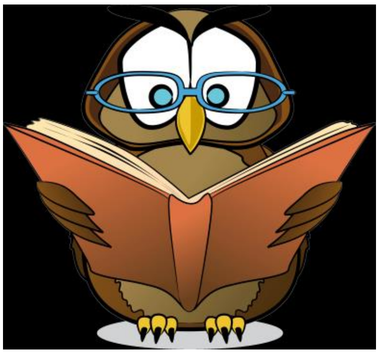


Volume

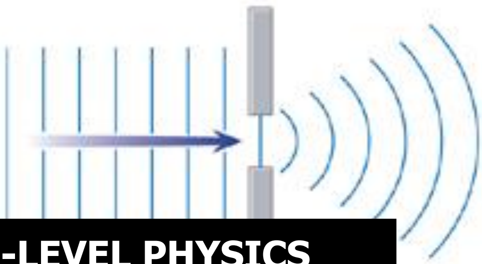
Two

ST MARY'S SCIENCE DEPARTMENT:

PHYSICS

A LEVEL PHYSICS **YEAR 1**
STUDENT PREPARATORY BOOK
WAVES
3.3.2: REFRACTION, DIFFRACTION AND INTERFERENCE

NAME	
PHYSICS CLASS	
MODULE TEACHER	
ALPS GRADE	



A-LEVEL PHYSICS

TOPIC 3

READING BOOK 2

THIS MUST BE BROUGHT TO ALL PHYSICS LESSONS.

Contents

OVERVIEW

This booklet provides the basic information and knowledge needed to access the A Level Physics course.
Over the course of the year, you will be directed to read this information in both lessons and in your spare time.
Ensure all information in this booklet is understood and remembered before examinations.

IMPORTANT NOTE

This booklet, along with the student workbook, must be brought to all Physics lessons with the appropriate teacher.

This booklet may be used as a learning resource in lessons, you are not fully equipped to learn if this is not used in lesson.

This booklet may also be used as a revision resource for intervention, internal assessments and external assessments.
Please keep this in your student file.

Definition List

Definitions you must learn for this module.

Key Word	Symbol	Definition
Coherent		When two sources of waves having a constant phase difference and the same frequency.
Critical Angle	**θ_C**	The angle of incidence of a light ray that must be exceeded for total internal reflection to occur. It is also the angle of incidence where the angle of refraction is zero.
Diffraction		The spreading of waves on passing through a gap or near an edge.
Diffraction Grating		A plate with many closely ruled parallel slits on it.
Fringe Spacing	**w**	The perpendicular distance between the centre of two fringes of the same type e.g. bright fringe and bright fringe (adjacent maxima or minima).
Interference		The formation of points of cancellation and reinforcement where two coherent waves pass through each other.
Intensity	**I**	The power per unit area of a wave.
Laser		a device which produces a parallel coherent beam of monochromatic light.
Maxima		Points produced when waves with a $n\lambda$ path difference (or $n2\Pi$ phase difference) constructively interfere.
Minima		Points produced when waves with a $n/2\lambda$ path difference (or $n\Pi$ phase difference) destructively interfere.
Modal Dispersion		The lengthening of a light pulse as it travels along an optical fibre, due to rays that repeatedly undergo total internal reflection having to travel a longer distance than the rays that undergo less total internal reflection.
Monochromatic Light		Light of single wavelength (and frequency) – the same colour.
Optical Fibre		A thin, flexible transparent fibre used to carry light pulses from one end to the other.
Path Difference		The difference in distances from two coherent sources to an interference fringe.
Phase Difference		The fraction of a cycle between the vibrations of two vibrating particles, measured either in degrees or radians.

Superposition		The effect of two waves adding together when they meet. This can be either displacement or any vector property of a wave
Refraction		The change in direction of a wave when it crosses a boundary where its speed changes. In refraction, frequency must remain constant.
Refractive Index	**n**	The speed of light in free space compared to the speed of light in the substance.
Total Internal Reflection		Occurs when a light ray travelling in a substance is reflected at the boundary with a substance of lower refractive index, if the angle of incidence is greater than a certain value known as the critical angle.
Young's Fringes		The parallel bright and dark fringes observed when light from a narrow-slit passes through two closely spaced slit.

IMPORTANT NOTE
These definitions must be memorised by students.

You will be tested on your knowledge of these definitions.

Equations
The equations below are used in this module.

Quantity/Concept	Equation(s)
Intensity	$I = P / A$ This is not given in your examination.
Fringe Spacing	$w = \frac{\lambda D}{s}$
Distance Between Slits on a Diffraction Grating	$d = n\lambda / \sin \theta$
Maximum Number of Diffraction Orders	$n = d / \lambda$ This is not given in your examination.
Refractive Index	$n = c/c_s$
Relative Refractive Index	${}_1n_2 = c_1 / c_2$ ${}_1n_2 = n_1 / n_2$ These two equations can be equated to each other.
Snell's Law	$n_1 \sin\theta_1 = n_2 \sin\theta_2$
Critical Angle	$\sin \theta_c = n_2 / n_1 = {}_1n_2$

IMPORTANT NOTE
These equations must be memorised by students.

You will be tested on these equations.

The Language of Measurement

The following subject specific vocabulary provides definitions of key terms used in the A-level Science specifications.

Accuracy
A measurement result is considered accurate if it is judged to be close to the true value.

Calibration
Marking a scale on a measuring instrument.
This involves establishing the relationship between indications of a measuring instrument and standard or reference quantity values, which must be applied.
For example, placing a thermometer in melting ice to see whether it reads 0 °C, to check if it has been calibrated correctly.

Data
Information, either qualitative or quantitative, that has been collected.

Errors
See also uncertainties.

Measurement error
The difference between a measured value and the true value.
anomalies
These are values in a set of results which are judged not to be part of the variation caused by random uncertainty.

Random error
These cause readings to be spread about the true value, due to results varying in an unpredictable way from one measurement to the next.
Random errors are present when any measurement is made and cannot be corrected. The effect of random errors can be reduced by making more measurements and calculating a new mean.

Systematic error
These cause readings to differ from the true value by a consistent amount each time a measurement is made.
Sources of systematic error can include the environment, methods of observation or instruments used.
Systematic errors cannot be dealt with by simple repeats. If a systematic error is suspected, the data collection should be repeated using a different technique or a different set of equipment, and the results compared.

Zero error
Any indication that a measuring system gives a false reading when the true value of a measured quantity is zero, e.g. the needle on an ammeter failing to return to zero when no current flows.
A zero error may result in a systematic uncertainty.

Evidence
Data which has been shown to be valid.

Fair test
A fair test is one in which only the independent variable has been allowed to affect the dependent variable.

Hypothesis
A proposal intended to explain certain facts or observations.

Interval
The quantity between readings, e.g. a set of 11 readings equally spaced over a distance of 1 metre would give an interval of 10 centimetres.

Precision
Precise measurements are ones in which there is very little spread about the mean value. Precision depends only on the extent of random errors – it gives no indication of how close results are to the true value.

Prediction
A prediction is a statement suggesting what will happen in the future, based on observation, experience or a hypothesis.

Range
The maximum and minimum values of the independent or dependent variables; important in ensuring that any pattern is detected.
For example, a range of distances may be quoted as either:
'From 10 cm to 50 cm'
or
'From 50 cm to 10 cm'

Repeatable
A measurement is repeatable if the original experimenter repeats the investigation using same method and equipment and obtains the same results.

Reproducible
A measurement is reproducible if the investigation is repeated by another person, or by using different equipment or techniques, and the same results are obtained.

Resolution
This is the smallest change in the quantity being measured (input) of a measuring instrument that gives a perceptible change in the reading.

Sketch graph
A line graph, not necessarily on a grid, that shows the general shape of the relationship between two variables. It will not have any points plotted and although the axes should be labelled they may not be scaled.

True value
This is the value that would be obtained in an ideal measurement.

Uncertainty
The interval within which the true value can be expected to lie, with a given level of confidence or probability, e.g. "the temperature is 20 °C ± 2 °C, at a level of confidence of 95%.

Validity
Suitability of the investigative procedure to answer the question being asked. For example, an investigation to find out if the rate of a chemical reaction depended upon the concentration of one of the reactants would not be a valid procedure if the temperature of the reactants was not controlled.

Valid conclusion
A conclusion supported by valid data, obtained from an appropriate experimental design and based on sound reasoning.

Variables
These are physical, chemical or biological quantities or characteristics.

Categoric variables
Categoric variables have values that are labels. E.g. names of plants or types of material.

Continuous variables
Continuous variables can have values (called a quantity) that can be given a magnitude either by counting (as in the case of the number of shrimp) or by measurement (e.g. light intensity, flow rate etc.).

Control variables
A control variable is one which may, in addition to the independent variable, affect the outcome of the investigation and therefore must be kept constant or at least monitored.

Dependent variables
The dependent variable is the variable of which the value is measured for each change in the independent variable.

Independent variables
The independent variable is the variable for which values are changed or selected by the investigator.

IMPORTANT NOTE
These definitions must be memorised by students.

You will be tested on your knowledge of these definitions.

VIDEO
COURSE OVERVIEW

To watch a video looking at all of the concepts in capacitance, please scan one of the following codes with your smartphone.

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TOPIC: 3.3.2.1 Interference
SPEC CHECK

Specification	Completed?
Path difference. Coherence.	
Interference and diffraction using a laser as a source of monochromatic light.	
Young's double-slit experiment: the use of two coherent sources or the use of a single source with double slits to produce an interference pattern.	
Fringe spacing, $w = \frac{\lambda D}{s}$	
Production of interference pattern using white light.	
Show awareness of safety issues associated with using lasers.	
Describe and explain interference produced with sound and electromagnetic waves.	
Appreciation of how knowledge and understanding of nature of electromagnetic radiation has changed over time.	
Investigate two-source interference with sound, light and microwave radiation.	

Student Checklist

Have I…….	Yes or No?
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	

Interference

Key Topic Warning
This topic is very common for questions on previous A-Level Papers.

Interference is a special case of superposition where the waves that combine are coherent.
Two waves are coherent if they have the same frequency and constant phase difference.
The waves overlap and form a repeating interference pattern of maxima and minima areas.
If the waves weren't coherent the interference pattern would change rapidly and continuously.
This is not considered at A-Level Physics.

Coherence: Waves which are of the same frequency, wavelength, polarisation and amplitude and in a constant phase relationship. A laser is a coherent source but a light bulb is not.

Exam Tip

It is a common examination question to define the term 'coherent sources'…

Same wavelength/ frequency (1 mark) Constant phase relationship (1 mark)

Constructive Interference: The path difference between the waves is a whole number of wavelengths so the waves arrive in phase adding together to give a larger wave.
This reinforces the wave and makes it larger.
This can also be expressed in terms of phase difference; two waves constructively interfere if they have a phase difference of n2Π radians.
For example: 2 peaks overlap

Study Tip

Learn the process of constructive interference in both terms of phase difference and path difference.

Destructive Interference: The path difference between the waves is a half number of wavelengths so the waves arrive out of phase cancelling out to give no wave at all.
This decreases the wave's amplitude and displacement.
This can also be expressed in terms of phase difference; two waves destructively interfere if they have a phase difference of nΠ radians.
For example: A peak and trough overlap

There is a continuous interference pattern going from constructive to destructive interference and vice-versa.

Study Tip

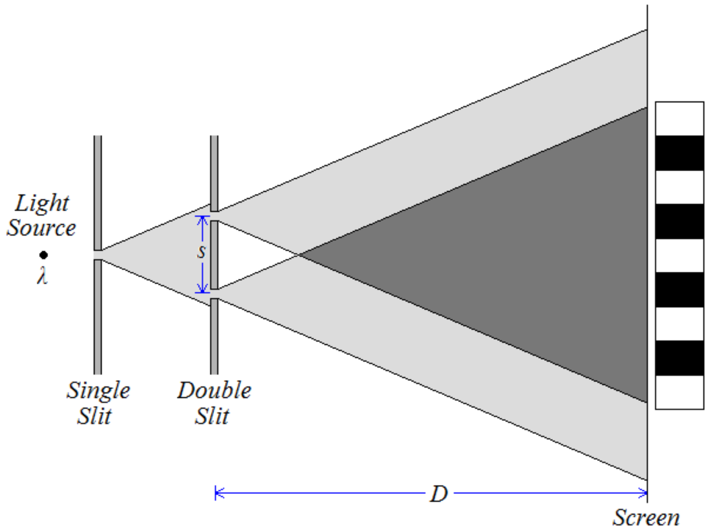
Learn the process of destructive interference in both terms of phase difference and path difference.

Young's Double Slit Experiment

In 1803 Thomas Young settled a debate started over 100 years earlier between Newton and Huygens by demonstrating the interference of light. Newton thought that light was made up of tiny particles called corpuscles and Huygens thought that light was a wave, Young's interference of light proves light is a wave.

Interference occurs where the light from the two slits overlaps. Constructive interference produces bright areas, while deconstructive interference produces dark areas.
These areas are called interference fringes.

Here is Young's double slit set up, the two slits act as coherent sources of waves



The waves produced are coherent as they come from the same light source.

This means a diffraction pattern must form.

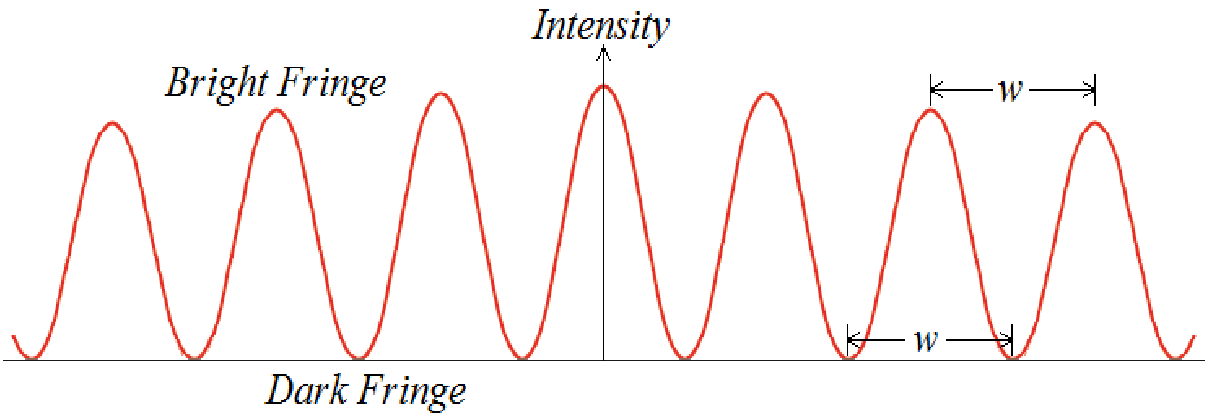
This was the first experimental proof that light must act like a wave.

Diffraction and interference are wave-only properties.

Fringes

There is a central bright fringe directly behind the midpoint between the slits with more fringes evenly spaced and parallel to the slits.

As we move away from the centre of the screen we see the intensity of the bright fringes decreases.



Physics Tip

In between bright and dark fringe, neither complete constructive or destructive interference takes place leading to a wave intensity being recorded.

Physics Tip

As usual, strong signals occur where the two sources interfere constructively, and weak signals occur when the two sources interfere destructively.

Physics Tip

In examinations, sources you will see will be in phase.

When you use the same oscillator or light source, you know the waves are coherent.

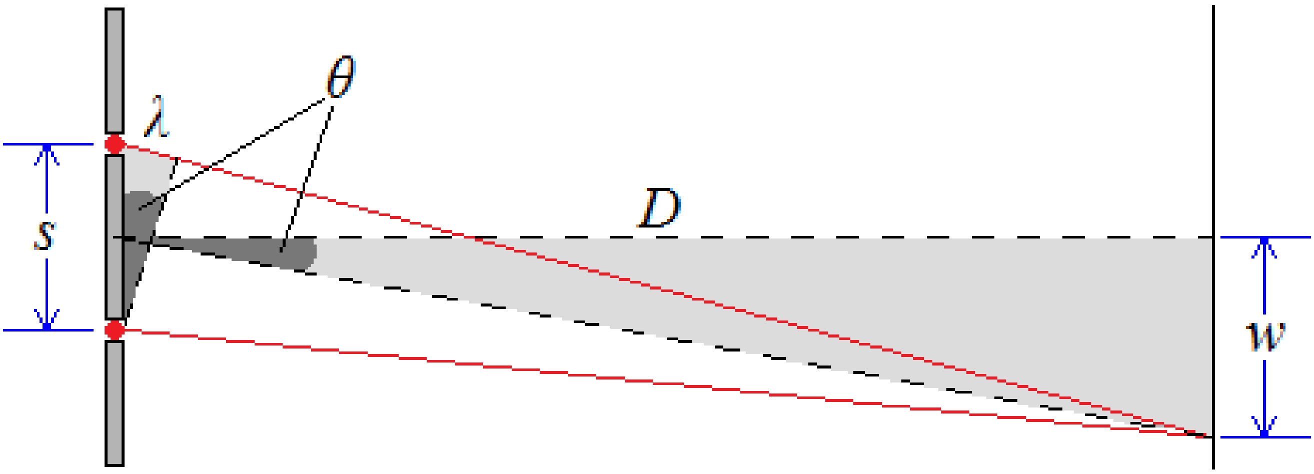
Double Source Experiment

The interference of sound is easy to demonstrate with two speakers connected to the same signal generator. Waves of the same frequency (coherent) interfere with each other.

Constructive interference produces loud fringes, while deconstructive interference produces quiet fringes.

Derivation

We can calculate the separation of the fringes (*w*) if we consider the diagram to the right which shows the first bright fringe below the central fringe. The path difference between the two waves is equal to one whole wavelength (λ) for constructive interference.



If the distance to the screen (*D*) is massive compared to the separation of the sources (*s*) the angle (θ) in the large triangle can be assumed the same as the angle in the smaller triangle.

$$\sin\theta = \frac{Opposite}{Hypotenuse}$$

For the small triangle: $\sin\theta = \frac{\lambda}{s}$

For the large triangle: $\sin\theta = \tan\theta = \frac{w}{D}$

This is only true for small angles, such as less than 10 degrees.

Physics Tip

This equation only fully works for an angular displacement of less than 10°.

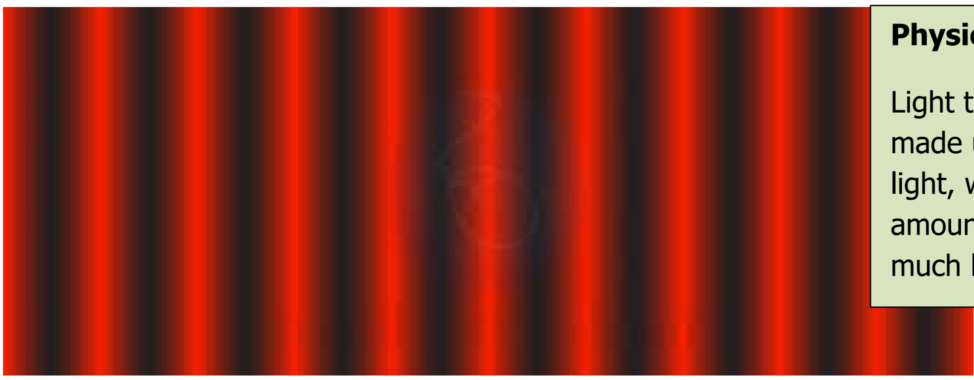
Since the angles are the same we can write $\frac{w}{D} = \sin\theta = \frac{\lambda}{s}$ or $\frac{w}{D} = \frac{\lambda}{s}$ which rearranges to:

$$w = \frac{\lambda D}{s}$$

Exam Tip

Whilst, this equation is given in your examination booklet, for greatest exam success, please memorise this equation and the conditions where it can be applied.

Fringe Separation, Source Separation, Distance to Screen and Wavelength are measured in metres, m



Physics Tip

Light that is not monochromatic is made up of different wavelengths of light, which will diffract by different amounts and makes the fringes much less clear.

Here is an example of an interference pattern produced by Young's slits.

Beware the fringe separation or spacing is measured from the centre of one fringe to the centre of the next corresponding fringe.

The more values which you measure over, the lower the percentage uncertainty of the value calculated.

However, be aware you are measuring the fringe spacing not the number of fringes produced. The number of fringe spacings is one less than the number of fringes.

Experimental Note

The fringes produced due to Young's slits are quite dim and blurry – this is because the wave is only passing through 2 slits.

This makes Young's slits a difficult investigation to gain valid results for.

Exam Tip

It is a common examination question to state why a bright fringe or loud sound is produced….

maximum (at position shown) (1 mark)

constructive interference / reinforcement (1 mark)

(the waves meet) 'in step' / peak meets peak / trough meets trough / path difference is (n)λ / in phase (1 mark)

Exam Tip

It is a common examination question to state why a dark fringe or no sound is produced….

minimum (at position shown) (1 mark)

destructive interference / cancellation (1 mark)

(the waves meet) 'out of step' / peak meets trough / path difference is (1/2 n)λ /out of phase (1 mark)

REQUIRED PRACTICAL
YOUNG'S SLIT EXPERIMENT

You can investigate the Young's slit experiment formula.
$W = \lambda D / s$
This can done using the double slit apparatus found on page 13 (or page 11).

You can measure D and w using a ruler.
s can be found on the double slit.

Since the wavelength of light is so small, you can see from the formula that a high ratio of D/s is needed to make the fringe spacing big enough to see.
Re-arranging, you can use $\lambda = ws / D$ to calculate the wavelength of the light.

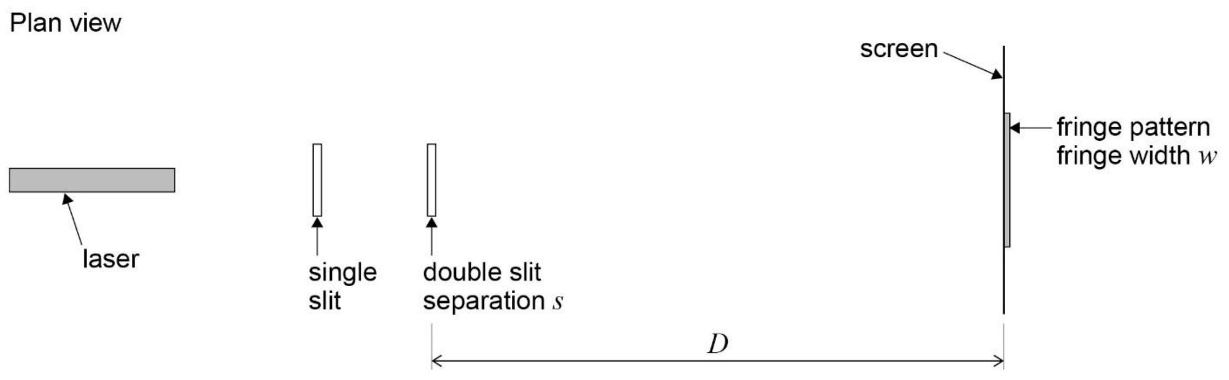
The fringes are usually so tiny that it is very hard to get an accurate value of w.
It is easier to measure across several fringes then divide by the number of fringe widths between them.

You can investigate…
1. Varying D to see how it affects w.
2. Varying s by using different double slit systems to see how it affects w.
3. Varying the wavelength/colour of light to see how it affects w.

Method

A partially darkened laboratory is required ensuring lasers are used safely.

Set up the apparatus as shown in the diagram, with the laser illuminating the double slit and the screen a distance *D* of initially about 1 metre. (With the laser the single slit might not be required, provided the laser beam is wide enough to illuminate across the double slit).



Carefully adjust the position of the laser until the light spreads evenly over the two slits. An interference pattern should be visible on the screen.

The fringe width (or fringe spacing), *w*, can be measured by measuring across a large number of visible fringes. (Take care when counting – counting from the first bright fringe to the tenth bright fringe would represent nine fringe widths!).

Use the metre ruler to measure *D*.

A measurement of the slit separation, *s*, is required. The value could be measured with vernier callipers or travelling microscope. If a travelling microscope is used it must only be used to measure slit separation and **not the fringe width**. Alternatively the manufacturer may quote the value on the slide.

Use the equation $\lambda = \frac{w\,s}{D}$

Alternatively, the value of *D* could be changed from approximately 0.5 m to 1.5 m and the fringe width, *w*, measured for each value of *D*.

A graph of *w* on the *y*-axis against *D* should be a straight line through the origin, with

gradient = λ / s .

VIDEO

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TOPIC: 3.3.2.2 Diffraction
SPEC CHECK

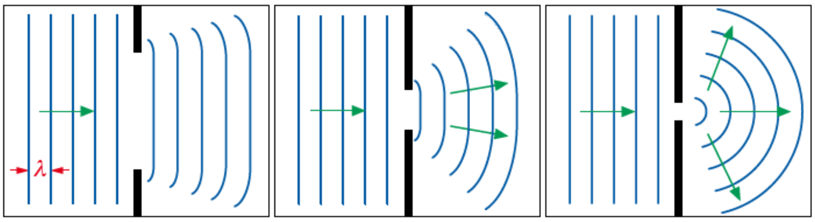
Specification	Completed?
Appearance of the diffraction pattern from a single slit using monochromatic and white light.	
Qualitative treatment of the variation of the width of the central diffraction maximum with wavelength and slit width.	
Plane transmission diffraction grating at normal incidence.	
Derivation of $d\sin\theta = n\lambda$	
Applications of diffraction gratings.	

Student Checklist

Have I…….	Yes or No?
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	

Diffraction

When waves pass through a gap they spread out, this is called diffraction. The amount of diffraction depends on the size of the wavelength compared to the size of the gap.



In the first diagram the gap is several times wider than the wavelength so the wave only spreads out a little.

When gap size > wavelength   there is little diffraction

In the second diagram the gap is closer to the wavelength so it begins to spread out more.

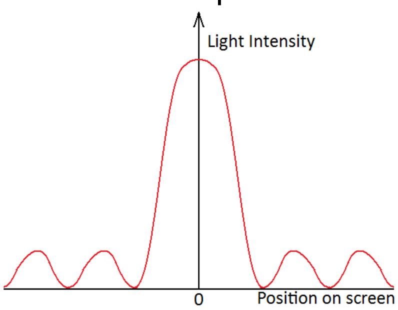
In the third diagram the gap is now roughly the same size as the wavelength so it spreads out the most.

When gap size ≈ wavelength   there is a lot of diffraction

> **Exam Tip**
>
> It is common for questions in examinations to show scenarios where the gap size is either the same size as wavelength, or much larger than the wavelength.
>
> Always check this.

Diffraction Patterns

Here is the diffraction pattern from light being shone through a single slit.
There is a central maximum that is twice as wide as the others and by far the brightest.
The outer fringes are dimmer and of equal width.



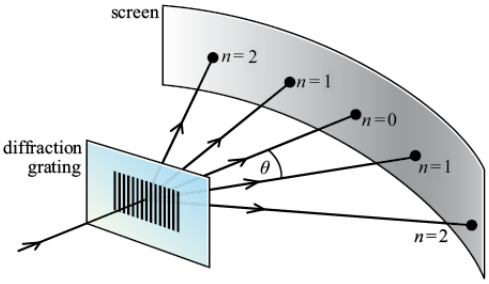
> The smaller the slit compared to the wavelength, the greater the diffraction.
>
> This means the central maximum would be wider but less intense.

If we use three, four or more slits the interference maxima become brighter, narrower and further apart.

Key Topic Warning
This topic is very common for questions on previous A-Level Papers.

Diffraction Grating

A diffraction grating is a series of narrow, parallel slits. They usually have around 500 slits per mm.
When light shines on the diffraction grating several bright sharp lines can be seen as shown in the diagram below.

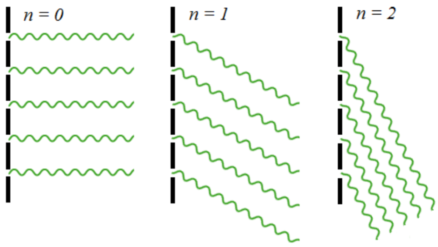


We call the different lines made by diffraction – orders of diffraction.

We label the middle one, the zeroth order and every order out from that is +1 order.

For example; 0th, 1st, 2nd, 3rd.

The first bright line (or interference maximum) lies directly behind where the light shines on the grating. We call this the zero-order maximum.
At an angle of θ from this lies the next bright line called the first-order maximum and so forth.



A diffraction grating gives a sharper, more intense fringe pattern than Young's slits since there is more light getting through as there are more slits.

This makes results easier to measure and the conclusion is more valid.

Exam Tip

It is a common examination question to discuss the using of diffraction gratings with spectrometers…

(spectral) analysis of light from stars (1 mark)

(analyse) composition of stars (1 mark)

Chemical analysis (1 mark)

Measuring red shift \ rotation of stars (1 mark)

The zero-order maximum (*n=0*)
There is no path difference between neighbouring waves. They arrive in phase and interfere constructively.
The order number refers to the number of wavelengths difference there are in the wave paths.

The first-order maximum (*n=1*)
There is a path difference of 1 wavelength between neighbouring waves. They arrive in phase and interfere constructively.

The second-order maximum (*n=2*)
There is a path difference of 2 wavelengths between neighbouring waves. They arrive in phase and interfere constructively.

Between the maxima
The path difference is not a whole number of wavelengths so the waves arrive out of phase and interfere destructively.

Exam Tip

It is a common question to ask what type of light is used in a diffraction grating and any safety precautions needed when using a laser.

Monochromatic light must be used, this is single frequency (or wavelength or photon energy) light (1 mark)

Don't shine towards a person (1 mark)

Avoid (accidental) reflections (1 mark)

Wear laser safety goggles (1 mark)

'laser on' warning light outside room (1 mark)

Stand behind laser (1 mark)

Eye / skin damage could occur (1 mark)

Exam Tip

It is a common question to ask how the interference pattern would change if white light is used instead of monochromatic light…

Central white (fringe) (1 mark)

Each/every/all subsidiary maxima are composed of a spectrum (1 mark)

Each/every/all subsidiary maxima are composed of a spectrum AND (subsidiary maxima) have violet (allow blue) nearest central maximum OR red furthest from centre (1 mark)

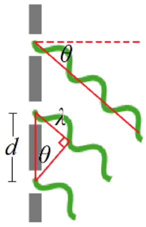
Fringe spacing less / maxima are wider / dark fringes are smaller (or not present) (1 mark)

Derivation

The angle to the maxima depends on the wavelength of the light and the separation of the slits. We can derive an equation that links them by taking a closer look at two neighbouring waves going to the first-order maximum.

Physics Tip:

The space between slits here is 'd' but for double slit experiments is 's'.



The distance to the screen is so much bigger than the distance between two slits that emerging waves appear to be parallel and can be treated that way.
Consider the triangle to the right.

$$\sin\theta = \frac{Opposite}{Hypotenuse} \quad \rightarrow \quad \sin\theta = \frac{\lambda}{d} \quad \rightarrow \quad d\sin\theta = \lambda$$

For the *n*th order the opposite side of the triangle becomes $n\lambda$, making the equation:

$$d\sin\theta = n\lambda$$

The highest possible angle is 90°, so to find the highest possible order to be produced by a diffraction grating, you must substitute ϴ = 90° into the equation.

Study Tip

Learn this formula. Look at how this formula can be re-arranged to find other terms in the equation.

Exam Tip

Whilst, this equation is given in your examination booklet, for greatest exam success, please memorise this equation and the conditions where it can be applied.

Always be aware of the angle given in the question – it may not be the angle specified in the equation.

Always be aware of converting wavelengths into metres and working out 'd' from lines per mm.

Exam Tip

In examination questions, the number of lines per m in the slit is given…

Remember d = 1 / Number of Lines per mm

Physics Tip:

Make sure your calculator is working in the correct mode, depending on whether you want degrees or radians.

Exam Tip

It is a common question to look how diffraction can be investigated.

For example, White light is incident on a single slit. After leaving the slit, the diffracted light passes through a green filter to reach the screen.

Describe the pattern produced on the screen.

Central maximum with lower intensity maxima (either side) (1 mark)

Central maximum is twice as wide/wider than other maxima (1 mark)

Exam Tip

It is a common question to look how diffraction can be investigated.

For example, White light is incident on a single slit. After leaving the slit, the diffracted light passes through a green filter to reach the screen.

The green filter is replaced with a red filter.

Describe the change in the pattern produced on the screen.

Wider (central) maxima (maximum) (1 mark)

(Subsequent) maxima further apart (1 mark)

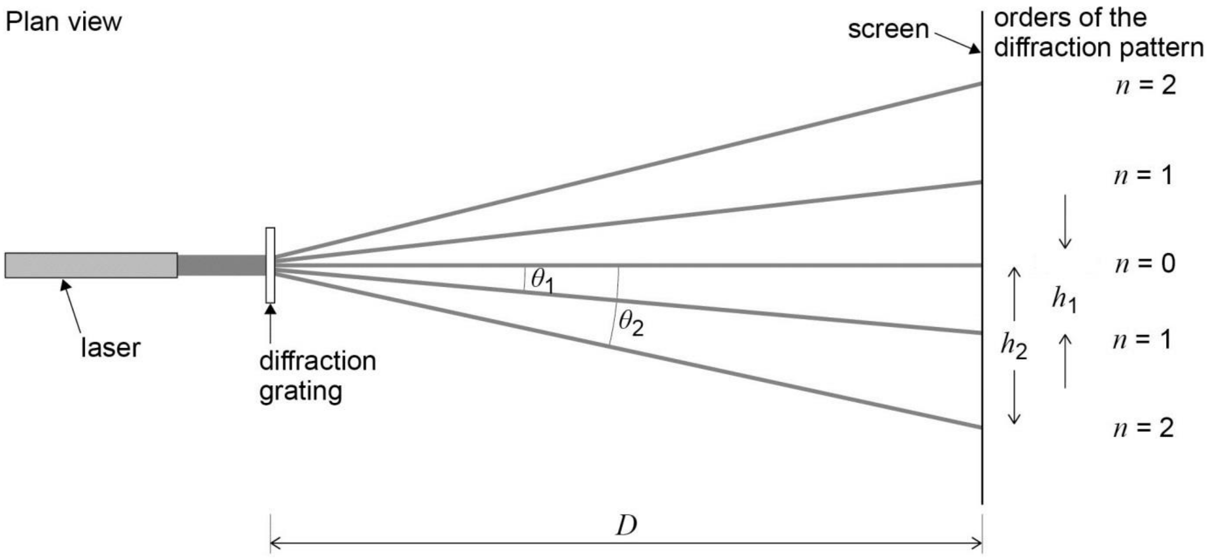
REQUIRED PRACTICAL
DIFFRACTION GRATING EXPERIMENT

You can investigate the patterns produced by diffraction gratings and the relationships described by the diffraction grating formula.
It has the same set up as the Young's slit experiment, however a diffraction grating is used instead of a mounted double slit card.
You can measure the spacing of a certain order maximum using a ruler. By using different laser sources, or coloured filters to select certain wavelengths of white light, you can investigate how the maxima spacing varies with wavelength.
You should find that as the wavelength increases, the distance to the nth order on the screen increases.
You can also investigate effects on fringe spacing by:
1. Changing the diffraction grating to vary d.
2. Changing D by moving the observation screen.

Method

A partially darkened laboratory is required. Please ensure lasers are used safely.

Set up the apparatus as shown in the diagram, with the laser illuminating the diffraction grating and the screen a distance *D* of initially about 1 metre.



Carefully adjust the position of the diffraction grating so that the diffraction grating is perpendicular to the beam of light from the laser. (A large set square might be useful).

The diffraction pattern should be visible on the screen. The number of orders shown will depend on the line spacing of the diffraction grating.

The angles θ_1 and θ_2 can be determined by measuring the distances h_1 , h_2 and D. (This gives the tangent of the angles, and hence the angles can be calculated).

The formula $n\lambda = d\sin\theta$ can be used to determine the wavelength of the laser light.

n is the order of the diffraction pattern

d is the grating spacing = 1/number of lines per metre

λ is the wavelength of light

The values of Θ for each order, both above and below the zero order, should be measured. A mean value for λ can be calculated from the data.

Single slit diffraction

This arrangement can also be used to illustrate diffraction at a single slit. The diffraction grating is replaced by an adjustable single slit. The effect of 'slit width' can easily be observed

VIDEO

To watch a video looking at this concept, please scan one of the following codes with your smartphone.

SCAN ME

SCAN ME

TOPIC: 3.3.2.3 Refraction at a Plane Surface

SPEC CHECK

Specification	Completed?
Refractive index of a substance, $n = \frac{c}{c_s}$	
Students should recall that the refractive index of air is approximately 1.	
Snell's law of refraction for a boundary $n_1 \sin \phi_1 = n_2 \sin \phi_2$	
Total internal reflection $\sin \phi_c = \frac{n_2}{n_1}$	
Simple treatment of fibre optics including the function of the cladding.	
Material and modal dispersion.	
Understand the principles and consequences of pulse broadening and absorption.	

Student Checklist

Have I…….	Yes or No?
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	

Refractive Index

Prior Knowledge Link
This is a topic found in a previous GCSE module – **Waves.**

The refractive index of a material is a measure of how the wave speed of a wave changes at it moves through different material. The refractive index of material, *s,* can be calculated using:

$$n = \frac{c}{c_s}$$

The speed of a wave can change as the wavelength of the wave changes, in slower mediums, the wavelength decreases.

Throughout refraction, frequency remains constant.

Study Tip

Learn this formula.

Remember this formula can be equated to the other refractive index formula in questions.

Exam Tip

Ensure you can remember the speed of light in a vacuum (3x 10^8 m/s).

In addition, most refractive index values are found between 1.0 – 2.0.

This equation is only valid if you consider the starting medium of the wave to be either a vacuum or air.

This is because the refractive index of air/vacuum is 1.00

If the starting medium is not air or a vacuum a more detailed equation must be used.

Where n is the refractive index, c is the speed of light in a vacuum and c_s is the speed of light in material s.
Refractive Index, n, has no units

If light can travel at c in material x then the refractive index is: $n = \frac{c}{c_x}$ → $n = \frac{c}{c}$ → $n = 1$

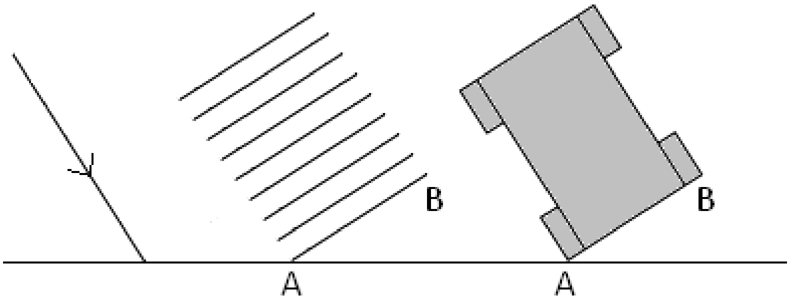
If light can travel at $c/2$ in material y then the refractive index is: $n = \frac{c}{c_y}$ → $n = \frac{c}{c/2}$ → $n = 2$

The higher the refractive index the slower light can travel through it

The higher the refractive index the denser the material

Bending Light

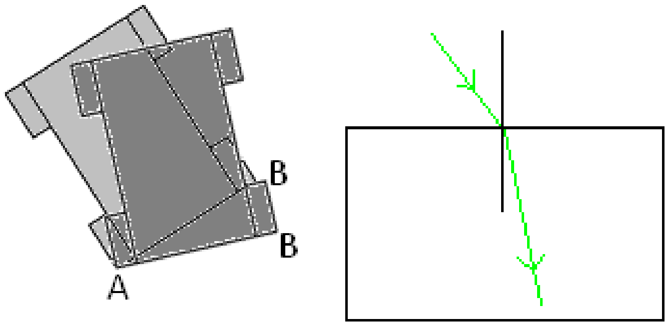
When light passes from one material to another it is not only the speed of the light that changes, the direction can change too.



If the ray of light is incident at 90° to the material then there is no change in direction, only speed.

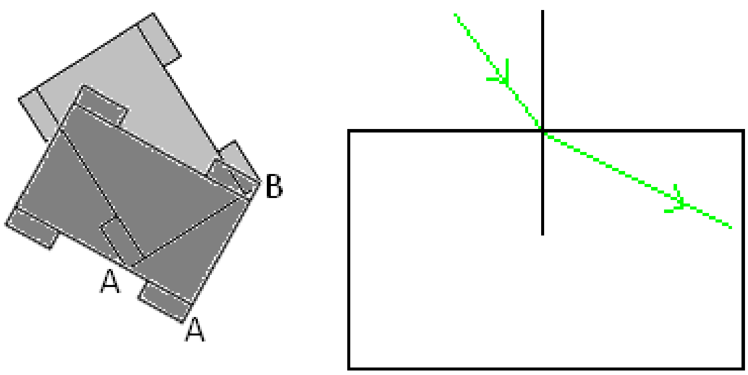
It may help to imagine the front of the ray of light as the front of a car to determine the direction the light will bend. Imagine a lower refractive index as grass and a higher refractive index in mud.

Entering a Denser Material



The car travels on grass until tyre A reaches the mud. It is harder to move through mud so A slows down but B can keep moving at the same speed as before. The car now points in a new direction.

Denser material – higher refractive index – bends towards the Normal
Entering a Less Dense Material



The car travels in mud until tyre A reaches the grass. It is easier to move across grass so A can speed up but B keeps moving at the same speed as before. The car now points in a new direction.

Less dense material – lower refractive index – bends away from the Normal

Relative Refractive Index

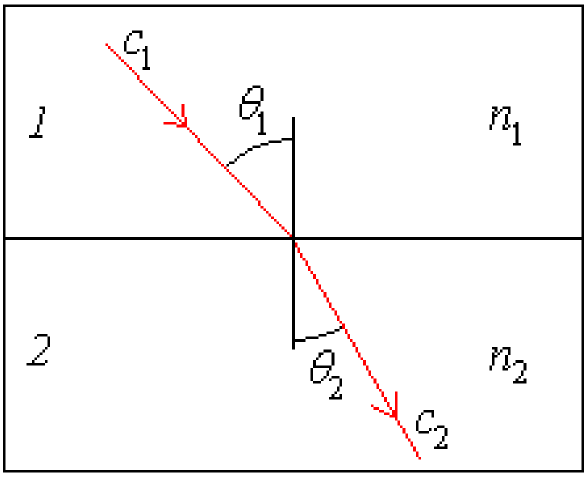
Whenever two materials touch the boundary between them will have a refractive index dependent on the refractive indices of the two materials.
We call this the relative refractive index.

When light travels from material *1* to material *2* we can calculate the relative refractive index of the boundary using any of the following:

Study Tip

This equation is given in the equation booklet.

Learn the terms of the equation and when the equation can be used.



$$ {}_1n_2 = \frac{n_2}{n_1} = \frac{c_1}{c_2} = \frac{\sin\theta_1}{\sin\theta_2} $$

This refractive index equation can be used in any situation.

Relative Refractive Index, $_1n_2$, has no units

Exam Tip

Whilst, this equation is given in your examination booklet, for greatest exam success, please memorise this equation and the conditions where it can be applied.

Always be aware of the angle given in the question – it may not be the angle specified in the equation.

Exam Tip

It is a common question to look how refraction can be investigated.

In 1870 John Tyndall sent a beam of light along a stream of water.

Water has a refractive index of 1.33 Explain why the laser beam stays inside the stream of water.

Because) the refractive index of water is greater than air (1 mark)

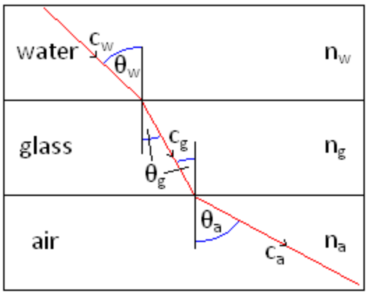
(and) the angle of incidence is greater than the critical angle (1 mark)

total internal reflection (of laser beam) occurs (1 mark)

Some questions may involve light travelling through several layers of materials. Tackle one boundary at a time.

$${}_{w}n_{g} = \frac{n_g}{n_w} = \frac{c_w}{c_g} = \frac{\sin\theta_w}{\sin\theta_g}$$ ---------------------------->

$${}_{g}n_{a} = \frac{n_a}{n_g} = \frac{c_g}{c_a} = \frac{\sin\theta_g}{\sin\theta_a}$$ ---------------------------->



Exam Tip

Some questions may ask to work out if the wave would reflect or refract at different mediums – do not get caught about what is taking place at each interface.

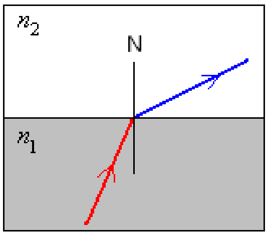
Total Internal Reflection

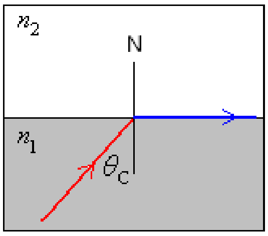
We know that whenever light travels from one material to another the majority of the light refracts but a small proportion of the light also reflects off the boundary and stays in the first material.

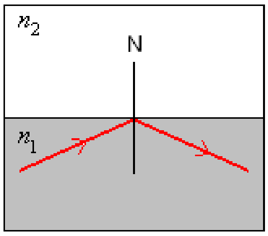
When the incident ray strikes the boundary at an angle **less than the critical angle** the light refracts into the second material.

When the incident ray strikes the boundary at an angle **equal to the critical angle** all the light is sent along the boundary between the two materials.

When the incident ray strikes the boundary at an angle **greater than the critical angle** all the light is reflected and none refracts, we say it is total internal reflection has occurred.







At exactly the critical angle, the angle of refraction and reflection is 90 degrees.

This is another way to define critical angle.

In addition, for total internal reflection to occur, the second medium must have a lower refractive index than the first medium.

$$\mathbf{n_1 > n_2}$$

If the **refractive index of the second medium was higher than the first medium**, then total internal reflection would not occur and **some of the wave would be refracted.**

Exam Tip

It is a common examination question to describe the conditions needed for total internal reflection…

The angle of refraction should be > angle of incidence when entering the optic (1 mark)

Cladding has a lower refractive index than glass \ light is faster in cladding than in glass (1 mark)

TIR could not happen \ there is no critical angle, when ray travels from cladding to core (1 mark)

TIR only occurs when ray travels from higher to lower refractive index \ air has a lower refractive index than optic core (1 mark)

Examination Tip

It is a common examination question to consider the effect of different colours when they carry out total internal reflection.

For example, for any material red light has a lower refractive index than green light, and blue light has a higher refractive index than green light. The angle of incidence at the glass–liquid interface is 58°.

Describe and explain the paths followed by the red and blue rays immediately after the light is incident on the glass–liquid interface.

Blue light undergoes TIR (1 mark)

Red light refracted (1 mark)

The critical angle for red light is more OR critical angle for blue light is less (1 mark)

OR

If refractive indices change by same factor (1 mark)

Critical angle stays constant (1 mark)

So path followed by red and blue light is the same (1 mark)

Critical Angle

We can derive an equation that connects the critical angle with the refractive indices of the materials.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

Exam Tip

Whilst, this equation is given in your examination booklet, for greatest exam success, please memorise this equation and the conditions where it can be applied.

Always be aware of the angle given in the question – it may not be the angle specified in the equation.

But at the critical angle θ_2 is equal to 90° which makes $\sin\theta_2 = 1$ this gives…

$$\frac{\sin\theta_1}{1} = \frac{n_2}{n_1}$$

θ_1 is the critical angle which we represent as θ_C making the equation:

$$\sin\theta_C = \frac{n_2}{n_1}$$

When the second material is air $n_2 = 1$,

So, the equation becomes:

$$\sin\theta_C = \frac{1}{n_1}$$

or

$$n_1 = \frac{1}{\sin\theta_C}$$

Exam Tip

Whilst, this equation is given in your examination booklet, for greatest exam success, please memorise this equation and the conditions where it can be applied.

Always be aware of the angle given in the question – it may not be the angle specified in the equation.

Exam Tip

It is a common examination question to link critical angle with how sparkly a material is.

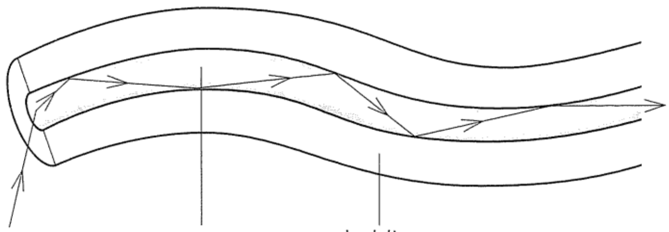
For a material to spark it has a small critical angle (1 mark)

Allowing more/same number/greater chance/increased probability of TIR's occurring (1 mark)

Giving the sparkle (1 mark)

Optical Fibres/Fibre Optics

An optical fibre is a thin piece of flexible glass.
Light can travel down it due to total internal reflection. Their uses include:



***Communication such as phone and TV signals:** they can carry more information than electricity in copper wires. The data is encrypted as a binary code of flashing of light.
This requires an optical material with a high critical angle to reduce the number of possible total internal reflection paths- **TO REDUCE MODAL DISPERSION**

***Medical endoscopes:** they allow us to see down them and are flexible so they don't cause injury to the patient.
This requires an optical material with a low critical angle to have a high number of possible total internal reflection paths. **– TO INCREASE THE AMOUNT OF LIGHT REACHING THE END**

Exam Tip

It is a common examination question to explain how data is transmitted down a fibre optic cable.

Draw a diagram showing core/cladding and light ray TIR at interface at least once with another TIR shown on the diagram or suggested in their explanation (1 mark)

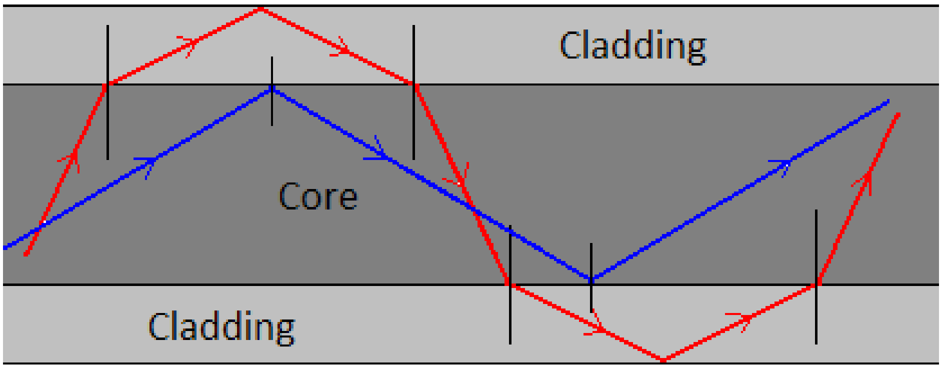
Light fibre consists of core and cladding with slightly lower refractive index/optical density (1 mark)

Light (incident) at angle greater than the critical angle (results in TIR) (1 mark)

Cladding

Cladding is added to the outside of an optical fibre to reduce the amount of light that is lost.

It does this by giving the light rays a second chance at total internal reflection as seen in the diagram.



Cladding is also used to protect the core from damage and to stop data transferring between the cores of different fibre optics.

It does increase the critical angle but the shortest path through the optical fibre is straight through, so only letting light which stays in the core means the signal is transmitted quicker.

Exam Tip

It is a common examination question to ask what the use of cladding is.

Protects the core (from scratches etc.) (1 mark)

Prevents crosstalk/stops signal crossing from one fibre to another/increases critical angle/reduces pulse broadening/reduces smearing/prevents multipath or modal dispersion (1 mark)

Allows fibre to be supported/touched (without losing light) (1 mark)

Consider the optical fibre with a refractive index of 1.5…

Without cladding $n_2 = 1$ $\quad \sin\theta_C = \frac{n_2}{n_1} \quad \sin\theta_C = \frac{1}{1.5} \quad \theta_C = 41.8°$

With cladding $n_2 = 1.4$ $\quad \sin\theta_C = \frac{n_2}{n_1} \quad \sin\theta_C = \frac{1.4}{1.5} \quad \theta_C = 69.0°$

If the cladding had a lower refractive index than the core it is easier for light to travel through so the light would bend away from the normal, **THIS GIVES TOTAL INTERNAL REFLECTION**

If the cladding had a higher refractive index than the core it is harder for light to travel through so the light would bend towards the normal, **THIS GIVES REFRACTION.**

Physics Tip:

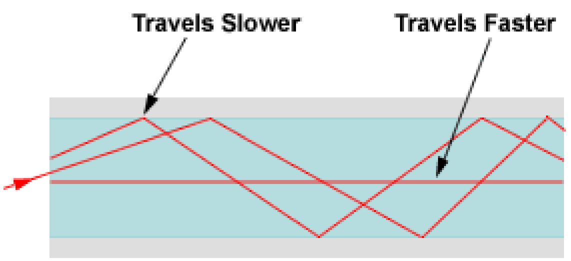
Optical fibres are called step-index optical fibres. The step down refers to the refraction index decreasing as you go from the core to the cladding.

There can be several issues with data transmission in fibre optics.

Modal Dispersion – If there are a variety of paths the incident light can totally internally reflect then the waves will spread out. Eventually, the waves will interfere with itself and produce an interference pattern. This spreads out the signal, this is called **PULSE BROADENING.**
Modal dispersion is reduced by having a high critical angle in the optic core – this is achieved by placing cladding around the core.
Another name of modal dispersion is multipath dispersion.

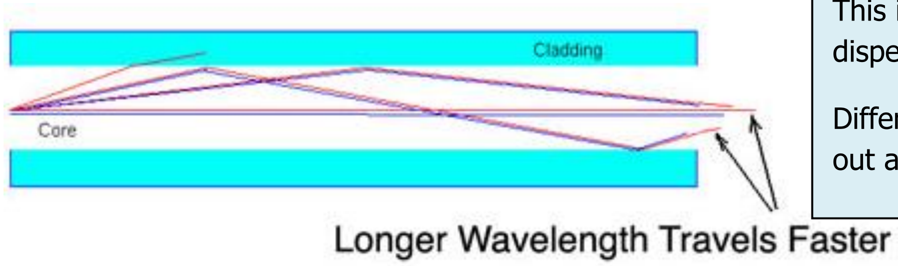
Material Dispersion – Different wavelengths of a single wave (if this is white light) can travel at different speeds inside the core, making the wave spread out. Eventually, the waves will interfere with itself and produce an interference pattern. This spreads out the signal, this is called **PULSE BROADENING.**
Material dispersion is reduced by using a monochromatic light source for the wave in the optic core – this is achieved by using laser light.

Attenuation – Some of the wave will be absorbed by the core as it passes through it, this is called attenuation.
Attenuation can be reduced by making the optic core out of a transparent material.



This is a diagram showing modal dispersion.

If the wave takes different paths in the core, it will spread out and pulse broaden.



This is a diagram showing material dispersion.

Different wavelengths of a wave spread out and pulse broaden.

Exam Tip

It is a common examination question to discuss the effect of placing white light into a fibre optic…

Blue travels slower than red due to the greater refractive index (1 mark).

Red reaches end before blue, leading to material pulse broadening (1 mark).

The time difference between red and blue light should be calculated using t = d/v for each type of light (1 mark).

Physics Tip:

You need to be able to explain how both absorption and dispersion cause signal degradation.

Exam Tip

It is a common question to discuss the properties of a step-index optical fibre.

Functions

Core

Propagates/Guides the wave/light

By TIR

(with) low attenuation/absorption

Refractive index of core > cladding

Cladding

Protects core from damage

Prevents cross talk between touching fibres

Provides 'clean' boundary for TIR

Dispersion Problems

Both: Cause pulse broadening/limited bandwidth

Material: different wavelengths have different speeds due to different refractive indices within the core – use monochromatic beam

Modal: different paths have different lengths so effective time along fibre differs – use single-mode fibre (narrow core/small Δn between core and cladding)

Exam Tip

It is a common question to discuss the effect of optical impurities in a fibre-optic core.

Light may encounter impurities at different positions/angles (1 mark)

Light may encounter different number of impurities (1 mark)

Light may encounter different sizes of impurities (1 mark)

Angle of incidence may become less than critical angle (1 mark)

Bending may cause cracks in the core/cladding (1 mark)

Light may be refracted (more/differently) (1 mark)

VIDEO

To watch a video looking at this concept, please scan one of the following codes with your smartphone.

SCAN ME

Note

SCAN ME

Note

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This external third-party content – please check the contents are appropriate.

REVISION CHECKLIST

Specification reference	Checklist questions	
3.3.2.1	Can you define path difference and coherence?	☐
3.3.2.1	Can you explain interference and diffraction using a laser as a source of monochromatic light?	☐
3.3.2.1	Can you describe Young's double-slit experiment?	☐
3.3.2.1	Can you describe the use of two coherent sources or the use of a single source with double slits to produce an interference pattern?	☐
3.3.2.1	Can you explain fringe spacing using the equation $w = \frac{\lambda D}{s}$?	☐
3.3.2.1	Can you describe the production of an interference pattern using white light?	☐
3.3.2.1	Can you describe safety issues associated with using lasers?	☐
3.3.2.1	Can you describe and explain interference produced with sound and electromagnetic waves?	☐
3.3.2.1	Can you explain how our knowledge and understanding of the nature of electromagnetic radiation has changed over time?	☐
3.3.2.1	Have you carried out an investigation of interference effects using the Young double-slit experiment and the diffraction grating?	☐
3.3.2.2	Can you describe the appearance of the diffraction pattern from a single slit using monochromatic and white light?	☐
3.3.2.2	Can you describe how the width of the central diffraction maximum varies with wavelength and slit width?	☐
3.3.2.2	Can you describe the diffraction pattern when light is shone on a plane transmission diffraction grating at normal incidence?	☐

Specification reference	**Checklist questions**	
3.3.2.2	Can you derive $d\sin\theta = n\lambda$?	☐
3.3.2.2	Can you suggest some applications of diffraction gratings?	☐
3.2.2.3	Can you calculate the refractive index of a substance using $n = \frac{c}{c_s}$?	☐
3.2.2.3	Can you recall that the refractive index of air is approximately 1?	☐
3.2.2.3	Can you recall and use Snell's law of refraction ($n_1\sin\theta_1 = n_2\sin\theta_2$) for a boundary?	☐
3.2.2.3	Can you explain total internal reflection using $\sin\theta_c = \frac{n_2}{n_1}$?	☐
3.2.2.3	Can you explain fibre optics, including the function of the cladding?	☐
3.2.2.3	Can you explain material and modal dispersion?	☐
3.2.2.3	Can you explain the principles and consequences of pulse broadening and absorption?	☐

DATASHEET

DATA – FUNDAMENTAL CONSTANTS AND VALUES

Quantity	Symbol	Value	Units
speed of light in vacuo	c	3.00×10^{8}	$\mathrm{m\,s^{-1}}$
permeability of free space	μ_0	$4\pi \times 10^{-7}$	$\mathrm{H\,m^{-1}}$
permittivity of free space	ε_0	8.85×10^{-12}	$\mathrm{F\,m^{-1}}$
magnitude of the charge of electron	e	1.60×10^{-19}	C
the Planck constant	h	6.63×10^{-34}	J s
gravitational constant	G	6.67×10^{-11}	$\mathrm{N\,m^{2}\,kg^{-2}}$
the Avogadro constant	N_A	6.02×10^{23}	$\mathrm{mol^{-1}}$
molar gas constant	R	8.31	$\mathrm{J\,K^{-1}\,mol^{-1}}$
the Boltzmann constant	k	1.38×10^{-23}	$\mathrm{J\,K^{-1}}$
the Stefan constant	σ	5.67×10^{-8}	$\mathrm{W\,m^{-2}\,K^{-4}}$
the Wien constant	α	2.90×10^{-3}	m K
electron rest mass (equivalent to 5.5×10^{-4} u)	m_e	9.11×10^{-31}	kg
electron charge/mass ratio	$\frac{e}{m_e}$	1.76×10^{11}	$\mathrm{C\,kg^{-1}}$
proton rest mass (equivalent to 1.00728 u)	m_p	$1.67(3) \times 10^{-27}$	kg
proton charge/mass ratio	$\frac{e}{m_p}$	9.58×10^{7}	$\mathrm{C\,kg^{-1}}$
neutron rest mass (equivalent to 1.00867 u)	m_n	$1.67(5) \times 10^{-27}$	kg
gravitational field strength	g	9.81	$\mathrm{N\,kg^{-1}}$
acceleration due to gravity	g	9.81	$\mathrm{m\,s^{-2}}$
atomic mass unit (1u is equivalent to 931.5 MeV)	u	1.661×10^{-27}	kg

ALGEBRAIC EQUATION

quadratic equation $x = \dfrac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

ASTRONOMICAL DATA

Body	Mass/kg	Mean radius/m
Sun	1.99×10^{30}	6.96×10^{8}
Earth	5.97×10^{24}	6.37×10^{6}

GEOMETRICAL EQUATIONS

arc length	$= r\theta$
circumference of circle	$= 2\pi r$
area of circle	$= \pi r^2$
curved surface area of cylinder	$= 2\pi rh$
area of sphere	$= 4\pi r^2$
volume of sphere	$= \frac{4}{3}\pi r^3$

Particle Physics

Class	Name	Symbol	Rest energy/MeV
photon	photon	γ	0
lepton	neutrino	ν_e	0
		ν_μ	0
	electron	$e^\pm$	0.510999
	muon	$\mu^\pm$	105.659
mesons	π meson	$\pi^\pm$	139.576
		π^0	134.972
	K meson	$K^\pm$	493.821
		K^0	497.762
baryons	proton	p	938.257
	neutron	n	939.551

Properties of quarks

antiquarks have opposite signs

Type	Charge	Baryon number	Strangeness
u	$+\frac{2}{3}e$	$+\frac{1}{3}$	0
d	$-\frac{1}{3}e$	$+\frac{1}{3}$	0
s	$-\frac{1}{3}e$	$+\frac{1}{3}$	-1

Properties of Leptons

		Lepton number
Particles:	$e^-, \nu_e ; \mu^-, \nu_\mu$	$+1$
Antiparticles:	$e^+, \overline{\nu_e}, \mu^+, \overline{\nu_\mu}$	-1

Photons and energy levels

photon energy $E = hf = hc/\lambda$

photoelectricity $hf = \phi + E_{k\,(max)}$

energy levels $hf = E_1 - E_2$

de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{mv}$

Waves

wave speed $c = f\lambda$ *period* $f = \frac{1}{T}$

first harmonic $f = \frac{1}{2l}\sqrt{\frac{T}{\mu}}$

fringe spacing $w = \frac{\lambda D}{s}$ *diffraction grating* $d \sin\theta = n\lambda$

refractive index of a substance s, $n = \frac{c}{c_s}$

for two different substances of refractive indices n_1 *and* n_2,

law of refraction $n_1 \sin\theta_1 = n_2 \sin\theta_2$

critical angle $\sin\theta_c = \frac{n_2}{n_1}$ for $n_1 > n_2$

Mechanics

moments $\text{moment} = Fd$

velocity and acceleration $v = \frac{\Delta s}{\Delta t}$ $a = \frac{\Delta v}{\Delta t}$

equations of motion $v = u + at$ $s = \left(\frac{u+v}{2}\right)t$

$v^2 = u^2 + 2as$ $s = ut + \frac{at^2}{2}$

force $F = ma$

force $F = \frac{\Delta(mv)}{\Delta t}$

impulse $F\Delta t = \Delta(mv)$

work, energy and power $W = Fs\cos\theta$

$E_k = \frac{1}{2}mv^2$ $\Delta E_p = mg\Delta h$

$P = \frac{\Delta W}{\Delta t}, P = Fv$

$efficiency = \frac{\text{useful output power}}{\text{input power}}$

Materials

density $\rho = \frac{m}{V}$ *Hooke's law* $F = k\Delta L$

Young modulus $= \frac{\text{tensile stress}}{\text{tensile strain}}$ *tensile stress* $= \frac{F}{A}$

tensile strain $= \frac{\Delta L}{L}$

energy stored $E = \frac{1}{2}F\Delta L$

Electricity

current and pd $I = \frac{\Delta Q}{\Delta t}$ $V = \frac{W}{Q}$ $R = \frac{V}{I}$

resistivity $\rho = \frac{RA}{L}$

resistors in series $R_T = R_1 + R_2 + R_3 + \ldots$

resistors in parallel $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$

power $P = VI = I^2R = \frac{V^2}{R}$

emf $\varepsilon = \frac{E}{Q}$ $\varepsilon = I(R + r)$

Circular motion

magnitude of angular speed $\omega = \frac{v}{r}$

$\omega = 2\pi f$

centripetal acceleration $a = \frac{v^2}{r} = \omega^2 r$

centripetal force $F = \frac{mv^2}{r} = m\omega^2 r$

Simple harmonic motion

acceleration $a = -\omega^2 x$

displacement $x = A\cos(\omega t)$

speed $v = \pm\omega\sqrt{(A^2 - x^2)}$

maximum speed $v_{max} = \omega A$

maximum acceleration $a_{max} = \omega^2 A$

for a mass-spring system $T = 2\pi\sqrt{\frac{m}{k}}$

for a simple pendulum $T = 2\pi\sqrt{\frac{l}{g}}$

Thermal physics

energy to change temperature $Q = mc\Delta\theta$

energy to change state $Q = m\,l$

gas law $pV = nRT$

$pV = NkT$

kinetic theory model $pV = \frac{1}{3}N\,m\,(c_{\text{rms}})^2$

kinetic energy of gas molecule $\frac{1}{2}m\,(c_{\text{rms}})^2 = \frac{3}{2}kT = \frac{3RT}{2N_A}$

Gravitational fields

force between two masses $F = \frac{Gm_1m_2}{r^2}$

gravitational field strength $g = \frac{F}{m}$

magnitude of gravitational field strength in a radial field $g = \frac{GM}{r^2}$

work done $\Delta W = m\Delta V$

gravitational potential $V = -\frac{GM}{r}$

$g = -\frac{\Delta V}{\Delta r}$

Electric fields and capacitors

force between two point charges $F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{r^2}$

force on a charge $F = EQ$

field strength for a uniform field $E = \frac{V}{d}$

work done $\Delta W = Q\Delta V$

field strength for a radial field $E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$

electric potential $V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r}$

$E = \frac{\Delta V}{\Delta r}$

capacitance $C = \frac{Q}{V}$

$C = \frac{A\varepsilon_0\varepsilon_r}{d}$

capacitor energy stored $E = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C}$

capacitor charging $Q = Q_0(1 - e^{-t/RC})$

decay of charge $Q = Q_0 e^{-t/RC}$

time constant RC

Magnetic fields

force on a current	$F = BIl$
force on a moving charge	$F = BQv$
magnetic flux	$\Phi = BA$
magnetic flux linkage	$N\Phi = BAN\cos\theta$
magnitude of induced emf	$\varepsilon = N\dfrac{\Delta\Phi}{\Delta t}$
	$N\Phi = BAN\cos\theta$
emf induced in a rotating coil	$\varepsilon = BAN\omega\sin\omega t$
alternating current	$I_{rms} = \dfrac{I_0}{\sqrt{2}}$ $V_{rms} = \dfrac{V_0}{\sqrt{2}}$
transformer equations	$\dfrac{N_s}{N_p} = \dfrac{V_s}{V_p}$
	$efficiency = \dfrac{I_sV_s}{I_pV_p}$

Nuclear physics

the inverse square law for γ radiation	$I = \dfrac{k}{x^2}$
radioactive decay	$\dfrac{\Delta N}{\Delta t} = -\lambda N,\ N = N_0 e^{-\lambda t}$
activity	$A = \lambda N$
half-life	$T_{½} = \dfrac{\ln 2}{\lambda}$
nuclear radius	$R = R_0 A^{1/3}$
energy-mass equation	$E = mc^2$

OPTIONS

Astrophysics

1 astronomical unit = 1.50×10^{11} m

1 light year = 9.46×10^{15} m

1 parsec = 206265 AU = 3.08×10^{16} m = 3.26 light year

Hubble constant, H = 65 km s^{-1} Mpc^{-1}

$$M = \frac{\text{angle subtended by image at eye}}{\text{angle subtended by object at unaided eye}}$$

in normal adjustment	$M = \dfrac{f_o}{f_e}$
Rayleigh criterion	$\theta \approx \dfrac{\lambda}{D}$
magnitude equation	$m - M = 5\log\dfrac{d}{10}$
Wien's law	$\lambda_{max}T = 2.9 \times 10^{-3}$ m K
Stefan's law	$P = \sigma A T^4$
Schwarzschild radius	$R_s \approx \dfrac{2GM}{c^2}$
Doppler shift for v << c	$\dfrac{\Delta f}{f} = -\dfrac{\Delta\lambda}{\lambda} = \dfrac{v}{c}$
red shift	$z = -\dfrac{v}{c}$
Hubble's law	$v = Hd$

Medical physics

lens equations	$P = \dfrac{1}{f}$
	$m = \dfrac{v}{u}$
	$\dfrac{1}{f} = \dfrac{1}{u} + \dfrac{1}{v}$
threshold of hearing	$I_0 = 1.0 \times 10^{-12}$ W m^{-2}
intensity level	$intensity\ level = 10\log\dfrac{I}{I_0}$
absorption	$I = I_0 e^{-\mu x}$
	$\mu_m = \dfrac{\mu}{\rho}$
ultrasound imaging	$Z = \rho c$
	$\dfrac{I_r}{I_i} = \left(\dfrac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$
half-lives	$\dfrac{1}{T_E} = \dfrac{1}{T_B} + \dfrac{1}{T_P}$

Engineering physics

moment of inertia $I = \Sigma mr^2$

angular kinetic energy $E_k = \frac{1}{2} I\omega^2$

equations of angular motion

$\omega_2 = \omega_1 + \alpha t$

$\omega_2{}^2 = \omega_1{}^2 + 2\alpha\theta$

$\theta = \omega_1 t + \frac{\alpha t^2}{2}$

$\theta = \frac{(\omega_1 + \omega_2)\, t}{2}$

torque $T = I\,\alpha$

$T = F\,r$

angular momentum $angular\ momentum = I\omega$

angular impulse $T\Delta t = \Delta(I\omega)$

work done $W = T\theta$

power $P = T\omega$

thermodynamics $Q = \Delta U + W$

$W = p\Delta V$

adiabatic change $pV^\gamma = \text{constant}$

isothermal change $pV = \text{constant}$

heat engines

efficiency $= \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H}$

maximum theoretical efficiency $= \frac{T_H - T_C}{T_H}$

work done per cycle = area of loop

input power = calorific value × fuel flow rate

indicated power = (area of $p - V$ loop) × (number of cycles per second) × (number of cylinders)

output or brake power $P = T\omega$

friction power = indicated power – brake power

heat pumps and refrigerators

refrigerator: $COP_{ref} = \frac{Q_C}{W} = \frac{Q_C}{Q_H - Q_C}$

heat pump: $COP_{hp} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C}$

Turning points in physics

electrons in fields $F = \frac{eV}{d}$

$F = Bev$

$r = \frac{mv}{Be}$

$\frac{1}{2} mv^2 = eV$

Millikan's experiment $\frac{QV}{d} = mg$

$F = 6\pi\eta r v$

Maxwell's formula $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$

$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}}$

special relativity $t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$

$l = l_0 \sqrt{1 - \frac{v^2}{c^2}}$

$E = mc^2 = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$

Electronics

resonant frequency $f_0 = \frac{1}{2\pi\sqrt{LC}}$

Q-factor $Q = \frac{f_0}{f_B}$

operational amplifiers: open loop $V_{out} = A_{OL}(V_+ - V_-)$

inverting amplifier $\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$

non-inverting amplifier $\frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_1}$

summing amplifier $V_{out} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \cdots\right)$

difference amplifier $V_{out} = (V_+ - V_-)\frac{R_f}{R_1}$

Bandwidth requirement:

for AM $bandwidth = 2f_M$

for FM $bandwidth = 2(\Delta f + f_M)$

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This document has been produced for educational purposes only.

This document has been produced for the AQA A Level Physics Specification.

Student Voice

If you when using this document, you believe there is an improvement to made, please state this in the space below….

Only constructive and reasoned feedback will be considered.