Chapter 1 Physics of the eye

1.1 Physics of vision

Learning objectives

→ Describe how the eye forms an image.
→ Explain why peripheral images lack detail and colour.
→ Determine the resolution of the eye.

The eye as an optical refracting system

The eye is an optical instrument that can focus automatically on objects over a wide range of distances, can adjust automatically to a wide range of light intensities, and is sensitive to a continuous range of electromagnetic waves from less than 400 nm to about 650 nm in wavelength.

The **cornea** is a protective transparent layer at the front of the eye. It has a fixed convex curvature and therefore acts as a fixed focus lens.

Behind the cornea is the **eye lens**, as shown in Figure 1. The eye lens is flexible and attached to muscles, called **ciliary muscles**. These muscles change the thickness of the eye lens, therefore altering the optical power of the eye lens. This enables it to form an image on the **retina** of the eye of any object within a range of distances.

The **ciliary muscle fibres** lie along concentric circles round the rim of the eye lens.

- To view a near object, the eye muscles must become taut so that the muscle fibres shorten and make the eye lens thicker and more powerful.
- To view a distant object, the eye muscles must relax so that the muscle fibres lengthen, allowing the eye lens to become thin and less powerful.

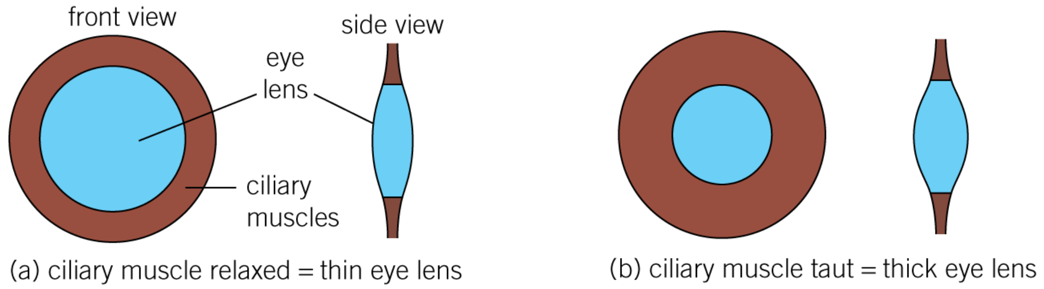


Figure 1 *The eye lens*

The **iris** between the cornea and the eye lens controls the amount of light entering the eye. It consists of concentric and radial muscle fibres around a circular hole, the **pupil** of the eye, which light must pass through to reach the eye lens.

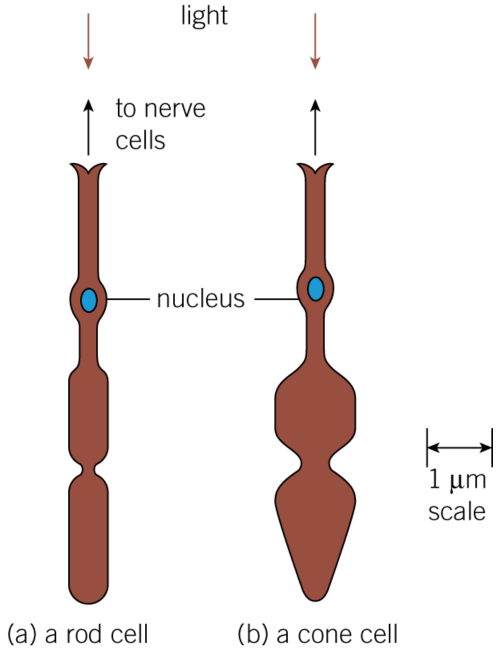
- In bright light, the concentric fibres contract and the radial fibres relax so the iris expands, making the eye pupil narrower so less light passes through it.
- In dim light, the concentric fibres relax and the radial fibres contract so the iris contracts, dilating (i.e., widening) the eye pupil so more light passes into the eye.

The range of the eye pupil's diameter is typically from less than 1 mm up to 10 mm. The area of the pupil determines the amount of light entering the eye which therefore increases by a factor of 100 when the diameter of the eye pupil increases from 1 mm to 10 mm.

Note: as explained below, the two types of retinal cells, rods and cones, when exposed to very bright light automatically become less sensitive; in dim light, the cones 'switch off' and the rods become more sensitive.

Sensitivity of the eye

The **retina** is a layer of light-sensitive cells at the back of the eye. There are two types of retinal cells: rods and cones. The retinal cells are most dense at the fovea, which is the region of the retina near the principal axis of the eye lens. The **fovea** consists mostly of cones, whereas rods predominate near the periphery of the retina.



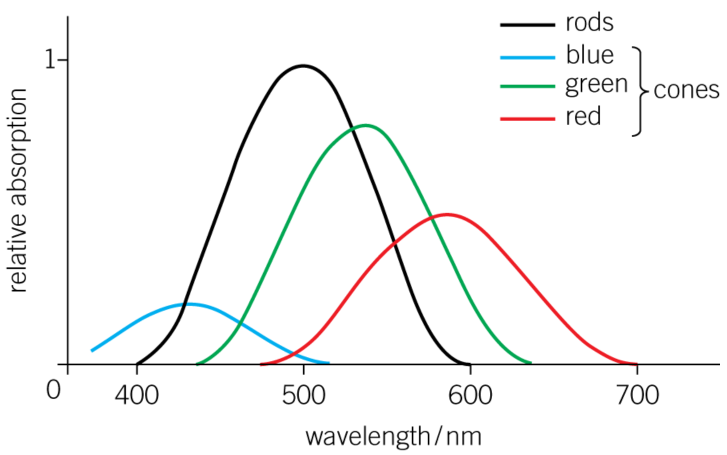


Figure 2 *Rods and cones*

Rods are sensitive to low levels of light intensity but cannot distinguish between colours. Because rods predominate at the periphery of the retina, dim objects viewed in dark conditions can often be seen at the edge of your field of view (but not at the centre), but you can't tell their colour. Rods contain rhodopsin, also known as visual purple, which consists of complex molecules that each can be split in two by light photons. This causes a change in the cell potential which helps to trigger the nerve fibre to which the cell is connected. Up to 10 photons need to be absorbed to trigger a rod. Several rods connected to the same nerve fibre need to be triggered to send an electrical impulse to the brain. The rhodopsin molecules regenerate slowly. In very bright light, the molecules are unable to regenerate so the rods have reduced sensitivity. Adaptation to dark conditions takes over 30 minutes as the rhodopsin molecules slowly re-form.

Cones are of three types, each sensitive to a different range of wavelengths. These ranges correspond broadly to red, green, or blue light, as shown in Figure 2. Cones do not respond to very low levels of light intensity and automatically become less sensitive at very high intensities.

After-images

An after-image is seen after a very bright image disappears. This is because the cones take up to a second or so to regain normal sensitivity and is known as persistence of vision. If the original image is coloured, the after-image will be the complementary colour. This is because the type of coloured cones stimulated by the original image do not respond effectively until they regain their normal sensitivity. During this time, the other cones operate normally and hence form a temporary after-image in the complementary colour. Television viewers rely on persistence of vision as the TV picture is renewed at least 25 times every second. The viewer sees a continuous sequence of frames because of persistence of vision. If the frame rate was significantly lower, the pictures would flicker noticeably.

QUESTION: State which cones are suppressed after you look at a yellow image.

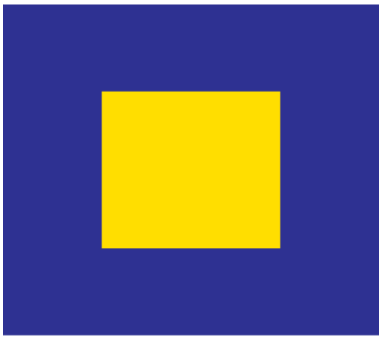


Figure 3 *An after-image*

Stare at the picture for a few seconds then close and cover your eyes to see the after-image.

Resolution

The resolution of the eye is determined by the size and closeness of the retinal cells. Light passing through the eye pupil of width 4 mm from a point object would form a diffracted image about 3 μm in diameter, covering two or three retinal cells. For two nearby point objects, because a single nerve fibre is usually connected to a number of rods or cones, the two diffracted images on the retina need to be separated by at least two retinal cells to be resolved (seen separately), as shown in Figure 4.

Link

Diffraction was looked at in Topic 5.6, Diffraction, in Year 1 of the *AQA Physics* student book.

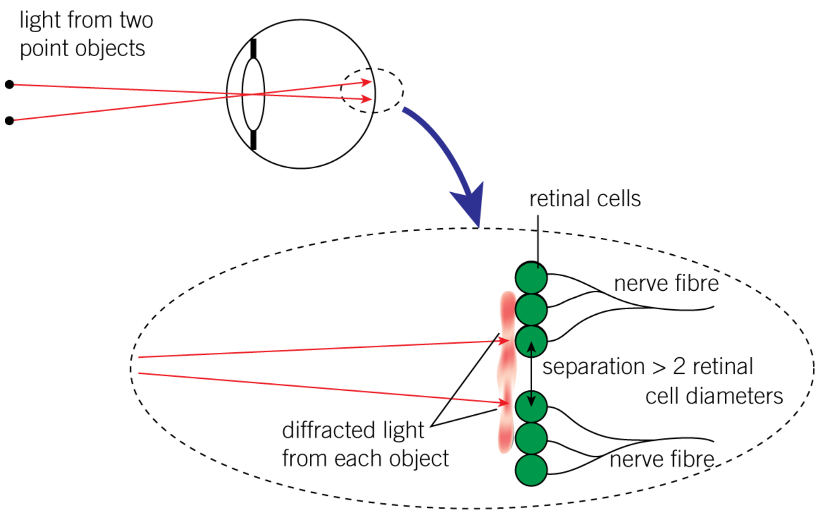


Figure 4 *Spatial resolution*

For two point objects at separation *d* and at distance *u* from the eye, as shown in Figure 5:

- their angular separation θ in radians = $\frac{d}{u}$
- the separation of their image centres $y = \theta v$, where *v* is the distance from the eye lens to the retina.

If the retinal cells where the image is formed are 1.5 μm in diameter, the two images must be separated by a distance of at least 3 μm (= 2 retinal cell diameters) to be resolved.

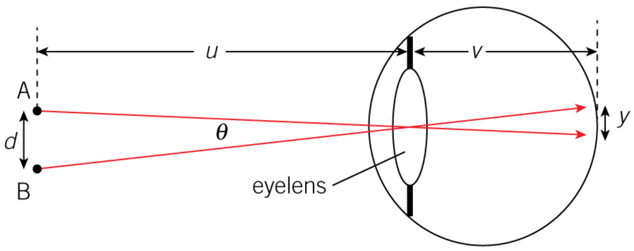


Figure 5 *Two nearby point objects*

How efficient is the eye?

The quantum efficiency of the eye is the number of nerve fibres triggered as a percentage of the number of photons entering the eye. A normal eye has an efficiency of about 1 to 2%. This is because about 50 to 100 photons are needed to trigger a retinal nerve fibre. About 10 photons may be needed to trigger a retinal cell and several cells are needed to trigger a nerve fibre. In addition, some photons will be absorbed by the eye lens or the aqueous or vitreous humour before reaching the retina. In comparison, a CCD detector used in a digital camera has a typical efficiency of 70% in terms of the number of electrons liberated in a pixel per 100 photons incident on the pixel.

Summary questions

1 **a** With the aid of a diagram, describe how an image of a point object is formed on the retina of the eye.

b Describe and explain the adjustment that takes place within the eye when it changes from viewing a nearby object to a distant object.

2 **a** State two ways in which the eye adapts when the incident light becomes:

i very intense

ii very dim.

b Sketch graphs on the same axes to show the response of rods and the three different types of cones to light of different wavelengths from about 350 nm to 700 nm. Label each graph with the type of retinal cell.

3 Explain why objects in dim light at the edge of the field of view:

a are more readily noticed than objects at the centre of the field of view

b are colourless.

4 Two point objects are 6 mm apart at a distance of 30 m from an eye. An image of each object is formed on the retina at a distance of 20 mm from the eye lens.

a Calculate the separation of the two point images.

b The images are formed on the retina where the retinal cells have a diameter of 1.5 μm. Discuss whether or not the two images are resolved by the eye.

1.2 Lenses

Learning objectives

→ Define converging lens, diverging lens, and focal length.
→ Describe how a lens forms an image.
→ Explain how we can predict the position and magnification of an image formed by a lens.

Converging and diverging lenses

Lenses are used in optical devices such as the camera, the telescope and the eye. A lens works by changing the direction of light at each of its two surfaces. Figure 1 shows the effect of a converging lens and of a diverging lens on a beam of parallel light rays.

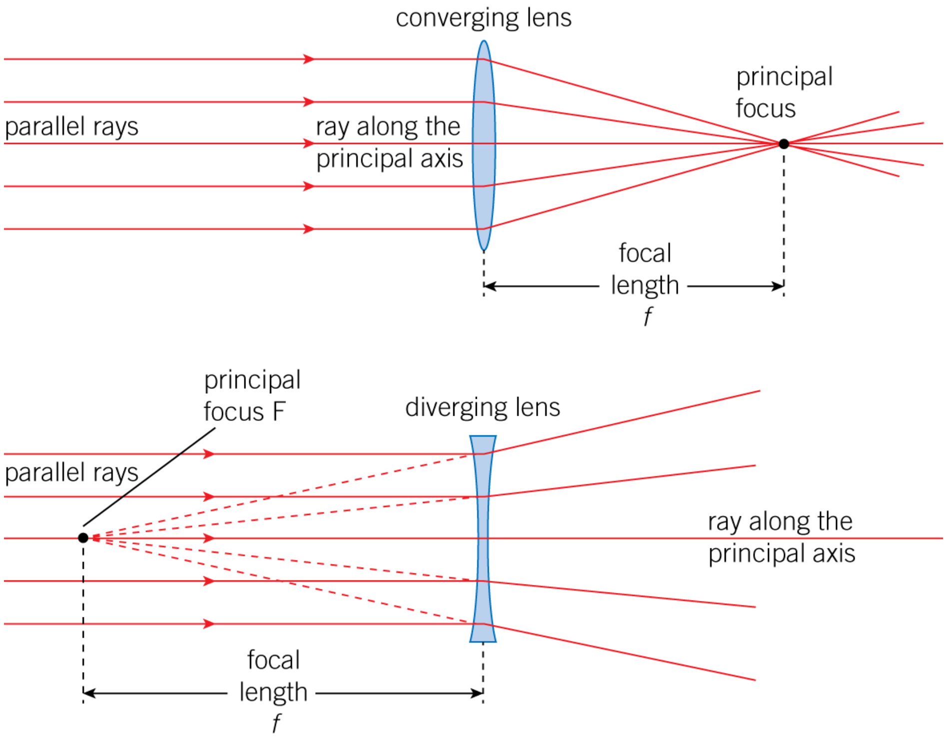


Figure 1 *Focal length*

A **converging lens** makes parallel rays converge to a focus. The point where parallel rays are focused to is called the **principal focus** or the **focal point** of the lens.

A **diverging lens** makes parallel rays diverge (spread out). The point where the rays appear to come from is the principal focus or focal point of this type of lens.

In both cases, the distance from the lens to the principal focus is the **focal length** of the lens.

Note

The **principal axis** of a lens is the straight line that passes normally through both surfaces at their centres. The plane on each side of the lens perpendicular to the principal axis containing the principal focus is called the **focal plane**.

Investigating the converging lens

The arrangement in Figure 2 can be used to investigate the image formed by a converging lens. Light rays from illuminated crosswires (the object) is refracted by the lens such that the rays form an image of the crosswires.

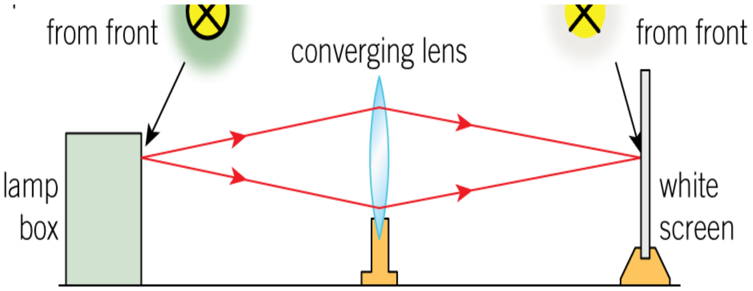


Figure 2 *Investigating images*

With the object at different distances beyond the principal focus of the lens, the position of the screen is adjusted until a clear image of the object is seen on the screen. The image is described as a **real image** because it is formed on the screen where the light rays meet.

If the object is moved nearer the lens towards its principal focus, the screen must be moved further from the lens to see a clear image. The nearer the object is to the lens, the larger the image is.

With the object nearer to the lens than the principal focus, a magnified image is formed. The lens acts as a magnifying glass. But the image can only be seen when you look into the lens from the other side to the object. The image is called a **virtual image** because it is formed where the light rays appear to come from.

QUESTION: A lens is used to form a real image of an object. Describe what happens to the distance to the image if the object is moved away from the lens.

Ray diagrams

The position and nature of the image formed by a lens depends on the focal length of the lens and the distance from the object to the lens.

If we know the focal length, f, and the object distance, u, we can find the position and nature of the image by drawing a ray diagram to scale in which:

- the lens is assumed to be thin so it can represented by a single line at which refraction takes place
- the principal focus F is marked on the principal axis at the same distance from the lens on each side of the lens
- the object is represented by an upright arrow as shown in Figure 3.

Note: The horizontal scale of the diagram must be chosen to enable you to fit the object, the image, and the lens on the diagram.

Formation of a real image by a converging lens

To form a real image, the object must be beyond the principal focus F of the lens. The image is formed on the other side of the lens to the object.

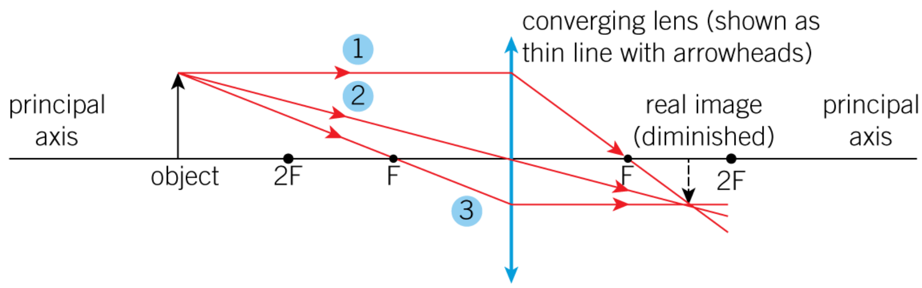


Figure 3 *Formation of a real image by a converging lens*

To locate the tip of the image, three key construction rays from the tip of the object are drawn, through the lens. The tip of the image is formed where these three rays meet. The image is real and inverted.

1 Ray 1 is drawn parallel to the lens axis before the lens so it is refracted by the lens through F,

2 Ray 2 is drawn through the lens at its centre without change of direction. This is because the lens is thin and its surfaces are parallel to each other at the axis,

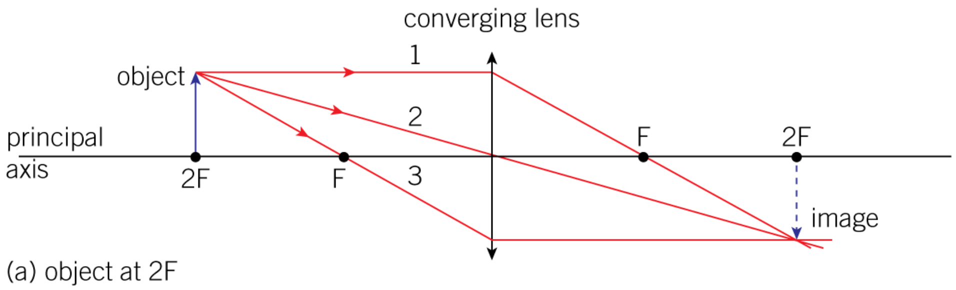
3 Ray 3 is drawn through F before the lens so it is refracted by the lens parallel to the axis.

In Figure 3, the image is smaller than the object. This is because the object is beyond 2F.

Figure 4(a) and (b) show respectively ray diagrams for the object at 2F and between F and 2F. The results for Figures 3 and 4 are described in Table 1.

Notice that the image is:

- diminished in size when the object is beyond 2F as in Fig 3
- the same size as the object when the object is at 2F as in Fig 4(a)
- magnified when the object is between F and 2F as in Fig 4(b).



(a) object at 2F

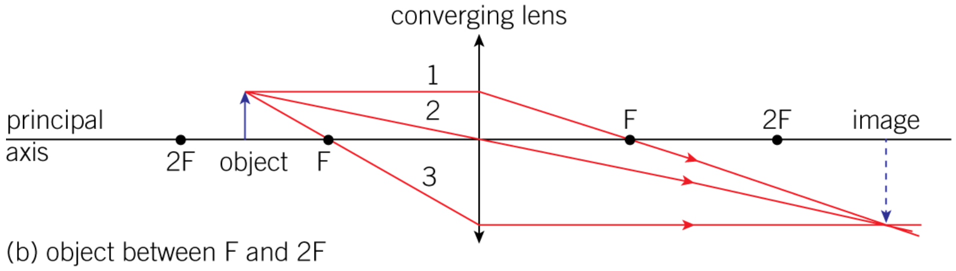


Figure 4 *Using ray diagrams to locate an image*

Formation of a virtual image by a converging lens

The object must be between the lens and its principal focus, as shown in Figure 5. The image is formed on the same side of the lens as the object.

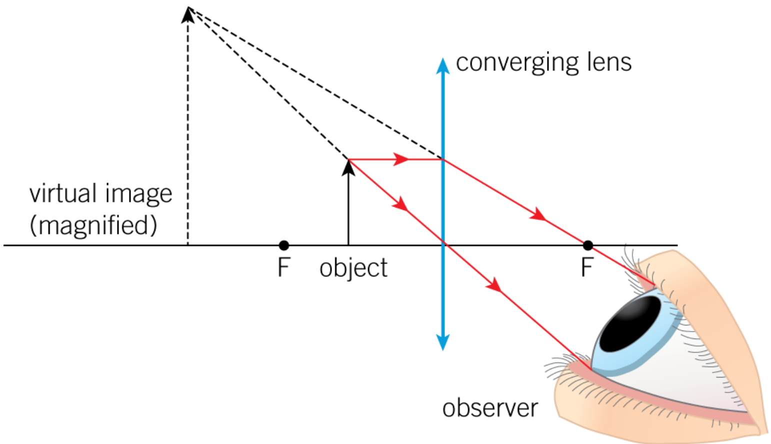


Figure 5 *Formation of a virtual image by a converging lens*

The diagram shows that the image is virtual, upright and larger than the object. The image is on the same side of the lens as the object and can only be seen by looking at it through the lens. This is how a **magnifying glass** works.

If the object is placed in the focal plane, light rays from any point on the object are refracted by the lens to form a parallel beam. A viewer looking at the object through the lens would therefore see a virtual image of the object at infinity.

Table 1 *Image formation by a converging lens*

Object position	Image position	nature of image	magnified or diminished	upright or inverted	application
> 2F	between F and 2F	real	diminished	inverted	camera
2F	2F	real	same size	inverted	inverter
between F and 2F	> 2F	real	magnified	inverted	projector
< F	same side as object	virtual	magnified	upright	magnifying lens

Formation of a virtual image by a diverging lens.

The lens makes light rays from a point object diverge. The image is formed on the same side of the lens as the object, as shown in Figure 6. To locate the tip of the image, three key construction rays from the tip of the object are drawn, as described below, through the lens. The tip of the image is formed where these three rays appear to come from. The image is always virtual, upright and smaller than the object.

1 Ray 1 is drawn parallel to the lens axis before the lens so it is magnified as if it passed through F before the lens.

2 Ray 2 is drawn through the lens at its centre without change of direction. This is because the lens is thin and its surfaces are parallel to each other at the axis.

3 The image position can be checked by drawing a third ray (shown in grey) from the tip of the object towards *F* on the other side of the lens so it is refracted by the lens parallel to the axis.

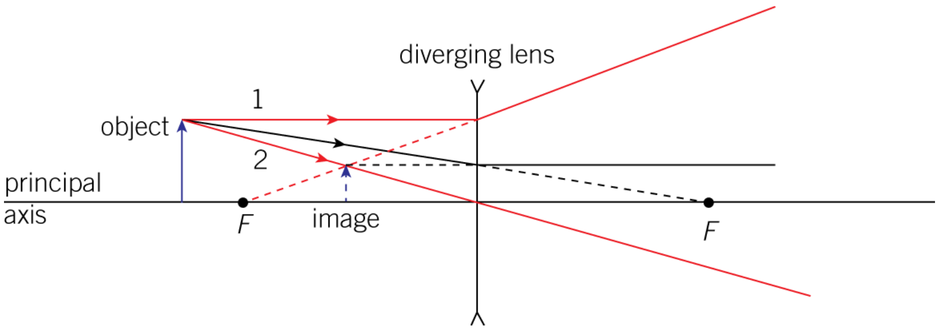


Figure 6 *Ray diagram for a diverging lens*

Note

The linear magnification, *m,* of the image = $\dfrac{\text{height of the image}}{\text{height of the object}}$.

It can be shown that this ratio is equal to $\dfrac{\text{the image distance, } v}{\text{the object distance, } u}$.

The image is said to be **magnified** if the image height is greater than the object height and **diminished** if it is smaller.

Study tip

When you draw a ray diagram, make sure you choose a suitably large scale that enables you to fit the object and the image on your diagram – and use a ruler to make sure your lines are straight!

The lens equation

For an object on the principal axis of a thin lens of focal length *f* at distance *u* from the lens, the distance from the image to the lens, *v,* is given by

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

Notes

1 Proof of the lens equation is not required in the option specification.

2 When numerical values are substituted into the equation, the sign convention **'real is positive; virtual is negative'** is used for the object and image distances. The focal length, f, of a converging lens is always assigned a positive value. A diverging lens is always assigned a negative value.

Worked example

An object is placed on the principal axis of a convex lens of focal length 150 mm at a distance of 200 mm from the centre of the lens. Calculate the image distance and state whether the image is real or virtual.

Solution

$f = +0.150$ m, $u = +0.200$ m,

Using the lens equation $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$ gives $\frac{1}{0.200} + \frac{1}{v} = \frac{1}{0.150}$

Hence $\frac{1}{v} = \frac{1}{0.150} - \frac{1}{0.200} = 6.67 - 5.00 = 1.67$

Therefore $v = +0.600$ m

The image is real (because v is positive).

Summary questions

1 a i Copy and complete the ray diagram in Figure 7 to show how a converging lens in a camera forms an image of an object.

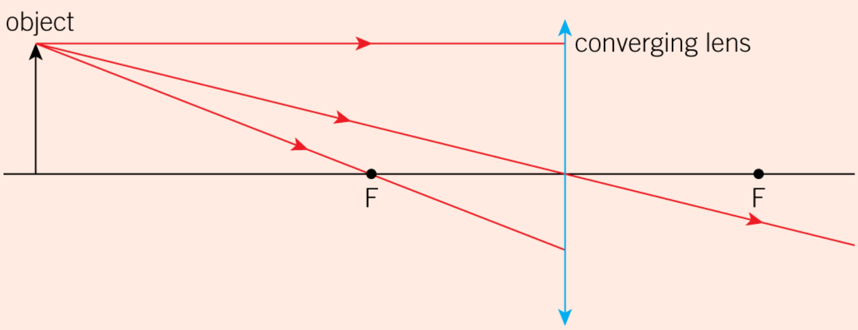


Figure 7

ii State whether the image in Figure 7 is real or virtual, magnified or diminished, upright or inverted.

b i Draw a ray diagram to show how a converging lens is used as a magnifying glass.

ii State whether the image in your diagram is real or virtual, magnified or diminished, and upright or inverted.

2 An object is placed on the principal axis of a thin converging lens at a distance of 400 mm from the centre of the lens. The lens has a focal length of 150 mm.

a Draw a ray diagram to determine the distance from the image to the lens.

b State whether the image:

i is real or virtual

ii upright or inverted.

c Use the lens equation to check the accuracy of your ray diagram.

3 An object is placed on the principal axis of a thin converging lens at a distance of 100 mm from the centre of the lens. The lens has a focal length of 150 mm.

a Draw a ray diagram to determine the distance from the image to the lens.

b State whether the image:

i is real or virtual

ii upright or inverted.

c Use the lens equation to check the accuracy of your ray diagram.

4 An object of height 10 mm is placed on the principal axis of a diverging lens of focal length 0.200 m.

Calculate the image distance and the height of the image for an object distance of:

a 0.150 m

b 0.250 m.

1.3 Defects of vision

Learning objectives

→ Explain what is meant by the power of a lens.
→ Explain what causes myopia (short sight) and hypermetropia (long sight) and how they are corrected.
→ Define astigmatism and explain how it is corrected.

Lens power

The power of a lens is defined as $\dfrac{\mathbf{1}}{\textbf{its focal length in metres}}$

The unit of power is the dioptre (D). For example, for:

- a converging lens with a focal length of 0.20 m (i.e., $f = +0.20$ m), its lens power = +5.0 D
- a diverging lens with a focal length of 0.25 m (i.e., $f = -0.25$ m), its lens power = –4.0 D.

The eye is capable of focusing objects at different distances. This process is called **accommodation** and is achieved by automatic adjustment of the thickness of the eye lens. A normal eye can see objects in focus in the range from infinity to 25 cm. In other words, the normal eye has a **near point** of 25 cm and a **far point** at infinity. A normal eye is that of a 40-year-old person with normal vision. Young people have a much wider range but the range decreases gradually with age.

- For near objects, the eye lens must be thicker and hence more powerful than for distant objects. Figure 1(a) shows the light rays from a nearby object brought to a focus on the retina.
- For distant objects, the eye lens must be thinner and hence less powerful than for distant objects. Figure 1(b) shows the light rays from a distant object brought to a focus on the retina.

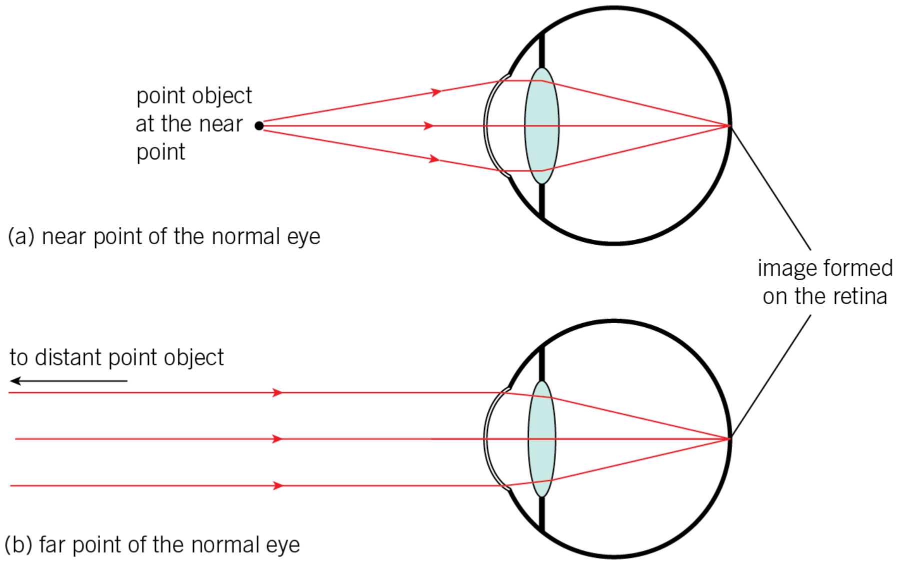


Figure 1 *The normal eye*

Myopia and hypermetropia

Myopia or **short-sight** occurs when an eye cannot focus on distant objects. The uncorrected far point of the defective eye is nearer than infinity. This is because the eye muscles cannot make the eye lens thin enough to focus an image on the retina of an object at infinity. The eye can focus nearby objects hence the defect is referred to as short-sight.

The cause of myopia is that light, after passing through the eye lens, converges in front of the retina, as shown in Figure 2. This happens if the eye lens cannot become thin enough to focus light onto the retina or if the eyeball that is too long.

To correct myopia using a lens, a diverging lens of a suitable focal length must be placed in front of the eye as shown in Figure 2. The correcting lens makes parallel rays from a distant object diverge so they appear to come from the uncorrected far point. Therefore, the correcting lens for myopia must:

- be a diverging lens
- have a focal length equal to the distance from the eye to the uncorrected far point.

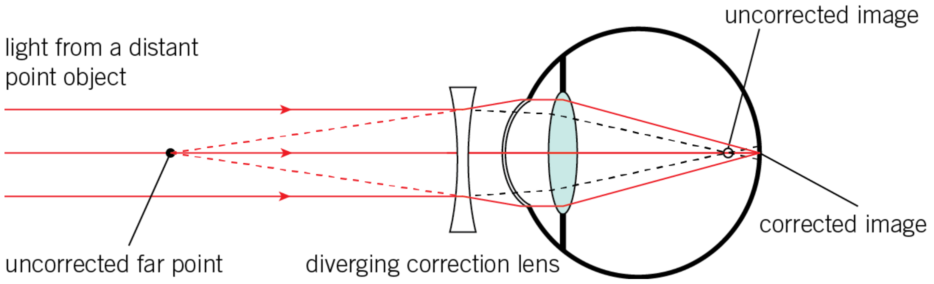


Figure 2 *Myopia and its correction*

Figure 2 shows that:

- the correcting lens forms a virtual image of the distant point object at the uncorrected far point
- the cornea and eye lens see the object as if it was at the uncorrected far point and form a real image of the object on the retina.

Note

The correcting lens effectively moves the far point of the uncorrected eye to infinity. It also 'moves' the near point away as shown in Figure 3. The correcting lens makes the image of an object placed at the least distance of distinct vision (i.e., 'new' near point) appear at the 'unaided' near point. Therefore, the image is virtual and nearer the lens than the object as shown.

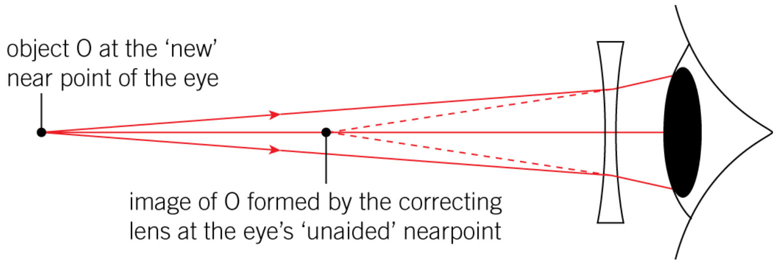


Figure 3 *Effect on the near point*

In Figure 3, if the object is at distance *u* and the image is at distance *v*, applying the lens equation $\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$ gives $\frac{1}{v}=\frac{1}{f}-\frac{1}{u}$. Since *f* is negative (as the correcting lens is a diverging lens), $\frac{1}{v}$ is more negative than $\frac{-1}{u}$ so the distance to the 'unaided' near-point (i.e., image distance *v*) is smaller than the 'new' near-point distance (i.e., object distance *u*).

Worked example

A short-sighted eye has a far point of 5.00 m and a near point of 0.25 m.

a State the type of lens needed to correct this defect and calculate the power of the correcting lens.

b Calculate the distance from the lens to the near point of the eye with the correcting lens in front of the eye.

Solution

a A diverging lens is needed. Its focal length is –5.0 m (= the distance to its far point).

Therefore the power of the correcting lens = $\frac{1}{f}$ = –0.20 D.

b Let *u* = least distance of distinct vision to an object with the correcting lens in place.

The image of this object is a virtual image formed at 0.25 m from the eye. Hence *v* = –0.25 m.

Using $\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$ with *v* = –0.25 m and *f* = –5.0 m gives

$$\frac{1}{u}=\frac{1}{f}-\frac{1}{v}=\frac{1}{-5.0}-\frac{1}{-0.25}=-0.20+4.00=+3.80\ \text{m}^{-1}$$

Hence $u=\frac{1}{3.80}=0.26(3)$ m

Hypermetropia or **long-sight** occurs when an eye cannot focus on nearby objects. The uncorrected near point of the defective eye is further away than 25 cm. This is because the eye muscles cannot make the eye lens thick enough to focus an image on the retina of an object 25 cm away. The eye can focus distant objects hence the defect is referred to as long-sight.

The cause of hypermetropia is that light, after passing through the eye lens, does not converge enough to form an image on the retina, as shown in Figure 4. This happens if the eye lens cannot become thick enough to focus light onto the retina or if the eyeball is too short.

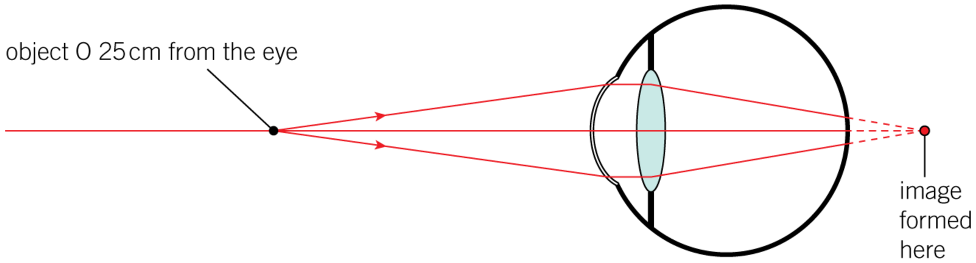


Figure 4 *Hypermetropia*

To correct hypermetropia using a lens, a converging lens of a suitable focal length must be placed in front of the eye as shown in Figure 5. The correcting lens makes the rays from an object 25 cm away diverge less so they appear to come from the uncorrected near point. Therefore, the correcting lens for hypermetropia must:

- be a converging lens
- have a focal length which makes an object placed 25 cm from the eye appear as if it is at the uncorrected near point.

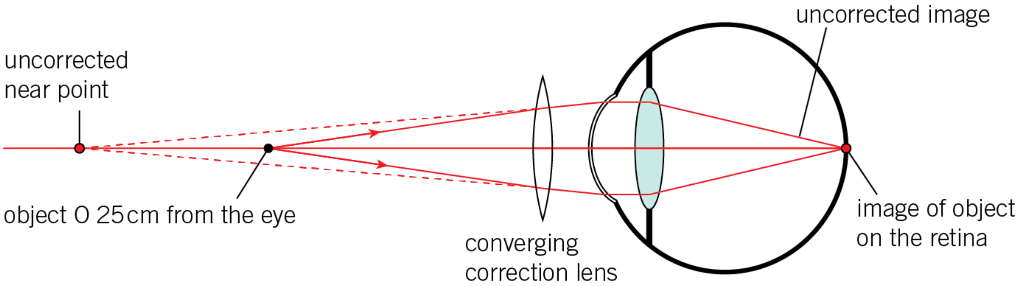


Figure 5 *Correction of hypermetropia*

Figure 5 shows that:

- the correcting lens forms a virtual image of the point object at the uncorrected near point
- the cornea and eye lens see the object as if it was at the uncorrected near point and form a real image of the object on the retina.

Note

The correcting lens effectively moves the near point of the uncorrected eye nearer the lens to 25 cm away (the near point of a normal eye). It also moves the far point from infinity nearer to the eye as shown in Figure 6. The correcting lens makes the image of an object at the 'new' far point appear to be at infinity.

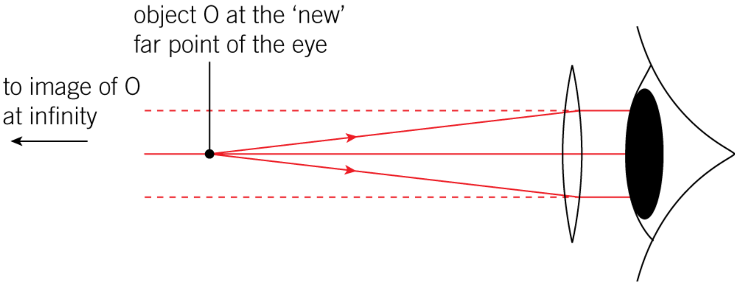


Figure 6 *Effect on the far point*

In Figure 6, the object must be at the focal point of the converging lens for the rays to become parallel after the lens to make the image at infinity. Therefore, the new far point is at distance f from the lens, where f is the focal length of the lens.

Worked example

A long-sighted eye has far point at infinity and a near point which is 40 cm from the eye.

a State the type of lens needed to correct this defect and calculate the power of the correcting lens.

b Calculate the distance from the lens to the far point of the eye with the correcting lens in front of the eye.

Solution

a A converging lens is needed.

For an object at 25 cm from the eye, the object distance $u = +25$ cm $= +0.25$ m.

The lens must form a virtual image of the object at the uncorrected near point of the eye.

Hence the image distance $v = -40$ cm.

Using $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$ with $u = +0.25$ m and $v = -0.40$ m gives

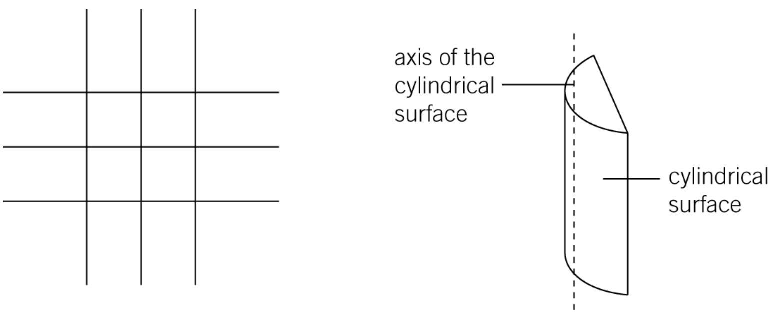
$$\frac{1}{f} = \frac{1}{+0.25} + \frac{1}{-0.40} = 4.00 - 2.50 = 1.50$$

Hence the power of the correcting lens $= \frac{1}{f} = +1.50$ D

b The distance from the lens to the 'new' far point $= f = \frac{1}{1.50} = 0.67$ m

Astigmatism

Astigmatism is a sight defect in which objects are seen to be sharper in focus in one direction than in other directions. It is most noticeable when observing parallel lines in perpendicular directions. A simple test for astigmatism is to observe two sets of parallel lines on a card that are perpendicular to each other, as shown in Figure 7a. If one set of lines stands out more than the other set at a certain orientation (e.g., vertical), the eye is astigmatic. When the card is rotated, the other set of lines stand out more as they reach the same orientation as the first set of lines were in when they were more prominent.



(a) *An astigmatism test* (b) *A cylindrical lens*

Figure 7

The cause of astigmatism is uneven curvature of the cornea. If the curvature is different in different directions, straight lines at different orientations cannot be focused on the retina at the same time. The more prominent line(s) will be in focus on the retina; the other lines will be out of focus.

The correction of astigmatism requires a lens with a cylindrical-shaped surface orientated so that it compensates for the uneven curvature of the cornea. Figure 7(b) shows the shape of a cylindrical lens. An optician's prescription for astigmatism will state:

- the curvature of the cylindrical-shaped surface
- the orientation of the axis of the cylindrical surface.

Summary questions

1 **a** State what is meant by myopia.

b **i** With the aid of a diagram, describe how myopia is corrected.

ii A short-sighted eye has a far point 8.0 m away. Calculate the power of the correcting lens to give a corrected far point at infinity.

2 **a** State what is meant by hypermetropia.

b **i** With the aid of a diagram, describe how hypermetropia is corrected.

ii A long-sighted eye has a near point at 0.50 m away. Calculate the power of the correcting lens to give a corrected near point at 25 cm from the eye.

3 **a** A short-sighted eye has a far point at 5.0 m away and a near point 25 cm away. Calculate:

i the power of the correcting lens needed to give a corrected far point at infinity

ii the distance from the lens to the corrected near point when the lens is in front of the eye.

b A long-sighted eye has a near point at 0.80 m away and a far point at infinity. Calculate:

i the power of the correcting lens needed to give a corrected near point at 25 cm from the eye

ii the distance from the lens to the corrected far point when the lens is in front of the eye.

4 **a** State what is meant by astigmatism and explain why it occurs.

b Describe how an astigmatic eye is corrected using a suitable lens, stating what measurements need to be made to ensure the lens is suitable.