Foundations of Physics: Atomic and Nuclear

Week 6 & 8 Content

Name: ____________________

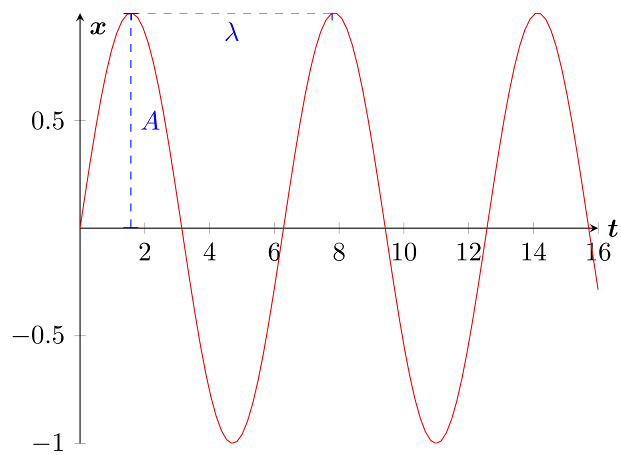
Date: ____________________

1 Introduction

I would like to begin this topic by detailing the physical properties of a wave.

Say we have an object which is undergoing "wave like" motion as per the diagram. As an example, let this be a string anchored on one end, and being displaced up and down on the other. This string will have an amplitude A, and a wavelength, λ, which is shown in the figure.

Noting that the below figure is a graph of the displacement of a singular point on the string with respect to time.



Some important physical characteristics of this oscillating string have the following definitions:

(1) Amplitude (A): Displacement from equilibrium point.

(2) Wavelength (λ) : Distance between two successive, identical points on the wave.

(3) Frequency (f) : The number of cycles that pass a given point per unit time, so for this string, the frequency f is given as,

$$f = \frac{1 \text{ cycle}}{6 \text{ seconds}} = \frac{1}{6} \text{ Hz}^1$$

Another example for measuring frequency is measuring heart rate. Say that I have a heart rate of 120bpm. This value corresponds to 2 Hz via: $\frac{120 \text{ beats}}{1 \text{ min}} = \frac{120 \text{ beats}}{60 \text{ seconds}} = 2$ Hz

(4) Period (T) : the time taken to complete 1 cycle. By definition, this is the reciprocal of frequency, and often, the following relationship is used,

$$T = \frac{1}{f} \iff f = \frac{1}{T}$$

[1] "Hz" is just the SI unit for frequency. Similarly to how seconds (t) is the SI unit for time.

(5) **Wave speed** (v): The speed at which any point on the wave shape moves forward.

Since a point on the wave travels a distance of λ in time $= T$, then the speed has to be,

$$v = \frac{\text{distance}}{\text{time}} = \frac{\lambda}{T}$$

But from the period frequency relation, we also have,

$$v = \frac{\lambda}{\frac{1}{f}} = \lambda f$$

2 Nature of Light

In the early 18th century, the analysis of light has taken the interest of many scientists. It is known that light can carry energy, (for example: magnifying a ray of sunlight can cause a hole to burn in paper), but the question arises as to how this energy is carried. Is it carried by particles, or by waves?

2.1 Measuring The Speed of Light

Intuitively, it is contradictory to think that light has a speed, as its perception from all frames of reference is instantaneous.

Through planetary observations, the speed of light was deduced to be finite, as light would not travel instantaneously across bodies.
Michelson was able to measure the speed of light using the following apparatus:

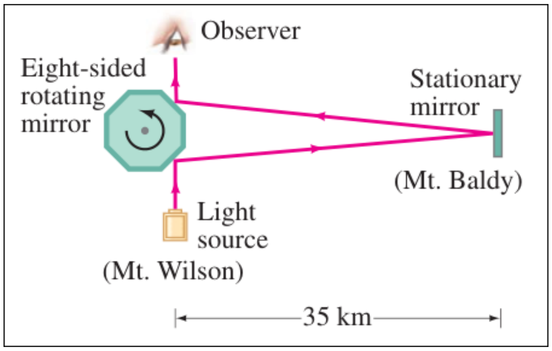


Figure 1: The mirror would have to rotate at a certain speed in order for the observer to receive the light source through reflection. Knowing this, and the distance between the mountains in Southern California, the speed of light was measured as being $c = 2.99792458 \times 10^8 \text{m/s} \approx 3 \times 10^8 \text{m/s}$.

Since this speed is constant through all reference frames, we can now redefine the notion of length. Specifically, we define the meter as being the length of path traveled by light in vacuum during a time interval of $1/299,792,458$ of a second.

Notably, this defininition hinges on the medium that light travels in being a vacuum (which is very similar to air). We find that when light enters a new medium, for example, a body of water, we have a new speed of light.

2.2 Wave-like Nature

Experimentally, the nature of light was established as being "wave-like".

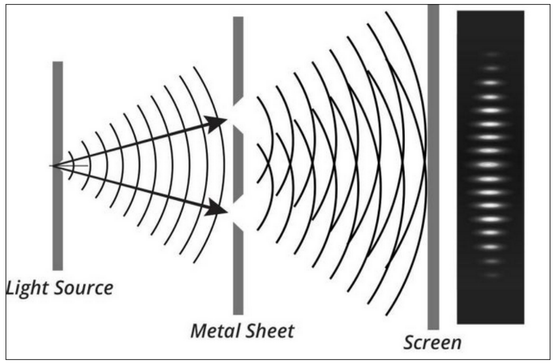


Figure 2: Young's Double Slit Experiment.

Meaning that we can apply all of the aforementioned equations to light:

$$c = f\lambda, \tag{1}$$

where c is the measured speed of light.

By measuring the frequency of incident light, the wavelength of light can be found via $\lambda = \frac{c}{f}$. It was found that the colour which differentiates light is attributed to the wavelength:

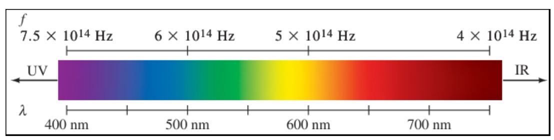


Figure 3: Spectrum of visible light. Note that colours that are not present in this spectrum are actually a combination of wavelengths.

3 Light as an Electromagnetic Wave

Now that we have defined the above attributes for waves, we can now investigate the notion that light itself is a wave, and an electromagnetic one at that.

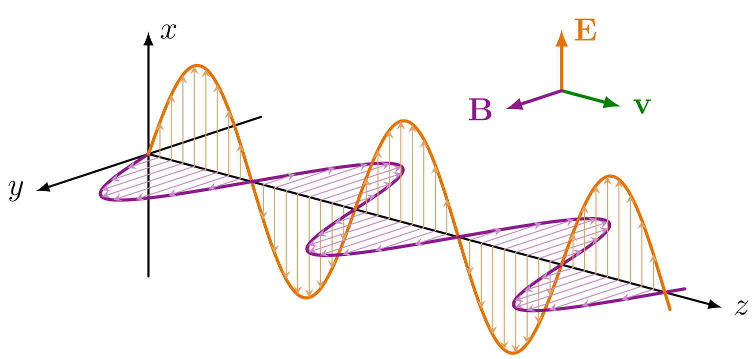


Figure 4: Electromagnetic wave. (Izaak Neutelings, 2018).

The finding of electromagnetic waves was derived from the concept that a changing electrical field produces a magnetic field, and vice versa. These two fields combine and propogate as a wave, which we denote to be the "electromagnetic wave".

The denotion of light being an electromagnetic wave is attributed to Maxwell, who stated this after the finding that EM waves travel at 3×10^8m/s, the speed of light. This was enough to convince scientists that there perhaps may be a relation.

Under analysis of the electromagnetic wave, it was found that the characteristics of reflection, refraction, and interference were all present, which are all descriptors of light. The main difference between light and electromagnetic waves were that electromagnetic waves had these characteristics, but were not visible. These findings concluded that light can be treated as a form of electromagnetic radiation.

We now turn our attention to the previously stated equation, $v = \lambda f$, and apply it to the context of light. This yields,

$$c = \lambda f.$$

Double slit experiment highlights dual nature of light. You can measure wavelength experimentally, and it was found that certain colours have different wavelengths.

4 Blackbody Radiation

A blackbody is a theoretical body which does not reflect any radiation incident on it, but rather, absorbs all of it. This body then emits thermal radiation in a continus spectrum which is dependent on the temperature, which we call "blackbody radiation". Notably, we approximate stars or planets to be blackbodies, with their electromagnetic radiation emitted as blackbody radiation.

However, the classical approach for explaining the physical properties of this system proved to be insufficient, and it was under the assumption that light did not act like a wave, but rather a discrete packet of energy, which allowed for the correct analysis of the blackbody.

This shift in thinking is credited to Planck, who instead of thinking that the energy of light is proportional to the square of the amplitude of the wave, $E \propto A^2$, proposed that,

$$E = nhf \tag{2}$$

From the study of thermal physics, we have that the intensity of an objects radiation is **proportional** to the fourth power of the absolute temperature (Kelvin). I.e.,

$$I \propto T^4$$

4.1 Planck's Hypothesis

In order to model the blackbody curve mathematically, Planck proposed a different perspective as classical mechanics could not explain this

$$E = hf$$

4.2 Photoelectric Effect

We revisit the notion of power.

Definition 4.1. Power, P, is defined as the rate at which work is done or, more generally, the rate of change of total mechanical energy. We use $\overline{P}$ to denote the average power, and it is given as the following:

$$\overline{P} = \frac{W}{t} = \frac{E}{t}$$

Photon theory of light states:

(1) All photons have the same energy, hf;

(2)

Where E is the energy of the photon, h is Planck's constant, and f is the frequency of the photon. 3