A. Diffraction

When light passes through an opening or simply goes by the edge of any obstacle, the wave bends into the region not directly exposed to the wavefront. This phenomena is called diffraction. When the size of the opening or object is large compared to the wavelength of the light, the spreading effect is small. That is why diffraction is not noticeable for a beam of light coming through a window or in the shadow cast by an opaque object. On close examination, however, even the sharpest shadow is blurred slightly at the edge.

The amount of diffraction depends on the wavelength of the light wave compared to the size of the obstruction. Standard AM radio waves are 180 to 6000 meters long. AM waves bend readily around objects. In comparison, the radio waves of the FM band range from 2.7 to 3.7 meters, and do not bend as much as AM waves. This is one of the reasons why AM reception is often better than FM reception in some regions.

A negative consequence of diffraction is the limitation it imposes on microscopy. The shadows of small objects become less and less well defined as the size of the object approaches the wavelength of the light illuminating it. If an object is smaller than the wavelength, no structure--or anything--can be seen. No amount of magnification or perfection of microscopy design can defeat this fundamental diffraction limit.
B. **Single Slit Diffraction**

Shown below is a wavefront incident on a single slit of width $b$. The screen is placed a distance $L$ from the slit.

The diffraction pattern is shown below. The central bright spot is considerably wider than the slit. In addition, the central bright spot is twice as wide as secondary bright bands.

The condition for a minimum (dark spot) is

$$b \sin \theta = n \lambda, \quad n = 1, 2, 3, \ldots$$

In most cases the angle $\theta$ will be small so the following approximation can be used with a high degree of accuracy

$$\sin \theta = \tan \theta = \frac{x}{L}$$

So the condition for a minimum can be written

$$b \left( \frac{x_n}{L} \right) = n \lambda$$
If \( x_n, L, n, \) and \( \lambda \) are known this method can be used to determine the width of the slit

\[
b = n\lambda L/x_n, \quad x_n = \text{location of the } n\text{th diffraction minimum}
\]

C. Double Slit Interference

When light passes through two narrow slits separated by a distance \( d \), the two light beams that emerge will interface with one another. Some of the time this interference will be constructive, while other times it will be destructive. The resulting pattern will be a series of bright and dark lines equally spaced as shown below.

The location of a particular maximum (bright spot) is given by a simple relation.

\[
ds \sin \theta = m\lambda, \quad m = 0, 1, 2, ...
\]

If the angle \( \theta \) is small we may use the following approximation

\[
ds \sin \theta \approx d(x_m/L) = m\lambda
\]

If \( x_m, L, m, \) and \( \lambda \) are known this method can be used to determine the separation of the two slits.

\[
d = m\lambda L/x_m, \quad x_m = \text{location of the } m\text{th interference minimum}
\]

D. Polarization

Diffraction and interference effects occur with any type of wave. However, since light is a transverse electromagnetic wave, it exhibits one property not common to all waves. This unique property is called polarization.

As a light wave travels through a medium, the electric and magnetic fields oscillate in a plane perpendicular to the direction of travel. If all light waves from a given source are such that their electric field vectors are parallel, the light is said to be plane polarized. If,
however, the individual light waves coming from a source have randomly oriented electric vectors the light is said to be "randomly polarized" or "unpolarized."

Unpolarized light can be conveniently plane-polarized by use of a Polaroid sheet. This is a sheet of transparent plastic in which special needlelike crystals of iodoquinine sulfate have been embedded and oriented. The resulting sheet will allow light through it only if the electric vector is vibrating in a specific direction. Hence, if unpolarized light is incidence upon the sheet, the transmitted light will be plane-polarized and will consist of the sum of the electric field components parallel to the permitted direction.

Consider what happens as unpolarized light is passed through two Polaroids as shown in the two cases below. In the first case, the first Polaroid allows only the vertical vibrations to pass. These are then transmitted by the second Polaroid, since it, too, is vertical. However, in the second case, the polarizer has been rotated through $90^\circ$ and allows only horizontal vibrations to pass. These are completely stopped by the vertically oriented Polaroid. Therefore, no light comes through the combination.

In the example shown in the next page the two Polaroids are oriented at an angle $\theta$ between $0^\circ$ and $90^\circ$. Malus' Law tells us that if $I_m$ is the intensity of the light transmitted when $\theta$ is $0^\circ$, then at any other angle the intensity of the light is $I = I_m \cos^2 \theta$. 
The incident unpolarized light is an equal mixture of vertically and horizontally polarized light. The first polarizer allows only vertically polarized light to pass. As a result, the transmitted light is polarized in the vertical plane and its intensity is reduced by a factor of two. When this plane polarized light of intensity $I_m$ strikes the second polarizer, Malus' Law tells us that the transmitted light has an intensity of $I_m \cos^2 \theta$. Where $\theta$ is the angle between the axis of the second polarizer and the plane of the polarized light which strikes it.

E. The Photometer

The PASCO Model 9152A Photometer is a battery powered, self contained, medium sensitivity instrument. The unit contains a selenium photovoltaic cell, high sensitivity amplifier and meter readout. In addition to six ranges of sensitivity, the instrument features a variable sensitivity control, internal battery check, and external chart recorder output jack. The 9152A may be used either to read the light directly incident on the selenium cell or, through the use of a detachable fiber optic probe, to measure the incident light up to 30 inches from the photometer. The fiber optic probe also makes it possible to measure light in areas which would not be accessible to the photometer.

OPERATING INSTRUCTIONS:

1. **Mechanical Zero** - Before turning the instrument on, check that the meter movement is mechanically zeroed. If not, turn the adjustment screw, directly below the meter face, until the needle is exactly over zero.

2. **Battery Check** - Turn the Power Switch to the "BATT.TEST" position. The meter needle should read to the right of the "Replace Batt." line. If the needle reads within the line then replace the battery according to the procedure given in the Maintenance Section. (NOTE: Instruments are shipped without the battery installed.)

3. **Electronic Zero** - Place the palm of one's hand tightly over the Optic Input connector which houses the selenium cell (if the fiber optic probe is not attached
to the photometer) or over the end of the fiber optic probe (if the probe is attached to the photometer). When all light has been prevented from entering the selenium cell turn the Sensitivity (Lux) Switch to the "1" position and turn the Zero Adjust Knob until the meter needle reads over zero. Again, when adjusting for electronic zero make certain no light can get to the selenium cell. Turn the Sensitivity Switch to the 300 Position.

4. **Measurements With the Fiber Optic Probe** - The fiber optic probe is attached to the photometer by slipping the connector of the fiber optic probe over the Light Probe Input connector on the photometer. A quarter twist clockwise locks the probe to the photometer. A quarter twist counterclockwise disengages the probe. The probe should be pointed directly at the light source to be measured. Turn the Variable Knob fully clockwise. Turn the Sensitivity Switch clockwise one step at a time until the meter reads the highest value without going off scale. The Photometer now will indicate relative intensity.

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**Procedure - Experiment 12**

**WARNINGS:**

*Do not look directly into the laser beam.*
*Misuse of the lasers will not be tolerated.*

1. **Single Slit Diffraction**

Position the laser 2-3 meters from the wall at the far end of the lab bench.

Attach the slide of single slits on a component carrier and position it 1-2 meters from a sheet of paper taped to the wall. Measure $L$ (the distance from the slit to the wall).

Place the narrowest single slit (nominal width = 0.02 mm) in the path of the laser beam.

Identify the central spot on the paper and place a mark at its center. On the paper identify as many dark fringes as possible. Choose a reliable dark fringe and record $n$ and $x_n$.

The width of the slit is given by

$$b = n \lambda L / x_n, x_n = \text{location of the } n\text{th dark fringe (diffraction minimum)}$$

$n = 1, 2, 3, \ldots$

Using $\lambda = 632.8$ nm determine the slit width.

Repeat this measurement using the slits with nominal widths of 0.04, 0.08, and 0.16 mm.
2. **Double Slit Interference**

Position the laser 2-3 meters from the wall.

Attach the slide of double slits on a component carrier and position it 1-2 meters from a sheet of paper taped to the wall. Measure L.

Place the double slits with nominal values of $b = 0.04$ mm and $d = 0.25$ mm in the path of the laser beam.

Since both double slit interference and single slit diffraction will both be evident in the observed pattern we can use this experiment to measure both the slit width and the slit separation. Identify the central spot on the paper and place a mark at its center. On the paper identify as many dark diffraction fringes as possible. Choose a reliable dark fringe and record $n$ and $x_n$. Now identify as many bright interference fringes as possible. Choose a reliable bright fringe and record $m$ and $x_m$.

Be careful with your counting of bright fringes. Remember that the center bright fringe corresponds to $m = 0$. In addition, if an interference maximum occurs at the same position as a diffraction minimum, then that bright spot will not be visible. However, you must still count the "m" of this missing bright spot.

Determine the slit width ($b$) and the separation between slits ($d$) using

\[
b = n\lambda L/x_n, \quad x_n = \text{location of the } n\text{th dark fringe (diffraction minimum)}
\]

$n = 1,2,3…$

and

\[
d = m\lambda L/x_m, \quad x_m = \text{location of the } m\text{th interference minimum}
\]

$m = 0,1,2,3….$

Repeat this measurement using the other three sets of double slits on the slide.

3. **Simultaneous Diffraction and Interference**

With double slits you may see that some interference maximums are absent because they are located at the same position as a diffraction minimum. Looking at the pattern
produced by the four sets of double slits what relation exists between missing interference bright spots and the ratio \( d/b \)?

4. **Polarization**

This part of today's experiment can be done with the lights on in the room.

Arrange a laser, the two converging lenses, angular translator, and viewing screen on an optical bench in the order shown below. (The angular translator is used here only so that the fiber optic probe can be attached to the arm to use the photometer laser.)

The purpose of the two lenses is to spread the laser beam. Adjust their relative positions so that a circular beam spot about 5 mm in diameter is visible on the screen.

Position a polarizer on a carrier after the second lens. Rotate the polarizer and observe that light is transmitted through this single polarizer at all angles.

Attach a second polarizer to a special component carrier and place it on the angular translator. Adjust the polarizer so that the \( 0^\circ-180^\circ \) axis is vertical. Rotate the second polarizer and observe the intensity of the laser beam spot on the screen. By visual inspection, under what conditions is the transmitted light of maximum intensity Minimum intensity?

Remove the screen. Check to make sure that the laser light strikes the fiber optic probe inserted in the arm of the angular translator. Adjust the two lenses to accomplish this if necessary.

Align the two polarizers so that both have the \( 0^\circ-180^\circ \) axis vertical. Measure the intensity of the light as measured by the photometer. Now carefully rotate the second polarizer so that the angle \( \theta \) between the two axes is 15, 30, 45, 60, 70, and 90°. Record the intensity in each case and compare with the prediction of Malus' Law.
Finally, arrange three polarizers as shown in below.

```
Laser light  Vertical polarizer  Polarizer rotated at an angle of 45° with respect to the vertical  Horizontal polarizer
```

Is light transmitted through the combination? Is light transmitted if the middle polarizer is removed? Explain these results?
Remember: \( b = \text{slit width} \)
\( d = \text{separation between slits} \)

1. **Single Slit Diffraction**
   Using your measurements calculate \( b \) (the slit width) for each case. Be careful with units and show your work for the first case. If your result is significantly different from the nominal value, repeat your measurement.

<table>
<thead>
<tr>
<th>Nominal slit width ( b ) (mm)</th>
<th>Slit to screen distance ( L ) (m)</th>
<th>Dark fringe selected ( n )</th>
<th>Location of the ( n )th dark fringe ( x_n ) (cm)</th>
<th>Calculated slit width ( b ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0.04</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. **Double Slit Interference**
   Using your measurements calculate \( b \) (the slit width) and \( d \) (the slit separation) for each case. Be careful with units and show your work for the first case (both \( b \) and \( d \)). If your results are significantly different from the nominal values, repeat your measurements.

<table>
<thead>
<tr>
<th>Nominal slit width/separation ( b ) (mm) ( d ) (mm)</th>
<th>Slit to screen distance ( L ) (m)</th>
<th>Dark fringe selected ( n )</th>
<th>Location of the ( n )th dark fringe ( x_n ) (cm)</th>
<th>Bright fringe selected ( m )</th>
<th>Location of the ( m )th bright fringe ( x_m ) (cm)</th>
<th>Calculated slit width/separation ( b ) (mm) ( d ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04 0.25</td>
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<tr>
<td>0.04 0.50</td>
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<tr>
<td>0.08 0.25</td>
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<tr>
<td>0.08 0.50</td>
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</tbody>
</table>
3. **Simultaneous Diffraction and Interference**

   When a diffraction minimum lands at the same location as an interference maximum the corresponding bright spot is missing. For the second case (b = .04 mm, d = 0.5 mm) which interference maximum is hidden by the first diffraction minimum? What about the second diffraction minimum? First predict these points using the equations, then check your results by observing the pattern produced by this set of slits.

4. **Polarization**

   By visual inspection, under what conditions is the intensity of the light transmitted through the two polarizers a maximum? A minimum?

   Intensity of light when both polarizers are oriented vertically: $I_m = \underline{\phantom{0000\text{lux}}}$ lux

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>$I$ (measured in lux)</th>
<th>$I = I_m \cos^2 \theta$ (lux)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90°</td>
<td></td>
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</tbody>
</table>
Explain the transmission of light that you observe through the set of three polarizers.