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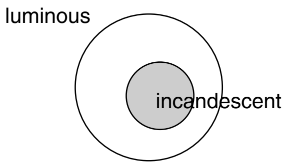
Unit 1 Area of study 1: Wave-like properties of light

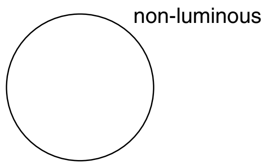
Chapter 1

Reflecting light

1. (a)



(b)



2. Light rays from the light source strike the object and are reflected in all directions. Some of the rays enter my eye.
3. (a) Light rays from the Sun reflected off the flower, travelled through the transparent glass window and entered my eye.
   (b) The points on the TV screen emitted coloured light into the room in all directions. The rays entered my eye.
4. (a) Near Mars,

$$\text{maximum distance} = (2.28 + 1.49) \times 10^{11}\text{ m} = 3.77 \times 10^{11}\text{ m}$$

$$\text{longest time} = \frac{\text{distance}}{\text{speed}} = \frac{3.77 \times 10^{11}}{3.00 \times 10^{8}} = 1257\text{ s} = 21\text{ min}$$

Near Mars,

$$\text{minimum distance} = (2.28 - 1.49) \times 10^{11}\text{ m} = 0.79 \times 10^{11}\text{ m}$$

$$\text{shortest time} = \frac{\text{distance}}{\text{speed}} = \frac{0.79 \times 10^{11}}{3.00 \times 10^{8}} = 260\text{ s} = 4.3\text{ min}$$

(b) Near Neptune,

$$\text{maximum distance} = (45 + 1.49) \times 10^{11}\text{ m} = 46.49 \times 10^{11}\text{ m}$$

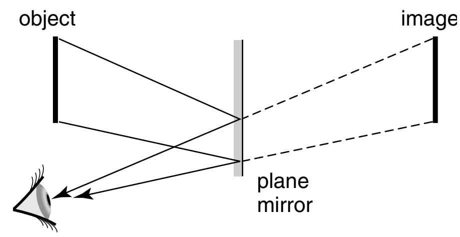
$$\text{longest time} = \frac{\text{distance}}{\text{speed}} = \frac{46.49 \times 10^{11}}{3.00 \times 10^{8}} = 1550\text{ s} = 260\text{ min}$$

Near Neptune,

$$\text{minimum distance} = (45 - 1.49) \times 10^{11}\text{ m} = 43.51 \times 10^{11}\text{ m}$$

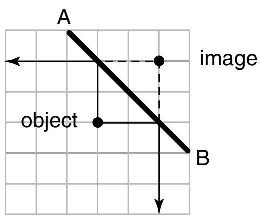
$$\text{shortest time} = \frac{\text{distance}}{\text{speed}} = \frac{43.51 \times 10^{11}}{3.00 \times 10^{8}} = 1.45 \times 10^{4}\text{ s} = 240\text{ min}$$

5.

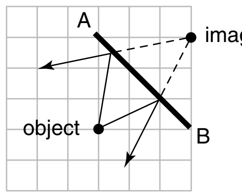


6. $a = 90° - 50° = 40°$
   $b = a = 40°$
   $c = 90° - b = 90° - 40° = 50°$
7. In each diagram, trace the emerging rays back to find where they appear to be coming from. The image is where the dotted lines meet. The image is the same distance behind the mirror as the object is in front.

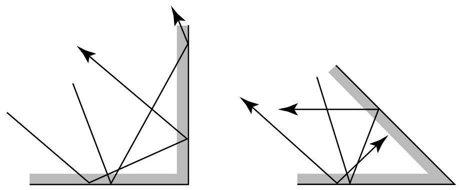
(a)



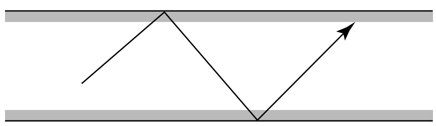
(b)



8. The image is laterally inverted: TOYOTA.
9. A camera captures an image in a similar way to the eye. Light rays coming from the object enter the camera lens. They appear to come from the virtual image. Therefore, if it can be seen, it can be photographed.
10. In the first case, each of the emerging rays is parallel to its corresponding incident ray. In the second case, the ray which is parallel to the angled mirror emerges along the same path from which it came.



11.

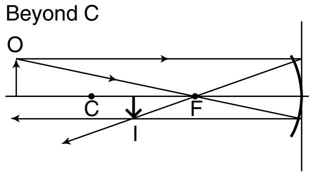


12. Your image is as far behind the mirror as you are in front of it. If you move one metre in one second, then so does your image. Image speed is 1.0 m/s. In that one second, the distance between you and your image decreases by two metres, so the speed of approach is 2.0 m/s.

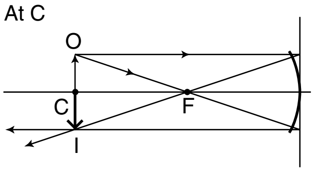
13. Full gloss paint has a mirror-like smooth surface because the paint particles are uniform in size. Matt paint reflects light in all directions; its surface is uneven because the paint particles vary in size.
14. The table can be completed using the ray diagrams shown below it.

Location of object	Location of image	Magnification	Nature	Orientation
beyond C	between C and F	< 1	real	inverted
at C	at C	= 1	real	inverted
between C and F	beyond C	> 1	real	inverted
at F	no image	nil	nil	nil
inside F	behind mirror	> 1	virtual	upright

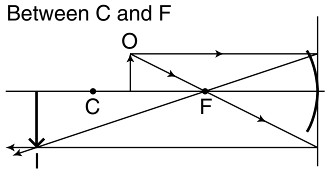
Beyond C



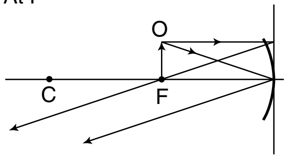
At C



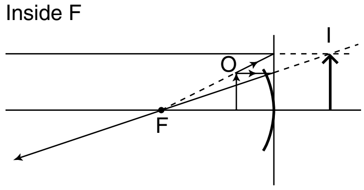
Between C and F



At F



Inside F



15. Using ray diagrams like those shown in the answer to the previous question, drawn to scale, the location, size, nature and orientation can be found. Alternatively, the concave mirror formula can be used, as shown below.
(a) $H_o = 2.0$ cm, $u = 12$ cm, $f = 8.0$ cm

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$
$$\Rightarrow \frac{1}{v} = \frac{1}{8.0} - \frac{1}{12}$$
$$= 0.0417$$
$$\Rightarrow v = 24 \text{ cm}$$
$$\frac{H_i}{H_o} = \frac{v}{u}$$
$$\Rightarrow H_i = \frac{24}{12} \times 2.0$$
$$= 4.0 \text{ cm}$$

The image is 24 cm in front of the mirror; it is 4.0 cm high, real and inverted.

(b) $H_o = 5.0$ cm, $u = 1.0$ m, $f = 10$ cm

$$\frac{1}{v} = \frac{1}{f} - \frac{1}{u}$$
$$= \frac{1}{10} - \frac{1}{100}$$
$$= 0.09$$
$$\Rightarrow v = 11 \text{ cm}$$
$$H_i = \frac{v}{u} \times H_o$$
$$= \frac{11}{100} \times 5.0$$
$$= 5.5 \text{ cm}$$

The image is 11 cm in front of the mirror; it is 5.5 cm, real and inverted.

(c) $H_o = 4.0$ cm, $u = 12$ cm, $f = 20$ cm

$$\frac{1}{v} = \frac{1}{f} - \frac{1}{u}$$
$$= \frac{1}{20} - \frac{1}{12}$$
$$= 0.033$$
$$\Rightarrow v = -30 \text{ cm}$$
$$H_i = \frac{v}{u} \times H_o$$
$$= \frac{-30}{12} \times 4.0$$
$$= -10 \text{ cm}$$

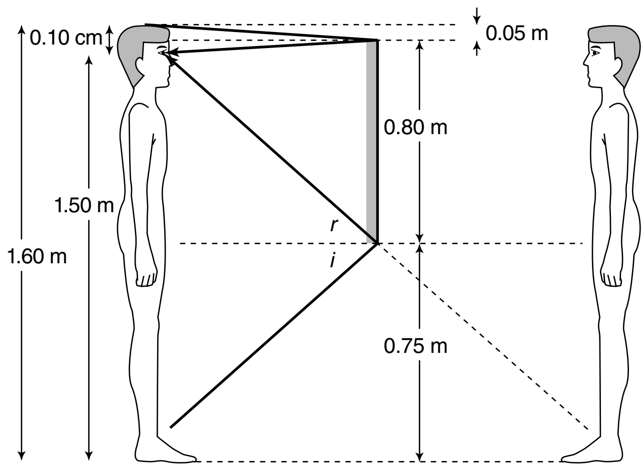
The image is 30 cm behind the mirror; it is 10 cm high, upright and virtual.

16. $H_o = 4.0$ cm, $u = 15$ cm, $f = -10$ cm

$$\frac{1}{v} = \frac{1}{f} - \frac{1}{u}$$
$$= \frac{1}{-10} - \frac{1}{15}$$
$$= -0.167$$
$$\Rightarrow v = -6.0 \text{ cm}$$
$$H_i = \frac{v}{u} \times H_o$$
$$= \frac{-6.0}{15} \times 4.0$$
$$= -1.6 \text{ cm}$$

The image is 6 cm behind the mirror; it is 1.6 cm high, upright and virtual.

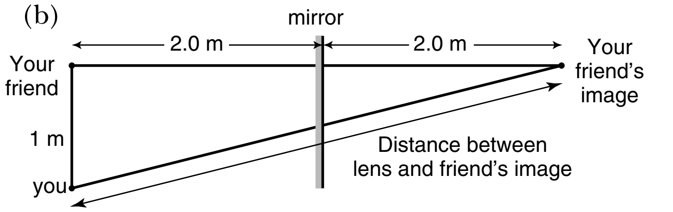
17. At night, people from across the globe can see the Moon, so the light from the Sun is reflected in all directions by the rough surface of the Moon. Some part of the Moon can be seen at all positions of its revolution about the Earth, except during an eclipse.
18. (a) 0.80 m (b) 0.80 m
(c) 0.80 m, 0.75 m (d) Unchanged



The answers are the same regardless of how far away you are from the mirror.

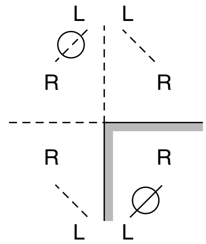
19. (a) Focus the camera lens at 4.0 metres away because your image is 4.0 metres from the camera.

(b)



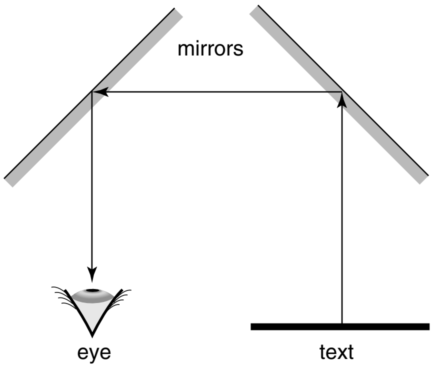
The camera, the friend and the friend's image form a right-angled triangle, so Pythagoras's theorem can be used to determine the distance from the camera to the image. The distance needs to be set at 4.1 m.

20.

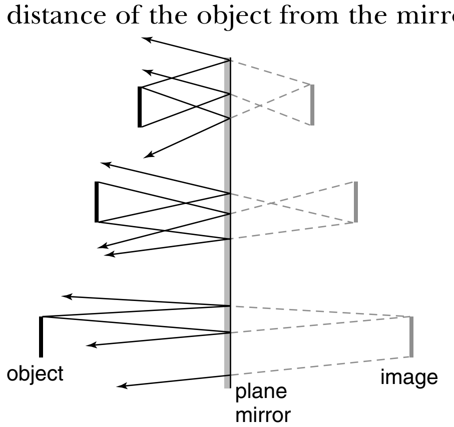


By tracing the rays from the points L and R on the object, three virtual images can be located. The image behind the point at which the mirrors touch is not laterally inverted. This question can also be answered experimentally.

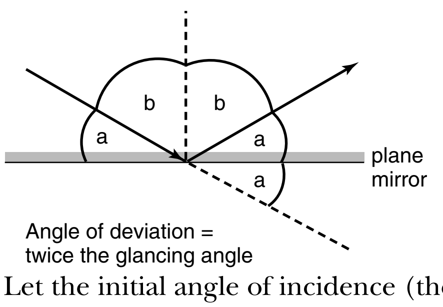
21. Use two plane mirrors with the text upside down on the patient's chest. The patient looks in one mirror at the image of the text in the other mirror.



22. The size of the image is the same regardless of the distance of the object from the mirror.

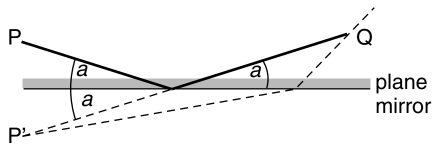


23.



24. Let the initial angle of incidence (the angle between I and N_1) = θ; then the angle between I and $N_2 = \theta - \alpha$, which will equal the angle between N_2 and R_2, so the angle between N_1 and $R_2 = \theta - \alpha - \alpha = \theta - 2\alpha$. However, the angle between N_1 and $R_1 = \theta$, so the angle between R_1 and $R_2 = 2\alpha$.

25.



The distance from Q to P' is the shortest when it is in a straight line, that is, when the angles with the mirror are equal.

26. Infinite. Using the mirror formula:

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

Image distance (v) = −object distance (u)

$$\Rightarrow \quad \frac{1}{f} = 0$$

$\Rightarrow$ f is infinite.

27. (a) $u = 30$ cm, $M = 2.0$,

since $M = \frac{v}{u}$, $v = -60$ cm

(negative because the image is upright and virtual)

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

$$\Rightarrow \frac{1}{f} = \frac{1}{30} + \frac{1}{-60}$$

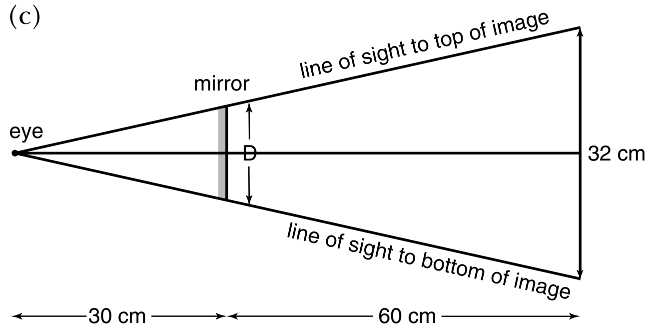
$$= \frac{1}{60}$$

$$\Rightarrow \quad f = 60 \text{ cm}$$

The focal length is 60 cm.

(b) The image is located 60 cm on the other side of the mirror (see answer to (a)).

(c)



$$M = 2$$

$$\Rightarrow H_i = 2H_o$$

$$= 32 \text{ cm}$$

The image is 90 cm away from your eye (30 cm + 60 cm).

Using similar triangles the diameter of the mirror, D, is given by:

$$\frac{D}{32} = \frac{30}{90}$$

$$\Rightarrow \quad D = 10.7 \text{ cm}$$

28. (a) $u = 2.0$ cm, $M = 3.0$,

since $M = \frac{v}{u}$, $v = -6.0$ cm

(negative because the image is upright and virtual)

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

$$\Rightarrow \frac{1}{f} = \frac{1}{2} + \frac{1}{-6}$$

$$= \frac{1}{3}$$

$$\Rightarrow \quad f = 3 \text{ cm}$$

The focal length is 3 cm.

(b) Parts of the tooth closer to the mirror will have a lesser magnification than those further away. This will create a distorted image of the tooth.

29. The object is located at the focus of the mirror.

30. $u = 3.8 \times 10^{10}$ cm
The image is formed at the focus.
$\Rightarrow \quad v = 20$ cm

$$\frac{H_i}{H_o} = \frac{v}{u}$$

$$\Rightarrow H_i = \frac{20}{3.8 \times 10^{10}} \times 2 \times 1.740 \times 10^8$$
$$= 0.18 \text{ cm}$$

The image can be made brighter by using a mirror with a larger diameter to collect more light.
The image can be made larger by increasing the focal length of the mirror because

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

$\Rightarrow$ larger v for larger f and $M = \dfrac{v}{u}$

31. If the top half of a concave mirror is removed, then the location, nature, orientation and size of the image are unchanged. The image is still the full image of the object, but the brightness is less because it is formed with half the light.

32. Place the mirror on the floor under your feet.

33. Some light is reflected off the surface of the drop and into your eye.

34. (a) Distance to moon $= \frac{1}{2} \times$ distance travelled by the light
$= \frac{1}{2} \times$ speed $\times$ time
Distance centre to centre
= distance to moon + radius of moon + radius of Earth

$$= \frac{0.5 \times 2.998 \times 10^8 \times 2.479}{1000} + 1740 + 6380 = 379\,722$$
$$= 3.80 \times 10^5 \text{ km}$$

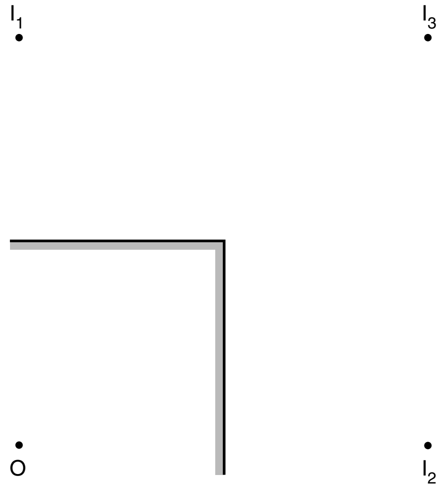
(b) Distance Earth travelled
= speed of Earth's surface $\times$ time taken by laser beam

$$= \frac{\text{circumference of Earth}}{\text{time of one day in seconds}} \times \text{time taken by laser beam.}$$

$$\Rightarrow \text{Distance (km)} = \frac{2 \times \pi \times 6380}{24 \times 60 \times 60} \times 2.479$$
$$= 1.15 \text{ km}$$

(c) Either (i) the transmitter and receiver have to be 1.15 km apart, or (ii) the reflector on the moon has been adjusted to send the beam forward of the incoming direction to arrive back at the same spot on the Earth, or (iii) the laser beam is designed to spread out sufficiently so that with a sensitive detector the spread-out return beam can be detected anywhere in a radius of a few kilometres. Which solution is more likely?

35. Seven images. One pair of mirrors produces three images of the object as shown in the following figure.
The third mirror produces an image of the object and an image of each of the three images produced by the first pair of mirrors.



36. The moon is such a long distance away that its image will be formed at the focus, that is, 3190 km below the surface of the lake (half the radius of curvature).
$v = f = 3190$ km
H_o = diameter of moon = 3480 km

$$\frac{H_i}{H_o} = \frac{v}{u}$$

$$\Rightarrow H_i = \frac{3190}{3.8 \times 10^5} \times 3480$$
$$= 29 \text{ km}$$

The image of the moon is 29 km across.

Chapter 2

Refracting light

1. $\sin\theta = \dfrac{\sin 40°}{1.33}$, $\theta = 29°$

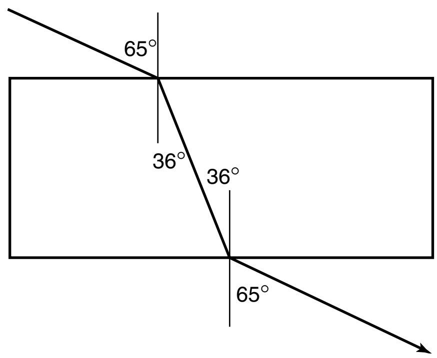
$\sin\theta = \dfrac{\sin 50°}{1.33}$, $\theta = 35°$

Angle of refraction increases by 6° when the angle of incidence increases by 10°.

2. $\sin 55° = n \sin 33°$, $n = \dfrac{\sin 55°}{\sin 33°}$

$n = 1.5$

3. $\sin\theta = \dfrac{\sin 65°}{1.55}$, $\theta = 36°$



The block is rectangular, so the opposite sides are parallel. Therefore, the angle of incidence at the bottom face is the same as the angle of refraction at the top face. Because Snell's Law applies regardless of the direction of the light ray, the angle of refraction as the light emerges will be the same as the angle with which it entered the block. This means the ray is parallel to the incoming ray, but shifted sideways.

4. (a) The different layers are parallel to each other, so the angle of refraction at the top surface of a liquid will equal the angle of incidence at the bottom surface. This means that:

$$n_{\text{air}} \times \sin \theta_{\text{air}} = n_{\text{acetone}} \times \sin \theta_{\text{acetone}}$$
$$= n_{\text{glycerol}} \times \sin \theta_{\text{glycerol}}$$
$$= n_{\text{carbon tet}} \times \sin \theta_{\text{carbon tet}}$$

$n_{\text{air}} = 1.0$, $\theta_{\text{air}} = 25°$, $\theta_{\text{acetone}} = 18.1°$, $\theta_{\text{glycerol}} = 16.7°$, $\theta_{\text{carbon tet}} = 16.8°$

$$\Rightarrow 1.0 \times \sin 25° = 1.357 \times \sin \theta_{\text{acetone}}$$
$$= 1.4746 \times \sin \theta_{\text{glycerol}}$$
$$= 1.4601 \times \sin \theta_{\text{carbon tet}}$$
$$\Rightarrow 1.4601 \times \sin \theta_{\text{carbon tet}} = 1.53 \times \sin \theta_{\text{glass}}$$

All expressions equal each other, so the angles of refraction will equal 1.0 × sin 25° / refractive index of the medium. So, for acetone the angle is 18°, for glycerol: 16.7°, carbon tetrachloride: 16.8°, and glass: 16.0°. Because the layers are parallel, the light ray will emerge from the glass into the air at the angle it left the air: 25°.

(b) When the light reflects off the mirror, the angle of reflection will equal the angle of incidence, so the light ray will leave the bottom medium at the same angle that it entered it. The light path up through the layers will be the reverse of the path coming down through the layers. All the angles will be the same.

5. $2.5 \times \sin \theta_c = \sin 90° = 1$

$$\sin \theta_c = \frac{1}{2.5} = 0.4$$
$$0.4\theta_c = 24°$$

6. Find the critical angle.
$1.33 \times \sin \theta_c = \sin 90° = 1$

$$\Rightarrow \sin \theta_c = \frac{1}{1.33} = 0.75$$
$$\Rightarrow \theta_c = 48.59 = 49°$$

The angle of incidence of 55° is greater than the critical angle, so the light ray will be totally internally reflected and will reflect off the water surface with an angle of reflection of 55°.

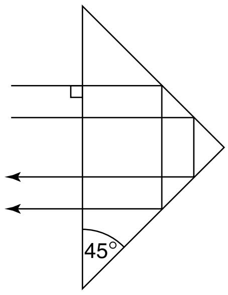
7. (a) The critical angle is 45°, so the refractive index $= \dfrac{1}{\sin 45°} = 1.4$.

For total internal reflection, $n \times \sin \theta_c \geq 1$.

If $n < 1.4$, then $n \times \sin \theta_c < 1$, so the ray will refract out of the glass.

$\Rightarrow n = 1.4$ is the minimum value for total internal reflection to occur for an angle of incidence of 45°.

(b) The positions of the rays are inverted. This device is used twice in binoculars to correct the normally inverted image produced by a telescope.

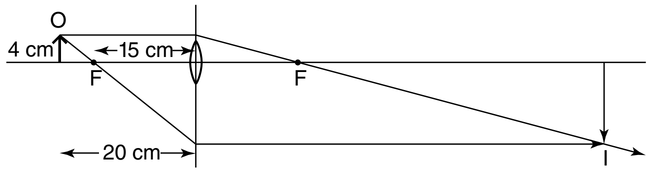


8. $1.500 \times \sin 82.0° = n \times \sin 90°$
$\Rightarrow n = 1.500 \times \sin 82.0° = 1.49$

9. (a) The wavelet produced at the surface projects into the air as well as into the glass.

(b) The surface cannot both attract and repel the particles at the same time.

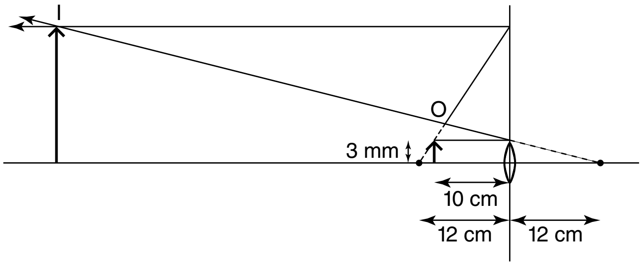
10. (a)



Note: horizontal and vertical scales are not the same.

The image is real and inverted and located 60 cm from the lens on the other side from the object. It is about 12 cm high.

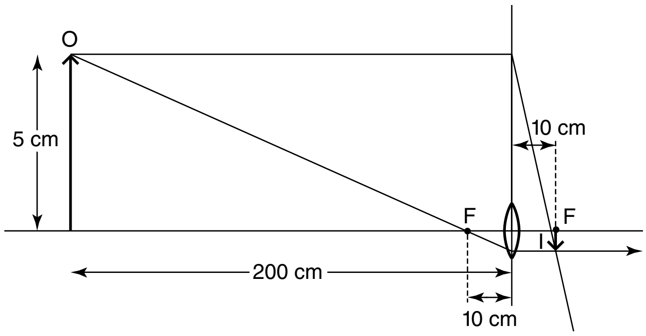
(b)



Note: horizontal and vertical scales are not the same.

The image is virtual and upright and located 60 cm from the lens on the same side as the object. It is 18 mm high.

(c)



Note: horizontal and vertical scales are not the same.

The image is real and inverted and located 10.5 cm from the lens on the other side from the object. It is about 2.5 mm high.

11. $u = 30$ cm, $v = 5.0$ cm, $f = ?$

$$\frac{1}{f} = \frac{1}{30} + \frac{1}{5.0} = 0.23$$
$$\Rightarrow f = 4.3 \text{ cm}$$

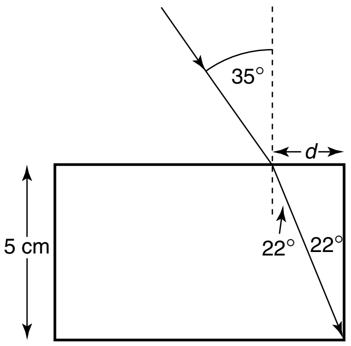
12. 'Accommodation mechanism' is the strategy that an animal's eye uses to keep an image sharp and in focus on the retina whether the object is near or distant. There are several different mechanisms. The thickening of the human lens to achieve a sharp image of nearby objects on the retina is an example. Another is the movement of a fixed focal length lens closer to the retina as the object moves further away.

13. (a) $1.0 \times \sin 35° = 1.55 \times \sin \theta$

$$\sin \theta = \frac{\sin 35°}{1.55} = 0.3700$$

$\theta = 22°$. The angle of incidence at the bottom surface is 22° and the angle of refraction is 35°.

(b)



$\tan 22° = \dfrac{d}{5.0}$ cm

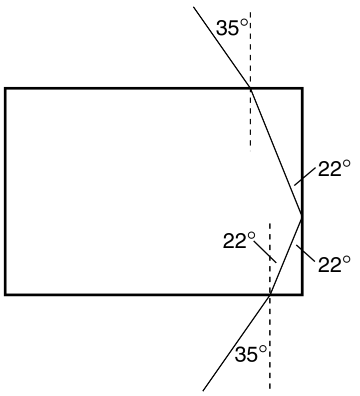
$\Rightarrow d = 5.0 \times \tan 22° = 2.0$ cm

(c) Angle of incidence at adjacent face = 90 − 22 = 68°. The critical angle is given by

$\sin \theta_c = \dfrac{1}{1.55}$

$\Rightarrow \theta_c = 40°$, so the light ray undergoes total internal reflection.

(d)



Because of symmetry the ray will meet the bottom surface at an angle of incidence of 22°, so the angle of refraction will be 35°.

(e) If the initial angle was less than 35°, then the ray would meet the adjacent face at a more glancing angle and so be totally reflected. The largest value for the initial angle is 90°. This gives an angle of refraction of 40° and so an angle of incidence of 50° at the adjacent face, which is greater than 40° and is totally reflected. So all rays, regardless of angles, will be totally reflected.

(f) Total internal reflection at the adjacent face does depend on the refractive index. Any values less than 1.414 will allow the light to pass out the adjacent face for some angles. The value 1.414 is the square root of 2, which is sin 45°, which is the case when the angle of refraction at the top face equals the angle of incidence at the adjacent face.

14. Above, the diver would see a circle in which was compressed a 180° view of the world above the water. Towards the edge of the circle, the image would look distorted. Outside the circle, the diver would see the reflected, inverted image of the world beneath the surface of the water due to the total internal reflection of the light rays from beneath the water as they meet the water–air boundary.

15. Critical angle for light travelling from glass into water is given by:

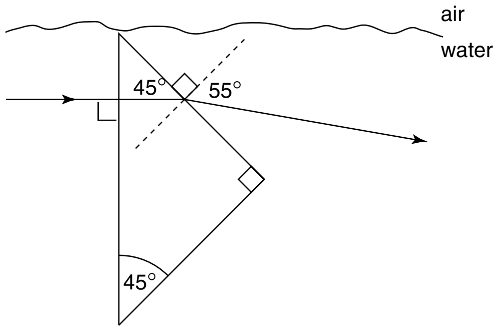
$1.55 \times \sin \theta_c = 1.33 \times \sin 90°$

$\sin \theta_c = \dfrac{1.33}{1.55} = 0.858$

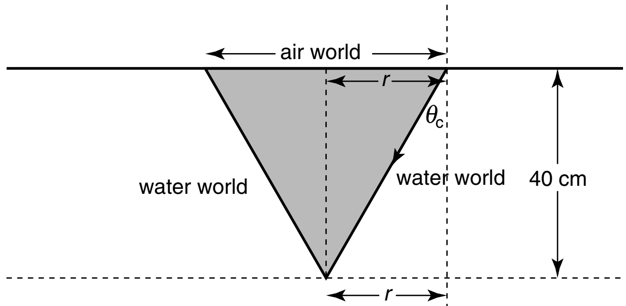
$\Rightarrow \theta_c = 59.1°$. The angle of incidence at the glass–water boundary is 45°, which is less than the critical angle, so the ray is refracted into the water. The angle of refraction, θ_w, is given by:

$1.55 \times \sin 45° = 1.33 \times \sin \theta_w$

$\Rightarrow \theta_w = 55°$



16.



At critical angle $1.33 \times \sin \theta_c = 1.0 \times \sin 90°$

$\Rightarrow \theta_c = 48.8°$

$\tan \theta_c = \dfrac{r}{40}$, so $r = 40 \times \tan 48.8°$

= 46 cm

17. (a) Path length of reflected ray

$= 2 \times \dfrac{r}{\cos 82°}$

$= 2 \times \dfrac{0.5 \times 1 \times 10^{-6}}{\cos 82°}$

$= 7.18 \times 10^{-6}$ m

Path length of straight ray

$= 2 \times r \tan 82°$

$= 2 \times 0.5 \times 1 \times 10^{-6} \times \tan 82°$

$= 7.11 \times 10^{-6}$ m

Path length difference is

$7.18 \times 10^{-6} - 7.11 \times 10^{-6}$

$= 7.0 \times 10^{-8}$ m

(b) Speed of light in the glass $= \dfrac{c}{n}$

$\sin \theta_c = \dfrac{1}{n}$

$\Rightarrow n = \dfrac{1}{\sin 82°}$

⇒ Speed of light in the glass

$= \dfrac{3.0 \times 10^8}{\sin 82°} = 3.0 \times 10^8$ m s^{-1}

Time difference $= \dfrac{\text{distance}}{\text{speed}}$

$= \dfrac{7.0 \times 10^{-8}}{3.0 \times 10^8} = 2.3 \times 10^{-16}$ s

This time is small, but in an optical fibre of 1.00 km, there would be $\dfrac{1.00 \times 10^3}{7.11 \times 10^{-6}}$ reflections, equals 1.4×10^8 reflections, corresponding to a total time difference of 3.28×10^{-8} s. This would limit the upper frequency of light pulses sent down the optical fibre. Too high a frequency and the pulses would overlap. The problem can be overcome by using a narrower optical fibre or using an optical fibre whose refractive index gets smaller the greater the distance from the centre.

18. (a) You would see an inverted image of the teacher.
    (b) The trees are further away, so their image is closer to the focus of the lens; so move the screen closer to the lens.

19. For objective lens $u = 5.2$ mm, $f = 5.0$ mm

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

$$\Rightarrow \quad \frac{1}{v} = \frac{1}{5.0} - \frac{1}{5.2}$$

$$\Rightarrow \quad v = 130 \text{ mm}$$

This is 20 mm in front of the eyepiece lens.

$$M = \frac{H_i}{H_o} = \frac{v}{u} = \frac{130}{5.2}$$

For eyepiece lens $u = 20$ mm, $f = 40$ mm

$$\frac{1}{v} = \frac{1}{20} - \frac{1}{40}$$

$$\Rightarrow \quad v = 40 \text{ mm}$$

$$M = \frac{v}{u} = 2$$

$$\text{Total magnification} = 2 \times \frac{130}{5.2} = 50$$

The same result can be obtained using a ray-tracing diagram.

20. (i) (f) (ii) (d) (iii) (b)
    (iv) (c) (v) (g) (vi) (a)

21. (a) $u = 4.0$ cm, $f = 5.0$ cm, $v = ?$

$$v = \frac{1}{\frac{1}{5} - \frac{1}{4}} = -20$$

$$\text{Magnification} = \frac{v}{u} = \frac{20}{4} = 5.$$

The image is located 20 cm behind the lens and is 5 times as big.

(b) $u = 3.0$ cm, $f = 5.0$ cm, $v = ?$

$$v = \frac{1}{\frac{1}{5} - \frac{1}{3}} = -\frac{15}{2} = -7.5$$

$$\text{Magnification} = \frac{7.5}{3} = 2.5.$$

The image is located 7.5 cm behind the lens and is 2.5 times as big.

22. (a) $v = 400$ cm, $f = 5.00$ cm, $u = ?$

$$u = \frac{1}{\frac{1}{5} - \frac{1}{400}} = -\frac{400}{79} = 5.06$$

The slide is located 5.06 cm from the lens.

(b) $\text{Magnification} = \frac{v}{u} = 79$

The size of each side of the square image is $79 \times 35 = 2765 = 2.76$ m.

(c) The image is inverted and will be an 'L', but upside down and back to front.
(d) A clear image needs to be formed closer to the lens, so the object, that is, the slide, needs to be moved further away from the lens.

23. The slide projector needs to be moved back and the lens moved closer to the slide.

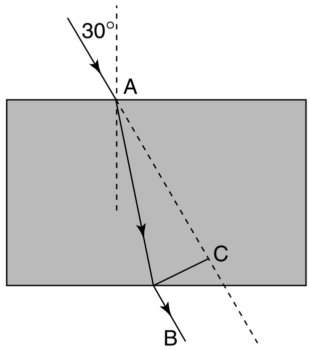
24. $u = 1500$ cm, $f = 5.00$ cm, $v = ?$

$$v = \frac{1}{\frac{1}{5} - \frac{1}{1500}} = 5.02 \text{ cm}$$

25. (a) Your refractive index must be the same as the air, the medium the body is in. Otherwise, images of objects behind you would appear to be distorted.
    (b) The light entering the eye is absorbed by the eye, so a person looking in the direction of a so-called invisible person would see a black screen the shape of the retina obscuring the view in front. So to be truly invisible the retina would not be able to absorb light. That is, a truly invisible person would not be able to see.

26. $1.00 \times \sin 65° = 1.55 \times \sin \theta$
Angle of refraction = 36°
⇒ Angle of deviation
= 65 − 36 = 19°

27.

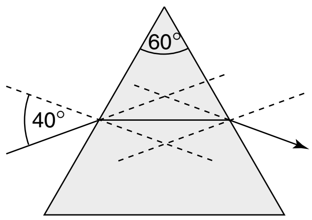


The angle of refraction is given by
$\sin 30° = 1.4 \times \sin \theta \Rightarrow \theta = 20.9°$.
Length of the path ray in the glass

$$= \frac{5.0}{\cos 20.9°}$$

Sideways deflection
= length of light path
$\times \sin(30.0 - 20.9) = 0.85$ cm

28.



The angle of refraction is obtained from
$\sin 40° = 1.5 \times \sin \theta \Rightarrow \theta = 25.4°$.
The angle where the normals meet equals 120°, so the angle of incidence at the exit face equals
180 − 120 − 25.4 = 34.6°.
The angle of refraction will therefore be 58.4°.
The angle of deviation will equal:
(angle of incidence − angle of refraction at the first face) + (angle of refraction − angle of incidence at the second face), which equals
(40° − 25.4°) + (58.4° − 34.6°)
= 34.4°.

29. $\sin 30° = 1.5 \times \sin \theta \Rightarrow \theta = 19.5°$
When the ray meets the opposite side of the glass sphere, the normal at this point passes through the centre of the sphere (i.e. it is a radius). This means that the triangle formed by the points on the glass sphere and the centre of the sphere is an isosceles triangle and that the angle of incidence at the opposite side of the sphere is 19.5°. This situation is the reverse of the entry into the sphere, so the angle of refraction is 30°.

30. (a)

	A	B	C	D
1	Angle of	Refractive	Refractive	Angle of
2	incidence	index	index	refraction
3	89	1.0003	1.00028	89.06794
4	89.06794	1.00028	1.00026	89.14124
5	89.14124	1.00026	1.00024	89.22141
6	89.22141	1.00024	1.00022	89.31085
7	89.31085	1.00022	1.0002	89.41379
8	89.41379	1.0002	1.00018	89.53917
9	89.53917	1.00018	1.00016	89.71526
10	89.71526	1.00016	1.00014	#NUM!

(b) In the seventh layer, the light will be totally internally reflected. With the refractive indices the same, if the initial angle of incidence was 88° the ray would not be reflected. If the initial angle was 89.5°, the reflection would occur in the first layer. If the rate of change in the refractive index was halved to 0.000 01, then the reflection would occur in the 15th layer.

31. Light bends away from the normal, so the refractive index gets smaller with height. This means the temperature rises with height.

32. (a) $u = 3.1$ mm, $f = 3.00$ mm, $v = ?$

$$v = \frac{1}{\frac{1}{3} - \frac{1}{3.1}} = 93 \text{ mm}$$

The real image formed by the objective lens is $100 - 93 = 7.0$ mm from the eyepiece lens.
$u = 7.0$ mm, $f = 15$ mm, $v = ?$

$$v = \frac{1}{\frac{1}{15} - \frac{1}{7}} = -13.1 \text{ mm}$$

The virtual image formed by the eyepiece lens is 13 mm in front of the lens.

(b) Magnification of objective lens $= \frac{93}{3.1} = 30$

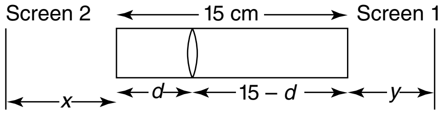
Height of image
$= 30 \times 1.0 \text{ mm} = 30$ mm

Magnification of eyepiece lens $= \frac{13.1}{7.0} = 1.87$

Height of final image
$= 1.87 \times 30 = 56$ mm

33. The eye should be placed several centimetres behind where the screen was. The rays that form the image on the screen will still pass through that point in space, regardless of whether the screen is there or not. If the screen is removed, these rays will leave that point so that the lens in the eye will form a real image on the retina.

34. Set the source at least a few metres away so that the image is formed very close to the focus. Measure the distance, y, from the end of the tube. Turn the tube around and measure the distance, x, again.



Focal length $= x + d = y + 15 - d$
$\Rightarrow 2d = 15 + y - x$
Then, substitute in focal length
$= x + d$

35. See figure 2.29 on p. 37 of the textbook and answers to Investigation 2.7 on the *jaconline* website. The images are always virtual and on the same side of the lens as the object. When the object is distant from the lens, the image is very small and located at or just inside the focus. As the object approaches the lens, the image gets bigger and closer to the lens, so that when the object is at the lens, so is the image.

36. (a) The image is virtual.
$u = 5.0$ cm, $v = -25$ cm, $f = ?$

$$f = \frac{1}{\frac{1}{5} - \frac{1}{25}} = 6.25 \text{ cm}$$

The focal length is 6.25 cm.

(b) The image is virtual. Assume the book is held 30 cm from the eyes and the magnifying glass is held 6 cm above the book.
$u = 6$ cm, $v = 30 - 50 = -20$ cm
$f = ?$

$$f = \frac{1}{\frac{1}{6} - \frac{1}{20}} = 8.6 \text{ cm.}$$

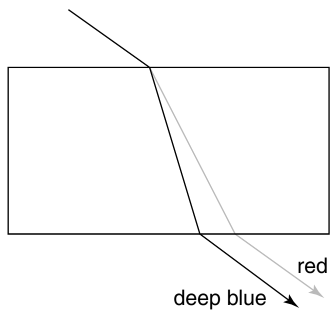
The focal length of the lens is 8.6 cm.

Chapter 3

Seeing colours

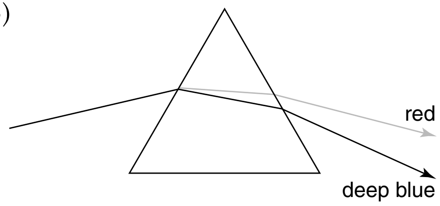
1. *Refraction:* bending of light as it passes from one material into another.
Reflection: light leaves a surface at the same angle it approached the surface.
Dispersion: the spreading of light into colours as it is refracted.
Spectrum: the range of colours into which light can be broken.
Refractive index: a measure of how much a material slows light down and therefore changes its direction.
Chromatic aberration: circumstances, such as the use of telescopes and cameras, where dispersion distorts the image.

2. (a)



The emerging coloured rays are parallel to each other.

(b)



In a triangle, the rays emerge at different angles and spread further apart the further they travel, so that on a distant wall the colours are seen separately. With the rectangle, the colours stay the same distance apart regardless of how far they travel.

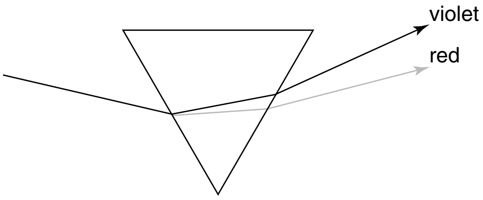
3. A periodic wave is a pulse that is repeated at regular intervals.
4. (a) 5 drops in 10 s = > 1 drop in 2 s: $T = 2$ s

   (b) $f = \frac{1}{T} = \frac{1}{2}\,\text{s}^{-1} = 0.5$ Hz
5. Red light, as it has a lower refractive index

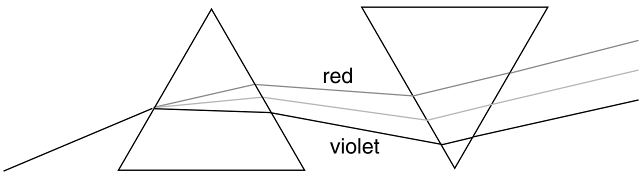
$$\text{Speed in red light} = \frac{c}{n_r} = \frac{3.00 \times 10^8}{1.514} = 1.981\,51 \times 10^8 \text{ m s}^{-1}$$

$$\text{Speed in violet light} = \frac{c}{n_b} = \frac{3.00 \times 10^8}{1.528} = 1.963\,35 \times 10^8 \text{ m s}^{-1}$$

   Difference = 1.82×10^6 m s^{-1}
6. Violet light is bent more as it has a greater refractive index.
7.



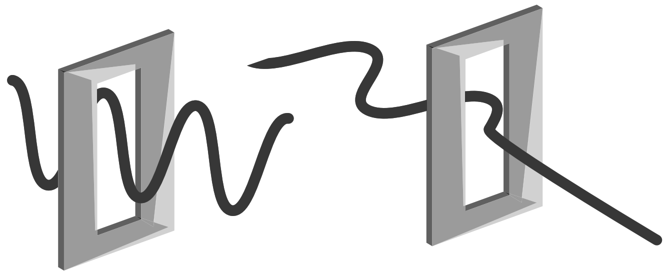
8.



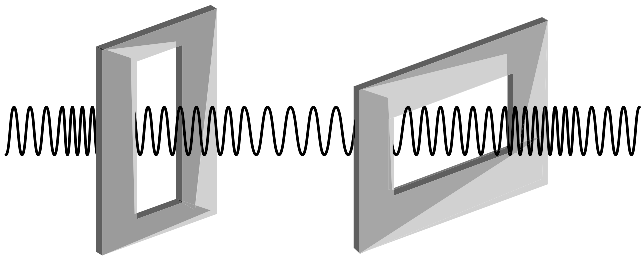
9. Because the violet light is bent more than the red at both the front and back surfaces of the lens, the violet light will come to a focus closer to the lens and so have a shorter focal length.
10. (a) In the morning the Sun is in the eastern sky. To see a rainbow, the Sun needs to be behind you so that light that is totally internally reflected from the raindrop enters your eye. You would need to look to the west. At midday it would be very difficult to see a rainbow as the Sun needs to be behind you, so you need to look down, preferably from a plane or a balloon.

    (b) In the northern hemisphere the directions are the same as in the southern hemisphere.
11. The Sun would be behind you on the other side of the plane. The rainbow will still be circular, but because you are in the air, you could see a full circle because there may be water droplets below.
12. (a) C

    (b) A and B
13. If light behaved like a longitudinal wave, it could not be restricted to travelling only in a plane that was not parallel to its direction of propagation.



Transverse waves:
polarisation can occur



Longitudinal waves:
no polarisation

14. For red light:
    $\sin\theta = n_r \sin 30° = 1.4742 \times 0.5$
    $\Rightarrow$ angle of refraction for the red light is 19.8°
    For blue light:
    $\sin\theta = n_b \sin 30° = 1.4810 \times 0.5$
    $\Rightarrow$ angle of refraction for the blue light is 19.7°
    The difference is 0.1°.
15. For red light:

$$\sin\theta_c = \frac{1}{n_d} = \frac{1}{2.40}$$

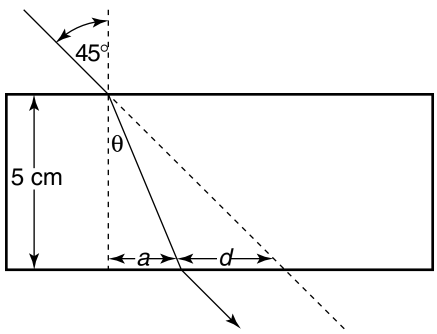
$$\Rightarrow \theta_c = 24.6°$$

    The critical angle for red light is 24.6°.
    For blue light:

$$\sin\theta_c = \frac{1}{n_d} = \frac{1}{2.24}$$

$$\Rightarrow \theta_c = 24.2°$$

    The critical angle for blue light is 24.2°.
16.



(a) For red light:

$$\sin\theta = \frac{\sin 45°}{n} = \frac{\sin 45°}{1.514}$$

$$\Rightarrow \theta = 27.8°$$

$$\tan 27.8° = \frac{a}{5.0}$$

$$\Rightarrow a = 2.64 \text{ cm}$$

$$\tan 45° = \frac{a + d}{5.0}$$

$$\Rightarrow a + d = 5.00 \text{ cm}$$

$$\Rightarrow d = 5.00 - 2.64 = 2.36 \text{ cm}$$

For deep blue light:

$\sin \theta = \frac{\sin 45°}{n} = \frac{\sin 45°}{1.528}$

$\Rightarrow \theta = 27.6°$

$\tan 27.6° = \frac{a}{5.0}$

$\Rightarrow a = 2.61$ cm

$\tan 45° = \frac{a + d}{5.0}$

$\Rightarrow a + d = 5.00$ cm

$\Rightarrow d = 5.00 - 2.61 = 2.39$ cm

Red light is shifted sideways by 2.36 cm, and deep blue light by 2.39 cm.

(b) Deep blue light is shifted more, by 0.03 cm.

(c) Each colour is shifted more as the angle of incidence increases for all angles. By calculating the shifts for different colours for various angles of incidence, you can show that the difference between the shifts for a given pair of colours increases for angles of incidence up to about 57°, then decreases.

17. $T = \frac{1}{f} = \frac{1}{4.8 \times 10^{14}} = 2.08 \times 10^{-15}$

$= 2.1 \times 10^{-15}$s

18. $f = 6.5 \times 10^{14}$

(a) $v = 3 \times 10^8$

$\lambda = \frac{v}{f} = \frac{3 \times 10^8}{6.5 \times 10^{14}} = 4.6 \times 10^{-7}\text{m} = 460\text{nm}$

(b) $v = 2.0 \times 10^8$

$\lambda = \frac{2 \times 10^8}{6.5 \times 10^{14}} = 3.1 \times 10^{-7}\text{m} = 310\text{nm}$

19. (a) Material dispersion is the spreading of light pulses as a result of spreads in frequency in the light source. Refractive index is different for different frequencies, so some parts of the pulses travel through an optical fibre at different speeds than others. Modal dispersion is the spreading of light pulses due to their varying paths as they travel through the fibre. Some have to travel longer distances through the fibre than others.

(b) Both material and modal dispersion cause distortion of signals sent through optical fibres.

(c) Using narrower fibres and using graded index fibres are two ways of reducing modal dispersion.

20. (a) Filters B and C

(b) Filters A+B only slightly

(c) Red–orange

(d) Black — no colour passes through all three filters.

21. For red light:

$\frac{1}{f} = 1.514 - 1\left(\frac{1}{10} + \frac{1}{10}\right)$

$\Rightarrow \quad f = 9.73$ cm

For deep blue light:

$\frac{1}{f} = 1.528 - 1\left(\frac{1}{10} + \frac{1}{10}\right)$

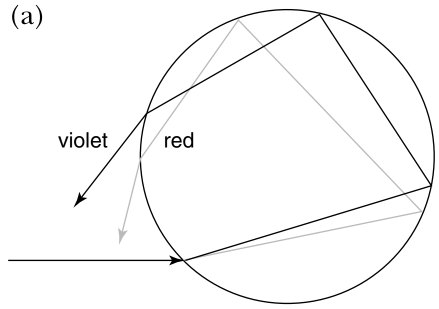
$\Rightarrow \quad f = 9.47$ cm

22. (a) When the Sun is about 40° above the horizon, a small part of the rainbow circle will be above the ground.

(b) When the Sun is on the horizon, half the circle of the rainbow will be above the ground.

23. The rainbow is produced by reflection only. As the light ray enters the raindrop, it is refracted towards the normal. Because a raindrop is approximately spherical, this normal passes through the centre of the raindrop; that is, it is a radius of the sphere. When the refracted ray meets the other side of the drop, the normal at this point will also be a radius. This means that the triangle formed by the centre of the drop and the two points on the surface that the light ray passes through form an isosceles triangle with the two angles at the surface the same. Since light can travel along a light path in either direction, the ray will be refracted out of the drop with an angle of refraction equal to the initial angle of incidence. Only some of the light entering the drops is reflected, but sufficient to see a rainbow, particularly against a dark background.

24. (a)



(b) The order of the colours should be reversed. The rainbow should be higher in the sky and probably the colours should be further apart due to the greater path for divergence of the colours.

25. (a) $v_r = \frac{3.00 \times 10^8}{1.514}$

$= 1.98 \times 10^8$ m s^{-1}

$v_v = \frac{3.00 \times 10^8}{1.532}$

$= 1.96 \times 10^8$ m s^{-1}

(b) For red light: $\sin \theta = \frac{\sin 45°}{1.514} \Rightarrow \theta = 27.8°$

For violet light: $\sin \theta = \frac{\sin 45°}{1.532} \Rightarrow \theta = 27.5°$

For red light, the length of the path, R, through the glass is given by:

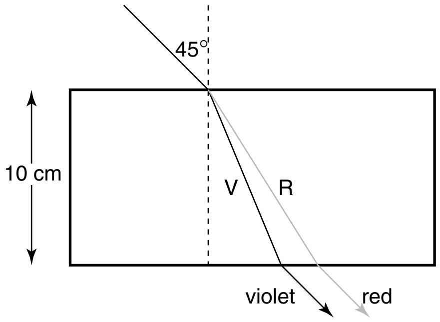
$\cos 27.8° = \frac{10}{R} \Rightarrow R = \frac{10}{\cos 27.8°} = 11.31$ cm

For violet light, the length of the path, V, through the glass is given by:

$\cos 27.5° = \frac{10}{V} \Rightarrow R = \frac{10}{\cos 27.5°} = 11.27$ cm

(c) Time to travel across the block is the distance the light travels divided by its speed. The red light emerges first in 0.0571 microseconds, while the violet light emerges in 0.0576 microseconds.

(d)



The rays will be parallel to each other and to the initial incident ray.

(e) The red ray ends up ahead even though it travels a greater distance in the glass.

26. The waves reflected from the top surface of the oil interfere with those reflected from the bottom surface. Each region of colour on the oil film is the result of constructive interference for that particular colour. Different colours appear because the thickness of the oil film is not constant, so constructive interference for different colours occurs at different places on the film.

27. Newton carried out this second stage of the experiment to see if the prism would further break up the red light.

28. (a) A concave lens has a longer focal length for red light. This is because the red light diverges parallel rays of light less than violet light due to a smaller amount of bending at the front and back surfaces of the lens.

(b) A convex lens diverges violet light more than red light. But the convex lens converges violet more than red light. When the two lenses are combined, the larger divergence of the violet light by the concave lens is compensated for by the larger convergence by the convex lens.