The human eye

Inside the eye there is a convex lens. This, together with the front part of the eye, focuses light onto the retina, where millions of light sensitive cells sense the light and send electrical signals to the brain.

The eye lens is made of a rubbery substance that can be squashed; squashing the lens makes it fatter and therefore more powerful. In this way the eye can be adapted to focus on objects that are close or far away as illustrated in Figure 15.31. There is a limit to how fat the lens can get. If an object is too close to the eye, then it can't focus the rays on the retina, and the image is 'out of focus'. The average closest distance is 25 cm, but this tends to get longer with age.

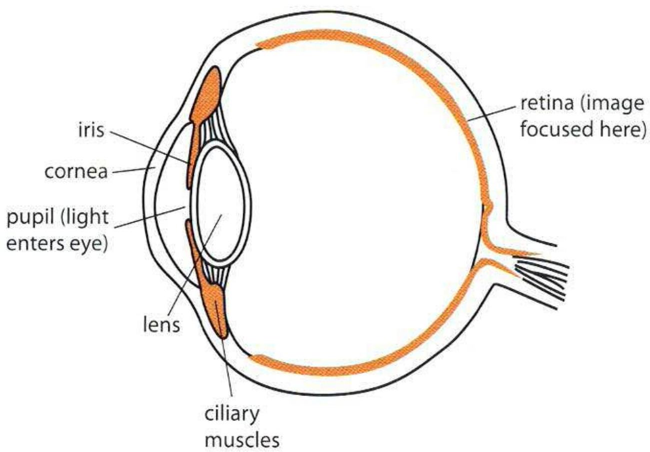


Figure 15.30 Parts of the human eye.

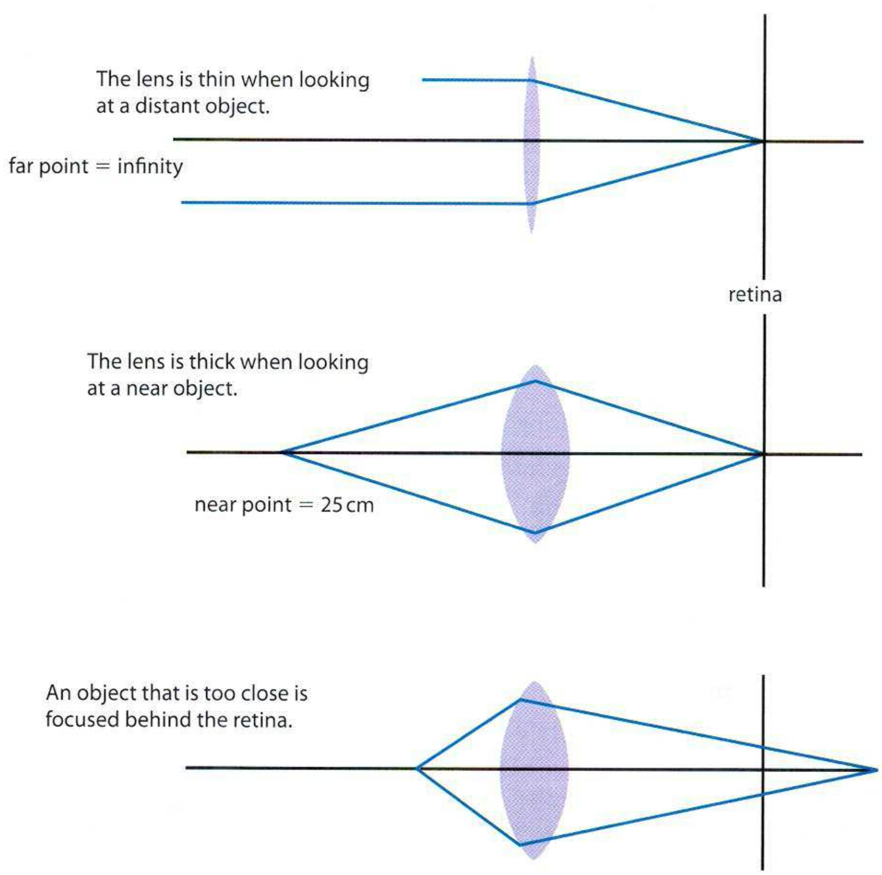


Figure 15.31 The eye lens changes shape to view different objects.

Short sight
Short sighted people have a near point that is closer to the eye than normal. This means they can read things that are much closer. Unfortunately it also means that they cannot see things that are far away.

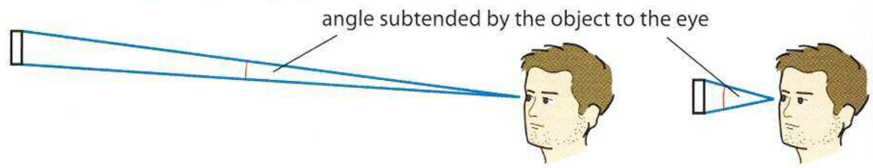
Although the wind turbines are all the same size the nearest one looks bigger.

The size of the Moon
You may have noticed that the moon looks bigger when it is just above the horizon than it does when it is up above. This is in fact an illusion, if you measure the size of the moon you find it never changes. Your brain decides how big something is depending on how your eyes are focused. When the moon is on the horizon your brain thinks it is closer because of the other objects in view. This is an example of how perception sometimes doesn't agree with measurement.

How big does an object appear?

We are all familiar with the fact that objects that are far away seem smaller than objects that are close. We can measure how big something appears using the angle that rays make when they enter the eye. In Figure 15.32 a) and b) we can see how the object subtends a bigger angle when viewed from a short distance. If we want to make an object appear as big as possible then we should view it as near as possible. This means at a distance of 25 cm.

The magnifying glass



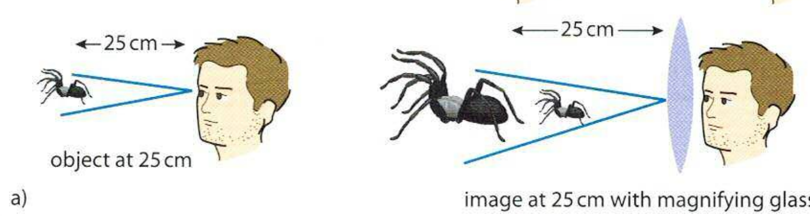


Figure 15.32 a) Using a magnifying glass with the image 25 cm away

We use a magnifying glass to make things look bigger; this is done by putting the object closer than the principal focus of a convex lens. Without a magnifying glass the best we can do is to put an object at our near point (25 cm in average eyes). The best we can do with a magnifying glass is also with the image at the near point, in other words as close as possible. The problem with looking at something so close is that it can be a bit tiring, since your eye muscles have to squash the lens.

Figure 15.32 b) Using a magnifying glass with the image 'at infinity'.

It is more relaxing to view the image at a distance, and then the eye is relaxed. This however doesn't give such a magnified image. If the final image is far away (we could say an infinite distance) the rays coming to the observer should be parallel. In the previous section we saw that this means the object must be at the focal point. In both cases the angle subtended when using the magnifying glass is bigger than without (see Figure 15.32).

Angular magnification(M)

The angular magnification tells us how much bigger an object looks.

$$\text{Angular magnification} = \frac{\text{angle subtended by image at eye } (\beta)}{\text{angle subtended by object at unaided eye } (\alpha)}$$

Angular magnification for a magnifying glass

1. Image at infinty

When the final image is an infinite distance away the object must be placed at the focal point. Looking at Figure 15.34, you can see why this image looks bigger than the image in the unaided eye.

If the angles are small (for the original object with the image at infinity) and measured in radians then

$$\alpha = \frac{h_o}{25}$$

$$\beta = \frac{h_o}{f}$$

Since angular magnification $M = \frac{\beta}{\alpha} = \frac{h_o}{f} \times \frac{25}{h_o}$

So $M = \frac{25}{f}$

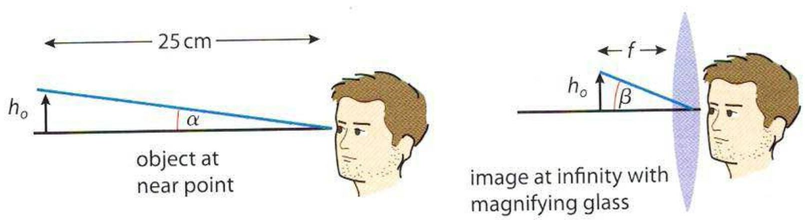


Figure 15.34 a) Angular magnification for an original object with image at infinity and viewed with a magnifying glass.

2. Image at the near point (normal adjustment)

Figure 15.34 b) compares an object as close as possible to the unaided eye to the same object viewed with a magnifying glass. So that the final image is also as close as possible, the object must be placed close to the lens.

This can be shown to give an angular magnification of $1 + \frac{25}{f}$. (One more than the previous example.)

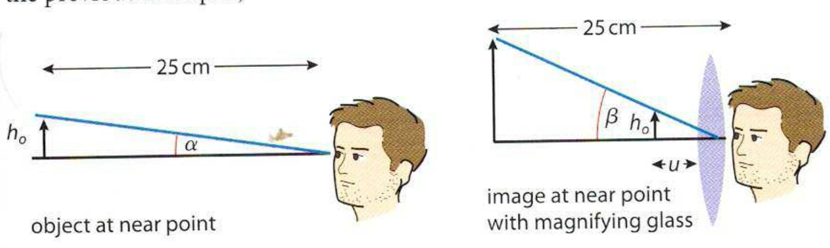


Figure 15.34 b)

Exercises

25 The Moon is about 3500 km in diameter and about 400 000 km away from the Earth. Estimate the angle subtended by the Moon to an observer on the Earth.

26 If a small insect 1 mm long is viewed at a distance of 25 cm from the eye, what angle will it subtend to the eye?

27 How close to a lens of focal length 5 cm should the insect of Exercise 26 be placed so that an image is formed 25 cm from the eye?

28 Use the formula to calculate the angular magnification of the insect viewed with a lens of focal length 5 cm if the final image is at the near point.

Derivation of $M = 1 + \frac{25}{f}$

Referring to Figure 15.34 b), if the angles are small then the angles expressed in radians are:

$\alpha = \frac{h_o}{25}$

$\beta = \frac{h_o}{u}$

so $M = \frac{\beta}{\alpha} = M = \frac{\beta}{\alpha} = \frac{h_o}{u} \times \frac{25}{h_o}$

$M = \frac{25}{u}$ (1)

but $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$ so $\frac{1}{u} = \frac{1}{f} - \frac{1}{v}$

but $v = -25$ cm so $\frac{1}{u} = \frac{1}{f} + \frac{1}{25}$

Rearranging gives $u = \frac{25f}{25 + f}$

Substituting for u in equation (1)

gives $M = \left(\frac{25 + f}{f}\right) = 1 + \frac{25}{f}$

So $M = 1 + \frac{25}{f}$

Remember the radian $= \frac{s}{r}$

If the angle is very small then the arc, s can be taken as a straight line.

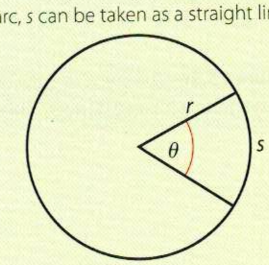


Figure 15.33

● **Examiner's hint:** If you draw the object before you draw the first ray you often end up with a final image that doesn't fit on the page (try it).

However, if the position of the object is given in the exam question you have to use it. The examiner will have made sure that everything will fit okay, so draw the ray in Step 1 from the top of the object and continue through the steps.

The microscope

The microscope is used to produce an enlarged image of a close object. The microscope consists of two convex lenses: the one closest to the object is called the *objective*; and the one you look through is the *eyepiece.* To give maximum magnification, the final image is at the near point of the eye. Figure 15.35 shows the ray diagram for a point object. This is called *normal adjustment.*

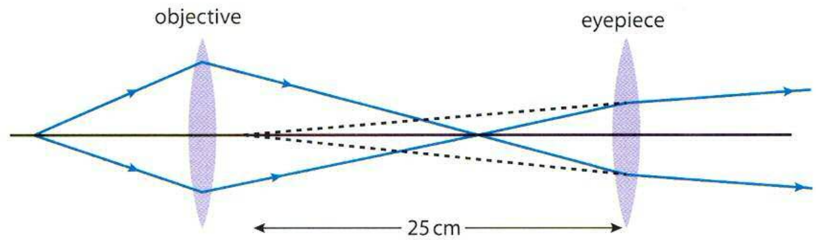


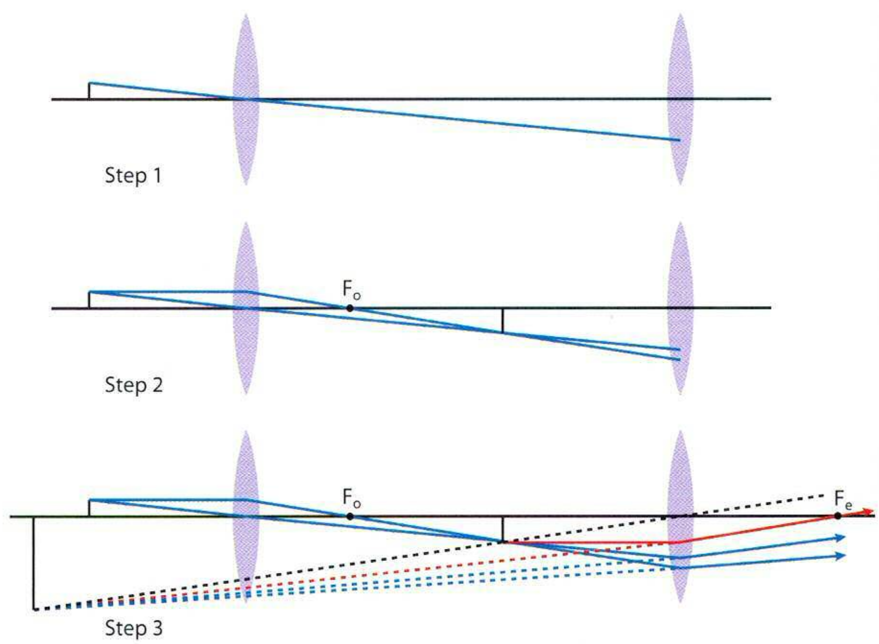
Figure 15.35 Simple ray diagram for a microscope.

Drawing the ray diagram with an extended object

Drawing the ray diagram for an extended object is a bit more difficult, but you need to know how to do it for the exam.

1 Draw the lenses and axis then a ray through the centre of the objective to a point half way down the eyepiece. Then draw an object a short distance from the objective.
2 Draw a ray from the object parallel to the axis. Continue this ray so that it hits the bottom of the eyepiece. Now mark F_o, it is the point where this ray crosses the axis.
3 To find the position of the final image draw a construction line (black) from the top of the first image through the middle of the eyepiece. The top of the image will lie on this line. Choose a point on this line beyond the objective and draw the rays coming from this point. Now add arrows to all the rays.

Figure 15.36 The steps in drawing a ray diagram with an extended object.



To find the focal point of the eyepiece, the red construction line can be drawn. This comes from the top of the first image and goes parallel to the axis. When it passes through the lens it appears to come from the top of the final image. The ray will pass through the focal point.

The astronomical telescope

The astronomical telescope is used to view stars and planets. It has no use for looking at things on Earth since the image is upside down. The simple telescope consists of two convex lenses that are used to produce a virtual image of a distant object at infinity (see Figure 15.38) The final image could be produced anywhere but in normal adjustment it is at infinity, in other words the rays come out parallel.

The objective lens forms an image of a distant object at its principal focus. This image is at the principal focus of the eyepiece, so the final image is at infinity (the rays are parallel).

How to draw the ray diagram

This diagram looks difficult to draw but is okay if done in stages.

1 Draw the lenses and axis but don't draw the foci yet.

2 Draw a ray passing through the centre of the objective hitting the eyepiece about half way down.

3 Draw two more rays entering the objective at the same angle as the first. Then draw the top ray hitting the bottom of the eyepiece.

4 The bottom ray will cross the other two at the same place; this is just below the principal focus. You can now mark this on the axis and draw in the first image (F_o).

5 The rays emerge from the eyepiece parallel. To find the angle, draw a construction line (dotted) from the top of the image straight through the centre of the eyepiece. All the rays will be parallel to this. Add arrows to all the rays.

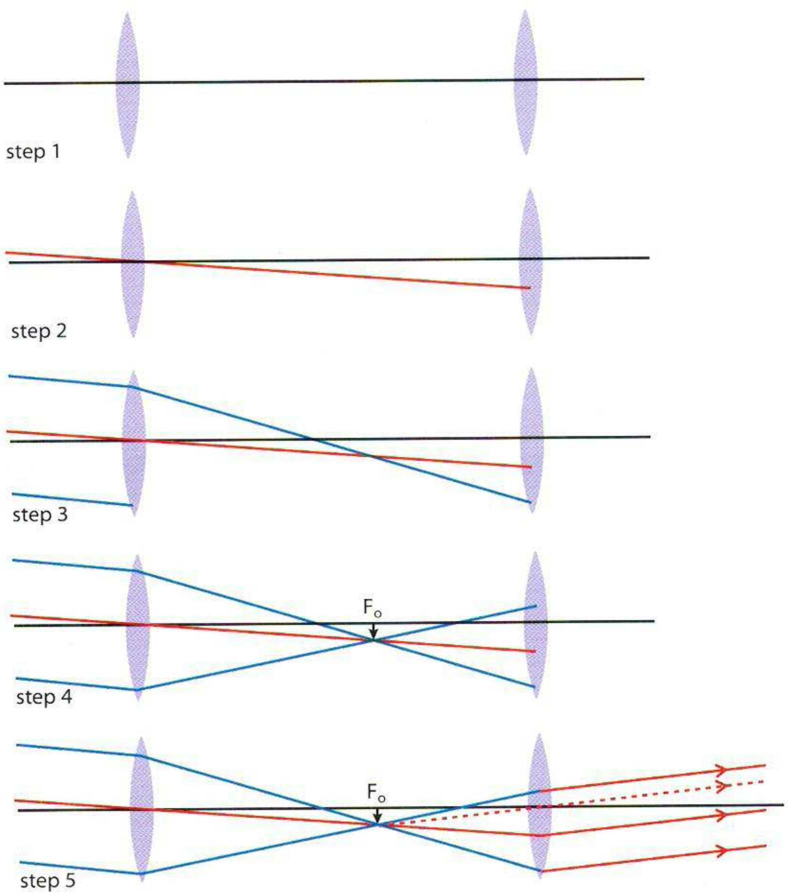


Figure 15.37 Steps in drawing the ray diagram for an astronomical telescope.

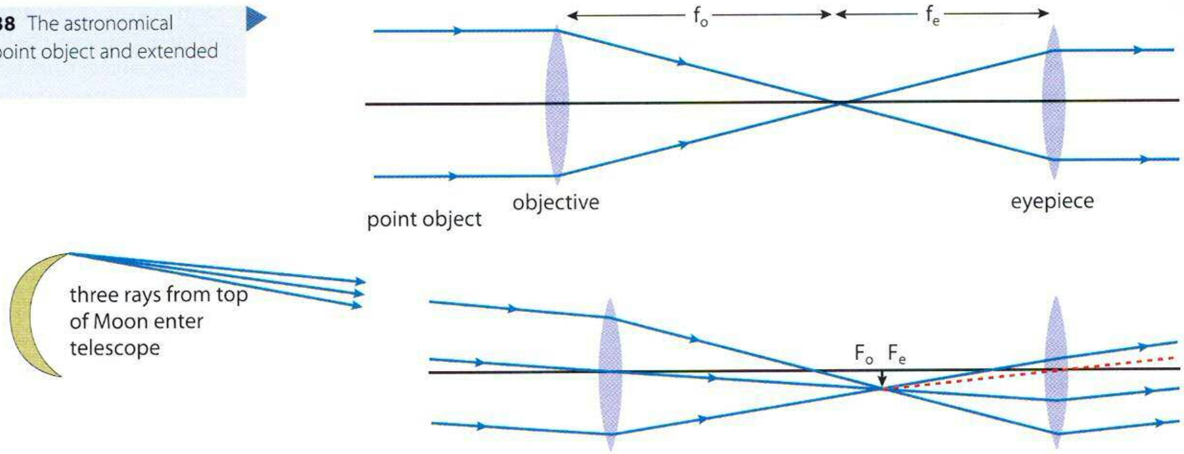


Figure 15.38 The astronomical telescope (point object and extended object).

To see how this produces a magnified image we must use an extended object. In the case in Figure 15.38 the object is the Moon. The three blue rays are coming from the top of the Moon and the bottom of the Moon is in line with the axis. By the time the rays reach the Earth they are very nearly parallel.

Angular magnification

Since the object is very far away, the image subtended to the unaided eye is the same as the image subtended to the telescope. The angles subtended by the object and the image are as shown in Figure 15.39.

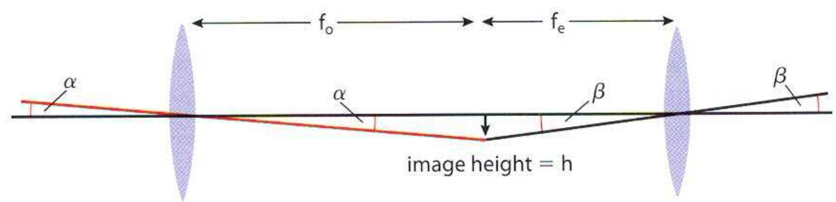


Figure 15.39 Angles subtended at the lenses in an astronomical telescope.

If the angles are small and measured in radians then:

$$\propto = \frac{h}{f_o}$$

$$\beta = \frac{h}{f_e}$$

$$\text{angular magnification} = \frac{\beta}{\propto} = \frac{h}{f_e} \times \frac{f_o}{h} = \frac{f_o}{f_e}$$

A telescope with a large angular magnification is very long. The problem then is that not much light can travel through it; this means that lenses with a large diameter should be used. These are difficult to make, so most high powered telescopes use mirrors not lenses.

• **Examiner's hint:** Before starting the calculation, draw a sketch showing the different positions of the lenses and object. Don't try to draw the rays, the sketch is just to help you see the relative positions.

To access a virtual optics lab, visit www.heinemann.co.uk/hotlinks, enter the express code 4266S and click on Weblink 15.7.

Exercises

29 A microscope is constructed from an objective of focal length 1 cm and an eyepiece of focal length 5 cm. An object is placed 1.5 cm from the objective.

(a) Calculate the distance from the objective to the first image.

(b) If the final image is a virtual image 25 cm from the eyepiece, calculate the distance between the first image and the eyepiece.

(c) Calculate the distance between the lenses.

30 A telescope is constructed from two lenses: an objective of focal length 100 cm and an eyepiece of focal length 10 cm. The telescope is used in normal adjustment (final image at infinity):

(a) Calculate the angular magnification.

(b) What is the distance between the lenses?

31 A telescope has an objective of focal length 50 cm. What focal length eyepiece should be used to give a magnification of 10?

15.6 Aberrations

Assessment statements

G.2.15 Explain the meaning of spherical aberration and of chromatic aberration as produced by a single lens.

G.2.16 Describe how spherical aberration in a lens may be reduced.

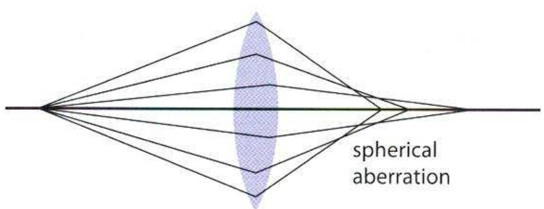
G.2.17 Describe how chromatic aberration in a lens may be reduced.

We have assumed in all the previous examples that parallel rays of light are brought to a point when they shine through a convex lens. However, this is not the case with a real lens.

Spherical aberration

Because of the spherical curvature of a lens, the rays hitting the outer part are deviated more than the ones on the inside (see Figure 15.40).

The result is that if the image is projected onto a screen there will be a spot instead of a point. If such a lens were used to take a photograph then the picture would be blurred. To reduce this effect, the outer rays are removed by placing a card with a hole in it over the lens. This is called *stopping*.



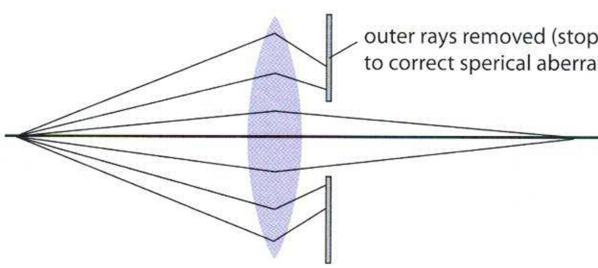


Figure 15.40 Spherical and chromatic aberration in a convex lens.

Chromatic aberration

It has been mentioned before that different wavelengths of light are refracted by different amounts. If white light is focused with a convex lens the different colours are focused at different points. This also causes the image to be blurred. It can be corrected by making the lens out of two lenses of different refractive index stuck together. This is called an *achromatic doublet*. The blue light is most converged by the convex lens and most diverged by the concave one. These two effects cancel each other out.

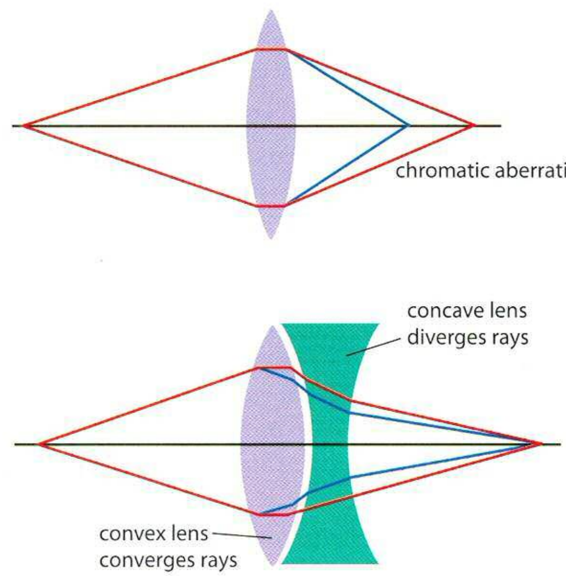
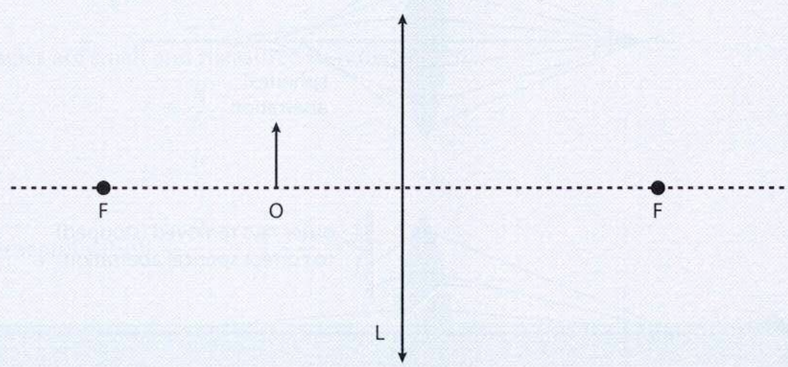


Figure 15.41 Chromatic aberration

Practice questions

1 This question is about converging lenses.

(a) The diagram shows a small object O represented by an arrow placed in front of a *converging* lens L. The focal points of the lens are labelled F.



(i) Define the *focal point* of a converging lens. (2)

(ii) On the diagram above, draw rays to locate the position of the image of the object formed by the lens. (3)

(iii) Explain whether the image is real or virtual. (1)

(b) A convex lens of focal length 6.25 cm is used to view an ant of length 0.80 cm that is crawling on a table. The lens is held 5.0 cm above the table.

(i) Calculate the distance of the image from the lens. (2)

(ii) Calculate the length of the image of the ant. (2)

(Total 10 marks)