IB Physics 1 HL Notebook

Finn Lestrange

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Contents

Chapter 1

Measurement

1.1 Orders of Magnitude

1000^m	10^n	Prefix	Symbol	Short scale	Long scale	Decimal
1000^8	10^{24}	yotta-	Y	Septillion	Quadrillion	1 000 000 000 000 000 000 000 000
1000^7	10^{21}	zetta-	Z	Sextillion	Trilliard	1 000 000 000 000 000 000 000
1000^6	10^{18}	exa-	E	Quintillion	Trillion	1 000 000 000 000 000 000
1000^5	10^{15}	peta-	P	Quadrillion	Billiard	1 000 000 000 000 000
1000^4	10^{12}	tera-	T	Trillion	Billion	1 000 000 000 000
1000^3	10^9	giga-	G	Billion	Milliard	1 000 000 000
1000^2	10^6	mega-	M	Million		1 000 000
1000^1	10^3	kilo-	k	Thousand		1 000
$1000^{2/3}$	10^2	hecto-	h	Hundred		100
$1000^{1/3}$	10^1	deca-	da	Ten		10
1000^0	10^0	*(none)*	*(none)*	One		1
$1000^{-1/3}$	10^{-1}	deci-	d	Tenth		0.1
$1000^{-2/3}$	10^{-2}	centi-	c	Hundredth		0.01
1000^{-1}	10^{-3}	milli-	m	Thousandth		0.001
1000^{-2}	10^{-6}	micro-	µ	Millionth		0.000 001
1000^{-3}	10^{-9}	nano-	n	Billionth	Milliardth	0.000 000 001
1000^{-4}	10^{-12}	pico-	p	Trillionth	Billionth	0.000 000 000 001
1000^{-5}	10^{-15}	femto-	f	Quadrillionth	Billiardth	0.000 000 000 000 001
1000^{-6}	10^{-18}	atto-	a	Quintillionth	Trillionth	0.000 000 000 000 000 001
1000^{-7}	10^{-21}	zepto-	z	Sextillionth	Trilliardth	0.000 000 000 000 000 000 001
1000^{-8}	10^{-24}	yocto-	y	Septillionth	Quadrillionth	0.000 000 000 000 000 000 000 001

1.2 Uncertainty

1.2.1 Random

$$\frac{Maximum\,Value\ -\ Minimum\,Value}{2} \tag{1.1}$$

Graph:

Dots on the graph are randomly scattered around the best fit line.

1.2.2 Reading

Digital Digital is not infinitely precise so you round your reading up and you have an uncertainty of ± one of the scale.

Analogue
Infinitely precise so you need to look at the scale of the measurement instrument and our uncertainty is half of the measurement range.

So for a ruler with scale 1cm, your uncertainness would be ± 0.5 *cm*

1.2.3 Systematic Uncertainty

Will effect all the results in the same way, unlike the random uncertainty above.

Graph:
All the point will make the best fit line shift up or down.

1.2.4 Combining Uncertainties

If things have the same units:

$$\Delta A + \Delta B = \Delta(A + B) \tag{1.2}$$

If things have different units:

$$\frac{\Delta A}{A} + \frac{\Delta B}{B} = \frac{\Delta C}{c} \tag{1.3}$$

Chapter 2

Mechanics

2.1 Newton's Laws

Newton's first law states that every object will remain at rest or in uniform motion in a straight line unless compelled to change its state by the action of an external force. This is normally taken as the definition of inertia. The key point here is that if there is no net force acting on an object (if all the external forces cancel each other out) then the object will maintain a constant velocity. If that velocity is zero, then the object remains at rest. If an external force is applied, the velocity will change because of the force.

The second law explains how the velocity of an object changes when it is subjected to an external force. The law defines a force to be equal to change in momentum (mass times velocity) per change in time. Newton also developed the calculus of mathematics, and the "changes" expressed in the second law are most accurately defined in differential forms. (Calculus can also be used to determine the velocity and location variations experienced by an object subjected to an external force.) For an object with a constant mass m, the second law states that the force F is the product of an object's mass and its acceleration a:

$$F = ma$$

The third law states that for every action (force) in nature there is an equal and opposite reaction. In other words, if object A exerts a force on object B, then object B also exerts an equal force on object A. Notice that the forces are exerted on different objects

2.2 Projectile Motion

A projectile is, an object that moves through space acted upon only by the earth's gravity.

2.2.1 Rules for Projectile motion

- Projectiles always maintain a constant horizontal velocity V_x
- Projectiles always experience a constant vertical acceleration of $-9.8ms^{-2}$
- Horizontal and Vertical motion are completely independent of each other. Therefore, the velocity of a projectile can be separated into horizontal and vertical components.
- For a projectile beginning and ending at the same height the time it takes to rise to its highest point equals the time it takes to fall from the highest point back to the original position. Vertical position is parabolic.
- Objects dropped from a moving vehicle have the same velocity as the moving vehicle.

2.3 SUVAT

Just a re-cap of the suvat equations of motion.

$$s = displacement(metres)$$
$$u = initial\ velocity(ms^{-1}))$$
$$v = final\ velocity(ms^{-1})$$
$$a = acceleration(ms^{-2})$$
$$t = time(seconds)$$

$$v = u + at$$
$$s = ut + \frac{1}{2}at^2$$
$$s = \frac{u+v}{2t}$$
$$v^2 = u^2 + 2as$$

2.4 Vectors

Vector quantities have both magnitude and direction.

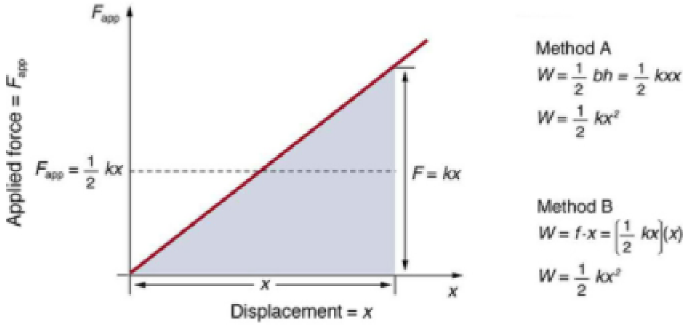
$$A_H = Acos(\theta)$$
$$A_V = Asin(\theta)$$

2.5 Energy

Energy is a body's capacity to do work. It is measured in Joules. Work is:

$$W = F * s * cos(\theta) \tag{2.1}$$

To do work the force must be in the same direction as the displacement. Work can be thought of as a movement of energy. The amount of energy moved is the area under a force / displacement graph.



2.5.1 Conservation of Energy

When a car applies its brakes, kinetic energy becomes heat energy. When the valves are opened on a steam train, heat energy becomes kinetic energy. **Kinetic energy is the energy things have because they move.**

$$E_k = \frac{1}{2}mv^2 \tag{2.2}$$

$$E_k = \frac{p^2}{2m} \tag{2.3}$$

Energy can be stored up. We call this **potential energy**. **Gravitational potential energy** is work stored up in the gravitational field:

$$W = Fs \tag{2.4}$$

$$\Delta E_p = mg\Delta h \tag{2.5}$$

Elastic potential energy is energy stored up in a body which can be stretched or compressed such as a spring.

$$E_p = \frac{1}{2}k\Delta x^2 \tag{2.6}$$

The principle of conservation of energy says that:

In a closed system the total energy is always the same.

$$(\frac{1}{2}mv^2)_1 + (mgh)_1 + Fs_1 = (\frac{1}{2}mv^2)_2 + (mgh)_2 + Fs_2 \tag{2.7}$$

2.5.2 Elastic and Inelastic

A system is not closed just because one property is conserved.

- In an inelastic collision, momentum is conserved but kinetic energy is not.
- In an elastic collision, both kinetic energy and momentum are conserved.
  - Perfect elastic collisions are not possible but very small particles can come close.

Explosions always gain kinetic energy as they start with no E_k and end with some.

Sticky collisions always lose kinetic energy because the combined velocity must be numerically smaller than either initial velocity (or they wouldn't have hit), consequently the velocity squared will always be smaller than the sum of the squares of the initial velocities.

2.6 Friction

2.6.1 Definitions

- Friction F_f
  - A contact force that resists sliding between surfaces.
- Kinetic friction F_k
  - Friction when an object slides along a surface. Direction is opposite the object's sliding direction and is parallel to the contact surface.
- Static friction F_{fs}
  - Friction that prevents an object from sliding along a surface. Direction stops the object from sliding against another surface and is parallel to the contact surface.
- Coefficient of friction μ
  - A number typically between 0 and 1 that describes the roughness between two surfaces, where 0 is slippery and 1 is very rough.

2.6.2 Equations

$$|F_{f,k}| = \mu_k |F_N|$$

Kinetic friction magnitude is directly proportional to the normal force magnitude and the roughness between the sliding surfaces.

$$|F_{f,s}| \leq \mu_s |F_N|$$

Static friction magnitude is directly proportional to the normal force magnitude and the roughness between the sliding surfaces.

2.7 Momentum and Impulse

2.7.1 Momentum

Momentum is a vector quantity. It has the symbol ρ and the units $kg\,ms^{-1}$.
Equation:

$$\rho = mv$$

Explosions; The mass starts together so the whole system starts at the same speed:

$$\rho_{before} = m_1 + m_2)u = m_1 v_v + m_2 v_2$$

Sticky; The mass ends together so the whole system ends at the same speed:

$$\rho_{after} = m_1 v_1 + m_2 v_2 = (m_1 + m_2)v$$

Momentum is a vector quantity. If a collision involves a direction change, it also involves a sign change. In situations where the force is not constant, the impulse can be calculated from the area under the force/time graph. If you increase the time for a collision, the momentum change stays the same. This means you experience less force. The area under a speed time graph stays the same.

2.7.2 Impulse

Momentum changes need to be caused by something. We call that cause an impulse. Momentum can be changed by a small force over a long time; or a big force over a short time.

$$Impulse = Ft \tag{2.8}$$

$$Ft = mv - mu \tag{2.9}$$

Impulse is a change in momentum so, impulse can also have the units: $kg\,ms^{-1}$

2.8 Forces

2.8.1 Concepts and Definitions

Test

2.9 Power and Efficiency

Energy cannot be created or destroyed but it can change form.

The rate at which energy changes form is called Power. It has the symbol P and is measured in Watts W.

$$P = \frac{E}{t} \tag{2.10}$$

Work is change in energy so:

$$P = \frac{W}{t}$$
$$P = \frac{Fs}{t} \tag{2.11}$$
$$P = F\frac{s}{t}$$

$$P = Fv \tag{2.12}$$

When energy changes form, it does not all have to end up in the same form.

When you cause energy to change form, not all of the energy will end up in the form you want (useful energy). The proportion of energy which does is called the efficiency.

$$Efficiency_{\%} = \frac{Useful\ Work\ Out}{Total\ Work\ In} * 100\% \tag{2.13}$$

The time you spend gaining the output is the same as the time you spend losing the input so, efficiency also works with power.

$$Efficiency = \frac{Useful\ Work\ Out}{Total\ Work\ In} = \frac{Useful\ Power\ Out}{Total\ Power\ In} \tag{2.14}$$

The more efficient something is, the less power it wastes. This means that you have to spend less money on energy you can't use.

Chapter 3

Waves and Wave Properties

IB Information:
Waves; Topic 4 SL; Wave Properties; Topic 9 HL

3.1 Oscillations

An oscillation is a motion which moves back and forth about a fixed point. Oscillations are **periodic** which means that they occur at regular intervals.

The time taken for something to complete one full oscillation is called the **period**. Period has the symbol $'T'$ and is measured in seconds s. *It is a scalar quantity.*

The maximum displacement from the fixed point in any direction is called the **amplitude**.

Amplitude has the symbol 'A' and is measured in metres [m]. It is a scalar quantity.

The fixed point is often called the equilibrium position. It is at displacement $x = 0$.

Waves fall into a class of oscillation known as **Simple Harmonic Motion (SHM)**.
To be considered SHM, an oscillation has to have a restoring force which satisfies two criteria:

- It acts towards the centre
- It is proportional to the displacement

As $F = ma$, This is often expressed as:

$$a\,\alpha - x \tag{3.1}$$

Example: Hooke's Law

According to Hooke's law the tension in a spring is given by the equation:

$$\begin{aligned} F &= ks \\ ma &= Ks \\ a = \frac{ks}{m} &= s\frac{k}{m} \end{aligned} \tag{3.2}$$

The spring will try to contract if you stretch it and expand if you contract it so, the spring constant k always acts in the opposite direction to the displacement $(s = -x)$

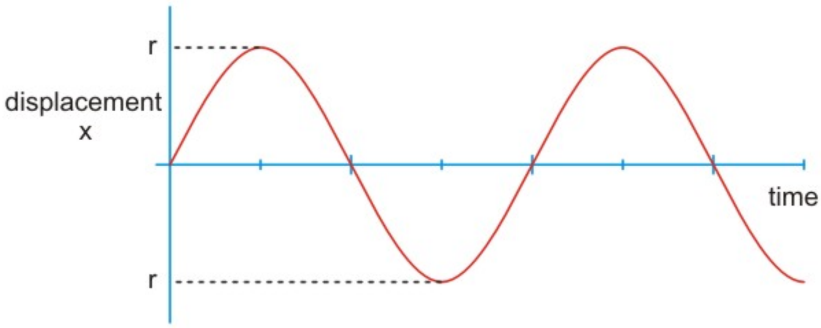
$$a = -x(k/m) \tag{3.3}$$

k and m are constant so:

$$a \; \alpha - x \tag{3.4}$$

Springs always follow SHM.

The displacement / time graph of SHM is generally a cosine wave.



3.1.1 Further Definitions

The number of full oscillations which occur in one second is called the frequency. Frequency has the symbol 'f' and is measured in Hertz Hz. *It is a scalar quantity.* Frequency is the number of waves per second and period is the number of seconds per wave so:

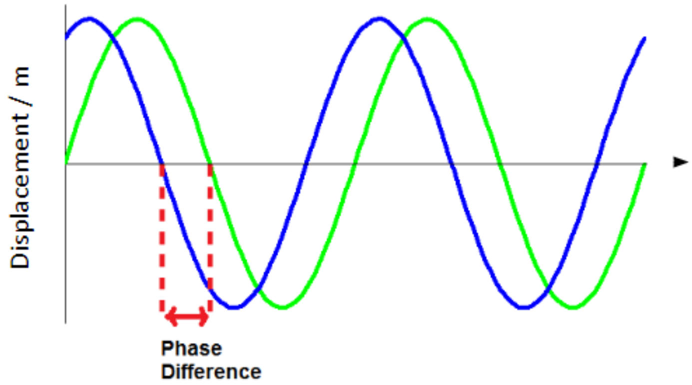
$$T = \frac{1}{f} \tag{3.5}$$

A cosine wave repeats every 360° (2π *radians*)

How far you are through an oscillation is normally expressed as an angle known as the **phase**.

Phase has the symbol ϕ and is measured in degrees or radians.

Two objects which will follow the same SHM but at different times will have graphs which look like this:



The difference is called a **phase change**.

Questions:

- Hertz is a derived unit. Express it in terms of SI units.
- If a fan's blades rotate 25 times per second and the fan moves back and forth twice per minute:
  - What is the frequency of the blades?
  - What is the period of the fan?

Answers:

- $\frac{1}{s}$
- 25 Hz
- 30 $seconds$

3.2 Equations of SHM - HL

Angular Frequency is the rate at which an oscillation changes phase angle. It will go through 2π *radians* in one period so the equation is:

$$\omega = \frac{2\pi}{T} \tag{3.6}$$

Where ω is angular frequency in $rad\ s^{-1}$

The range of any oscillation will be from x_0 (the amplitude) to $-x_0$

The phase angle at time "t" will be given by $\theta = \omega t$.

It follows that the displacement from the equlibrium point (x) at any point can be given by:

$$x = x_0 \cos(\omega t) \tag{3.7}$$

$$x = x_0 \sin(\omega t) \tag{3.8}$$

$\frac{d}{dx}(x^n) = nx^{n-1}$	$\frac{d}{dx}(fg) = fg'+gf'$	$\frac{d}{dx}\left(\frac{f}{g}\right) = \frac{gf'-fg'}{g^2}$
$\frac{d}{dx}f(g(x)) = f'(g(x))g'(x)$	$\frac{d}{dx}(\sin x) = \cos x$	$\frac{d}{dx}(\cos x) = -\sin x$
$\frac{d}{dx}(\tan x) = \sec^2 x$	$\frac{d}{dx}(\cot x) = -\csc^2 x$	$\frac{d}{dx}(\sec x) = \sec x \tan x$
$\frac{d}{dx}(\csc x) = -\csc x \cot x$	$\frac{d}{dx}(e^x) = e^x$	$\frac{d}{dx}(a^x) = a^x \ln a$
$\frac{d}{dx}(\ln x) = \frac{1}{x}$	$\frac{d}{dx}(\sin^{-1} x) = \frac{1}{\sqrt{1-x^2}}$	$\frac{d}{dx}(\cos^{-1} x) = \frac{-1}{\sqrt{1-x^2}}$
$\frac{d}{dx}(\tan^{-1} x) = \frac{1}{1+x^2}$		

Accelertion can be described as rate of change of velocity, or:

$$a = \frac{dv}{dt} = \frac{d}{dt}(-\omega x_0 \sin(\omega t)) \tag{3.9}$$

This is an important result.
If: $x = x_0 \cos(\omega t)$
And: $a - \omega^2 x_0 \cos(\omega t)$
Then:

$$a = -\omega^2 x \tag{3.10}$$

$$a\alpha - x \tag{3.11}$$

Any equation in this form fits the criteria for SHM.

SHM moves between velocity v (at equilibrium) and zero velocity (at x_0).

At equilibrium the system has kinetic energy.
At x_0 the system has potential energy.

Conservation of energy tells us that the energy at these points is the same. We call this the total energy of the system.

The potential energy at 'x' is the work done moving the object to that point:

$$\begin{aligned} E_p = -W = -\frac{1}{2}Fx^* \\ E_p = -\frac{1}{2}(ma)x \\ E_p = -\frac{1}{2}(m(-\omega^2 x))x \\ E_p = \frac{1}{2}m\omega^2 x_0^2 \end{aligned} \tag{3.12}$$

The maximum energy is the potential energy at the maximum displacement:

$$E_T = \frac{1}{2}m\omega^2 x_0^2 \tag{3.13}$$

If there are only kinetic and potential energies in the system; whatever is not potential is kinetic and vice versa:

$$E_T = \frac{1}{2}m\omega^2 (x_0 - x)^2 \tag{3.14}$$

Given $E_T = \frac{1}{2}m\omega^2(x_0 - x)^2$ and $E_K = \frac{1}{2}mv^2$:

$$v = \pm\omega\sqrt{x_0^2 - x^2} \tag{3.15}$$

Special Cases:
Springs:

$$T = 2\pi\sqrt{\frac{m}{k}} \tag{3.16}$$

Pendulum:

$$T = 2\pi\sqrt{\frac{L}{g}} \tag{3.17}$$

3.2.1 Travelling Waves

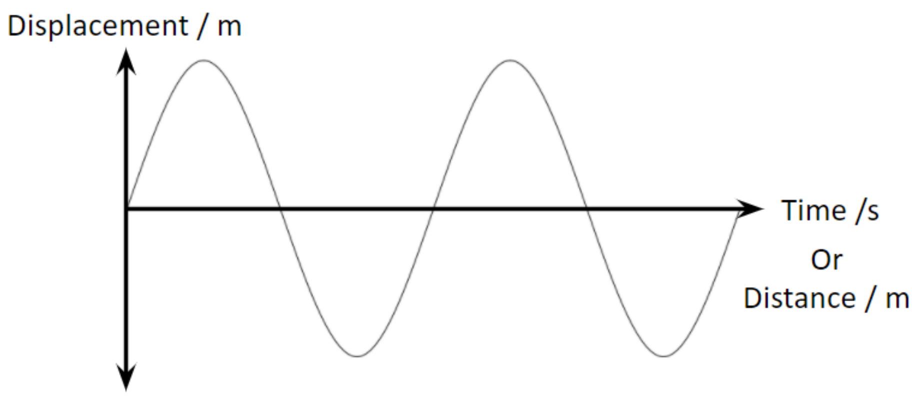
A wave is a disturbance in a medium which transfers energy without transferring mass.

Travelling waves are waves which move forwards in space and time.

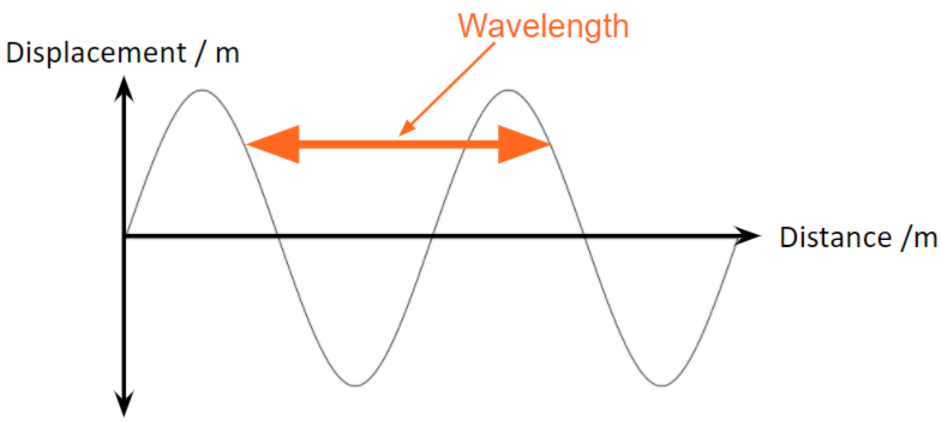
All waves have some things in common:

- They make something oscillate with SHM.
- They transfer energy.
- They can be used to send signals.

he graph of a wave would look like this:



The wavelength is the distance from one wave to the same point on the next wave. The symbol is λ and the unit is metres[m]. *It is a scalar quantity.*



In a longitudinal wave the particles move in the same direction as the energy.

Sound is a longitudinal wave.

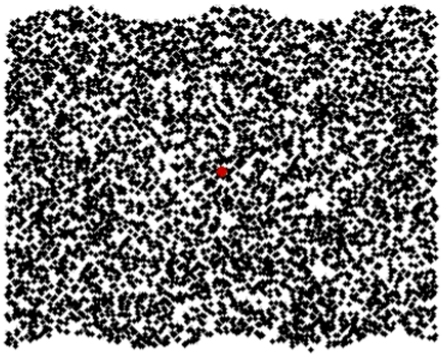
The direction the energy moves is called the direction of **propagation**.

A sound wave can be a pulse. This means that the oscillation doesn't have to repeat. You do still have to have a whole oscillation to put the particles back where they were.

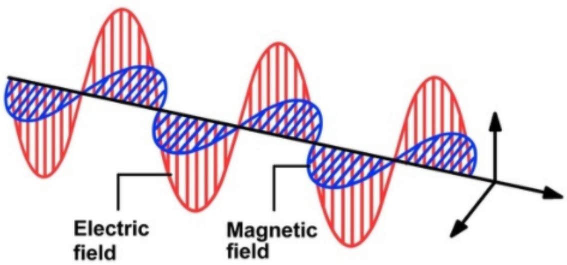
The speed of sound waves depends on the **MEDIUM**.

n a transverse wave the particles move perpendicular to the direction of propagation.

Water waves are transverse.

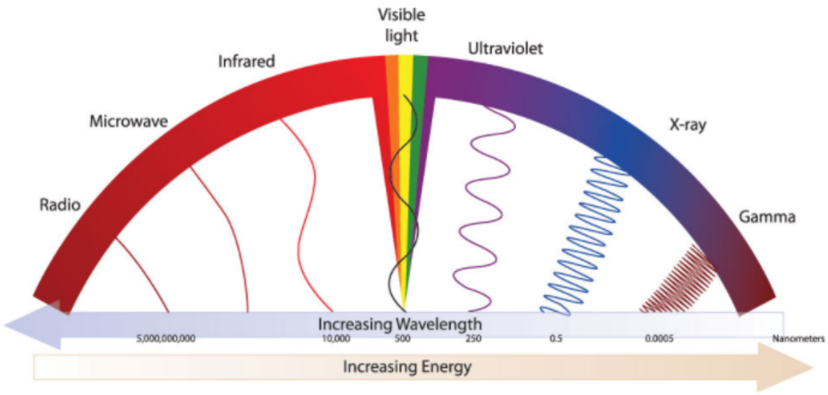


Electromagnetic waves oscillate in two directions each of which is perpendicular to the propagation and the other. This still counts as transverse.



Electromagnetic waves don't need particles, what they vibrate are the electric and magnetic fields.

Electromagnetic waves are defined by their wavelength:



The speed of a wave is given by:

$$v = \frac{s}{t} \tag{3.18}$$

But for one wave:

$$v = \frac{\lambda}{T} \tag{3.19}$$

Normally written as:

$$v = f\lambda \tag{3.20}$$

It follows that if the speed of a wave is constant (e.g. the speed of light or the speed of sound), then wavelength is inversely proportional to frequency.

Light:

$$c = f\lambda \tag{3.21}$$

Sound:

$$m = f\lambda \tag{3.22}$$

3.3 Intensity

The energy in electromagnetic waves is determined by the amplitude or, more accurately the amplitude squared.

$$I \ \alpha \ A^2 \tag{3.23}$$

This is difficult to measure so it is normally measured in terms of the power (P) they can deliver to a square meter of a surface. This is called the intensity which has the symbol I and the units Wm^{-2}.

$$I = P \ / \ Area \tag{3.24}$$

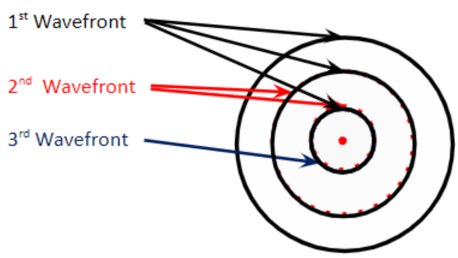
3.4 The Doppler Effect

The Doppler effect is that:

If there is a difference in speed between the source of a wave and an observer, the observer will experience the speed difference as a change in frequency.

It can be helpful to talk about waves in terms of what one point in that wave (e.g. a peak) does. That point is called a **wavefront**.

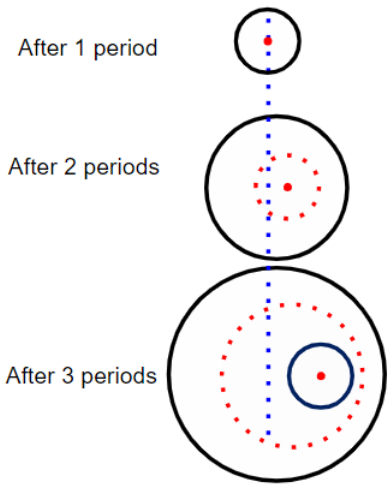
Imagine a series of waves moving outwards from a source:

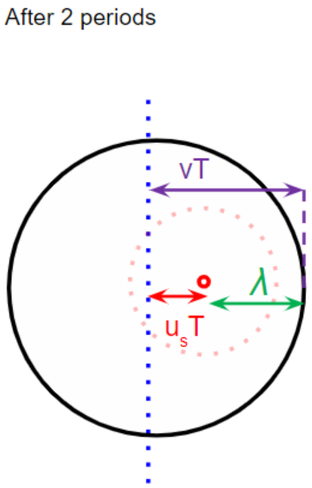


The waves in front of the source appear closer together (shorter wavelength).

The waves behind the source appear further apart (longer wavelength).

As frequency is easier to measure, we express the change in wavelength as a change in frequency. $v = f\lambda$ and the speed of the wave is constant.





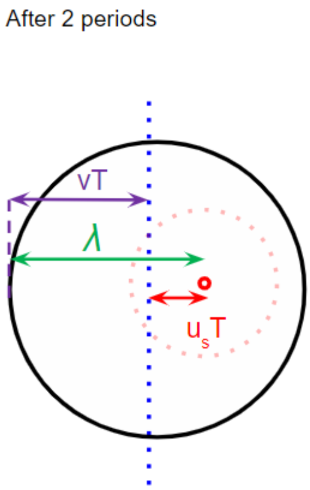
The time between wavefronts is the period (T).
The distance travelled by the source:
d = u_s x T
The distance travelled by the wave:
d = v x T
The observed wavelength:
λ= v x T - u_s x T
λ= (v - u_s) x T

$$\lambda = \frac{v - u_s}{f}$$

The observed frequency (v = f'λ):

$$\frac{v}{f'} = \frac{v - u_s}{f}$$

$$f' = f\left(\frac{v}{v - u_s}\right)$$



The time between wavefronts is the period (T).
The distance travelled by the source:
d = u_s x T
The distance travelled by the wave:
d = v x T
The observed wavelength:
λ= v x T + u_s x T
λ= (v + u_s) x T

$$\lambda = \frac{v + u_s}{f}$$

The observed frequency (v = f'λ):

$$\frac{v}{f'} = \frac{v + u_s}{f}$$

$$f' = f\left(\frac{v}{v + u_s}\right)$$

The observed frequency of a moving **SOURCE** is given by:

$$f\prime = f(\frac{v}{v \pm u_s}) \tag{3.25}$$

Where:
v is the speed of the wave.
us is the speed of the source.
f is the frequency of the source.
$f\prime$ is the frequency experienced by the observer.
$\pm$ is + if the source is moving away from the observer
$\pm$ is - if the source is moving towards the observer

The observed frequency of a moving **OBSERVER** is given by:

$$f\prime = f(\frac{v \pm u_o}{v}) \tag{3.26}$$

Where:
v is the speed of the wave.
us is the speed of the observer.
f is the frequency of the observer.
$f\prime$ is the frequency experienced by the observer.
$\pm$ is + if the observer is moving away from the source
$\pm$ is - if the observer is moving towards the source

3.5 EM Spectrum and Light

3.5.1 RedShift

There are many types of electromagnetic waves. They all propagate in the same way at the same speed (the speed of light).

They differ by their wavelength (and by extension their frequency).

EM waves are affected by the Doppler effect in the same way as sound waves.

This has an important consequence in astronomy:
By comparing the colour of a star to the colour we would expect, we can determine the speed and direction of movement of that star.

The missing (Frauenhoffer) lines from a star's EM spectrum depend on the chemical elements in that star.
If the star is moving away those lines move to the red side. They are red-shifted.
If it is moving towards us they are blueshifted.

The symbol for redshift is 'z' (no units). Redshift can be calculated using:

$$\frac{\delta\lambda}{\lambda} = \frac{\delta f}{f} \approx \frac{v}{c} \tag{3.27}$$

Outside our galaxy, all stars are redshifted.

This means that the universe is expanding.

3.5.2 Uses

Radar
RaDAR stations send out a radio signal and measure the frequency of the reflection. From the change in frequency, they can work out the speed.

Weather stations use doppler shifting to analyse storms (using microwaves).
The police use it to analyse vehicles' speeds.

Ultrasound

Doctors use ultrasound to image the blood flow in your body. They can see where liquids are moving by the change in frequency of the ultrasound waves.

3.6 Polarization

EM waves are transverse oscillations in electric and magnetic fields.

In each field, the oscillation can happen in any direction perpendicular to propagation (as long as the electric oscillations stay perpendicular to the magnetic ones).

A polarized wave is one that only oscillates in one direction (in each field).

A polarizer is something that turns un-polarized light into polarized light.

Normally by blocking out the perpendicular components of oscillations.

As a result, the total intensity of an un-polarized wave will half to become the intensity of the polarized wave.

For every component $<$ 45 degrees there is a component $<$ 45 degrees which balances it out

When you use a polarizer on an already polarized wave it is called an analyser. Again, it blocks perpendicular components. As a result, the wave always leaves the analyser polarized in the orientation of the analyser.

Malus's law says that the intensity allowed through an analyser is given by:

$$I = I_o \cos^2(\theta) \tag{3.28}$$

Where I is the transmitted intensity, I_o is the original intensity and θ is the angle between the analyser and the original oscillation.

When an EM wave reflects of a plane surface, it will become polarized in line with that surface if the angle of incidence is Brewster's angle.

Polarizing lenses are polarized at 90o to the horizontal to block this light out and cut down on glare.

3.7 Snell's Law

When light changes medium, it can change speed. If it enters the medium at an angle this can make it change direction. The amount by which it changes direction can be quantified using Snell's law:

$$\frac{v_2}{v_1} = \frac{\sin\theta_2}{\sin\theta_1} \tag{3.29}$$

Snell's law can be simplified using refractive index.

Refractive index is the ratio of the speed of light in a vacuum to speed of light in a material.
For example, the speed of light in a vacuum ($3 * 108\ ms^{-1}$) is 1.5 times greater than the speed of light in glass ($2 * 108\ ms^{-1}$) so glass has a refractive index of 1.5.

The refractive index for air is taken as 1.

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1} \tag{3.30}$$

Where:
n_1 is the refractive index of material 1
n_2 is the refractive index of material 2
v_1 is the speed of light in material 1
v_2 is the speed of light in material 2
θ_1 is the angle to the normal in material 1 (angle of incidence)
θ_2 is the angle to the normal in material 2 (angle of refraction

3.7.1 Critical Angle

When light moves into a medium with a lower refractive index it speeds up. This means that the angle of refraction is bigger than the angle of incidence.

When this happens Snell's law will sometimes predict an angle of refraction greater than 90°. This can't happen. If the angle of refraction > 90°, the light is reflecting.

The angle of incidence that gives you a refraction of 90° is called the critical angle. Above the critical angle you reflect, below it you refract. You can calculate the critical angle using:

$$\sin\theta_c = \frac{1}{n} \tag{3.31}$$

If all of a ray of light reflects when it should refract, it is called **total internal reflection** (TIR).
Optical fibres keep light above the critical angle between the two ends. thus are an example of TIR.

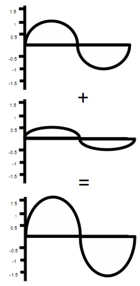
The frequency of a wave is always the same as the frequency of the source.

$v = f\ \lambda$, so the wavelength will also change when a ray is refracted.

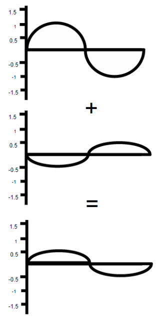
3.8 Interference

Interference is a property of all waves. It is when two waves cross paths and combine. When you combine two waves you add the y values at each x coordinate.

When two waves combine and make each other bigger, it is called **constructive interference**.



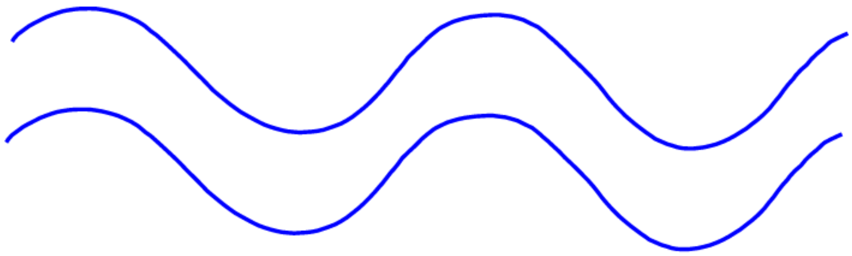
When two waves combine and make each other smaller, it is called **destructive interference**.



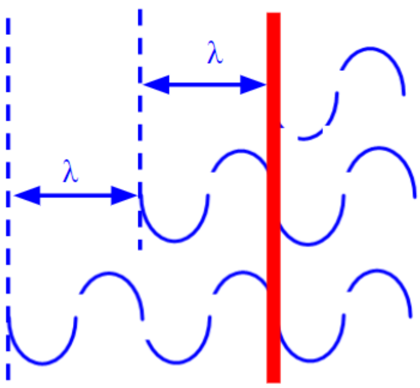
Key Vocabulary:

- Phase: How far the wave is through its oscillation normally measured as an angle.
- In phase: At the same point in the cycle.
- Out of phase: At a different point in the cycle.
- Coherent: The difference in phase is always the same. This can only happen if the waves have the same frequency and wavelength.

Path difference: The difference in the distance two waves have travelled to reach a point.



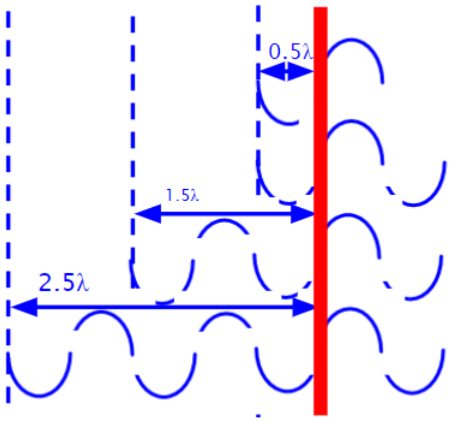
To get a maximum value we need the waves to be coherent and in phase. This happens when similar waves are a whole number of wavelengths apart at a point:



Constructive Interference:

$$path\ difference = n * \lambda \tag{3.32}$$

To get the minimum possible value you need the waves to be π radians out of phase (trough to peak). This happens when coherent waves are half a wavelength apart.



Destructive Interference:

$$path\ difference = (n * \frac{1}{2}) * \lambda \tag{3.33}$$