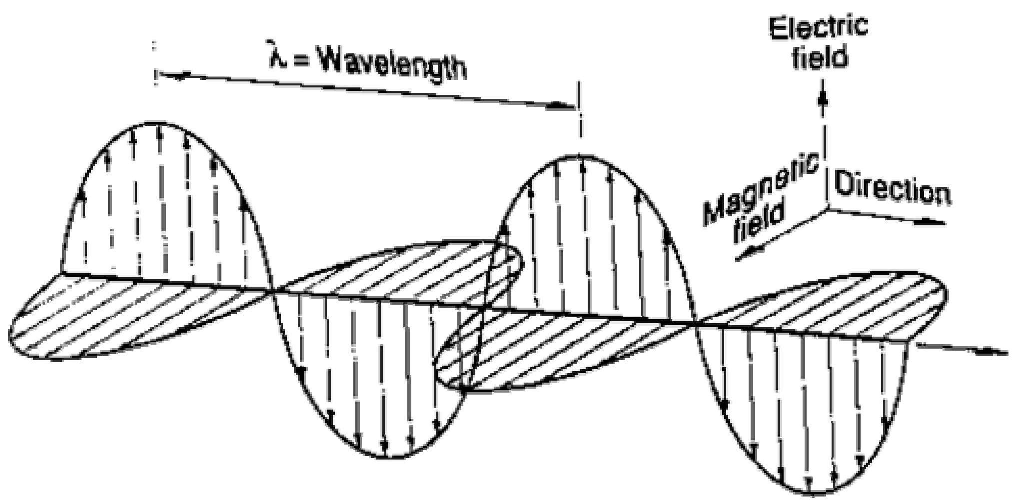
Electromagnetic Radiation.

The electromagnetic spectrum is the continuum of all electromagnetic waves arranged according to their frequency and wavelength. The spectrum is divided into regions based on their wavelength and proportionate energy. At the bottom of the spectrum are Gamma rays, which have the shortest wavelengths (less than 1x10^-12 m), and radio waves at the apex of the spectrum with extraordinarily long wavelengths that exceed a kilometre in length. While nearly all electromagnetic waves are invisible, there is a visible section that makes up, what normal people know as the colour spectrum.

The sun, earth and other astrophysical bodies radiate electromagnetic energy in the form of a wave. These waves are given the name 'electromagnetic' because they are transmitted as a combination of varying electric and magnetic fields. These sinusoidal waves travel at right angles to each other and all at the same speed of 3x10^8 m/s in a vacuum.



(electromagnetic wave)

The fundamental behaviors of all the components of the electromagnetic spectrum are the same. The most obvious scientific difference is their varying wavelengths and frequencies and in the devices used to generate and detect them. All electromagnetic waves exhibit diffraction and interference as well as reflection and refraction. They also all obey the following equation:

$$V = f.\lambda$$

(where v = velocity, f = frequency, λ = wavelength)

Using this equation and because 'v' is a constant for a given medium, we discover that as the wavelength is decreased, the frequency is increased.

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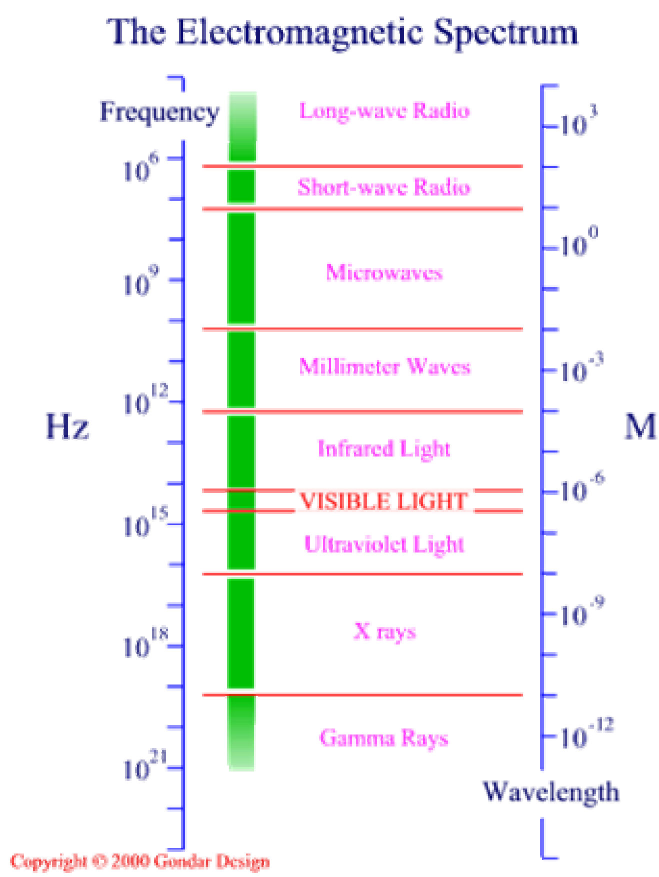
There are seven main sections of the electromagnetic spectrum. They are, in ascending order of wavelength (where λ represents wavelength):

- Gamma Rays (λ = approx. 0.01 nm)
  These rays are emitted by certain radioactive nuclei and are the most penetrating and energetic.
- X – Rays (λ = 10 nm – 10^{-2} nm)
  These rays are produced by bombarding a surface with very fast electrons.
- Ultra Violet Rays (λ = 380 nm – 60 nm)
  These rays come from very hot bodies such as the sun or from electrical discharges through gases.
- The Visible Spectrum (λ = 400 nm (violet) – 700 nm (red))
  This is the only part of the spectrum visible to the naked eye.
- Infrared (λ = 10^{-4} m – 10^{-6} m)
  Bodies at below 500°C that are not glowing, radiate these electromagnetic rays.
- Microwaves (λ = 1mm – 30cm)
  These rays are used in radar and microwave ovens.
- Radio Waves (λ = approx. 100 m)
  There are three types of radio waves: FM, shortwave and AM.



(The Electromagnetic Spectrum)[1]

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[1] Purchon, D. 2000

All electromagnetic rays travel at the same velocity in a vacuum and exhibit the same fundamental behavior. Infrared and ultraviolet radiation are two perfect examples to compare. Both travel at the same speed in a vacuum and as an electromagnetic wave and they similarly generate 'heat' (they make our skin feel warm when in contact with it). Conversely, both rays have unique wavelengths and frequencies as well as different methods of creation. Infrared radiation is emitted by anything we consider 'glowing red' with heat, such as hot embers and an electric hot-plate and occurs when molecules inside a material begin to vibrate and rotate. Ultraviolet radiation is produced mainly from sun and the experimental discharges of an electric arc.

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The 20^{th} century saw the beginning of the Theory of Quantum Physics. Up until this time electromagnetic radiation was considered purely as waves that shared many characteristics with light. However, when it was seen that electricity could be produced by light striking a metal, Albert Einstein hypothesized that radiation exhibited the characteristics and nature of a particle. Einstein suggested that light behaves like concentrated packets of energy which he called 'light quanta' (now referred to as photons). Scientists believed that these packets of energy could be transmitted by the translation of particles that have momentum and that the particles did not interact with each other because of their extremely small size and high speeds. The discovery of this 'particle' theory set in motion the evolution of Quantum physics and the photoelectric effect.

The 'particle theory,' was successful when considering only some of the optical phenomena and excluding the demand for precise and quantitative agreement between predictions and results. The model can account for the interaction of light. Its properties explain both specular and diffuse reflection, as well as Snell's law of refraction. It can be shown through this, that the diminution of the intensity of illumination is inversely proportional to the distance. The 'theory' also accounts for the idea that light absorption is associated with heating.

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Wave particle duality is now considered an essential part of nature; waves can exhibit particle-like characteristics and particles can demonstrate wave like characteristics, however the 'particle theory' is able to explain only some optical and EMR phenomena. The model accounts for the interaction of light and explains both specular and diffuse reflection as well as Snell's Law of Refraction.

Through the 'particle theory,' it can be seen that Einstein's photon, which is the carrier of electromagnetic energy, also carries linear momentum:

$$p = m.v$$

(where p = momentum, m = mass)

The momentum,'p', of a photon is related to the wavelength. Similarly, Einstein showed that the energy of a single photon is related to the frequency of the wave: (Keep in mind that photons are massless and are essentially embodiments of energy.)

$$p = h / \lambda$$

(where h = Planck's Constant)

These equations heralded the demise of Maxwell's classical views of electromagnetic radiation. Einstein's photoelectric effect of light (EMR), along with the 'Compton Effect' and the production of x-rays had revolutionary impact. Compton found that photons could be made to behave like particles with momentum.

Compton bombarded a block of granite with high- energy x-rays, and found that the wavelength of the scattered x-rays was increased depending on the angle of scattering. He proposed that this scattering was caused by a collision of x-ray photons with electrons in the material. He further proposed that photons have a measurable momentum and can behave like particles in high- energy interactions with electrons. This phenomenon is known as the 'Compton Effect'.

This idea of photons implies that light can interact with matter as if it were a stream of particles and led to the realization of the wave-particle duality of electromagnetic radiation.

The 'particle theory' of electromagnetic radiation failed in several important aspects. It failed to account for the propagation of light. It did not fully account for the speed of light in refractive materials, diffraction, reflection and refraction, the polarization of light or most importantly, interference. This theory, however, was popular until a century after Newton's death as it was thought that electromagnetic radiation did not exhibit interference effects as seen when considering water waves. Young's 'double- slit' experiment put an end to this theory, because if electromagnetic radiation was strictly particle-like, the physical arrangement of the experiment would either produce two bright lines on the screen or nothing at all. Experimental research proves otherwise! Young demonstrated the constructive and destructive interference of light, as it behaved as though it were a kind of wave.

The behavior of all electromagnetic waves can be predicted from Maxwell's equations and knowledge of the composition and shape of all components involved in generating and trapping each type of wave. Maxwell showed mathematically that the linked electric and magnetic fields travel in the form of a wave.

Around 1865, Maxwell published a theory that explained the existence of electromagnetic waves that travel at the speed of light and the notion that light are purely waves. Numerous scientists attempted to generate and detect electromagnetic radiation using forms of electrical equipment, thought the most significant and prevalent were professor Hertz, Philip Lenard, J.J Thomson and Albert Einstein. Basically, these scientists discovered that light could be shone onto a metal to release electrons and produce a photoelectric current.

The most important of all the experiments involving the photoelectric effect was probably performed by Lenard, who studied how the energy of emitted photoelectrons varied with intensity of light. Using a powerful carbon arc lamp, he projected electrons onto a metal plate and produced a photoelectric current. He utilized a precise ammeter to measure the magnitude of current produced by the lamps light-waves and discovered that there was an obvious minimum voltage required for any current to travel through the circuit, entitled ‘Vstop’. Strangely enough, Lenard found that Vstop did not depend on the intensity of the light, but on the wavelength of the specific light. By examining the effects of different colours of light, he realized that when the wavelength of a certain coloured light possessed a shorter wavelength and greater frequency it would produce a stronger current as the electrons contained a higher energy than compared to waves of longer wavelength. For instance, violet and blue coloured light will generate high energy, whereas red coloured light will produce little energy and maybe not even be able to complete the circuit.

In 1905, Einstein summarized Lenard’s results and produced something more practical:

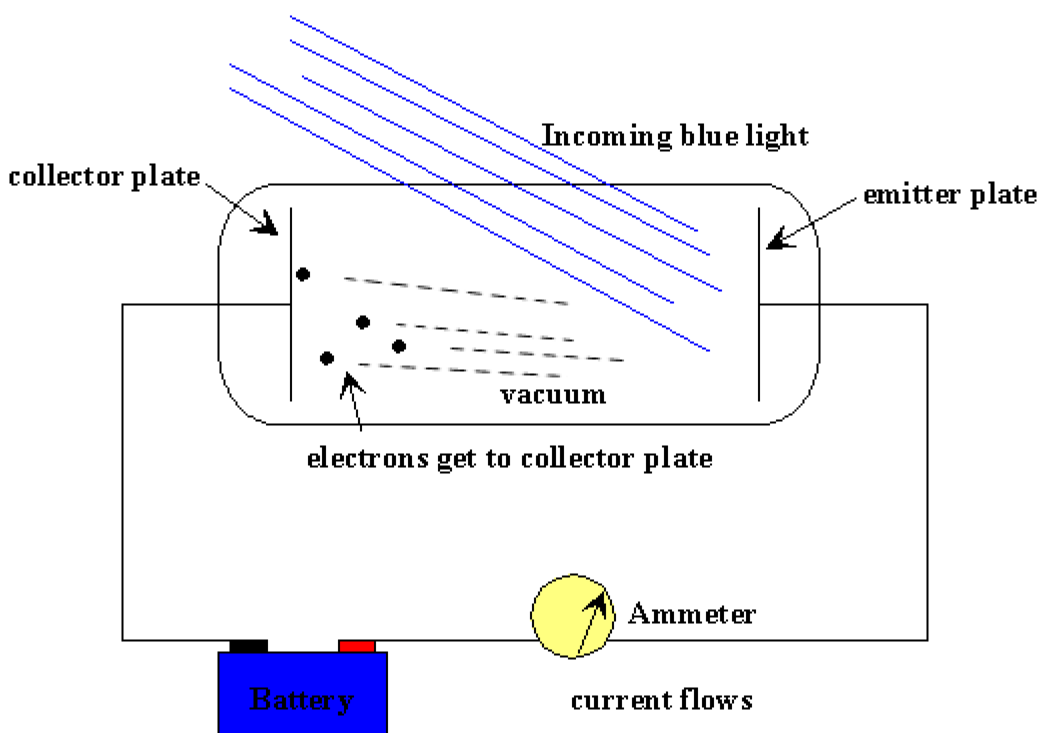
$$E = hf - W$$

(where hf is quanta of frequency, W is work function)

and…

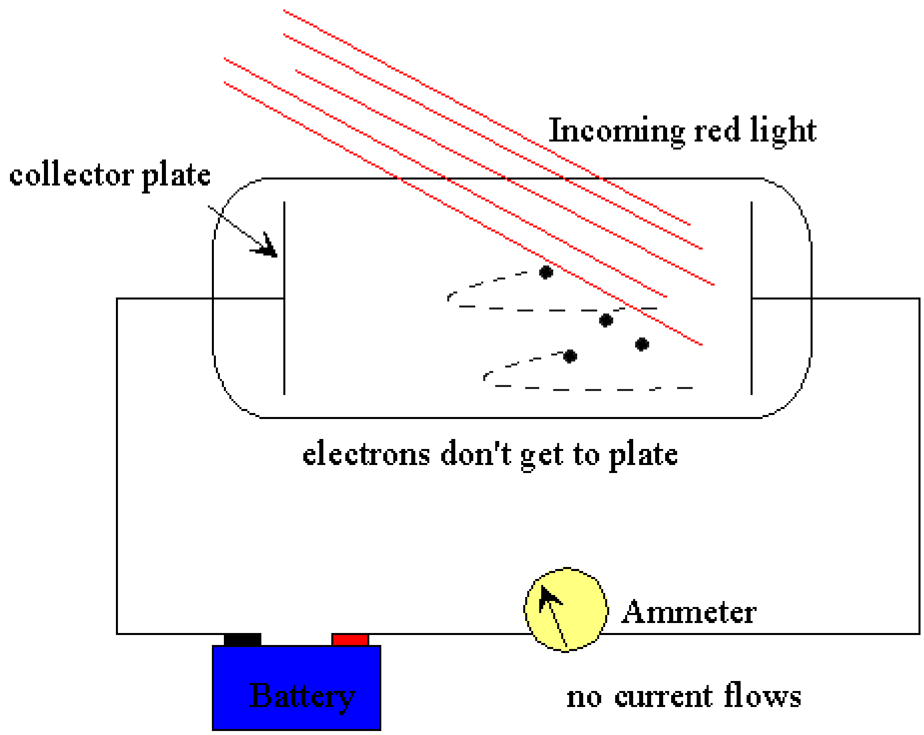
$$eVstop = hf - W$$

(where hf is quanta of frequency, W is work function)



(Lenard’s photoelectric experiment with blue light)[2]

[2] Michael Fowler. 1997



(Lenard's photoelectric experiment with red light)[3]

It was obvious that neither theory entirely explained the behavior of electromagnetic radiation and thus we turned to the idea of electromagnetic radiation having a wave-particle duality. This suggested that electromagnetic radiation can propagate from one place to another as if it were a wave as well as, behave like a particle travelling at c, the speed of light.

There is no real conflict between the wave and particle behaviors of electromagnetic radiation, no recorded information to prove the other theory of being wrong, however it is not possible to say each section is one or the other. All electromagnetic radiation shows behavior of both waves and particles but only one, predominately under different conditions. Some areas of the electromagnetic spectrum exhibit more of the characteristics of one of the theories and therefore it can be said that they are more concerned with that type of behavior.

In general, the electromagnetic radiation's with higher frequencies and shorter wavelengths, like X-rays and gamma rays show more characteristics of particle behavior because they show, far more clearly the properties of the interaction of electromagnetic radiation, rather than the propagation of light. On the other hand sections with low frequencies and long wavelengths like radio waves and microwaves can been seen more as waves and are concerned with the propagation and interference of electromagnetic radiation and similar attributes of physical waves.

In certain experiments concerned with the propagation of electromagnetic radiation, the mathematical laws of wave motion can describe the behavior, however in other

[3] Michael Fowler. 1997

experiments concerned with the interaction of electromagnetic radiation with individual particles, it can be described by the mathematical laws of particle physics.

Light is considered to have a 'dual character,' it is neither a 'pure' wave nor a 'pure' particle. From the knowledge of wave- particle duality of electromagnetic radiation, French physicist, Prince Louis de Broglie, proposed that all moving matter has a wavelength associated to it, displaying both particle and wave characteristics. He proposed that energy, momentum and wavelength are applicable to particles and waves. He derived and explained this equation:

$$P = h / \lambda$$

(where h = Planck's Constant)

This was confirmed by experiments performed by Clinton Davisson, Lester Germer and George Thomson in 1927. Davisson and Germer directed a beam of electrons onto a crystal of nickel and observed behaviour similar to when x-rays are diffracted by a crystal. The wavelength of the diffracted electrons matched that expected by de Broglie's hypothesis. In 1925 Erwin Schrodinger put forward an equation which can be viewed as a form of the wave equation applied to matter waves, and Einstein derived two formulae to calculate the frequency and energy of a photon:

$$f = (E2-E1) / h$$

and

$$E=hf$$

(where f is frequency, E is energy level of a photon, and h is Planck's constant (6.63*10^-34 J.s))

The research of these brilliant scientists helps us to comprehend the extraordinary structure, behavior and history behind the discovery of electromagnetic radiation. Their relentless investigation has paved the way for future investigation and discoveries in this complex field of science.