Electromagnetic Radiation and Waves

Study Design

- identify all electromagnetic waves as transverse waves travelling at the same speed, c, in a vacuum as distinct from mechanical waves that require a medium to propagate
- identify the amplitude, wavelength, period and frequency of waves
- calculate the wavelength, frequency, period and speed of travel of waves using: $\lambda = \frac{v}{f} = vT$
- explain the wavelength of a wave as a result of the velocity (determined by the medium through which it travels) and the frequency (determined by the source)
- describe electromagnetic radiation emitted from the Sun as mainly ultraviolet, visible and infrared
- compare the wavelength and frequencies of different regions of the electromagnetic spectrum, including radio, microwave, infrared, visible, ultraviolet, x-ray and gamma, and compare the different uses each has in society
- calculate the peak wavelength of the radiated electromagnetic radiation using Wien's Law: $\lambda_{max}T =$ constant
- compare the total energy across the electromagnetic spectrum emitted by objects at different temperatures

Introduction

Most information about our surroundings comes to us in some form of waves. It is through wave motion that sounds come to our ears, light to our eyes, and electromagnetic signals to our radios and televisions. Through *wave motion***,** energy can be transferred from a source to a receiver without the transfer of matter between the two points.

If a stone drops into a quiet pool of water, a disturbance is created where the stone enters the water. This disturbance spreads out to eventually reach all parts of the pool.

The stone entering the water sets into motion the particles of the water that it strikes. These particles set neighbouring particles into motion and so the disturbance is propagated (spread) through the liquid. However, no individual particle travels far from its initial position –The wave transports of energy without transporting matter. The motion of the wave through the medium is a result of the action of successive parts of the medium on each other. If the particles were completely independent of each other, no wave could pass through.

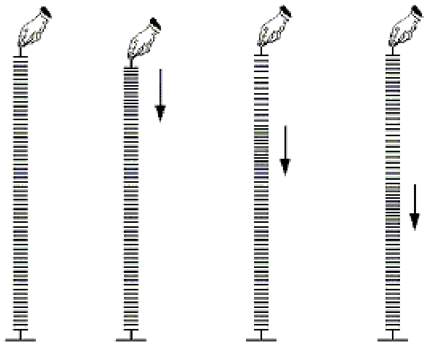
All forms of wave motion allow the transfer of energy without the net transfer of matter.

Categories of Waves

You will be familiar with several types of waves, water waves being the most obvious. You may be familiar with others such as pulses down a slinky, or the motion a string as illustrated in the diagram below. Other phenomenon, such as sound and light are waves. Waves can be grouped into two different categories, longitudinal and transverse waves.

Longitudinal Wave

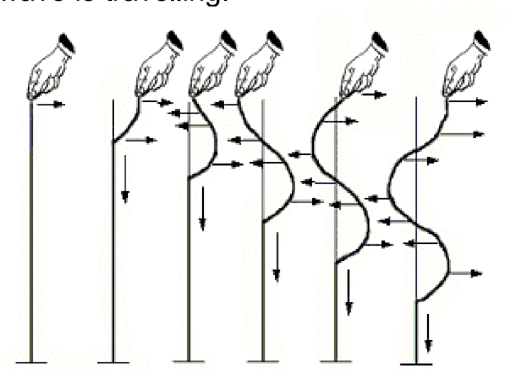
In a longitudinal wave, such as a pulse down a slinky as illustrated in the diagram below, the wave disturbance is in the same direction as the wave is travelling.



Examples: sound, pulses in slinkies.

Transverse Wave

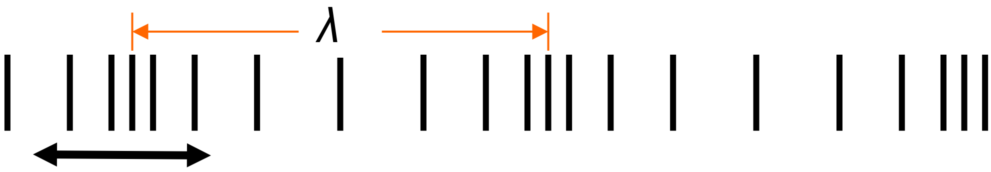
In a transverse wave, such as a pulse down a spring as illustrated in the diagram below, the wave disturbance is perpendicular to the direction as the wave is travelling.



Examples: Light, water waves.

Longitudinal waves

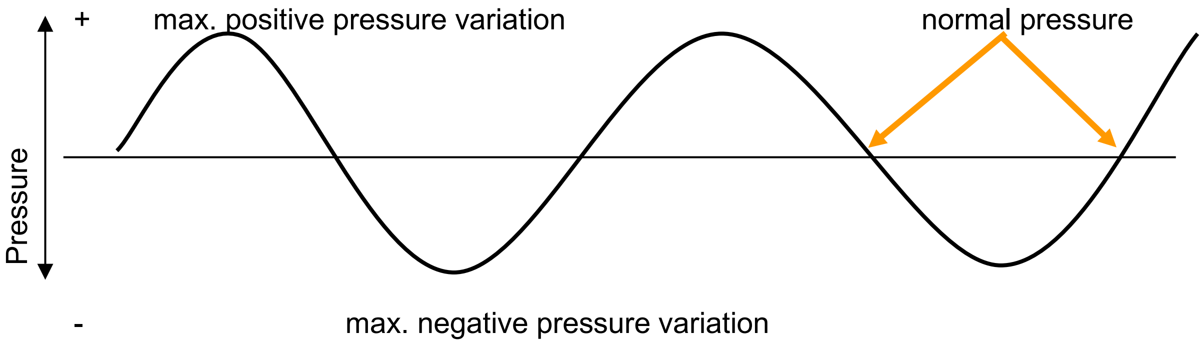
When the vibration of the waves is in the same direction as the line of travel, then the wave is longitudinal. In a longitudinal wave the motion is in the same direction as the motion of the wave, but the particles do not move forward, they vibrate around an equilibrium position.
The distance between any two identical points is called the wavelength λ.



The movement of particle is in this direction.

compression rarefaction

It is possible to represent this particle movement as a pressure variation

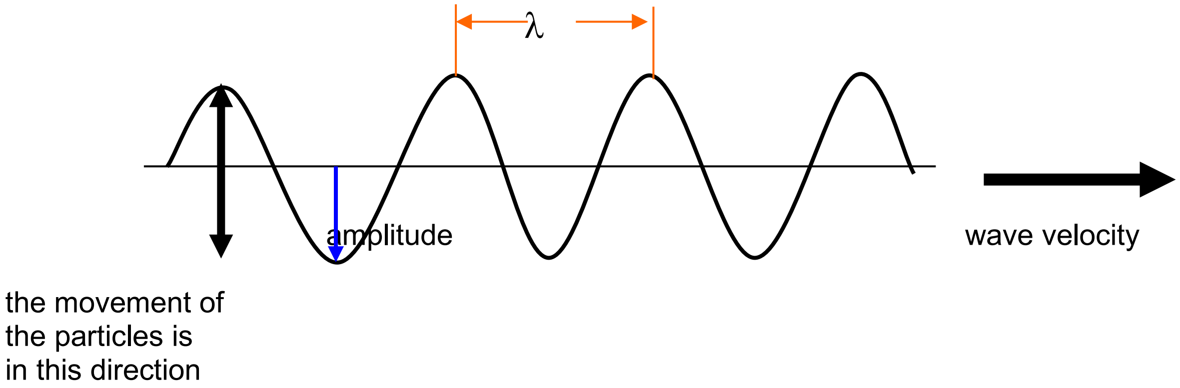


Lines close together represent high pressure regions, where there is less shading there is a lower pressure region. At the two positions of maximum pressure variation (compressions and rarefactions) the molecules at these points are in their rest position. The minimum pressure variation occurs when particles are the furthest from their rest positions. The air pressure is normal, (pressure variation is zero) midway between the compressions and rarefactions. When sound travels through air it is a series of compressions and rarefactions.

Transverse waves

When waves vibrate up and down in a direction perpendicular to the direction of motion of the wave, it is referred to as a transverse wave. e.g. water waves, where the motion of the water particles is at right angles (up and down) to the direction of the wave (forward).

A transverse wave is modelled below



Describing Waves

Waves can be characterised by key quantities: speed, frequency, period, amplitude and wavelength.

Frequency

Frequency is a measure of how rapidly the source of the wave is vibrating. The frequency (f) is defined as the number of vibrations per second. The units for frequency are Hertz, Hz, which are cycles per second.

Period (T)

The period is the length of time required for one full cycle of the wave to be complete. Frequency is the number of cycles per second, $\therefore$ f = $\frac{1}{T}$, where T is the period, the time taken for 1 cycle.

Frequency is measured in Hertz or cycles per second.

Speed (v)

The speed of the wave is obviously how fast the wave is travelling. Sound waves propagate at about 330 m/s. The speed of light in a vacuum is 3×10^8 m/s. For a uniform medium, the speed is constant. The frequency, amplitude and wavelength of a wave do not change its speed.

Wave equation (v = f λ)

The wave equation links the velocity of the wave to the frequency and the wavelength.

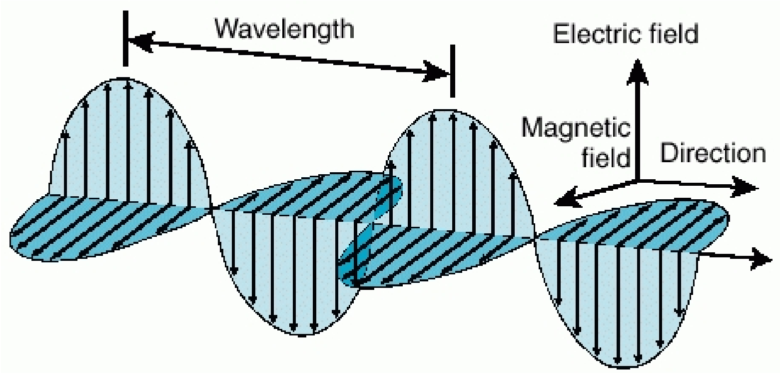
v = f λ

where v is the velocity in m/s, f is the frequency in Hz and λ is the wavelength in metres.

Amplitude

The amplitude of a wave is the distance from the rest position to the limit of a crest or trough; the total from crest to trough is **twice** the amplitude. The amplitude of the wave is an indication of the amount of energy that the wave is carrying.

Light is the only thing that we can see. But what is light? Maxwell developed an answer to question of what the nature of light is, when he discovered that light was an electromagnetic radiation within the frequency range of 4.3×10^{14} to 7×10^{14} Hz. These waves activate the “electrical antennae” in the retina of the eye. He understood that light of any kind is energy carrying waves of electric and magnetic fields that continually regenerate each other and travel at a single fixed speed, the speed of light.



An accelerating charge creates a changing current. Every current is surrounded by a magnetic field, so every changing current is surrounding by a changing magnetic field. We also know that every changing magnetic field will induce an EMF, in other words, generates an electric field. This is electromagnetic induction.

If the magnetic field is oscillating, the electric field that it generates will be oscillating, too. This oscillating electric field induces an oscillating magnetic field. The vibrating electric and magnetic fields regenerate each other to make up an **electromagnetic wave**, which emanates from the vibrating charge.

In summary, light is an energy- carrying electromagnetic wave that emanates from vibrating electrons in atoms.

Speed of Light (in a vacuum)

There is only one speed for which the electric and magnetic fields remain in perfect balance, reinforcing each other as they carry energy through space. If light were to slow down, its changing electric field would generate a weaker magnetic field, which in turn, would generate a weaker electric field, and so on, until the wave dies out. This would result in a loss of energy, which is incompatible with the law of conservation of energy. So light can't slow down.

If light were to speed, up a similar argument prevails.

At only one speed does mutual induction continue indefinitely, with neither loss nor gain in energy, and this is accepted as 3.0×10^8 m s^{-1}, c (from the Latin word for speed celeritas) – the speed of light.

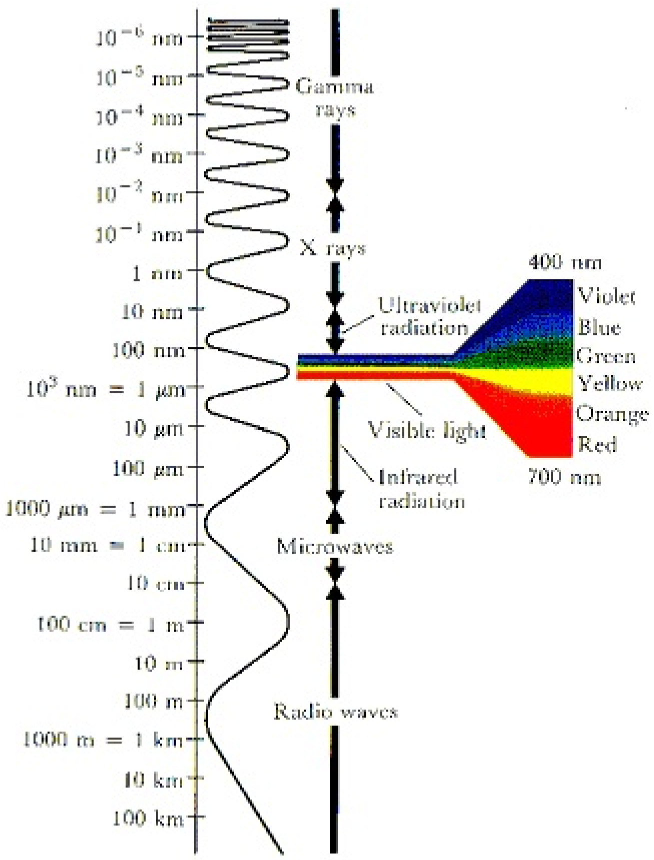
Electromagnetic spectrum

In a vacuum, all electromagnetic waves move at the same speed, c, the speed of light. They differ from one another in their wavelength (and thus frequency). The electromagnetic spectrum includes waves with an enormous range of wavelengths, from hundreds of kilometres to smaller than the size of the nucleus of an atom.

Visible light, (~4.3×10^{-7}m to ~6.9×10^{-7}m) is detected by the retina of the eye. The longer wavelengths (lower frequency waves) appear red, and the shorter wavelengths (higher frequency waves) appear violet. The limits of the visible spectrum are not well defined, because eye sensitivity drops off gradually at both long and short wavelengths.

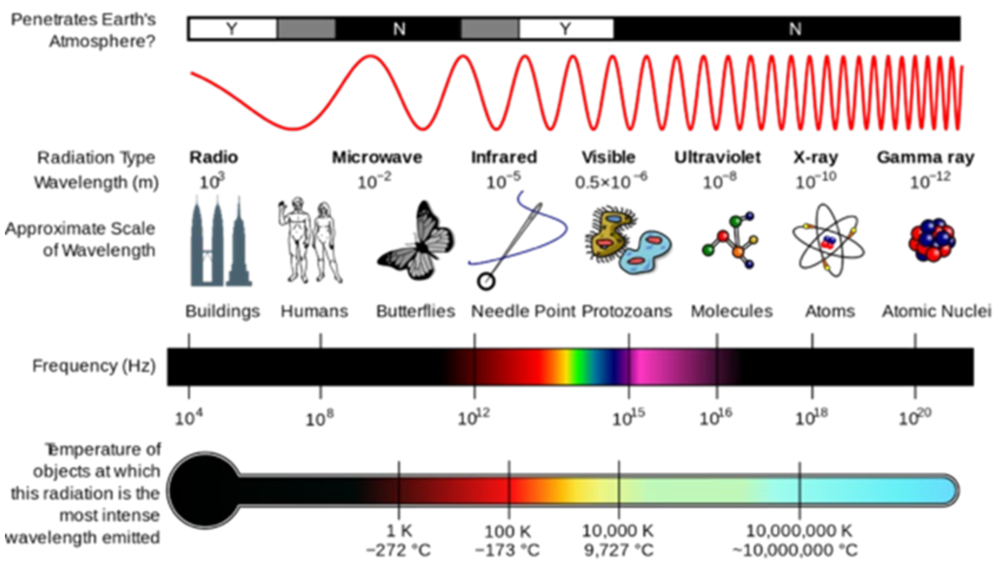
Visible light makes up less than 10^{-6} % of the measured electromagnetic (EM) spectrum.

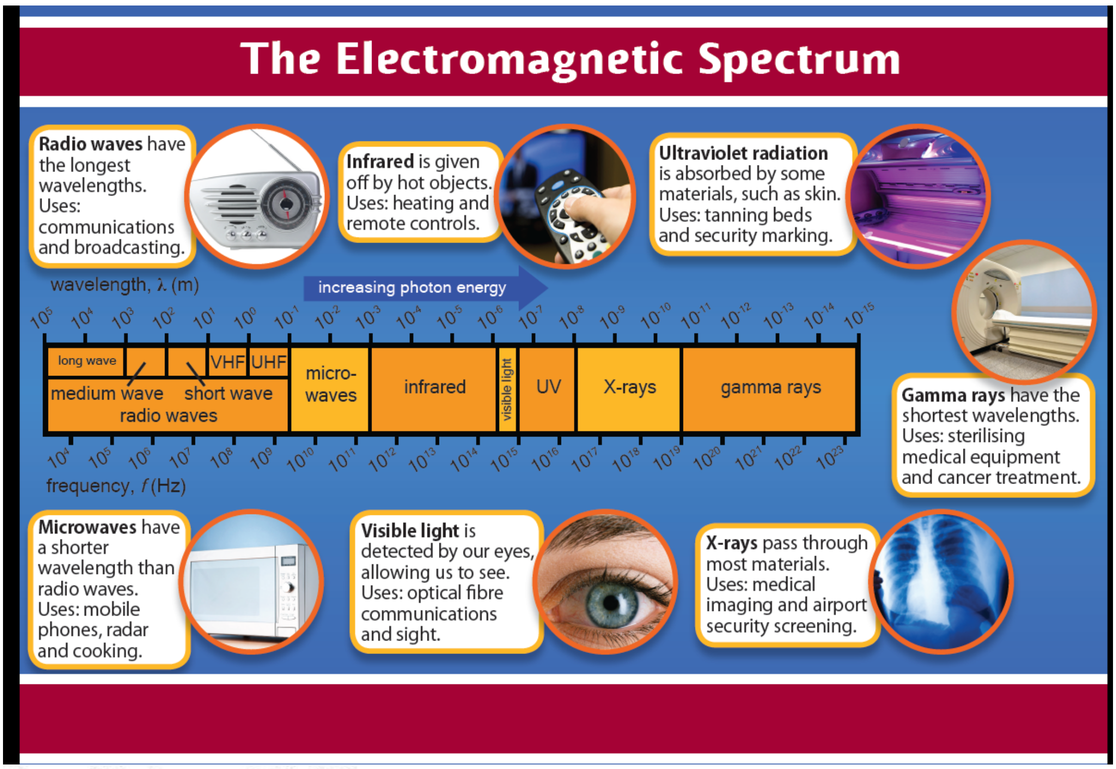
By 1864 the Scottish physicist, James Maxwell, had worked out a mathematical theory of electromagnetism. He developed a series of equations to show that the energies of heat, light and electricity are propagated in free space (vacuum) as electromagnetic waves, their different properties being due to differences in wavelength and frequency. Such waves travel at the same speed - the speed of light. They are *transverse waves* in which the disturbance is a time variation in both an electric and a magnetic field set at right angles to each other.

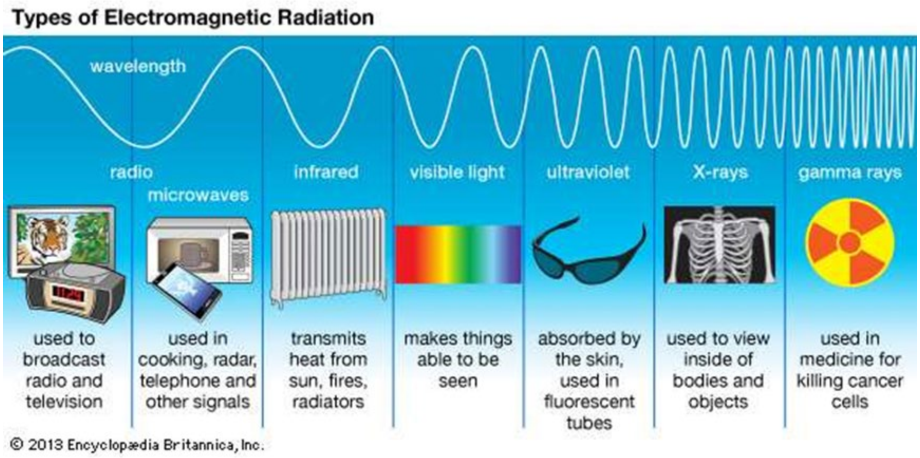


Maxwell suggested that the vibrating electric charges that produced light were the electric charges in the atom. Maxwell's theory also did not require, as a necessity, the idea that light had to have a medium through which to travel. For years scientists had been searching for the medium or 'aether' through which light travelled. Maxwell's work only assumed light to be travelling in an electromagnetic field and not necessarily a 'particle medium'.

Region	Wavelength range (approx.)	Frequency range (approx.)	Comments
Long-wave radio	>10 m	$<3x10^7$ hz	Includes traditional AM radio region. These frequencies can travel long distances by multiple reflections between the surface of the earth and its ionosphere.
Short-wave radio	10 cm - 10 m	$3x10^7$ - $3x10^9$	Used for TV, FM, and other communication purposes. Generally travels only relatively short distances because the ionosphere is transparent to it.
Microwave	1 mm - 10 cm	$3x10^9$ - $3x10^{11}$	Present limit of radio technology for most purposes.
Far infrared	30 mm - 1 mm	$3x10^{11}$ - 10^{13}	3 K radiation fills universe.
Thermal infrared	3 mm - 30 mm	10^{13} - 10^{14}	Thermal emission of earth and planets.
Near infrared	700 nm - 3mm	10^{14} - $4x10^{14}$	Solar and stellar emission.
Visible	400 nm -700nm (1.7 - 3 eV)	$4x10^{14}$ -$7x10^{14}$	Peak of solar radiation. Visible to human eye, standard photographic film and CCD video detectors.
Ultraviolet	200 nm -400nm (3 - 6 eV)	$7x10^{14}$ - $1.5x10^{15}$	Divided at 300 nm by atmospheric (ozone) cutoff. Appreciable solar flux causes sunburn.
Vacuum UV (EUV)	10 nm - 200 nm (6 - 120 eV)	$1.5x10^{15}$ -$3x10^{16}$	Very strong absorption in matter, hence very difficult to observe.
X-rays	120 eV-100keV	$3x10^{16}$ -$3x10^{19}$	Produced by electron beams in X-ray tubes, and by inner atomic transitions. Progressively more penetrating as E increases, up to many centimeters in water.
γ-rays	100 keV	$3x10^{19}$	Produced by nuclear and other high energy processes. Can penetrate up to meters in water.


Penetrates Earth's Atmosphere?
Y
N
Y
N
Radiation Type
Wavelength (m)
Radio
10^3
Microwave
10^-2
Infrared
10^-5
Visible
0.5×10^-6
Ultraviolet
10^-8
X-ray
10^-10
Gamma ray
10^-12
Approximate Scale of Wavelength
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^12
10^15
10^16
10^18
10^20
Temperature of objects at which this radiation is the most intense wavelength emitted
1 K
−272 °C
100 K
−173 °C
10,000 K
9,727 °C
10,000,000 K
~10,000,000 °C


The Electromagnetic Spectrum
Radio waves have the longest wavelengths. Uses: communications and broadcasting.
Infrared is given off by hot objects. Uses: heating and remote controls.
Ultraviolet radiation is absorbed by some materials, such as skin. Uses: tanning beds and security marking.
wavelength, λ (m)
increasing photon energy
long wave
medium wave
short wave
VHF
UHF
radio waves
micro-waves
infrared
visible light
UV
X-rays
gamma rays
frequency, f (Hz)
Gamma rays have the shortest wavelengths. Uses: sterilising medical equipment and cancer treatment.
Microwaves have a shorter wavelength than radio waves. Uses: mobile phones, radar and cooking.
Visible light is detected by our eyes, allowing us to see. Uses: optical fibre communications and sight.
X-rays pass through most materials. Uses: medical imaging and airport security screening.


Types of Electromagnetic Radiation
wavelength
radio
microwaves
infrared
visible light
ultraviolet
X-rays
gamma rays
used to broadcast radio and television
used in cooking, radar, telephone and other signals
transmits heat from sun, fires, radiators
makes things able to be seen
absorbed by the skin, used in fluorescent tubes
used to view inside of bodies and objects
used in medicine for killing cancer cells
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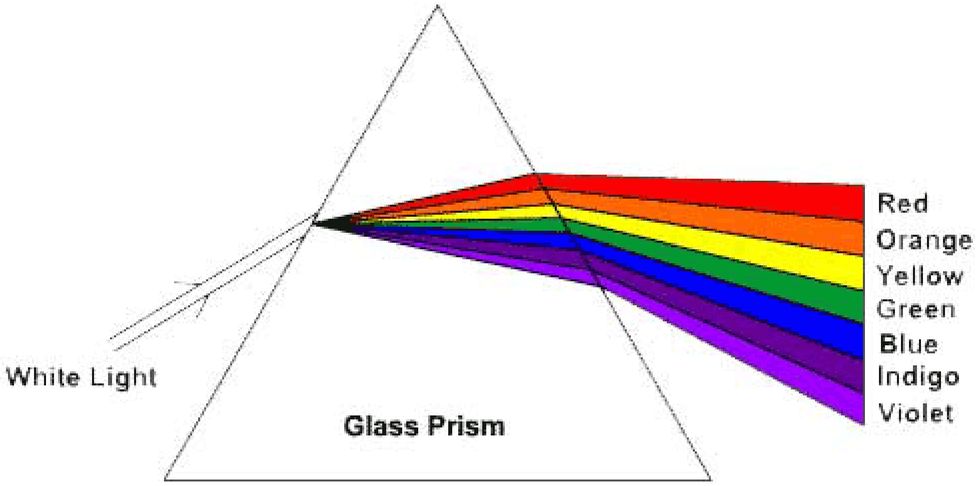
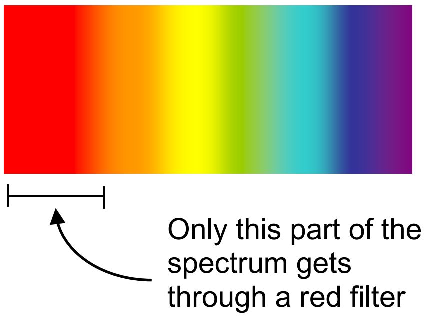
White Light

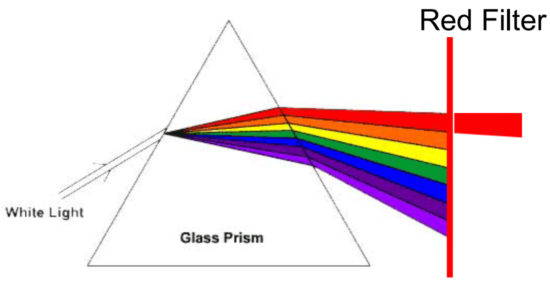
White light is made up of all of the colours of the visible spectrum. The light can be split into its constituent colours by shining it through a prism, as shown in the diagram below. These same colours are observed when you look at a rainbow.



Colour by Filtering

When you look through a piece of coloured cellophane, everything you see is tinged with the colour of the cellophane. The cellophane is acting as a *filter*. A filter is an object that only lets through a small part of the visible spectrum through. For instance, a red filter would only let through the red part of the visible spectrum. The filter would absorb all of the other colours.

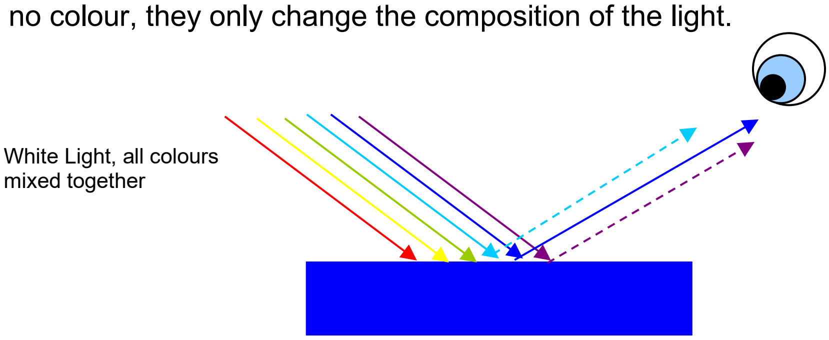




When you look at an object through a red filter, only red light from an object will pass through the filter, so you observe the object to be red. If you have two filters in a row, light will only pass through both of them if there is a region of overlap between the two filters. For example, a red filter followed by a yellow filter would let through a little orange light, as the orange light can pass through both filters.

Colour by Reflection

Coloured objects do not reflect the entire visible spectrum equally. An object that appears blue will reflect blue light, and a little cyan and violet. Hence these are the only colours that reach your eye, so you perceive the object to be blue. Note that it is the *light* that is blue, not the *object*. Objects have no colour, they only change the composition of the light.

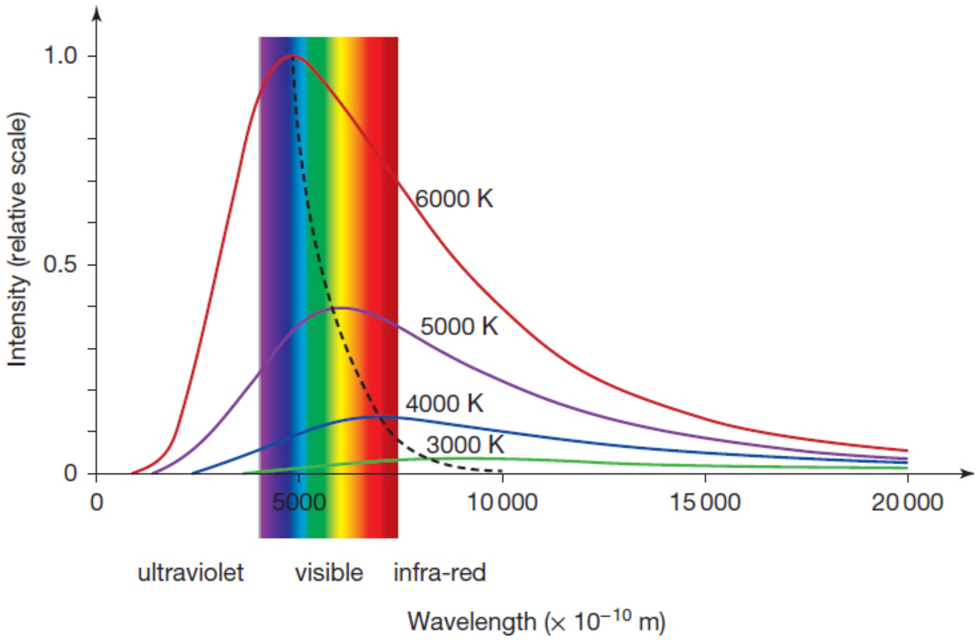


Wein's Law

The graph below shows the emission spectrums for bodies at different temperatures. The black dotted line indicates the peak emissions from a body at a certain temperature, from this it is possible to work out the temperature of an object from its emission spectrum. This relationship is known as Wein's Law and can be stated as

$$\lambda_{max} = \frac{2.898\times10^{-3}}{T} \quad or\ \lambda_{max}T = 2.898 \times 10^{-3}\ m\,K,$$

where λ_{max} is the wavelength at which the maximum emission take place and T is the surface temperature in kelvin (K).



Absolute temperature in kelvin = temperature in °C + 273

Total energy emitted every second is described by **Stefan-Boltzmann Law**

$$P = e\sigma AT^4$$

where *e* is the the emissivity of the surface of the object (emissivity is the measure of an object's ability to emit energy. Emissivity can have a value from 0 (shiny mirror) to 1.0 (blackbody)), σ is the Stefan-Boltzman constant ($5.67 \times 10^{-8}\ Wm^{-2}K^{-4}$), T is the temperature in Kelvin and A is the surface area.

If the object is at temperature T and the temperature of surroundings is T_s

$$P = e\sigma A(T^4 - T_s^4)$$