Lesson 30: Diffraction & Interference

The wave model of light eventually replaced Newton's particle theory.
- This did not happen overnight, and it certainly wasn't the work of one person.
- Three specific concepts became the best evidence of a wave model of light.
  -

Huygen's Principle

One special property of waves is **diffraction** around obstacles and through openings.
- As we already briefly discussed, diffraction happens when waves appear to fill in the missing spots after hitting or going through these situations.
  - If water waves go through a small opening then they will spread out on the other side to eventually be wider than the opening they went through.
  - After hitting an obstacle, water waves will fill in the missing area behind the obstacle so that it doesn't look like anything was ever blocking the wave.

Christiaan Huygens tried to explain this property in his model known as **Huygen's Principle**.

> **Huygen's Principle** is a model that helps us understand waves, but is not necessarily what the waves are actually doing.

- Huygen's Principle says you should imagine a wave as being made up of an infinite number of tiny point wave sources, each of which spreads out on its own and allows the wave to continue.
  - All these little waves are called **wavelets**.
- These wavelets look like individual ripples in a pond spreading outwards after a rock is thrown in.
  - The difference in this model is that we only picture the portion of the "ripple" that spreads forwards in the direction the wave is traveling.
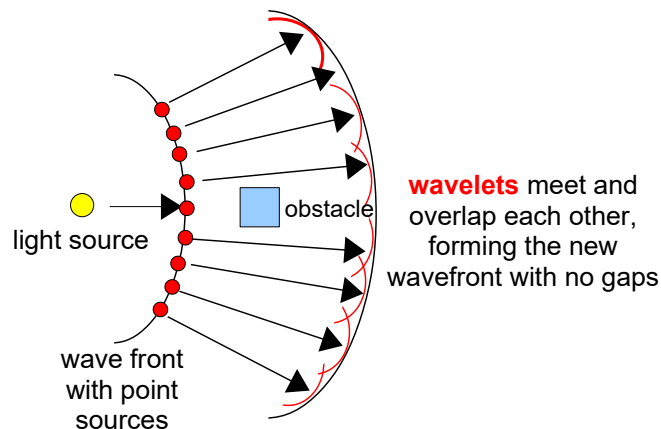

Illustration 1: The wavelets coming from one wave front diffract around an obstacle.

For diffraction to be observed, the size of the opening or obstacle needs to be about the same size as the wavelength of the wave.
- If the wavelength is much bigger or smaller, the diffraction will be difficult (if not impossible) to see.
- Originally, this was a weakness in the wave model of light.
  - Scientists did not understand just how small the wavelengths of visible light really were, so their experiments originally had opening and obstacles that were far too big.
    - No diffraction was observed, so they thought that maybe light was not a wave.
  - Even as they started to realize just how small the wavelengths of visible light might be, there was the problem of how to get an obstacle or opening that small.

Young's Double Slit Experiment

These problems were solved in 1801 by Thomas Young.
- There are different ways to explain how he did this, but they all get you to the same result.
- For the purposes of our explanation, we will be using the idea of a screen with two narrow slits cut through it.
  - Imagine if you took a sheet of paper and made two parallel slits in the middle with a razor blade and you'll have the right idea.

Young placed a screen that had two slits cut into it in front of a monochromatic (single color) light.

Illustration 2: Thomas Young

- The results of Young's Double Slit Experiment should be very different if light is a wave or a particle.
- Let's look at what the results would be in both situations, and then see how this experiment supports the wave model.

Young had to be very careful with his setup. He needed the light rays to be parallel and in phase (waves with crests and troughs at the same times) in order to work. He did this by using a single light source and shining it through a single opening first, then this single beam of light hit the double slits.

If light is a particle…

We set up our screen and shine a bunch of monochromatic light onto it.
- If light is a particle, then only the couple of particles of light that go exactly where the slits are will be able to pass through.
  - Imagine it as being almost as though we are spraying paint from a spray can through the openings.

- Since they are little particles they will make a pattern of two exact lines on the viewing screen.
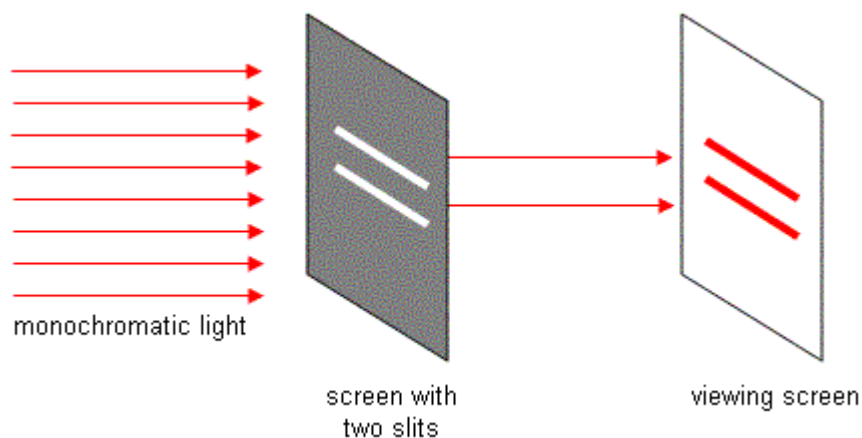

Illustration 3: If light is a particle...

If light is a wave…

If light is a wave, everything starts the same way, but the results we get are very different.

- There are still only two light rays that actually go through the slits, but as soon as they pass through they start to diffract (*Illustration 4*).
- Notice that at some points the two sets of waves will meet **crest** to **crest** (or **trough** to **trough**), at other spots **crest** meets **trough**.
  - o Where **crest** meets **crest** (or **trough** to **trough**), there will be **constructive interference** and the waves will make it to the viewing screen as a **bright spot**.
  - o Where **crest** meets **trough** there will be **destructive interference** that cancel each other out… a **black spot** will appear on the screen.
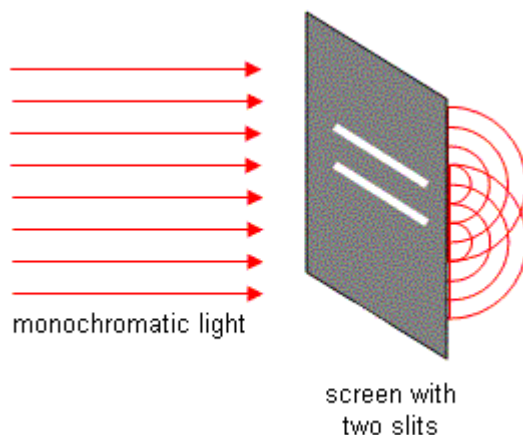

Illustration 4: The light passing through the small slits starts to diffract on the other side.

When this experiment is performed we actually see this interference if we look at the light that hits a screen placed away from the double slit screen (*Illustration 5*).

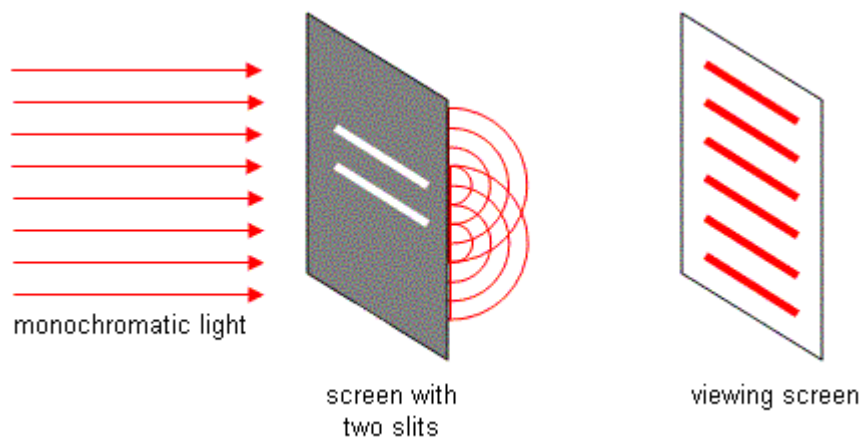- We must conclude that light is made up of waves, since particles can not diffract.

Illustration 5: The interference pattern seen on the viewing screen.

Young's Double Slit Calculations

When you set up this sort of an apparatus, there is actually a way for you to calculate where the bright lines caused by constructive interference (called **antinodes**) will appear.

- There is always a middle line, which is the brightest. We call it the **central bright fringe** or **central antinode** or **central maximum** and give it an n value of **0**.
  - o The formula we will use has a variable, "n", that is a count of how many bright fringes you are *away* from the **central antinode**.

Illustration 6: The orders of the fringes. Note, for monochromatic light these lines are all the same color.

- The antonode to either side of the **central antonode** has an order of **n = 1** (the **first order bright fringe** or **first order antinode** or **first order maximum**).
- The order of the next antonode out on either side is **n = 2** (the **second order bright fringe** or **second order antinode** or **second order maximum**), and so on.
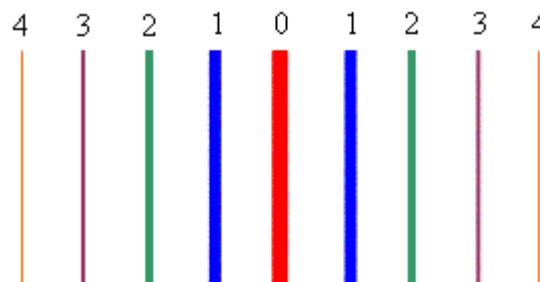
The **dark spaces** that happen between the bright fringes are referred to as **nodes** and have values that are between the n values of the bright fringes.

- For example, the dark space that appears between the bright antinodes numbered 0 and 1 (the first time a dark spot appears) would have an n value of **0.5**. It would be called the **first order dark fringe** or **first order node** or **first order minimum**.
- This pattern continues for the nodes. As a general rule, whichever node number it is, subtract 0.5 to use as your n value. Calculated examples of this will be shown soon.

Method 1: The Small Angle Approximation

One formula that we can use to figure out problems involving double slit experiments is easy to mix up.
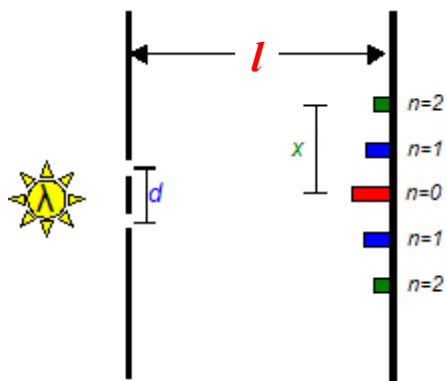
- It is based on measuring a bunch of distances, so sometimes you might get confused about which is which.

- It also only gives us an approximate value, and it goes really wonky if the angle away from the central fringe is more than about 10°.
- For this reason, we will often refer to this formula as the **small angle approximation**.

$$\lambda = \frac{xd}{nl}$$

λ = wavelength of light used (m)
x = distance from central fringe (m)
d = distance between the slits (m)
n = the order of the node or antinode
l = length from the screen with slits to the viewing screen (m)

It is very easy to mix up the measurements of x, d, and l.
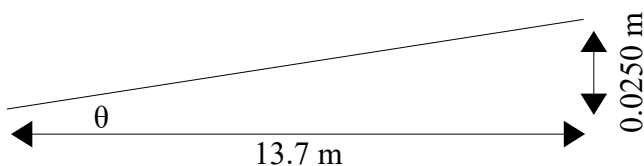
- Make sure to look at *Illustration 7* and see the different things each is measuring.
- If you mix up x and d it's not so bad, since they are both on top in the formula. If you were to mix them up with L, you would get the wrong answer.
- Almost all questions that you will see for this formula just involve sorting out what each variable is... you might find it helpful to write out a list of givens.

Illustration 7: Symbols in the formula measure different parts.

Example 1: A pair of screens are placed 13.7m apart. When a visible light source shines on a set of double slits, a fourth order node is seen on the screen 2.50cm from the central maximum. If the slits were cut 0.0960 cm apart, **determine** the wavelength of this light. **Identify** (roughly) what colour its is.

First of all, using the small angle approximation here should give us a pretty good answer, since according to the measurements above...

$$\tan \theta = \frac{opp}{adj}$$
$$\tan \theta = \frac{0.0250}{13.7}$$
$$\theta = 0.105^o$$

Wow! I'd say that's less than 10°!

Just to make sure you've got all the numbers from the question matched with the correct variables…

l = 13.7 m
n = 3.5 (since it is a node, fourth order would be 4 – 0.5 = 3.5)
x = 2.50cm = 0.0250 m
d = 0.0960cm = 9.60e-4 m

$$\lambda = \frac{xd}{nl}$$
$$\lambda = \frac{0.0250(9.60\text{e-}4)}{3.5(13.7)}$$
$$\lambda = 5.00521\text{e-}7 \, m$$
$$\lambda = 501\text{e-}9 = 501 \, nm$$

Given the wavelength we've measured it's probably a green light being used.
We don't have to do the conversions from the original answer in metres into nanometres, it's just makes it easier to identify the colour.

Method 2: Sine Theta Formula

There is also a version of the formula where you measure the angle between the central fringe and whatever fringe you are measuring.

- The formula works the same way, with the only difference being that we measure the angle instead of x and l.

$$\lambda = \frac{d \sin \theta}{n}$$

- Make sure that your calculator is in degree mode before using this version of the formula.

Warning!
Use the sine theta method when it is obvious the angle is bigger than 10⁰.
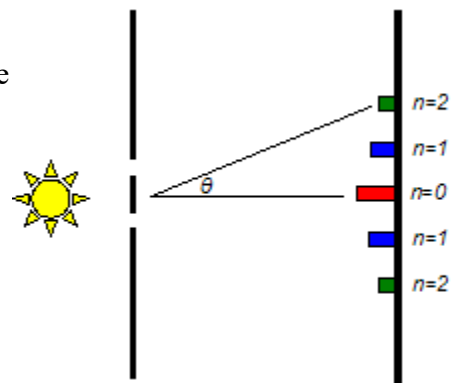

Illustration 8: Measuring the angle in Young's Double Slit.

Example 2: If a yellow light with a wavelength of 540 nm shines on a double slit with the slits cut 2.20e-3 mm apart, **determine** what angle you should look away from the central fringe to see the second order maximum.

Do not forget to:
1. Change the wavelength into metres.
2. Change the slit separation into metres.
3. "Second order" is a perfect number and has an infinite number of sig digs.
4. Take the inverse sign at the end to get the angle.

$$\lambda = \frac{d \sin \theta}{n}$$

$$\sin \theta = \frac{\lambda\, n}{d}$$

$$\sin \theta = \frac{540\text{e-}9\,(2)}{2.20\text{e-}6}$$

$$\theta = 29.400351 = 29.4^o$$

Diffraction Gratings

You know the old saying "two hands are better than one?" Well, we're going to take it to the extreme.

- If you want, you can get a wimpy interference pattern with light using just a single slit (that's what you did with your fingers).

> You can actually do the single slit experiment wherever you are right now! Hold two of your fingers very close together; there should be only the tiniest little gap between them that you can barely see through. Look towards a light source, light a light bulb, through the gap in your fingers. In the gap between your fingers you shold see very faint gray lines that run parallel to your fingers... these are the destructive interference "dark" fringes!

- A double slit apparatus like the one that Young used works well to give clear images of the fringes of the interference pattern.
- What if we increased the number of slits? The interference pattern will become more clearly defined.

This was an idea that some physicists thought of after Young's work had been published.

- Was there a way to make an apparatus like Young's that had a lot of slits in the first screen?
  - Now, when I say a lot of slits, I really do mean a lot. These guys wanted to figure out a way to have hundreds, or thousands of slits, cut into the screen.
- They figured that this would produce incredibly sharp interference fringes that they would be able to measure even more accurately than those in Young's experiment, which would allow them to measure the wavelengths of light even more carefully.

The problem was, how could you possibly cut that many slits into a screen… you simply can't.

- Their solution was to look at things a little differently.
- Have you ever been driving in a car that had a big crack in the windshield? You probably found it was very distracting if the crack was right in front of your eyes. This is because light doesn't travel very well through cracks in glass. In fact, even scratches in glass block the passage of light.

Illustration 9: The piece of glass with parallel scratches.

- The idea these scientists had was to take a piece of glass and cut very narrow parallel scratches into the surface using a diamond.
  - These scratches won't let light through, but light will still be able to pass through the spaces in between… it will be like thousands of little slits cut into a screen!
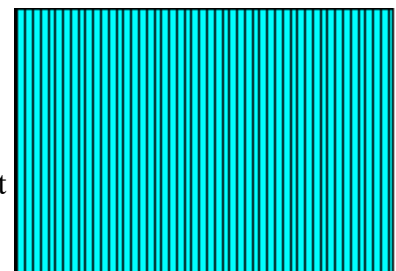
These are called [diffraction gratings](#), since they diffract light though the little gratings cut into them.

Illustration 10: Diffraction grating.

- Held up near a source of white light, they will easily split the light up into a rainbow of colors.
- You can also use a monochromatic light and see *very* distinct bright and dark fringes.
- If we use these diffraction gratings it is possible to measure the wavelength of light very accurately, even if the most basic measurements are taken.

If a white light is used with a diffraction grating, the different colours will be split up on the viewing screen according to their wavelengths.

- The **violet end** of the spectrum (with the shortest wavelengths) refracts at a very small angle and is closer to the central fringe
- **Red** (with the longer wavelength) refracts at a big angle and is far away from the central fringe.
- ***This is significant since it is the exact opposite of what we see when white light passes through a prism (See Lesson 28).***

Real diffraction gratings are made out of pieces of glass cut by a diamond, are about the size of two postage stamps, and cost at least $50 each!

Illustration 11: Replica diffraction gratings barely show any colors in this image.

- Replica diffractions gratings are made by rubbing an acetate sheet (the kind teachers use on overheads) on top of a real diffraction grating to pick up some of the scratches.
- The advantage is that a replica diffraction grating only costs about $2.
- The downside is that the fringes are not nearly as clear.

Whether you are using a true diffraction grating or just a replica, you can still use both of the formulas that we looked at in Young's Double Slit Experiment last lesson.

- What you will have to watch out for is the way that you get the value for "d" to use in the formulas.
  - The spacings between the scratches are incredibly small.
  - Because of this, the traditional way of labeling a diffraction grating is to say how many scratches there are in a certain amount of length on the glass.
  - In both *Illustrations 10* and *11* the gratings had spacings of 600 lines/mm.
- It means that you have to do a quick conversion to find "d" for the formula.
  - Since "d" is the distance between the scratches in metres and we have the number of grooves per millimetre, the first thing we would do is take the inverse.
  - Then, since we want metres instead of millimetres, we divide by 1000 (the number of millimetres in one metre).

> **Did You Know?**
> The reason a CD or DVD has a rainbow of colors on it is because the thousands of circular grooves pressed into the aluminum subsurface act as a diffraction grating.
> Also, the latest series of Canadian polymer bills have a diffraction grating built in for security purposes. Check out the Bank of Canada for more information.

Example 3: **Determine** the value of "d" for the true diffraction grating shown in *Illustration 10* that is labeled as 600 lines/mm.

600 lines / mm   ←*Take the inverse*

1 / 600 = 0.00166666 mm/line ← *Divide by 1000 to get metres*

0.00166666 ÷ 1000 = 1.6666666e-6 = 1.67e-6 m/line

Example 4: Using the value for "d" for the diffraction grating you just calculated, determine the color of light being used if the angle from the central maximum to the second bright fringe is 28.7°.

Since this is the second bright fringe from centre, n = 2. Also, make sure your calculator is in degree mode!!!

$$\lambda = \frac{d \sin \theta}{n}$$
$$\lambda = \frac{1.666666\text{e-}6 (\sin 28.7^{o})}{2}$$
$$\lambda = 4.0018624\text{e-}7 \; = \; 400\text{e-}9 \; = \; 400 \, nm$$

This is about indigo-violet colored light.

Homework

p691 #1,3
p693 #1
p697 #6, 8