The Nature Of Waves

Aaaah... waggling ropes about. It's all good clean fun as my mate Richard used to say...

A **Wave** Transfers **Energy** Away From Its **Source**

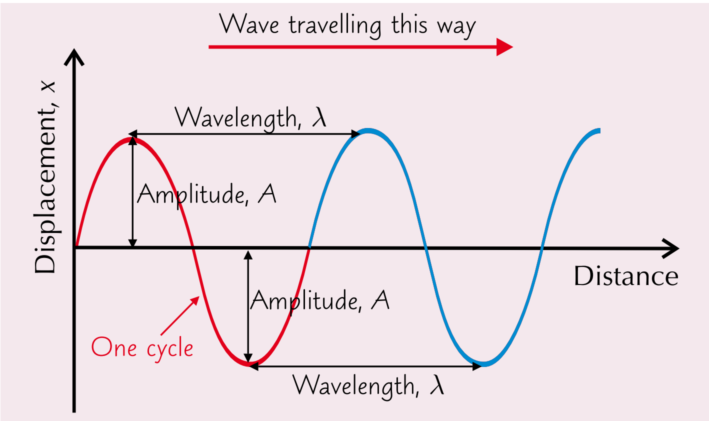
A **progressive** (moving) wave carries **energy** from one place to another **without transferring any material**. The transfer of energy is in the **same direction** as the wave is **travelling**. Here are some ways you can tell waves carry energy:

1) Electromagnetic waves cause things to **heat up**.
2) **X-rays** and **gamma rays** knock electrons out of their orbits, causing **ionisation**.
3) Loud **sounds** cause large oscillations in air particles which can make things **vibrate**.
4) **Wave power** can be used to **generate electricity**.

Since waves carry energy away, the **source** of the wave **loses energy**.

You Need to Know These **Bits** of a **Wave**

1) **Displacement**, ***x***, metres — how far a **point** on the wave has **moved** from its **undisturbed position**.
2) **Amplitude**, ***A***, metres — the **maximum magnitude** of the **displacement**.
3) **Wavelength**, **λ**, metres — the **length** of **one whole wave cycle**, e.g. from **crest** to **crest** or **trough** to **trough**.



4) **Period**, ***T***, seconds — the **time taken** for a **whole cycle** (vibration) to complete.
5) **Frequency**, ***f***, hertz — the **number** of **cycles** (vibrations) **per second** passing a given **point**.
6) **Phase** — a measurement of the **position** of a certain **point** along the wave cycle.
7) **Phase difference** — the amount one wave lags behind another.

Phase and phase difference are measured in angles (in degrees or radians). See p.74.

The **Frequency** is the **Inverse** of the **Period**

$$\text{Frequency} = \frac{1}{\text{Period}} \qquad f = \frac{1}{T}$$

It's that simple.
Get the **units** straight: **1 Hz = 1 s^{-1}**.

The **Wave Equation** Links **Wave Speed, Frequency** and **Wavelength**

1) **Wave speed** can be measured just like the speed of anything else:

$$\text{Wave speed } (v) = \frac{\text{Distance } (d)}{\text{Time } (t)}$$

2) You can use this equation to derive the **wave equation** (but thankfully you don't have to do that, you just need to be able to use it).

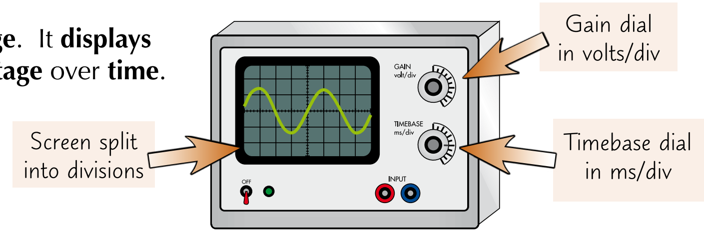
$$\text{Speed of wave } (v) = \text{frequency } (f) \times \text{wavelength } (\lambda) \qquad v = f\lambda$$

Remember, you're not measuring how fast a physical point (like one molecule of rope) moves. You're measuring how fast a point on the **wave pattern** moves.

The Nature Of Waves

Oscilloscopes Display Waves

1) A cathode ray **oscilloscope** (CRO) measures **voltage**. It **displays** waves from a **signal generator** as a function of **voltage** over **time**.
2) The displayed wave is called a **trace**.
3) The screen is split into squares called **divisions**.
4) The vertical axis is in **volts**. The **volts per division** shown on this axis is controlled by the **gain dial**.
5) The horizontal axis is in **seconds** — also called the **timebase**. The **seconds per division** shown on this axis is controlled by the **timebase** dial.
6) You can alter the gain and timebase to make it **easy to read** off measurements.

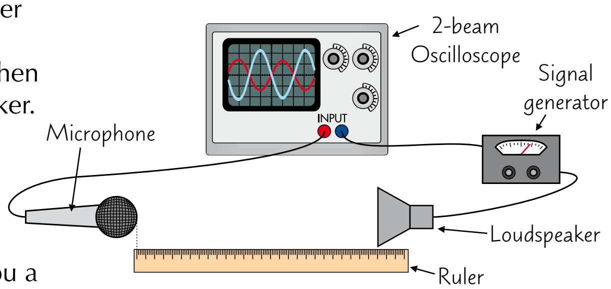


The period of a wave is found from: the no. of divisions in one complete wave × the timebase setting.

If you plug an **AC** (**alternating current**) **supply** into an oscilloscope, you get a trace that goes up and down in a regular pattern — some of the time it's positive and some of the time it's negative.
A **microphone** converts **sound waves** into **electrical signals** which can be seen on an **oscilloscope**.

An *Oscilloscope* Can be Used to Find the *Speed of Sound*

1) Set up the experiment as shown in the diagram below and set the **frequency** of the signal generator to around 2-6 kHz. A **2-beam oscilloscope** must be used as this can display **two waves** — one for the **signal generator** generating a **sound wave** and one for the **same sound wave** being **received** by the **microphone**.
2) A 2-beam oscilloscope has **three dials** — two are the gain dials for **each** input signal and the other dial is the timebase dial for **both** input signals. Adjust the **dials** so that you can see at least one **complete cycle** of each wave.
3) **Change** the **distance** between the microphone and loudspeaker so that the **peaks** of one wave **line up** with the **troughs** of the other wave (i.e. the waves are **out of phase** — see p.74) and then **measure** the distance between the microphone and loudspeaker.
4) Calculate the **frequency** of the wave by measuring the **period** of the wave from the oscilloscope display and using it in $f = \frac{1}{T}$ (see p.66). The **resolution** of the oscilloscope will be **better** than the resolution of the signal generator, so measuring and calculating the frequency this way will give you a **smaller uncertainty** than just reading the frequency from the signal generator.



5) Move the microphone **away from** (or **towards**) the loudspeaker so that the microphone's corresponding wave on the oscilloscope **moves** one **full wavelength** along the signal generator's wave — the peaks of one wave and the troughs of the other wave will **line up** again. Measure the **new** distance between the microphone and loudspeaker.
6) The **difference** in your two recorded distances is equal to the **wavelength** of the sound wave.
7) Repeat steps 5-6 and use your results to find a **mean value** for the distance moved by the microphone each time (i.e. the **wavelength**). Then use the equation $v = f\lambda$ to find the value for the **speed of sound**.

Practice Questions

Q1 Define and give the units of the frequency, displacement, amplitude, speed and period of a wave.

Q2 Write down the wave equation.

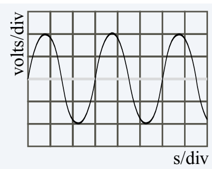
Q3 Describe an experiment involving a 2-beam oscilloscope, a loudspeaker and a microphone to measure the speed of sound.

Exam Question

Q1 An oscilloscope has the gain set to 2.0 volts/div and a timebase set to 3.0 ms/div.
It is displaying the trace of a wave that has a wave speed of 280 ms^{-1}.

a) State the maximum voltage of the trace. [1 mark]

b) Calculate the frequency and wavelength of the wave. [5 marks]



Hope you haven't phased out...

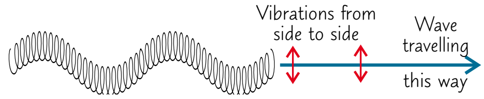
Make sure you know what all the waves terms (amplitude, frequency etc.) mean — or this section could get confusing...

Types of Wave

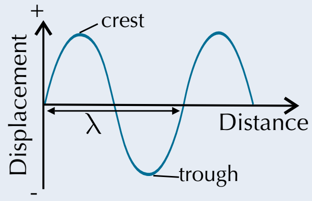
Get a long spring and have a go at making different waves. Or sit there beeping pretending to be a microwave.

In **Transverse Waves**, **Vibration** is at Right Angles to the **Direction** of Travel

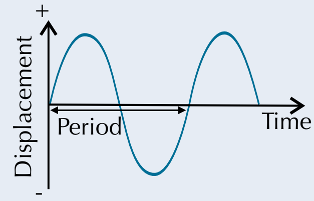
1) All **electromagnetic waves** are **transverse**. Other examples of transverse waves are ripples on water or waves on strings.
2) There are **two** main ways of **drawing** transverse waves:



They can be shown as **graphs** of **displacement** against **distance along the path of the wave**.



Or, they can be shown as graphs of **displacement against time** for a point as the wave passes.

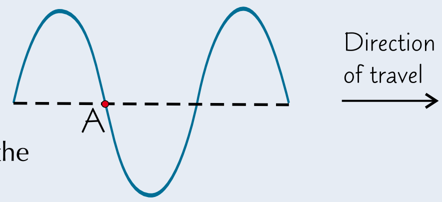


Displacements **upwards** from the centre line are given a **+ sign**. Displacements downwards are given a **– sign**.

3) Both sorts of graph often give the **same shape** (a **sine wave**), so make sure you check out the label on the ***x*-axis**.
4) You can work out what **direction** a point on a wave is moving in when given a snapshot of the wave.

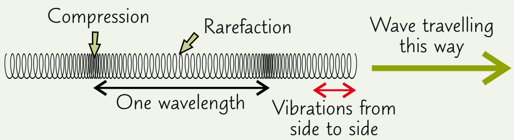
Example: Look at the snapshot of the wave on the right. Which direction is point A on the wave moving in?

1) Look at which **direction** the wave is **travelling** in — here the wave is moving from **left** to **right**.
2) The displacement of the wave **just to the left** of point A is **greater** than point A's. So as the wave travels along, point A will need to move **upwards** to have that displacement. (If the displacement to the left was less than point A's, point A would need to move down.)



In **Longitudinal Waves** the **Vibrations** are **Along** the Direction of Travel

The most **common** example of a **longitudinal wave** is **sound**. A sound wave consists of alternate **compressions** and **rarefactions** of the **medium** it's travelling through. (That's why sound can't go through a vacuum.)



Some types of earthquake shock waves are also longitudinal.

The compressions and rarefactions create **pressure variations** in the medium the wave is travelling through — at the points of compression, the **molecules** of the medium are **closer** together, **increasing** the pressure at that point. At the points of rarefaction, the molecules are **further apart**, which means a **lower** pressure at that point.

It's hard to **represent** longitudinal waves **graphically**. You'll usually see them plotted as **displacement** against **time**. These can be **confusing** though, because they look like a **transverse wave**.

Waves Can Be **Reflected** and **Refracted**

Reflection — the wave is **bounced back** when it **hits a boundary**. E.g. you can see the reflection of light in mirrors. The reflection of water waves can be demonstrated in a ripple tank.

Refraction — the wave **changes direction** as it enters a **different medium**. The change in direction is a result of the wave slowing down or speeding up.

Tim refused to accept that his long lost twin was just a reflection at an air-water boundary.

Types of Wave

Intensity is a Measure of How Much Energy a Wave is Carrying

1) When you talk about "**brightness**" for light or "**loudness**" for sound, what you really mean is **how much light** or **sound** energy hits your eyes or your ears **per second**.
2) The scientific measure of this is **intensity**.

Intensity is the **rate of flow** of **energy** per **unit area** at **right angles** to the **direction of travel** of the wave. It's measured in **Wm^{-2}**.

$$\textbf{Intensity} = \frac{\textbf{Power}}{\textbf{Area}} \qquad I = \frac{P}{A}$$

Example: Light is hitting a 12 cm^2 piece of paper at right angles to its surface. The power received at the paper is 0.26 W. Calculate the intensity of the light received.

The area of the piece of paper = 12 cm^2 = 0.0012 m^2

Using the equation for intensity:

$I = \frac{P}{A} = \frac{0.26}{0.0012} = 216.6... =$ **220 Wm^{-2} (to 2 s.f.)**

Don't forget to convert from cm^2 to m^2 — 1 cm^2 = 0.00001 m^2.

Intensity is Proportional to Amplitude Squared

1) This comes from the fact that **intensity** is **proportional** to **energy**, and the energy of a wave depends on the square of the **amplitude**.
2) From this you can tell that for a **vibrating source** it takes four times as much energy to double the size of the vibrations.

Intensity $\propto$ (Amplitude)^2

All Electromagnetic (EM) Waves Have Some Properties In Common

1) All EM waves travel in a **vacuum** at a **speed** of **3.00 × 10^8 ms^{-1}** (to 3 s.f.), and at **slower** speeds in other media.
2) They are **transverse** waves consisting of **vibrating electric** and **magnetic fields**. The **electric** and **magnetic** fields are at **right angles** to each other and to the **direction of travel**.
3) Like all waves, EM waves can be **refracted** (p.78), **reflected** and **diffracted** (p.82-83) and can undergo **interference** (p.74). They also obey $v = f\lambda$ (v = velocity, f = frequency, λ = wavelength).
4) Like all progressive waves, progressive EM waves **carry energy**.
5) EM waves are transverse so, like all transverse waves, they can be **polarised** (see page 70).

Practice Questions

Q1 Draw a displacement-time graph for a transverse wave. Label a point of maximum displacement and the wavelength of the wave on the graph.

Q2 Draw a displacement-time graph for a point on a longitudinal wave as the wave passes.

Q3 Describe the difference between the vibrations in a transverse wave and a longitudinal wave.

Q4 Describe a longitudinal wave in terms of pressure variations in the medium through which the wave is travelling.

Q5 Give the equation relating power, intensity and area.

Exam Question

Q1 a) A 10.0 W light beam is shone onto a screen with an area of 0.002 m^2. Calculate the intensity of the light beam on the screen. [1 mark]

b) The intensity of the light on the screen is increased until it is exactly triple the original beam intensity. Which of the following describes the amplitude of the light waves in the beam compared to their original amplitude?

A It is 3 times larger. B It has halved. C It is 9 times larger. D It is √3 times larger. [1 mark]

So many waves — my arms are getting tired...

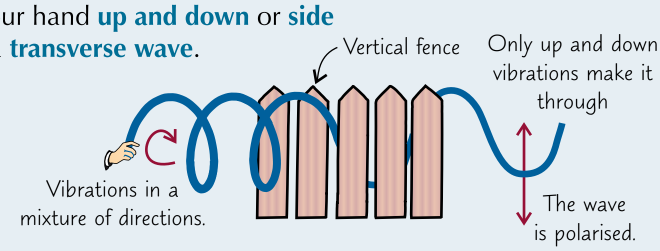
Make sure you know the difference between transverse and longitudinal waves — one is up-y down-y and the other is forward-y backward-y. There's nothing quite like a hand-wavey explanation of something (no pun intended...no, really).

Polarisation of Waves

Light waves shake about all over the place. Polarisation is just getting rid of the directions that you don't want.

A **Polarised Wave** Only **Oscillates** in One Direction

1) If you **shake a rope** to make a **wave** you can move your hand **up and down** or **side to side** or in a **mixture** of directions — it still makes a **transverse wave**.
2) But if you try to pass **waves in a rope** through a **vertical fence**, the wave will only get through if the **vibrations** are **vertical**. The fence filters out vibration in other directions. This is called **polarising** the wave.



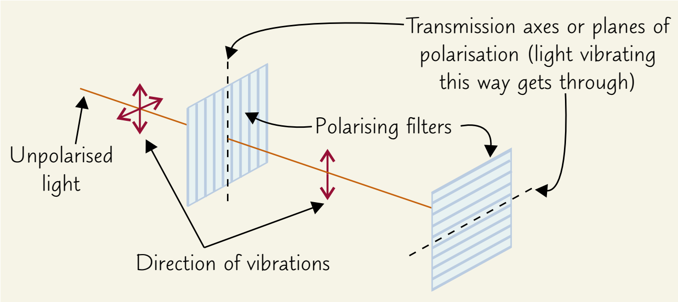
3) The **plane** in which a wave **vibrates** is called the **plane of polarisation** — e.g. the rope wave was polarised in the **vertical** plane by the fence.
4) Polarising a wave so that it only oscillates in one direction is called **plane polarisation**.
5) Ordinary **light waves** are a mixture of **different directions** of **vibration**. (The things vibrating are electric and magnetic fields).

Polarisation can only happen for **transverse waves**. So polarising light is one piece of **evidence** that it's a transverse wave.

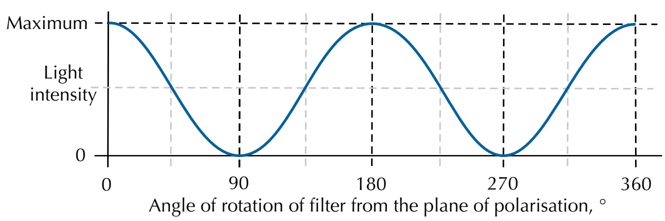
For polarised light, the direction of the vibrations (or the plane of polarisation) is always perpendicular to the direction of the propagation of light.

Polarising Filters Only **Transmit** Vibrations in **One Direction**

1) Ordinary **light waves** can be **polarised** using a **polarising filter**.
2) When the transmission axes of the two filters are **aligned**, **all** of the light that passes through the first filter also passes through the second.
3) As you rotate the second filter, the amount of light that passes through the second filter **varies**.
4) As the second filter is rotated, **less** light will get through it as the **vertical** component of the second filter's transmission axis **decreases**. This means the **intensity** of the light getting through the second filter will gradually **decrease**.
5) When the two transmission axes are at **45°** to each other, the intensity will be **half** that getting through the first filter. When they're at **right angles** to each other **no** light will pass through — **intensity** is **0**.



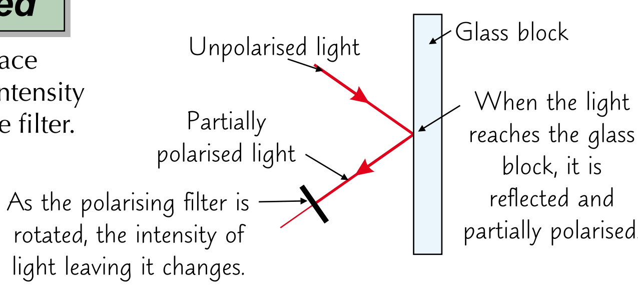
3D films use polarised light to create depth — the filters in each lens are at right angles to each other so each eye gets a slightly different picture.



6) As you continue turning, the intensity should then begin to **increase** once again.
7) When the two axes **realign** (after a 180° rotation), **all** the light will be able to pass through the second filter again.

When **Light Reflects** it is **Partially Polarised**

1) If you direct a beam of unpolarised light at a reflective surface then view the **reflected ray** through a polarising filter, the intensity of light leaving the filter **changes** with the **orientation** of the filter.
2) The intensity changes because at certain **angles**, light is **partially polarised** when it is **reflected**.
3) This effect is used to remove **unwanted reflections** in photography and in **Polaroid sunglasses** to remove **glare**.



Polarisation of Waves

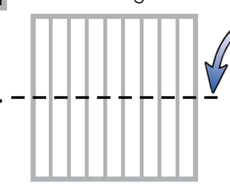
Television and Radio Signals are Polarised

If you look up at the **TV aerials** on people's houses, you'll see that the **rods** (the sticky-out bits) on them are all **horizontal**. This is because **TV signals** are **polarised** by the orientation of the **rods** on the **broadcasting aerial**. To receive a strong signal, you have to **line up** the **rods** on the **receiving aerial** with the **rods** on the **transmitting aerial** — if they aren't aligned, the signal strength will be lower.

It's the **same** with **radio** — if you try **tuning a radio** and then **moving** the **aerial** around, your signal will **come and go** as the transmitting and receiving aerials go in and out of **alignment**.

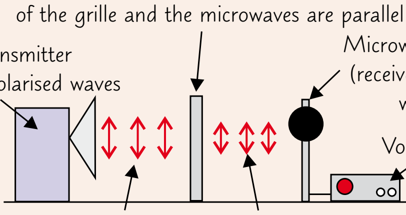
Metal Grilles are Used to Polarise Microwaves

Polarising filters don't work on **microwaves** — their **wavelength** is too long. Instead, **metal grilles** (squares full of metal wires which are all aligned) are used to polarise them.



You can investigate the polarisation of microwaves using a **microwave transmitter** and a **microwave receiver** linked to a **voltmeter**.

1) Place a metal **grille** between the microwave **transmitter** and **receiver** as shown on the right. (Handily, microwave transmitters transmit **polarised** microwaves, so you only need one metal grille.)
2) The intensity of microwaves passing through the grille is at a **maximum** when the direction of the vibration of the microwaves and the plane of polarisation of the grille are **parallel** to each other.
3) As you rotate the grille, the **intensity** of polarised microwaves able to pass through the grille **decreases**, so the reading on the voltmeter **decreases**.
4) When the plane of polarisation of the metal grille is **perpendicular** with the direction of the vibration of the microwaves, **no signal** will be shown on the voltmeter.



The **intensity** drops to **zero** when the plane of polarisation of the metal grille is at **right angles** to the plane of polarisation of the microwaves, because the grille is **absorbing their energy**.

Make sure all of your electrical equipment is safely connected before you turn it on — microwave transmitters operate at very high voltages.

Practice Questions

Q1 What is plane polarisation?

Q2 Why can't you polarise sound waves?

Q3 Why do you have to line up transmitting and receiving television aerials?

Exam Question

Q1 Two polarising filters are placed on top of each other and held in front of a source of white unpolarised light.

a) No light can be seen through the filters. State the angle between the transmission axes of the two filters. [1 mark]

b) The filters are rotated so that the angle between their transmission axes is 45°. Describe the difference in the intensity of the light once it has passed through both filters compared to the light once it has only passed through the first filter. [1 mark]

Forget polarisation, I need a mental filter...

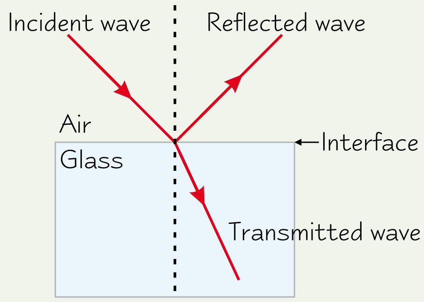
...to stop me talking rubbish all the time. Polarisation isn't too bad once you get your head around it. It's just a case of filtering out different directions of wave vibrations. Make sure you really know it though as you'll have to be able to explain how both the experiments for polarising light and microwaves work. Doesn't that sound like a barrel of laughs.

Ultrasound Imaging

I wrote these next two pages for you, because I know what you're thinking — 'This is great, but I want to learn about waves in medical imaging. Also, as a side note, I think CGP books are brilliant.' Oh stop, no really, I'm blushing...

Waves are Reflected and Transmitted at Interfaces

1) The **boundary** between two different media is called an **interface**.
2) When a wave passes from one medium to another, some of its **energy** is **reflected** and some of it is **transmitted** — as shown in the diagram.
3) The proportion of energy reflected or transmitted depends on the two media involved. If the media have very **different densities**, most of the energy is **reflected**. If they are quite **similar**, most of the energy is **transmitted**.



The Reflection of Ultrasound Waves is Used in Ultrasound Scans

1) **Ultrasound waves** are **sound waves** that have too high a **frequency** for humans to **hear**.
2) Ultrasound scans use short pulses of **ultrasound radiation** to form images of the inside of your body.
3) The ultrasound is directed into your body using a **transducer**. If you have air between the transducer and your skin, most of the waves are **reflected** because air has a very **different** density from skin. A **gel** is applied to the skin so there is no air between the transducer and your skin to **increase** the proportion of ultrasound waves that **enter** your body.
4) When the ultrasound waves reach an **interface** inside your body — e.g. between different types of tissue — some of them are **reflected**. A computer attached to the transducer calculates how far from the surface of your skin the interface is by **timing** how long it takes for the reflected waves to **return**.
5) The computer uses the information about the **location** of the boundaries between different tissues to build up an **image** of the inside of your body.

Sending out ultrasound waves and detecting the reflections is known as a pulse-echo technique.

A similar technique is used in **sonar** — e.g. ships send sonar pulses (**ultrasound waves**) down towards the seabed and the pulses are **reflected** back from any **submerged** objects. It can also be used to measure the **speed** of objects.

Shorter Pulses Produce Clearer Images

Ultrasound transducers cannot **transmit** and **receive** pulses at the same time. If **reflected** waves reach the transducer while it is **transmitting**, the information they contain will be **lost** and image **quality** will be reduced. This means:

1) The **pulses** of ultrasound transmitted must be **very short** (a few microseconds long) so that the reflections from nearby interfaces don't reach the transducer before the pulse has ended.
2) The gap between pulses must be **long** (at least 1 millisecond) so that all the reflected waves from one pulse return to the transducer **before** the next pulse is transmitted.

Jack didn't know how to tell Joanna that most of the image quality had been lost.

Ultrasound Imaging

Shorter Wavelengths Produce Clearer Images

Ultrasound scanning can be a really useful technique — but only if the images are **clear**.
The **properties** of the ultrasound **radiation** used has a big effect on the clarity of the images produced.

1) **Shorter** wavelengths **diffract** much **less** than longer wavelengths.
2) This means that the shorter the **wavelength** of the ultrasound, the less the waves **spread out** as they travel and the more **precisely** the location of the interfaces between tissues can be mapped.
3) So ultrasound scanners use waves with a **high frequency** and **short wavelength**.

For more on diffraction of waves, see page 82.

In order for an **object** to be **resolved** (distinguished from other objects), the **wavelength** of the ultrasound wave must be of a **similar size** to the width of the object being resolved.

Example: Ultrasound of frequency 0.95 MHz is used to image a spherical tumour with a diameter of 3.2 mm. If the speed of ultrasound waves in the body is 1540 ms^{-1}, will the tumour be resolved in the ultrasound image?

Find the wavelength of the ultrasound by rearranging $v = f\lambda$:

$$\lambda = \frac{v}{f} = \frac{1540}{0.95 \times 10^6} = 962\,500$$
$$= 1.6210... \times 10^{-3} \text{ m}$$
$$= 1.6210... \text{ mm}$$

Take a look back at p.66 for a reminder on the wave equation.

The wavelength used is approximately half the size of the tumour, so the wavelength and tumour are similar in size. This means it is reasonable to assume that **the tumour will be resolved**.

Practice Questions

Q1 What is an interface?

Q2 What happens to a wave when it reaches an interface?

Q3 How is sonar similar to ultrasound scanning?

Q4 State and explain two things you can do to improve the clarity of an ultrasound image.

Q5 How long does the wavelength of ultrasound used to form an image need to be compared to the size of the object in order to be able to resolve it?

Exam Questions

Q1 Explain how pulse-echo techniques are used to image the inside of a patient's body, including what happens when waves meet an interface between media. [5 marks]

Q2 Explain why a transducer used in medical imaging produces pulses of ultrasound waves with the following properties:

a) A short wavelength. [3 marks]

b) A short pulse length and a long time between pulses. [4 marks]

Ultrasound — Mancunian for 'très bien'

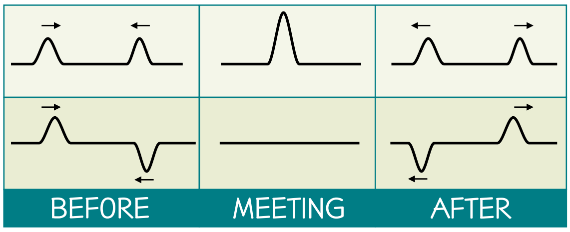
Next time you're watching TV and they show a pregnant woman having her unborn baby scanned, turn to the person you're sat next to and explain how the procedure works. You'll also be able to explain why they put a gel on their stomach first. Just make sure you know the person first before you launch into an explanation about transducers.

Superposition and Coherence

When two waves get together, it can be either really impressive or really disappointing.

Superposition *Happens When* ***Two*** *or* ***More*** *Waves* ***Pass Through*** *Each Other*

1) At the **instant** the waves **cross**, the **displacements** due to each wave **combine**. Then **each wave** goes on its merry way. You can **see** this if **two pulses** are sent **simultaneously** from each end of a rope.
2) The **principle of superposition** says that when two or more **waves cross**, the **resultant** displacement equals the **vector sum** of the **individual** displacements.



"**Superposition**" means "one thing on top of another thing". You can use the same idea in **reverse** — a **complex wave** can be separated out mathematically into **several simple** sine waves of various sizes.

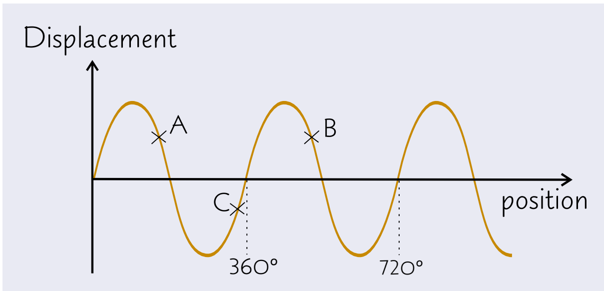
Interference *can be* ***Constructive*** *or* ***Destructive***

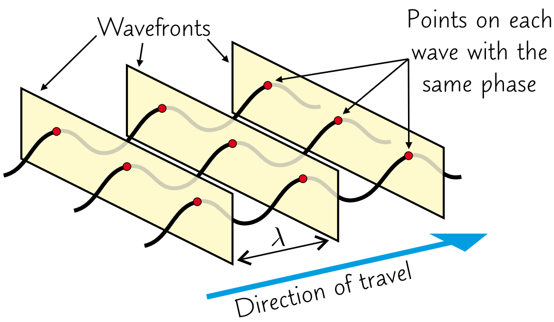
1) When two or more waves **superpose** with each other, the effect is called **interference**.
2) A **crest** plus a **crest** gives a **bigger crest**. A **trough** plus a **trough** gives a **bigger trough**. These are both examples of **constructive interference**.
3) A **crest** plus a **trough** of **equal size** gives... **nothing**. The two displacements **cancel each other out** completely. This is called **destructive interference**.
4) If the **crest** and the **trough** aren't the **same size**, then the destructive interference **isn't total**. For the interference to be **noticeable**, the two **amplitudes** should be **nearly equal**.

Graphically, you can superimpose waves by adding the individual displacements at each point along the *x*-axis, and then plotting them.

In ***Phase*** *Means In* ***Step*** *— Two Points* ***In Phase*** *Interfere* ***Constructively***

1) Two points on a wave are **in phase** if they are both at the **same point** in the **wave cycle**. Points in phase have the **same displacement** and **velocity**.
2) On the graph on the right, points **A** and **B** are **in phase**; points **A** and **C** are **out of phase**.
3) It's mathematically **handy** to show one **complete cycle** of a wave as an **angle of 360° (2π radians)**.
4) **Two points** with a **phase difference** of **zero** or a **multiple of 360°** are **in phase**.
5) **Points** with a **phase difference** of **odd-number multiples** of **180° (π radians)** are **exactly out of phase**.





6) You can also talk about two **different waves** being **in phase**. **In practice** this usually happens because **both** waves came from the **same oscillator**. In **other** situations there will nearly always be a **phase difference** between two waves.
7) Two or more waves that are **coherent** (see below), **in phase** and travelling in the **same direction** will have **wavefronts**. These are imaginary planes that cut **across** all the waves, joining up all the **points** that are **in phase** with each other. The **distance** between each wavefront is equal to one **wavelength**, i.e. each wavefront is at the same point in the **cycle**.

To Get ***Interference Patterns*** *the* ***Two Sources*** *Must Be* ***Coherent***

Interference **still happens** when you're observing waves of **different wavelength** and **frequency** — but it happens in a **jumble**. In order to get clear **interference patterns**, the two or more sources must be **coherent**.

Coherent sources — they have the **same wavelength** and **frequency** and a **fixed phase difference** between them.

Superposition and Coherence

Constructive or *Destructive* Interference Depends on the *Path Difference*

1) Whether you get **constructive** or **destructive** interference at a **point** depends on how **much further one wave** has travelled than the **other wave** to get to that point (assuming the sources are coherent and in phase).
2) The **amount** by which the path travelled by one wave is **longer** than the path travelled by the other wave is called the **path difference**.
3) At **any point an equal distance** from both sources you will get **constructive interference**. You also get constructive interference at any point where the **path difference** is a **whole number of wavelengths**, because the waves arrive at the same point **in phase**. At points where the path difference is an odd number of **half wavelengths**, the waves arrive **out of phase** and you get **destructive interference**.

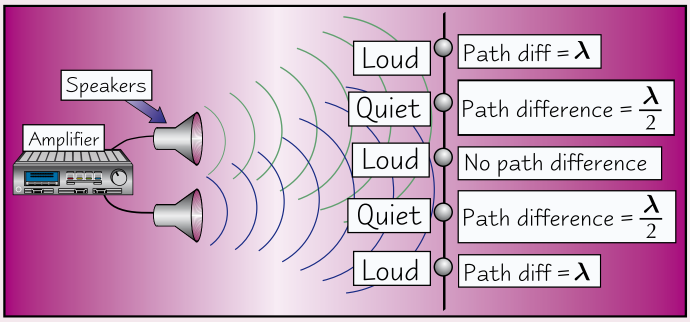
Constructive interference occurs when: **path difference = $n\lambda$ (where n is an integer)**

Destructive interference occurs when: **path difference = $\frac{(2n+1)\lambda}{2} = (n + \frac{1}{2})\lambda$**

If the sources are not in phase but are coherent, there will be constructive and destructive interference, but they will not occur at these path differences.

You Can *Observe Interference* With *Sound* Waves

1) Connect two **speakers** to the same oscillator (so the sound waves from them are **coherent** and **in phase**) and place them in line with each other.
2) Walk slowly across the room in front of them.
3) You will hear varying volumes of sound. At the points where the sound is **loudest**, the **path difference** is a **whole** wavelength.
4) The sound will be quietest at points where the path difference is an **odd** number of **half wavelengths**.



You may still hear some sound at the quietest points due to sound being reflected off walls and around the room.

Practice Questions

Q1 What is the principle of superposition?

Q2 If two points on a wave have a phase difference of 1440°, are they in phase?

Q3 What is a wavefront?

Q4 If there was a path difference of 5λ between two coherent, in phase waves, what kind of interference would occur?

Exam Questions

Q1 a) Two wave sources are coherent. Explain what this means. [2 marks]

b) Explain why you might have difficulty in observing interference patterns in an area affected by two waves from two sources even though the two sources are coherent. [1 mark]

Q2 Two waves from coherent sources meet and interfere. Which row of the table shows the correct type of interference that would occur with the stated phase and path difference? [1 mark]

	Phase Difference	Path Difference	Type of Interference
A	180°	λ	Constructive
B	180°	λ/2	Constructive
C	360°	λ	Destructive
D	360°	λ/2	Constructive

Learn this and you'll be in a super position to pass your exam...

...I'll get my coat.

A few crucial concepts here: a) interference can be constructive or destructive, b) you get constructive interference when the path difference is a whole number of wavelengths (for sources in phase), c) the sources must be coherent.

Stationary (Standing) Waves

Stationary waves are waves that... er... stand still... well, not still exactly... I mean, well... they don't go anywhere... um...

*You get Stationary Waves When a **Progressive Wave** is **Reflected** at a **Boundary***

A stationary wave is the **superposition** of **two progressive waves** with the **same wavelength**, moving in **opposite directions**.

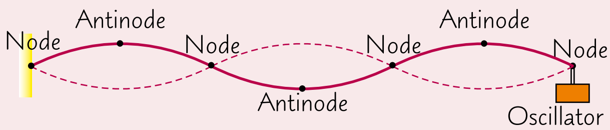
The progressive waves must also have the same speed and frequency.

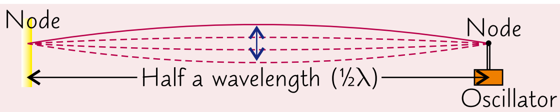
1) Unlike progressive waves, **no energy** is transmitted by a stationary wave.
2) You can demonstrate stationary waves by attaching a **vibration transducer** at one end of a **stretched string** with the other end fixed. The transducer is given a wave frequency by a **signal generator** and creates that wave by vibrating the string.
3) The wave generated by the vibration transducer is **reflected** back and forth.
4) For most frequencies the resultant **pattern** is a **jumble**. However, if you alter the **signal generator** so the **transducer** produces an **exact number of waves** in the time it takes for a wave to get to the **end** and **back again**, then the **original** and **reflected** waves **reinforce** each other.
5) At these **"resonant frequencies"** you get a **stationary** (or **standing**) **wave** where the **pattern doesn't move** — it just sits there, bobbing up and down. Happy, at peace with the world...

A sitting wave.

*Stationary Waves in **Strings** Form **Oscillating "Loops"** Separated by **Nodes***

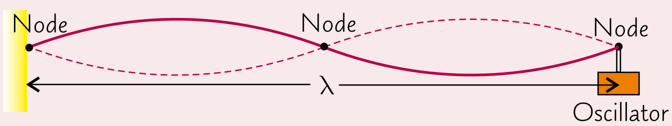
1) Each particle vibrates at **right angles** to the string.
2) **Nodes** are where the **amplitude** of the vibration is **zero**.
3) **Antinodes** are points of **maximum amplitude**.
4) At resonant frequencies, an **exact number** of **half wavelengths** fits onto the string.

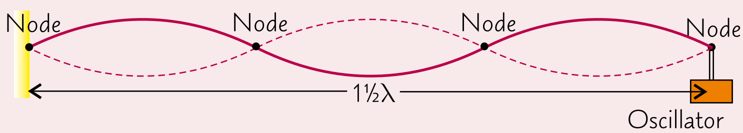




The standing wave above is vibrating at the **lowest possible** resonant frequency (the **fundamental mode of vibration** — also called the **first harmonic**). It has **one** "**loop**" with a **node at each end**.

This is the **second harmonic**. It is **twice** the **fundamental mode of vibration**. There are two "**loops**" with a **node** in the **middle** and **one at each end**.



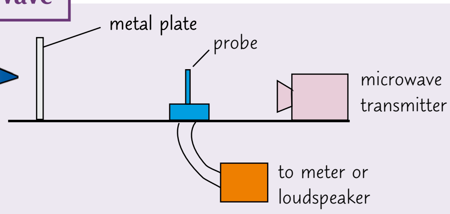


The **third harmonic** is **three times** the fundamental mode of vibration. **1½ wavelengths** fit on the string.

*You can **Demonstrate Stationary Waves** with Microwaves and Sounds*

Microwaves Reflected Off a Metal Plate Set Up a Stationary Wave

Microwave stationary wave apparatus

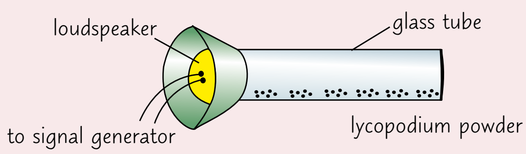


You can find the **nodes** and **antinodes** by moving the **probe** between the **transmitter** and **reflecting plate**.

Powder Can Show Stationary Waves in a Tube of Air

Stationary **sound** waves are produced in the **glass tube**.

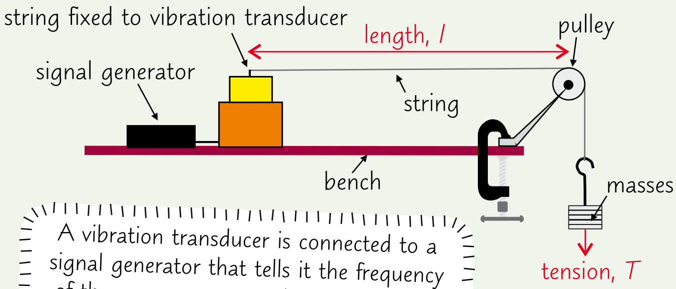
The lycopodium **powder** (don't worry, you don't need to know what that is) laid along the bottom of the tube is **shaken away** from the **antinodes** but left **undisturbed** at the **nodes**.



Stationary (Standing) Waves

You Can Investigate *Factors* Affecting the *Resonant Frequencies* of a String

1) Start by measuring the **mass** (M) and **length** (L) of strings of different types using a **mass balance** and a ruler. Then find the **mass per unit length** of each string (μ) using: $\boxed{\mu = \frac{M}{L}}$ The units of μ are kgm^{-1}



2) Set up the apparatus shown in the diagram with one of your strings. Record μ, measure and record the **length** (l) and work out the **tension** (T) using:

$\boxed{T = mg}$ where m is the total mass of the masses in kg

A vibration transducer is connected to a signal generator that tells it the frequency of the wave you want. A vibrating plate on the transducer creates the wave.

3) Turn on the **signal generator** and vary the frequency until you find the **first harmonic** — i.e. a stationary wave that has a **node** at each end and a single **antinode**. This is the **frequency** of the first harmonic, f.
4) The **wavelength** of the wave, λ, is given by $\lambda = 2l$ for the **fundamental mode frequency**. The **frequency**, f, and the **velocity** of the wave, v, for the first harmonic are:

$$\boxed{f = \frac{1}{2l}\sqrt{\frac{T}{\mu}}} \qquad \boxed{v = \sqrt{\frac{T}{\mu}}}$$

The equation for v is true for <u>any</u> transverse wave on a string.

You can investigate how the **length**, **tension** or **mass per unit length** of the string affects the **resonant frequency** by:

1) Keeping the string **type** (μ) and the **tension** (T) in it the same and altering the **length** (l). Do this by moving the **vibration transducer** towards or away from the pulley. Find the **first harmonic** again, and record f against l.
2) Keeping the string **type** (μ) and **length** (l) the same and **adding** or **removing masses** to change the tension (T). Find the first harmonic again and record f against T.
3) Keeping the **length** (l) and **tension** (T) the same, but using **different string** samples to vary μ. Find the first harmonic and record f against μ.

You can do this experiment with a different harmonic — just remember to use the same one throughout the experiment. You won't be able to use the equation for f though — this is just for the fundamental mode of vibration.

You should find the following from your investigation:

1) The **longer** the string, the **lower** the resonant frequency — because the **half wavelength** at the resonant frequency is longer.
2) The **heavier** (i.e. the more mass per unit length) the string, the **lower** the resonant frequency — because waves travel more **slowly** down the string. For a given **length** a **lower** wave speed, v, makes a **lower** frequency, f.
3) The **looser** the string the **lower** the resonant frequency — because waves travel more **slowly** down a **loose** string.

Practice Questions

Q1 How do stationary waves form?

Q2 Sketch the first three fundamental modes of vibration of a standing wave on three different diagrams.

Q3 At four times the frequency of the first harmonic, how many half wavelengths would fit on a violin string?

Q4 How does the displacement of a particle at one antinode compare to that of a particle at another antinode?

Exam Questions

Q1 A string of fixed length 2.8 m is oscillating at its fundamental mode of vibration. Calculate the mass of the string if the standing wave has velocity 16 ms^{-1} and the tension on the string is 3.2 N. [2 marks]

Q2 A stationary wave at the first harmonic frequency, 10 Hz (to 2 s.f.), is formed on a stretched string of length 1.2 m.

a) Calculate the wavelength of the wave. [2 marks]

b) The tension is doubled whilst all other factors remain constant. The frequency is adjusted to once more find the first harmonic of the string. Calculate the new frequency of the first harmonic. [3 marks]

c) Explain how the variation of amplitude along the string differs from that of a progressive wave. [2 marks]

Don't get tied up in knots...

Remember — the lowest frequency at which a standing wave is formed is the fundamental mode of vibration.

Refractive Index

The stuff on the next two pages explains why your legs look short in a swimming pool.

***Refraction** Occurs When the **Medium** a Wave is Travelling in Changes*

Refraction is the way a wave **changes direction** as it enters a **different medium**. The change in direction is a result of the wave **slowing down** or **speeding up**. You can tell if the wave is speeding up or slowing down by the way it **bends towards** or **away** from the normal.

1) If a light ray bends **towards** the normal — it is **slowing** down. The ray is going from a **less** optically dense material to a **more** optically dense material.
2) If the ray bends **away** from the normal — the wave is **speeding up**. It is going from an optically **denser** material to a **less** optically dense material.
3) The speed changes because the **wavelength** of the wave is changing and the **frequency** stays **constant** ($v = f\lambda$).

The more optically dense material will have a higher refractive index (see below).

If light travels from a **less** optically dense material to a **more** optically dense material, the wave **slows down**, the **wavelength decreases** and the **frequency** stays the **same**.

*The **Refractive Index** of a Material Measures **How Much** It Slows Down Light*

Light goes fastest in a **vacuum**. It **slows down** in other materials, because it **interacts** with the particles in them. The more **optically dense** a material is, the more light **slows down** when it enters it.

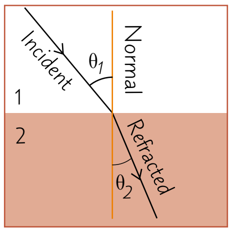
The **refractive index** of a material, n, is the **ratio** between the **speed of light** in a **vacuum**, c, and the speed of light in that **material**, v.

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

$c = 3.00 \times 10^8\ \text{ms}^{-1}$.

The speed of light in air is only a tiny bit smaller than c. So you can assume the refractive index of air is 1.

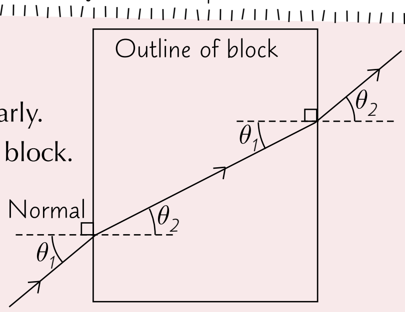
***Snell's Law** uses **Angles** to Calculate the Refractive Index*



1) The **angle** the **incoming light** makes to the **normal** is called the **angle of incidence**, θ_1. The **angle** the **refracted ray** makes with the **normal** is the **angle of refraction**, θ_2.
2) The light is crossing a **boundary**, going from a medium with **refractive index** n_1 to a medium with refractive index n_2.
3) When light enters an **optically denser** medium it is refracted **towards** the normal.
4) n_1, n_2, θ_1 and θ_2 are related by **Snell's law**: $\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$

You can use a **ray box** to find the **refractive index** of a glass block:

You can do this experiment to find the refractive index of any solid, transparent material.



1) Place a glass block on a piece of paper and draw around it.
2) Use the ray box to shine a beam of light into the glass block. Turn off any other lights so you can see the path of the light beam through the block clearly.
3) **Trace** the path of the **incoming** and **outgoing** beams of light either side of the block.
4) Remove the block and join up the two paths you've drawn with a **straight line** that follows the path the light beam took through the glass block. You should be able to see from your drawing how the path of the ray **bent** when entering and leaving the block.
5) Measure the angles of incidence (θ_1) and refraction (θ_2) where the light enters and exits the block. Air is **less** optically dense than glass, so as the light **enters** the glass block it **bends towards** the normal ($\theta_1 > \theta_2$) as it **slows down**. The beam should **bend away** from the normal as it **exits** the block ($\theta_2 > \theta_1$) and **speeds up**.
6) Rearrange **Snell's law** to make the refractive index of the **material** the subject, and substitute in $n = 1$ for **air** and the values you found for θ_1 and θ_2 to calculate a value for n.
7) The **percentage uncertainty** (see p.10) in your measurements for θ_1 and θ_2 will be **smaller** for **larger angles**, so it's better to do the experiment at large angles and then **repeat** the experiment to find an **average** of your results.
8) Your result should be more **precise** (see p.12) if you use a **narrower** beam of light as the **uncertainty** in the **position** of the beam will be lower.

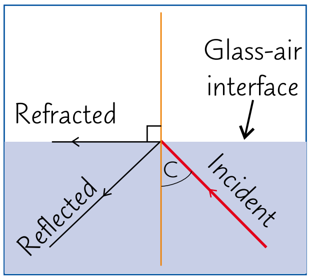
Alternatively, you could plot a graph of $\sin\theta_1$ against $\sin\theta_2$. The gradient of the graph will be equal to the refractive index of the material.

Refractive Index

When the Angle of Refraction is a Right Angle, the Angle of Incidence is Critical

When light **goes from** an optically dense material into an optically **less dense** material (e.g. glass to air), interesting things can start to happen.

Shine a ray of light at a **glass to air** boundary, then gradually **increase** the angle of incidence. As you increase the angle of incidence, the angle of **refraction** gets closer and closer to **90°**. Eventually the angle of incidence, θ_1 reaches a **critical angle** C for which the angle of refraction, $\theta_2 = 90°$. The light is refracted **along the boundary**.



At angles of incidence **greater than** C, refraction is **impossible**. That means **all** the light is reflected back into the material. This effect is called **total internal reflection**.

For light hitting a **material-to-air boundary** (assuming the material is more optically **dense**) at the critical angle, **Snell's law** simplifies to become:

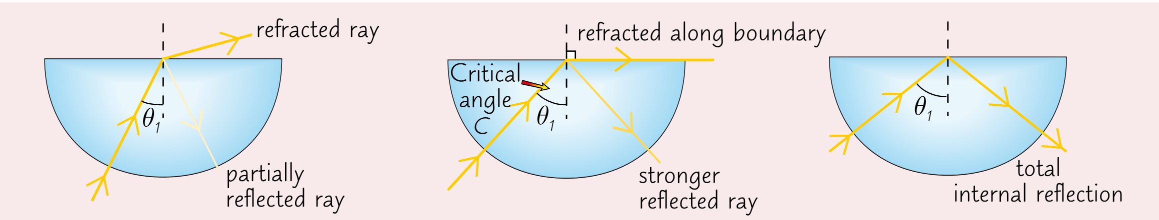
$$\sin C = \frac{1}{n}$$

This happens because $n_{air} = 1$ and $\sin(90°) = 1$. n is the refractive index of the material.

You can Investigate Critical Angles and Total Internal Reflection with Glass Blocks

1) Shine a light ray into the **curved face** of a semi-circular glass block so that it always enters at **right angles** to the edge — this means the ray won't **refract** as it enters the block, just when it leaves from the straight edge.
2) Vary the angle of **incidence**, θ_1, until the light beam refracts so much that it exits the block along the **straight edge**. This angle of incidence is the **critical angle**, C, for glass-air boundary.
3) If you increase the angle of incidence so it's **greater** than C, you'll find the ray is reflected from the straight edge of the block.

You can rearrange the formula for the critical angle above and put in your value for C to find the refractive index of the block.



Here the angle of incidence is **less** than the critical angle

Here the angle of incidence is **equal** to the critical angle

Here the angle of incidence is **greater** than the critical angle.

Practice Questions

Q1 What happens to the wavelength of light as it passes from water into air?

Q2 Why does light go fastest in a vacuum and slow down in other media?

Q3 Diamond has a higher refractive index than sapphire. Is total internal reflection possible for light travelling in sapphire when it meets a sapphire-diamond interface?

Q4 Describe an experiment you could do to determine the critical angle of a boundary between a material and air.

Exam Questions

Q1 a) Light travels in diamond at 1.24×10^8 ms^{-1}. What is the refractive index of diamond? [1 mark]

b) Calculate the angle of refraction if light strikes a facet of a diamond ring at an angle of exactly 50° to the normal of the air/diamond boundary. [2 marks]

Q2 An adjustable underwater spotlight is placed on the floor of an aquarium tank. When the light points upwards at a steep angle a beam comes through the surface of the water into the air, and the tank is dimly lit. When the spotlight is placed at a shallower angle, no light comes up through the water surface, and the tank is brightly lit.

a) Explain what is happening. [2 marks]

b) It is found that the beam into the air disappears when the spotlight is pointed at any angle of less than 41.25° to the floor. Calculate the refractive index of water. [2 marks]

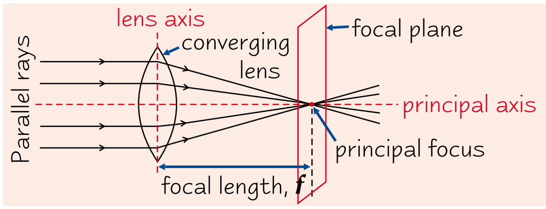
Critical angles are never happy...

Total internal reflection doesn't sound like the most riveting subject, but it's super useful. Optical fibres wouldn't work without it, and we use them for all sorts of things — broadband connections, telephone cables, making things sparkly...

Lenses

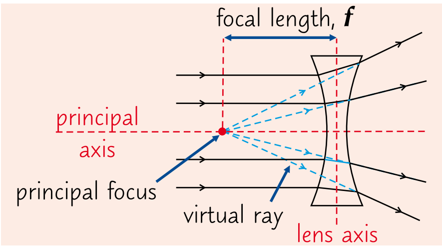
Lenses are pretty useful — they're used in glasses to help you see, they're used in telescopes to help you see, they're used in magnifying glasses to help you see, they're used in your eyes to help... you get the picture.

Converging Lenses Bring Light Rays ***Together***



1) **Lenses** change the **direction** of light rays by **refraction**.
2) **Converging** lenses bulge **outwards**.
3) Rays **parallel** to the **principal axis** of the lens converge onto a point called the **principal focus**. Parallel rays that **aren't** parallel to the principal axis converge somewhere else on the **focal plane** (see diagram).
4) The **focal length**, f, is the distance between the **lens axis** and the **focal plane**.
5) f is **positive** for a **converging** lens because it is **in front of** the lens.

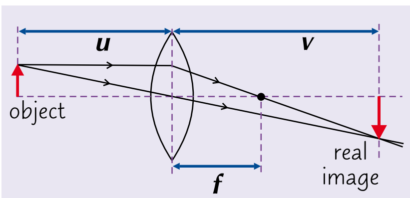
Diverging Lenses Spread Light Rays ***Out***

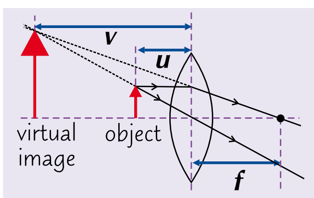


1) **Diverging** lenses cave **inwards**.
2) The **principal focus** of a diverging lens is at a point **behind** the lens.
3) The principal focus is the point that rays from a **distant** object, assumed to be parallel to the principal axis, **appear** to have come from. The dotted lines in the diagram show **virtual rays**. The light **doesn't** actually follow this path, but **appears** to have done so.
4) The **focal length**, f, is the distance between the **lens axis** and the **principal focus**.
5) f is **negative** for a **diverging** lens because it is **behind** the lens.

Images can be ***Real*** or ***Virtual***

1) A **real image** is formed when light rays from a point on an object are made to **pass through** another point in space. The light rays are **actually there**, and the image can be **captured** on a **screen**.
2) A **virtual image** is formed when light rays from a point on an object **appear** to have come from another point in space. The light rays **aren't really where the image appears to be**, so the image **can't** be captured on a screen.
3) Converging lenses can form both **real** and **virtual** images, depending on where the object is. If the object is **further** than the **focal length** away from the lens, the image is **real**. If the object's **closer**, the image is **virtual**.
4) To work out where an image formed by a converging lens will appear, you can draw a **ray diagram**. Draw **two rays** from the same point on the object (the top is best) one **parallel** to the principal axis that passes through the **principal focus**, and one passing through the **centre** of the lens that **doesn't get refracted** (bent). The image will form where the **two rays meet** if the image is real. If the rays don't meet, the image is **virtual**. **Extend** the rays back (draw **virtual rays**) to locate where the two rays appear to have **come from**:

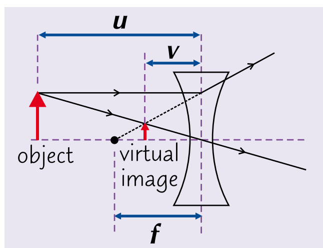




If an object sits on the principal axis, so will the image.

In the diagram, u = distance between object and lens axis, v = distance between image and lens axis (**positive** if image is **real**, **negative** if image is **virtual**), f = focal length.

5) A diverging lens will **always** form a virtual image — the **position** of the **object** in relation to the **focal length** will not affect the **type** of image formed.
6) To draw a **ray diagram** for a diverging lens, draw **two rays** from the same point on the object. One must pass through the **centre** of the lens without getting refracted. The other travels **parallel** to the **principal axis** until it meets the centre of the lens. Then it **refracts** so that it **appears** to come from the **principal focus**. The image will form where the real and virtual rays **meet**.
7) The values u, v and f are related by the **lens equation**:



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

This equation only works for thin lenses.

Lenses

Power Tells You How Much a Lens **Bends** Light

1) You can calculate the **power** of a lens, which tells you the lens' ability to **bend light**. The higher the power, the more the lens will **refract** light.

$$P = \frac{1}{f}$$

where P is the power of the lens in dioptres (D).

2) Imagine you have two or more **thin** lenses in a line, with their principal axes lined up. If the lenses are **touching** or are very **close together**, the **total power** of the lenses is found by just **adding** all the powers together — how simple.

$$P = P_1 + P_2 + P_3 + ...$$

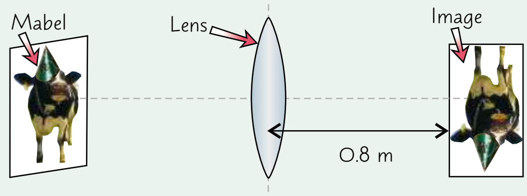
Example: An image of Mabel the cow is being projected onto a screen 80 cm from a 3.25 D converging lens. How far must the picture slide of Mabel be from the lens?

$P = \frac{1}{f} = 3.25$ D, and the image must be real as it is captured on a screen, so $v = 80$ cm $= 0.8$ m.

Rearrange the lens equation: $\frac{1}{u} = \frac{1}{f} - \frac{1}{v} = 3.25 - \frac{1}{0.8}$
$= 3.25 - 1.25 = 2$

$u = \frac{1}{2} = 0.5$ m,

so the slide must be **0.5 m** from the lens.



A Lens Can Produce a **Magnified Image**

Magnification is a ratio and so has no units.

The magnification, m, of an image can be calculated in two different ways. They are:

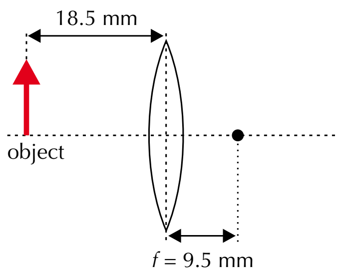
$$m = \frac{\text{image height}}{\text{object height}}$$

$$m = \frac{v}{u}$$

Practice Questions

Q1 Define the focal length and power of a converging lens.

Q2 Draw a ray diagram for the converging lens and object shown on the right. State whether the image formed is real or virtual.



Q3 State whether real or virtual images are produced by diverging lenses.

Q4 Write an equation to show how the object distance (u), image distance (v) and focal length of a thin lens (f) are related.

Q5 A diverging lens has a magnification of 3.4. An image of an object created by the lens is 12.8 cm wide. How wide is the object?

Exam Questions

Q1 a) Define the principal focus of a converging lens. [1 mark]

b) An object was placed 0.20 m in front of a converging lens of focal length 0.15 m. Calculate how far behind the lens the image was formed. [2 marks]

Q2 The length of a seed is 12.5 mm. A lens is placed in front of the seed, so that the principal axis of the lens is parallel to the seed. An image of the seed is projected onto a screen. The image has a length of 47.2 mm.

a) Calculate the linear magnification of the lens. [1 mark]

b) If the seed is 4.0 mm from the lens, calculate how far the screen is from the lens. [2 marks]

c) Calculate the power of the lens in dioptres. [2 marks]

d) A second lens is placed directly after the first lens. The focal length of the combined lenses is 0.22 cm. Calculate the power of the second lens. [2 marks]

The physics is real, the fun is virtual...

Ray diagrams might look complicated, but once you've practised them a few times it'll all be a doddle. Or a doodle...

Diffraction

Diffraction is some funky stuff — it's all about waves squeezing through spaces and then spreading out. Kind of like whipped cream from a can. Actually, it's nothing like that... read the pages and learn some stuff.

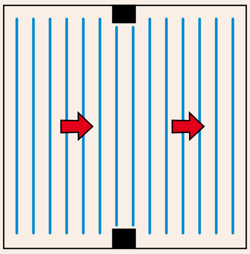
Waves Go **Round Corners** and **Spread out** of **Gaps**

The way that **waves spread out** as they come through a **narrow gap** or go round obstacles is called **diffraction**. **All** waves diffract, but it's not always easy to observe. The amount of diffraction depends on the **size of the gap** in comparison to the **wavelength** of the wave.

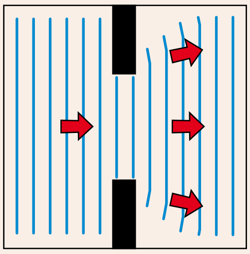
You Can Use a **Ripple Tank** to Investigate **Diffraction**

Take a look back at p.74 for a reminder on what a wavefront is.

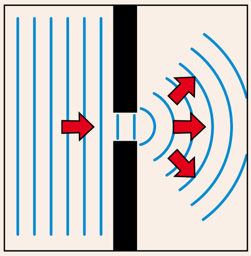
1) **Ripple tanks** are shallow tanks of water that you can generate a wave in.
2) This is done by an **oscillating paddle**, which continually dips into the water and creates regular waves with straight, parallel wavefronts.
3) Objects are then placed into the ripple tank to create a **barrier** with a **gap** in the middle of it.
4) This gap can be varied to see the effects this has on how the waves spread through the tank.



When the gap is a lot bigger than the wavelength, diffraction is unnoticeable.



You get noticeable diffraction through a gap several wavelengths wide.



You get the most diffraction when the gap is the same size as the wavelength.

As the gap decreases, the diffraction becomes more noticeable until the gap becomes too small and the water waves cannot pass through it anymore. The waves are then **reflected** back on themselves.

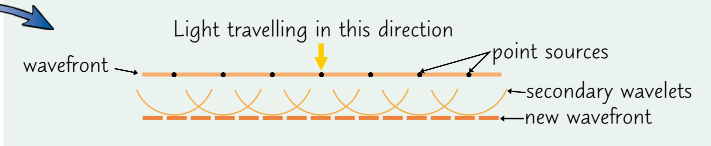
When sound passes through a doorway, the size of gap and the wavelength are usually roughly equal, so a lot of diffraction occurs. That's why you have no trouble hearing someone through an open door to the next room, even if the other person is out of your line of sight. The reason that you can't see him or her is that when light passes through the doorway, it is passing through a gap around a hundred million times bigger than its wavelength — the amount of diffraction is tiny.

Diffraction can be **Explained** Using **Huygens' Construction**

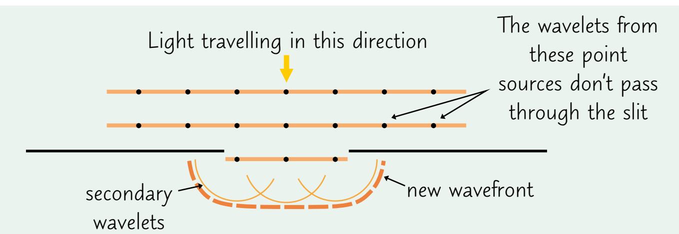
1) Huygens developed a **general model** of the propagation of **waves** in what is now known as **Huygens' construction**:

HUYGENS' CONSTRUCTION: Every point on a wavefront may be considered to be a point source of secondary wavelets that spread out in the forward direction at the speed of the wave. The new wavefront is the surface that is tangential to all of these secondary wavelets.

This diagram shows how this works:

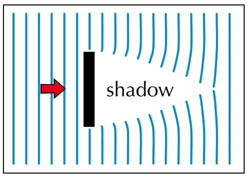


2) Huygens' construction can be used to explain the shape of the wavefronts as light travels through a **slit**. The **secondary wavelets** that pass through the slit are what produce the curve of the **new wavefront** emerging from the slit.



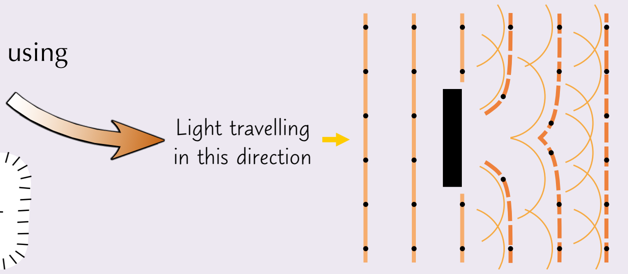
Diffraction

You Get *Diffraction* Around an *Obstacle* Too



When a wave meets an **obstacle**, you get diffraction around the edges. Behind the obstacle is a '**shadow**', where the wave is blocked. The **wider** the obstacle compared with the wavelength of the wave, the less diffraction you get, and so the **longer** the shadow.

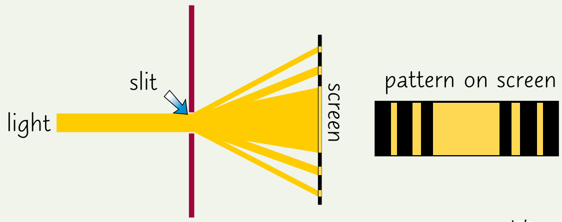
This can also be shown using Huygens' construction:



This diagram looks more complicated than the ones on p.82, but don't panic — exactly the same principles apply here.

With *Light Waves* you get a Pattern of *Light* and *Dark Fringes*

1) If the **wavelength** of a **light wave** is roughly similar to the size of the **aperture**, you get a **diffraction pattern** of light and dark fringes.
2) The pattern has a **bright central fringe** with alternating **dark and bright fringes** on either side of it.
3) The **spread** of the diffraction pattern depends on the **relative sizes** of the wavelength and the slit width. The **longer** the wavelength is **compared** to the **width** of the slit, the **wider** the diffraction pattern.



You need to use a coherent light source (page 74) for this experiment.

Practice Questions

Q1 What is diffraction?

Q2 For a long time some scientists argued that light couldn't be a wave because it did not seem to diffract. Suggest why they might have got this impression.

Q3 Light passes through a slit that is a few wavelengths wide. Use Huygens' construction to explain the shape of the wavefronts of the light as they emerge from the other side of the slit.

Q4 Sketch what happens when plane waves meet an obstacle about as wide as one wavelength.

Q5 Light passing through a slit produces a diffraction pattern. State what effect decreasing the wavelength of the light would have on the width of the diffraction pattern.

Exam Questions

Q1 A mountain lies directly between you and a radio transmitter.
Explain, with the use of a diagram, why you can pick up long-wave radio broadcasts from the transmitter but not short-wave radio broadcasts. [3 marks]

Q2 Describe how you would use a ripple tank to investigate how the wavelength of a wave and the size of the gap a wave travels through relates to the amount of diffraction which occurs. Comment on when maximum diffraction will be seen. [3 marks]

Even hiding behind a mountain, you can't get away from long-wave radio...

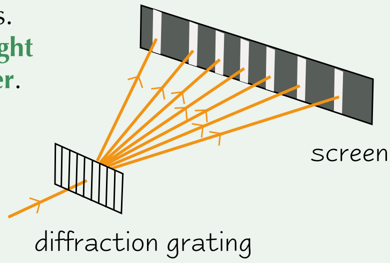
Unfortunately "Bay FM" don't transmit using long wave radio. So as I'm giving the singing-in-the-car performance of my life, I go over a hill and the signal cuts out. Where's diffraction when I need it then hmm? How will I ever become famous? Diffraction crops up again in stuff like quantum physics so make sure you really understand it.

Diffraction Gratings

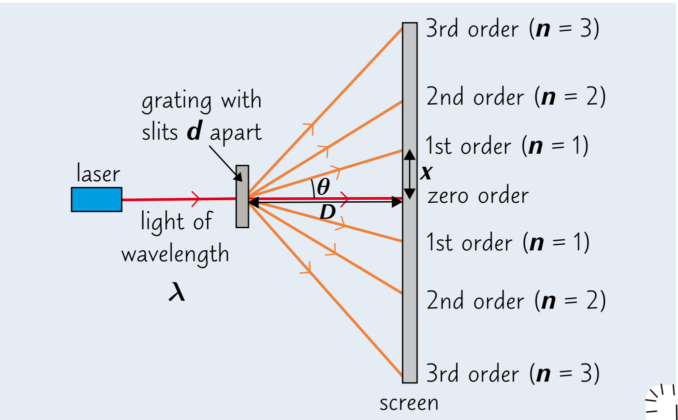
What could possibly be more exciting than shining a laser through two slits? Shining a laser through more than two slits of course. Jeez, ask a stupid question...

Interference Patterns Get **Sharper** When You Diffract Through **More Slits**

1) You saw on pages 74-75 that **two sources** that produce waves that are **coherent** and **in phase** will result in an **interference pattern** (alternating bands of constructive and destructive interference). If you are using **light waves**, you can pass one **monochromatic** (one wavelength) **beam of light** through **two slits**. The slits are cut into the **same** piece of material, so that the wave passes through them at the **same time**. The light **diffracts** at both slits, producing two coherent sources of light. The interference pattern is made up of alternating **dark bands** and **light bands**.
2) You can repeat this experiment with **more than two equally spaced** slits. You get basically the **same shaped** pattern as for two slits — but the **bright bands** are **brighter** and **narrower** and the **dark areas** between are **darker**.
3) When **monochromatic light** is passed through a **grating**, which has **hundreds** of slits per millimetre, the interference pattern is **really sharp** because there are so **many beams reinforcing** the **pattern**.
4) Sharper fringes make for more **precise** measurements as they are easier to tell apart and so are **easier** to measure.



Measurements Can be Made from **Interference Patterns**



1) For monochromatic light, all of the maxima are sharp lines. (It's different for white light — see the next page).
2) This means the distance between the maxima can be easily measured (**fringe width**).
3) There's a line of **maximum brightness** at the centre called the **zero order** line.
4) The lines just **either side** of the central one are called **first order lines**. The **next pair out** are called **second order** lines and so on.

If the grating has N slits per metre, then the slit spacing, d, is just $1/N$ metres.

Measuring the Wavelength of Light using a Diffraction Grating

1) Position a **laser** (or other monochromatic light source) in front of a **diffraction grating** so that the light travels through the grating and creates an interference pattern on a **flat wall** or **screen** a few metres away.
2) Measure the **distance**, ***D***, between the diffraction grating and the wall.
3) Measure the **distance**, ***x***, between the **zero order maximum** and the **1st order maximum** for both sides and take an **average** of the two readings.
4) Using the **fringe width**, ***x***, and the distance to the wall, ***D***, the angle the 1st order fringe makes with the zero order line can be calculated using **small angle approximations**.

Make sure the light is travelling at right angles to the diffraction grating and wall.

Don't forget to set your calculator to radians when using this equation.

$$\boxed{\tan\theta \approx \theta \text{ and } \tan\theta = \frac{x}{D}, \text{ so } \boldsymbol{\theta \approx \frac{x}{D}}}$$

The value for d is usually given on the grating. Don't forget that n = 1 for the zero order line.

5) You can then use the following **equation** to **calculate** the **wavelength** of light: $\boxed{\boldsymbol{d \sin\theta = n\lambda}}$
6) **Repeat** the measurements for more **order lines** to find an **average** for the wavelength.
7) Repeat the experiment for a diffraction grating that has a **different distance** between the **slits**.

Diffraction Gratings

You can Draw **General Conclusions** from **d sin θ = nλ**

1) If λ is **bigger**, **sin θ** is **bigger**, and so **θ** is **bigger**. This means that the larger the **wavelength**, the more the pattern will **spread out**.
2) If **d** is **bigger**, **sin θ** is **smaller**. This means that the **coarser** the **grating**, the **less** the pattern will **spread out**.
3) Values of **sin θ** greater than **1** are **impossible**. So if for a certain **n** you get a result of **more than 1** for **sin θ** you know that that order **doesn't exist**.

Shining **White Light** Through a **Diffraction Grating** Produces **Spectra**

1) **White light** is really a **mixture** of **colours**. If you **diffract** white light through a **grating** then the patterns due to **different wavelengths** within the white light are **spread out** by **different** amounts.
2) Each **order** in the pattern becomes a **spectrum**, with **red** on the **outside** and **violet** on the **inside**. The **zero order maximum** stays **white** because all the wavelengths just pass straight through.

3) **Astronomers** and **chemists** often need to study spectra to help identify elements. They use diffraction gratings rather than prisms because they're **more accurate**.
4) Another example of white light being **split** into a spectrum due to diffraction can be seen on **CDs** and **DVDs**. There are **grooves** etched into the **reflective surface**, which causes the light to **diffract**. Constructive interference occurs at different points for light with different wavelengths, so you end up seeing a **rainbow pattern**.

Practice Questions

Q1 Why do more slits in a diffraction grating lead to a sharper diffraction pattern?

Q2 What is the formula for finding the wavelength of light incident on a diffraction grating?

Q3 A beam of light is diffracted through a diffraction grating. State what will happen to the diffraction pattern if the wavelength of the light decreases.

Q4 Describe an experiment to find the wavelength of monochromatic light using a diffraction grating.

Exam Questions

Q1 Yellow laser light of wavelength 6.00×10^{-7} m is transmitted through a diffraction grating of 4.0×10^5 lines per metre.

a) State the angle to the normal where the first and second order bright lines are seen. [4 marks]

b) State whether there is a fifth order line. Explain your answer. [1 mark]

Q2 Visible, monochromatic light is transmitted through a diffraction grating of 3.70×10^5 lines per metre. The first order maximum is at an angle of 14.2° to the incident beam.

Calculate the wavelength of the incident light. [2 marks]

Oooooooooooo — pretty patterns...

Yes, it's the end of another beautiful topic. Three important points for you to take away — the more slits you have, the sharper the image, monochromatic light leads to sharp fringes and one lovely equation to get to know. Make sure you get everything in this topic — there's some good stuff waiting in the next one and I wouldn't want you to be distracted.

Light — Wave or Photon?

You probably already thought light was a bit weird — but oh no... being a wave that travels at the fastest speed possible isn't enough for light — it has to go one step further and act like a particle too...

Light Behaves Like a **Wave**... or a **Stream of Particles**

1) In the **late nineteenth century**, if you asked what light was, scientists would happily show you lots of nice experiments showing how light must be a **wave**.
2) Light produces **interference** and **diffraction** patterns — **alternating bands** of **dark** and **light**. These patterns can **only** be explained using **waves**.
3) That was all fine and dandy... until the **photoelectric effect** (p.88), which mucked up everything. The only way you could explain this effect was if light acted as a **particle** — called a **photon**.

Take a look back at p.82-85 for a reminder on interference and diffraction.

A **Photon** is a **Quantum** of **EM Radiation**

1) When Max Planck was investigating **black body radiation** (don't worry — you don't need to know about that right now), he suggested that **EM waves** can **only** be **released** in **discrete packets**, called **quanta**. A single packet of **EM radiation** is called a **quantum**.

   The **energy carried** by one of these **wave-packets** had to be:

   $$\boxed{E = hf = \frac{hc}{\lambda}}$$

   where h = Planck constant = 6.63×10^{-34} Js, f = frequency (Hz), λ = wavelength (m) and c = speed of light in a vacuum = 3.00×10^{8} ms^{-1}

2) So, the **higher** the **frequency** of the electromagnetic radiation, the more **energy** its wave-packets carry.
3) **Einstein** went **further** by suggesting that **EM waves** (and the energy they carry) can only **exist** in discrete packets. He called these wave-packets **photons**.
4) He believed that a photon acts as a **particle**, and will either transfer **all** or **none** of its energy when interacting with another particle, e.g. an electron.
5) Photons have **no charge** — they are **neutral**, like neutrons.

Electrons in **Atoms** Exist in **Discrete Energy Levels**

1) **Electrons** in an **atom** can **only exist** in certain **well-defined energy levels**. Each level is given a **number**, with **n = 1** representing the **ground state**.
2) Electrons can **move down** energy levels by **emitting** a **photon**.
3) Since these **transitions** are between **definite energy levels**, the **energy** (and therefore the **frequency**) of **each photon** emitted can **only** take a **certain allowed value**.
4) The diagram on the right shows the **energy levels** for **atomic hydrogen**.
5) The **energies involved** are **so tiny** that it makes sense to use a more **appropriate unit** than the **joule**. When you **accelerate** an electron between two electrodes, it transfers some electrical potential energy (eV) into kinetic energy.

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

   e is the size of the charge on an electron: 1.60×10^{-19} C. See page 43.

6) The **electronvolt (eV)** is defined as:

   > The **kinetic energy carried** by an **electron** after it has been **accelerated** through a **potential difference** of **1 volt**.

   So 1 electron volt = $e \times V = 1.60 \times 10^{-19}$ C $\times$ 1 JC^{-1}.

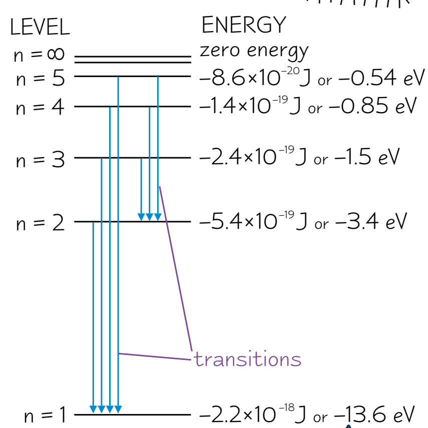
   $$\boxed{1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}}$$

7) On the diagram, energies are labelled in **both units** for **comparison's** sake.
8) The **energy** carried by each **photon** is **equal** to the **difference in energies** between the **two levels**. The equation below shows a **transition** between a higher energy level n = 2 where the electrons have energy E_2 and a lower energy level n = 1 with electrons of energy E_1:

   $$\boxed{\Delta E = E_2 - E_1 = hf = \frac{hc}{\lambda}}$$

9) Electrons can also **move up** energy levels if they **absorb a photon** with the **exact energy difference** between the two levels. The movement of an electron to a higher energy level is called **excitation**.

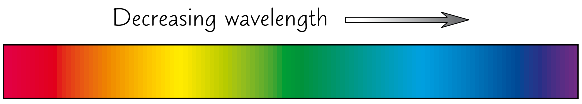
The ground state is the lowest energy state of the atom.



The energies are only negative because of how "zero energy" is defined. Just one of those silly convention things — don't worry about it.

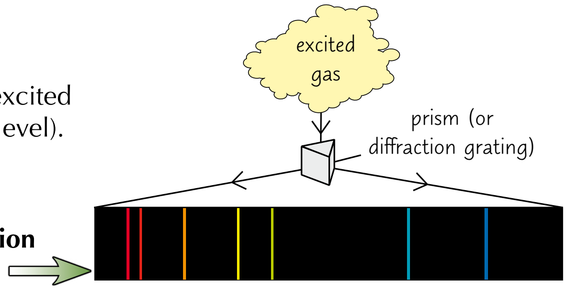
Light — Wave or Photon?

Continuous Spectra Contain All Possible Wavelengths



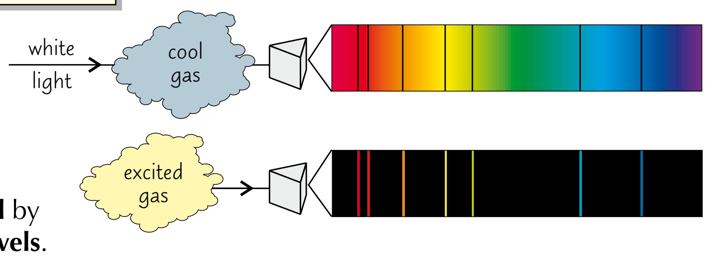
1) The **spectrum** of **white light** is **continuous**.
2) If you **split** the **light** up with a **prism**, the **colours** all **merge** into each other — there **aren't** any **gaps** in the spectrum.

Hot Gases Produce Line Emission Spectra



1) If you heat a gas to a **high temperature**, the **atoms** become excited (one or more of their **electrons** is moved to a **higher** energy level).
2) As electrons within the atoms **fall** back to the **lower energy levels**, they **emit energy** as **photons** (see previous page).
3) If you **split** the light from a **hot gas** with a **prism** or a **diffraction grating** (see pages 84-85), you get a **line emission spectrum**.
4) A line emission spectrum is seen as a **series** of **bright lines** against a **black background**, as shown above.
5) Each **line** on the spectrum corresponds to a **particular wavelength** of light **emitted** by the source. Since only **certain photon energies** are **allowed**, you only see the **corresponding wavelengths**.

Cool Gases Produce Line Absorption Spectra



1) You get a **line absorption spectrum** when **white light** passes through a cool gas and then a **diffraction grating** or **prism**.
2) At **low temperatures**, **most** of the **electrons** in the **gas atoms** will be in their **ground states**.
3) **Photons** of the **correct wavelength** are **absorbed** by the **electrons** to **excite** them to **higher energy levels**.
4) These **wavelengths** are then **missing** from the **continuous spectrum** when it **comes out** the other side of the gas.
5) You see a **continuous spectrum** with **black lines** in it corresponding to the **absorbed wavelengths**.
6) If you **compare** the **absorption** and **emission spectra** of a **particular gas**, the **black lines** in the **absorption spectrum match up** to the **bright lines** in the **emission spectrum**.

Practice Questions

Q1 Give two different ways to describe the nature of light.

Q2 What is a photon?

Q3 Write down the two formulas you can use to find the energy of a photon. Define all the symbols you use.

Q4 What is an electronvolt? What is 1 eV in joules?

Q5 Describe line absorption and line emission spectra. How are these two types of spectra produced?

Exam Question

Q1 An electron is accelerated through a potential difference of 12.1 V.

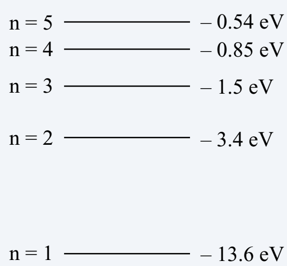
a) How much kinetic energy has it gained in i) eV and ii) joules? [2 marks]

b) This electron hits a hydrogen atom in its ground state and excites it.

i) Explain what is meant by excitation. [1 mark]

ii) Using the energy values on the right, calculate which energy level the electron from the hydrogen atom is excited to. [1 mark]

iii) Calculate the energies and frequencies of all the photons that might be emitted as the electron returns to its ground state. [6 marks]



Light can be a particle — well that's a twist in the tale...

Physics is just ridiculous sometimes. But learn it you must — get your head around those energy levels in atoms folks.

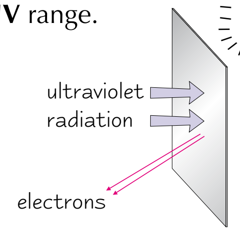
The Photoelectric Effect

I think they should rename 'the photoelectric effect' as 'the piece-of-cake effect' — it's not easy, I just like cake.

Shining Light** on a **Metal** can **Release Electrons

If you shine **light** of a **high enough frequency** onto the **surface of a metal**, the metal will **emit electrons**. For **most** metals, this **frequency** falls in the **UV** range.

1) **Free electrons** on the **surface** of the metal **absorb energy** from the light.
2) If an electron **absorbs enough** energy, the **bonds** holding it to the metal **break** and the electron is **released**.
3) This is called the **photoelectric effect** and the electrons emitted are called **photoelectrons**.



'Light' means any EM radiation — not just visible light.

You don't need to know the details of any experiments on this, you just need to learn the three main conclusions:

Conclusion 1 For a given metal, **no photoelectrons are emitted** if the radiation has a frequency **below** a certain value — called the **threshold frequency**.

Conclusion 2 The photoelectrons are emitted with a variety of kinetic energies ranging from zero to some maximum value. This value of **maximum kinetic energy** increases with the **frequency** of the radiation, and is **unaffected** by the **intensity** of the radiation.

Conclusion 3 The **number** of photoelectrons emitted per second is **proportional** to the **intensity** of the radiation.

These are the two that had scientists puzzled. They can't be explained using wave theory.

Intensity is the power (the energy transferred per second) hitting a given area of the metal (see page 69).

*The **Photoelectric Effect Couldn't** be Explained by **Wave Theory**...*

According to wave theory:

1) For a particular frequency of light, the **energy** carried is **proportional** to the **intensity** of the beam.
2) The energy carried by the light would be **spread evenly** over the wavefront.
3) **Each** free electron on the surface of the metal would gain a **bit of energy** from each incoming wave.
4) Gradually, each electron would gain **enough energy** to leave the metal.

SO... The **higher the intensity** of the wave, the **more energy** it should transfer to each electron — the kinetic energy should increase with intensity. There's **no explanation** for the **kinetic energy** depending only on the **frequency**.

There is also **no explanation** for the **threshold frequency**. According to **wave theory**, the electrons should be emitted **eventually**, no matter what the **frequency** is.

Charlotte thought that landing on her head would get her top marks for beam intensity.

*The **Photon Model** Explained the **Photoelectric Effect** Nicely*

According to the photon model (see page 86):

1) When light hits its surface, the metal is **bombarded** by photons.
2) If one of these photons is **absorbed** by a free electron, the electron will gain energy equal to ***hf***.

Before an electron can **leave** the surface of the metal, it needs enough energy to **break the bonds holding it there**. This energy is called the **work function energy** (symbol ϕ, phi) and its **value** depends on the **metal**.

The Photoelectric Effect

The **Photon Model** Explains the **Threshold Frequency**...

1) If the energy **gained** by an electron (on the surface of the metal) from a photon is **greater** than the **work function**, the electron is **emitted**.
2) If it **isn't**, the metal will heat up, but **no electrons** will be emitted.
3) Since, for **electrons** to be released, $hf \geq \phi$, the **threshold frequency** must be:

$$f = \frac{\phi}{h}$$

...and the **Maximum Kinetic Energy**

1) The **energy transferred** to an electron is hf.
2) The **kinetic energy** the electron will be carrying when it **leaves** the metal is hf **minus** any energy it's **lost** on the way out. Electrons **deeper** down in the metal lose more energy than the electrons on the **surface**, which explains the **range** of energies.
3) The **minimum** amount of energy it can lose is the **work function**, so the **maximum kinetic energy** of a photoelectron, $E_{k\ (max)}$, is hf minus the work function, which gives the photoelectric equation:

$$hf = \phi + \frac{1}{2}mv_{max}^2$$

You should recognise this — this part of the equation is just the maximum kinetic energy, $E_{k\ (max)}$.

4) The **kinetic energy** of the electrons is **independent of the intensity** (the **number** of photons **per second** on an **area**), as they can **only absorb one photon** at a time. Increasing the **intensity** just means **more photons per second** on an **area** — each photon has the **same energy** as before.

Practice Questions

Q1 Explain what the photoelectric effect is.

Q2 What three conclusions were drawn from experimentation on the photoelectric effect?

Q3 What is meant by the term threshold frequency?

Q4 Write down the equation that relates the work function of a metal and the threshold frequency.

Q5 Write down an equation that relates the maximum kinetic energy of a photoelectron released from a metal surface and the frequency of the incident light on the surface.

Exam Questions

$h = 6.63 \times 10^{-34}$ Js; $e = 1.60 \times 10^{-19}$ C

Q1 The work function of calcium is 2.9 eV. Calculate the threshold frequency of radiation needed for the photoelectric effect to take place. [2 marks]

Q2 The surface of a copper plate is illuminated with monochromatic ultraviolet light, with a frequency of 2.0×10^{15} Hz. The work function for copper is 4.7 eV.

a) Calculate the energy in eV carried by one photon of the ultraviolet light. [2 marks]

b) Calculate the maximum kinetic energy of a photoelectron emitted from the copper surface. [2 marks]

Q3 Explain why the photoelectric effect only occurs after the incident light has reached a certain frequency. [2 marks]

I'm so glad we got that all cleared up...

Yep, the photoelectric effect is a bit tricky. The most important bits here are why wave theory doesn't explain the phenomenon, and why the photon theory does. A good way to learn conceptual stuff like this is to try to explain it to someone else. You'll get most formulas in your handy data sheet, but it's probably a good idea to learn them too...

Wave-Particle Duality

Is it a wave? Is it a particle? No, it's a wave. No, it's a particle. No it's not, it's a wave. No don't be daft, it's a particle. (etc.)

*There's Evidence for Light Being a **Wave** and for Light Being a **Particle***

Towards the end of the **17th century**, two important **theories of light** were published — one by Isaac Newton and the other by Huygens. Newton's theory suggested that light was made up of tiny particles, which he called "**corpuscles**", and Huygens put forward a theory using **waves**.

Interference** and **Diffraction** show **Light** as a **Wave

The **corpuscular** theory could explain **reflection** and **refraction**, but **diffraction** and **interference** (p.84-85) are both uniquely wave properties. Over 100 years later, it was shown that light could interfere and diffract, so that settled the argument... for now.

*The **Photoelectric Effect** Shows **Light** Behaving as a **Particle***

After another 100 years or so, the debate was raging once again after the photoelectric effect was observed (p.88).

1) **Einstein** explained the results of **photoelectricity experiments** by thinking of the **beam of light** as a series of **particle-like photons** (see p.86). He published his particle theory of light in **1905**.
2) If a **photon** of light is a **discrete** bundle of energy, then it can **interact** with an **electron** in a **one-to-one way**.
3) **All** the **energy** in the **photon** is **given** to one **electron**.

De Broglie** Came up With the **Wave-Particle Duality Theory

I'm not impressed — this is just speculation. What do you think Dad?

1) In **1924**, Louis de Broglie made a **bold suggestion** in his **PhD thesis**:

> If '**wave-like**' **light** showed **particle properties** (photons), '**particles**' like **electrons** should be expected to show **wave-like properties**.

2) The **de Broglie equation** relates a **wave property** (**wavelength**, λ) to a **moving particle property** (momentum, p). h = Planck constant = 6.63×10^{-34} Js.

$$\boxed{\lambda = \frac{h}{p}}$$

3) The de Broglie wave of a particle can be interpreted as a '**probability wave**' — the **likelihood** of finding a particle at a point is **directly proportional** to the **square** of the **amplitude** of the wave at that point.
4) Many physicists at the time **weren't very impressed** — his ideas were just **speculation**. But later experiments **confirmed** the wave nature of electrons.

Electron Diffraction** shows the **Wave Nature** of **Electrons

1) In **1927**, two American physicists, **Clinton Davisson** and **Lester Germer**, succeeded in diffracting **electrons**.
2) **Diffraction patterns** are observed when **accelerated electrons** in a vacuum tube **interact** with the **spaces** between **carbon atoms** in **polycrystalline graphite**.
3) This **confirms** that electrons show **wave-like** properties.
4) According to wave theory, the **spread** of the **lines** in the diffraction pattern **increases** if the **wavelength** of the wave is **greater**.
5) In electron diffraction experiments, a **smaller accelerating voltage**, i.e. **slower** electrons, gives **widely spaced** rings.
6) **Increase** the **electron speed** and the diffraction pattern circles **squash together** towards the **middle**. This fits in with the **de Broglie** equation above — if the **momentum** is **higher**, the **wavelength** is **shorter** and the **spread** of lines is **smaller**.
7) Electron diffraction was a **huge** discovery — this was the first **direct evidence** for de Broglie's theory.

> In general, λ for **electrons** accelerated in a **vacuum tube** is about the **same size** as **electromagnetic waves** in the **X-ray** part of the spectrum.

Wave-Particle Duality

Particles Don't show Wave-Like Properties All the Time

1) You **only** get **diffraction** if a particle interacts with an object of about the **same size** as its **de Broglie wavelength**.
2) A **tennis ball**, for example, with **mass 0.058 kg** and **speed 100 ms^{-1}** has a **de Broglie wavelength** of **10^{-34} m**. That's **10^{19} times smaller** than the **nucleus** of an **atom**! There's nothing that small for it to interact with.

Example: An electron of mass 9.11×10^{-31} kg is fired from an electron gun at 7.00×10^6 ms^{-1}. What size object will the electron need to interact with in order to diffract?

Momentum of electron = $p = mv = (9.11 \times 10^{-31}) \times (7.00 \times 10^6) = 6.377 \times 10^{-24}$ kg ms^{-1}

$\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34}}{6.377 \times 10^{-24}} = \mathbf{1.04 \times 10^{-10}}$ **m (to 3 s.f.)**

Electrons with a wavelength of around **1×10^{-10} m** are **likely** to be diffracted by the atoms in **polycrystalline structures**.

3) A **shorter wavelength** gives **less diffraction effects**. This fact is used in the **electron microscope**.
4) **Diffraction** effects **blur detail** on an image. If you want to **resolve tiny detail** in an **image**, you need a **shorter wavelength**. **Light** blurs out detail more than '**electron-waves**' do, so an **electron microscope** can resolve **finer detail** than a **light microscope**. They can let you look at things as tiny as a single strand of DNA... which is nice.

Practice Questions

Q1 Which observations show light to have a 'wave-like' character?

Q2 Which observations show light to have a 'particle' character?

Q3 What happens to the de Broglie wavelength of a particle if its velocity increases?

Q4 Describe the experimental evidence that shows electrons have a 'wave-like' character.

Exam Questions

proton mass, $m_p = 1.673 \times 10^{-27}$ kg; electron mass, $m_e = 9.11 \times 10^{-31}$ kg

Q1 a) State what is meant by the wave-particle duality of electromagnetic radiation. [1 mark]

b) Calculate the momentum of an electron with a de Broglie wavelength of 590 nm. [2 marks]

Q2 Electrons travelling at a speed of 3.50×10^6 ms^{-1} exhibit wave properties.

a) Calculate the wavelength of these electrons. [2 marks]

b) Calculate the speed of protons which would have the same wavelength as these electrons. [2 marks]

c) Some electrons and protons were accelerated from rest by the same potential difference, giving them the same kinetic energy. Explain why they will have different wavelengths. [3 marks]

Q3 Electrons are directed at a thin slice of graphite at high speed and a diffraction pattern is observed. Which of the following statements correctly describe a conclusion that this observation supports? [1 mark]

1 Electrons can show particle-like behaviour.
2 Waves can show particle-like behaviour.
3 Photons can show wave-like behaviour.
4 Electrons can show wave-like behaviour.

A 1, 2 and 4 B 4 only C 3 only D 1 and 4 only

Don't hide your wave-particles under a bushel...

Right — I think we'll all agree that quantum physics is a wee bit strange when you come to think about it. What it's saying is that electrons and photons aren't really waves, and they aren't really particles — they're both... at the same time. It's what quantum physicists like to call a 'juxtaposition of states'. Well they would, wouldn't they...