Cambridge IGCSE · Physics 0625 · Notes

Light

Read online at **pastopic.com/cambridge/physics-0625/notes/light**

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Read first: **General properties of waves**

What you need to know

This topic covers what light does at mirrors, at the surfaces of glass and water, in lenses and in a prism. The parts marked **Extended only** are tested on Papers 2 and 4 only. By the end of it you should be able to:

Reflection

1. **Define and use the terms** normal, angle of incidence and angle of reflection.
2. **Describe how a plane mirror forms an image**, and give its characteristics: the same size as the object, the same distance behind the mirror as the object is in front, and virtual.
3. **State and use the law of reflection**: the angle of incidence equals the angle of reflection.
4. **Extended only:** use simple constructions, measurements and calculations for reflection by plane mirrors.

Refraction

5. **Define and use the terms** normal, angle of incidence and angle of refraction.
6. **Describe an experiment** that shows light refracting in transparent blocks of different shapes.
7. **Describe what happens to light** as it passes into and out of a transparent material (at a boundary between two materials).
8. **State what the critical angle means.**
9. **Describe internal reflection and total internal reflection**, with experimental and everyday examples.
10. **Extended only:** define **refractive index** n as the ratio of the speeds of light in two regions.
11. **Extended only:** recall and use $n = \dfrac{\sin i}{\sin r}$.
12. **Extended only:** recall and use $n = \dfrac{1}{\sin c}$.
13. **Extended only:** describe how **optical fibres** are used, especially in telecommunications.

Thin lenses

14. **Describe what thin converging and diverging lenses do** to a parallel beam of light.
15. **Define and use the terms** focal length, principal axis and principal focus (focal point).
16. **Draw and use ray diagrams** for a real image formed by a converging lens.
17. **Describe an image** using the words enlarged / same size / diminished, upright / inverted and real / virtual.

18. **Know that a virtual image** is where diverging rays seem to come from when you trace them backwards, and that it cannot be shown on a screen.
19. **Extended only:** draw and use ray diagrams for a **virtual image** formed by a converging lens.
20. **Extended only:** describe how one converging lens is used as a **magnifying glass**.
21. **Extended only:** describe how converging and diverging lenses **correct long sight and short sight**.

Dispersion

22. **Describe dispersion**: a glass prism splits white light into colours.
23. **Know the seven colours of the visible spectrum** in order of frequency and in order of wavelength.
24. **Extended only:** recall that light of a single frequency is called **monochromatic**.

Understand it

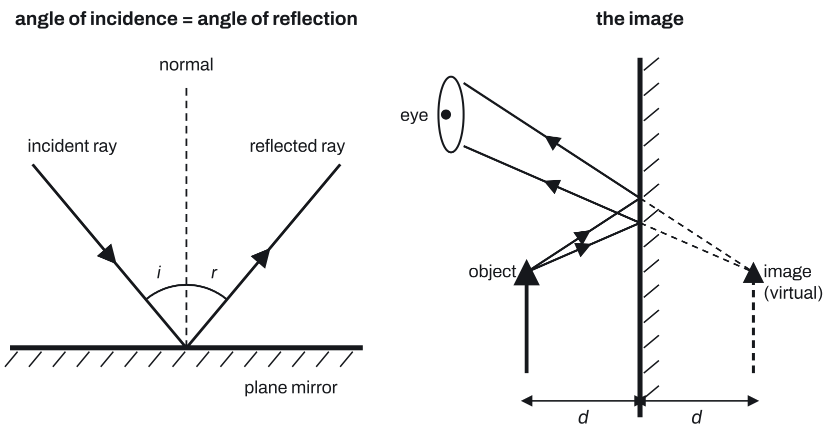
Rays and the normal

A **ray** is a straight line with an arrow that shows the path and direction of light. Light travels in straight lines until it meets a surface. At the point where a ray meets a surface, draw the **normal**: a (dashed) line **at right angles to the surface**. Every angle in this topic is measured **from the normal**, never from the surface.

- **Angle of incidence** i: between the incoming ray and the normal.
- **Angle of reflection** r: between the reflected ray and the normal.
- **Angle of refraction** r: between the refracted ray (the one that goes into the new material) and the normal.

If a question gives the angle between a ray and the **surface**, take it away from 90°: a ray at 35° to a mirror has $i = 90^\circ - 35^\circ = 55^\circ$.

Reflection in a plane mirror



The **law of reflection**: the angle of incidence equals the angle of reflection, $i = r$. The incident ray, the reflected ray and the normal all lie in the same flat plane. A ray that hits the mirror along the normal ($i = 0$) comes straight back.

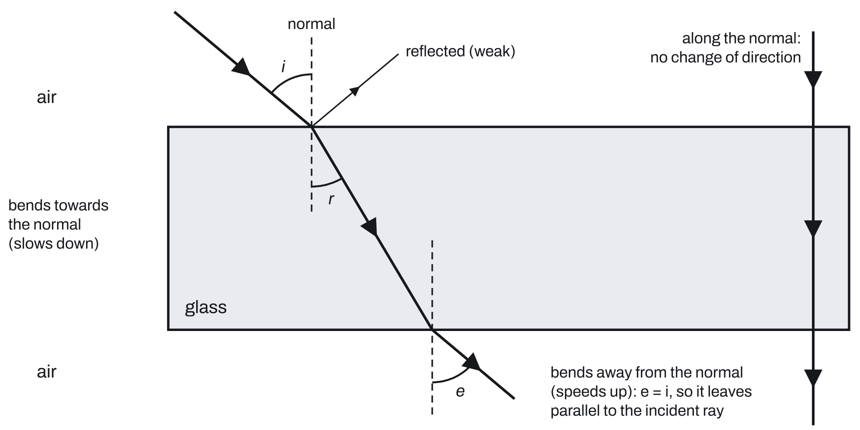
How the image forms. Rays from each point of an object spread out, hit the mirror and reflect into your eye. Your brain assumes light travels in straight lines, so it traces the reflected rays straight back: they seem to come from a point **behind** the mirror. No light actually goes there, so the image is **virtual**: it cannot be caught on a screen. The image in a plane mirror is:

- the **same size** as the object;
- the **same distance behind** the mirror as the object is in front, on the line through the object at right angles to the mirror;
- **virtual**;
- **upright**, but **laterally inverted** (left and right swapped), which is why writing looks reversed in a mirror.

Extended only: constructions. To find where the image of a point P is, draw a line from P at right angles to the mirror and carry it on the same distance behind. To draw the ray that reaches an eye E, join the image to E with a straight line: where it crosses the mirror is where the ray reflects. Draw P to that point and then to E as solid lines with arrows, and the part behind the mirror dashed.

Refraction

Light travels at about 3.0×10^8 m/s in a vacuum and nearly as fast in air, but **more slowly in glass, water and plastic**. When light crosses a boundary at an angle, the change of speed makes it change direction. This is **refraction**.



- **Into a slower material** (air → glass or water): the ray bends **towards** the normal, so the angle of refraction is **smaller** than the angle of incidence.
- **Into a faster material** (glass or water → air): the ray bends **away from** the normal.
- **Along the normal** ($i = 0$): the speed changes but the ray **does not change direction**.
- **What changes**: the **speed** and the **wavelength** both decrease in glass. The **frequency does not change** (the source sets it), and the colour depends on frequency, so red light stays red.
- A **rectangular block** with parallel sides: the ray comes out **parallel** to the ray that went in, shifted sideways.
- Some light is always **reflected** at the surface too (a weak partial reflection).

The experiment. Put a glass block on paper and draw round it. Shine a narrow ray from a **ray box** at the side of the block and mark the ray going in and coming out with small crosses. Remove the block, join the marks with a ruler, draw the normal where the ray entered, and measure i and r with a **protractor**. Repeat for several angles of incidence, and with blocks of other shapes (a semicircle, a triangular prism).

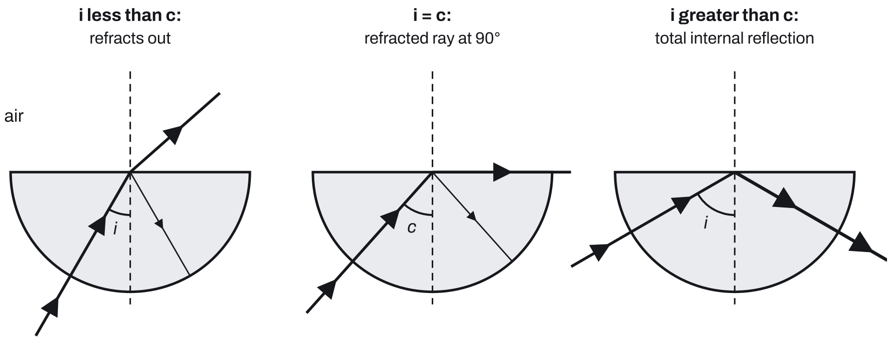
Extended only: refractive index. The **refractive index** n of a material says how much it slows light down:

$$n = \frac{\text{speed of light in air (or a vacuum)}}{\text{speed of light in the material}} \qquad \text{and} \qquad n = \frac{\sin i}{\sin r}$$

where i is the angle in **air** and r is the angle in the **material**. n is a ratio, so it has **no unit**, and it is always more than 1. Glass is about 1.5, so light in glass travels at $\frac{3.0\times10^8}{1.5} = 2.0 \times 10^8$ m/s. A **bigger** n means **slower** light and **more** bending.

Critical angle and total internal reflection

When light goes from glass (or water) into air, it bends away from the normal, so the angle of refraction is always bigger than the angle of incidence. Increase the angle of incidence and the refracted ray gets closer to the surface.



glass, n = 1.5, critical angle c ≈ 42°

- The **critical angle** c is the angle of incidence (in the glass or water) for which the angle of refraction is exactly 90°: the refracted ray runs along the surface.
- If $i < c$: most light refracts out; a little is reflected inside (**internal reflection**).
- If $i > c$: **no** light refracts out. **All** of it is reflected back inside: **total internal reflection** (TIR).

Total internal reflection needs **both** conditions: the light is travelling in the **slower (denser) material towards the faster one** (glass → air, water → air, never air → glass), **and** the angle of incidence is **greater than the critical angle**.

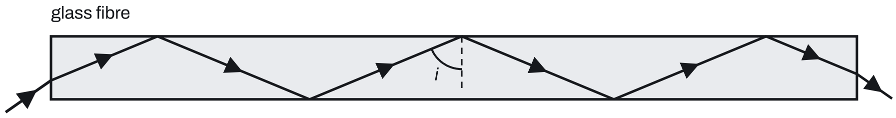
In the semicircular block, a ray aimed at the centre of the flat side meets the curved side **along the normal** (a radius), so it enters without bending. That is why a semicircular block is used to show the critical angle. Everyday examples of TIR: optical fibres, the sparkle of a cut diamond, a prism with 45° angles that turns light through 90° or 180° in binoculars and periscopes, and light from a pool lamp that can't get out of the water at steep angles.

Extended only: the critical angle and the refractive index are linked by

$$n = \frac{1}{\sin c} \qquad \text{so} \qquad c = \sin^{-1}\left(\frac{1}{n}\right).$$

For glass with $n = 1.5$, $c = \sin^{-1}(0.667) = 42^\circ$. For water ($n = 1.33$), $c = 49^\circ$. A bigger refractive index gives a **smaller** critical angle, so TIR happens more easily.

Extended only: optical fibres. An optical fibre is a very thin, flexible strand of very clear glass (or plastic). Light (usually infrared) enters one end and hits the wall at an angle greater than the critical angle, so it is totally internally reflected, again and again, and follows the fibre even round gentle bends.

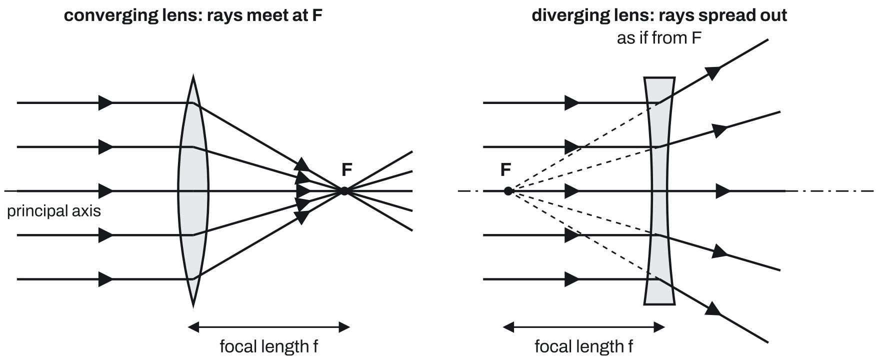


at every reflection, i (about 68°) is greater than the critical angle (42°), so all the light is totally internally reflected and stays in the fibre

Fibres carry **telephone, internet (broadband) and cable television** signals as pulses of light, and are used in **endoscopes** to see inside the body. Compared with electrical signals in copper wires they carry **data at a much higher rate** and **much more of it**, with **little loss of signal** over long distances (the glass is very transparent to the infrared they use), and they are hard to tap (**secure**).

Lenses

A lens refracts light at both its surfaces. In ray diagrams we draw a **thin** lens and bend each ray **once, at the centre line** of the lens.



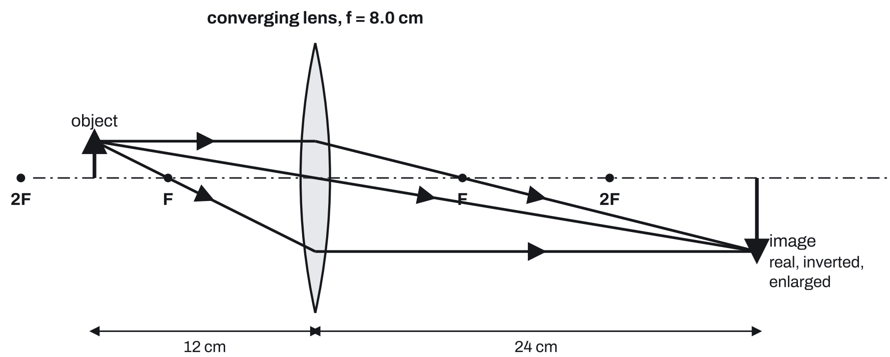
- The **principal axis** is the line through the centre of the lens at right angles to it.
- A **converging** (convex) lens, thicker in the middle, makes rays parallel to the principal axis **meet at one point**: the **principal focus** (focal point) F.
- A **diverging** (concave) lens, thinner in the middle, makes parallel rays **spread out** as if they came from a principal focus on the side the light comes from.
- The **focal length** f is the distance from the **centre of the lens** to the principal focus. A lens has a principal focus on **each side**, at the same distance f.
- A fatter (more curved) converging lens bends light more, so it has a **shorter** focal length.

Ray diagrams for a converging lens

To find an image, draw **two** (or three) of these rays from the **top** of the object:

1. A ray **parallel to the principal axis** refracts **through the principal focus** F on the far side.
2. A ray through the **centre of the lens** goes **straight on**, without bending.
3. A ray **through** F **on the near side** comes out **parallel** to the principal axis.

Where the rays cross is the top of the image. Draw the image as an arrow from the principal axis to that point.



A **real** image forms where rays **actually meet**. It is always **inverted** and on the **opposite side** of the lens, and you can catch it on a **screen**. Where it forms depends on where the object is (2F means twice the focal length from the lens):

Object position	Image position	Image
Very far away	At F	Real, inverted, diminished (a point, for parallel rays)
Beyond $2F$	Between F and $2F$	Real, inverted, **diminished** (a camera or the eye)
At $2F$	At $2F$	Real, inverted, **same size**
Between F and $2F$	Beyond $2F$	Real, inverted, **enlarged** (a projector)
At F	No image	Rays leave parallel
Closer than F	Same side as the object, further away	**Virtual, upright, enlarged** (a magnifying glass)

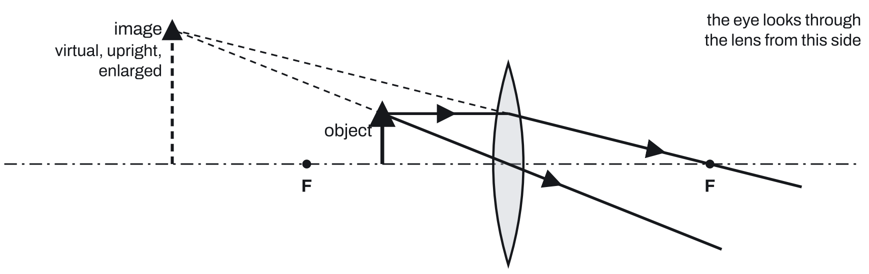
As the object moves in from far away towards F, the image moves further out and grows. Two rules of thumb: the object and a real image are on **opposite sides** of the lens, and whichever of them is **further** from the lens is the **bigger** one.

Virtual images and the magnifying glass

When the rays leaving the lens **spread apart**, they never meet. Traced **backwards** (dashed lines), they seem to come from a point: that is a **virtual image**. It cannot be formed on a screen, because no light actually passes through it.

Extended only. A converging lens used as a **magnifying glass** has the object **closer to the lens than F**. You look through the lens from the other side and see a **virtual, upright, enlarged** image, on the **same side** of the lens as the object and further away.

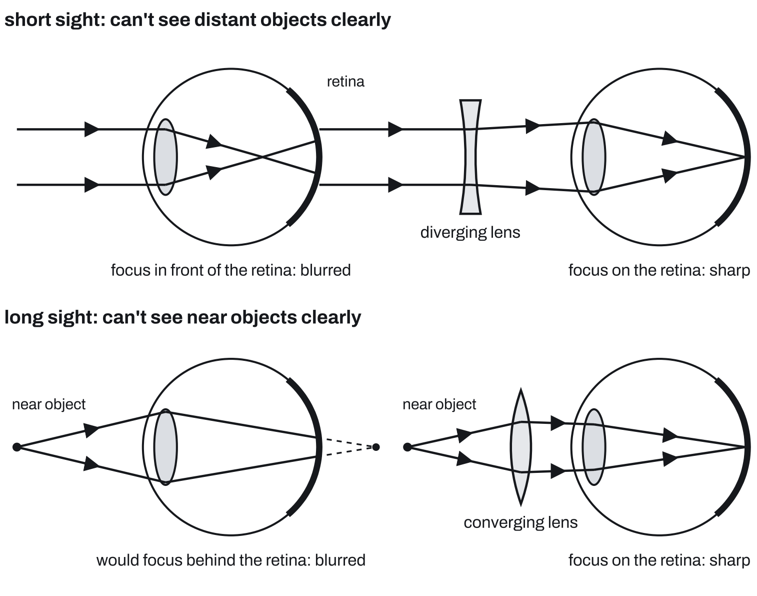
magnifying glass: object closer to the lens than F



To draw it, use the same two rays as before, then extend the two rays **backwards** with dashed lines until they cross, on the object's side. The image is the dashed-line arrow from the principal axis to that crossing.

Extended only: correcting sight

The eye's lens focuses light onto the **retina** at the back of the eye.

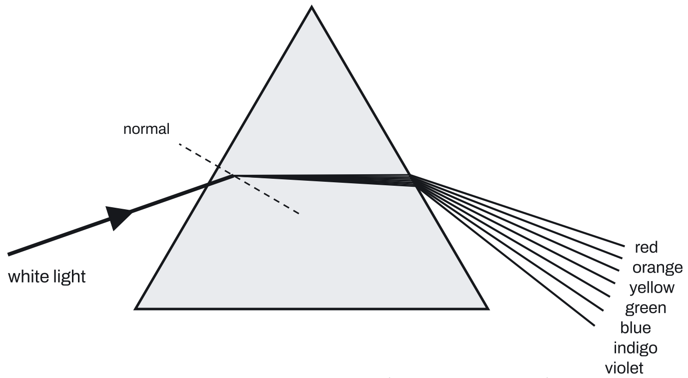


- **Short sight** (short-sightedness): distant objects look blurred, because the eye brings their rays to a focus **in front of** the retina. It is corrected by a **diverging** lens, which spreads the rays out a little before they enter the eye.
- **Long sight** (long-sightedness): near objects look blurred, because the eye would bring their rays to a focus **behind** the retina. It is corrected by a **converging** lens, which converges the rays a little before they enter the eye.

A memory aid: **short sight** needs the rays to go **further**, so spread them (diverging); **long sight** needs them to focus **sooner**, so converge them.

Dispersion

White light is a mixture of colours. In glass, each colour travels at a slightly different speed, so each is refracted by a slightly **different amount**. A triangular **prism** separates them into a **spectrum**: this is **dispersion**.



glass prism: violet bends most, red least (spread exaggerated)

The seven colours, in order: **red, orange, yellow, green, blue, indigo, violet** (a memory aid: **R**ichard **O**f **Y**ork **G**ave **B**attle **I**n **V**ain).

- **Red** is refracted **least**, and has the **longest wavelength** and **lowest frequency**.
- **Violet** is refracted **most**, and has the **shortest wavelength** and **highest frequency**.
- The colours start to separate when the light **enters** the prism, and spread further when it **leaves**.

Extended only: light of a **single frequency** is **monochromatic**, for example the red light from a laser. A prism refracts it but **cannot disperse it**, because there is only one colour to bend. "Light of one colour" is not a good enough definition: say one **frequency** (or one wavelength).

Key facts and formulas

The 0625 papers have no formula sheet, so learn every equation.

Formula	Status
Angle of incidence $=$ angle of reflection (both measured from the normal)	Learn it
Angle from the normal $= 90^\circ -$ angle from the surface	Learn it
Plane-mirror image: same size, same distance behind the mirror, virtual, upright, laterally inverted	Learn it
Extended only: $n = \dfrac{\text{speed of light in air}}{\text{speed of light in the material}}$	Learn it
Extended only: $n = \dfrac{\sin i}{\sin r}$ (i in air, r in the material)	Learn it

Formula	Status
Extended only: $n = \dfrac{1}{\sin c}$, so $c = \sin^{-1}\left(\dfrac{1}{n}\right)$	Learn it
Extended only: speed of light in a vacuum $= 3.0 \times 10^8$ m/s (about the same in air)	Learn it
$v = f\lambda$ (for the frequency or wavelength of light)	Learn it
TIR: light in the slower material heading for the faster one, and $i > c$	Learn it
Ray rules: parallel → through F; through the centre → straight on; through F → parallel	Learn it
Spectrum: red, orange, yellow, green, blue, indigo, violet (frequency increases, wavelength decreases)	Learn it

How to do it

We have tagged 270 questions for this topic across Papers 1–4, 2021–2025; 46 are repeats on other papers, leaving 224 different questions. 48 of the 224 mix two or more types (most structured questions do), so the counts add up to more than 224.

Question type	Questions
Thin lenses: ray diagrams, focal length and image characteristics	68
Reflection in a plane mirror	52
Dispersion, the spectrum and monochromatic light	44
Refraction: terms, ray paths and what changes	42
Critical angle, total internal reflection and optical fibres	36
Refractive index calculations (Extended)	35
Correcting short and long sight (Extended)	9

1. Thin lenses: ray diagrams, focal length and image characteristics (68 questions)

1. **Label what's there.** The horizontal line through the lens is the **principal axis**. The points marked F are the **principal focuses** (focal points), one on each side, each a **focal length** from the centre of the lens. If the focal length is given, mark both Fs on the axis at that distance, using the grid or the scale.
2. **Draw two rays** from the top of the object (the ray rules in "Understand it"), with a ruler, bending each ray at the **centre line** of the lens. Put arrows on them.

3. **Find the image.** Where the rays cross is the top of the image. Draw the image as an arrow from the principal axis up or down to that point, and label it. If the rays spread apart after the lens, extend them backwards with dashed lines to find a virtual image (**Extended only**).
4. **Describe the image** with one word from each pair: enlarged / same size / diminished; upright / inverted; real / virtual. Real images are always inverted; virtual images from one lens are always upright.
5. **Read distances** with the scale: count grid squares or measure with a ruler, then multiply by the scale.

Variations you will meet:

- **"Determine the focal length"**: find where a ray that was **parallel** to the principal axis crosses the axis after the lens, and measure from the **centre of the lens** to that point.
- **Focal length from a labelled diagram**: the distance from the lens to where the parallel ray crosses the axis. If a diagram marks 9 cm from the lens to where the parallel ray crosses the axis, then 6 cm more to the image, the focal length is 9 cm, not 15 cm. Don't add or average distances without a reason.
- **Locate the lens** from an object and its image: the ray from the tip of the object to the tip of the image is straight through the **centre**, so the lens is where that line crosses the principal axis. Then a ray parallel to the axis from the object tip, bent at the lens to the image tip, crosses the axis at F.
- **Locate the object from the image**: the same rays work backwards (rays are reversible).
- **Which object position gives…?** Use the table: a diminished real image needs the object beyond $2F$; enlarged real between F and $2F$; same size at $2F$; a magnifying glass needs it closer than F.
- **A source at F**: the light leaves the lens as a **parallel** beam.
- **Why do parallel rays meet at F?** Because the lens **refracts** them (not reflects or diffracts).
- **Real or virtual, and why**: real: rays actually meet, and it can be shown on a screen. Virtual: rays only appear to come from it; it can't be shown on a screen; (with one lens) it is on the **same side** of the lens as the object.
- **The object moves**: as it moves towards F (still outside it) the real image moves away from the lens and gets bigger; once it is inside F the image becomes virtual and upright.
- **A lens that projects an image** (camera, projector, screen): the image is real and inverted. On a screen seen from behind, it is also turned left–right.
- **Extended only: magnifying glass**: object between the lens and F; the eye on the other side; the image is virtual, upright and enlarged, and further from the lens than the object.

2. Reflection in a plane mirror (52 questions)

1. **Draw or find the normal** at the point where the ray hits the mirror.
2. **Measure angles from the normal.** If the angle is given from the mirror surface, subtract from 90°.
3. **Use $i = r$.** Draw the reflected ray on the other side of the normal at the same angle, with an arrow pointing away from the mirror.
4. **For the image**: same size, same distance behind the mirror, virtual, upright, laterally inverted.

Variations you will meet:

- **Angle between the incident and reflected rays** $= i + r = 2i$. If it is 80°, $i = 40^\circ$. A ray at 35° to the mirror has $i = 55^\circ$, so the angle between the two rays is 110°.
- **Distance from object to image** $= 2\times$ the distance from object to mirror. 30 cm in front means the image is 60 cm from the object.
- **Moving**: if you walk towards a mirror at 1.5 m/s, your image also comes towards the mirror at 1.5 m/s, so it approaches **you** at 3.0 m/s. If the **mirror** moves away from you at a speed v, the image moves away from you at $2v$.
- **Reversed writing or a clock**: the image is laterally inverted. A clock that looks like $2{:}20$ in a mirror actually shows $12{:}00 - 2{:}20 = 9{:}40$. For a letter, flip it left to right (a card held facing the mirror).
- **Which lines are rays?** In an image diagram, solid lines with arrows in front of the mirror are rays; dashed lines behind it are construction lines, not light.
- **Graph of r against i**: a straight line through the origin at 45° (gradient 1).
- **Two mirrors**: apply $i = r$ at each mirror in turn, drawing a new normal each time. Two mirrors at 90° send a ray back parallel to where it came from.
- **Extended only: constructions**: to show how a driver sees a car in a mirror at a junction, or which part of a wall is seen in a mirror, find the image of the object (same distance behind the mirror), join it to the eye, and draw the real ray from the object to where that line meets the mirror, then to the eye. The reflected ray must make $i = r$ with the normal.

3. Dispersion, the spectrum and monochromatic light (44 questions)

1. **Name it**: splitting white light into colours with a prism is **dispersion**. The bending at each surface is **refraction**. Not diffraction.
2. **Order**: red, orange, yellow, green, blue, indigo, violet. **Frequency increases** from red to violet; **wavelength decreases**.
3. **Draw it**: the white ray bends **towards** the normal as it enters, and the colours start to spread **inside** the glass; they bend **away** from the normal and spread further as they leave. **Violet** is bent most (nearest the base of the prism), **red** least.

Variations you will meet:

- **"Which colour refracts more than green?"** Any colour on the violet side (blue, indigo, violet). Less than green: yellow, orange, red.
- **Estimating an in-between value**: orange lies between red and yellow, so its frequency is between theirs (if red is about 4.3 and yellow about 5.1×10^{14} Hz, orange is about 4.8×10^{14} Hz).
- **A beam of two colours** (such as yellow and blue): both refract; blue bends more at every surface.
- **A different colour on the same path**: draw the new ray from the same point, bent more (bluer) or less (redder) at **both** faces.
- **Extended only: monochromatic** means **one frequency** (or one wavelength). A monochromatic beam passes through a prism without dispersing; only white (or mixed) light disperses.

- **Frequency from wavelength**: $f = \dfrac{v}{\lambda}$ with $v = 3.0 \times 10^8$ m/s. Light of wavelength 5.0×10^{-7} m has $f = \dfrac{3.0 \times 10^8}{5.0 \times 10^{-7}} = 6.0 \times 10^{14}$ Hz. Convert nm to m first (1 nm $= 10^{-9}$ m).

4. Refraction: terms, ray paths and what changes (42 questions)

1. **Draw the normal** at the point where the ray crosses the boundary.
2. **Decide the direction of bending**: into glass or water → towards the normal (slower); out into air → away from the normal (faster); along the normal → straight through.
3. **Label the angles**: angle of incidence on the incoming side, angle of refraction on the other side, both from the normal.
4. **Say what changes**: speed and wavelength change (decrease in glass), frequency does not. The change of **speed** causes the change of direction.

Variations you will meet:

- **A rectangular block**: the ray leaves **parallel** to the incoming ray. The angle of incidence at the first face equals the angle of refraction at the second face.
- **A prism**: bend towards the normal at the first face and away from the normal at the second; the ray ends up bent towards the thicker base.
- **Which angle is the angle of refraction?** The angle between the refracted ray (in the second material) and the **normal**. A diagram angle of 50° from the surface means 40° from the normal.
- **Several layers**: where the ray bends **towards** the normal, the light has **slowed down**. The material in which the ray is closest to the normal is the slowest.
- **Why does light change direction?** Because its **speed changes** as it crosses the boundary (not its frequency, colour or amplitude).
- **The experiment**: ray box, glass block, protractor, ruler, sharp pencil, paper; mark the rays, draw the normal, measure i and r, repeat for other angles.
- **Light waves drawn as wavefronts** entering glass: closer together (shorter wavelength) and turned towards the boundary.

5. Critical angle, total internal reflection and optical fibres (36 questions)

1. **State the conditions for TIR**: the light is in the denser (slower) material going towards the less dense one, **and** the angle of incidence is **greater than the critical angle**.
2. **Define the critical angle**: the angle of incidence for which the angle of refraction is 90°.
3. **Draw the path**: compare i with c at the boundary.
   - $i < c$: the ray refracts out, bending away from the normal (plus a weak reflection).
   - $i = c$: the refracted ray runs along the surface.
   - $i > c$: **all** the light reflects inside, with $i = r$. Draw no refracted ray.
4. **Extended only: calculate** $c = \sin^{-1}(1/n)$ if needed (type 6).

Variations you will meet:

- **A semicircular block**: the ray aimed at the centre enters the curved side along the normal, so it does not bend. At the flat side, compare i with c.
- **A 45° prism** (critical angle about 42°): a ray entering one short face along the normal meets the long face at 45°, which is more than 42°, so it is totally internally reflected and turned through 90°, then leaves through the other short face along the normal.
- **A lamp under water**: rays that meet the surface at less than the critical angle (about 49° for water) escape into the air; steeper ones are totally reflected back down.
- **"State and explain what happens"**: "the angle of incidence is greater than the critical angle, so **all** the light is (totally internally) reflected". "It reflects" alone is not enough.
- **Extended only: blue and red light**: blue travels more slowly in glass, so the glass has a larger n and a **smaller** critical angle for blue. A ray that just escapes as red may be totally internally reflected as blue.
- **Extended only: optical fibres**: draw the ray reflecting off the walls with $i = r$ each time, all the way to the far end, and leaving there. Uses: telecommunications (phone, internet, cable TV) and endoscopes. Advantages over copper wires: high rate of data transfer, large amounts of data, little signal loss, secure.
- **Extended only: better fibres**: glass that slows light more has a bigger n and a **smaller** critical angle, so more of the rays are totally internally reflected.

6. Extended only: refractive index calculations (35 questions)

1. **Choose the equation** from what you are given:
   - two speeds: $n = \dfrac{\text{speed in air}}{\text{speed in the material}}$;
   - two angles: $n = \dfrac{\sin i}{\sin r}$, with i in **air** and r in the material;
   - the critical angle: $n = \dfrac{1}{\sin c}$.
2. **Check every angle is from the normal.** Subtract from 90° if not.
3. **Rearrange and substitute.** Give angles to the nearest degree (or 3 s.f.) and n to 2 or 3 s.f., **with no unit**.

Some examples of each:

- $n = 1.6, i = 45^\circ$: $\sin r = \dfrac{\sin 45^\circ}{1.6} = 0.442$, so $r = 26^\circ$.
- $i = 50^\circ, r = 30^\circ$: $n = \dfrac{\sin 50^\circ}{\sin 30^\circ} = 1.53$.
- Light travels at 2.25×10^8 m/s in a liquid: $n = \dfrac{3.0 \times 10^8}{2.25 \times 10^8} = 1.33$.
- $n = 1.6$: $c = \sin^{-1}\left(\dfrac{1}{1.6}\right) = 39^\circ$. And a critical angle of 40° means $n = \dfrac{1}{\sin 40^\circ} = 1.56$.

Variations you will meet:

- **Speed in the material**: $v = \dfrac{3.0 \times 10^8}{n}$. For $n = 1.5$, 2.0×10^8 m/s. Light at 60% of its speed in air means $n = \dfrac{1}{0.60} = 1.67$.
- **Two steps**: find n from $\dfrac{\sin i}{\sin r}$ (or from c), then use it for the speed.

- **Light leaving the material** (glass → air): the angle **in air** is still on top. A ray at 20° in glass with $n = 1.5$: $\sin(\text{angle in air}) = 1.5 \times \sin 20^\circ = 0.513$, so it leaves at 31°.
- **The angle given from the surface**: a ray at 58° to the surface has $i = 32^\circ$.
- **"Show that"**: write the equation in symbols, substitute, and give the answer to one more significant figure than the value printed (for example $n = 1.41$ to show 1.4, or $c = 41.8^\circ$ to show 42°).
- **The largest angle x with the surface** at which TIR happens: find c, then $x = 90^\circ - c$.
- $v = f\lambda$ **in the same question**: the frequency does not change in the glass; the wavelength is divided by n.

7. Extended only: correcting short and long sight (9 questions)

1. **Name the defect** from what the person can't see: distant objects blurred = **short sight**; near objects blurred = **long sight**.
2. **Say where the image forms**: short sight, **in front of** the retina; long sight, **behind** it.
3. **Choose the lens**: short sight, **diverging** (concave); long sight, **converging** (convex).
4. **Draw it**: for long sight, the rays inside the eye still converging when they reach the retina (they would meet behind it). With the correcting lens drawn in front of the eye, the rays meet **on** the retina.

Variations you will meet:

- **"How does a converging lens help a long-sighted person?"** It makes the rays converge **before** they reach the eye, so the eye's lens can bring them to a focus **on** the retina.
- **Matching diagrams**: pick the row with the right defect, the right place for the uncorrected image, **and** the right lens shape.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **M1** method mark: for a correct method, even if the numbers slip.
- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

A ray of light hits a plane mirror. The angle between the ray and the surface of the mirror is 28°.

(a) State the angle of incidence and the angle of reflection. **[2]**

(b) Calculate the angle between the incident ray and the reflected ray. **[1]**

(c) A girl stands 40 cm in front of the mirror. State the distance between the girl and her image, and give two other characteristics of the image. **[3]**

(d) She walks towards the mirror at 0.5 m/s. State the speed at which her image comes towards her. **[1]**

(a) Angle of incidence $= 90^\circ - 28^\circ = 62^\circ$ **B1** (measured from the normal). Angle of reflection $= 62^\circ$ **B1**.

(b) $62^\circ + 62^\circ = 124^\circ$ **B1**.

(c) 80 cm (the image is 40 cm behind the mirror) **B1**. The same size as the girl **B1**; virtual (or upright, or laterally inverted) **B1**.

(d) The image moves towards the mirror at 0.5 m/s as she does, so it approaches her at 1.0 m/s **B1**.

Example 2

An object 2.0 cm tall stands on the principal axis, 12 cm from a thin converging lens of focal length 8.0 cm.

(a) Draw a full-scale ray diagram to locate the image. **[3]**

(b) Use your diagram to find the distance of the image from the lens and its height. **[2]**

(c) State three characteristics of the image. **[2]**

(a) Mark both principal focuses 8.0 cm from the centre of the lens. From the top of the object, draw a ray parallel to the axis, bent at the lens through F on the far side **M1**, and a ray straight through the centre of the lens **M1**. Draw the image as an inverted arrow from the axis to where the rays cross **A1**. (A third ray, through the near F and out parallel, crosses at the same point: a good check.) The fourth diagram in "Understand it" shows this construction.

(b) The image is 24 cm from the lens **B1** and 4.0 cm tall **B1**.

(c) Real, inverted, enlarged **B2** (all three for 2 marks, two for 1 mark). The object is between F and $2F$, which matches the table.

Example 3

Extended only. A ray of light in air meets a glass block with an angle of incidence of 50°. The angle of refraction is 30°. The speed of light in air is 3.0×10^8 m/s.

(a) Calculate the refractive index of the glass. **[2]**

(b) Calculate the speed of light in the glass. **[2]**

(c) Calculate the critical angle for the glass. **[2]**

(d) Inside the block, the ray later meets another face with an angle of incidence of 45°. State and explain what happens to it. **[2]**

(a) $n = \dfrac{\sin i}{\sin r}$ **C1** $= \dfrac{\sin 50^\circ}{\sin 30^\circ} = 1.53$ **A1**.

(b) $n = \dfrac{\text{speed in air}}{\text{speed in glass}}$, so speed $= \dfrac{3.0 \times 10^8}{1.53}$ **C1** $= 1.96 \times 10^8$ m/s **A1**.

(c) $\sin c = \dfrac{1}{n} = \dfrac{1}{1.53}$ **C1**, so $c = 41^\circ$ **A1**.

(d) Total internal reflection: **all** the light is reflected back into the glass **B1**, because the angle of incidence (45°) is greater than the critical angle (41°) **B1**.

Example 4

Extended only. An optical fibre is made of glass of refractive index 1.47. It carries light of wavelength 6.0×10^{-7} m (in air) along a cable 6.0 km long.

(a) Calculate the critical angle for the glass. **[2]**

(b) A ray inside the fibre meets the wall with an angle of incidence of 72°. Explain why the light stays inside the fibre. **[2]**

(c) Calculate the speed of the light in the fibre and the time it takes to travel 6.0 km along it. Ignore the extra distance of the zigzag path. **[4]**

(d) Calculate the frequency of the light. **[2]**

(e) State two advantages of optical fibres over copper cables for sending data. **[2]**

(a) $\sin c = \dfrac{1}{1.47}$ **C1**, $c = 43^\circ$ **A1**.

(b) 72° is greater than the critical angle **B1**, so the light is totally internally reflected every time it meets the wall **B1**.

(c) Speed $= \dfrac{3.0 \times 10^8}{1.47}$ **C1** $= 2.04 \times 10^8$ m/s **A1**. Time $= \dfrac{\text{distance}}{\text{speed}} = \dfrac{6000}{2.04 \times 10^8}$ **C1** $= 2.94 \times 10^{-5}$ s **A1**.

(d) $f = \dfrac{v}{\lambda} = \dfrac{3.0 \times 10^8}{6.0 \times 10^{-7}}$ **C1** $= 5.0 \times 10^{14}$ Hz **A1**. (Use the speed and wavelength **in air** together; the frequency is the same in the fibre.)

(e) Any two: a higher rate of data transfer; more data carried at once; less signal loss; more secure **B2**.

Common mistakes

- **Measuring angles from the surface.** The angles of incidence, reflection and refraction are all measured from the **normal**. Examiners report that many candidates cannot pick out the angle of incidence on a diagram.
- **Thinking a plane-mirror image is inverted or real.** It is upright and virtual; only left and right are swapped.

- **Using "focus" for "principal focus"**, or marking only one F, or marking F on the lens itself. There is a principal focus on **each** side, on the principal axis, one focal length from the centre.
- **Vague definitions of principal focus and focal length.** Principal focus: the point where rays **parallel to the principal axis** meet after the lens. Focal length: the distance from the **centre of the lens** to the principal focus.
- **Careless ray diagrams.** Freehand rays, rays bent at the lens surface instead of the centre line, and images not drawn from the axis to the crossing point all lose marks. Use a ruler and a sharp pencil.
- **Contradictory answers** when describing an image, such as ticking both "real" and "virtual" or both "enlarged" and "diminished". Any contradiction cancels the mark.
- **Explaining a virtual image vaguely.** "It is in front of the lens" is not enough; say it is on the **same side of the lens as the object**, or that the rays **don't actually meet**, or that it **can't be shown on a screen**.
- **Getting TIR backwards.** Many candidates think it can happen for light going from air into water or glass. The light must be in the **denser (slower)** material, and i must be **greater than** c.
- **"The light reflects"** is not total internal reflection. Say **all** the light is reflected, and give the reason ($i > c$). Don't compare i with the refractive index or with the angle of refraction.
- **Extended only: wrong angle in $n = \frac{\sin i}{\sin r}$**: using the angle from the surface, or putting the glass angle on top. For the critical angle, rearranging to $c = 1/\sin n$, or working out $\cos 49^\circ$ or $90^\circ - 49^\circ$, are common slips.
- **Extended only: a unit on n.** Refractive index has no unit.
- **Extended only: "monochromatic means one colour".** The definition is **one frequency** (or one wavelength).
- **Showing dispersion only as the light leaves the prism.** The colours begin to separate as soon as the white light enters.
- **Dispersing a single colour.** A ray of red (or any single-colour) light is refracted by a prism but not dispersed.
- **Extended only: mixing up short and long sight.** Short sight (can't see far) → image in front of the retina → diverging lens. Long sight (can't see near) → behind the retina → converging lens.

How to get the marks

- **Drawing rays**: use a ruler, put an arrow on every ray, draw normals as dashed lines at right angles to the surface, and make $i = r$ look right when you reflect a ray (use a protractor).
- **Ray diagrams**: two correct rays from the **same point** of the object earn the method marks; the image arrow from the axis to the crossing point earns the last one. Mark and label both Fs if the question asks for them.
- **"State the characteristics"**: give exactly as many as asked, one from each pair, with no contradictions: for example "real, inverted, diminished".
- **Definitions** need the key words: critical angle, "the angle of incidence **for which the angle of refraction is** 90°"; monochromatic, "**single frequency**"; principal focus, "where rays **parallel to the principal axis** converge"; focal length, "distance from the **centre of the lens** to the principal focus".

- **"State and explain"** for TIR: name the effect **and** compare the angle of incidence with the critical angle.
- **Extended only: calculations**: write the equation in symbols first ($n = \frac{\sin i}{\sin r}$, $n = \frac{1}{\sin c}$), then the numbers, then the answer. The equation and substitution earn **C1** marks even if the final answer is wrong. Give angles to the nearest degree unless told otherwise.
- **"Show that"**: equation, substitution, and an answer with one more significant figure than the printed value.
- **Multiple choice with two columns** (image type **and** size, lens **and** image position): check both halves of each row; most wrong options get one half right.
- **Extended only: optical fibre advantages**: make each point specific ("carries data at a higher rate", "less signal loss"); "better" or "faster internet" alone is too vague.

Quick check

1. A ray of light hits a plane mirror at 25° to its surface. State the angle of reflection and the angle between the incident and reflected rays.
2. An object is 25 cm from a converging lens of focal length 10 cm. State where the image forms and give three characteristics of it.
3. **Extended only.** Water has a refractive index of 1.33. Calculate the critical angle for water and the speed of light in water.
4. **Extended only.** A ray in air enters a plastic block with an angle of incidence of 40°. The angle of refraction is 25°. Calculate the refractive index of the plastic.
5. List the colours of the visible spectrum in order of increasing frequency. Which is refracted most by a prism? **Extended only:** a laser gives monochromatic light. What does this mean, and what happens when its beam passes through a prism?

Answers

1. $i = 90^\circ - 25^\circ = 65^\circ$, so the angle of reflection is 65°. The angle between the rays is $65^\circ + 65^\circ = 130^\circ$.
2. The object is beyond $2F$ (20 cm), so the image forms on the other side of the lens, between F and $2F$ (between 10 cm and 20 cm from the lens). It is real, inverted and diminished.
3. $c = \sin^{-1}\left(\frac{1}{1.33}\right) = 48.8^\circ$. Speed $= \frac{3.0 \times 10^8}{1.33} = 2.26 \times 10^8$ m/s.
4. $n = \frac{\sin 40^\circ}{\sin 25^\circ} = 1.52$ (no unit).
5. Red, orange, yellow, green, blue, indigo, violet. Violet is refracted most. Monochromatic means a single frequency (one wavelength); the beam is refracted but not dispersed, so it stays one colour.

Past questions to try

- **0625/31/M/J/24 Q7**: the angle of reflection, completing a lens ray diagram and the seven colours of the spectrum (Core).
- **0625/43/M/J/25 Q5**: defining refractive index, drawing rays at a water surface and explaining total internal reflection (Extended).
- **0625/42/F/M/23 Q5**: critical angle in a semicircular block, a full-scale lens diagram and correcting short sight (Extended).
- **0625/42/M/J/25 Q6**: locating an object from its image, and correcting long sight (Extended).