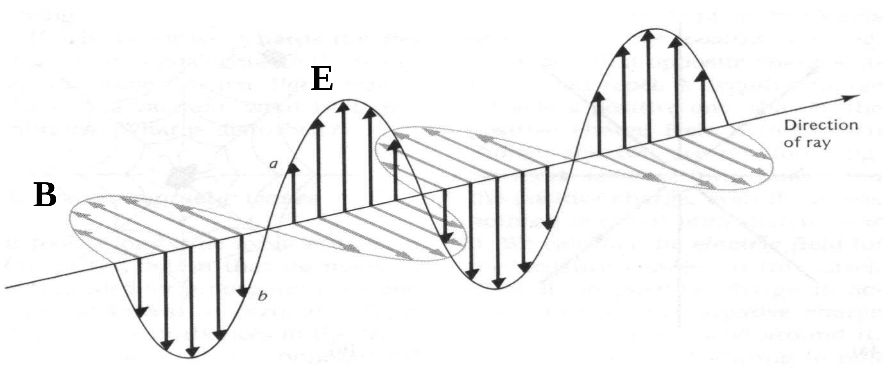
Optics 3:   More on the Nature of light

Maxwell showed that light is an electromagnetic wave – meaning that it is made up of perpendicular electric, **E**, and magnetic, **B**, fields oscillating together. A single, infinitesimally thin, ray can be represented by the figure below.



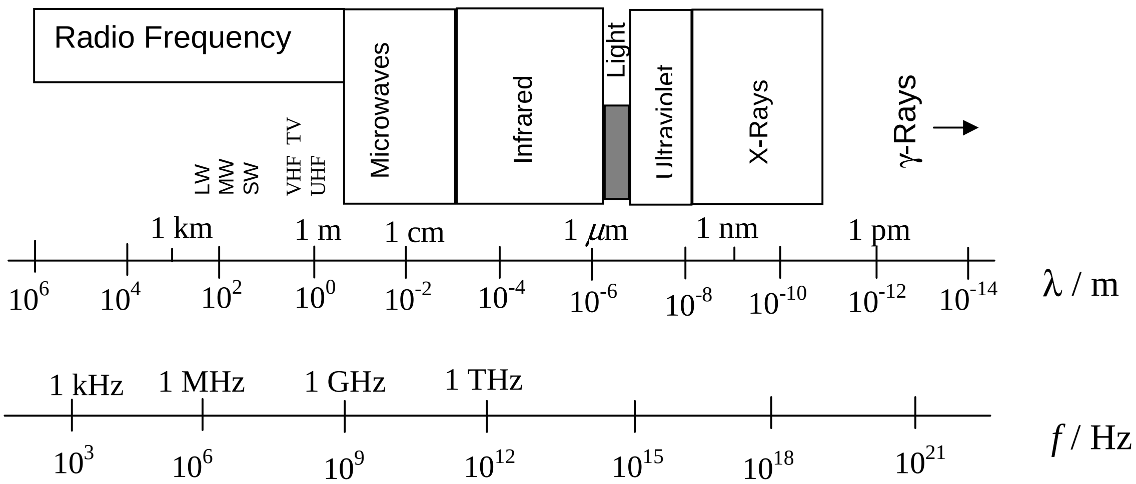
The magnetic field interacts much more weakly with matter than the electric field and can often be ignored. Light can then be modeled as if it were a single oscillating transverse wave.

Generating and Detecting EM waves

The disturbance that generates an EM wave is the movement of charge - but this can happen on a huge range of scales - from nuclear to galactic. This gives rise to a huge range of possible wavelengths. EM waves are detected when they interact with matter and cause charges to move.

The Electromagnetic Spectrum

The wavelength of an electromagnetic wave can vary from millions of kilometers to γ-rays with $\lambda \sim 10^{-12}$ m and less.



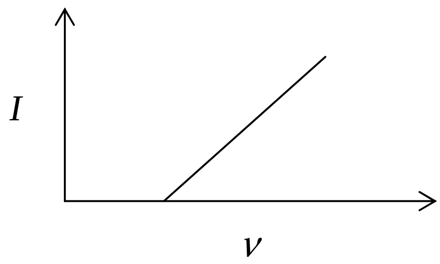
Light forms a very narrow band of frequencies from 780-390 nm. It is usually produced by a rearrangement of outer electrons in atoms and molecules.

Colour	λ/nm	$f\,/10^{12}$Hz
Red	780-622	384-482
Orange	622-597	482-503
Yellow	597-577	503-520
Green	577-492	520-610
Blue	492-455	610-659
Violet	455-390	659-769

Different processes give rise to EM waves at other wavelengths. Broadly speaking, radio waves are formed by the movement of electrons in aerials, infrared is generated by molecular rotations and vibrations, X-rays are radiated when inner electrons are excited and γ-rays arise from nuclear processes. These processes are in order of increasing energy. The behaviour of EM radiation at low frequencies is well described by classical wave theory but at high frequencies it interacts with matter increasingly according to quantum theory.

The Photoelectric effect

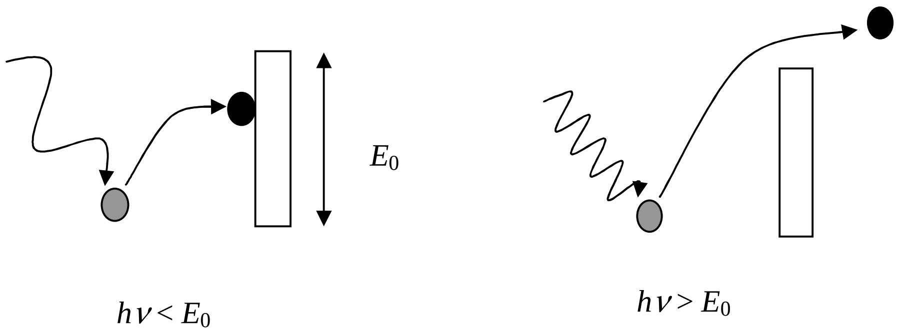
Shining a light on the surface of metals may free some electrons and allow them to escape the surface. In a vacuum, they can be collected some distance away and a current made to flow. However, it is found the light must have a high enough frequency. For example a blue light (more usually UV) may produce a photocurrent but a red light might not – no matter how bright the light.



This is an experimental fact that cannot be explained by classical wave theory. It is a quantum effect first explained by Einstein. This treats EM radiation as packets of energy called photons. The energy contained in each photon is proportional to the frequency f

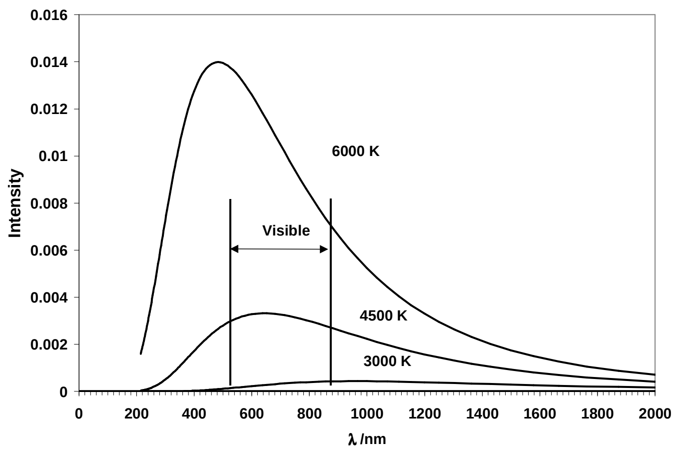
$$E = hf \text{ or, more commonly } E = h\nu$$

using the symbol ν (Greek nu) for the frequency. The constant h = 6.626×10^{-34} Js has units that convert frequency in Hz to energy in Joules and is called Planck's constant. To knock electrons out of the metal they must be hit by a photon with sufficient energy. No matter how many photons of low energy are beamed at the surface they will not add together to surmount the barrier.



Black body radiation

One way of making light is to heat an object up. Heating causes the molecules in an object to jiggle about randomly and this means that the charges making up the atoms are forced to oscillate and radiate energy. Our experience tells us that the hotter something is the more brightly it glows. We may also notice that the colour changes. A bright red fire becomes dull red as it cools. Steel from a furnace is almost white hot while the light from a welding torch in action is bright blue. The hotter the object, the faster the atoms jiggle and the higher the frequency that they radiate. The way that EM radiation is emitted from hot objects is usually described for a “black body”. This is an idealized object that absorbs all radiation that falls on it. A small window in a furnace is a good approximation. The curve below shows how the intensity of EM radiation changes with temperature over a range of wavelength. Note that the intensity of light in the visible band increases and shifts to shorter wavelengths (blue) as the temperature is increased.



Detection of EM radiation

Just as moving charges emit EM radiation it can set charges in motion when it strikes a material. This may have secondary effects that can lead to detection. But, as with emission, the way that this happens depends on the wavelength. Radio waves set up currents in an aerial which can be amplified to give a signal that may contain information. In the eye the photochemical rhodopsin becomes excited and changes shape generating an electrical signal. We cannot see IR but we can feel it as radiative heat. Many insects can see into the UV – we only detect this frequency by sunburn!

Intensity

The amount of energy illuminating a surface is called the irradiance and is the average energy per unit area per unit time. In the wave picture it is proportional to the square of the amplitude of the electric field $I \propto \langle \mathbf{E}^2 \rangle$.

In the quantum picture, for a particular frequency, this is proportional to the number of photons hitting an area in unit time.

Inverse square law

Light from a point source emanates in all directions and produces spherical waves. The surface area of a sphere radius *r* is

$$A = 4\pi r^2$$

so as the wave spreads out the energy is spread more thinly over the surface. The irradiance falls in proportion to the inverse square of the distance from the source

$$I \propto \frac{1}{r^2} \quad .$$

Modeling Light

The study of optics requires *models* for the behaviour of light. These allow us to predict what light will do in the real world. There are traditionally two major branches of optics: physical and geometrical. Nowadays there is a third branch called Quantum optics.

Physical optics – or Wave optics deals primarily with the nature and properties of light itself. It is an approximation valid when energy changes are negligible. Light is treated as a wave. Allows an understanding of the "microscopic" effects such as diffraction, interference and polarization.

Geometrical optics – a further approximation adequate when objects are large compared to the wavelength of light. Light is treated as rays traveling in straight lines. This is sufficiently accurate for most calculations involving eyes and lenses.

Quantum optics - The best, but most complex, description we have. Needed when light interacts with matter and there are significant energy changes e.g. for an understanding of the photoelectric effect, spectra, Lasers, Electro-optic devices, and esoteric things like photon-entanglement & cryptography.

We will mainly use physical and geometric optics to understand optical problems.