is in accordance with Snell's law. At some angle of incidence, the angle of refraction will be 90°. The incident angle for which this happens is called the **critical angle** (θ_c).

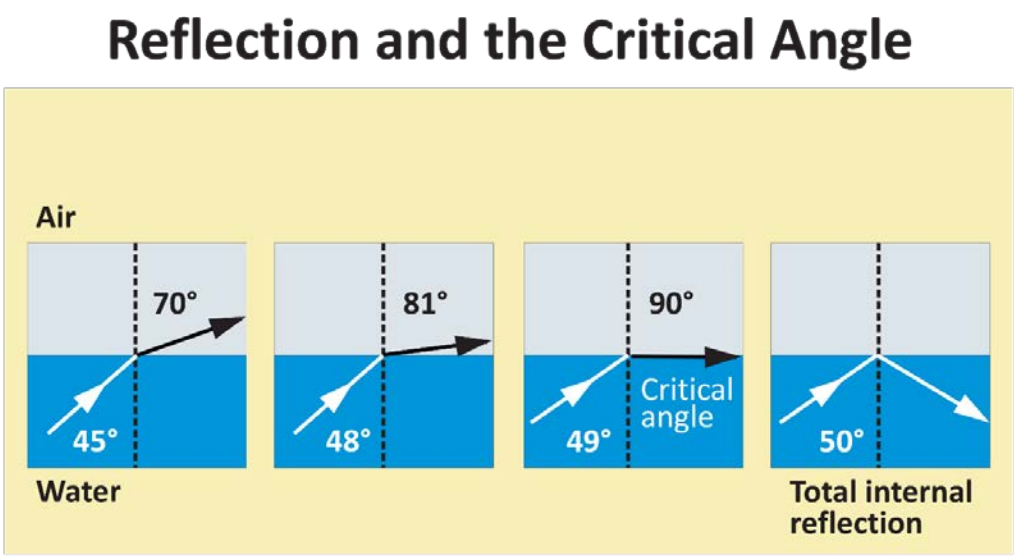


Figure 3.4: *Rays at the Water/Air interface with varying incident angle.*

Note that this happens only when light moves from an optically denser medium to an optically less dense one.

What happens if light is incident on a boundary at an angle greater than the critical angle? The answer is that the light is completely reflected at the interface, remains in the original material, and none is transmitted. This is called **total internal reflection.** As previously stated, some light is reflected at each boundary between media. For small angles of incidence, this is only a small percentage. As the angle of incidence gets larger and larger, a bigger percentage of the incident light is reflected. Beyond the critical angle, 100 percent of the incident light is reflected.

Because of total internal reflection, when one is under water, one sees only the reflection off the undersurface of the water when looking in a direction greater than the critical angle.

USES OF TOTAL INTERNAL REFLECTION

The sharpness and brightness of a light beam are better preserved by total internal reflection than by reflection from an ordinary mirror. Accordingly, many optical instruments, such as binoculars, use the former rather than the latter whenever light is to be changed in direction.

The advantage is that very nearly 100 percent of the light is reflected, whereas even the best mirrors reflect somewhat less than 100 percent. Thus the image is brighter. For glass with n = 1.50, the critical angle is 41.8°. Therefore, 45°prisms will reflect all the light internally.

As illustrated below, totally reflecting prisms are also used for other purposes:

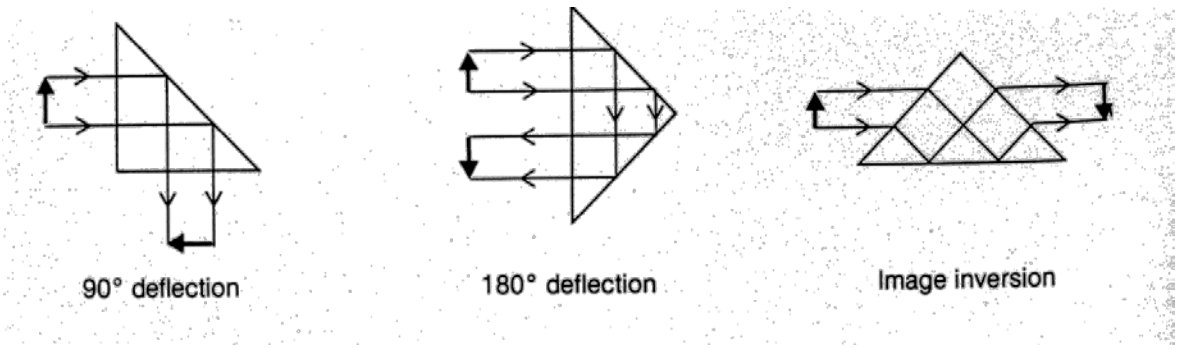


Figure 3.5: *Deflection and inversion in totally reflecting prisms*

Total internal reflection is the principle behind **fibre optics.** Glass and plastic fibres can now be made as thin as a few micrometers in diameter. A bundle of such tiny fibres is called a **light pipe,** and light can be transmitted along it with almost no loss because of total internal reflection. Even if the light pipe is bent into a complicated shape, the critical angle still won't (usually) be exceeded, so light is transmitted practically undiminished to the other end.

Light pipes can be used to illuminate difficult places to reach, such as inside the human body. They can be used to transmit telephone calls and other communication signals (90% of long distance communications go through fibre optics); the signal is a modulated light beam (a light beam of varying intensity) and is transmitted with less loss than an electrical signal in a copper wire. One sophisticated use of fibre optics, particularly in medicine, is to transmit a clear picture.

For example, a patient's stomach can be examined by inserting a light pipe through the mouth. Light is sent down one set of fibres to illuminate the stomach. The reflected light returns up another set of fibres. Light directly in front of each fibre travels up that fibre. At the opposite end, a viewer sees a series of bright and dark spots, much like a TV screen; that is, a picture of what lies at the opposite end. The fibres must be optically insulated from one another, usually by a thin coating of material whose refractive index is less than that of the fibre. The fibres must be arranged precisely parallel to one another if the picture is to be clear. The more fibres there are and the smaller they are the more detailed the picture. Such an "endoscope" is useful for observing the stomach or other hard-to-reach places for surgery or searching for lesions without surgery.

WHITE LIGHT IS POLYCHROMATIC

Ordinary white light, such as that from the sun, is actually polychromatic: it consists of a number of colours / wavelengths. This idea of the compound nature of white light was first demonstrated by the German astronomer Kepler. It was more thoroughly investigated by Sir Isaac Newton in a series of experiments described below.

In Newton's first experiment, the sun's light, entering the room through a small hole in a window shutter, was allowed to fall onto a triangular glass prism. The refracted light was seen on the opposite wall. Instead of the incident white light, a coloured band of light was seen.

The spectrum obtained contained all the colours of the rainbow. In addition, they were in the same order as in the rainbow. It should be noted, however, that the colours showed a good deal of overlap and the designation of the colours as red, orange, yellow, green, blue, indigo and violet could not be sharply separated.

Newton concluded that the white sunlight was actually of a composite nature containing the various colours seen. To check his conclusion about the composite nature of white light, Newton attempted to recombine the coloured light by allowing it to fall onto (a) a second prism identical to the first (but inverted) and (b) a converging lens.

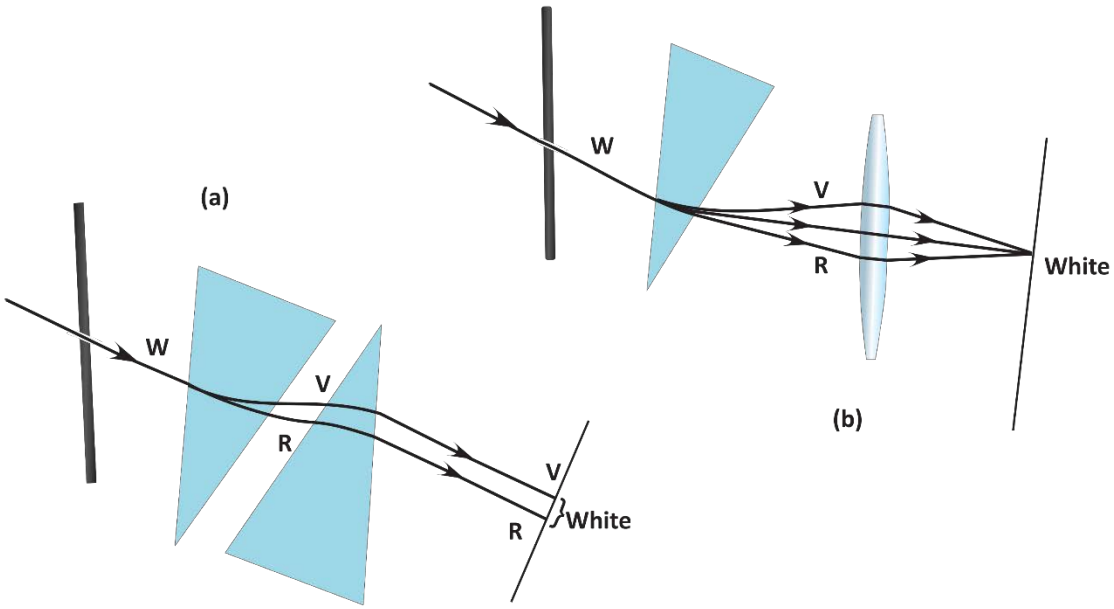


Figure 3.6: *Newton's experiment to recombine colours*

In each of these cases the light was recombined into white light, similar to the original sunlight. This confirmed that the white light was indeed polychromatic.

Newton now arranged for each of the colours in the spectrum to pass through a second prism, one at a time, by placing a slit in the appropriate position.

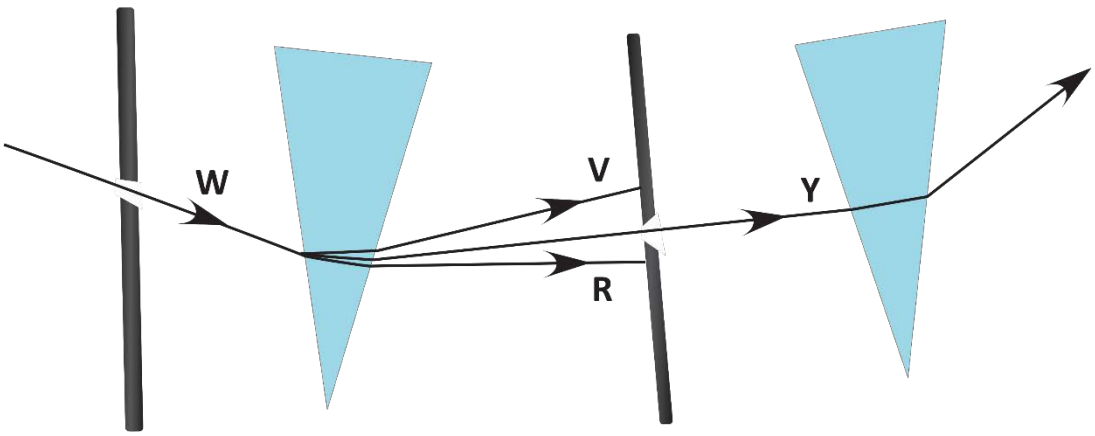


Figure 3.7: *Newton's experiment to separate colours*

In addition to making quantitative measurements of the deviations of the separate colours, he was able to show that no further dispersion was caused by the second prism. Newton concluded that the coloured lights were contained in the original white light, and it was not the prism which was introducing the colours. They appeared because of their differing deviations through the prism.

The following figure shows the imperfect separation of colours Newton achieved.

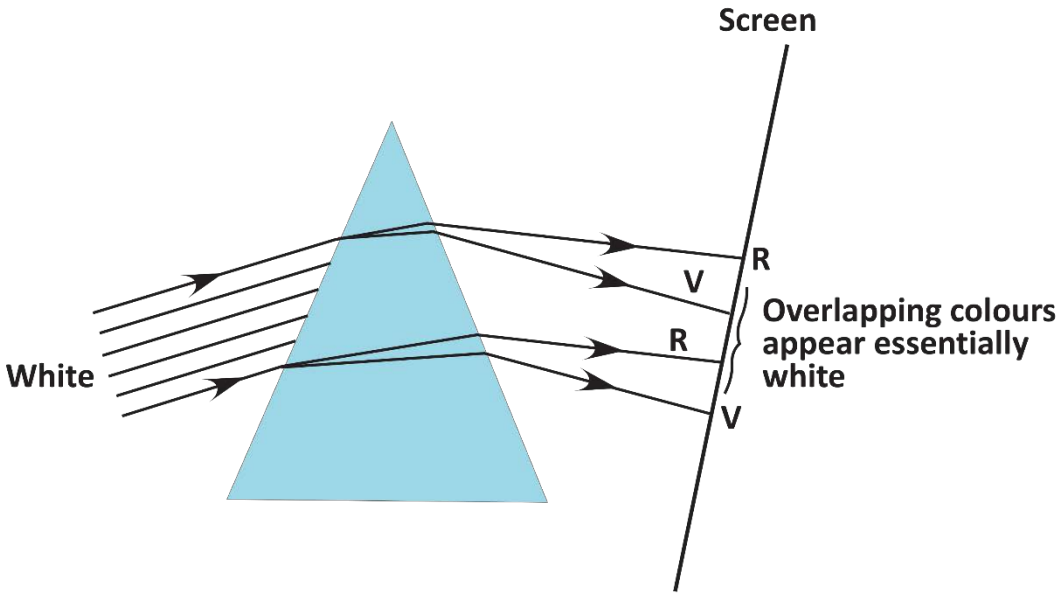


Figure 3.8: *Imperfect separation of colours*

Only the red and violet emergent pencils from rays at the margin of the incident pencil have been drawn, and it can be seen that there will be considerable overlapping of the different coloured images on the screen. This spectrum of overlapping colours is called an **impure spectrum** as the only colour effects are near the edges. Most of Newton's spectra were impure.

DISPERSION

The splitting of white light into its various coloured components is an effect referred to as **dispersion**. It is a result of the fact that the different colours travel with different velocities in a transparent medium such as glass. (The speed of light in air is almost independent of colour.) For example, blue light travels slower than red light in glass. Thus, blue light is associated to a higher refractive index and is refracted to a larger extent than red light. (This is famously illustrated on Pink Floyd's Dark Side of the Moon album).

We have seen that dispersion occurs in a transparent medium because the refractive index of the medium varies with the colour of the light. This follows from Snell's Law, since n is a function of wavelength. Therefore, light of different wavelengths will be bent at different angles. Manufacturers of optical glass, from which lenses and prisms are made, supply data regarding the dispersive characteristics of these materials. Single lenses and, of course, single prisms exhibit dispersion, and it is possible to construct composite prisms for which dispersion effects are negligible.
A single ray of light incident on a prism emerges bent away from its original direction of travel by an angle δ, called the angle of deviation. The deviation experienced by a particular colour is expressed as the angle between the undeviated ray and the ray of that colour emerging from the prism. Newton showed that each colour had a particular angle of deviation, the largest being for violet and the smallest for red light.

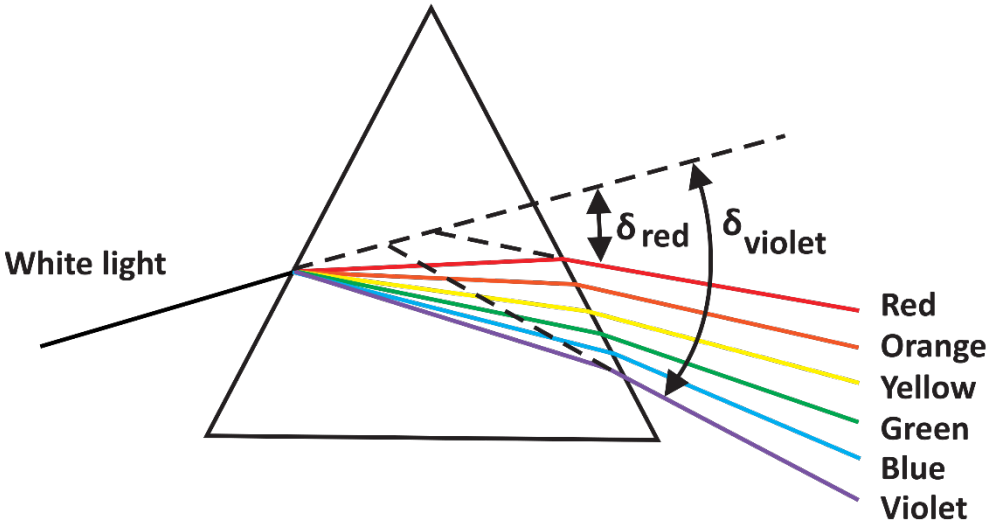


Figure 3.9; *Angle of deviation for each colour*

In the next figure, a ray of white light is incident on one face of a triangular prism. The angle between the red and blue rays emerging from the prism is called the **angular dispersion**, or sometimes simply the **dispersion**, of the prism. It is denoted by the symbol α.

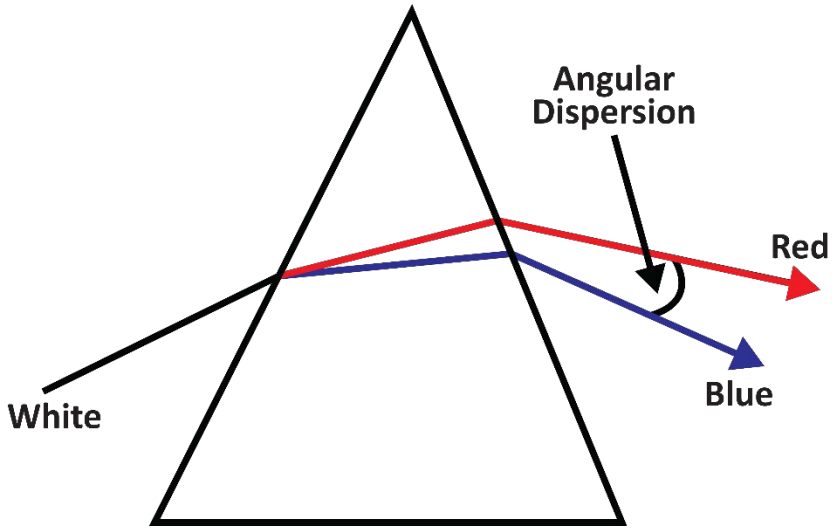


Figure 3.10: *Representation of angular dispersion*

It is convenient to consider also the deviation of a yellow colour of light, which is near the middle of the spectrum. For this reason the yellow ray is called the **mean ray**, and its deviation is referred to as the **mean deviation**.

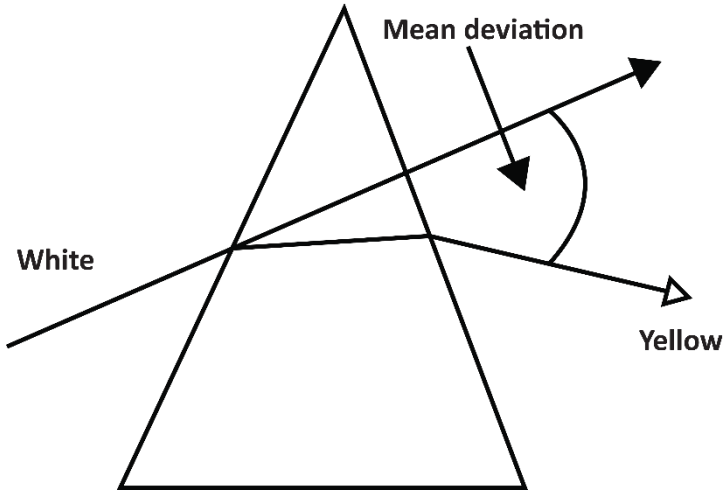


Figure 3.11: *Mean deviation in a given prism*

For the exact definitions of the dispersive properties of optical materials, three precisely specified colours of light are used. These three colours are:

(a) In the red region of the spectrum: the specific red light wavelength in the spectrum of a cadmium vapour lamp, called the C line, having a wavelength of 643.8 nm.

(b) In the yellow region of the spectrum: the specific yellow light wavelength in the spectrum of a helium lamp, called the d line, having a wavelength of 587.6 nm.

(c) In the blue region of the spectrum: the specific blue light wavelength in the spectrum of a cadmium vapour lamp, called the F line, having a wavelength of 480.0 nm.

The refractive indices of substances for these three precise colours are denoted by n_C, n_d, and n_F respectively. In particular, n_d is called the **mean refractive index** of a substance, and is the value understood by the term refractive index unless otherwise stated.

The **angle of dispersion**, or **angular dispersion**, α, is defined as the angle between the direction of the C (red) and F (blue) rays in the emergent pencil. The value of α, which depends on the angle of incidence of the polychromatic light, is a measure of the chromatic effect of the prism. It is often referred to as the **chromatic aberration** of the prism.

The **dispersive power**, ω, of a refracting substance is the angle of dispersion relative to the deviation of the mean (d) ray: that is, by definition,

$$\textbf{dispersive power } \omega = \frac{\textbf{angle of dispersion}}{\textbf{mean deviation}}$$

If a small angled (thin) prism of material is considered, the relationship between the dispersive power of the material and the refractive indices for the three standard wavelengths may be deduced.

THE FOLLOWING DERIVATION IS NOT FOR EXAMINATION PURPOSES.

Recall that the deviation of a particular ray of light, by a small angled prism in air, is given by:

$$d = (n-1)a$$

where n is the refractive index of the prism, a is the apical angle, and d is the deviation which is independent of the angle of incidence if the latter is small (less than 10°).

Hence, for the F (blue) ray the deviation is

$$d_F = (n_F - 1)a$$

and for the C (red) ray the deviation is

$$d_C = (n_C - 1)a$$

Since α is the angle between these two rays in the emergent pencil, α is given by

$$\alpha = d_F - d_C = (n_F - 1)a - (n_C - 1)a = (n_F - n_C)a$$

Now, the deviation of the mean ray is

$$d_d = (n_d - 1)a.$$

From the definition of ω we now have

$$\omega = \frac{\text{angle of dispersion}}{\text{mean deviation}} = \frac{\alpha}{d_d} = \frac{(n_F - n_C)a}{(n_d - 1)a}$$

Eliminating the term a in the above equation we get

$$\omega = \frac{(n_F - n_C)}{(n_d - 1)}$$

More commonly used in the optical industry is the reciprocal of the dispersive power, called the *constringence* of a substance. This is denoted by **V**.

That is, the constringence, **V**, is given by

$$V = \frac{1}{\omega}$$

We can therefore write the expression

$$V = \frac{n_d - 1}{n_F - n_C}$$

It follows from the previous equation that the more a medium disperses white light into its components, the smaller the constringence will be. The constringence is more commonly referred to in optics as the V-number or Abbe number.

For low dispersion materials, V ≥ 45; for medium dispersion materials,
39 ≤ V < 45 and for high dispersion materials V < 39.

Ordinary crown glass and plastic materials such as CR-39 have V-values in the region of 59. Experience has shown that these low dispersion materials almost never give rise to complaints of coloured fringes or off-axis blur. In contrast, for the more dispersive flint glasses, the constringence will be much lower, at about 30.

COLOUR

Colour is **subjective**. By this we mean that the colours we see are qualities of our mental image, and are entirely different in kind from the physical light rays focused on the retina of the eye. As evidence of this we need only consider the colour perception of a person with normal colour vision in relation to that of a person whose colour vision is defective. In the latter case, the person may be unable to distinguish between red and green, and these two colours cannot have the same appearance to him as they do to the normal observer.

It is also quite a common experience that the colour of an object depends on the nature of the light used to illuminate it, and on the nature of the surface and its surroundings, as well as on the observer.

SELECTIVE TRANSMISSION

An object appears to have a certain colour by virtue of the light reflected from it, and involves the process known as **selective transmission of light**. Much of the colour of nature owes its origin to the polychromatic character of white light. If some of the components of white light are subtracted from the incident light, the remainder that is reflected appears coloured. Consequently, if we view a piece of blue paper in white light, the paper reflects the blue light very well, but absorbs all the other colours. A smaller percentage of the colours bordering blue in the spectral order, namely green and violet, will also be reflected, but the dominant reflected colour is blue. The surface thus appears blue, although the colour actually comes from the incident white light.

If the blue paper is viewed in the yellow light of a sodium lamp, it appears a dull brown. This is because no blue light is emitted from a sodium lamp. Blue paper can only appear blue if the illuminating light itself contains a blue light component.

Thus, when a coloured surface is viewed in coloured artificial light, the appearance of the surface will change. This effect is referred to as **colour distortion**. Colour distortion is observed with many types of modern indoor and outdoor lighting. Certain fluorescent tubes, which emit light having the appearance of white, accentuate blue objects rather than red due the emission of a disproportionately larger quantity of blue light.

PRIMARY, SECONDARY & COMPLEMENTARY COLOURS

We have noted that white light is composed of all the colours of the visible spectrum. Therefore, if we shine all the colours of visible light on a screen, we will perceive it as white light. We can conveniently divide the visible spectrum into three regions: red, green and blue. In order to perceive white light, we do not need to see all the wavelengths between 400 and 700 nm. We only need light from these three regions of the spectrum to be present. The distribution of colours in terms of wavelengths is given in the following table. The greater the number of these wavelengths that are present, the more the radiation has the appearance of white light.

Six main bands are identified. (Indigo is left out because of the low visual response it causes. Scales that include indigo list the relative wavelength as 446 to 464 nm.)

COLOUR	WAVELENGTH (nm)
Red	**700 - 635**
Orange	**635 - 590**
Yellow	**590 - 560**
Green	**560 - 490**
Blue	**490 - 450**
Violet	**450 - 400**

Table 3.3: *The six main bands of coloured light*

By adding various amounts of red, green and blue (the colours to which each of the three types of cones in our eyes is sensitive), **we can produce any colour in the spectrum**. For this reason, red, green and blue are called the **additive primary colours**. They cannot be created by any combination of other colours.

This is how the variety of colours is produced for the theatre or for a television screen. The output from three sources - red, green and blue - is combined in various ratios to produce all the required colours.

Note that this is not the only possible set of primary colours. For example, another is Red, Yellow and Blue. The RGB set gives the best rendition of the other visible colours for most practical purposes and is therefore preferred.

When two of these primary colours are mixed in equal intensities, they produce **secondary colours**:

Red and Blue produce Magenta (Purple).

Red and Green produce Yellow.

Green and Blue produce Cyan (Turquoise).

Any two colours of light that when mixed together in equal intensities produce white are said to be **complementary colours** of each other. The complementary colour of red light is cyan light. This is reasonable since cyan light is the combination of blue and green light; and blue and green light when added to red light will produce white light. Thus, red light and cyan light (blue + green) represent a pair of complementary colours; they add together to produce white light. This is illustrated in the equation below:

$$R + C = R + (B + G) = White$$

Using the above reasoning, each primary colour has a secondary colour of light as its complement:

Red and Cyan

Green and Magenta

Blue and Yellow

PIGMENTS, PAINTING AND PRINTING

For printing and painting the mixing of colours is different to what we have discussed previously. This is because the mixing of coloured lights results in addition, whereas the pigments used in painting and printing **absorb** certain wavelengths and cause **subtractive mixing.** Each dye or pigment in a mixture will absorb its own wavelengths. Therefore, mixing inks or pigments gives a different result compared to mixing coloured lights.

For example, if you mix red, green and blue paint, the result will not be white. Instead, it will be a dark brown! This because the light in all three regions of the spectrum is absorbed; and none is reflected. If the absorption was perfect, it would appear to be black. The absorption that is less than 100% results in the brown colour.

Red, yellow and blue is an historical set of subtractive primary colours. It is primarily used in art and printing. This set is problematic in that a limited range of colours can be produced by combining them. In an attempt to improve the range of colours obtained, white is often added as another primary by painters.

For this reason, modern printing processes and colour photography use **yellow, magenta and cyan as the subtractive primary colours**. Colour printers use a fourth ink - black - because no combination of the primary dyes yields a good, solid black.

In order to understand the colours obtained when **dyes and pigments** are mixed, remember that they **absorb their complementary colour**.

Therefore: Yellow absorbs Blue; Cyan absorbs Red, and Magenta absorbs Green.

OPTICAL PATH LENGTH

The path, d, of a light ray in any medium is the product of speed and time:

$$d = vt$$

By definition, n = c/v and therefore v = c/n. This gives:

$$d = ct/n \text{ or } nd = ct$$

nd is called the optical path length. **The optical path length (nd) represents the distance light travels in a vacuum in the same time it travels a distance d in a medium of refractive index n.**

The above equation implies that the distance light travels in a medium (d) is less than the distance travelled in vacuum in the same time (by a factor of 1/n). A consequence of this is that the wavelength of light is smaller in the medium than it is in vacuum (by the same factor).

REFRACTION AT CURVED SURFACES

If a spherically curved surface separates two media of different refractive index, the refracting power (ability to change vergence) is given by

$$F = \frac{n_2 - n_1}{r}$$

- F = Power of the surface (dioptres)
- r = radius of curvature of the surface (m)
- n_1 = refractive index of initial medium
- n_2 = refractive index of medium the light enters

The impact that the difference in refractive index of the two media has on the power is dramatically illustrated by the following:

We can consider the cornea in a simplified human eye to have two spherical surfaces. The anterior surface interfaces with the air and has radius of curvature of 7.7 mm. The posterior surface is in contact with the aqueous humor and has a radius of curvature of 6.8 mm. We will assume that the cornea has a constant refractive index of 1.376 and that the refractive index of the aqueous humor is 1.336.

Power of ant. surface: F = (1.376 – 1)/ 0.0077 = 48.83 D

Power of post. surface: F = (1.336 – 1.376)/ 0.0068
= –5.88 D
Total power = F1 + F2 = +42.95 D

IF THE CORNEA WAS IN AIR:

Power of anterior surface is as before: 48.83 D

Power of post. surface: F = (1 – 1.376)/ 0.0068
= –55.29 D
Total power **IN AIR** = F1 + F2 = 48.83 – 55.29

= –6.46 D

In **air**, the cornea would be a **DIVERGING** optical element in the eye. The greater refractive index of the aqueous humor makes it ***CONVERGING*** when it is in place ***in the eye***.

LENS CLOCK II

We noted in Chapter 2 that a lens clock actually determines the radius of curvature of a lens surface by measuring the aperture and the sagitta by means of the three pins placed against the surface ($r = y^2/2s$). However, its purpose is to indicate the **power** of the lens surface.

From the previous section we saw that we can compute the power of a refracting surface if the refractive indices of the media surrounding the surface are known. In practical situations, we know that n_1 is 1 since the lens is in air. However, in order to get an accurate reading, we need to calibrate the lens clock using the refractive index of the lens material.

Lens clocks are calibrated on the assumption that the lens material is spectacle crown glass (n = 1.523). For lenses made with refractive indexes **greater than 1.523**, the lens clock will **underestimate** the true lens power and for those lenses with indexes of refraction ***less than 1.523***, the lens clock will ***overestimate*** the true lens power.

The powers of the two surfaces are added to give the overall lens power. To calculate the power of a lens, one must consider the thickness of that lens. Adding the power of the two surfaces to obtain the overall lens power is only a good approximation when the lenses are thin. This means that a lens clock will not give good results for thick lenses. Furthermore, they cannot be used for aspheric and freeform lenses.