

Bending light: refraction, critical angle and lenses

Physics grades 9-10 (GCSE · IGCSE · O Level · Class 9-10) · Lesson

Quick answer: Refraction is the bending of light as it changes speed between materials, and its size is given by the refractive index $n = \sin i \div \sin r$. Beyond the critical angle, light inside a dense material is totally reflected. Converging lenses focus parallel rays to a principal focus and form real or virtual images.

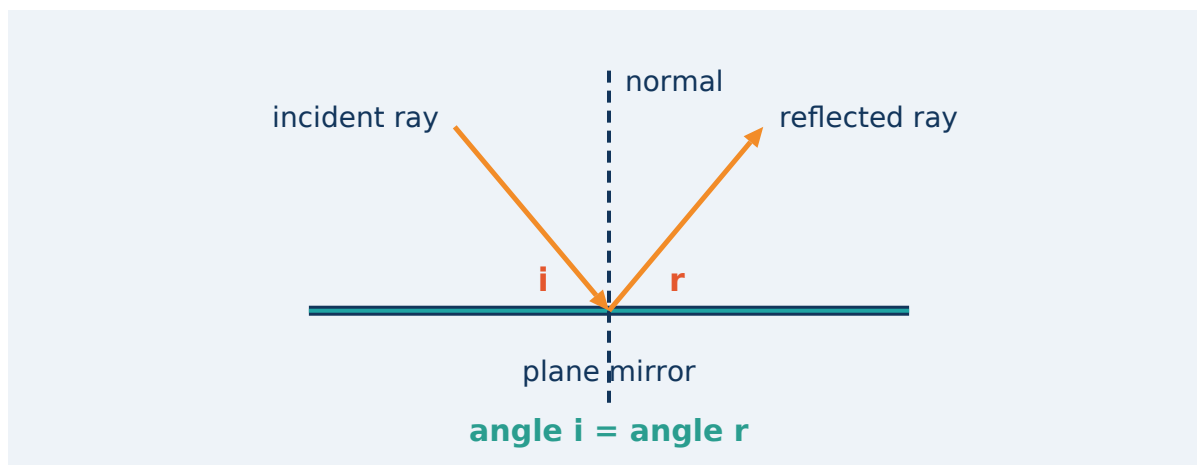
Level: Physics grades 9-10 (GCSE · IGCSE · O Level · Class 9-10) · **Curriculum:** IGCSE 3.2

How does light reflect from a mirror?

When a ray of light hits a smooth surface, it bounces off in a predictable direction. To describe it, we draw the **normal**, a line at 90° to the surface at the point where the ray lands.

Key law

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 plane.



The law of reflection: the angle of incidence i equals the angle of reflection r . Both angles are measured from the normal.

What is refraction and how do you calculate refractive index?

Light travels fastest in a vacuum, at 3.0×10^8 m/s. In a denser material such as glass it slows down, and when a ray meets the boundary at an angle, the change of speed makes it change direction. This bending is called refraction.

Definition

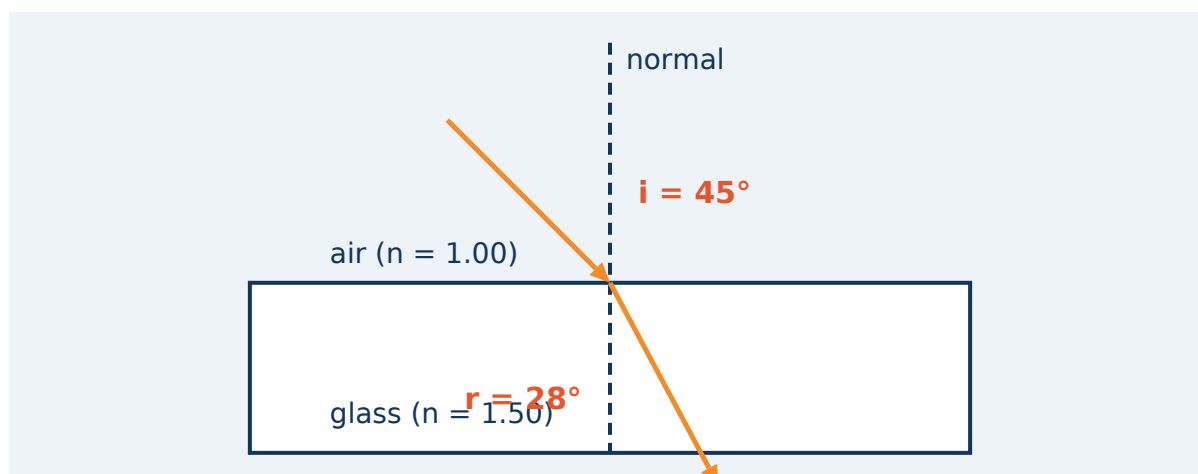
Refraction is the change of direction of a wave when it passes from one material into another, caused by a change in its speed. The **refractive index** n of a material tells you

how strongly it bends light.

Formula

$$n = \sin i \div \sin r$$

n = refractive index (no unit), i = angle of incidence in air ($^{\circ}$), r = angle of refraction in the material ($^{\circ}$). Also $n = c \div v$, where c is the speed of light in air and v the speed in the material.



Entering glass, the ray slows down and bends towards the normal: $i = 45^{\circ}$ gives $r = 28^{\circ}$, so $n = \sin 45^{\circ} \div \sin 28^{\circ} = 1.5$.

A ray entering a denser material bends *towards* the normal. A ray leaving it bends *away* from the normal. A ray travelling along the normal (0°) is not bent at all.

Worked example 1

Chiamaka in Lagos shines a ray onto an acrylic block at $i = 40^{\circ}$. She measures $r = 25^{\circ}$. Calculate the refractive index.

$$n = \sin 40^{\circ} \div \sin 25^{\circ} = 0.643 \div 0.423 = \mathbf{1.52}$$

Material	Refractive index n	Speed of light (10^8 m/s)
Air	1.00	3.00
Water	1.33	2.26
Perspex	1.49	2.01
Glass	1.52	1.97
Diamond	2.42	1.24

A higher n means slower light and stronger bending. Diamond bends light far more than water does.

What is total internal reflection?

When light tries to leave a dense material for air, it bends away from the normal. Make the angle of incidence larger and the refracted ray swings closer and closer to the surface. At one special angle it just skims along it.

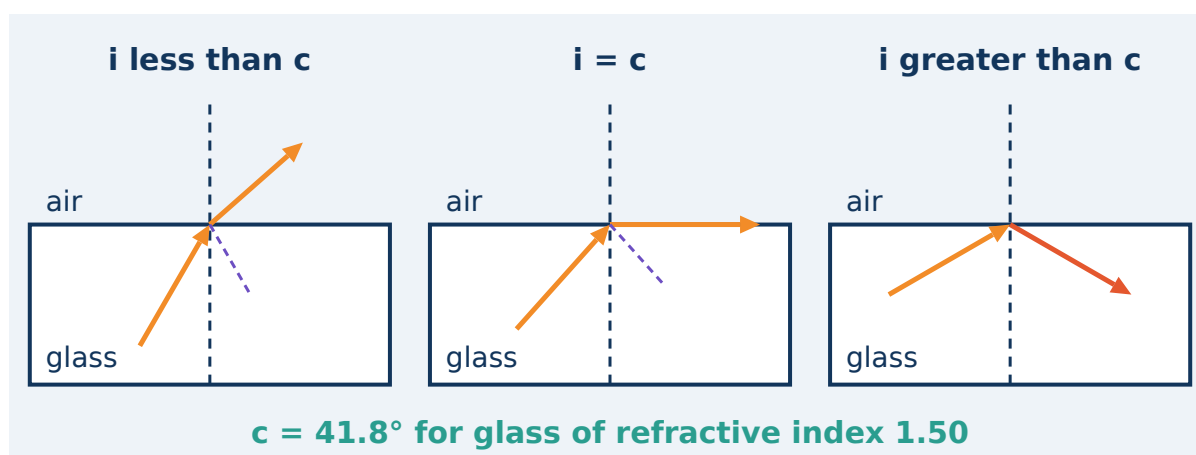
Definition

The **critical angle c** is the angle of incidence inside a dense material for which the refracted ray travels along the boundary ($r = 90^\circ$). For any larger angle, **total internal reflection** occurs: all the light reflects back into the material.

Formula

$$\sin c = 1 \div n$$

c = critical angle ($^\circ$), n = refractive index of the material (boundary with air).



Left: light mostly escapes. Middle: the refracted ray runs along the surface. Right: total internal reflection, so no light leaves.

Total internal reflection needs two conditions: the light travels from a denser to a less dense material, and the angle of incidence is greater than c .

Worked example 2

Calculate the critical angle for water, $n = 1.33$.

$\sin c = 1 \div 1.33 = 0.752$, so $c = \mathbf{48.8^\circ}$. A ray inside water hitting the surface at 55° is totally reflected.

Common mistake

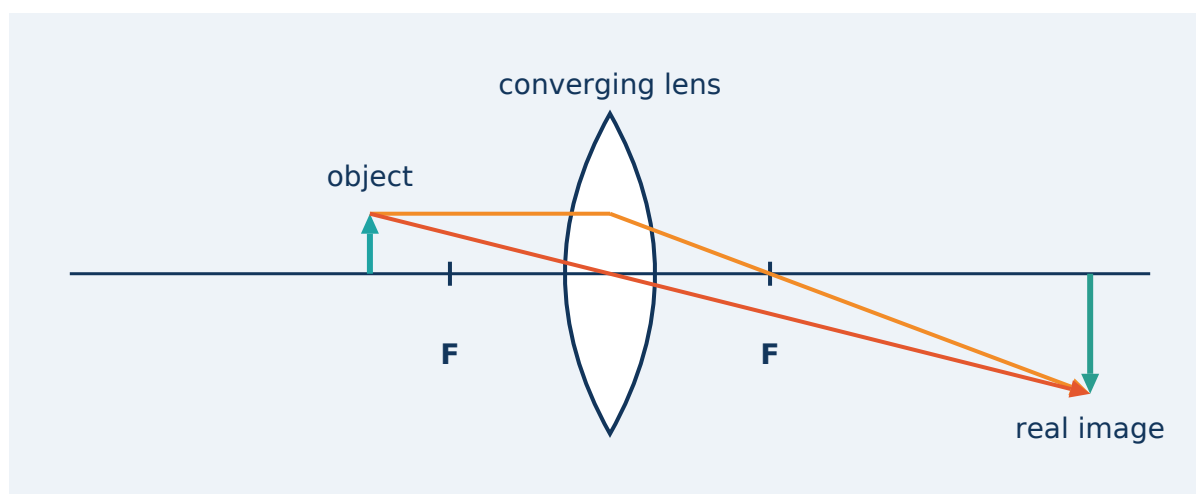
Measuring angles from the surface instead of from the normal. Every angle in reflection, refraction and critical-angle work is measured from the normal.

Optical fibres carry internet signals as light that bounces by total internal reflection along a thin glass strand. Prisms in binoculars and bicycle reflectors work the same way.

How do converging lenses form images?

A converging (convex) lens is thicker in the middle and refracts parallel rays so that they meet at the **principal focus** F. The distance from the lens to F is the focal length f. To find an image you only need two of three special rays:

- A ray parallel to the principal axis refracts through the principal focus on the far side.
- A ray through the centre of the lens carries straight on.
- A ray through the near principal focus emerges parallel to the axis.



Object between F and 2F: the image is real, inverted, magnified and beyond 2F. Two rays are enough to locate it.

Formula

magnification m = image height $\div$ object height

m has no unit. If m is greater than 1 the image is bigger than the object.

Worked example 3

Mei in Singapore photographs a leaf 4.0 cm long. Its image on the sensor is 1.2 cm long. Calculate the magnification.

$m = 1.2 \div 4.0 = \mathbf{0.30}$. The image is smaller than the object.

Object position	Image	Used in
Beyond 2F	Real, inverted, smaller	Camera
Between F and 2F	Real, inverted, larger	Projector
Closer than F	Virtual, upright, larger	Magnifying glass

A **real** image can be caught on a screen. A **virtual** image cannot: the rays only appear to come from it, as when you look through a magnifying glass.

Lina's tip

Draw the two easy rays first, one parallel to the axis and one through the centre, with a

ruler. Where they cross is the top of the image. Always add arrows to every ray.

Key points to remember

- Law of reflection: angle of incidence i = angle of reflection r , both from the normal.
- Refractive index: $n = \sin i \div \sin r = c \div v$.
- Critical angle: $\sin c = 1 \div n$; total internal reflection needs i greater than c .
- A converging lens focuses a parallel beam at the principal focus F .
- Magnification $m = \text{image height} \div \text{object height}$.

Bending light: refraction, critical angle and lenses: frequently asked questions

What is the formula for refractive index?

$n = \sin i \div \sin r$, where i is the angle in air and r is the angle in the material, both measured from the normal. It can also be written $n = c \div v$, the speed of light in air divided by its speed in the material.

When does total internal reflection happen?

It happens when light travels from a denser material towards a less dense one and the angle of incidence is bigger than the critical angle. All the light is then reflected back, with none refracted out.

How do you find the critical angle?

Use $\sin c = 1 \div n$ for a boundary with air. For glass with $n = 1.50$, $\sin c = 0.667$, so $c = 41.8^\circ$.

What is the difference between a real and a virtual image?

A real image is formed where light rays actually meet and can be shown on a screen. A virtual image is formed where rays only appear to come from, so it cannot be caught on a screen.

Why does a ray bend towards the normal in glass?

Light travels more slowly in glass than in air. The side of the wavefront that enters first slows first, which turns the ray towards the normal.