Introduction to Optics

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Chapter 1: Laws of Reflection & Refraction

Law of Reflection

The law of reflection states that incoming light to a reflective surface will leave that surface at an angle reflected across the line normal to the surface at that point. That is the angle at which the light contacts the reflective surface and leaves the surface are the same. A mathematical description is $\theta_2 = \pi - \theta_1$. The virtual imaged formed behind the mirror is also the same distance as the real image is in front of the mirror and so when the mirror moves away from the object the reflection must move twice as far from the object. And so, if the object moves toward the mirror or mirror to object the image will move with half the speed. Images are the same size, as a result of being the same distance from the mirror. Mirrors when rotated by an angle will rotate the angle by twice the initial angle of rotation.

Reflection flips images but does not flip the image upside down. That is the left side of the image will be on the perceived right side of the image if facing the same way the image is. (out of the mirror)

These are special cases for flat mirrors as concave and convex reflection can create other types of images like holograms.

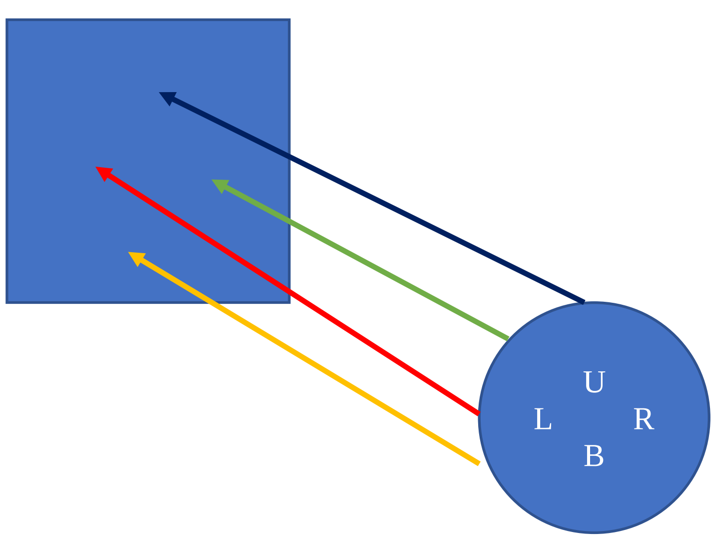
The light must also travel in the shortest distance path. Well, the light will move in the shortest distance because that is what will reach the other point first.

Mirrors use the law of reflection, as well mirrors are used in a lot of other technologies such as cameras.

How to test the law of reflection

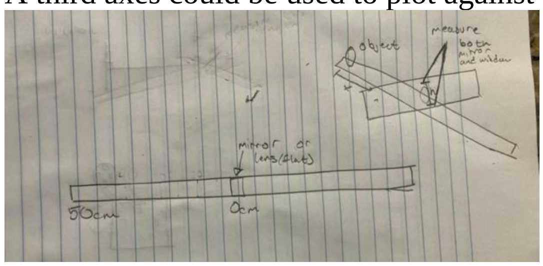
Measuring orientation

1. To test the reflections orientation on a simple marker put 4 markings on an object specifying which direction they are.
2. Place the image a set distance away from a mirror normal to the object.
    a. On the mirror put markings specifying the up, down, left, and right sides of the mirror.
    b. Before measuring ensure that the mirror is still normal to the object.
3. Mark in a separate color which side of the mirror shows the left side of the image and which side shows the right.
4. Repeat step 3 for the up and down markers.
5. Take the mirror and compare which markers align and don't align.



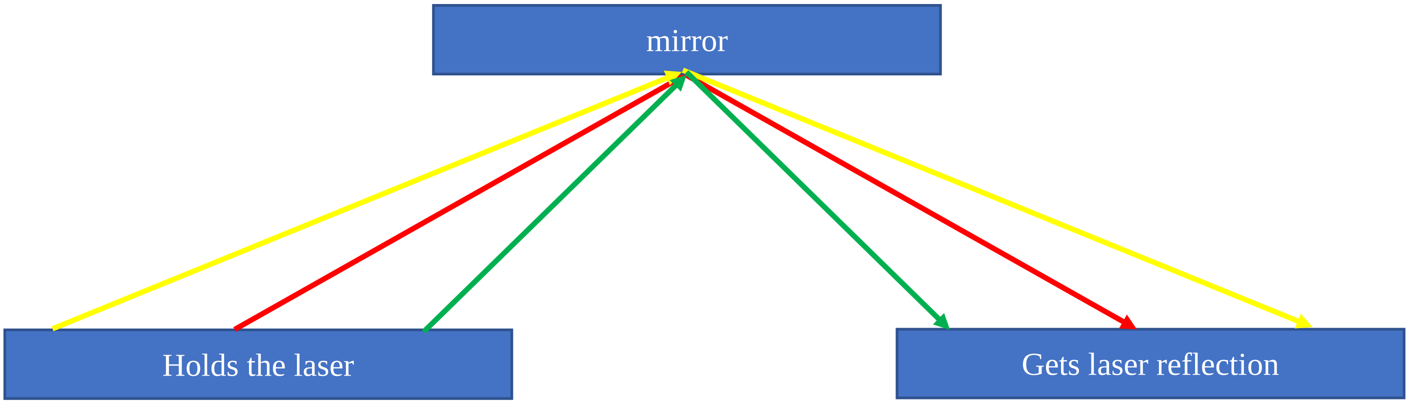
Measuring size

1. Using a meter stick place a holder at the midpoint, 50cm. This holder will hold both a mirror and a lens.
2. Place and object at 50cm away from the mirror and use calipers to measure the height and width of the object in the mirror.
3. Repeat this process every 10cm decrements until reaching 0cm
4. Replace the mirror with a thin lens
5. Place the object at the same distances as in steps 2 and 3.
6. Record the heights and widths of the objects as before from the opposite side as the mirror (side opposite the object)
7. For the data at zero distance, where, the object would be next to the mirror, record the data for the actual object.
8. Plot the height of the reflected image against the height of the object
    a. Repeat with width
    b. A third axes could be used to plot against distance from the midpoint



Measuring angle of reflection

1. Set up a mirror parallel and next to a meter stick at the midpoint.
2. Set up a white board or board with paper on it to mark.
    a. This should extend from the midpoint (50cm) to the end of the
3. Set up a holder for a laser pointer.
    a. Adjacent to the board but on reflected across the line through the midpoint
4. Every 10 centimeters from 50cm out measure the location of the end of the laser pointer’s beam aiming at the midpoint (mark for easy calibration)
    a. Include 0 cm
5. Measure this and the distance of the two sides (mirror and board sides) to calculate the angle
6. Plot the angle of incident against the angle of reflection.
    a. A third axes could be used to plot against distance from the midpoint



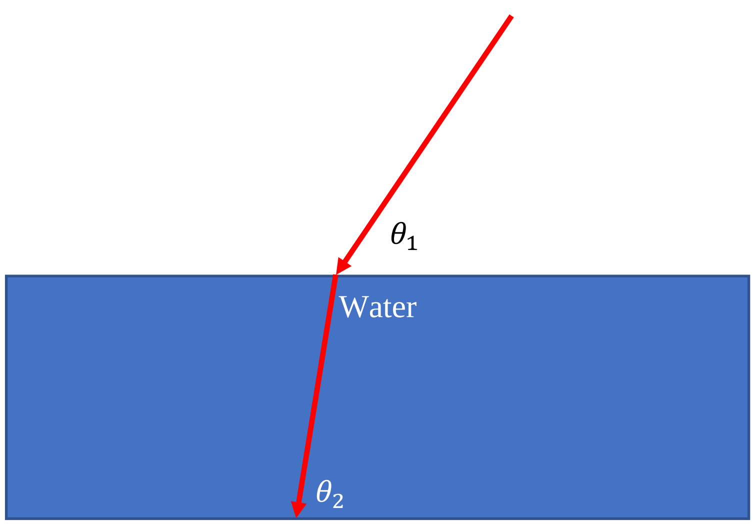
The law of refraction states that the angle of refraction is dependent upon the incident ray and the refractive index. The higher the refractive index, the smaller the angle of refraction. When going between mediums, the angle of incidence and refractive index of the medium are equal. That is

$$n_1 sin\theta_1 = n_2 sin\theta_2$$

Human eyes do refract light. This ensures light entering goes to the retina so you can process the light, coincidentally this is how you can read what I have just typed. The light enters the eye and is refracted towards the center. The eye also uses muscles to adjust the focal distance to focus at different lengths. This is done by slightly changing the structure and curvature of the eye.

<u>Measuring the law of refraction</u>

1. Measure the index of refraction of the materials water
    a. Water
2. Do this by using a known angle of incidence and measure the corresponding angle.
    a. Measure the angle by seeing where the laser pointer is on the bottom of the material and the height of entry.
3. Use angles of incidence from every 5 degrees to 90 degrees
    a. 0..5..10 and so on
4. Measure the distance of each medium and calculate where the laser pointer is along with the origin to find the 2 angles.
5. Plot the $n_i sin\theta_i$ against each other for all different angles.
    a. This should return a straight line if the law of refraction is true. Close to a slope of 1.



This θ_2 can be calculate in a variety of ways. Most simply by measuring the height of the water and the distance from the point of entry on the bottom of the tub to create a triangle.

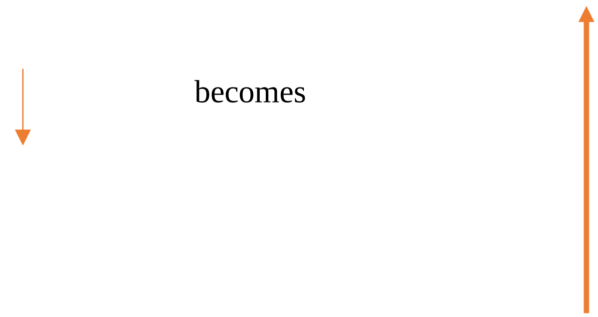
$$\arctan\left(\frac{H}{D}\right) = \theta_2$$

Chapter 2: Telescopes

Optical Telescope

An optical telescope gathers light entering the object lens and magnifies the resulting image. The telescope magnifies the image by amplifying the angle seen through the eyepiece. This is done the same way that a magnifying glass acts, the second lens is simply used to refract the light to be parallel. This image can be observed directly or the reflection of the image in the case of lasers. (Don't look at them).

In daily life, examples of optical telescopes are binoculars. The use of magnifying glass onto electronic sensors is the basis for digital cameras. Celestial telescopes invert the image. That is:



after magnification. The image however does lose some quality and view is not what the image would look like if viewed at a smaller distance. The image, the more zoomed in it is, loses pixels. Telescopes are used to view far away objects

Lenses

Lenses are based on the principle

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

where p is the distance from the object, q is the distance from the resulting image of the object, and f is the focal length. This means that the distance from the object to the lens is p. The focal length is where the beams of light entering the lens plane perpendicular meet. These combine to show where the image will be.

The power of a lens if inversely proportional to the focal length.

$$P = \frac{1}{f}$$

Convex lenses

Convex lenses take light from a source and redirect it to a specific point.

Concave lens

Concave lenses send the light diverging in opposite directions.

Magnification

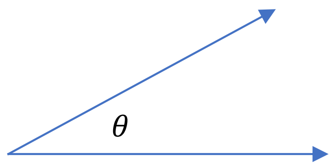
Magnification is the ratio of the object to the image generated. This can be and real number, negative numbers mean that the image is flipped upside down. Magnification with a magnitude less than 1 simply means that the image is smaller than the object itself.

$$M = \frac{I}{O}$$

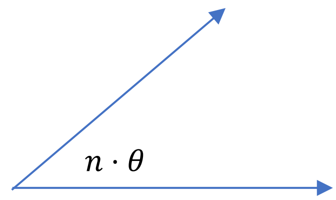
Where M is the magnification, I is the image size and O is the original size of them object.

The magnification a telescope or how large the image appears to be compared to how large the object appears is based on the focal lengths of the 2 lenses.

This is the angular magnification. For an angular magnification of *n*:



will appear as



This is defined as the ratio of the 2 lenses. In order to achieve this magnification, the 2 focal points should be at the same point. The angular magnification is the ratio of the 2 focal lengths.

$$M = \frac{I}{O} = \frac{f_1}{f_2}$$

<u>Increase laser diameter</u>

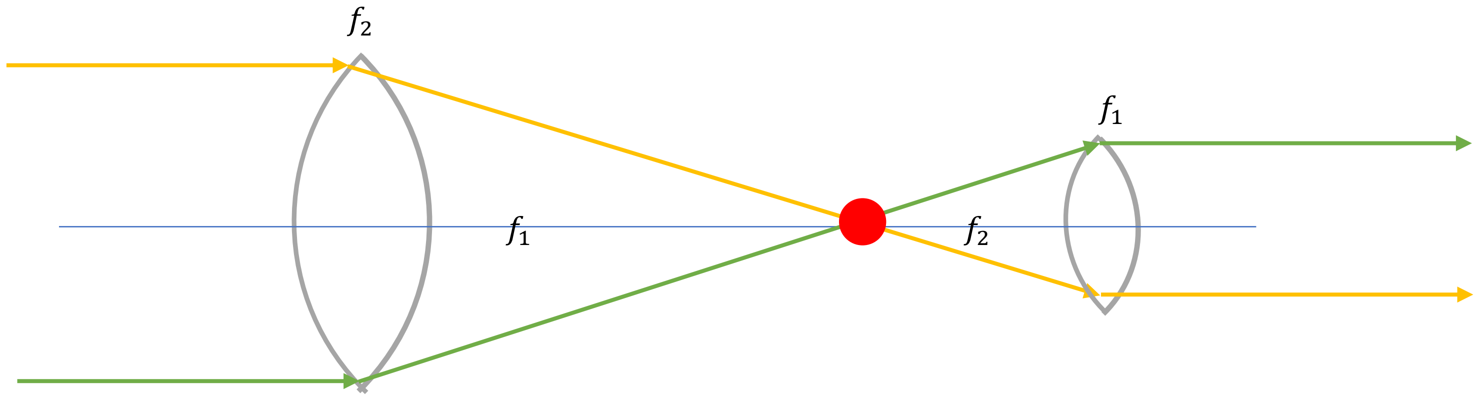
In order to increase the width of the laser beam being shot into the object lens, the first lens must diverge the light to increase the size of the laser. The second object must return the light passing through to the original angle that the light was coming through in.

Then after magnifying the size of the image if a opposite lens (convex-concave) is used, the initial angle of the light should return to normal.

Once placing the concave lens that will bring back the initial angles (with the same radius of curvature) the image of the laser should be magnified 4 times.

For an optical telescope, the magnification is the ratio of the focal length over the diameter of the eyepiece. This is what we need to be 4.

The diagram of the telescope is below. This will invert the laser.



Notice how the image is inverted. The distance between the 2 lenses will be the sum of the focal lengths so that the two focal points are at the same distance. The red dot is the focal points of both lenses. The magnification is $f_1 \div f_2$. We can use a 100mm and 25mm focal length lens to create a magnification value of 4.

Chapter 3: Microscopes

Microscope

A microscope is an optical device comprising of 2 lenses that amplifies the image twofold. The first lens, the object lens provides a linear magnification. The second lens the eyepiece creates an angular magnification. The resulting magnification is the product of the two magnifications.
A microscope enlarges the image of an object that is close to the object lens and enlarges it. The microscope is comprised of two lenses, both convex and creates an inverted image at infinity. The microscope repositions the entire optical device (both lenses) in order to maintain the difference between the two lenses, constant.
The microscope thus has a constant amplification excluding the distance the eye is from the eyepiece.

Setup:

The microscope was set up with the two lenses 8 dots away from each other. Each dot is 25mm apart. The resulting distance was 200mm, 20cm or .2m. The object lens was on the left side in the image, and had a focal length of 25mm, the eyepiece had a focal length of 100mm and was on the right.
The laser was used to calibrate the height and direction of the 2 lenses to ensure the light was travelling through the instrument in a straight path as to be visible by the viewer.

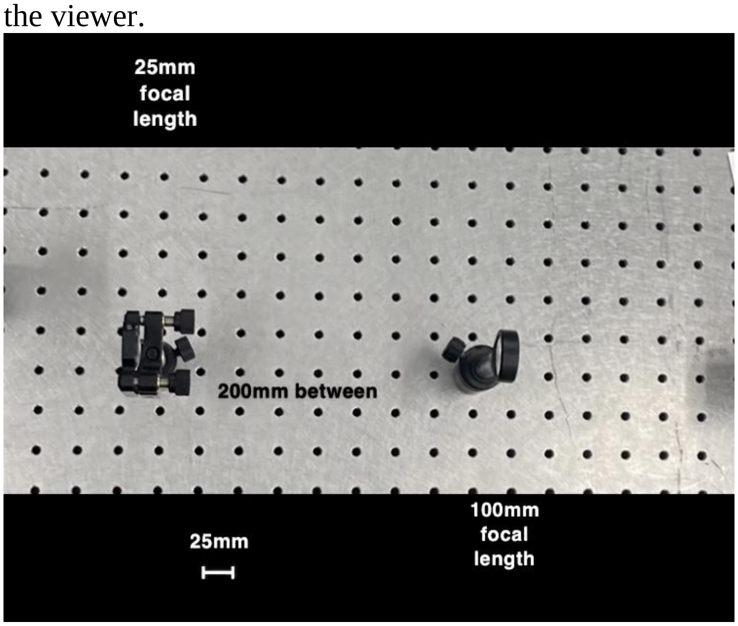
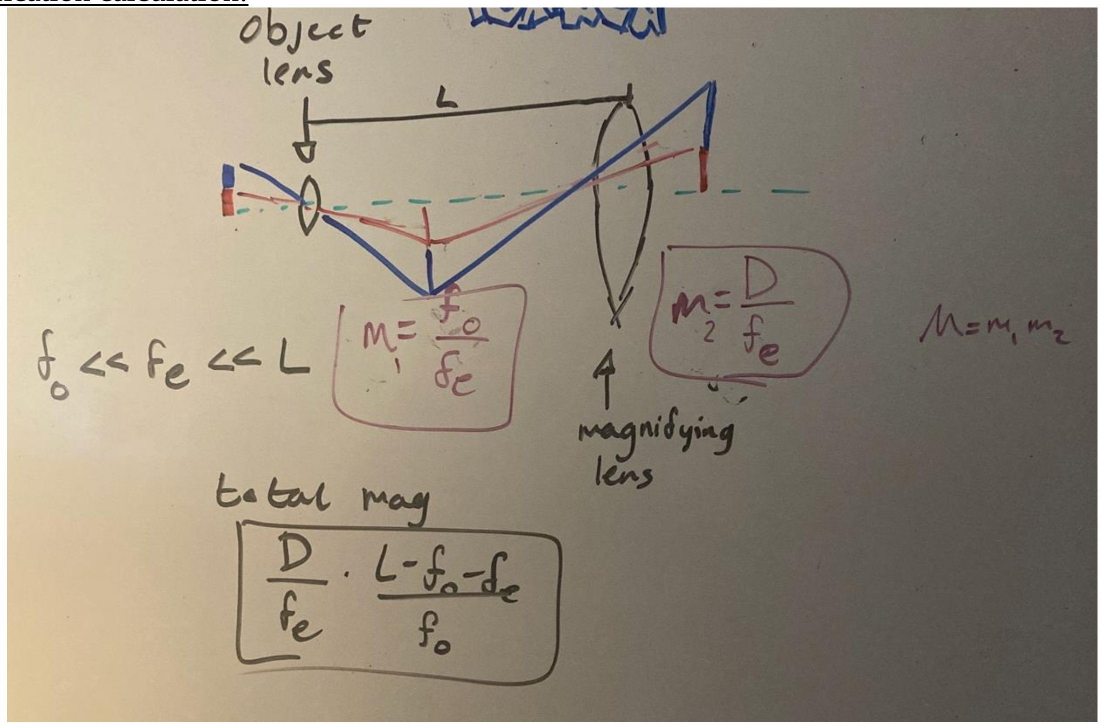


Image. Set up of the microscope.

Amplification calculation:



The magnification of a microscope is the product of the linear magnification from the objective lens and the angular magnification from the eyepiece.
These, respectively, are

$$M_L = \frac{L - f_1 - f_2}{f_1}$$

and

$$M_A = \frac{D}{f_2}$$

This results in a total magnification of

$$M = \frac{D(L - f_1 - f_2)}{f_1 f_2}$$

The variables in these equations are listed in this table.

M_L	Linear Magnification
M_A	Angular Magnification
f_1	Focal length of the objective lens
f_2	Focal length of the eyepiece
L	Length between lenses
D	Distance to near point. Typically .25m

Focusing the microscope:

After setting the microscope up it was observed that the location of the object to be examined was incredibly important for the clarity of the image. The object typically needed to be between 1-2 focal lengths of the object lens. The best results were found at approximately 1 focal length distance.

<u>Specifics of the microscope:</u>

The lenses used in the microscope were 25mm focal length and 100mm focal length. The object lens being 25mm and eyepiece being 100mm. The distance between the two lenses was 200mm. This left the resulting magnification at 7.5 times. The image of the moon appeared with such high magnification that the dots the printer creates were visible.

$D = .25$	$= 0.25$
$L = .2$	$= 0.2$
$f_e = .1$	$= 0.1$
$f_o = .025$	$= 0.025$
$M = \frac{D\left(L - \left(f_e + f_o\right)\right)}{f_e \cdot f_o}$	$= 7.5$

Figure. The calculation of the magnification of the setup. Note that f_e=f_1 and f_o=f_2. However, due to the equation using multiplication and addition with respect to the two lengths it is either. This means the order of the lens is interchangeable. This can affect the resolution, however.

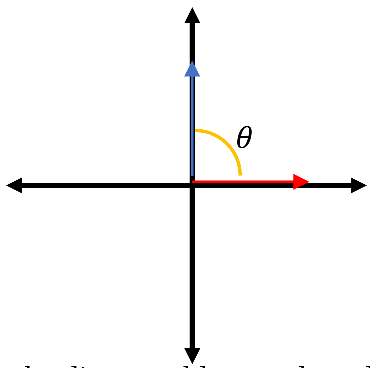
Figure. This is the resulting magnification of a printed picture of the moon, The paper, originally being white had dots printed onto it with varying densities depending on the darkness of the image at that point.

<u>Improvements:</u>

Using the microscope revealed some issues with the ease of use. It is difficult to line the microscope up perfectly and often you will see outside of the object lens. A simple solution is to encase the microscope. This does require calculation for how wide to make the image to ensure no part if the image is cutoff. The orientation of the microscope is also difficult to use, but that would be easy to fix in a constructed microscope with more than just optical components.

Chapter 4: Power and Polarization

Polarization is a measurement of the direction of light. This is which way the waves of light "wave." It is arbitrary which way vertical and horizontal are called. However, the actual direction of light has effects on light. The power is the average amount energy received from the photons per unit time.



In the diagram, blue can be called vertical, and red is called horizontal. The Jones calculus notation of the polarizations is as follows: $|V\rangle = \binom{0}{1}$, and $|H\rangle = \binom{1}{0}$. The angle θ is from the "horizontal."

Components:

The components used are polarizing beam splitters which are polarizers, and halfwave plates.

Half-waveplate:

Figure 1. *Half waveplate diagram.* Vectors described below.

The half-waveplate takes an incoming beam of linearly polarized light and rotates it by an angle of 2θ. The angle θ, is the difference between the fast axis of the waveplate, $\hat{\boldsymbol{f}}$, and the polarization vector of the incoming light, $\hat{\boldsymbol{p}}$. The light is then rotated after passing through the plate. This phenomenon is due to the features of some crystals and the difference of length in the lattices of the material. The final angle of polarization is dependent on the initial angle of incidence to the plate. The Jones calculus operator for the H.W.P. is:

$$HWP = \begin{pmatrix} \cos^2\theta - \sin^2\theta & 2\sin\theta\cos\theta \\ 2\sin\theta\cos\theta & \sin^2\theta - \cos^2\theta \end{pmatrix}$$

Polarizing Beam Splitter (PBS):
"this lab was made possible thanks to viewers like you."

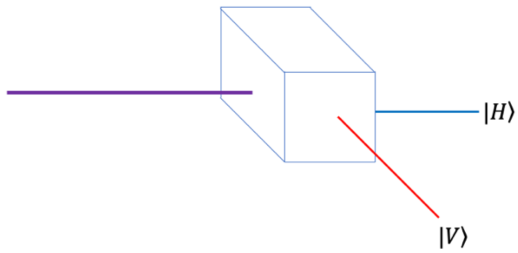


Figure 2. *Polarizing beam splitter diagram*. "Horizontal" and "vertical" light leave splitter in perpendicular directions. There is not true horizontal or vertical, but the 2 exit streams of light are always orthogonal.

The polarizing beam splitter is treated as a polarizer. In either direction a beam of polarized light exits. A non-polarized beam will on average send an even amount of light through both setups. The Jones calculus matrix of a polarizer, as the experiment uses just 1 beam leaving, is that of a horizontal polarizer: **note in the lab I used the vertical light leaving**

$$P = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Setup:
The instrument used to control the polarization and power is comprised of 3 optical instruments, 2 half waveplates, and a beam splitter or polarizer. The first two components are used to control the power and the final component is used to control the polarization. As the light exiting the beam splitter or polarizer is linearly polarized a half wave plate can be used to realign the light.
The laser should be aligned where the initial laser is diagonal light, this is done by checking through the power from both beams is approximately equal.

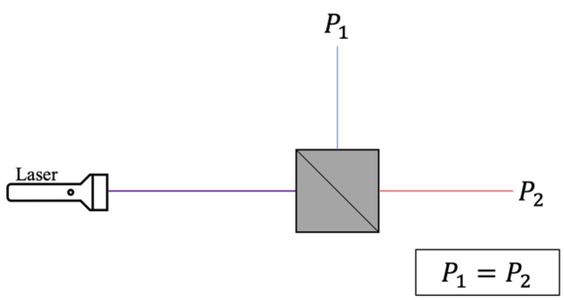


Figure 3. Alignment of laser polarization, P_1, P_2 are the respective powers.

Aligning the half waveplates. For both waveplates find the zero on the rotary mount. That is the angle at which the beam will not be affected at all.
With the newly aligned laser, send a beam through the waveplate. Send this beam then into a polarizing beam splitter. To find what 0° is on the waveplate the horizontal

component of this should be zero. That is P_2 in the previous diagram is 0. Any angle θ is now in reference to this angle. Set up both polarizers in this fashion.

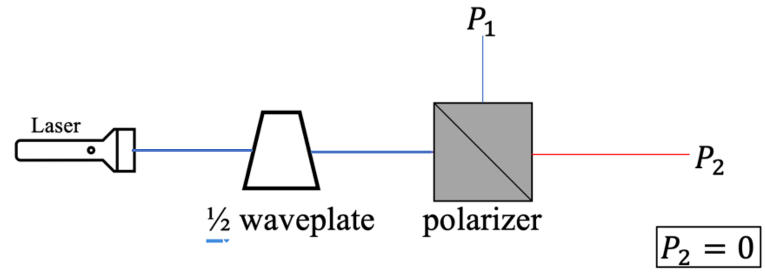


Figure 4. *Alignment of waveplates with horizontally polarized light.*

EX|

40° = zero point

Rotary Mount	θ
70°	30°
130°	90°

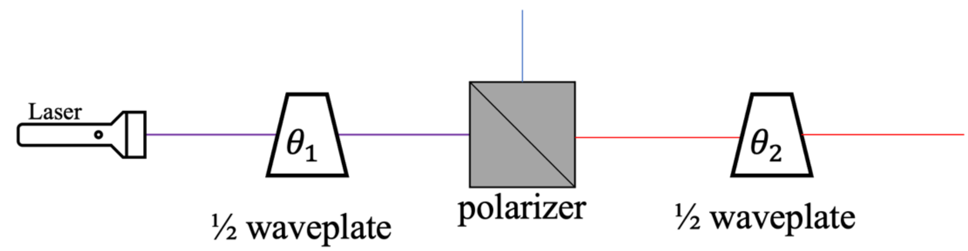


Figure 5. *The complete setup.* With both waveplates and the laser aligned, this optical instrument gives complete control of the light.

The setup of the instrument is made of 2 waveplates and a polarizer, which in this case is a polarizing beam splitter. The light passes through the first waveplate and is rotated by $2\theta_1$, which is then used to select the amount of power we want through the first 2 components. After the polarizer, solely horizontal light exits, and must be rotated by our next waveplate to achieve our desired polarization.

The equation of the entire instrument given the initial light $|P\rangle$, assuming it is normalized.

$$\boxed{|L\rangle = \begin{pmatrix} \cos^2\theta_2 - \sin^2\theta_2 & 2\sin\theta_2\cos\theta_2 \\ 2\sin\theta_2\ \cos\theta_2 & \sin^2\theta_2 - \cos^2\theta_2 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \cos^2\theta_1 - \sin^2\theta_1 & 2\sin\theta_1\cos\theta_1 \\ 2\sin\theta_1\cos\theta_1 & \sin^2\theta_1 - \cos^2\theta_1 \end{pmatrix} |P\rangle}$$

<u>Jones Calculus Calculation:</u>

Using a ½ waveplate with the fast axis at angle θ and a vertical polarizer (in place of a beam splitter). We also know that the intensity is proportional to the power, and thus want a resulting intensity of 1/3 the original intensity. This means the vertical component should be $\frac{1}{\sqrt{3}}$.

<u>Power:</u>

To first calculate the power, take the first 2 components and the initial polarization of the light

$$\frac{1}{\sqrt{2}}\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix}\begin{pmatrix}c^2-s^2 & 2sc\\ 2sc & s^2-c^2\end{pmatrix}\begin{pmatrix}1\\1\end{pmatrix}$$

Our desired result is:

$$\sqrt{(\frac{1}{3})}\begin{pmatrix}1\\0\end{pmatrix}$$

Some calculation gives us.

$$\frac{1}{\sqrt{2}}\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix}\begin{pmatrix}c^2-s^2+2sc\\ s^2-c^2+2sc\end{pmatrix}=\sqrt{(\frac{2}{3})}\begin{pmatrix}1\\0\end{pmatrix}$$

The next matrix multiplication gives:

$$\frac{1}{\sqrt{2}}\begin{pmatrix}c^2-s^2+2sc\\ 0\end{pmatrix}=\sqrt{(\frac{2}{3})}\begin{pmatrix}1\\0\end{pmatrix}$$

$$\cos^2\theta-\sin^2\theta+2sin\theta cos\theta=\frac{2}{\sqrt{3}}$$

$$\boxed{\theta\approx .7004+n\pi}$$

$$\boxed{\theta\approx 40.129°}$$

<u>Polarization:</u>

Starting with the last polarization of light.

$$\sqrt{(\frac{1}{3})}\begin{pmatrix}1\\0\end{pmatrix}$$

The desired polarization is vertical light with the specified power.

$$\sqrt{(\frac{1}{3})}\begin{pmatrix}0\\1\end{pmatrix}$$

Our lost component and operator:

$$\sqrt{\frac{1}{3}}\begin{pmatrix}c^2-s^2 & 2sc\\ 2sc & s^2-c^2\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix}=\sqrt{(\frac{1}{3})}\begin{pmatrix}0\\1\end{pmatrix}$$

$$\begin{pmatrix}c^2-s^2 & 2sc\\ 2sc & s^2-c^2\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix}=\begin{pmatrix}0\\1\end{pmatrix}$$

Matrix multiplication:

$$\begin{pmatrix}cos^2\theta-sin^2\theta\\ 2sin\theta cos\theta\end{pmatrix}=\begin{pmatrix}0\\1\end{pmatrix}$$

Simply, this gives us:

$$\theta=45° \text{ or } \theta=\frac{\pi}{4}$$

This makes sense as the rotation would be 90° or $\frac{\pi}{2}$, double the angle incidence with the half waveplate.

<u>Measurement and alignment:</u>

The final power can be measured by a power meter, but the polarization is more difficult. Given a separate polarizer, that will be aligned in the same axes as the polarizer in the setup; set the new polarizer to let no vertical light through. The power meter then should read 0 or have average ambient light entering the screen.

Chapter 5: Lasers

Lasers

Introduction:

Laser stands for Light amplification by stimulated emission of radiation. Lasers are used in many different industries and have impact. The defining properties of lasers are the polarization of the light exiting, the power, the collimation, the light leaving is all the same color and the waves of a laser are in-phase. There are 2 main types of lasers, pulsed and continuous wave lasers. Pulsed are specified with a time-interval in the name of the laser. Continuous are what most everyday lasers are sending out a beam of light as the name says continuously.

Some examples of lasers used in the real world are fiber-optics in computing and sending packets, cutting/etching; this allows for unprecedented levels of precision, medicinal which can be used for eye surgery and treating cancers.

Process:

Stimulated Emission:

This is a process in which an incident photon with a very specific energy level specified by the relationship $\hbar\omega = \Delta E$. Where $\Delta E$is the difference between the excited state E_1, and the ground state E_0. The first term is the energy of a photon. The two photons exiting have the same energy as the initial photon. The electron struck is also never between the two states and is always in one of the quantized states.

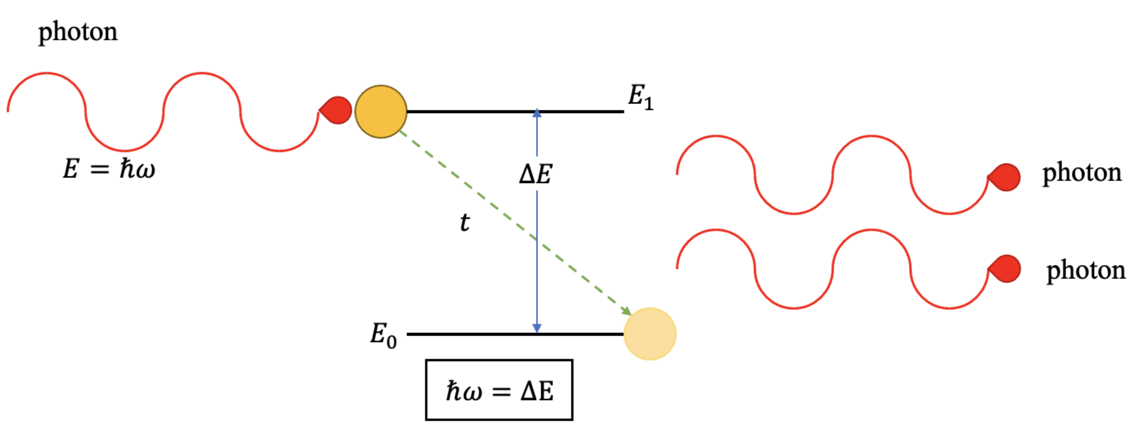


Figure 1. *Stimulated Emission of photon.* The process conserves energy as the energy of the new additional photon is the same as the difference between the 2 energy states of the atom the photon collides with.

Population Inversion:

As mentioned in class before, a laser needs more than 2 states in order to properly lase. The simplest case of this being fulfilled is using 3 states. The difference in states E_2 and E_1 is now required to be equal to the energy of the incident photon, or rather the only photons that will produce lasing must be of the specified energy. Another criterion that must be met is the energy source. This source is what maintains the majority of the atoms into the excited state E_2. The first excited state must be more stable. i.e. it must have a slower coefficient of decay than the growth from the power source exciting atoms in the ground state to E_2.

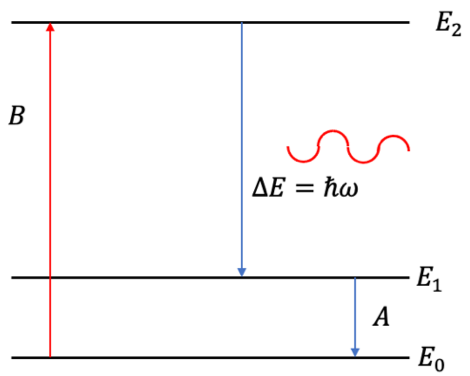


Figure 2. *Population Inversion.* In order to continue the emission there must be more atoms in the excited state. If there is an equilibrium between the ground state and excited states the probabilities that the atom will absorb, and release a photon are the same and no new light will be released.

<u>Gain medium:</u>

The gain medium is the substance inside the laser which increases the . This also relies on 2 reflective surfaces, one that has a transmission coefficient of 0 and the other that is nonzero but is quite small. That is $T = 0, R = 1$ for the reflective surface, and for the somewhat transparent side allowing some photons out of the laser chamber, $T = .01, R = .99$. With the mirrors in place, each reflection doubles the number of photons in the chamber. This may seem like a way to create infinite energy or a surefire way too make something explode with such a high energy density however, it is limited by the number of atoms in the excited state able to release a photon, which this is limited by the power source.

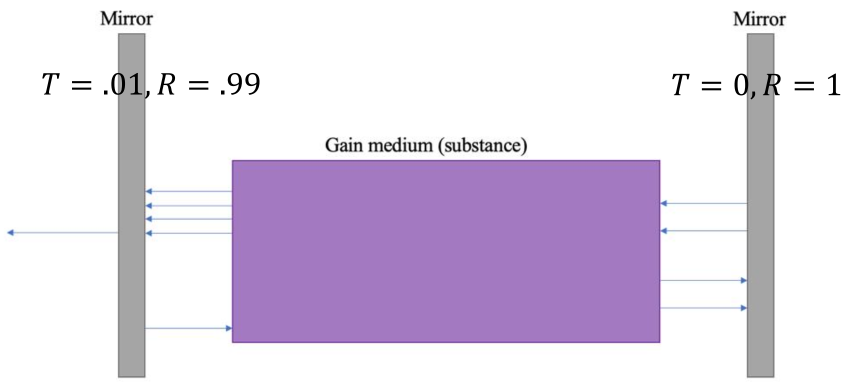


Figure 3. *Lasers use mirrors and a gain medium.* The gain medium is attached to a power source in order to keep the atoms at an excited state. This is the limiting factor in how many photons are released, and directly how powerful the beam is.

Elements:

Lasers exist and a created from a variety of elements and materials including but not limited to: HeNe, Nd:YAG, CO2, HF, Dueterium Floride laser, ethylene. All lasers rely on the stimulated emission. However, the difference is the gain medum is powered differently in most of these. For simplicity, the diagram and description of the laser will be the HeNe laser, which has been used in lab.

Design:

The selected laser for the diagram is the HeNe laser. It is a laser that excites a gas of Neon (Ne) and Helium (He).

The ratio between helium to neon is 10:1. Most HeNe lasers are powered by electrical potential between anodes and cathodes (anode -, cathode +). This puts the atoms in the excited state 2*s* and 1*s* states of He+.

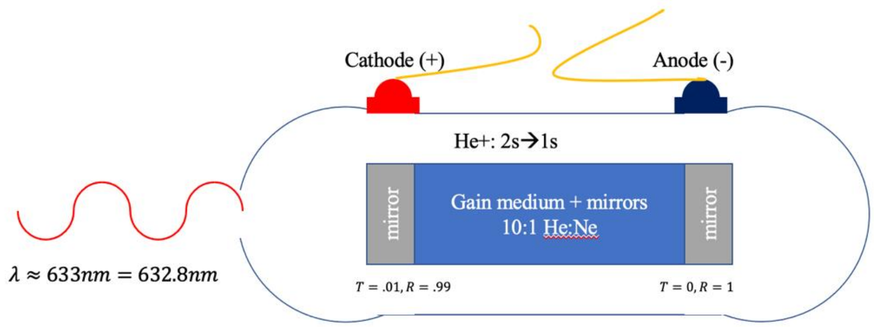


Figure 4. *HeNe laser.* The laser has helium in its excited state which is 2s. This when struck by photons with the specific wavelength 633.8nm has a chance to release another photon. The mirror on the left allows so photons to pass through as denoted by the transmission and reflection coefficients. The laser is powered by electrical potential or a voltage between the cathodes and anodes.

Uses:

HeNe lasers are most used for industrial and academic applications. This is because of their ease of use and stability. They are also relatively cheap in respect to other optical equipment and lasers. They also were the laser used for barcode scanners until diode lasers were more widespread.

Specifications:

HeNe lasers have a mirror with transmission coefficient of 1% and reflectivity of 99%. This means 1% of the light will exit the laser over any interval. The power levels vary between .5mW and 50mW. Most have the wavelength of 633nm which is the classic red laser.

Chapter 6: Diffraction

Diffraction refers to the phenomena of waves interacting with obstacles and corners. It does not apply to solely light waves, but rather all waves including water and gravitational waves. It is often thought of as the interaction of waves with themselves, leading to interference but this is a result of the interaction with barriers. Diffraction actually led to the discovery of the double helix shape in DNA. The experiment was conducted with x-ray diffraction.

The credit for the discovery was given to Watson and Crick but the experiment was conducted in Franklin's Lab.

Principles:

All waves diffract and through quantum mechanics proof that all matter has wave like properties, matter will diffract. On small scales, subatomic to molecular. There's not a diffraction pattern for humans as fun as that may be.

Examples:

In this chapter there will be 3 cases of diffraction patterns that are looked at. We care more about the distance between bright peaks and dark fringes than the actual intensity however interesting patterns do exist in these relationships, but it will not be the focus.

Single Slit:

In the single slit case the distribution will appear as follows. Mathematically this is represented by the equation:

$$\Delta y = \frac{\lambda D}{a}$$

The variables of this equation are Δy, the displacement between nodes, λ, the wavelength of the light, a, the width of the slit, and D, the distance to the screen. This generates a distribution like:

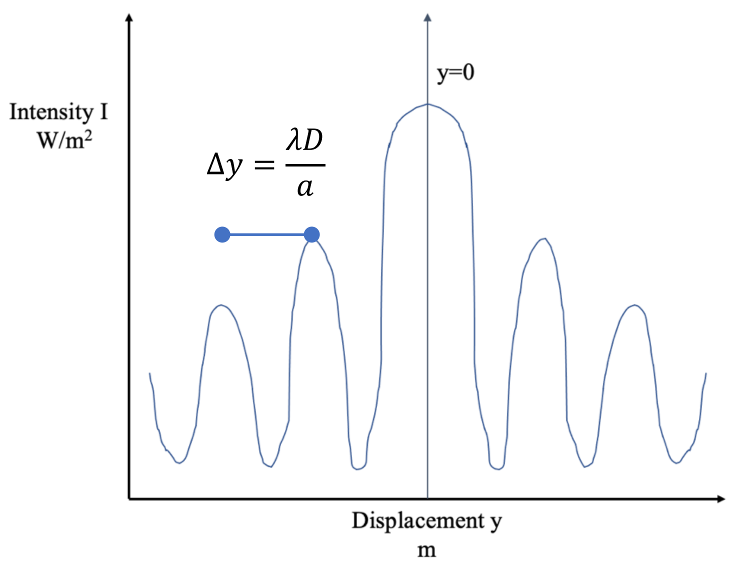


Figure 1. *Single slit diffraction pattern*. This is generated by the intensity of the light on the screen. The function should be smooth; however, PowerPoint does not have a great way to create good curves.

Double Slit:

In the double slit experiment, there is an evenly distributed, harmonic oscillator distribution. That is the intensity of the peaks is constant no matter how far the peak is from the central node. However, this is solely in theory, in practice there is a confounding effect from the two single slits the double slit, both acting as a single slit diffractor. The distance between nodes (peaks/fringes) is:

$$\Delta y = \frac{\lambda D}{d}$$

In this equation Δy, is the distance between peaks, λ is the wavelength, D is the distance to the screen and d is the distance separating the two slits. This theoretical distribution could occur if there were 2 point sources. This is what would appear if both slits were point sources.

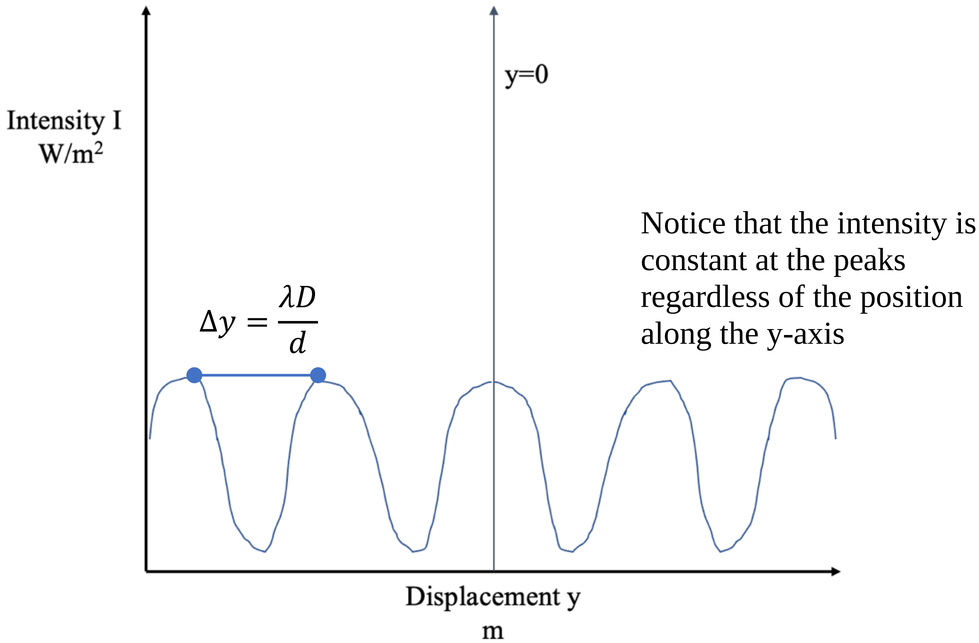


Figure 2a. *Theoretical Double Slit*. The intensity and distance between the nodes are constant. That is the peak intensities. There will be dark fringes. For the next example consider the condition d >>a.

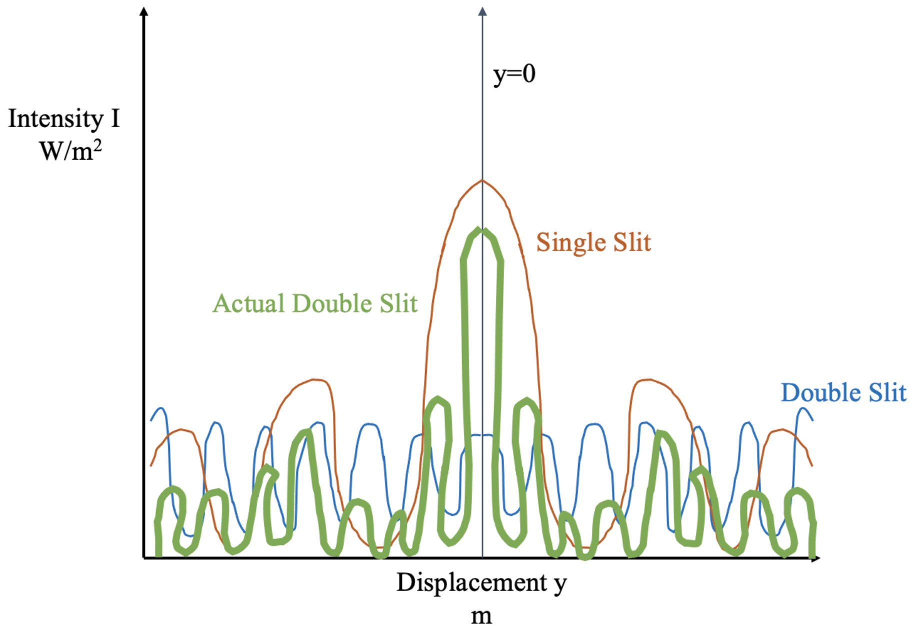


Figure 2b. *Experimental Double Slit.* This is what appears when we measure the double slit experiment. The intensity decreases away from the central node. This is actually because the resulting intensity is the product of the respective intensities of the theoretical doubles slit and the single slit experiment. Both slits can be treated as being in the same position and acting as a single slit diffractor, thus creating the overall single slit diffraction patter, with the much more frequent peaks and fringes of the double slit. This frequency difference comes from our condition *d*>>*a*.

<u>Circular Aperture:</u>

A circular aperture creates a diffraction pattern known as an airy disk. There are rings that are equally spaced radially. The distance between the rings peaks or dark fringes is the same and is spherically symmetric.

$$\Delta R = D\frac{\lambda}{d}$$

The variables are ΔR is the distance between rings, D is the distance from the aperture to the screen, d is the width of the pinhole (circular aperture) and λ is the wavelength.

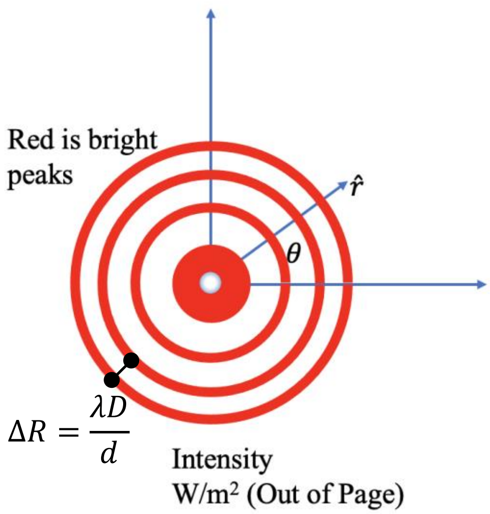


Figure 3. *Pinhole Aperture Diffraction Pattern.* This is the pattern created by a circular pinhole or a circular aperture. The distance between the peaks is constant with r.

<u>Experiments:</u>

Both experiments will use a marked background with measures for scale, an example:

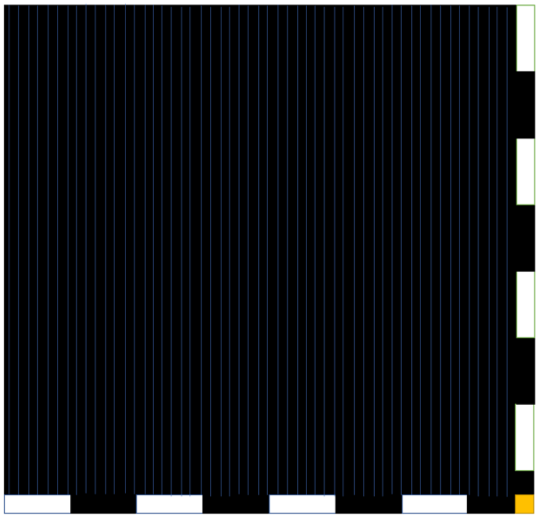


Figure 4. *Background with regular scale*. This will help find the horizontal and vertical distance from the aperture and the laser simultaneously.

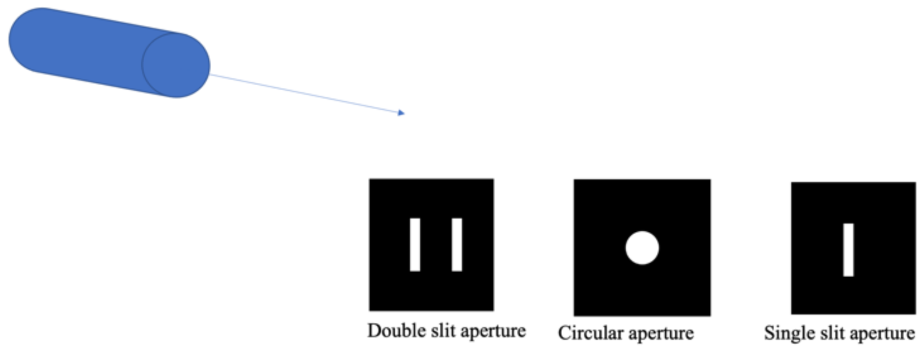


Figure 5. *Setup.* The setup is very simple, point the laser at the whole in the aperture and see the diffraction pattern.

<u>Circular Aperture:</u>

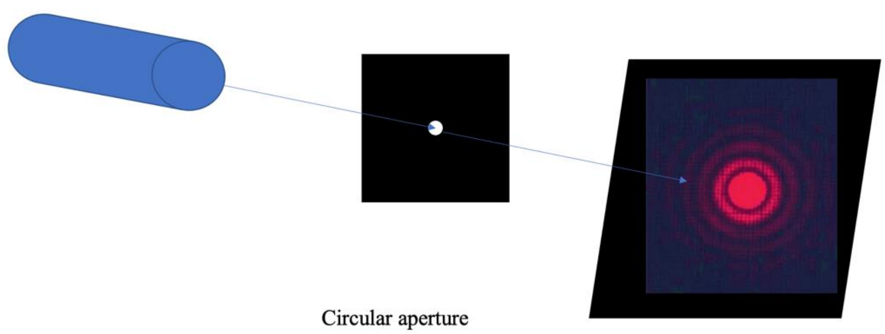


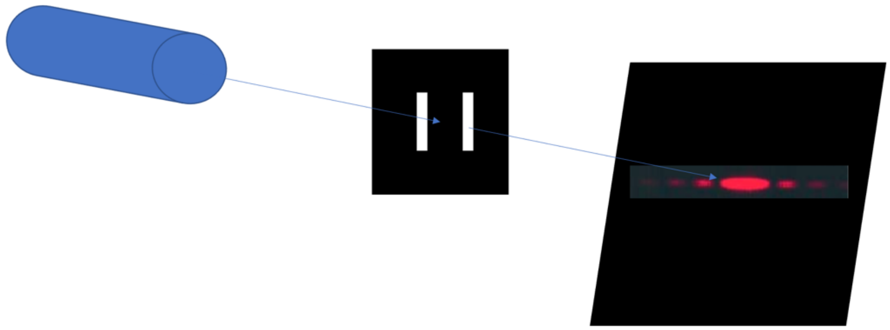
Figure 6. *Circular Aperture Test.* This is a diagram of the lab for a circular aperture's diffraction and the pattern that should appear on the screen.

1. Place a laser with known intensity and width and wavelength
2. Directly in front of this place out circular aperture. The width should be less than the laser's width.
3. Measure the intensity at different radii around the center.
4. Record the intensities as in a table or as a function of radial displacement.
5. Use the distance between the aperture and the board to find the angle θ.
   Note for this experiment, a should square scale probably be used. Or a circular scale in as the background to easily find the radius from the center.

   The data should support an equation of the form

$$I = I_0 \left(\frac{J_1(kasin\theta)}{kasin\theta} \right)^2$$

<u>Single and Double Slit Aperture:</u>
Single slit



Single slit aperture

Figure 7. *Single Slit Diffraction*. This is the setup and resultant pattern of the single slit diffraction experiment.

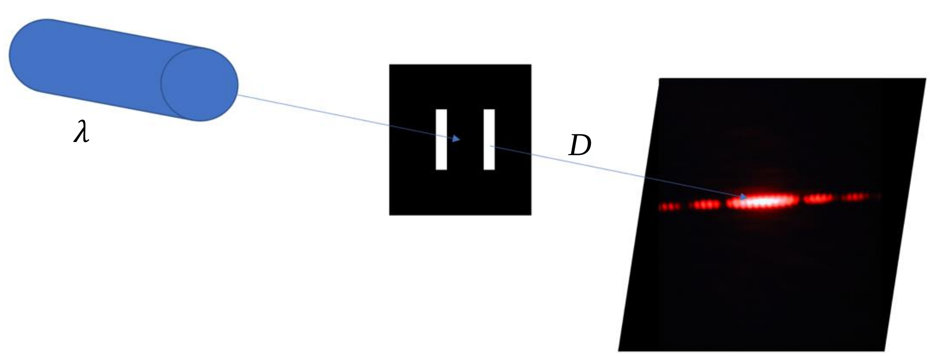
1. Place a laser in front of a single slit aperture. Know the wavelength intensity and width of the laser.
    a. The slit should be less than the width of the laser.
2. Measure the intensity at each strong node and map this to the horizontal distance.
    a. Observe the pattern as well and note the strong points of intensity
3. Translate the distances to angles by using the distance from the aperture to the board.

The variables effecting the intensity are the width of the aperture, and the angle from the center and the wavelength.

$$I = I_0 sinc^2(\frac{d\pi}{\lambda} sin\theta)$$

This experiment can be repeated by comparing the functions over. Repeat the above experiment for different widths and keep the data separate. Then set 2 of the variables to be constant and plot the Intensity against the new responding variable. The data collection as described will be the same.

Double Slit



Double slit aperture

Figure 8. *Double Slit Diffraction*. The setup of the double slit experiment with a rough sketch of what the pattern should appear as on the screen. There are two widths of the interference pattern the smaller of the two is the result of the double slit interference the larger is acting as the single slit would.

1. Place a laser in front of a double slit aperture. Know the wavelength intensity and width of the laser.
   a. The slit should be less than the width of the laser.
2. Measure the intensity at each strong node and map this to the horizontal distance.
   a. Observe the pattern as well and note the strong points of intensity
3. Translate the distances to angles by using the distance from the aperture to the board.
4. Repeat varying the separator width and the wavelength. I did this experiment in high school.

Show that the relationship between the locations of bright and dark spots is linear and of the form:

$$y = \frac{m\lambda D}{d}$$

Where *y* is the location of the bright spots, *m* is the number-eth spot, *D* is distance to the screen and *d* is the separator between the two slits.

While performing the experiment, as seen in this collage (Figure 13) using the scale to measure the displacements was quite difficult and a scale background would have proved very beneficial.

Angle Translation:

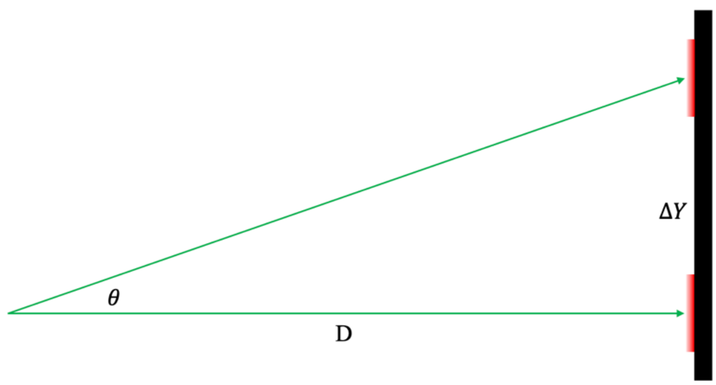


Figure 9. *Angle and side length diagram.* Where Δy, and *D* are the distance between nodes or the height on the screen and distance to the screen from the object creating the diffraction, respectively.

To find the angle θ for the background we use the relationship:

$$\frac{\Delta y}{D} = tan\theta$$

Rearranged:

$$\arctan\left(\frac{\Delta y}{D}\right) = \theta$$

However, we are fine with using simply the distance values and not solving for the angles. However, for the equations involving angles, this is what we can use to solve for.

Diffraction

Lab I:

Calculations

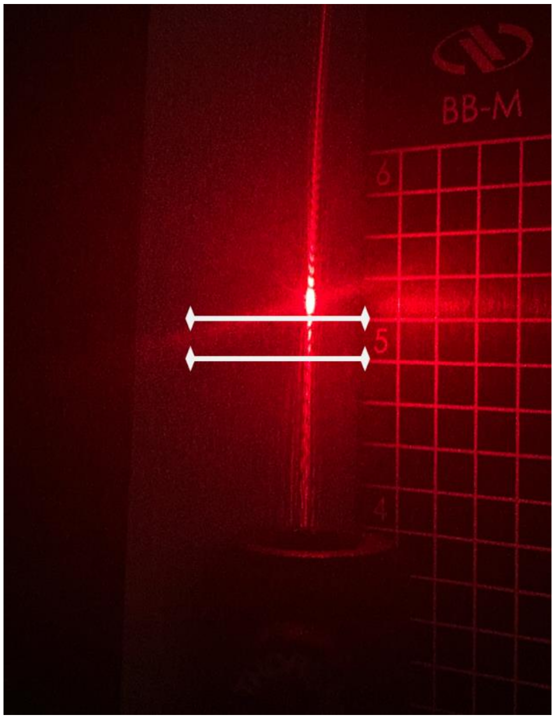


Figure 10. *Diffracted light on measuring surface*. The marked tower structure has ¼ inch markings along the length. This is how the difference between nodes is measured. For our separation, the nodes were about 3 per each mark. That makes the separation 1/12 inches; this is .211 cm and .00211m. This measurement will be used for the calculation further on in the section. The nodes were counted by seeing how many bright nodes there where when looking at a distance specified by the marking differences.

The relation between separation of nodes and the distance between the slits is:

$$y \approx \frac{m\lambda D}{d}$$

The distance *y* is the height from the center, *D* is the distance to the screen and *d* is the distance between the slits. The *m* is the which node from the central peak it is. This is an integer; however, what is relevant is the distance between the peaks. This distance is constant along the entire axis. That is, the distance between nodes 1 and 2 or 4 and 5 will be the same. This relationship is:

$$\Delta y \approx \frac{\lambda D}{d}$$

The laser specified a 633nm wavelength. The distance from the slit to the diffraction pattern was .375m. The distance between the peaks was previously measured and noted at .00211m. This calculation, solving for *d*, is:

$$d \approx \frac{\lambda D}{\Delta y}$$

When plugged in the final value of d is 112.5 microns. This is about 1/10 of a millimeter and is reasonable. The slit in the brass appeared incredibly narrow.

Lab II:

More measurements:

A similar procedure was done for 6 separate diffraction patterns. 6 slits or apertures were used. 3 were created in the lab using brass shims and 3 were the manufactured ones. A bonus diffraction pattern over a strand of hair was generated and will be included.
The measurements were taken from fringe to fringe or peak to peak, whichever was clearer for that pattern. For the double slit experiment, 2 measurements were taken. This is due to the practical effects appearing in the double slit experiment as described above.

The data was collected and compiled with photos to show what each value means.

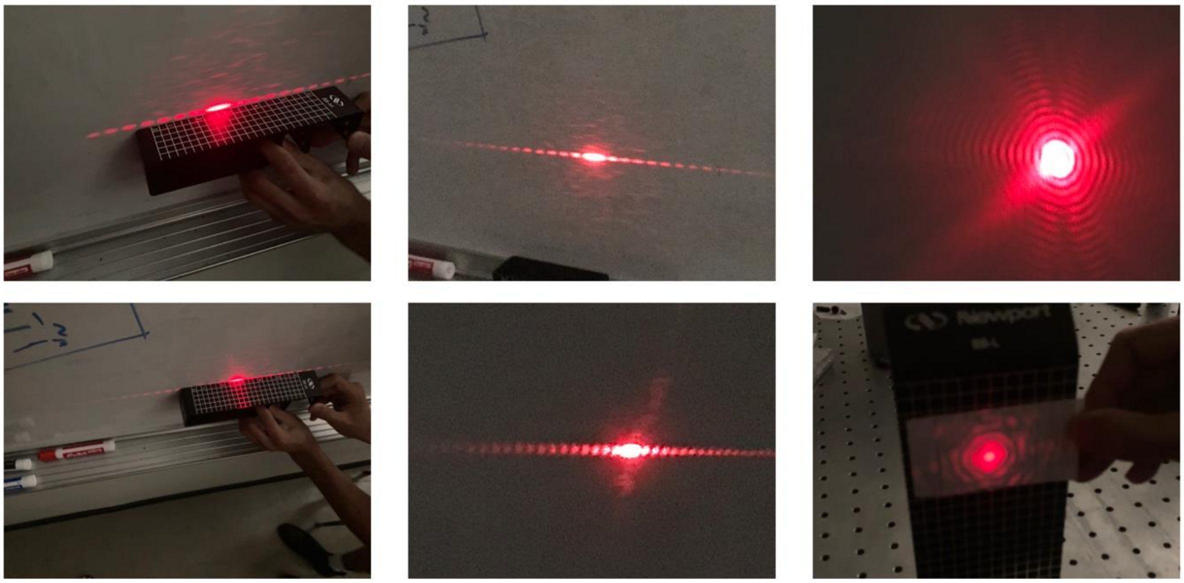


Figure 11. *Diffraction patterns for all 6 of the diffractions*. The first figure (top left) is the double-slit from the kit, the bottom left is the double slit created using brass. The middle column is the single slit distributions. The right column is the 2 pinhole and circular apertures.

Our distance from the apertures to the screen is 7’2”. In SI units this is 2.2098m

Double Slit calculations

Double Slit Experiments	Distance between Double Slit nodes	Distance between Single Slit nodes	*d*, slit separation	*w*, each slit width
Pre-manufactured	.002115m	.0127m	661 μm	110 μm
In Lab	.002988m	.0539m	468 μm	25.9 μm

Single Slit calculations

Single Slit Experiments	Distance between nodes	*w*, each slit width
Pre-manufactured	.01694m	82μm (actual 75 μm)
In Lab	.00843m	164 μm

Pinhole/Circular Aperture calculations

Pinhole Experiments	Distance between peaks	Pinhole diameter
Pre-manufactured	0.079985119m	.0000174m 17.4μm
In Lab	.00134056m	0.00104m ~1mm

Using a strand of hair and creating a diffraction pattern, what is the hairs width?

The diffraction pattern of the hair is the next figure and the relationship between width of wire/strand of hair is:

$$\Delta y = \frac{\lambda D}{d}$$

Which is the same as the double slit. This is essentially that the hair is the divider between 2 slits.

Figure 12. *Hair diffraction pattern*. The distance from peak to peak was measured, this, combined with the other factors allowed the calculation of my hair width.

The final width of my hair is 77.8 μm. The nominal value of hair is often chosen to be 75 μm. The measurement and calculation appear to be in the correct ballpark.

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