Edexcel IAL Physics A-level

Topic 2.3: Waves and Particle Nature of Light

Notes

2.3 - Waves and Particle Nature of Light

2.3.33 - Definitions

Amplitude	A wave's maximum displacement from the equilibrium position.
Frequency (f)	The number of complete oscillations passing through a point per second.
Period (T)	The time taken for one full oscillation.
Speed (v)	The distance travelled by the wave per unit time.
Wavelength (λ)	The length of one whole oscillation (e.g. the distance between successive peaks/troughs).

2.3.34 - Wave equation

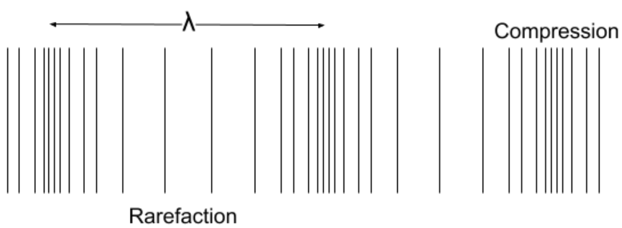
The **speed (v)** of a wave is equal to the wave's frequency multiplied by its wavelength.

$$v = f\lambda$$

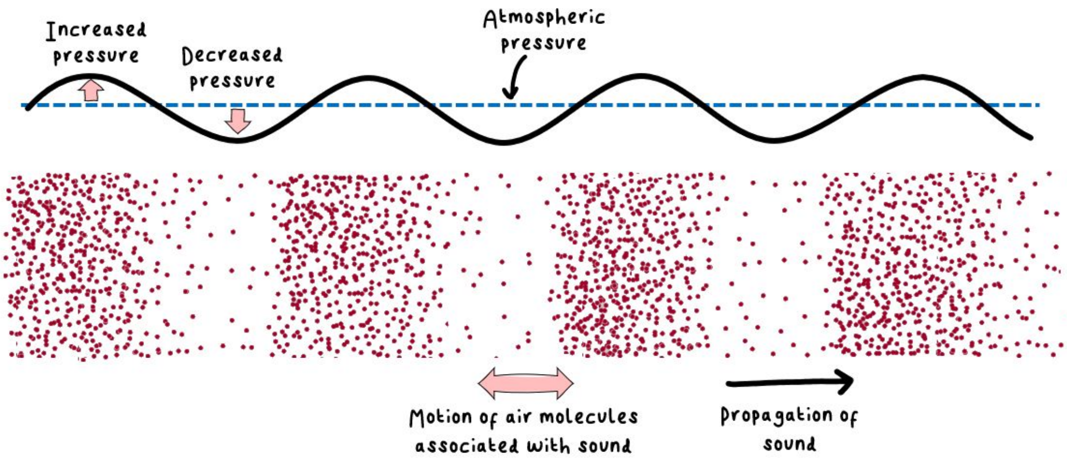
2.3.35 - Longitudinal waves

In **longitudinal waves**, the oscillation of particles is parallel to the direction of energy transfer.

- These are made up of compressions and rarefactions and can't travel in a vacuum.
- Sound is an example of a longitudinal wave, and they can be demonstrated by pushing a slinky horizontally.



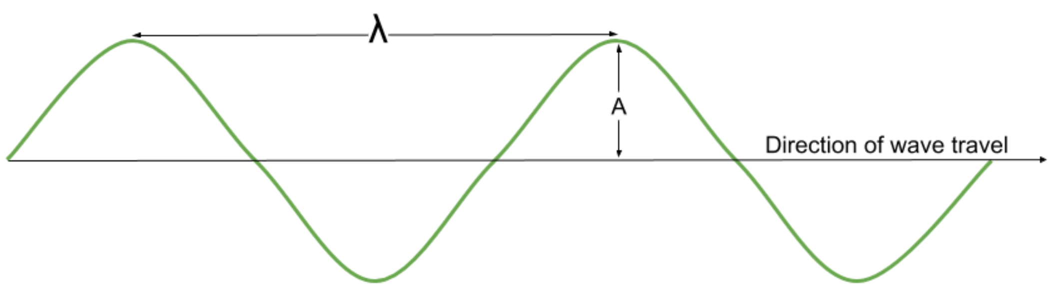
Stage	**Rarefaction**	**Compression**
Pressure	Decreased	Increased
Displacement of particles	Neighbouring particles move away from each other	Neighbouring particles move towards a point



2.3.36 - Transverse waves

In **transverse waves**, the oscillations of particles (or fields) is at right angles to the direction of energy transfer

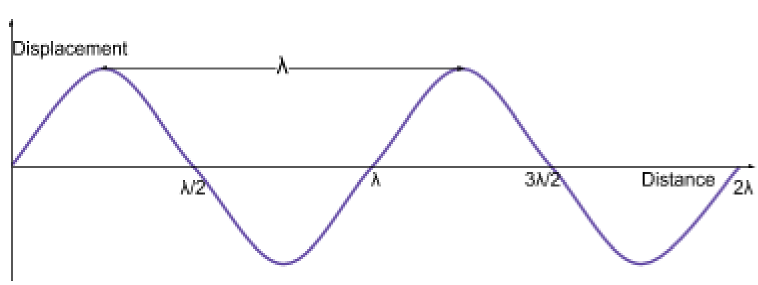
- All electromagnetic (EM) waves are **transverse** and travel at 3×10^8 ms^{-1} in a vacuum.
- Transverse waves can be demonstrated by shaking a slinky vertically or through the waves seen on a string, when it's attached to a signal generator.



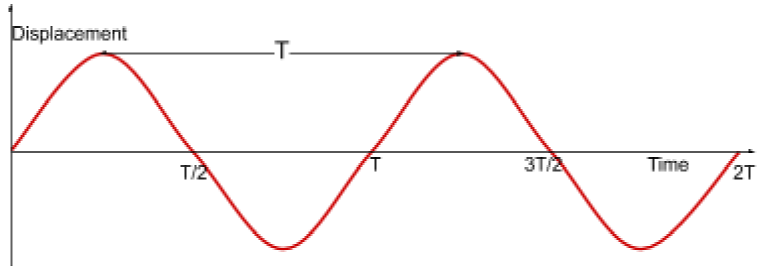
2.3.37 - Graphs of transverse and longitudinal waves

There are two types of graphs which can be used to represent waves:

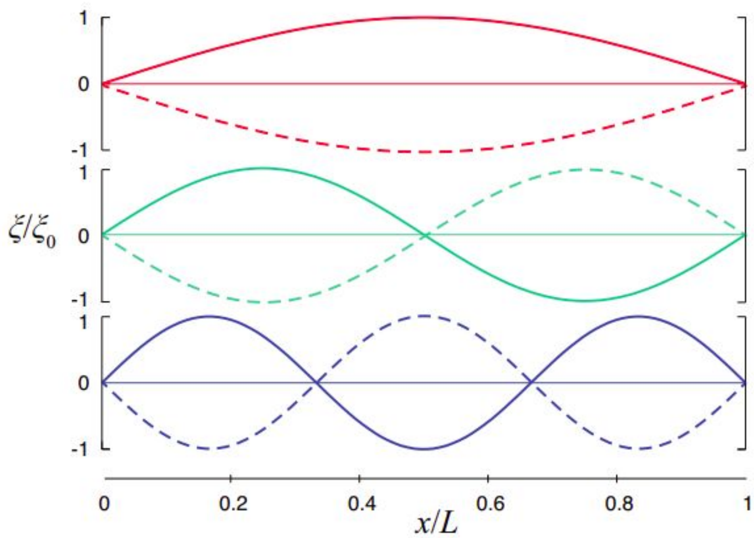
➔ **Displacement-distance graphs** **-** these show how the displacement of a particle varies with the distance of wave travel and can be used to measure **wavelength**.
For a transverse wave, the displacement distance graph will look very similar to the actual wave, whereas for a longitudinal wave the graph will look very different from the wave.



➔ **Displacement-time graphs** - these show how the displacement of a particle varies with time and can be used to measure the **period** of a wave.



A **standing wave** (*explained further in 2.367*) can be represented on a displacement-distance graph as shown below:



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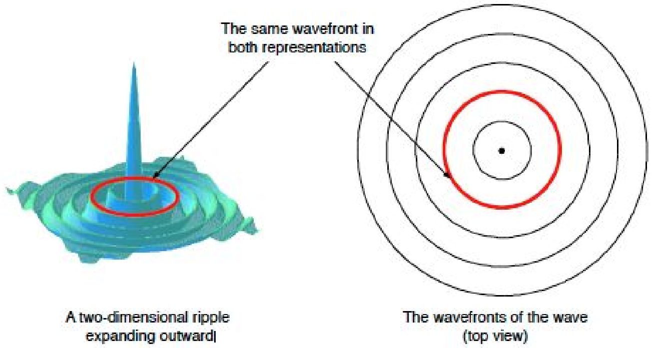
2.3.39 - Further definitions

Phase	The position of a certain point on a wave cycle. This can be measured in radians, degrees or fractions of a cycle.
Phase difference	How much a particle/wave lags behind another particle/wave. This can be measured in radians, degrees or fractions of a cycle.
Path difference	The difference in the distance travelled by two waves.
Superposition	Where the **displacements** of two waves are combined as they pass each other, the resultant displacement is the **vector sum** of each wave's displacement.
Coherence	A **coherent** light source has the **same** frequency and wavelength and a **fixed** phase difference.

Wavefront	A wavefront is a surface which is used to represent the points of a wave which have the **same** phase.

As an example of a **wavefront**, consider a rock being dropped into a pond, the peak of each ripple formed can be considered as a wavefront. This is shown in the diagram below:



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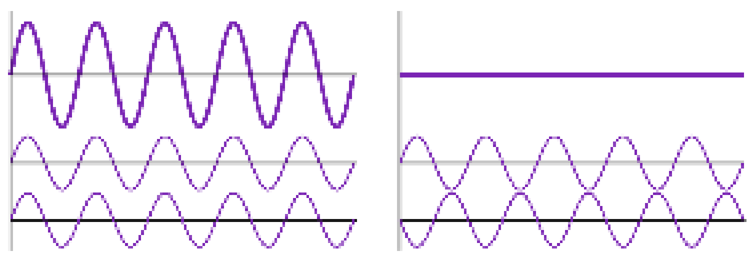
There are two types of **interference** that can occur during **superposition** and they are:

- **Constructive interference** - this occurs when two waves are **in phase** (explained below) and so their displacements are added
- **Destructive interference** - this occurs when the waves are **completely out of phase** (explained below) and so their displacements are subtracted

The image below shows the interference of two waves (which are pictured below the resultant wave). On the left is constructive interference and on the right is destructive interference.



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2.3.40 - Phase difference and path difference

Two waves are **in phase** if they are both at the same point of the wave cycle, meaning they have the **same frequency and wavelength** (are coherent) and their **phase difference is an integer multiple of 360°** (2π radians). The waves do not need to have the same amplitude, only the same frequency and wavelength.

Two waves are **completely out of phase** when they have the **same frequency and wavelength** (are coherent) and their **phase difference is an odd integer multiple of 180°** (π radians).

The **phase difference** (in radians) of two waves with the same frequency and their **path differences** are related as shown below:

$$\Delta x = \frac{\lambda}{2\pi}\Delta\phi$$

Where **Δx** is the path difference, **λ** is the wavelength of the waves and **ΔΦ** is their phase difference.

Below is an example question where you have to use the above relation.
Two waves have a path difference of 6m and both have a wavelength of 2m, what is the phase difference of these two waves?

Firstly, rearrange the above relation so that the phase difference is the subject.

$$\Delta\phi = 2\pi \times \frac{\Delta x}{\lambda}$$

Then, substitute in the given values.

$$\Delta\phi = 2\pi \times \frac{6}{2} = 6\pi$$

And so, their phase difference is **6π**. As 6π is a multiple of 2π, the waves must be **in phase**.

2.3.41 - Stationary waves

A **stationary wave** (also known as a standing wave) is formed from the **superposition of 2 progressive waves**, travelling in **opposite directions** in the same plane, with the **same frequency, wavelength and amplitude**.

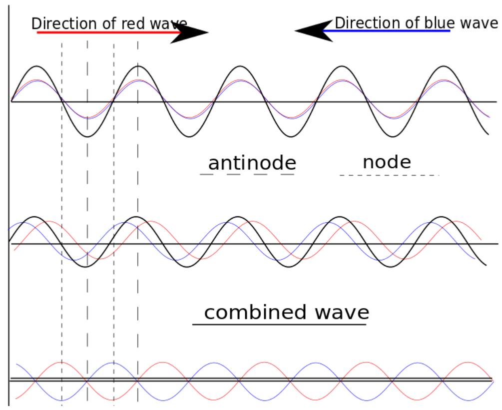
No energy is transferred by a stationary wave.

Where the waves meet:

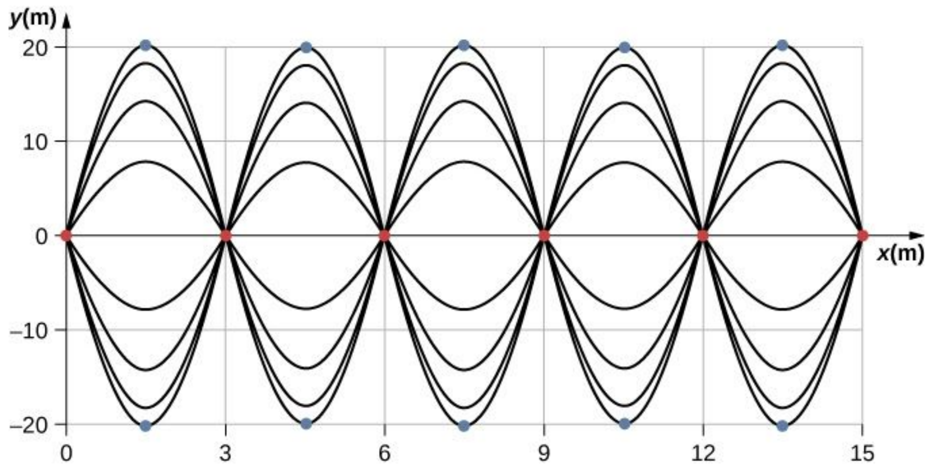
- ➔ **In phase** - **constructive interference** occurs so **antinodes** are formed, which are regions of maximum displacement.
- ➔ **Completely out of phase** - **destructive interference** occurs and **nodes** are formed, which are regions of no displacement.

A string fixed at one end, and fixed to a driving oscillator at the other gives a good example of the formation of a stationary wave:

- A wave travelling down the string from the oscillator will be reflected at the fixed end of the string, and travel back along the string causing superposition of the two waves. Because the waves have the same wavelength, frequency and amplitude, a stationary wave is formed. (Labelled combined wave on the diagram below).



The diagram below shows multiple possible standing waves on a displacement-distance graph. The blue points indicate antinodes, while the red points indicate nodes.



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2.3.42 - Speed of a transverse wave on a string

You can calculate the speed of a transverse wave on a string by using the formula below:

$$v = \sqrt{\frac{T}{\mu}}$$

Where **v** is the speed, **T** is the tension in the string, and **μ** is the mass per unit length of the string (which is constant).

2.3.44 - Intensity of radiation

Intensity is the power (energy transferred per unit time) per unit area, and can be calculated using the equation below:

$$I = \frac{P}{A}$$

Where **P** is the power and **A** is the area.

2.3.45 - Refractive index and Snell's law

A **refractive index (n)** is a property of a material which measures how much it slows down light passing through it. It is calculated by dividing the speed of light in a vacuum (c) by the speed of light in that substance (v).

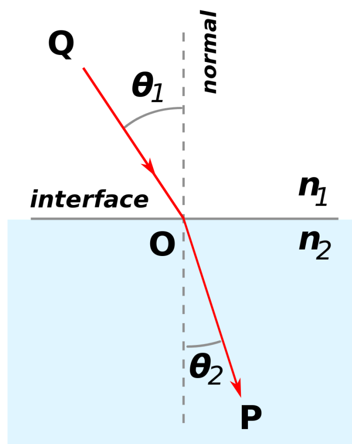
$$n = \frac{c}{v}$$

A material with a **higher refractive index** can also be known as being **more optically dense**.

Refraction occurs when a wave enters a different medium, causing it to change direction, either towards or away from the normal depending on the material's refractive index.
Snell's law is used for calculations involving the refraction of light:

$$n_1 sin\theta_1 = n_2 sin\theta_2$$

- **n_1** is the refractive index of material 1,
- **n_2** is the refractive index of material 2,
- **θ_1** is the angle of incidence of the ray in material 1
- **θ_2** is the angle of refraction of the ray in material 2



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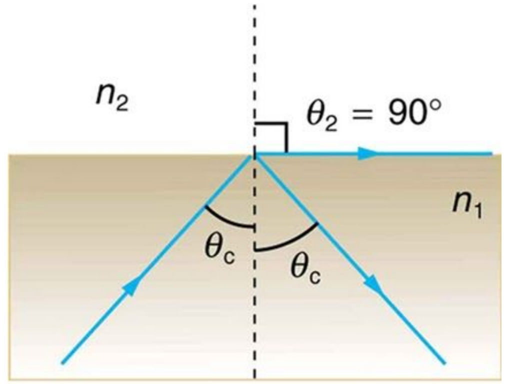
As the light moves across the boundary of the two materials, its **speed changes**, which causes its **direction** to change.

In the example above, **n_2 is more optically dense than n_1**, therefore the ray of light slows down and **bends towards the normal**. However, in the case where **n_2 is less optically dense than n_1** the ray of light will **bend away from the normal**.

2.3.46 - Critical angle

As the angle of incidence is increased, the angle of refraction also increases until it gets closer to 90°. When the angle of refraction is **exactly 90°** and the light is **refracted along the boundary**, the angle of incidence has reached the **critical angle (C)**.



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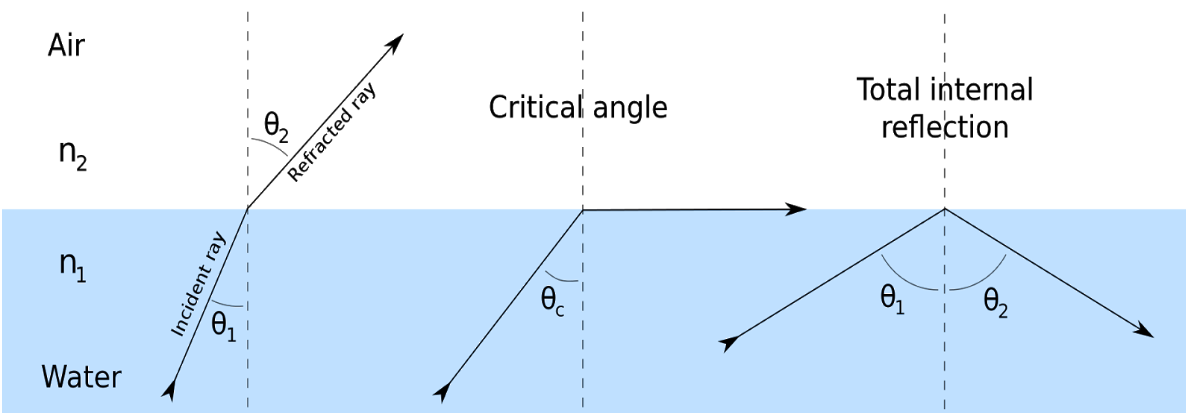
In the case that one of the materials (n_2) is air (which has a refractive index of approximately 1), you can use the following formula to find the critical angle (C):

$$\sin C = \frac{1}{n} \quad \text{where } n > 1$$

2.3.47 - Total internal reflection

Total internal reflection (TIR) can occur when the angle of incidence is **greater than the critical angle** and the incident refractive index (n_1) is **greater** than the refractive index of the material at the boundary (n_2).



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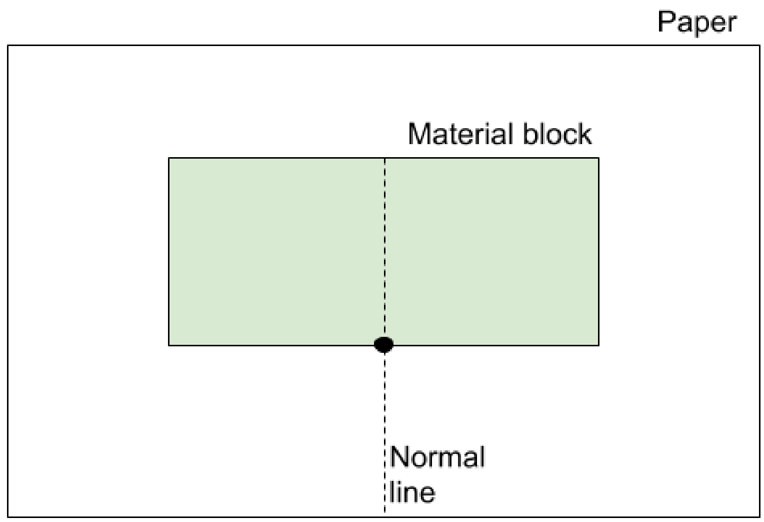
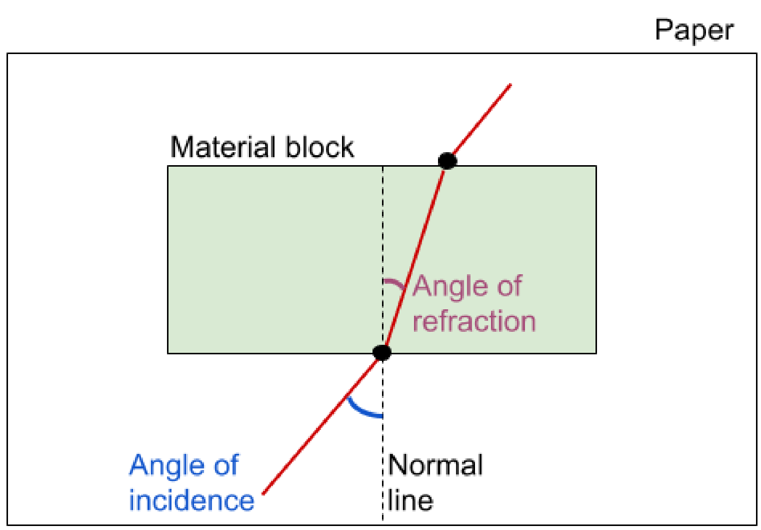
2.3.48 - Measuring the refractive index of a solid material

The procedure for finding the refractive index of a solid material is as follows:

1. Place the material in the centre of a piece of paper and draw around it using a pencil.
2. Next, put the material block aside and mark a point on the outline of the material (preferably in the centre) and draw a line perpendicular to the outline at this point (as shown below). This is the **normal line**. Use a protractor to make sure that the line is at exactly 90° (perpendicular).

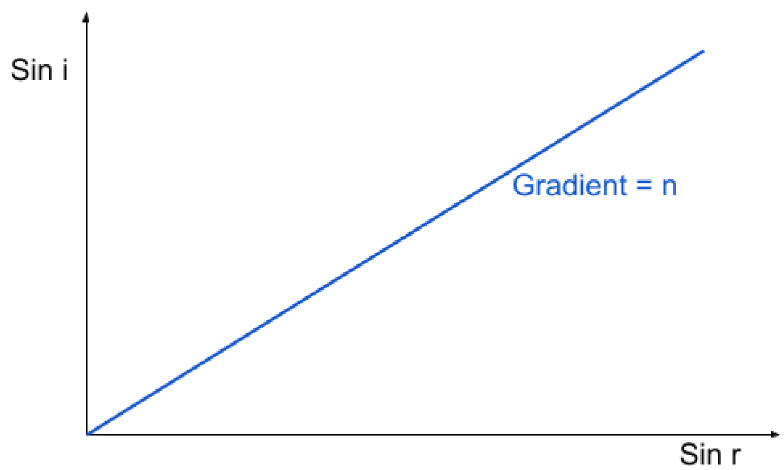


3. Using a protractor, draw lines leaving the point you have marked **at 10° intervals** from 10° - 70°, where the angle is measured from the normal line to the line you are drawing. These will be the incident rays.
4. Put the material block back, making sure that it fits the outline as well as possible.
5. Using a ray box, shine a ray of line along the 10° line and mark the point at which the light ray leaves the material block.
6. Join the point you have just marked down to the point on the normal line, at which the light ray enters the block. Using a protractor, measure the angle between this line and the normal. This is the angle of refraction.



7. Repeat the above two steps for all of the incident angles.
8. Repeat the above method two more times and find the average value of the angle of refraction for each incident angle.

9. Plot a graph of sine of the incident angles (**sin i**) against sine of the refracted angles (**sin r**). Plot a line of best fit and find the **gradient** - this is the refractive index of the material used.



You can derive the above result using snell's law:

$$n_1 sin\theta_1 = n_2 sin\theta_2$$

Our initial material is air, which has a refractive index of 1, so the snell's law equation above can be simplified to:

$$sin\theta_1 = n_2 sin\theta_2$$

If you replace θ_1 (the angle of incidence) with i, θ_2 (the angle of refraction) with r, and n_2 with n to represent the refractive index of our material, you get:

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

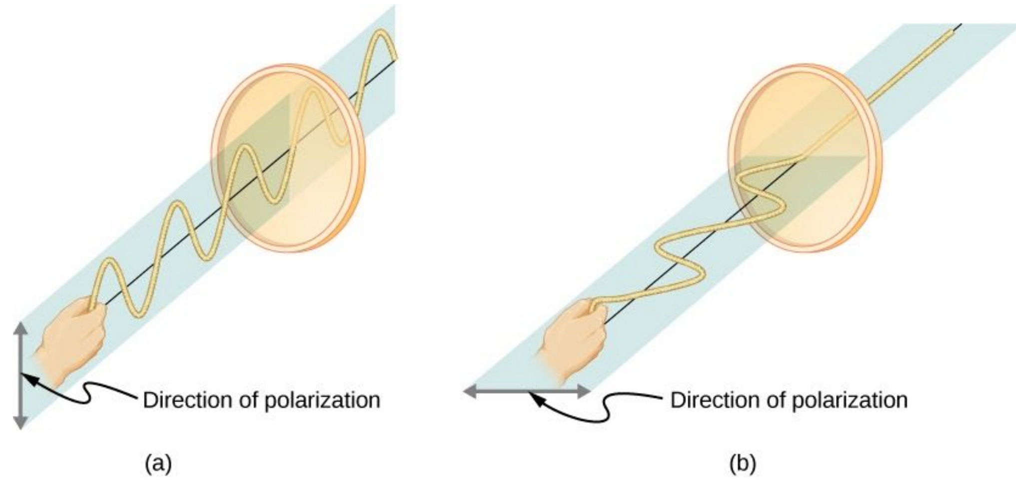
$$Y\ \ = mx$$

This is simply the equation of the straight line in a graph of sin i against sin r, meaning that its **gradient must be n**.

2.3.49 - Plane polarisation

A **polarised wave oscillates in only one plane** (e.g only up and down if vertically polarised), **only transverse waves can be polarised.**

Below is a diagram which shows the effect of vertically polarised and horizontally polarised waves passing through a block with vertical slits, which acts as a vertically polarising filter.



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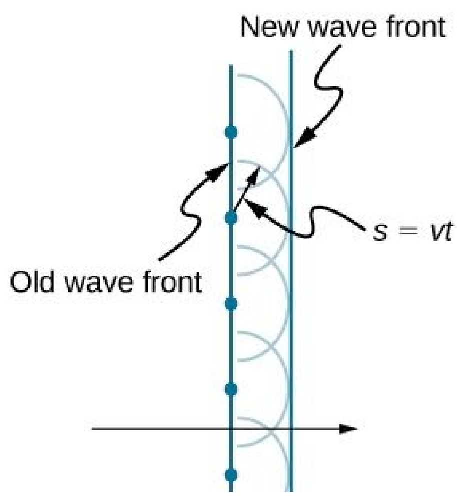
(a) The vertically polarised wave passes through the filter without a problem.
(b) The horizontally polarised wave cannot pass through the filter as it blocks waves which are not in the vertical plane.

Polarised sunglasses are an application of polarisation. They reduce glare by **blocking partially polarised light** reflected from water and tarmac, as they only allow oscillations in the plane of the filter to pass through, making it easier to see.

2.3.50 - Diffraction and Huygens' construction

Diffraction is the spreading out of waves when they pass through or around a gap.

Huygens' construction states that every point on a wavefront is a point source to secondary wavelets, which spread out to form the next wavefront, as shown in the diagram below:



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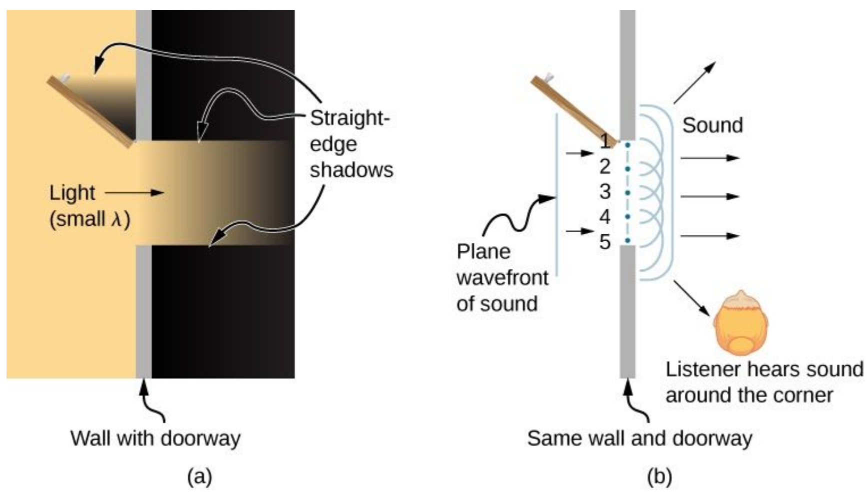
Huygens' construction can be used to explain the diffraction of light when it meets an obstacle or passes through a gap.

For example, consider a sound wave travelling through a doorway. From experience, you know that the sound will (probably) be heard throughout the entire room, this is because, as the sound wave travels through the doorway, it **diffracts**, spreading through the entire room. Diffraction occurs here because each point on the wavefront passing through the doorway (labelled 1 - 5), is a **source of wavelets**, which spread out from the gap of the doorway forming further circular wavefronts.

In contrast to this, consider light travelling through a doorway. The light passes through the doorway **without diffracting much at all**, which is why you get straight-edged shadows (as shown in the diagram below).



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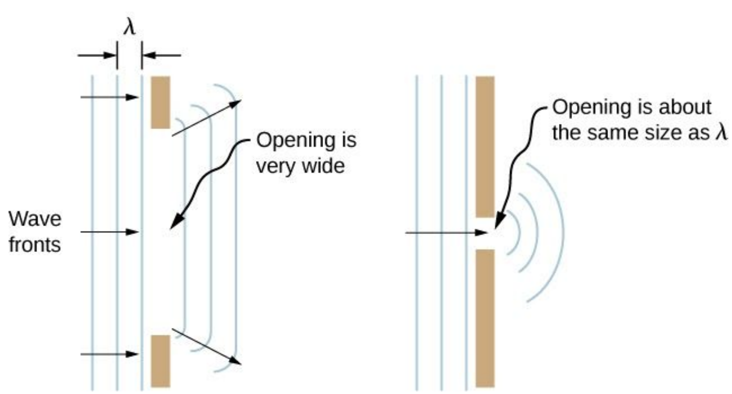
The reason the light waves barely diffract, while the sound waves diffract a lot, is because their wavelength is much smaller in comparison to the size of the doorway. Whereas, the wavelength of the sound wave is much closer to that of the doorway, and the greatest amount of diffraction occurs when the gap is the **same size** as the wavelength.



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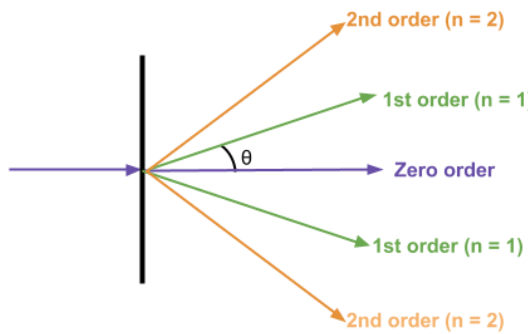
2.3.51 - Diffraction grating equation

A **diffraction grating** is a slide containing many **equally spaced slits very close together**. When light is passed through a diffraction grating, it forms an interference pattern composed of light and dark fringes.
The ray of light passing through the centre of a diffraction grating is called the zero order line, lines either side of the zero order are the first order lines, then the lines outside the two first order lines are the second order lines, and so on as showcased in the diagram below.



The diffraction grating equation is:

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

Where **d** is the distance between the slits (in the diffraction grating), **θ** is the angle to the normal made by the maximum (light fringe), **n** is the order and **λ** is the wavelength.

2..3.53 - Electron diffraction as evidence for the wave nature of electrons

Electron diffraction experiments can be performed using an electron gun, which accelerates electrons through a vacuum tube towards a crystal lattice, where they **interact with the small gaps between atoms** and form an interference pattern on a fluorescent screen behind the crystal.

The interference pattern created by the type of experiment described above, looks like a set of concentric rings as shown below:

If electrons **only** had a particle nature, you would expect the pattern to look like a single point, where the electron beam has passed through the lattice. However, this is not the case as the **electrons undergo diffraction**, which is something **only** waves can experience. This is why electron diffraction provides evidence for the **wave nature of electrons**.

2.3.54 - de Broglie relation

The **de Broglie hypothesis** states that all particles have a wave nature and a particle nature, and that the wavelength of any particle can be found using the following equation:

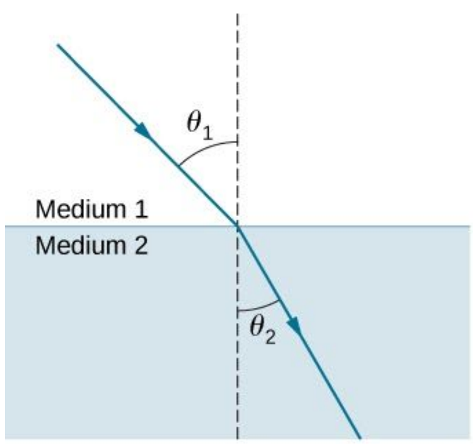
$$\lambda = \frac{h}{p}$$

Where **λ** is the de Broglie wavelength, **h** is the Planck constant and **p** is the momentum of the particle.

2.3.55 - Wave behaviour at an interface

An **interface** is a boundary between two materials. At an interface, waves can be:

- **Transmitted** - where they pass into the next material. They may experience refraction if the materials have different refractive indices. (Shown on the left diagram below).
- **Reflected** - where the waves bounce off the interface **without** passing into the next material. (Shown on the right diagram below).



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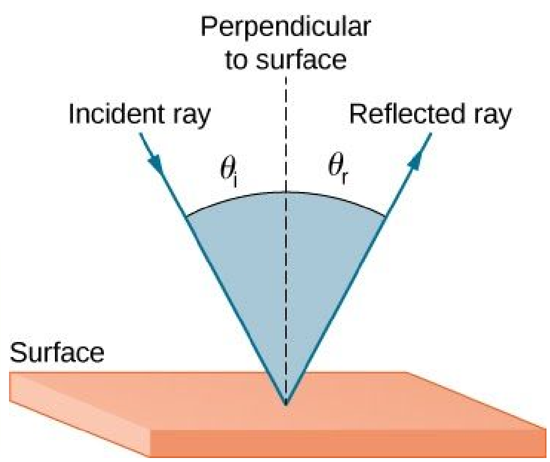

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2.3.56 - Pulse-echo technique

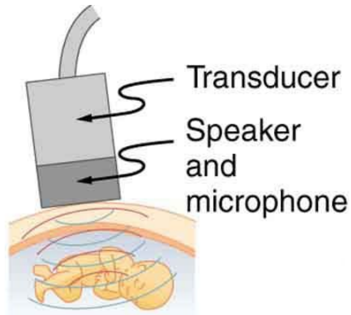
The **pulse-echo technique** is used with ultrasound waves (sounds waves with a frequency greater than 20 kHz) for the imagining of objects, notably for medical imaging. This technique relies on the fact that waves are reflected when they meet **boundaries** between different materials.

Below is a brief description of the **pulse-echo technique**:

1. **Short pulse** ultrasound waves are transmitted into the target (e.g the body in medical imaging).
2. The pulse travels inside the body until it reaches a **boundary between two mediums** where some of the pulse is reflected back. The amount of reflection depends on the

difference in densities of the materials; the greater this difference, the greater the reflection.

3. The reflected waves are detected as they leave the target.
4. The intensities of the reflected waves are used to determine the **structure** of the target and the time taken for these reflected waves to return is used to determine the **position** of objects in the target (using s = vt).



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If the **duration** of the pulses is **too long**, they will likely overlap, meaning that the amount of information you obtain (the resolution of the image) will **decrease**.

Also, as the **wavelength** of the waves used **increases**, the less fine details can be resolved, meaning that amount of information you obtain will **decrease**.

2.3.57 - Wave model and photon model of electromagnetic radiation

The **photon model** states that: EM waves travel in **discrete packets** called **photons**, which have an energy directly proportional to their frequency ($E = hf$).

On the other hand, in terms of the **wave model**, EM radiation can be described as a **transverse wave**.

Initially, light (which is a type of EM wave) was believed to be composed of tiny particles as this could explain the reflection and refraction of light. However, light was later proved to act as a wave through diffraction experiments, so people believed it was instead formed of waves. Before long, due to the discovery of photoelectricity (*explained in 2.392*), the attitude towards the composition of light (and EM waves) changed once again. Light had now been proven to act as both a particle **and** a wave, which led to development of the **photon model of light** and **wave-particle duality**.

2.3.58 - Photon energy

Photons have an energy which is **directly proportional** to their frequency, as described by the equation below:

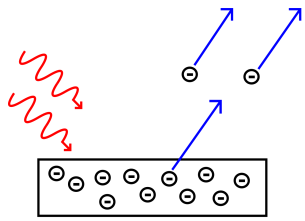
$$E = hf$$

Where **E** is the photon energy, **h** is Planck's constant and **f** is the wave frequency.

2.3.59 - Photoelectricity

The **photoelectric effect** is where photoelectrons are emitted from the surface of a metal after light above a certain frequency is shone on it. This certain frequency is different for different types of metals and is called the **threshold frequency**.

Photoelectrons are emitted because electrons near the surface of the metal **absorb a photon** and gain enough energy to leave the surface.



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2.3.60 - Threshold frequency, work function and the photoelectric equation

As described above, the **threshold frequency** is the **minimum** frequency of light required to emit photoelectrons, and this varies depending on the type of metal.

The **work function** of a metal is the **minimum** energy required for electrons to be emitted from the surface of a metal, and it is denoted by Φ.

The **photoelectric equation** shows the relationship between the work function, the frequency of light (shone onto the metal) and the maximum kinetic energy of the emitted photoelectrons.

$$E = hf = \Phi + E_{k\,(max)}$$

Where **E** is the photon energy, **Φ** is the work function and $\mathbf{E_{k(max)}}$ is the maximum kinetic energy.

2.3.61 - Electronvolt

The **electronvolt (eV)** is a unit of energy, usually used to express small energies. 1 eV is equal to the kinetic energy of an electron accelerated across a potential difference of 1 V or 1.6×10^{-19} J.

You can convert between joules and electron volts quite easily:

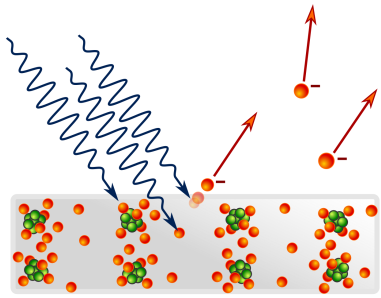
- **Joules to electron volts** - **divide** by 1.6×10^{-19}
- **Electron volts to joules** - **multiply** by 1.6×10^{-19}

2.3.62 - The photoelectric effect as evidence for the particle nature of EM radiation

The photoelectric effect also couldn't be explained by wave theory as:

1. **Wave theory suggests that any frequency of light should be able to cause photoelectric emission** as the energy absorbed by each electron will gradually increase with each incoming wave, and so can't explain the existence of a **threshold frequency**.

2. The **photoelectric effect is immediate**, which contradicts wave theory which suggests time is needed for the energy supplied to the electrons to reach the **work function** (minimum energy required for electrons to be emitted from the surface of a metal).
3. **Increasing the intensity** of the light does not increase the speed of photoelectric emission as would be suggested by wave theory, but instead it **increases the number of photoelectrons released per second**.
4. Photoelectrons are released with a **range of kinetic energies**.



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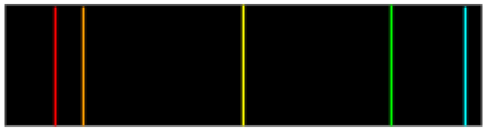
The photon model of EM radiation, which suggests that EM waves are released in discrete packets called photons, which have particle-like interactions, could be used to explain all the points above which wave theory couldn't:

1. When a photon interacts with an electron, **all of its energy is transferred to it**, and **an electron can only interact with a single photon**. If this energy is above the work function, a photoelectron is emitted, if this energy is below the work function, the electron remains in place. As the energy of a photon is directly proportional to frequency ($E = hf$), the **threshold frequency is the frequency at which the photon energy is equal to the work function of the metal**.
2. The photon energy is transferred to the electron immediately when they interact, leading to photoelectrons being emitted immediately.
3. **Intensity is equal to the number of photons released per second**, if this is increased the number of photoelectrons emitted is increased because **more photons interact with electrons per second**.
4. All electrons will receive the **same amount of energy** from a photon of light, however electrons which are deeper in the **metal will lose energy through collisions** when leaving the metal, and will therefore have a lower kinetic energy.

2.3.63 - Atomic line spectra

Electrons in atoms can only exist in discrete energy levels. If an electron gains enough energy it can move up in energy level (this is known as excitation), however it will quickly return to its original energy level and release the energy it gained in the form of a **photon** of light.

Inside a fluorescent tube, electrons are accelerated, causing gas atoms to become excited and then de-excite, releasing photons. By passing the light from a fluorescent tube through a diffraction grating or prism, you get a **line spectrum**. Each line in the spectrum represents a different wavelength of light emitted by the tube. As this spectrum is not continuous but rather contains only discrete values of wavelength, the photon energies emitted will correspond to these wavelengths. This is evidence to show that the electrons in atoms can only transition between discrete energy levels.



Line spectrum

The difference between two energy levels is equal to a specific photon energy **emitted** by a fluorescent tube, or **absorbed** in a line absorption spectrum.
Therefore, you can calculate the energy of an emitted photon by using the following formula:

$$\Delta E = E_1 - E_2$$

Where **ΔE** is the photon energy and **E_1/E_2**, represent energy levels.

Using the photon energy equation ($E = hf$), you can see that you can find the photon **frequency** by using the following equation:

$$\Delta E = hf = E_1 - E_2$$

$$f = \frac{E_1 - E_2}{h}$$

Where **f** is the photon frequency and **h** is the Planck constant.