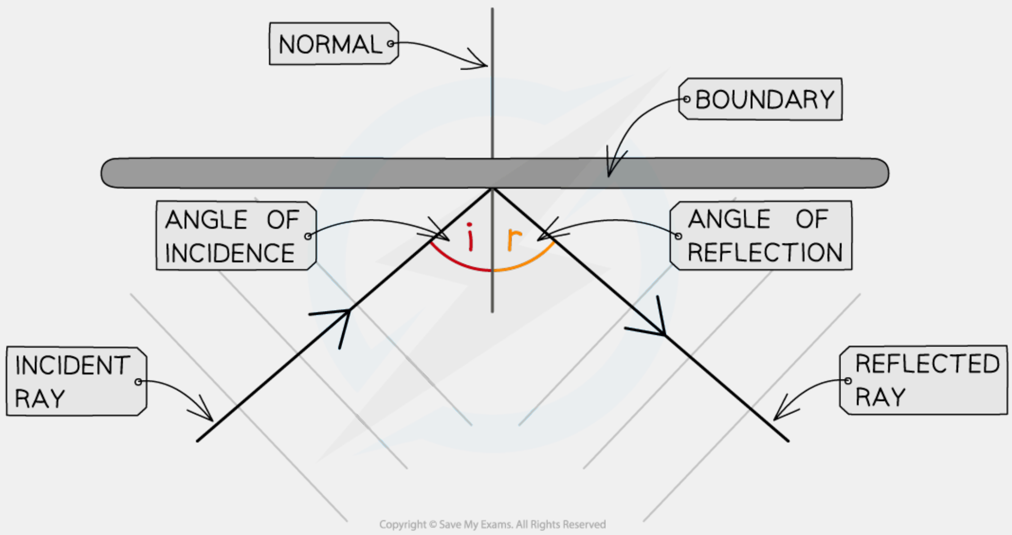
3.2 Light

Reflection of Light

Ray diagrams

- In optics, a **normal line** is drawn at **right angles** to the **boundary** between two **media**
- In reflection, angles are measured between the ray (showing the wave direction) and the normal line
  - The angle of the wave approaching the boundary is called the **angle of incidence *(i)***
  - The angle of the wave leaving the boundary is called the **angle of reflection *(r)***
- When drawing a ray diagram an arrow is used to show the direction the wave is travelling
  - An **incident** ray has an arrow pointing **towards** the boundary
  - A **reflected** ray has an arrow pointing **away** from the boundary

Ray diagram of reflection



A ray diagram for light reflecting at a boundary, showing the normal, angle of incidence and angle of reflection

The law of reflection

- The **law of reflection** states that the angles of incidence and reflection are equal:

Angle of incidence (*i*) = Angle of reflection (*r*)

- This law of reflection is used in many devices such as:
  - mirrors
  - cameras
  - optical fibres
  - periscopes

Reflection in a plane mirror

- When an object is placed in front of a plane mirror, an image of that object can be seen in the mirror
- The image will be:
  - The **same size** as the object
  - The **same distance behind** the mirror as the object is in front of it
  - **Virtual**
- A **plane mirror** defines a **flat, smooth** and **polished surface**
- The formation of this image can be understood by drawing a ray diagram

Ray diagram showing reflection in a plane mirror

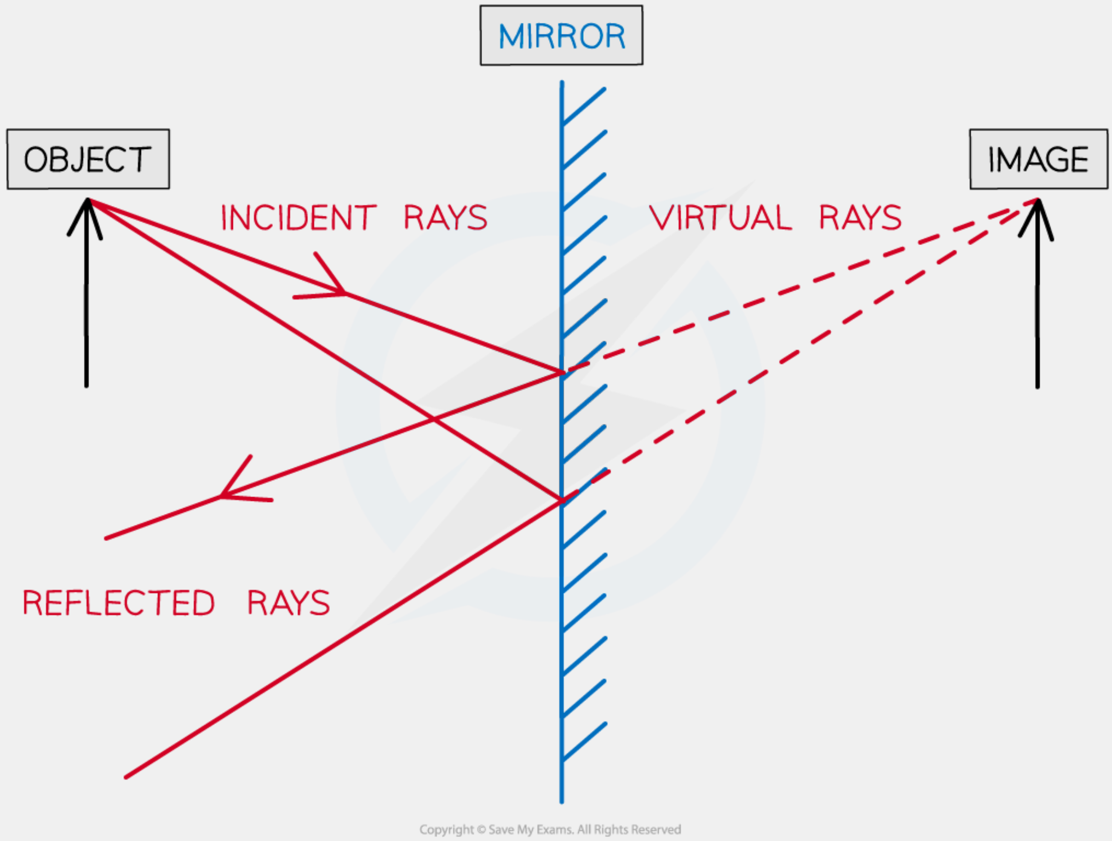


Diagram showing the formation of an image in a mirror by the reflection of light

- Each incident ray on the diagram above can be drawn following these steps:
    - Light from the object hits the mirror, reflecting from it (*i*=*r*)
    - To an observer, the reflected ray appears to have come from behind the mirror
    - The reflected ray can be traced back in this same direction behind the mirror, forming a **virtual ray**
    - This process is **repeated** for another ray travelling in a slightly different direction
- An image of the object will appear where these two **virtual rays cross**

- The type of image formed in the mirror is called a **virtual image** because of the divergence of the rays from the image
    - It cannot be projected onto a piece of paper (because the rays don't go through the image)

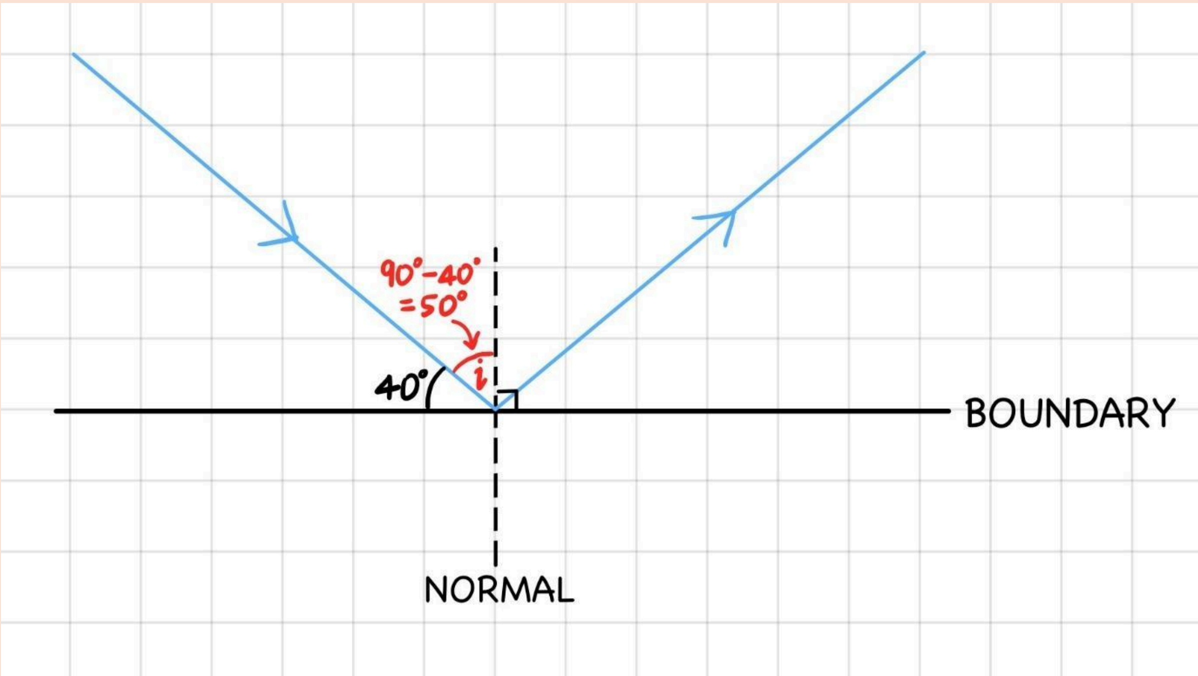
Examiner Tips and Tricks

When drawing light waves being reflected **take care to get the angle right.**

If they are slightly out it won't be a problem, but if there is an obvious difference between the angle of incidence and the angle of reflection then you will probably lose a mark.

When identifying angle of incidence or reflection, make sure the angle you're looking at is between the ray and the normal. Many students mistake the angle between the ray and the boundary to be the angle of incidence or reflection, which is incorrect.

If the angle of incidence/reflection is not given, but the angle between the ray and the boundary is given, take note you can find i or r by using the fact that the normal is perpendicular to the boundary.



<u>Investigating Reflection</u>

Aims of the experiment

- To investigate reflection by a Plane mirror

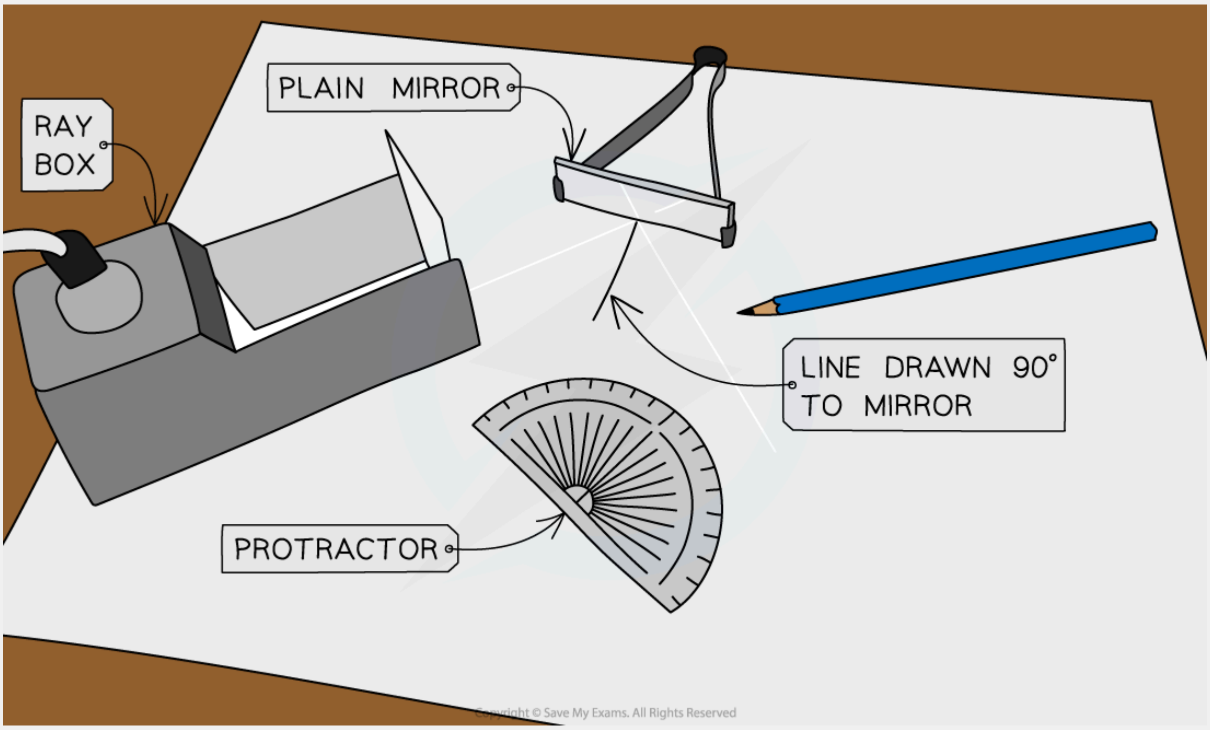
Variables

- **Independent variable** = angle of incidence, *i*
- **Dependent variable** = angle of reflection, *r*
- Control variables:
  - Distance of ray box from mirror
  - Width of the light beam
  - Same frequency / wavelength of the light

Equipment list

Equipment	Purpose
Ray Box	To provide a narrow beam of light that can be easily reflected
Protractor	To measure the angles of incidence and reflection
Sheet of Paper	To mark the lines indicating the incident and reflected rays
Pencil	To draw the incident and reflected ray lines onto the paper
Ruler	To draw the incident and reflected ray lines onto the paper
Plane mirror	To reflect the light beam

Method



Apparatus to investigate reflection

1. Set up the apparatus as shown in the **diagram**
2. In the middle of the paper use a ruler to mark a straight line about **10 cm** long
3. Use a protractor to draw a **90° line** that bisects (cuts in half) the 10 cm line
4. Place the mirror on the **first line** as shown in the diagram above
5. Switch on the **ray box** and aim a beam of light at the point where the two **drawn lines cross** at an angle
6. Use the pencil to mark **two positions** of the light beam:
    - A point just after leaving the ray box
    - The point on the reflected beam about 10 cm away from the mirror
7. Remove the ray box and mirror
8. **Use a ruler t**o join the two marked positions to the point where the originally drawn lines crossed

9. Use the protractor to measure the two angles from the 90° line. The angle for the ray towards the mirror is the angle of incidence, and the other is the angle of reflection

10. **Repeat** the experiment three times with the beam of light aimed at different angles

Results

Example results table

Angle of incidence, *i* (°)	Angle of reflection, *r* (°)
10	
30	
45	
80	

Analysis of results

- The law of reflection states:

$$i = r$$

- Where:
    - i = angle of incidence in degrees (°)
    - r = angle of reflection in degrees (°)
- If the experiment was carried out correctly, the angles of incidence and reflection should be the same

Evaluating the experiment

Systematic errors

- An error could occur if the 90° lines are drawn incorrectly
    - Use a set square to draw perpendicular lines

- If the mirror is distorted, this could affect the reflection angle, so make sure there are little to no blemishes on it

Random errors

- The points for the incoming and reflected beam may be inaccurately marked
    - Use a sharpened pencil and mark in the middle of the beam
- The protractor resolution may make it difficult to read the angles accurately
    - Use a protractor with a higher resolution

Safety considerations

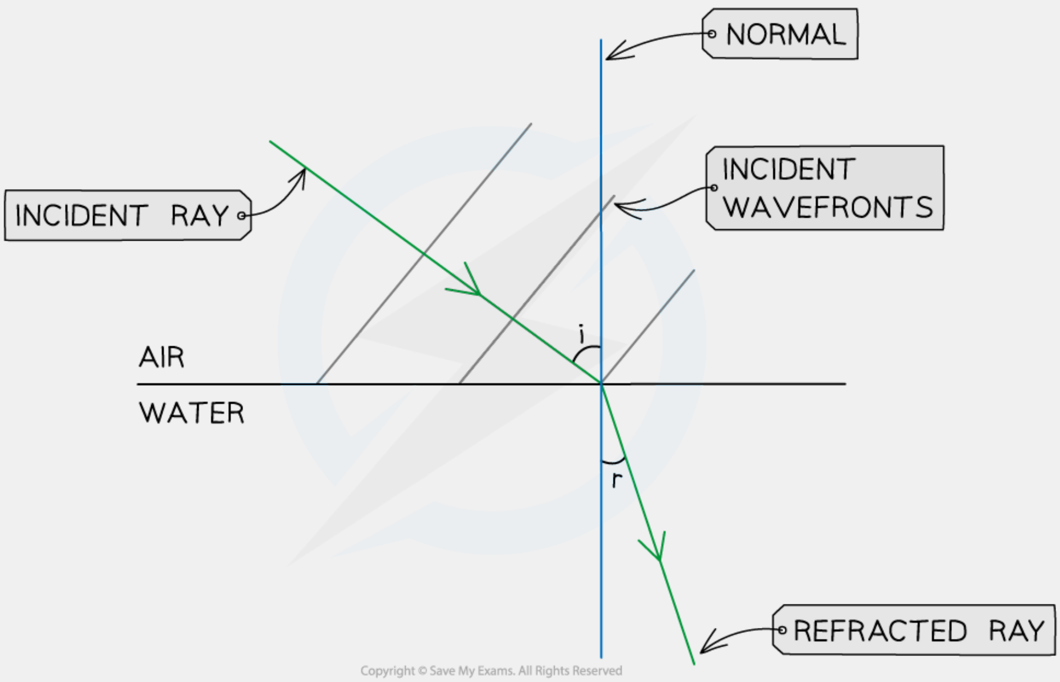
- The ray box light could cause **burns** if touched
    - Run burns under cold running water for at least five minutes
- Looking directly into the light may **damage the eyes**
    - Avoid looking directly at the light
    - Stand behind the ray box during the experiment
- Keep all **liquids** away from the electrical equipment and paper
- Take care using the **mirror**
    - Damages on the mirror can affect the outcome of the reflection experiment

Refraction of Light

Ray diagrams for refraction

- In refraction, angles are measured between the ray (showing the direction of the wave) and the normal line
  - The angle of the wave approaching the boundary is called the **angle of incidence *(i)***
  - The angle of the wave leaving the boundary is called the **angle of refraction *(r)***
- When drawing a ray diagram an arrow is used to show the direction the wave is travelling
  - An **incident** ray has an arrow pointing **towards** the boundary
  - A **refracted** ray has an arrow pointing **away** from the boundary
- The **angles** of **incidence** and **refraction** are usually labelled ***i*** and ***r*** respectively

Refraction ray diagram

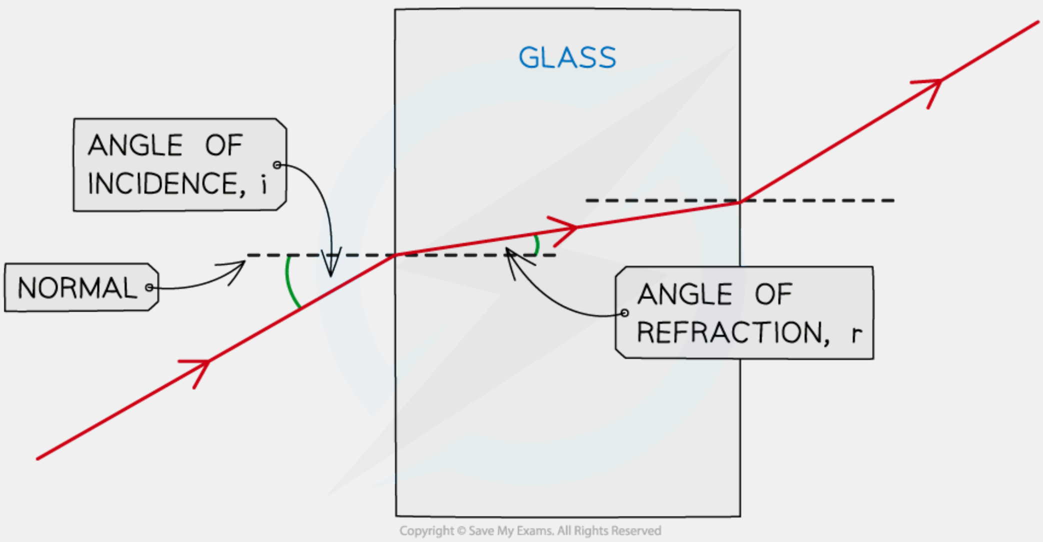


A ray diagram for light refracting at a boundary, showing the normal, angle of incidence and angle of refraction

Refraction of light

- **Refraction** occurs when light passes a **boundary** between two different transparent materials
    - At the boundary, the rays of light change **direction**
- This change in direction depends on the difference in **density** between the two media:
    - From **less dense to more dense** (e.g air to glass), light bends **towards** the normal
    - From **more dense to less dense** (e.g. glass to air), light bends **away** from the normal
    - When passing along the **normal** (perpendicular) the light **does not bend** at all
- Note that when a light wave enters and leaves the glass block there are **two** boundaries
    - The **refracted** ray at the **first** boundary becomes the **incident** ray at the **second** boundary

Refraction diagram of light from air through a glass block

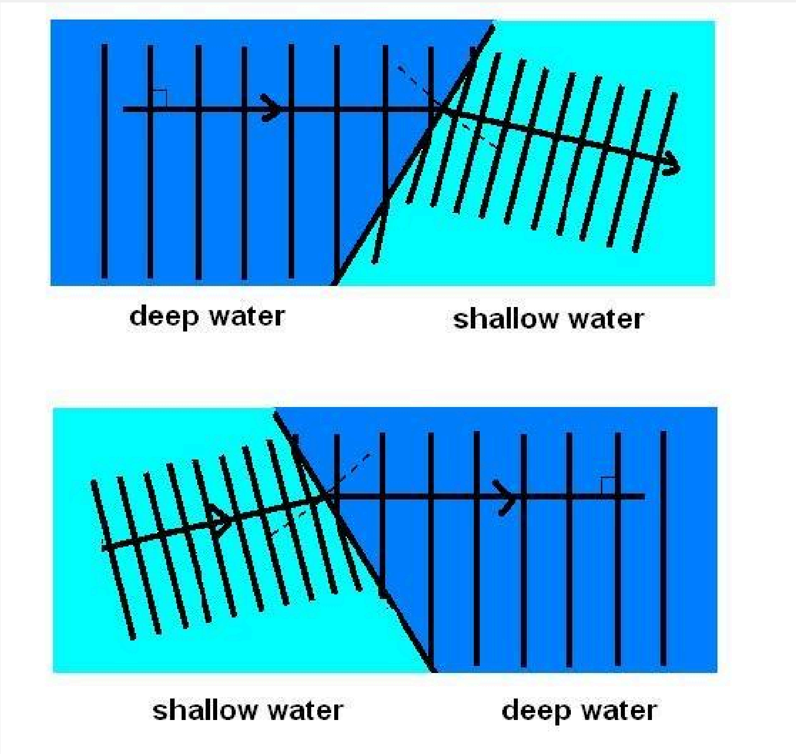


How to construct a ray diagram showing the refraction of light as it passes through a rectangular block

- The **change in direction** occurs due to the **change in speed** when travelling in different substances
    - When light passes into a denser substance, the waves will **slow down**; hence, they bend **towards the normal**
- The only properties that **change** during refraction are **speed and wavelength** – the frequency of waves **does not change**
    - Different frequencies account for different **colours** of light (red has a low frequency, whilst blue has a high frequency)
    - When light refracts, **it does not change colour** (think of a pencil in a glass of water), therefore, the frequency does not change

Refraction due to change in depth of water

- From **shallow water to deep water**, light bends **away** from the normal
- Density in water is the **same** throughout regardless of the depth
- At shallow water, due to **friction** with the ground, waves travel **slower**
- As waves are slower in shallow water and faster in deep water, they refract as shown below:



Examiner Tips and Tricks

Practice drawing refraction diagrams as much as you can! It's very important to remember which way the light bends when it crosses a boundary:

As the light **enters** the block it bends **towards** the normal line

Remember: Enters Towards

When it **leaves** the block it bends **away** from the normal line

Remember: Leaves Away

You only need to know about light passing through the boundaries between **two** media.

Investigating Refraction

Aims of the experiment

- To investigate the refraction of light using rectangular blocks, semi-circular blocks and triangular prisms

Variables

- **Independent variable** = shape of the block
- **Dependent variable** = angle of refraction
- Control variables:
  - Width of the light beam
  - Same frequency / wavelength of the light

Equipment list

Equipment	Purpose
Ray box	To provide a narrow beam of light that can be easily refracted
Protractor	To measure the angles of incidence and refraction
Sheet of paper	To mark the lines indicating the incident and refracted rays
Pencil	To draw the incident and refracted ray lines onto the paper
Ruler	To draw the incident and refracted ray lines onto the paper
Perspex blocks (rectangular, semi-circular & prism)	To refract the light beam

- **Resolution** of measuring equipment:
  - Protractor = 1°
  - Ruler = 1 mm

Refraction diagram for equipment

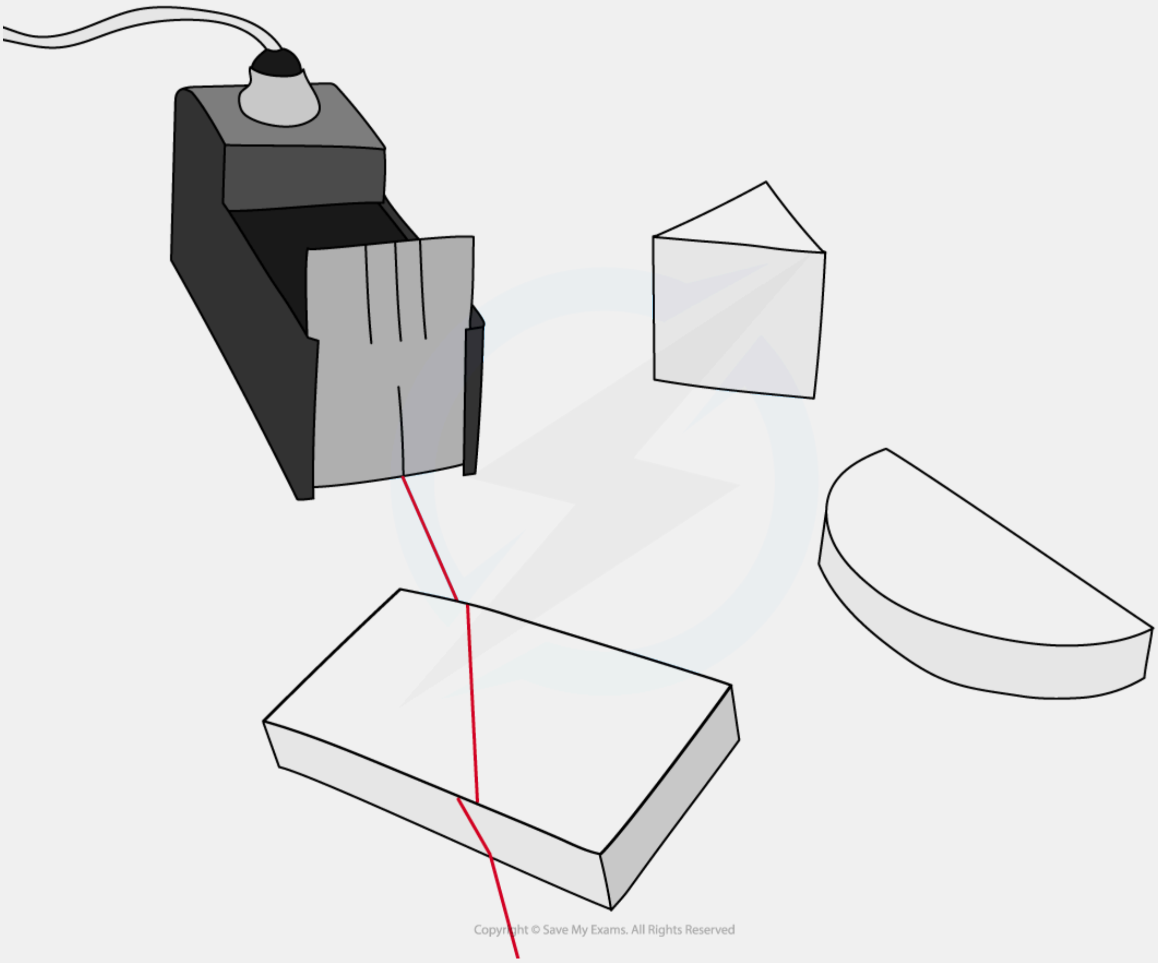
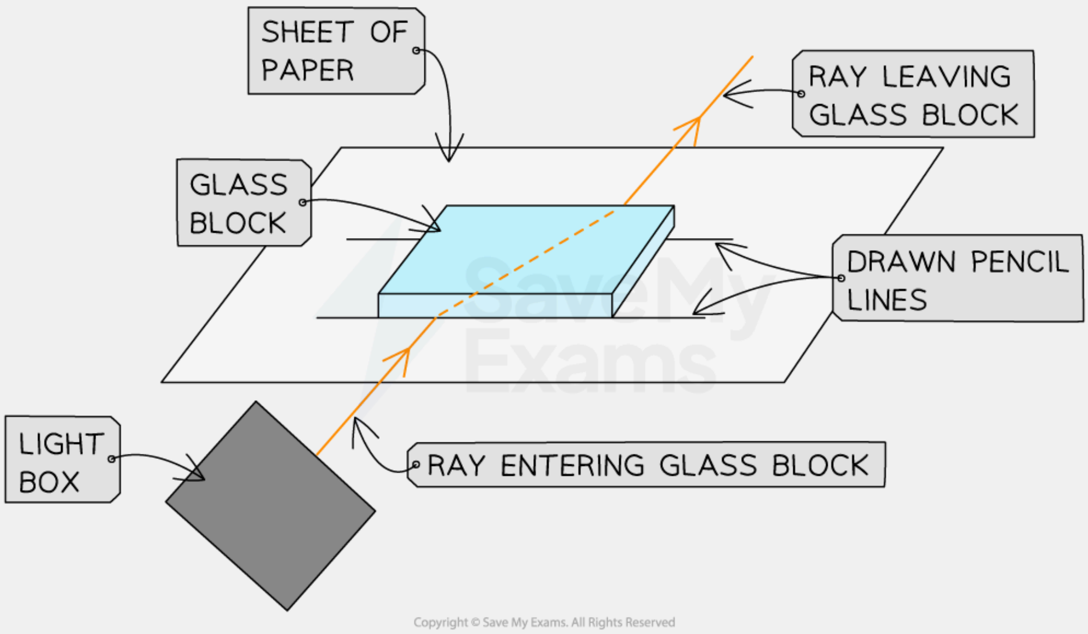


Diagram showing a ray box alongside three different-shaped glass blocks

Method

Refraction diagram set up



Apparatus to investigate refraction

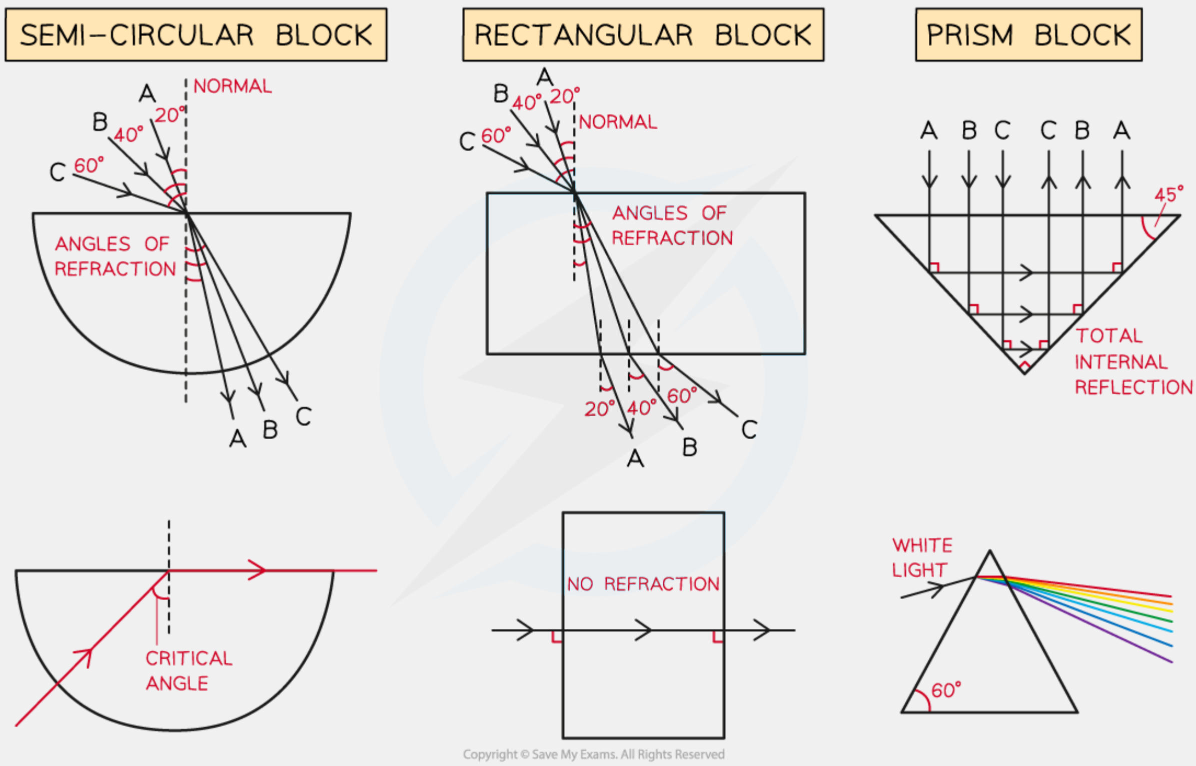
1. Place the glass block on a sheet of paper, and carefully draw around the rectangular Perspex block using a pencil
2. Switch on the ray box and direct a beam of light at the side face of the block
3. Mark on the paper:
    - A point on the ray close to the ray box
    - The point where the ray enters the block
    - The point where the ray exits the block
    - A point on the exit light ray which is a distance of about 5 cm away from the block

4. Draw a dashed line normal (at right angles) to the outline of the block where the points are
5. Remove the block and join the points marked with three straight lines
6. Replace the block within its outline and repeat the above process for a ray striking the block at a different angle
7. Repeat the procedure for each shape of Perspex block (prism and semi-circular)

Analysis of results

- Consider the light paths through the different-shaped blocks

Refraction experiment results with different media



Refraction of light through different shapes of Perspex blocks

- The final diagram for each shape will include multiple light ray paths for the different angles of incidences (*i*) at which the light strikes the blocks
- This will help demonstrate how the angle of refraction (*r*) changes with the angle of incidence
    - Label these paths clearly with (1) (2) (3) or **A**, **B**, **C** to make these clearer

- Use the laws of refraction to analyse these results

Evaluating the experiment

Systematic errors

- An error could occur if the 90° lines are drawn incorrectly
  - Use a set square to draw perpendicular lines

Random errors

- The points for the incoming and reflected beam may be inaccurately marked
  - Use a sharpened pencil and mark in the middle of the beam
- The protractor resolution may make it difficult to read the angles accurately
  - Use a protractor with a higher resolution

Safety considerations

- The ray box light could cause burns if touched
  - Run burns under cold running water for at least five minute
- Looking directly into the light may damage the eyes
  - Avoid looking directly at the light
  - Stand behind the ray box during the experiment
- Keep all liquids away from the electrical equipment and paper

Examiner Tips and Tricks

In your examination, you might be asked to write a method explaining how you might investigate the refraction of light through different shaped blocks

As part of this method you should describe:

- What equipment you need
- How you will use the equipment

- How you will trace the rays of light before, while and after they pass through the block

Refractive Index

Refractive index as a ratio of speed

- The refractive index can be calculated in two different ways:
    1. Using the **ratio of speeds**
    2. Using the **ratio of angles**
- The refractive index is a number that is **always larger than 1** and is different for different materials
    - Objects which are more **optically dense** have a **higher** refractive index, e.g. *n* is about 2.4 for diamond
    - Objects which are less **optically dense** have a **lower** refractive index, e.g. *n* is about 1.5 for glass
- Since the refractive index is a **ratio**, it has **no units**
- The refractive index, *n*, for the ratio of speeds, is defined as:

The ratio of the speeds of a wave in two different regions

- The refractive index, *n*, for the ratio of speeds, is given by the equation:

$$n = \frac{speed\ of\ light\ in\ vacuum\ (3.0\times10^{8})}{speed\ of\ light\ in\ medium}$$

Refractive index as a ratio of angles

- The refractive index, *n*, for the ratio of angles, is defined as:

The ratio of the sine of the angle of incidence and the sine of the angle of refraction of a wave in two different regions

- The refractive index, *n*, for the ratio of angles, is given by the equation:

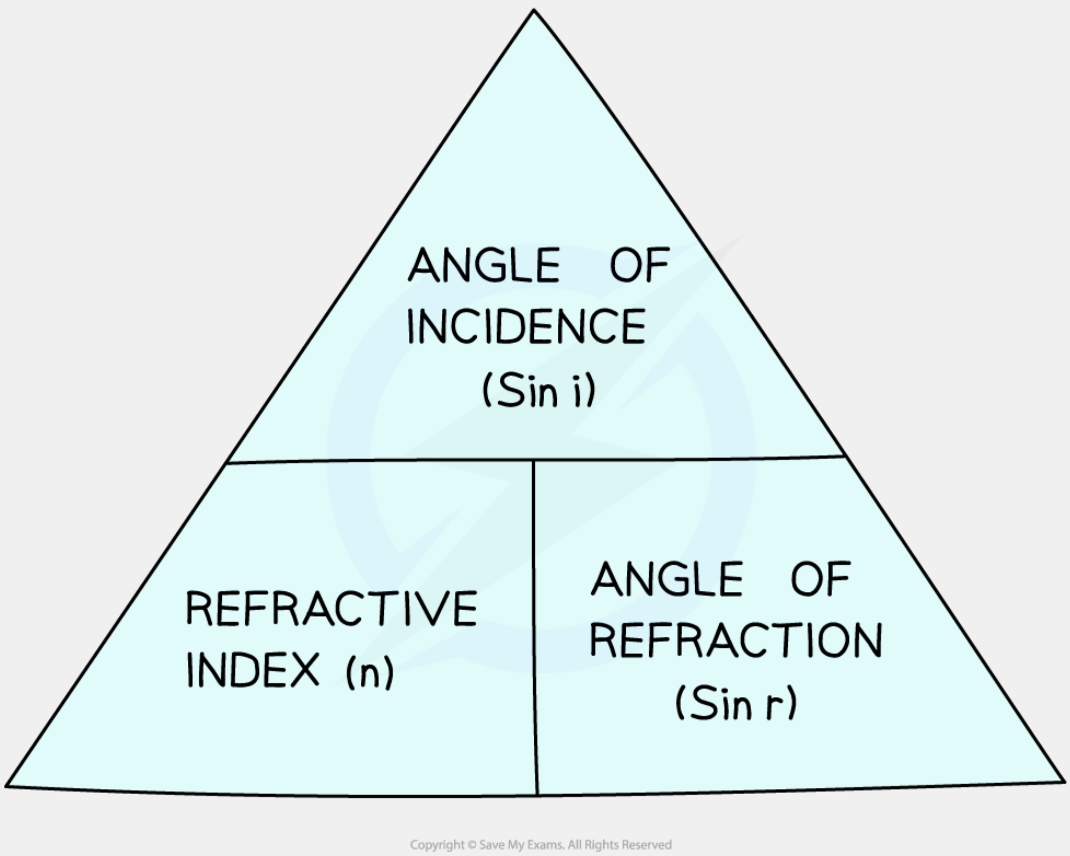
$$n = \frac{\sin \sin i}{\sin \sin r}$$

- Where:

- n = the refractive index of the material
- i = angle of incidence of the light (°)
- r = angle of refraction of the light (°)

- This equation can be rearranged with the help of the formula triangle:

A refractive index formula triangle



Formula triangle for the refractive index in terms of angles

- See the example of **1.2 Motion** under *Speed & Velocity* which explains how to use the formula triangle to rearrange equations

Worked Example

A ray of light enters a glass block of refractive index 1.53 making an angle of 15° with the normal before entering the block.

Calculate the angle it makes with the normal after it enters the glass block.

Answer:

Step 1: List the known quantities

- Refractive index of glass, *n* = 1.53
- Angle of incidence, *i* = 15°

Step 2: Write the equation for refractive index in terms of the ratio of angles

$$n = \frac{\sin sin\, i}{\sin sin\, r}$$

Step 3: Rearrange the equation and calculate sin (r)

$$\sin sin\, r = \frac{\sin sin\, i}{n}$$

$$\sin sin\, r = \frac{\sin sin\, 15}{1.53}$$

$$\sin sin\, r = 0.1692...$$

Step 4: Find the angle of refraction (*r*) by using the inverse sin function

$$r = sin^{-1}(0.1692)$$

$$r = 9.7 \approx 10° \ (2\ s.f.)$$

Examiner Tips and Tricks

$n = \frac{\sin sin\ i}{\sin sin\ r}$ is also known as Snell's law but you do not need to know this for your exam.

Important: ($\frac{\sin sin\ i}{\sin sin\ r}$) is not the same as ($\frac{i}{r}$). Incorrectly cancelling the sin terms is a very common mistake!

When calculating the value of *i* or *r* start by calculating the value of sin *i* or sin *r*.

You can then use the **inverse sin** function ($\sin^{-1}$ on most calculators by pressing 'shift' then 'sine') to find the angle.

One way to remember which way around *i* and *r* are in the fraction is remembering that '*i*' comes before '*r*' in the alphabet, and therefore is on the top of the fraction (whilst *r* is on the bottom).

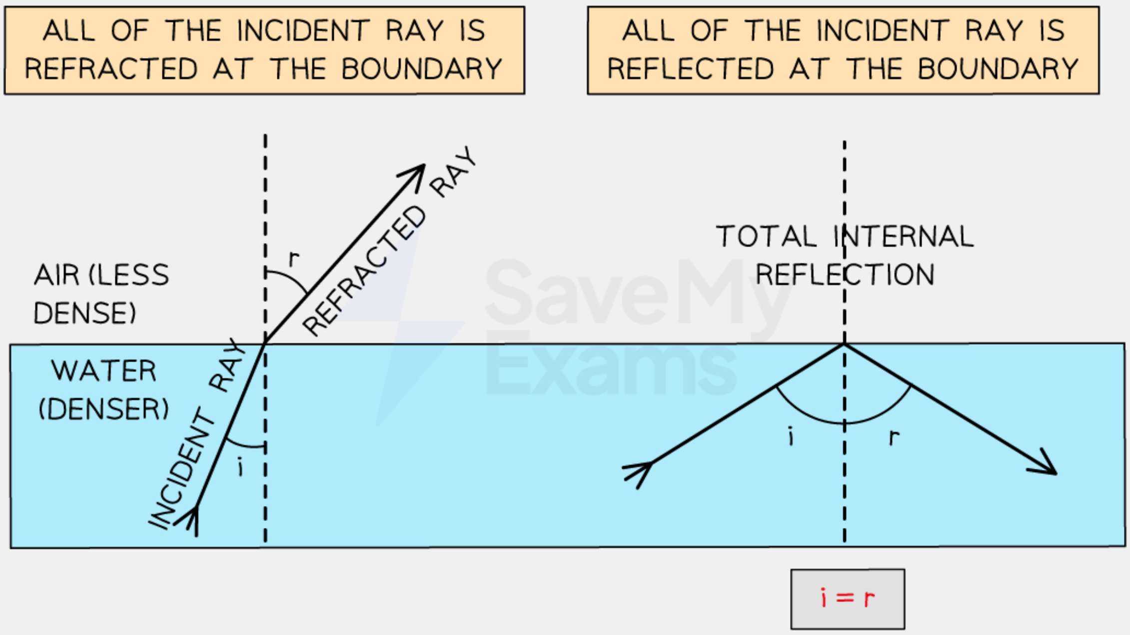
Total Internal Reflection

- **Total internal reflection** (TIR) occurs at the boundary between two media when:

  All the incident ray in medium 1 is reflected back into medium 1

- When light passes between the boundary of an optically **dense** to a **less dense** medium and the **angles of incidence are small**
  - The **refracted ray** is **strong**
  - The **reflected ray** is **weak**
- The weak ray is reflected back into the **denser medium**
  - This means **some internal reflection** occurs
- It is not TIR because not all of the ray is reflected, only **some** of it

Comparing refraction and total internal reflection

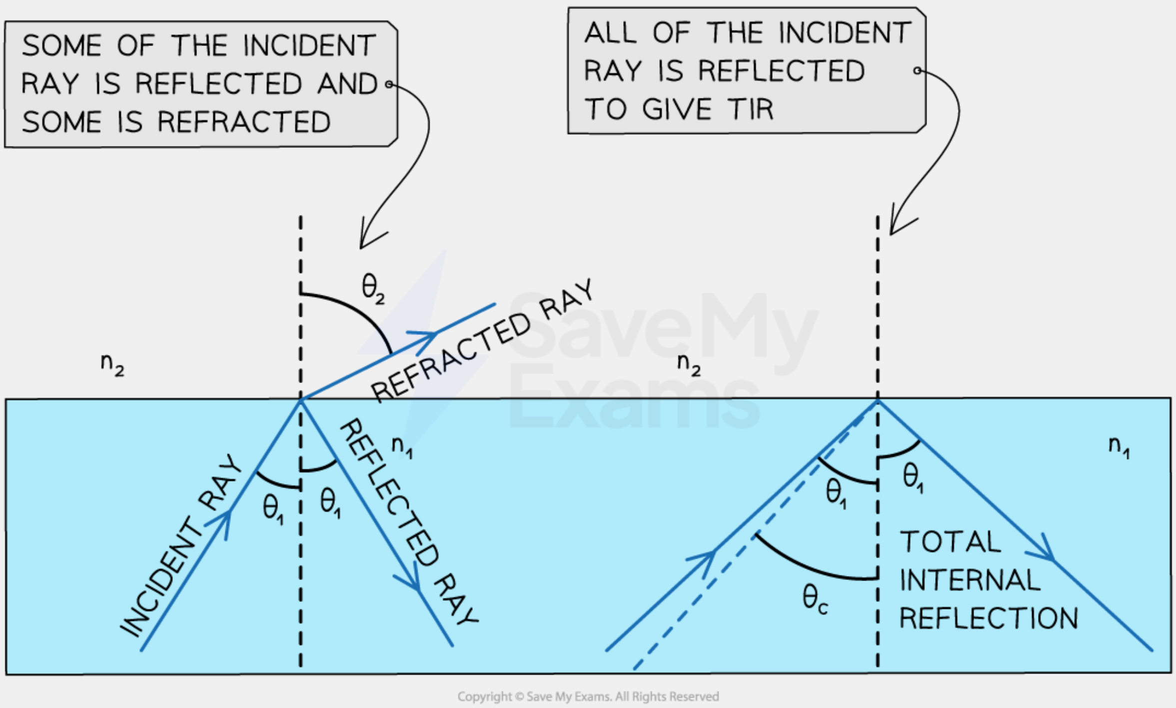


Refraction happens when the angle of incidence is smaller and total internal reflection happens when the angle of incidence equals the angle of reflection

Comparing internal reflection and total internal reflection

- Normal reflection produces a less intense light compared to TIR
  - In **TIR** 100% of the ray is reflected back, whereas in normal reflection, a very small portion of the ray is refracted.
- Normal reflection occurs **independent** of the **refractive indices** of both media
  - For **TIR** to occur, the incident material must be **denser** than the second material

Conditions for internal reflection



Total internal reflection happens with the angle of incidence is bigger than the critical angle

Internal reflection examples

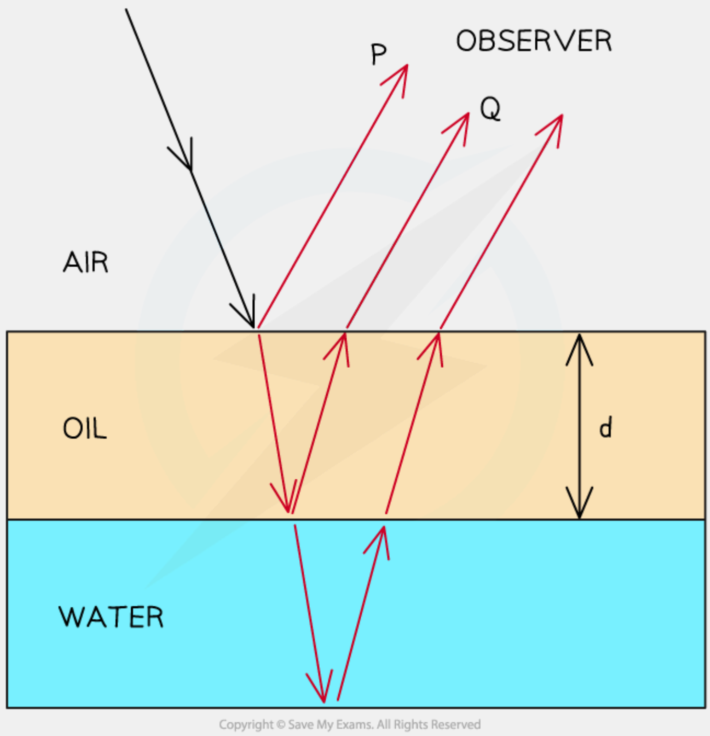
- **Thin film interference** is an example of **internal reflection**
- An example of this is the shiny side of a CD

Example of internal reflection

The colourful pattern observed on a CD is a result of thin film interference

- Other examples of thin film interference include:
  - Soap bubbles
  - Thin layers of oil on water
- In these examples, internal reflection occurs at the boundaries between:
  - Air and water
  - Water and oil
- A spectrum of colours will be seen by the observer due to the rays partially reflected at the boundary

A ray diagram of an example of internal reflection

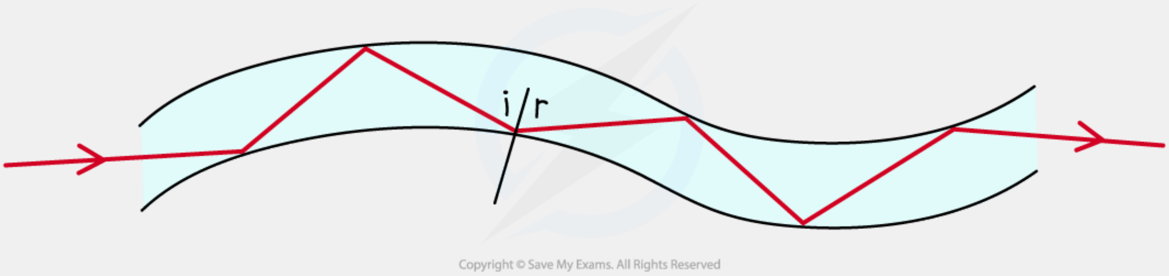


Light is reflected and transmitted at the boundary from a less dense to a more dense material. Light is transmitted only at the boundary from a more dense to a less dense material. Hence, in this diagram P and Q exist but the third unlabelled ray does not.

Total internal reflection examples

- Total internal reflection is used to reflect light along **optical fibres**, meaning they can be used for
  - communications
  - endoscopes
  - decorative lamps
- Light travelling down an optical fibre is totally internally reflected each time it hits the edge of the fibre

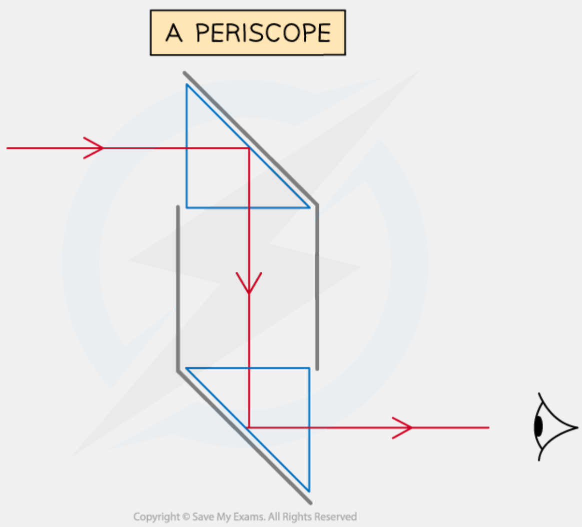
Total internal reflection example: optical fibre



Optical fibres utilise total internal reflection for communications

- Prisms are used in a variety of optical instruments, including:
  - Periscopes
  - Binoculars
  - Telescopes
  - Cameras
  - Safety reflectors
- A **periscope** is a device that can be used to see over tall objects
  - It consists of two right-angled prisms

Total internal reflection example: a periscope



Reflection of light through a periscope

- The light totally internally reflects in both prisms

Examiner Tips and Tricks

If asked to name the phenomena make sure you give the whole name – **total internal reflection**

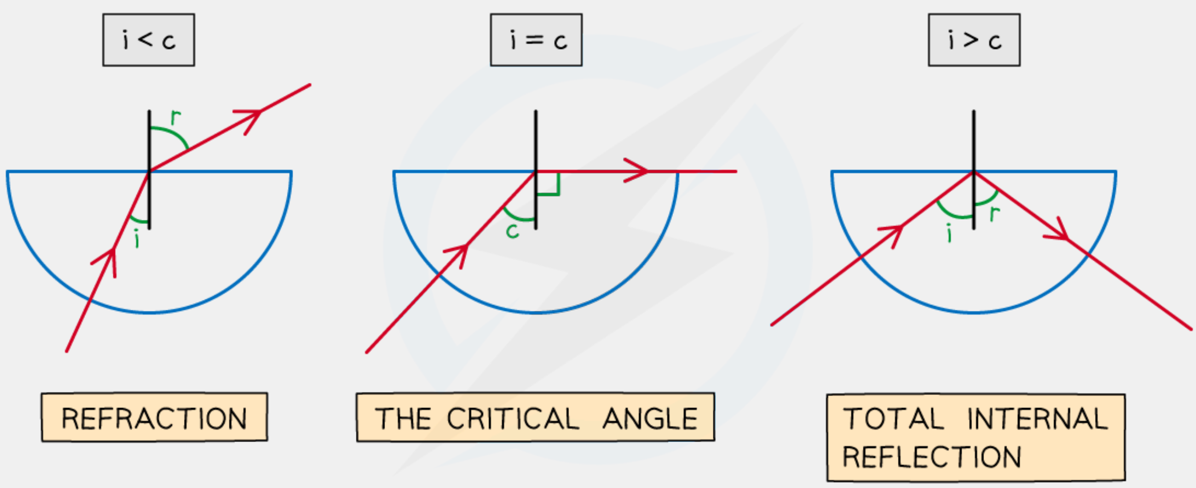
Remember: total internal reflection occurs when light travels from a denser material to less dense material and **ALL** of the light is reflected.

If asked to give an example of a use of total internal reflection, first state the name of the object that causes the reflection (e.g. a right-angled prism) and then name the device in which it is used (e.g. a periscope)

Critical angle

- At the boundary between a more dense and a less dense medium, as the angle of incidence is increased, the angle of refraction also increases until it gets closer to 90°
- When the angle of refraction is exactly 90° the light is refracted along the boundary
    - At this point, the angle of incidence is known as the **critical angle** *c*

Obtaining total internal reflection examples

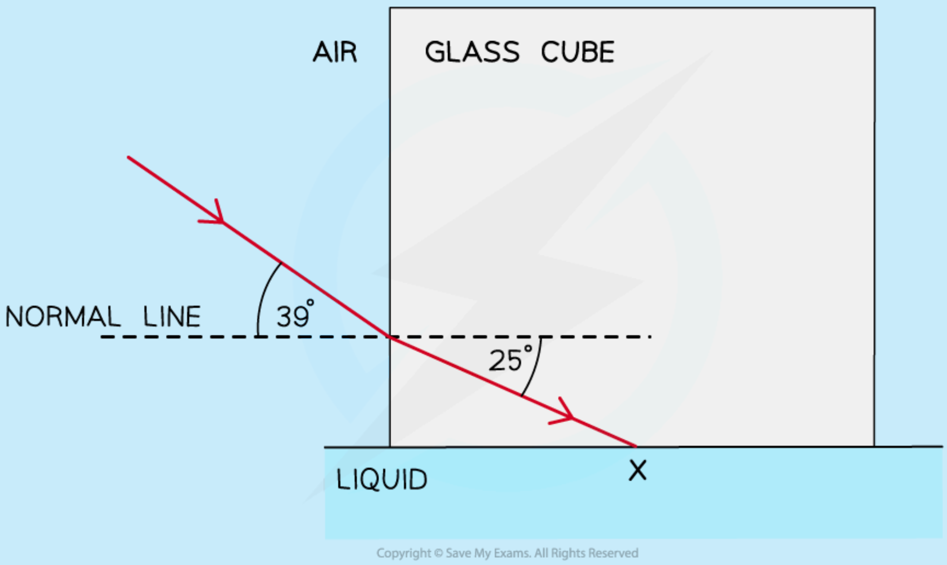


As the angle of incidence increases it will eventually surplus the critical angle and lead to total internal reflection of the light

- When the angle of incidence is larger than the critical angle, the refracted ray is now **reflected**
  - This is **total internal reflection**

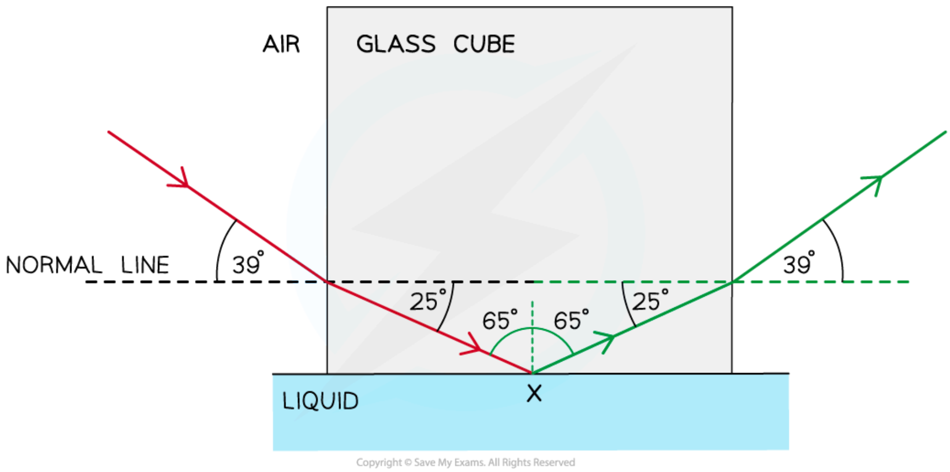
Worked Example

A glass cube is held in contact with a liquid and a light ray is directed at a vertical face of the cube. The angle of incidence at the vertical face is 39° and the angle of refraction is 25° as shown in the diagram. The light ray is totally internally reflected for the first time at **X**.



Complete the diagram to show the path of the ray beyond **X** to the air and calculate the critical angle for the glass-liquid boundary.

Answer:



Step 1: Draw the reflected angle at the glass-liquid boundary

- When a light ray is reflected, the angle of incidence = angle of reflection
- Therefore, the angle of incidence (or reflection) is 90° – 25° = 65°

Step 2: Draw the refracted angle at the glass-air boundary

- At the glass-air boundary, the light ray refracts **away** from the normal
- Due to the reflection, the light rays are symmetrical to the other side

Step 3: Calculate the critical angle

- The question states the ray is "totally internally reflected for the first time" meaning that this is the lowest angle at which TIR occurs
- Therefore, 65° is the critical angle

Examiner Tips and Tricks

If you are asked to explain what is meant by the critical angle in an exam, you can be sure to gain full marks by drawing and labelling the same diagram above (showing the three semi-circular blocks)

Refractive index & critical angle equation

- The critical angle, *c*, of a material, is related to its **refractive index**, *n*
- The relationship between the two quantities is given by the equation:

$$\sin sin\, c = \frac{1}{n}$$

- This can also be rearranged to calculate the refractive index, *n*:

$$n = \frac{1}{\sin sin\, c}$$

- This equation shows that:
    - The larger the **refractive index** of a material, the smaller the **critical angle**
    - Light rays inside a material with a **high refractive index** are more likely to be **totally internally reflected**

Worked Example

Opals and diamonds are transparent stones used in jewellery. Jewellers shape the stones so that light is reflected inside. Compare the critical angles of opal and diamond and explain which stone would appear to sparkle more.

The refractive index of opal is about 1.5

The refractive index of diamond is about 2.4

Answer:

Step 1: List the known quantities

- Refractive index of opal, n_o = 1.5
- Refractive index of diamond, n_d = 2.4

Step 2: Write out the equation relating critical angle and refractive index

$$\sin sin\, c = \frac{1}{n}$$

Step 3: Calculate the critical angle of opal (c_o)

$$\sin sin\, (c_o) = \frac{1}{1.5} = 0.6667$$

$$c_o = sin^{-1}(0.6667) = 41.8 \approx 42°$$

Step 4: Calculate the critical angle of diamond (c_d)

$$\sin sin\, (c_d) = \frac{1}{2.4} = 0.4167$$

$$c_o = \sin^{-1}(0.4167) = 24.6 \approx 25°$$

Step 5: Compare the two values and write a conclusion

- Total internal reflection occurs when the angle of incidence of light is **larger** than the critical angle ($i > c$)
- In opal, total internal reflection will occur for angles of incidence between 42° and 90°
- The critical angle of diamond is **lower** than the critical angle of opal ($c_o > c_d$)
- This means light rays will be totally internally reflected in diamond over a **larger** range of angles (25° to 90°)

- Therefore, more total internal reflection will occur in diamond hence it will appear to sparkle more than the opal

Examiner Tips and Tricks

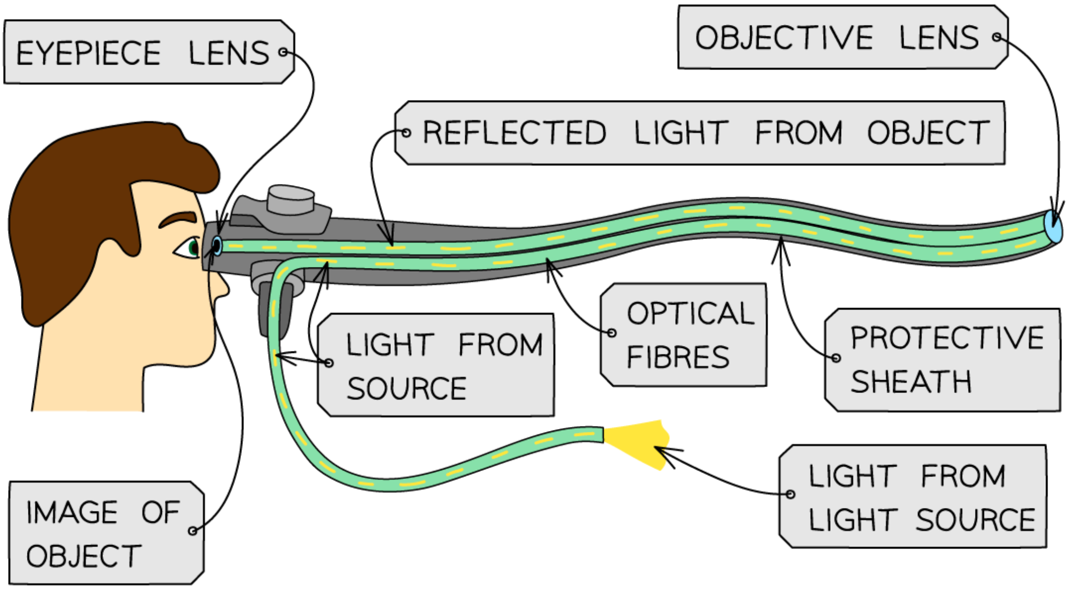
When calculating the value of the critical angle using the above equation:

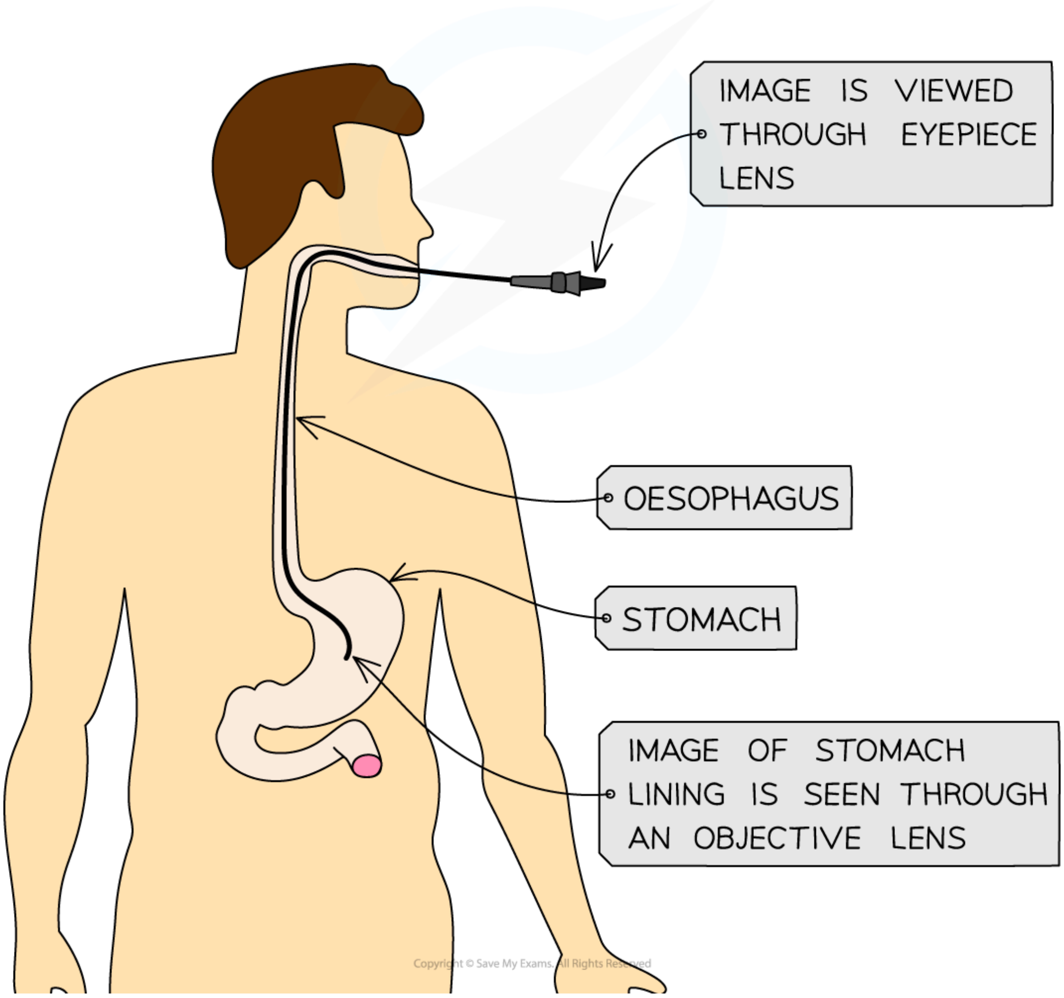
- First use the refractive index, *n*, to find sin(*c*)
- Then use the **inverse** sin function ($\sin^{-1}$) to find the value of *c*

Optical fibres

- Optical fibres have many uses, particularly in telecommunications
- **Endoscopes** are used to look within the human body
  - A camera on the end of an optical fibre is placed down the throat and moved into the stomach
  - Light from inside the stomach is captured by the camera, is totally internally reflected along the optical fibre and viewed by doctors through the eyepiece

Total internal reflection example: endoscope



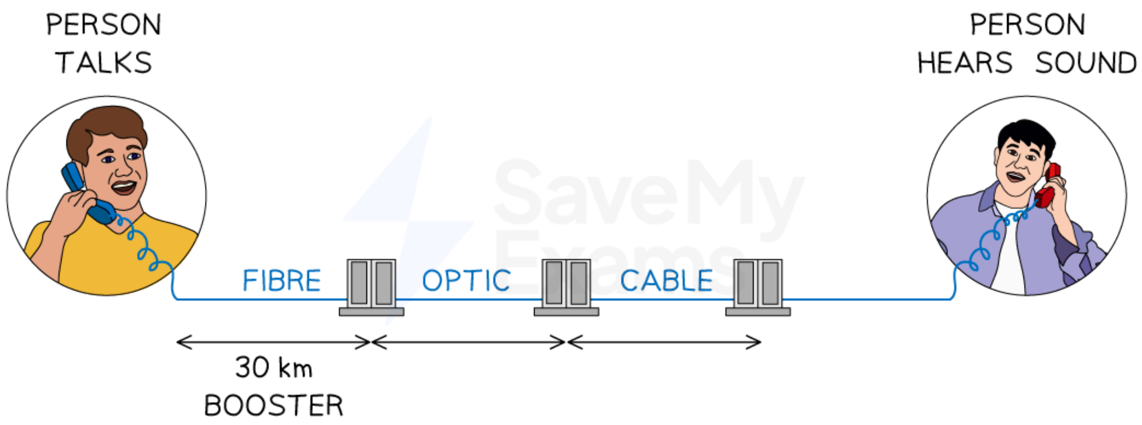


Endoscopes utilise total internal reflection to see inside a patient's body

Total internal reflection using telecommunication

- **Optical fibres** can be used to transmit:
  - Home (landline) telephone signals
  - Internet signals
  - Cable television signals
- In **phone calls** from landline phones:
  - Electrical signals are converted to **light pulses**
  - That travel close to the speed of light along optical fibres
  - At the receiving end, the digital signal is converted into **sound**

Total internal reflection example: landline telephone signal path



Sound from a landline telephone travels through optical fibres to the landline of the person listening

- Optical fibres are installed:
  - In cables attached to telephone (or telegraph) poles in the street
  - Underground from the service box to the telegraph pole or under the sea

Ray Diagrams

Features of ray diagrams

- Ray diagrams can be described using the following terms:
  - Principal axis
  - Principal focus, or focal point
  - Focal length
- The principal axis is defined as:

A line which passes through the centre of a lens

- The principal focus, or focal point, is defined as:

The point at which rays of light travelling parallel to the principal axis intersect the principal axis and converge or the point at which diverging rays appear to proceed

- Focal length is defined as:

The distance between the centre of the lens and the principal focus

Converging & Diverging Lenses

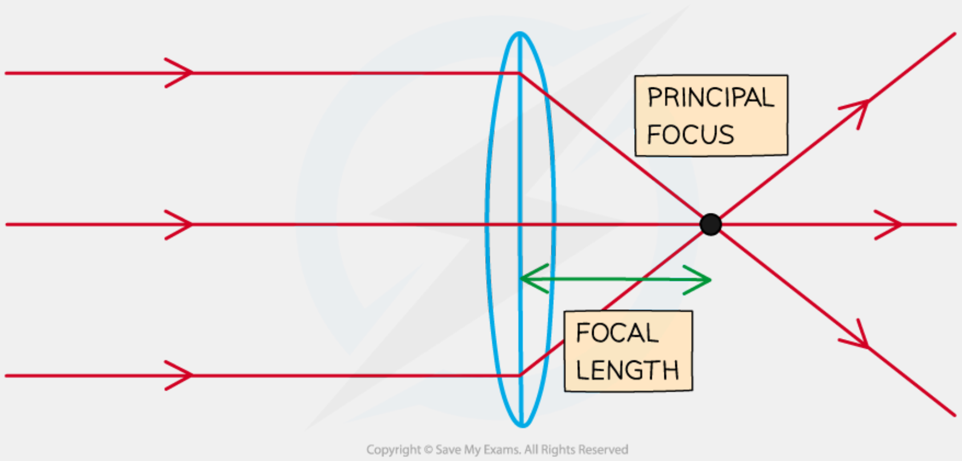
- A lens is a piece of equipment that forms an image by **refracting** light
- There are two types of lenses:
  - Converging
  - Diverging

Converging lenses

- In a converging lens, parallel rays of light are brought to a focus
  - This point is called the **principal focus**

- This lens is sometimes referred to as a **convex** lens
- The distance from the lens to the principal focus is called the **focal length**
    - This depends on how **curved** the lens is
    - The **more** curved the lens, the **shorter** the focal length

Converging lens diagram

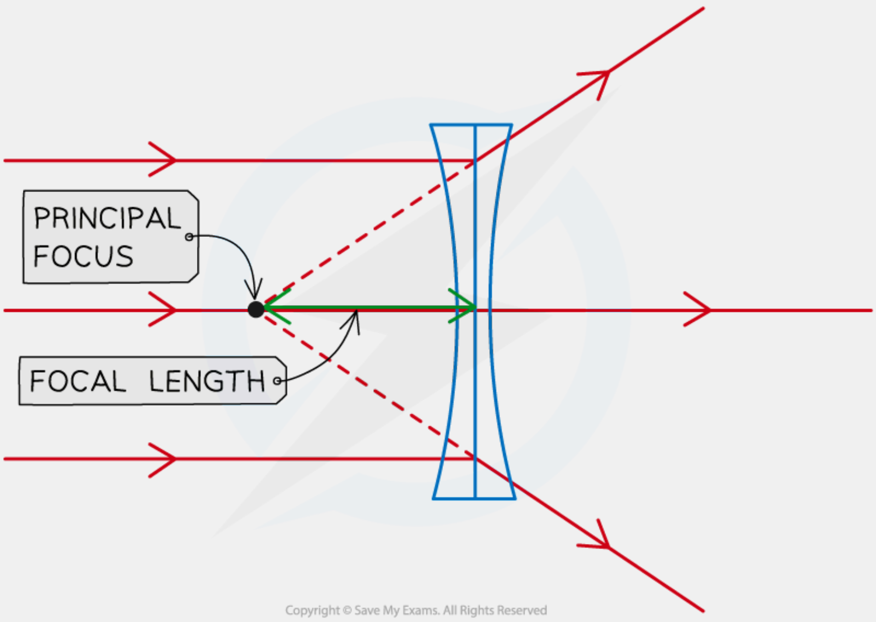


The focal length is the distance from the lens to the principal focus

Diverging lenses

- In a diverging lens, parallel rays of light are made to diverge (spread out) from a point
    - This lens is sometimes referred to as a **concave** lens
- The principal focus is now the point from which the rays appear to diverge from

Diverging lens diagram

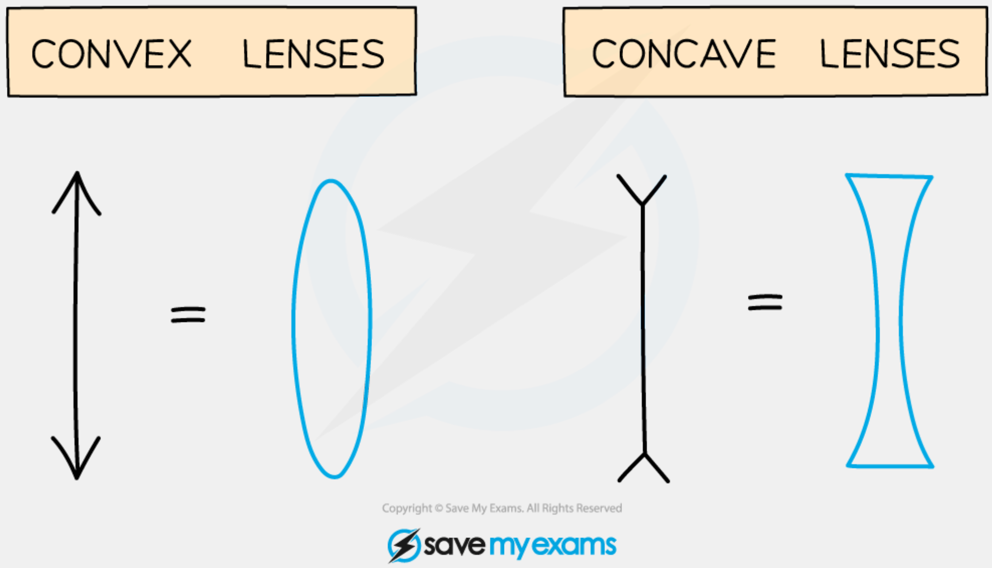


Parallel rays from a diverging lens appear to come from the principal focus

Representing lenses

- In diagrams, the following symbols are often used to represent each type of lens:

Converging and diverging lens symbols



Concave and convex lens symbols

Examiner Tips and Tricks

To remember which lens is converging or diverging, think of the following: Con**v**ex lens = Con**v**erging. You need to be able to describe how the lenses affect the light rays.

Real & Virtual Images

- Images produced by lenses can be one of two types:
  - A real image
  - A virtual image
- Images can be described **compared to their object** as:
  - **Enlarged**/same size/**diminished**
  - **Upright/inverted**
  - **Real/virtual**

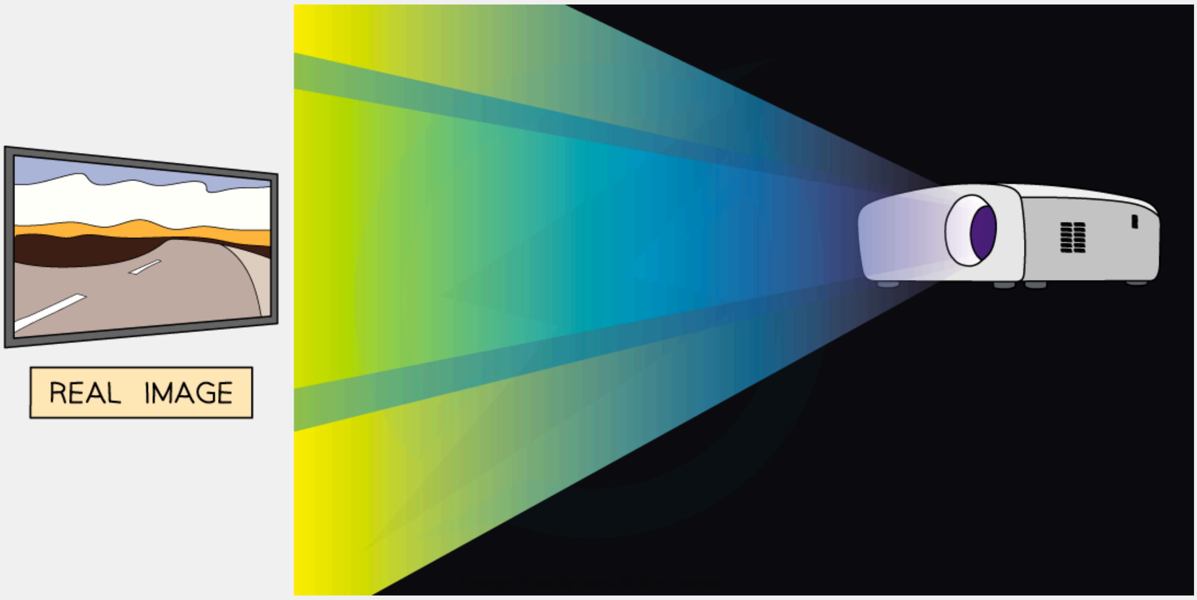
Real images

- A real image is defined as:

An image that is formed when the light rays from an object converge and meet each other and can be projected onto a screen

- A real image is one produced by the **convergence** of light towards a focus
- Real images are always **inverted**
- Real images can be projected onto pieces of paper or screens
  - An example of a real image is the image formed on a cinema screen

A real image



A real image can be projected onto a screen

Virtual images

- A virtual image is defined as:

An image that is formed when the light rays from an object do not meet but appear to meet behind the lens and cannot be projected onto a screen

- A virtual image is formed by the **divergence** of light away from a point
- Virtual images are always **upright**
- Virtual images **cannot** be projected onto a piece of paper or a screen
  - An example of a virtual image is a person's reflection in a mirror

A virtual image

A reflection in a mirror is an example of a virtual image

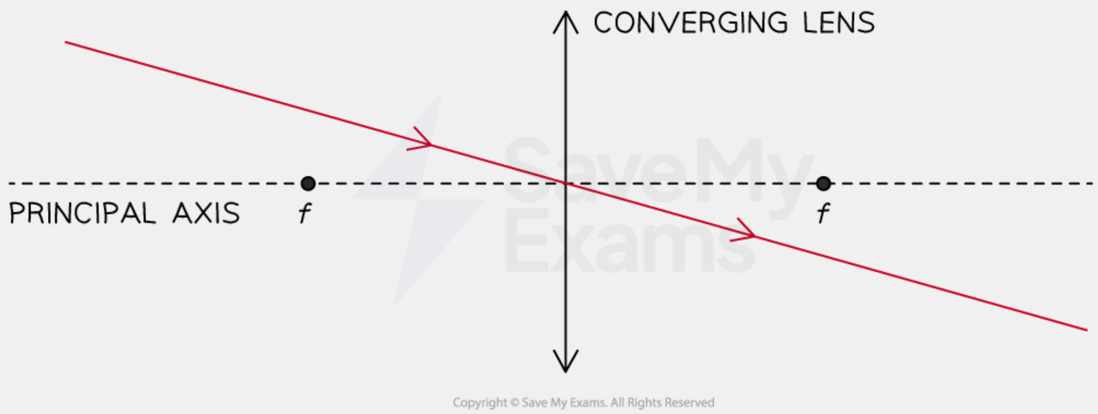
Real Images

Converging lens - real image

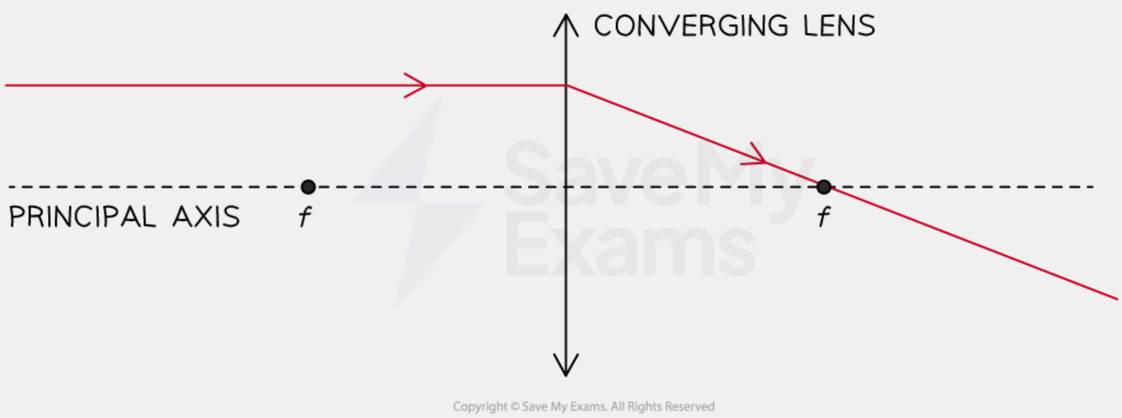
Constructing converging ray diagrams

- The three main rules for constructing ray diagrams are as follows:

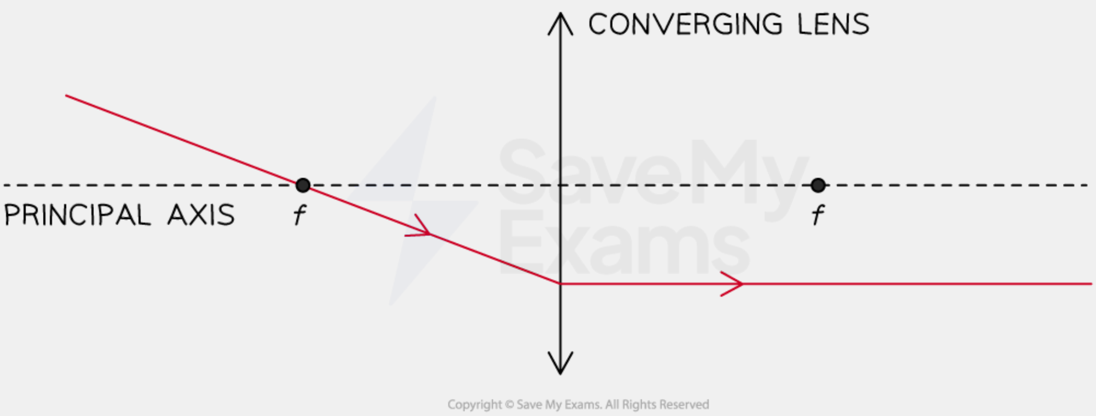
1. **Rays passing through the principal axis will pass through the optical centre of the lens undeviated**



2. **Rays that are parallel to the principal axis will be refracted and pass through the focal point *f***

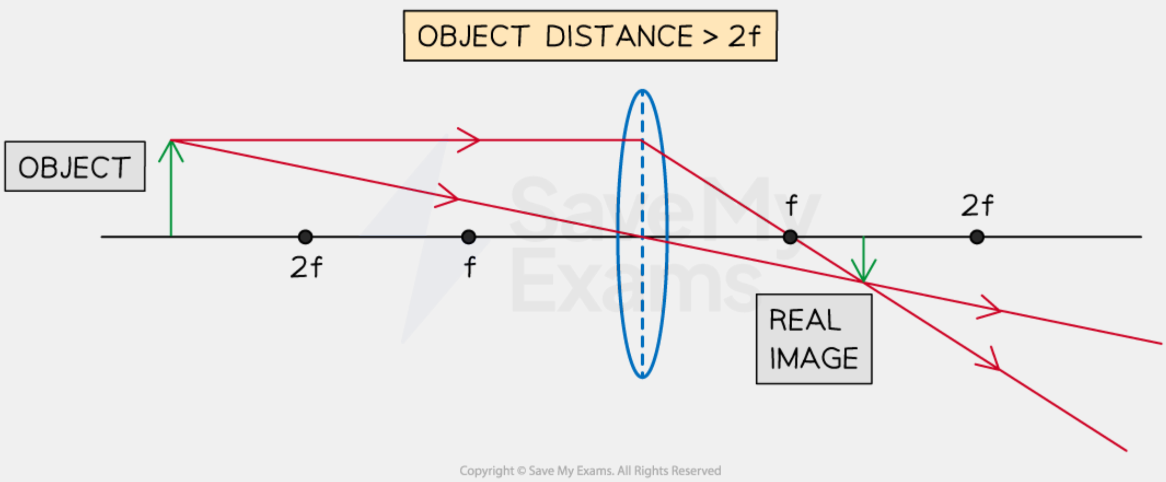


3. **Rays passing through the focal point *f* will emerge parallel to the principal axis**



Drawing converging ray diagrams of real images

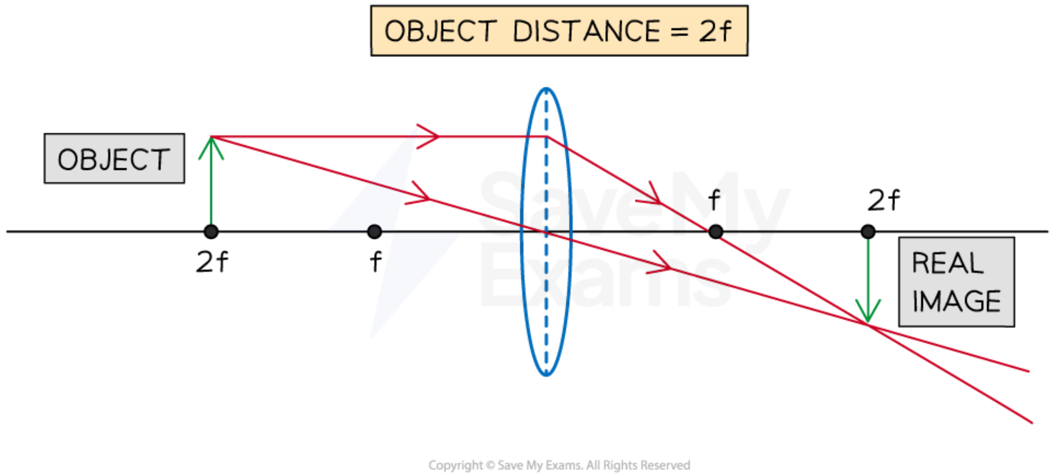
Object placed beyond 2f



- When an **object** is placed **beyond 2*f*** (to the left of the lens), the **image** that forms (to the right of the lens) will have the following properties:

The image forms...	between *f* and 2*f*
The nature of the image is...	real
The orientation of the image is...	inverted
The size of the image is...	diminished

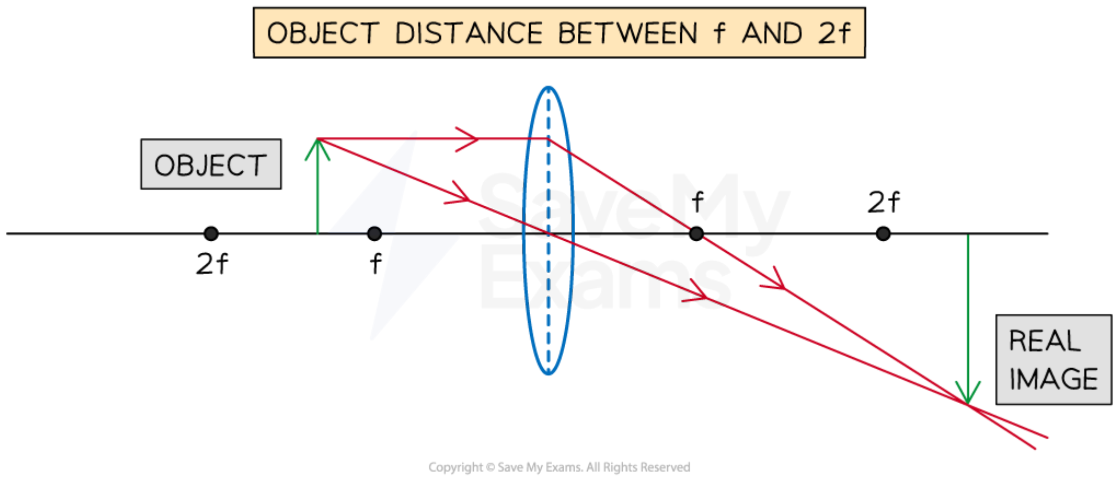
Object placed at 2f



- When an **object** is placed at ***2f*** (to the left of the lens), the **image** that forms (to the right of the lens) will have the following properties:

The image forms...	at 2*f*
The nature of the image is...	real
The orientation of the image is...	inverted
The size of the image is...	the same

Object placed between f and 2f



- When an **object** is placed **between *f* and 2*f*** (to the left of the lens), the **image** that forms (to the right of the lens) will have the following properties

The image forms...	beyond 2*f*
The nature of the image is...	real
The orientation of the image is...	inverted
The size of the image is...	magnified

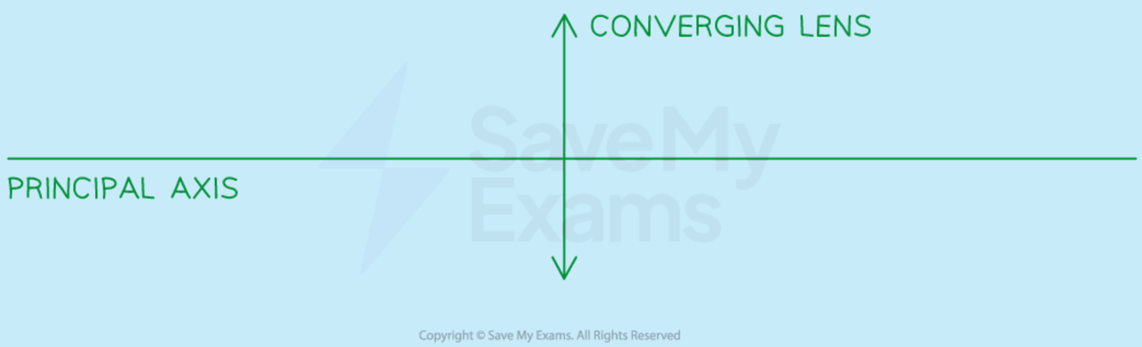
Worked Example

Draw a ray diagram to show how a converging lens can be used to form a diminished image of a real object.

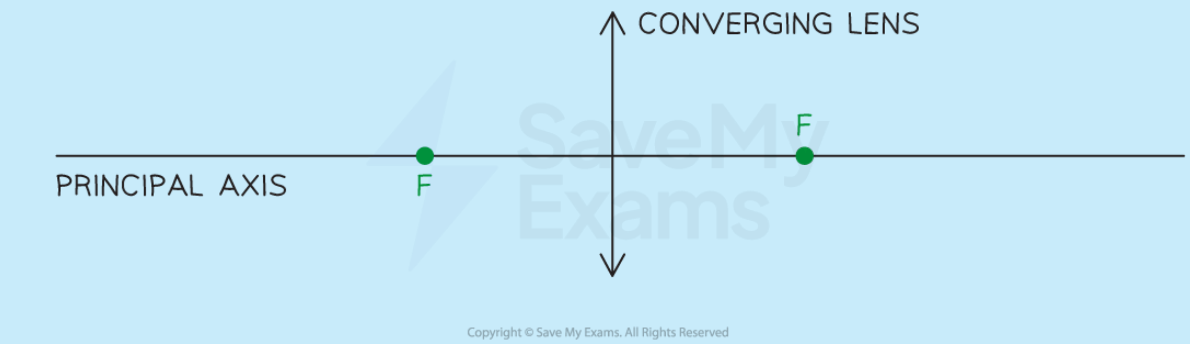
Label the object, image and principal foci of the lens on your diagram.

Answer:

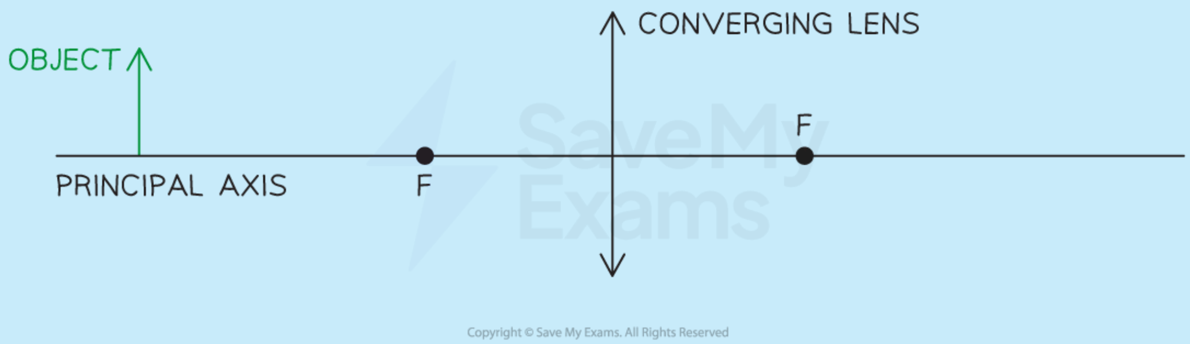
Step 1: Start by drawing and labelling a principal axis and the lens as a line or a very thin ellipse



Step 2: Mark and label the focal points on each side of the lens

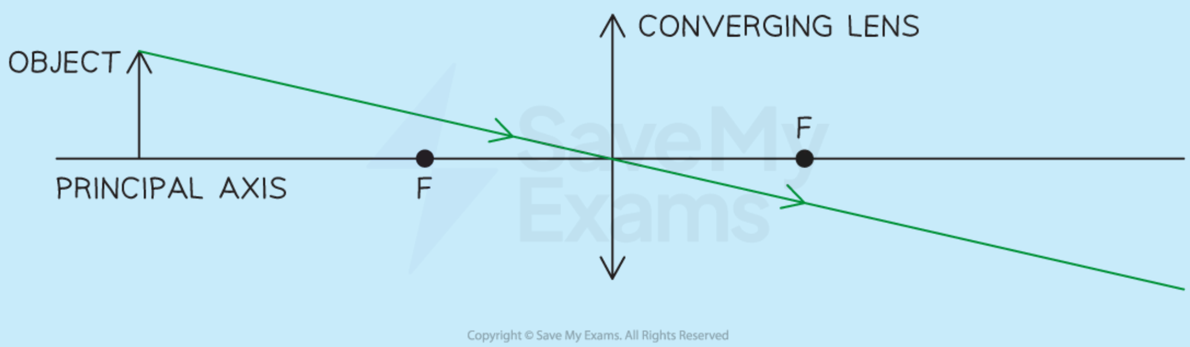


Step 3: Draw and label the object at a distance greater than the focal length on the left side of the lens

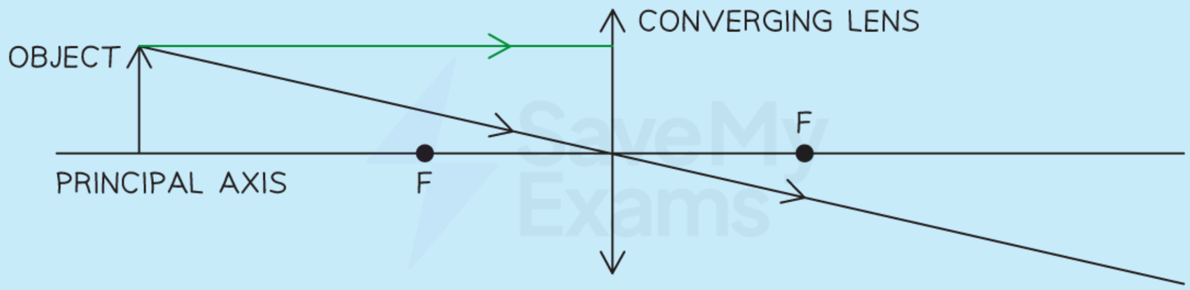


- Tip: For a diminished image the object should be placed a distance of at least 2F away from the lens

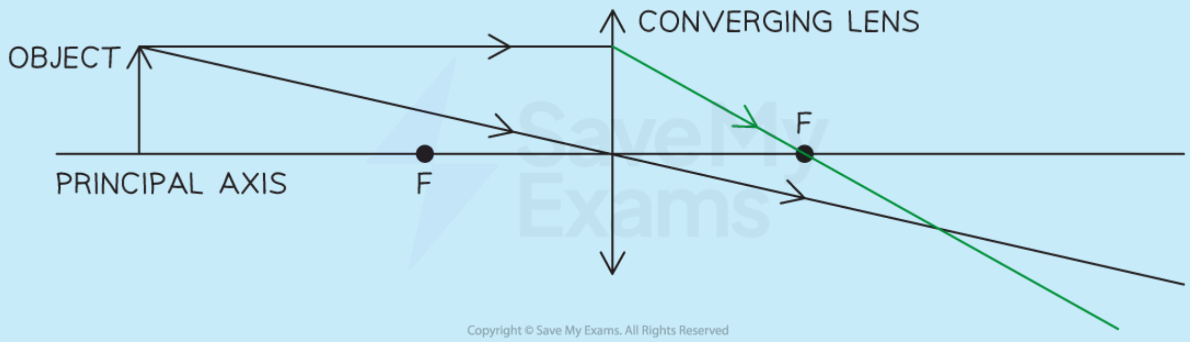
Step 4: Draw a ray through the optical centre of the lens



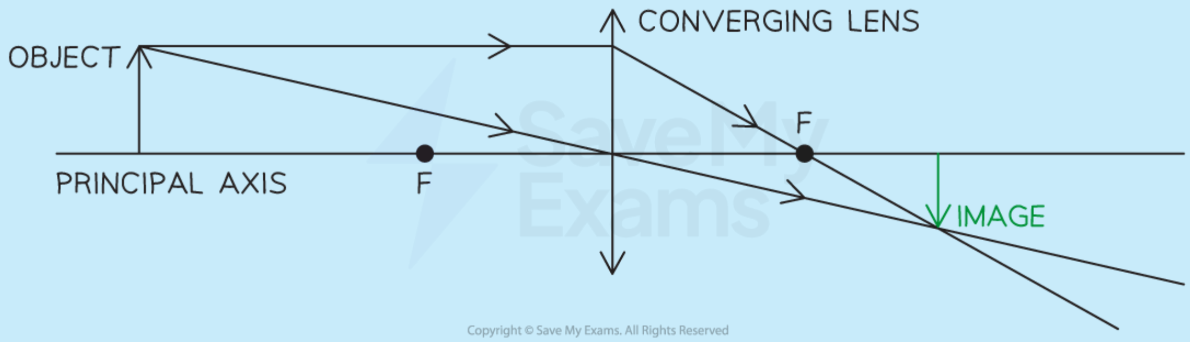
Step 5: Draw a second ray from the object to the lens which is parallel to the principal axis



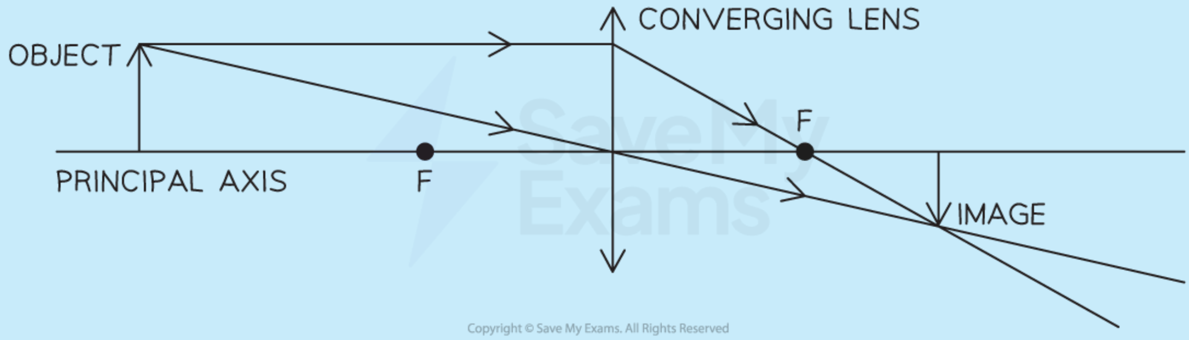
Step 6: Draw the continuation of the ray passing through the focal point on the right side of the lens



Step 7: Draw and label the image at the point where the rays meet



Step 8: Check your final image and make sure everything is included to gain the marks



- For a three-mark question, examiners will be looking for:
  - One ray drawn through the optical centre of the lens
  - A second ray drawn which produces a diminished (smaller) image (which must pass through a labelled focal point)
  - Both the object and the image must be drawn and labelled correctly

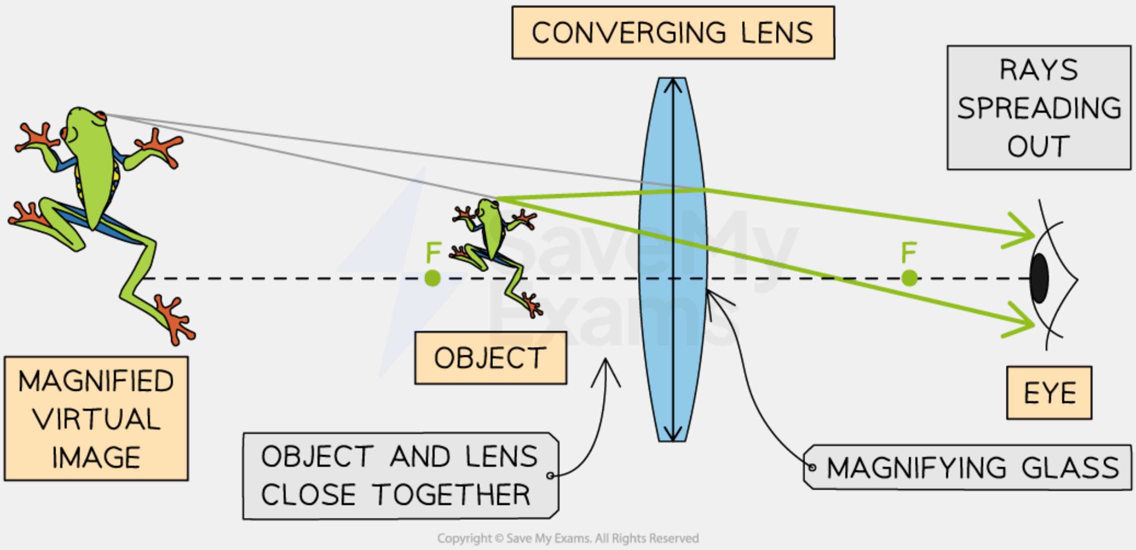
Virtual Images

Converging lens - virtual image

Constructing converging ray diagrams of virtual images

- A single lens placed at a distance **less than** the focal length of an object can be used as a **magnifying glass**

A converging lens ray diagram for an object placed less than f



Ray diagram showing light converging through a magnifying glass to form a magnified virtual image

- The image that forms will have the following properties:

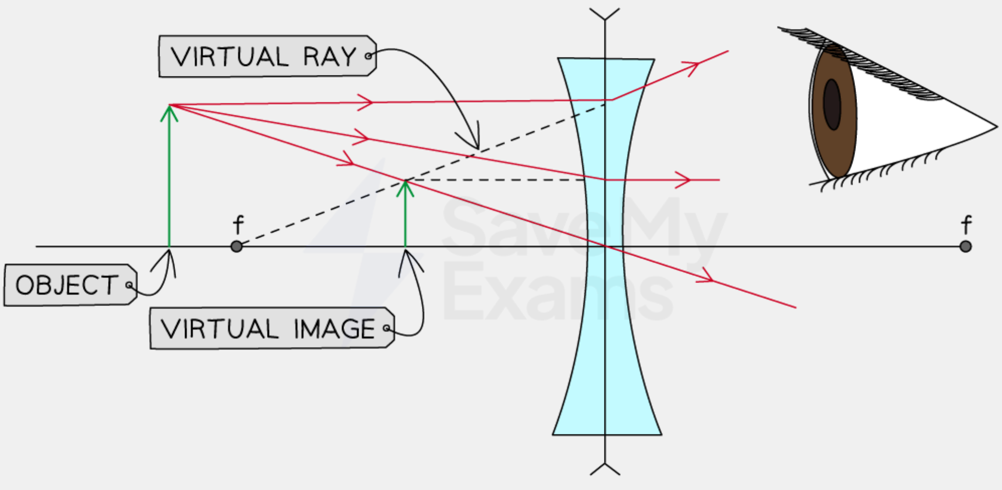
The image forms...	at $2f$ (on the same side as the object)
The nature of the image is...	virtual
The orientation of the image is...	upright
The size of the image is...	magnified

Diverging lens - virtual image

Image formation by a diverging lens

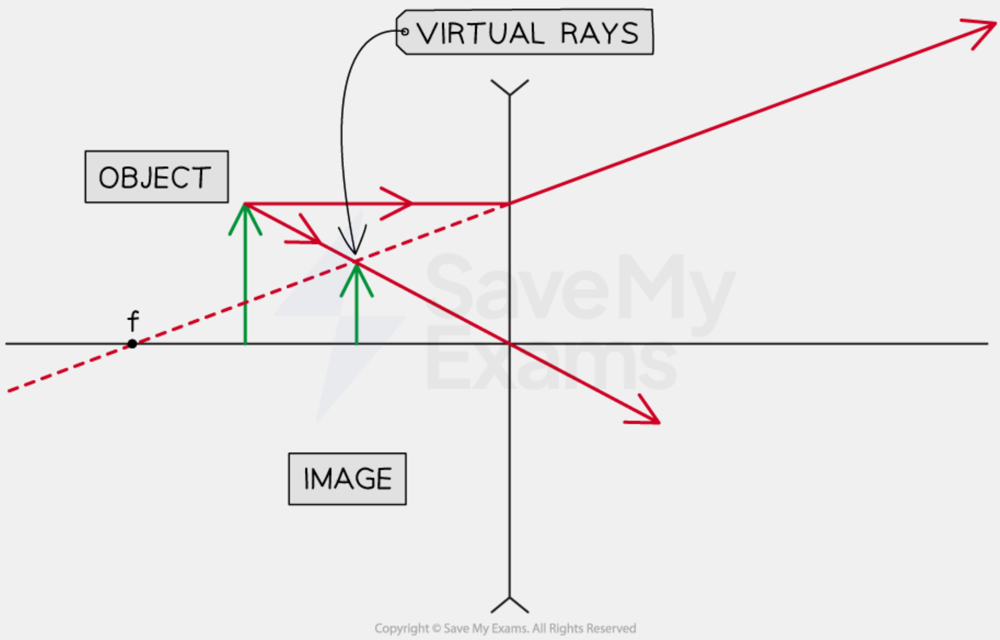
- No matter the position of the object all images formed by diverging lenses are:
  - **Virtual** (and not real)
  - **Upright** (the same as the object)
  - **Diminished** (smaller than the object)
  - On the **same side** of the lens as the object
- For an object placed at any distance away from the lens (further than the focal point or closer than):
  - The ray of light incident on the centre of the lens does not change direction
  - The rays of light parallel to the principal axis are refracted
  - These rays can be extrapolated backwards
    - It appears that they come from a **virtual focus**
  - A visible projection cannot be formed on a screen

Virtual image produced by a diverging lens with object beyond f



A diverging lens always produces a virtual image no matter the position of the object in relation to the focal point or the lens. Here the object is further away from the lens than the focal point.

Virtual image produced by a diverging lens with object closer than f



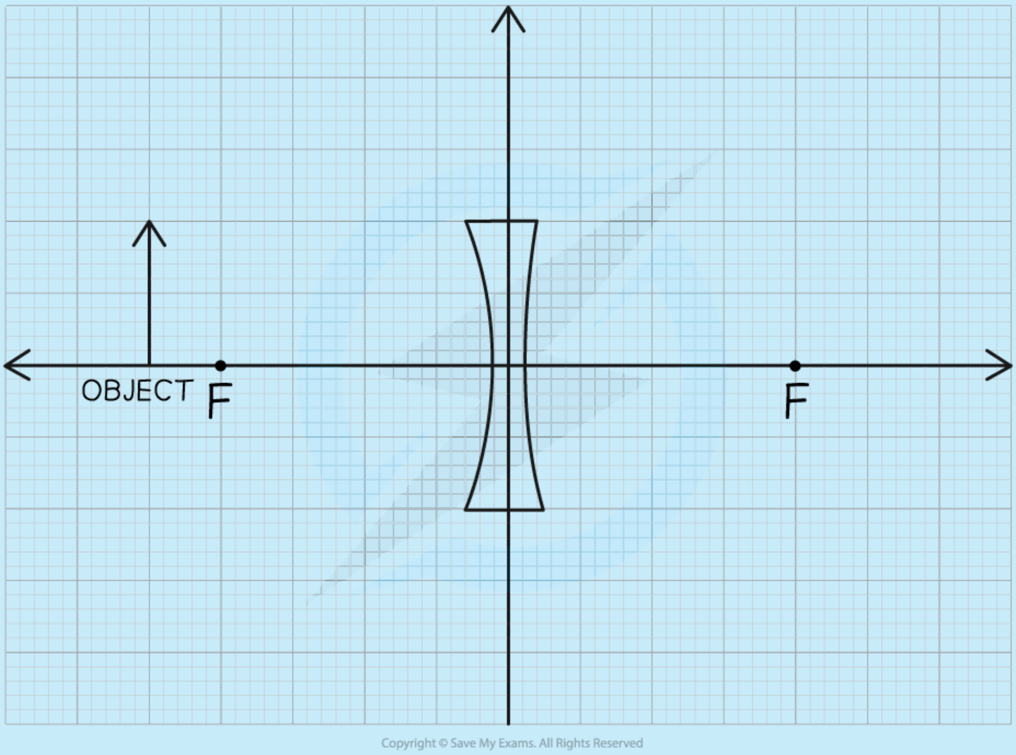
A diverging lens always produces a virtual image no matter the position of the object in relation to the focal point or the lens. Here the object is closer to the lens than the focal point.

Comparing converging & diverging lenses

- The image produced by a **converging** lens can be either **real** or **virtual**
  - This means the image can be inverted (real) or upright (virtual)
- The image produced by a **diverging** lens is always **virtual**
  - This means the image will always be upright

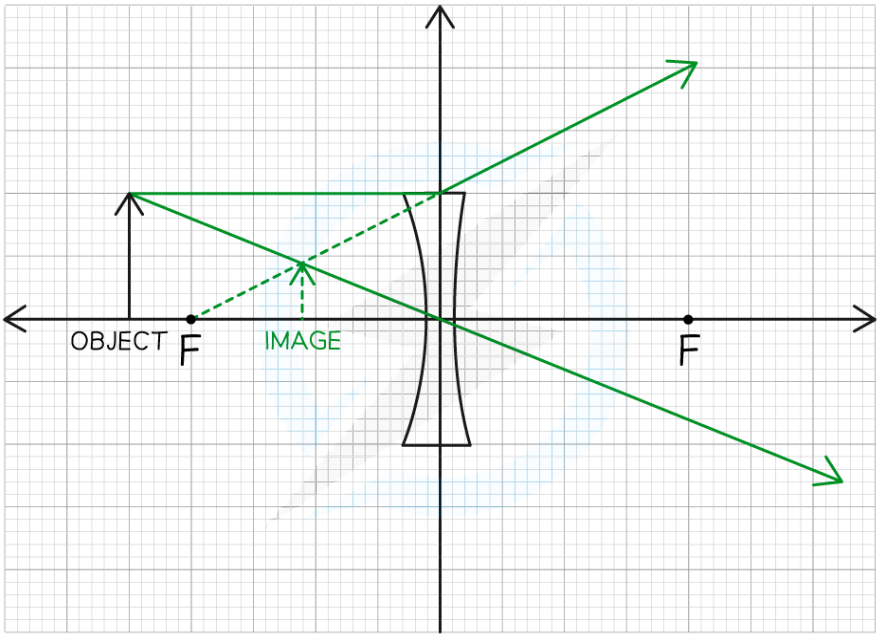
Worked Example

An object is placed outside the focal point of a diverging lens.



Complete the ray diagram by drawing where the image of this object will be seen.

Answer:



Step 1: Draw a line from the top of the object through the middle of the lens

- The top of the image lies somewhere along this line

Step 2: Draw a line from the focal point through the top of the lens

- The dashed line shows the continuation of the upward arrow
- The top of the image is where the two lines cross

Examiner Tips and Tricks

You are not expected to draw ray diagrams for a diverging lens but you must be able to explain how the virtual images are formed.

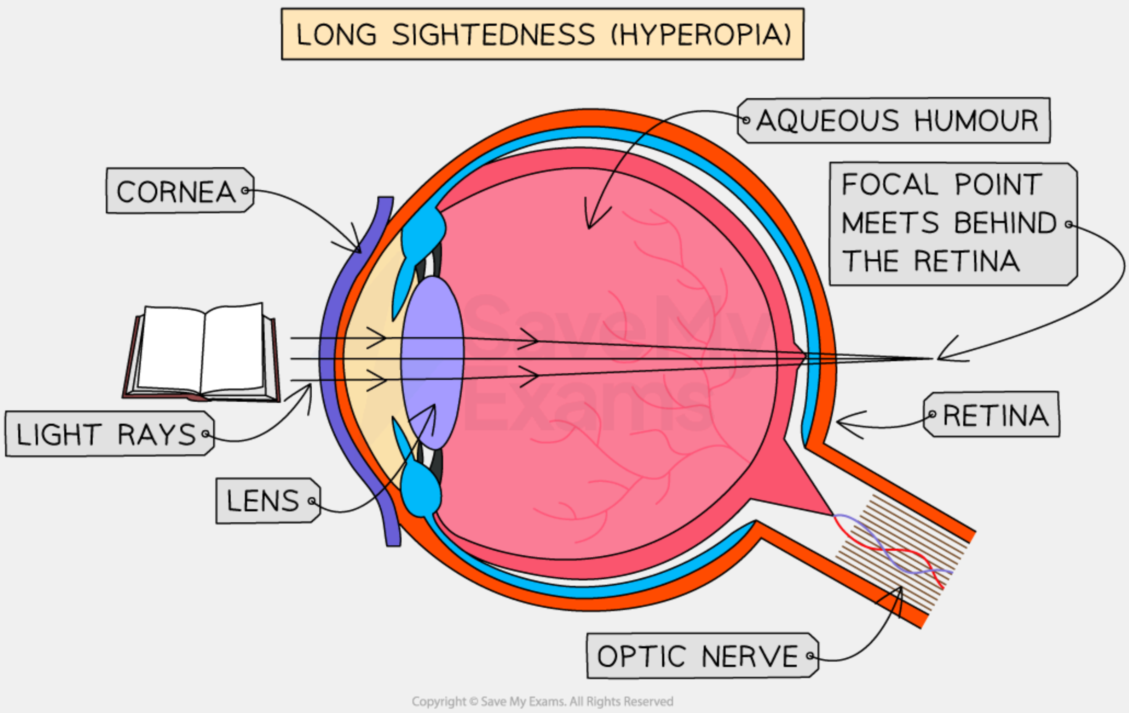
Correcting Sight

- Converging and diverging lenses are commonly used in glasses and contact lenses to correct defects of sight
  - Converging lenses can be used to correct long-sighted vision
  - Diverging lenses can be used to correct short-sighted vision

Use of lenses to correct long-sightedness

- Long-sighted people have eyes that are **less curved** than normal or the eyeball is **too short**
  - This means they cannot see things that are close and can only clearly see things that are far away

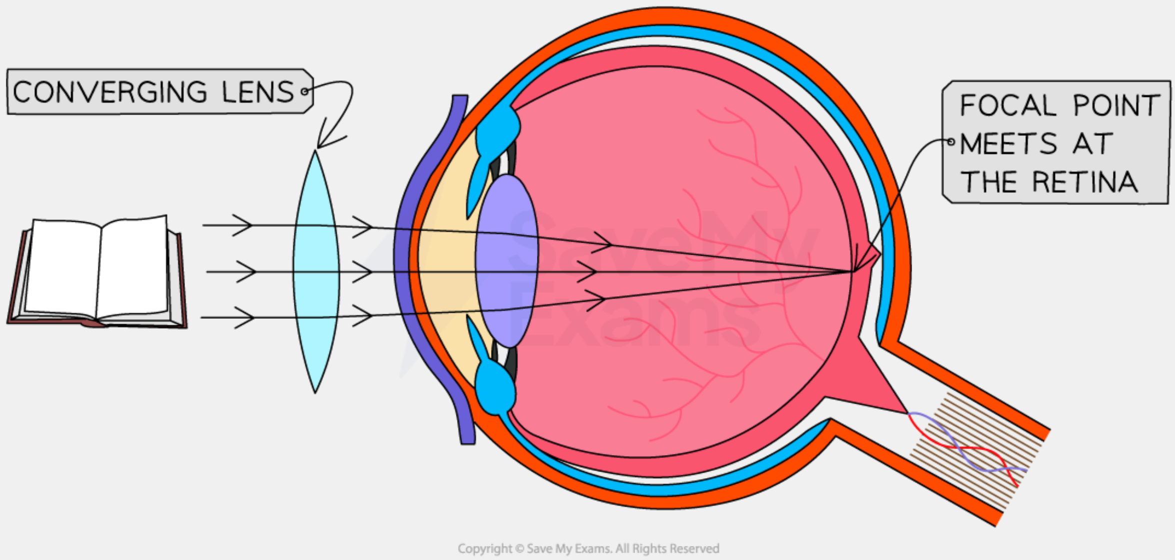
Ray diagram to show long-sightedness



An eye that is long-sighted has a narrower lens with a smaller focussing power so the light rays meet and form an image behind the retina and not on it

- The eye refracts the light rays and they are brought to a focus **beyond** the retina
    - In other words, the focus point is behind the retina at the back of the eye
- This can be corrected by using a convex or **converging lens**

The effect of a converging lens on a long-sighted eye

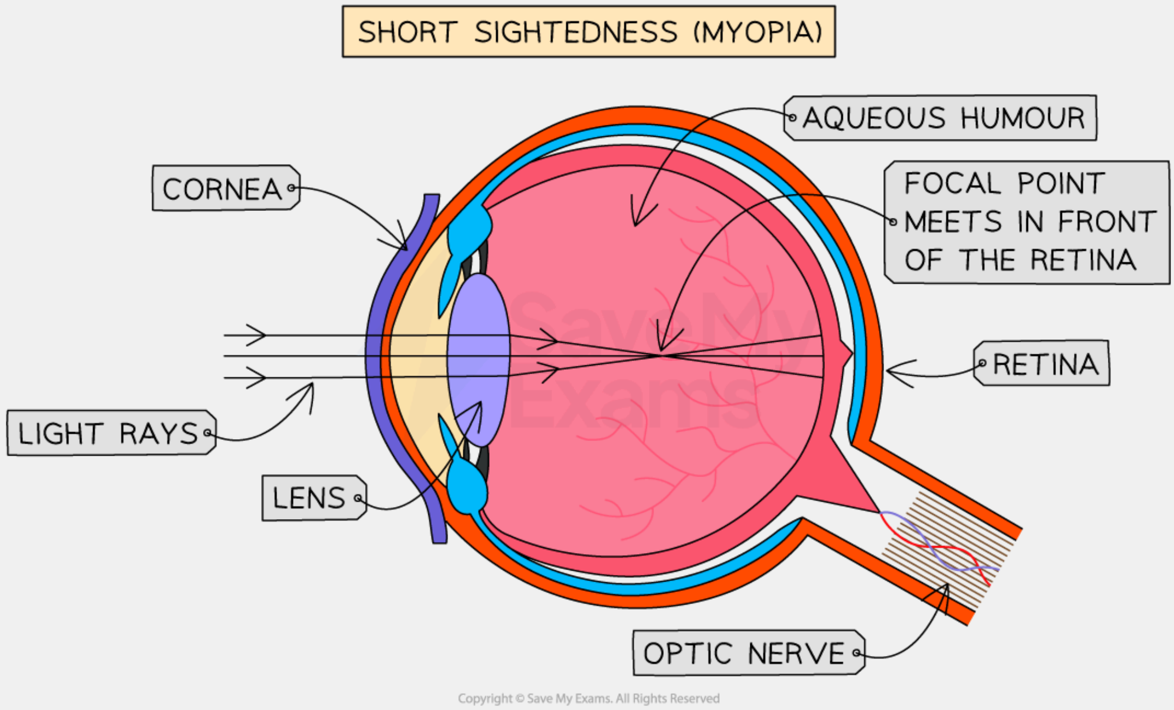


The converging lens causes the rays to converge before they reach the eye, so the image is formed on the retina and not behind it

Use of lenses to correct short-sightedness

- People who are **short-sighted** have eyes that are **more curved** than normal or have an eyeball that is **too long**
    - This means they cannot see things that are far away, and only see things that are close to them

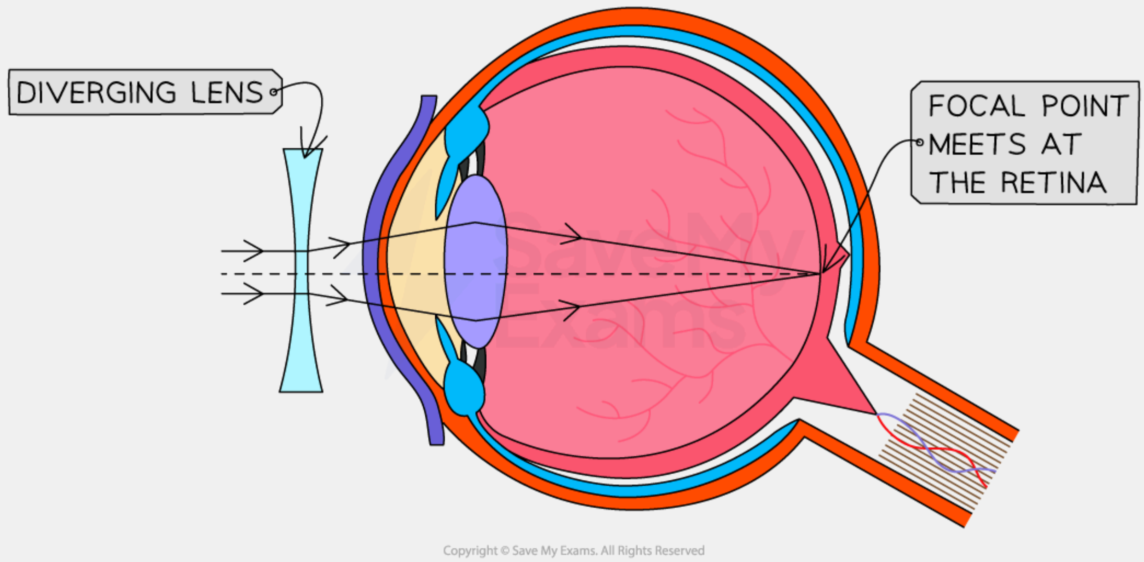
Ray diagram of short-sightedness



An eye that is short-sighted has a wider lens with a larger focussing power so the light rays meet and form an image in front of the retina and not on it

- This is because the eye refracts the light and brings it to a focus **before** it reaches the retina
    - In other words, the focus point is in front of the retina at the back of the eye
- This can be corrected by using a concave or a **diverging lens**

The effect of a diverging lens on a short-sighted eye

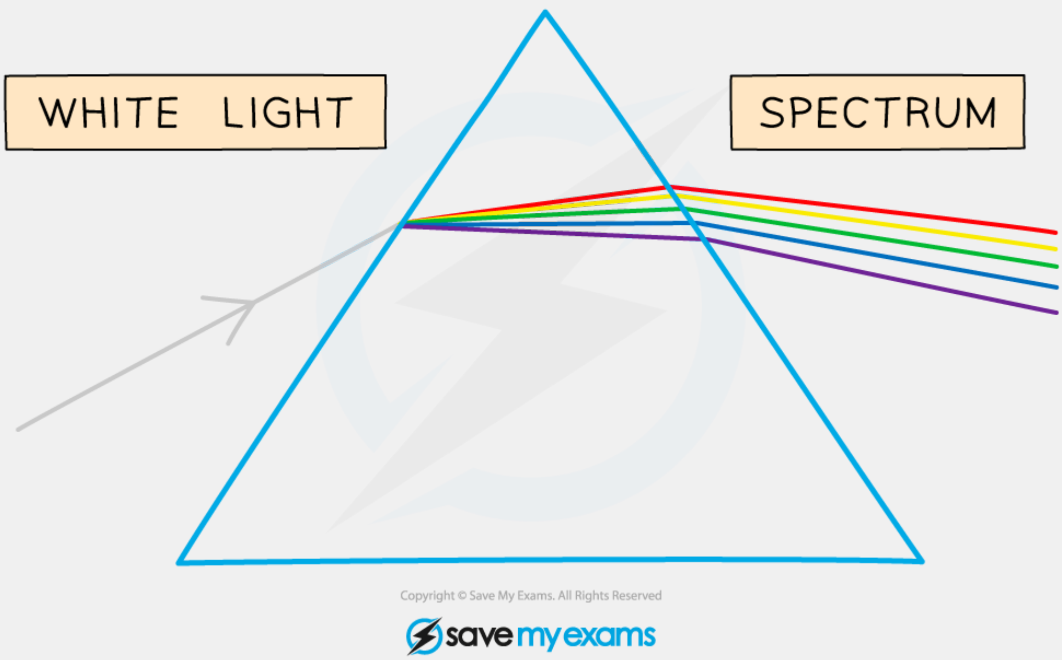


The diverging lens causes the rays to diverge before they reach the eye, so the image is formed on the retina and not in front of it

Dispersion of Light

- The **dispersion** of light is illustrated by the **refraction** of **white light** by a **glass prism**
- White light contains the wavelengths of **all** the colours of the spectrum
    - Each colour has a different wavelength (and frequency), making up a very narrow part of the electromagnetic spectrum
- White light may be separated into all its colours by passing it through a **glass prism**
    - This is done by **refraction**
    - Violet light is refracted the most, whilst red light is refracted the least
    - This splits up the colours to form a **spectrum**
- This process is similar to how a rainbow is created

Dispersion of light through a prism

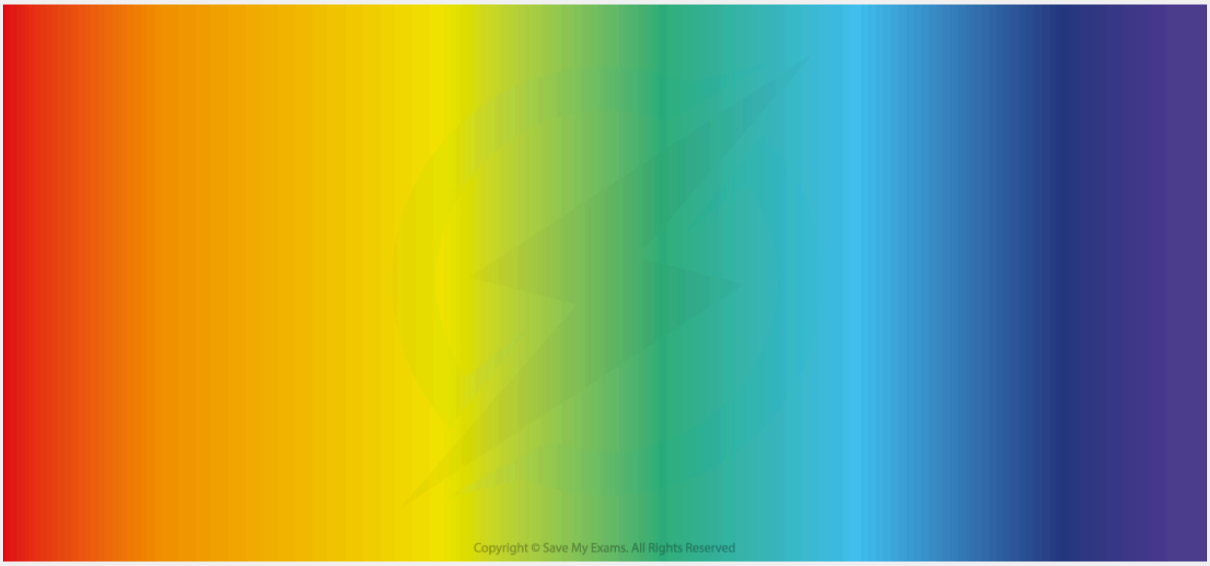


White light may be separated into all its colours by passing it through a prism

The visible spectrum of light

- Visible light is the **only** part of the spectrum detectable by the human eye
  - In the natural world, many animals, such as birds, bees and certain fish, can perceive beyond visible light and can see infra-red and UV wavelengths of light
- The seven different colours of visible light waves correspond to different wavelengths
- In order of longest wavelength and lowest frequency to shortest wavelength and highest frequency :
  - **Red**
  - **Orange**
  - **Yellow**
  - **Green**
  - **Blue**
  - **Indigo**
  - **Violet**

The dispersion of light creates the seven colours of the visible spectrum



The colours of the visible spectrum: red has the longest wavelength; violet has the shortest

Examiner Tips and Tricks

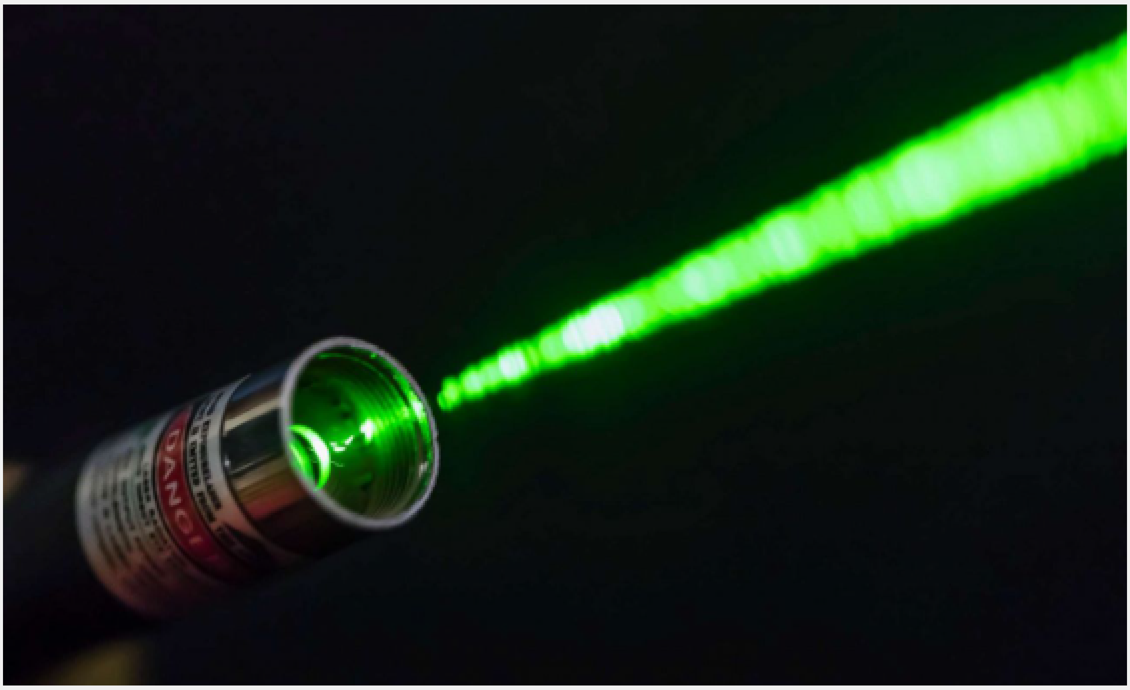
To remember the colours of the visible spectrum you could remember either:

- The name “Roy G. Biv”
- Or the saying “Richard Of York Gave Battle In Vain”

Monochromatic light

- A visible light source of a single frequency (a single colour) is **monochromatic**
- A laser beam is monochromatic because it emits a single colour of light

A laser beam



The laser emits monochromatic green light