"Your x-ray showed a broken rib, but we fixed it with Photoshop."

SPH4UI

Unit 4: Light

Unit 4 Overview

Lesson	Text Reference	Topic	Questions	Done
1	9.1 10.4 9.2	a) Review of Waves b) Electromagnetic Waves c) Refraction	Pg 443 Q#6, 16; Pg 531 Q#3, 5; Pg 458 Q #5, 9, 10	
2	10.5	Polarization	Pg 537 Q#4, 8, 9	
3	9.5	Interference & Young's Experiment	Pg 484 Q#2, 4 – 8	
4	10.1	Thin Film Interference	Pg 507 P#1 – 4; Pg 511 Q#2, 3	
5	10.2	Diffraction	Pg 519 Q#1 – 7	
L4.1	--	Determining an Unknown Wavelength Using Diffraction and Interference	Lab Write-up & Discussion	

Lesson 1a – Wave Review

Review of Wave Theory

Waves carry energy from one location to another via some disturbance. In general, there are several different types of waves: transverse, longitudinal and torsional to name a few. Light is thought to be a transverse wave, where sound is a longitudinal wave.

Waves are considered periodic – their motion repeats itself at known intervals. Any repeated motion is called periodic motion or **harmonic motion**.

Period –

Frequency –

Wavelength –

Amplitude –

Phase Shift –

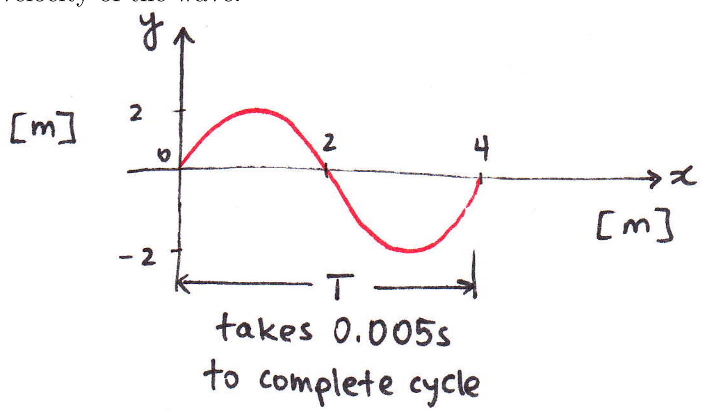
The type of motion that can be represented by the sine or cosine function is called simple harmonic motion and is given by the following formulas:

Example 1

Calculate the period and frequency of a plane's propeller if it completes 250 cycles in 5.0 s.

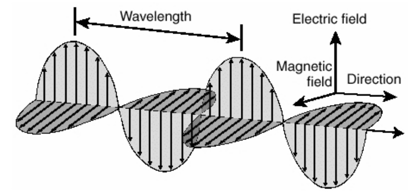
Example 2

Using the diagram of a periodic wave below, find the amplitude, wavelength, frequency and velocity of the wave.



Lesson 1b – Electromagnetic Waves

In addition to the waves studied in grade 11 physics (mechanical waves) there are other types of waves crucial to the study of light. We will turn our attention to electromagnetic waves now.



Electromagnetic waves have the following five properties:

1.

2.

3.

4.

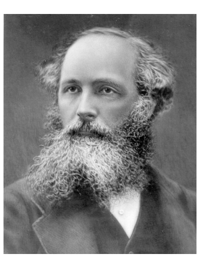
5.

The Speed of Light

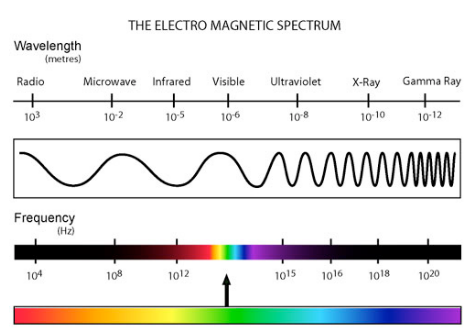
Recall from grade 11 physics, the **universal wave equation**:

$$v = f\,\lambda$$

Where v is the speed of the wave, and f & λ are it's frequency and wavelength, respectively.



James Clerk Maxwell proved that light was a traveling wave of electric and magnetic fields and over time, many different types of electromagnetic waves have been added to the list. Today, we use a spectrum to illustrate the many different waves that are included as electromagnetic waves.



Maxwell also proved that electromagnetic waves travel through a vacuum at the speed of light, $c = 3.0 \times 10^8$ m/s.

Example 1

Calculate the time is would take for light to reach us from the Sun, 1.49×10^{11} m away. Compare this value to the time it would take a supersonic plane to fly the same distance at Mach 3.

Example 2

Infrared light is invisible to the human eye except through special sensors. Given the range of wavelengths of infrared light, calculate their corresponding frequencies.

Lesson 1c – Refraction

Refraction is a phenomenon of light that arises from the fact that light travels at different speeds in different mediums. If light enters a medium at a certain angle to the boundary, it is bent either towards or away from the normal, depending on the medium.

The refractive index, n, is a measure of how much light slows down when it enters a medium. It is defined as the ratio between the speed of light in vacuum and the speed of light in the medium.

Example 3

Calculate the index of refraction for diamond if the speed of light in a diamond is 1.24×10^8 m/s.

Snell's Law

The relationship between the angle of incidence, the angle of refraction and the refractive index is given by Snell's Law:

Where the subscripts 1 and 2 refer to the incident and refractive mediums. For a proof of Snell's Law, check out your textbook, page 503.

Example 4

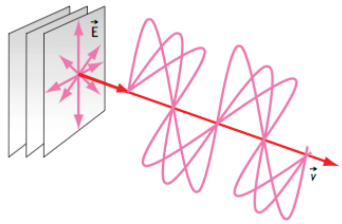
Find the angle of refraction for light travelling from air to diamond if the angle of incidence in the air is 20°.

Example 5

Calculate the index of refraction for a substance where the angle of incidence is 30.0°, the angle of refraction is 50.0°, and the index of refraction of the second substance is 1.50.

Lesson 2 – Polarization

Recall that electromagnetic waves are transverse and made up of mutually orthogonal (perpendicular) electric and magnetic fields. Under normal circumstances, these electric and magnetic fields are oriented randomly with respect to the direction of propagation of the waves.



In an ordinary beam of light, the atoms of the light source emit a large number of waves. Each atom gives off a wave having a particular orientation of its electric field. The result is a randomly distributed electric field created by the superposition of the individual electric fields giving an **unpolarized** light beam as demonstrated in the diagram below.

It is possible to remove one or more of the components of the electric field creating a **polarized electromagnetic wave**. **Polarization**, then, is the removal of one component of the electric field.

A simple analogy:

Polarization of Light

There are several methods used to polarize light. These include the use of **reflection** and **polarizing filters**.

A **Polariod** is the name given to a sheet of clear plastic embedded with tiny crystals of an iodine compound. The crystals are arranged with the same orientation in regular rows. As light passes through one of these filters, the crystals absorb one of its electric field components. The other component passes through, unhindered.

Malus' Law
A consequence of polarizing filters is not only the removal of one component of electric field, but also a decrease in the intensity of light. In fact, by removing one component of the electric field, we decrease the intensity by half.

$$I_1 = \tfrac{1}{2} I_o$$

Where I_o is the intensity of the original or incident light and I_1 is the intensity of the light exiting the filter.

With the addition of a second filter, the intensity is further affected. Consider the diagram below:

The **polarizer** is the first filter.

The **analyzer** is the second filter.

The light emerging from the second filter, the analyzer, is further reduced in intensity and this intensity is given by Malus' Law:

$$I_2 = I_1 \cos^2 \theta$$

Where I_2 is the intensity of the light ray after exiting the second polaroid, I_1 is the intensity of light that enters the second polaroid and θ is the angle between the two.

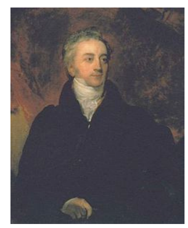
Example 1

If two Polaroids are crossed with an angle of 60° between their polarizing directions, what percentage of light is transmitted through both Polariods?

Lesson 3 – Interference and Young's Experiment

Throughout history, scientists have debated over the nature of light. Newton held the thought that light was a particle, while others fought for a description of light that consisted of waves. Both theories held convincing arguments, but because of his stature, Newton's particle theory remained most widely accepted.

Robert Hooke and Christian Huygens championed the wave theory of light, but it wasn't able to explain all of the phenomena that the particle theory did. We have seen some evidence so far, the wave theory explains refraction and polarization well. But in the early 1800s, Thomas Young, a British scientist, performed a famous experiment that could only be explained using a wave theory.



Interference Theory

When we combine two or more waves to form a single wave we use the **principle of superposition** to arrive at the final waveform. The amplitudes of the wave combine in one of two ways:

Constructive Interference –

Destructive Interference –

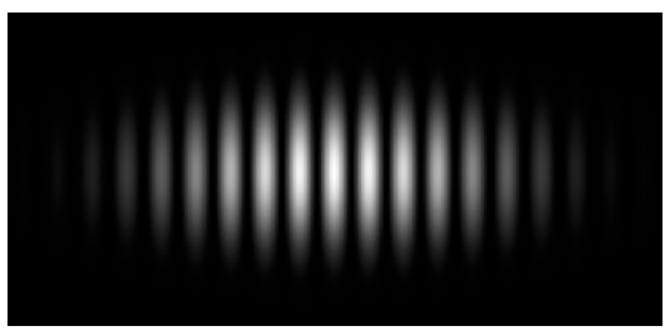
Many things can cause waves to interfere as above, but the **path difference** between two waves has a large effect. If two waves from different sources arrive at the same point in space but travel a different distance the waves may be *shifted* relative to one another. This effect is called a *phase shift* and is described well by the diagram below.

When these two waves meet in time and space, there are an infinite number of possible shifts between them. They may be out of phase by 1.0λ, 1.5λ, 1.113λ, and so on. The two extremes of this phase shift are considered here.

Young's Double Slit Experiment

Using a light source and two opaque cards, Young performed an experiment that convinced most physicists of the wave nature of light. In the first card, he punched a tiny pinhole to allow light through. He then punched two closely spaced pinholes in the second card.

The card with the single hole was placed in front of the light and the card with two holes was placed a distance away. He then set up a screen a distance away and observed an interference pattern.



In most modern day recreations of Young's experiment, we use slits as opposed to pinholes producing the fringe pattern seen here. The bands are numbered on each side and these integers are called order numbers.

Young's Double Slit Equations

To develop the mathematics that describe Young's findings, we will first observe an overhead view of his set up.

We know from interference theory, that for constructive interference to happen, the difference in path length must be a whole (or integer) number of wavelengths.

$$m\lambda = \left| P_m S_1 - P_m S_2 \right| \qquad ①$$

We can also write this relationship in terms of the path length and the angle to a given maximum.

Here, it must be noted that θ depends on the order number (i.e. what maximum you are trying to find).

$$m\lambda = d \sin \theta_m \qquad ②$$

Finally we can also derive an expression for the distance any maximum is from the central axis.

And we arrive at the third and final equation:

$$m\lambda = \frac{d\,(x_m)}{L} \qquad ③$$

We can also use these three equations to find the location of any minimum as well, but instead of imposing the condition for constructive interference $m\lambda$, we impose the condition for destructive interference $(m + ½)\lambda$.

Example 1
A monochromatic source of 450 nm illuminates two slits that are 3.0×10^{-6} m apart. Find the angle at which the first-order maximum occurs.

Example 2
A monochromatic source of 450 nm illuminates two slit that are 3.0×10^{-6} m apart. Find the distance to the third order maximum if the screen is 1.3 m away.

Lesson 4 – Thin Film Interference

With the work of Thomas Young providing evidence that light is a wave, we are now able to investigate different types of interference. One interesting phenomenon is the appearance of colours, visible on soap bubbles and thin films of oil and gasoline. The thickness of these thin films and the refractive index of the materials play an important role in the interference occurring.

With thin films, some of the light falling onto the top surface of the transparent film is reflected. Some light, unreflected, travels through the film until it meets the lower surface where, again, some light is reflected. This light reflected from the bottom surface travels back through the medium and rejoins the reflected light from the top surface.

Path Difference Effect

The path difference between the reflected light and the light that travels down and back through the film is what determines the relative phase shift between the two waves. Due to its journey within the film and its reflection from the bottom surface, this light wave may have a different phase to the light reflected from the upper surface.

Recall the conditions for interference:

Constructive	Destructive

We also need to correct for the changing wavelength of light as it moves through the film, which has a different refractive index.

The Reflection Effect

Recall that when a wave reflects off of a dense barrier, it changes its phase. In grade 11 physics, we investigated this effect with springs and applied its use to sound.

Combining the Effects

When the two waves, now phase shifted with respect to each other recombine, interference happens. If they interfere constructively, a bright colour appears. If they interfere destructively, no colour appears.

In general, there is no one formula to define this behaviour. To solve these types of problems we follow a specific process. Here is an outline of some simple steps to follow.

1. Determine the number of wavelengths the incident ray travels inside the film. Remember that since the velocity of light changes in the new medium and the frequency does not, the wavelength must change. Find the new wavelength using $\frac{n_2}{n_1} = \frac{\lambda_1}{\lambda_2}$.

2. If the number of wavelengths above is an integer multiple of λ, this is the condition for constructive interference, indicate this be writing down a C. If the number of wavelengths is a half-integer multiple of λ, $(n + \frac{1}{2})\lambda$, this is the condition for destructive interference, indicate this by writing a D.

3. Determine if the incident ray in the first medium was phase shifted after reflection. Recall that if $n_2 > n_1$ the second medium is more optically dense and the reflected ray phase shifts by $\frac{1}{2}\lambda$. If $n_1 > n_2$ it does not. If there is a phase shift, change the letter you wrote down above to the opposite.

4. Determine if the ray in the second medium gets phase shifted after reflection using the method in step 3. If it does, change your letter again.

Example 1

Light reflects off of a thin film of gasoline (n = 1.40) on water (n = 1.33). If the wavelength of the light is 560 nm and the thickness of the film is 4.8×10^{-6} m, will a bright area or dark area result?

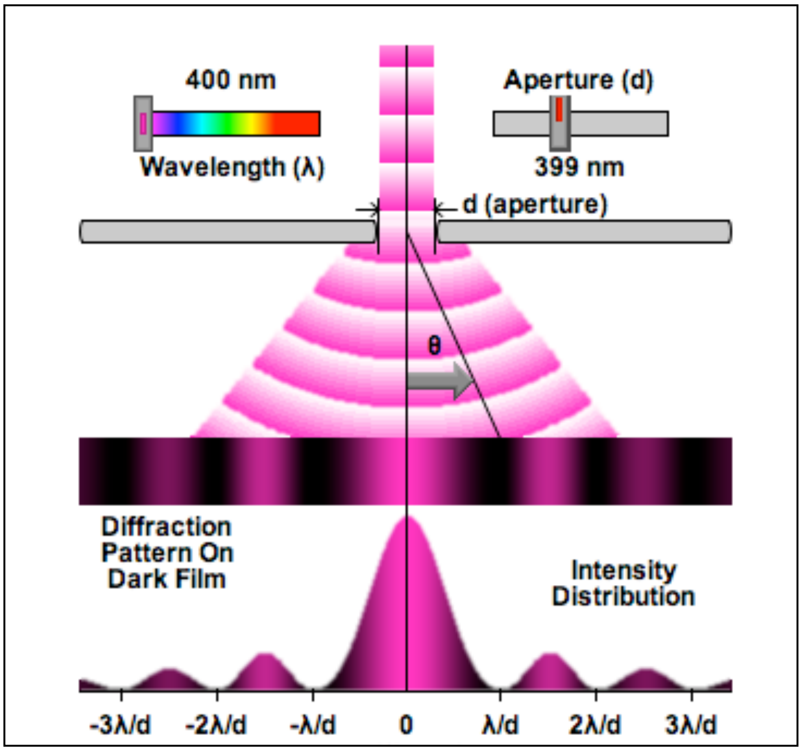
Example 2

A film of gasoline of thickness 510 nm formed on water is illuminated by light of wavelength 476 nm. The refractive index of gasoline is 1.40. Does a bright area or dark area result?

Lesson 5 – Diffraction

Francesco Grimaldi, a researcher at the University of Bologna, first coined the term **diffraction** as it referred to the bending of light around edges. There is a small, but important difference between interference and diffraction. Interference is defined as the superposition effect originating from two or more discrete sources of waves. Diffraction refers to the interference effects that originate from a single source or wavefront.

Waves can bend around objects when their wavelengths are comparable in size to the objects. When monochromatic light shines through a single slit which has a size close to that of the wavelength of the light, an interference pattern occurs.



Good to Know

Q: If Thomas Young used only one source in his famous experiment, why is it a classic example of interference and not diffraction?

A:

- ✓ The central maximum has a width that is double the size of any single maximum.
- ✓ Away from the centre, the bands are equally spaced.
- ✓ Intensity decreases with distance from the central max.

Fraunhofer Diffraction –

Fresnel Diffraction –

The Single Slit Equations

Example 1

A slit with a width of 2.0×10^{-5} m is illuminated by red light of wavelength 620 nm. At what angle does the third order maximum occur?

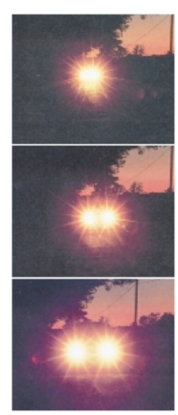
Example 2

A single slit of width 9.5×10^{-6} m is illuminated by a monochromatic source of light (λ = 640 nm). If the screen is 1.3 m away:

a) Find the distance from the centre of the pattern to the first order minimum.
b) Find the width of the central maximum.

The Rayleigh Criterion

When two objects that are close together are viewed from far away, they can appear to be one object. Lord Rayleigh suggested that two images become resolvable when the central maximum of one image lies on the first order maximum of the second image. This is known as the Rayleigh criterion and can be calculated using:



$$\theta_R = \frac{1.22\lambda}{d}$$

Where d is the diameter of a circular aperture and θ_R is the minimum angle between the two objects at the Rayleigh criterion.