POLARIZATION

OBJECTIVES

• To study the general phenomena of electromagnetic wave polarization
• To investigate linearly polarized microwaves
• To investigate linearly polarized visible light

OVERVIEW OF POLARIZED ELECTROMAGNETIC WAVES

Electromagnetic waves are time varying electric and magnetic fields that are coupled to each other and that travel through empty space or through insulating materials. The spectrum of electromagnetic waves spans an immense range of frequencies, from near zero to more than $10^{30}$ Hz. For periodic electromagnetic waves the frequency and the wavelength are related through

$$c = \lambda f,$$  \hspace{1cm} (1)

where $\lambda$ is the wavelength of the wave, $f$ is its frequency, and $c$ is the velocity of light. A section of the electromagnetic spectrum is shown in Figure 1.

In Investigation 1, we will use waves having a frequency of $1.05 \times 10^{10}$ Hz (10.5 GHz), corresponding to a wavelength of
2.85 cm. This relegates them to the so-called **microwave** part of the spectrum. In Investigation 2, we will be using visible light, which has wavelengths of 400 – 700 nm (1 nm = 10^{-9} m), corresponding to frequencies on the order of 4.3 \times 10^{14}-7.5 \times 10^{14} Hz (430 - 750 THz). These wavelengths (and hence, frequencies) differ by nearly five orders of magnitude, and yet we shall find that both waves exhibit the effects of **polarization**.

Electromagnetic waves are **transverse**. In other words, the directions of their electric and magnetic fields are perpendicular to the direction in which the wave travels. In addition, the electric and magnetic fields are perpendicular to each other.

When the electric field of a wave is oriented in a particular direction, that is to say, not in random directions, we say the wave is **polarized**. In this workshop, we will investigate the polarization of two types of electromagnetic waves that have somewhat different wavelengths and frequencies: microwaves and visible light. We will both produce and analyze polarized waves.

Figure 2 shows a periodic electromagnetic wave traveling in the z-direction and polarized in the x-direction. E is the vector of the electric field and B is the vector of the magnetic field. Study this figure carefully. We will refer to it often.

Electromagnetic waves are produced whenever electric charges are **accelerated**. This makes it possible to produce electromagnetic waves by letting an alternating current flow through a wire, an **antenna**. The frequency of the waves created in this way equals the frequency of the alternating current. The light emitted by an incandescent light bulb is caused by thermal motion that accelerates the electrons in the hot filament sufficiently to produce visible light. Such thermal electromagnetic wave sources emit a continuum of wavelengths. The sources that we will use today (a microwave generator and a laser), however, are designed to emit a single wavelength.
The inverse effect also happens: if an electromagnetic wave strikes a conductor, its oscillating electric field induces an oscillating electric current of the same frequency in the conductor. This is how the receiving antennas of a radios or television sets work. The associated oscillating magnetic field will also induce currents, but, at the frequencies we will be exploring, this effect is swamped by that of the electric field and so we can safely neglect it.

Even though the electric field vector is constrained to be perpendicular to the direction of propagation, there are still infinitely many orientations possible (illustrated in Figure 3). Electromagnetic waves from ordinary sources (the sun, a light bulb, a candle, etc.), in addition to having a continuous spectrum, are a mixture of waves with all these possible directions of polarization and, therefore, don’t exhibit polarization effects.

Some possible directions of the electric field vector

![Figure 3](image-url)

It is, however, possible to produce linearly polarized electromagnetic waves. In other words, waves whose electric field vector only oscillates in one direction. Look again at Figure 2. It schematically shows a linearly polarized electromagnetic wave polarized in the $x$-direction.

The electric field of a plane wave of wavelength $\lambda$, propagating in the $z$-direction and polarized in the $x$-direction, can be described by:

$$E_x = iE_x \sin \left( \frac{2\pi}{\lambda} (z - ct) \right),$$  \hspace{1cm} (2)
where $\mathbf{E}_x$ is the vector of the electric field, $E_x$ its amplitude, and $\mathbf{i}$ the unit vector in the $x$-direction. A wave of the same wavelength, polarized in the $y$-direction, is described by:

$$\mathbf{E}_y = jE_y \sin \left( \frac{2\pi}{\lambda} (z - ct) + \phi \right).$$  \hfill (3)

Here, $j$ is the unit vector in the $y$-direction and $\phi$ is a constant that accounts for the possibility that the two waves might not have the same phase. From two such waves, one can construct all plane waves of wavelength $\lambda$ traveling in the $z$-direction.

If both $x$- and $y$-components are present and their phase difference is zero (or $180^\circ$), the wave will be linearly polarized in a direction somewhere between the $x$-direction and the $y$-direction, depending on the relative magnitudes of $E_x$ and $E_y$ (see Figure 4a). Mathematically such a wave is described by:

$$\mathbf{E} = \mathbf{E}_x + \mathbf{E}_y = (\mathbf{i}E_x \pm jE_y) \sin \left( \frac{2\pi}{\lambda} (z - ct) \right),$$  \hfill (4)

where the plus sign refers to a phase difference of zero and the minus sign to one of $180^\circ$ ($\pi$ radians). The angle $\theta$ between this polarization direction and the $x$-direction is given by

$$\tan \theta = \frac{E_y}{E_x}. \hfill (5)$$

If the phase shift is not zero (or $180^\circ$), the wave will not be linearly polarized. While we will only be investigating linear polarization in this lab, it is useful to know something about other types of polarization. Consider the case where the magnitudes are equal, but the phase shift is $\pm 90^\circ$ ($\pm \pi/2$ radians). In other words:

$$E_x = E_y \quad \text{and} \quad \phi = \pm \frac{\pi}{2}, \quad (6)$$
The resulting wave, called a *circularly polarized* wave, can be written:

\[
E = E_x + E_y = E \left[ i \sin \left( \frac{2\pi}{\lambda} (z - ct) \right) \pm j \cos \left( \frac{2\pi}{\lambda} (z - ct) \right) \right] \tag{7}
\]

by making use of the fact that \( \sin (\alpha + \pi/2) = \pm \cos \alpha \). With the plus sign, this equation describes a wave whose electric field vector, \( E \), rotates clockwise in the \( x \)-\( y \) plane if the wave is coming toward the observer. Such a wave, illustrated by Figure 4b, is called a *right circularly polarized* wave. With the minus sign, the equation describes a *left circularly polarized* wave.

With the phase shift still \( \pm 90^\circ \), but with different magnitudes

\[
E_x \neq E_y \quad \text{and} \quad \phi = \pm \frac{\pi}{2}, \tag{8}
\]

the \( E \) vector will still rotate clockwise or counterclockwise but will trace out an ellipse as shown Figure 4c. If there are many component waves of different \( E_x, E_y, \) and \( \phi \), the resulting wave will be unpolarized.

Polarized electromagnetic waves can be obtained in two ways:

1. by using sources, such as certain lasers, that produce only waves with one plane of polarization, or
2. by polarizing unpolarized waves by passing them through a *polarizer*, a device that will let only waves of one particular plane of polarization pass through.

Some sources of electromagnetic waves generate linearly polarized waves. Examples include the microwave generator we'll use today as well as some types of lasers. Other sources generate unpolarized waves. Examples include thermal sources such as the sun and incandescent lamps.

One way of producing linearly polarized electromagnetic waves from unpolarized sources is to make use of a process that directs waves of a given polarization in a different direction than waves polarized in a perpendicular direction. Earlier we noted that the electric field of an electromagnetic wave incident upon a wire induces an oscillating current in the wire. Some energy will be lost through resistive heating, but most will be re-radiated (scattered). Only the component of the oscillating electric field that is parallel to the wire will induce a current and be scattered. The electric field component perpendicular to the wires, on the other hand, will be essentially unaffected by the wires (assuming a negligible wire diameter). Hence, both the scattered and unscattered electromagnetic waves are linearly polarized.
For microwaves, we can (and will) use an array of actual wires. For visible light, we use a Polaroid filter. Polaroid filters are made by absorbing iodine (a conductive material) into stretched sheets of polyvinyl alcohol (a plastic material), creating, in effect, an oriented assembly of microscopic “wires”. In a Polaroid filter the component polarized parallel to the direction of stretching is absorbed over 100 times more strongly than the perpendicular component. The light emerging from such a filter is better than 99% linearly polarized.

\[ I_e = I_i \cos^2 \theta. \] (9)

This is known as Malus’ Law, after the French physicist who discovered the polarizability of light.

Initially unpolarized electromagnetic waves can be thought of as a mixture of all possible polarizations. Each possible polarization will be attenuated according to Malus’ law, and so the total intensity will be the initial intensity times the average of \( \cos^2 \theta \) (which is 1/2). In other words, the intensity is reduced to one half of the incident intensity.
Except in the case where $\theta$ is zero (or 180°), $E_e$ (the electric field of the electromagnetic waves exiting the polarizer) will have a component that is perpendicular to $E_i$. If we place yet another polarizer after $P$ (call it $P'$) with its polarization axis right angles to incident wave’s polarization axis, we will get electromagnetic waves out whose polarization is orthogonal to the incident waves’ polarization. We have effectively rotated the polarization of the incident waves (with some loss of intensity). Applying Malus’ Law, we get:

$$I' = I \cos^2 \theta \cos^2 \theta'$$  \hspace{1cm} (10)

where $\theta$ is the angle between the initial polarization and the first polarizer, $P$, and $\theta'$ is the angle between $P$ and the second polarizer, $P'$. But $P'$ is at right angles to the initial wave's polarization, so $\theta + \theta' = 90°$. Hence, $\cos^2 \theta' = \sin^2 \theta$. Using another trigonometric identity ($\sin 2\theta = 2 \sin \theta \cos \theta$), we finally get $I' = 0.25 I \sin^2 2\theta$.

We can see we get the maximum transmission when $\theta = 45°$ ($\sin 2\times45° = 1$) and that it is one quarter of the intensity of the incident polarized waves ($I_i$).

**Absorptive Polarizers**

(Taken from Wikipedia [http://en.wikipedia.org/wiki/Polarizer](http://en.wikipedia.org/wiki/Polarizer))

The simplest polarizer in concept is the **wire-grid polarizer**, which consists of a regular array of fine parallel metallic wires, placed in a plane perpendicular to the incident beam. Electromagnetic waves which have a component of their electric fields aligned parallel to the wires induce the movement of electrons along the length of the wires. Since the electrons are free to move, the polarizer behaves in a similar manner as the surface of a metal when reflecting light; some energy is lost due to Joule heating in the wires, and the rest of the wave is reflected backwards along the incident beam.

For waves with electric fields perpendicular to the wires, the electrons cannot move very far across the width of each wire; therefore, little energy is lost or reflected, and the incident wave is able to travel through the grid. Since electric field components parallel to the wires are absorbed or reflected, the transmitted wave has an electric field purely in the direction perpendicular to the wires, and is thus linearly polarized. Note that the polarization direction is **perpendicular** to the wires; the notion that waves "slip through" the gaps between the wires is incorrect.
A wire-grid polarizer converts an unpolarized beam into one with a single linear polarization. Coloured arrows depict the electric field vector. The diagonally-polarized waves also contribute to the transmitted polarization. Their vertical components are transmitted, while the horizontal components are absorbed and reflected. (This is not clearly shown.)

For practical use, the separation distance between the wires must be less than the wavelength of the radiation, and the wire width should be a small fraction of this distance. This means that wire-grid polarizers are generally only used for microwaves and for far- and mid-infrared light. Using advanced lithographic techniques, very tight pitch metallic grids can be made which polarize visible light. Since the degree of polarization depends little on wavelength and angle of incidence, they are used for broadband applications such as projection.

It is interesting to consider why there is a reflected beam, but no transmitted beam, when the symmetry of the problem suggests that the electrons in the wires should re-radiate in all directions. In simple terms the transmitted beam does "exist", but is in exact antiphase with the continuing incident beam, and so "cancels out". This, in turn, seems to contradict the idea that the incoming wave is "driving" the electrons in the wires, and so is "used up" (leaving no continued beam to cancel out the transmitted wave). In fact, if we assume that there is no heating, then no energy is used to drive the electrons — a better mental image is to think of them as "riding" on the waves that result from the interaction.

Certain crystals, due to the effects described by crystal optics, show dichroism, a preferential absorption of light which is polarized in a particular direction. They can therefore be used as polarizers. The best known crystal of this type is tourmaline. However, this crystal is seldom used as a polarizer, since the dichroic effect is strongly wavelength dependent and the crystal appears colored. Herapathite is also dichroic, and is not strongly colored, but is difficult to grow in large crystals.
Polaroid film was in its original form an arrangement of many microscopic herapathite crystals. Its later H-sheet form is rather similar to the wire-grid polarizer. It is made from polyvinyl alcohol (PVA) plastic with an iodine doping. Stretching of the sheet during manufacture ensures that the PVA chains are aligned in one particular direction. Electrons from the iodine dopant are able to travel along the chains, ensuring that light polarized parallel to the chains is absorbed by the sheet; light polarized perpendicularly to the chains is transmitted. The durability and practicality of Polaroid makes it the most common type of polarizer in use, for example for sunglasses, photographic filters, and liquid crystal displays. It is also much cheaper than other types of polarizer.

An important modern type of absorptive polarizer is made of elongated silver nanoparticles embedded in thin (≤0.5 mm) glass plates. These polarizers, are more durable and can polarize light much better than Polaroid film, achieving polarization ratios as high as 100,000:1 and absorption of correctly-polarized light as low as 1.5%. Such glass polarizers perform best for short-wavelength infrared light, and are widely used in optical fiber communications.

End Wikipedia insert.

**INVESTIGATION 1: MICROWAVE POLARIZATION**

For this experiment, you will need the following:

- Gunn diode microwave transmitter
- Microwave receiver
- Wire grid polarizer

**CAUTION: DO NOT ALLOW THE RECEIVER’S METER TO PEG AT ANY TIME!**

To *peg* the meter means to allow the needle to go beyond the maximum value on the scale. If you find the meter pegged, immediately turn down the sensitivity and/or move the receiver away from the microwave generator!

**ACTIVITY 1-1: POLARIZATION OF MICROWAVES FROM A GUNN DIODE**

Inside the microwave generator is a solid state device called a Gunn diode. When a DC voltage is applied to a Gunn diode, current flows through it in bursts at regular intervals. For your diode, these bursts come at $9.52 \times 10^{-11}$ seconds apart causing, in addition to the dc current, an ac current at $1.05 \times 10^{10}$ Hz (10.5 GHz). As a result, a large AC voltage, oscillating at that frequency, is present across the slot, and so a wave is radiated from the horn. The *electric* field of this wave oscillates in the same
orientation as the Gunn diode. The polarization of an electromagnetic wave is determined by the direction of the electric vector \( \mathbf{E} \). The magnetic field \( \mathbf{B} \) encircles the current in the Gunn diode and so emanates in the orientation perpendicular to \( \mathbf{E} \).

**Important Note:** The Gunn diode is placed inside the generator in a way that the electric field will oscillate vertically when the knob on the back is placed at 0°.

Just inside the horn of the receiver is a microwave detector. In addition, there is some circuitry, which amplifies the signals received by the detector and outputs this amplified signal to a d’Arsonval meter and to an external output. The amplification, or alternatively its inverse, the sensitivity, (also labeled METER MULTIPLIER), is controlled via two knobs. The VARIABLE SENSITIVITY knob allows for fine adjustment. As you turn up the sensitivity (from 30 to 1), the signal is amplified more and more.

1. Set up the generator and receiver as shown in Figure 6, with about 75 cm between the faces of the horns.

**Prediction 1-1:** With what relative orientation of the transmitter and receiver angles do you expect to find minimum intensity? What does this tell you about the electromagnetic microwaves? Do this before coming to lab.

2. Set the knobs on back of both pieces so the angle indicator is at 0°. Adjust the sensitivity on the receiver to obtain a signal near 0.5 on the meter. If you cannot achieve this with a sensitivity of
30, 10 or 3, move the receiver closer to the generator. Rotate the receiver and verify that it is sensitive to the polarization of the wave. Return the receiver angle to 0°.

**Question 1-1:** Does it make sense that maximum intensity is obtained when both generator and receiver are oriented the same way? Explain why. Why does the received signal go to zero when they are at 90° with respect to one another?

**Activity 1-2: Wire Grid Polarizer**

**Prediction 1-2:** With the generator and receiver oriented the same way, what orientation (relative to the generator) of a wire grid placed in between them will give the maximum received intensity? Do this before coming to lab.

**Prediction 1-3:** With the generator and receiver oriented at 90° with respect to one another, what orientation (relative to the generator) of a wire grid placed in between them will give the maximum received intensity? Do this before coming to lab.

1. Make sure that the generator and the receiver are oriented the same way: with the E field vertical (indicators at 0°).

2. Insert the wire grid polarizer between the generator and the receiver so that the wires are initially oriented vertically
(parallel to the direction of the $\mathbf{E}$ field). Slowly rotate the polarizer so that the wires become perpendicular to the $\mathbf{E}$ field.

**Question 1-2:** With what relative orientation(s) of the wire grid polarizer did the receiver indicate the highest intensity? The lowest?

3. Remove the wire grid. Rotate the receiver’s angle by $90^\circ$ so that the generator and receiver are orthogonal. Turn up the receiver’s sensitivity to 1.

4. Repeat step 2.

**Question 1-3:** With what orientation(s) of the polarizer did the receiver indicate the highest intensity? The lowest?

**Question 1-4:** Explain the phenomena you observed in step 4 and reported in the previous question.

**NOTE:** Turn off your receiver and unplug the generator.
INVESTIGATION 2: POLARIZATION OF A HIGH-INTENSITY LAMP

Note: The room lights will have to be out during the remainder of this lab.

In this investigation, the unpolarized light from a high-intensity lamp will be linearly polarized. This polarization will be investigated with a second Polaroid analyzer. In addition, a third polarizer will be added to investigate the effect of the orientation of a third polarizer on the intensity. A schematic diagram of what happens is shown in Figure 7.

For this you will need the following:

- Optical bench with lens holders
- Two polarizers with stands
- Bausch and Lomb polarized light demonstrator kit
- Small support stand
- Desk lamp (high intensity light source)
- Light sensor and cable

ACTIVITY 2-1: LIGHT SOURCE AND POLAROIDS

Note: The light sensor that will be used for the rest of the experiments is a photodiode with a sensitivity that ranges from 320 nm to 1,100 nm. This includes not only visible light, but also some ultraviolet and infrared. Make sure to not allow the output voltage from the sensor to go above 4.75 V. At this point, the light sensor is saturated and will give poor results.

1. Set up the lamp, polarizers, and light sensor as shown in Figure 8. **DO NOT TURN YOUR LAMP ON YET.** Make sure your lamp is on the opposite end of the table from the
1. The computer and is pointing towards the wall, not towards the center of the room. We want to minimize the interference of the light coming from the desk lamp into each other’s light sensor.

2. The polarizer and analyzer in Figure 8 are Polaroid sheets and are exactly the same material. We sometimes use the term “polarizer” when we are polarizing light and “analyzers” when we are analyzing the light polarization. When it doesn’t matter or if we refer to them generically, we generally called them polarizers.

![Figure 8](image)

Figure 8 Optical bench setup. The lamp should be close to the heat absorbing filter to prevent stray light reaching other tables.

3. The heat-absorbing filter (item #1 in the box of components) absorbs infrared light and should be mounted on the small support stand in between the light source and the first polarizer. Place it as close to the polarizer as you can so that little, if any, light can get into the polarizer without first passing through the heat filter. Move the lamp up close to the heat filter so that stray light will not reach other tables’ light sensor.

4. Ensure that the heights of the light, heat absorbing filter, polarizers and light sensor are lined up. Your lamp (light source) can now be turned on.

**ALWAYS PLACE THE HEAT ABSORBING FILTER BETWEEN THE LIGHT AND THE FIRST POLAROID FILTER TO BLOCK THE INFRARED LIGHT AND PREVENT HEAT DAMAGE.**

**Note:** The infrared light emitted from the lamp will not be polarized by the filters, but will be seen by the photodetector.
5. Connect the light sensor to channel A in the PASCO interface. Set the sensitivity on the side of the light sensor to 100.

6. Open the experiment file named **L08.A2-1 Light Source**.

7. When looking toward the polarizers from the lamp, you will see angle indications on the polarizers. Set them both to $0^\circ$ (straight up). See Figure 9. *The Polaroid Filters we are using allow the electric field $E$ vector of the transmitted light to oscillate in the direction of the indicator tab (angle) on the Polaroid.*

8. Start taking data with the computer. Look at the digits window, which shows the voltage produced by the light sensor. **This should never be greater than 4.75 V.** Move the lamp (light source) so that this reading is less than 4.0 V. The units for intensity are not volts but Lumens. However, the output of the light sensor probe in volts is directly proportional to the light intensity.

9. Stop the computer and delete the test data. Start taking data; the computer will stop after 2 minutes.

10. Note that the light intensity is not constant. Write down the mean light intensity and standard deviation:

    Mean light intensity: _____ %     Standard deviation: _____ %

11. **Print** out the graph of light intensity vs. time for your group report.

    The purpose of having you do this brief measurement is to note that the intensity of the lamp is not very constant. This will have some effect on the subsequent measurements that you take, so certain measurements that require a series of measurements (like changing polarization angles) need to be taken quickly so that the lamp intensity does not have a large effect.

**Activity 2-2: Light Polarizer and Analyzer**

You will need a third polarizer for this activity.
1. Use the same experimental setup as before and place the new polarizer on the optical bench between the other two. We will renumber the polarizers starting from the lamp (1, 2, 3).

2. Set the angle of the first and third polarizers to +90°. Take out the (new) polarizer #2 for now.

3. Use the same experimental file as before and start taking data.

4. Adjust the angle of the 3rd polarizer and find all the angles for which you detect the maximum and minimum light intensity in the light sensor. Write those angles below:

   Angle for maximum intensity: __________________

   Angle for minimum intensity: __________________

**Question 2-1:** In light of what you know about Polaroids, explain the angles you just determined.

**Question 2-2:** Consider what happens when the two polarizers are crossed (the first polarizer is at +90º and the third at 0º). What is the orientation of the electric field after it passes through the first polarizer? What will happen to this light when it passes through the 3rd polarizer?

5. Now put the 2nd polarizer back in between the other two polarizers. Set the angle of the 3rd polarizer to 0°.
6. Rotate the 2nd polarizer over its entire angular range and observe the light intensity detected. Find the orientation for which the light intensity output shown on the computer is a maximum. Record the angle at which the maximum occurs.

\textbf{Angle} ____________

7. Click on the red square to stop the data collection.

\textbf{Question 2-3:} Describe what happened as the angle of the 2nd polarizer was rotated. Explain this behavior. (Hint: can any visible light pass through this system?)

\textbf{Question 2-4:} Explain your findings in terms of the orientation of the electric field after the light travels through each polarizer. Why would the angle found in step 6 produce the maximum intensity?

8. Move the light sensor aside and look from where the light sensor was through all three polarizers towards the lamp. Rotate the 2nd polarizer over its entire angular range.

\textbf{Question 2-5:} Describe what you see now and explain these phenomena.

You should conclude from these measurements that there must be some electromagnetic radiation background that is not visible light and that is not affected by the Polaroid sheets. It is, however, detected by the light sensor. You should keep this in mind as we progress through this lab.
ACTIVITY 2-3: LINEARLY POLARIZED LIGHT AND MALUS’ LAW

1. Remove the 2nd polarizer. You should now have two polarizers, both set to $0^\circ$. Replace the light sensor. Your apparatus will be similar to that shown in Figure 8.

2. Open the experimental file L08.A2-3 Linearly Polarized. There should be a data table when you open the file.

3. In the data table, the first column will be the values for Angle that you enter. The second column is Light Intensity. This column shows the percentage of maximum light intensity that is currently being put out by the sensor. The third column is the Voltage column.

4. Press Start to begin collecting data. The output from the light sensor will be shown in the digits window. Check to make sure the light sensor output voltage is still not greater than 4.0 V. If it is, move the lamp back until it is not. You should be okay if you are in the range 2 – 4 V.

5. Now set the first polarizer to $0^\circ$ and the analyzer to $-90^\circ$.

6. Read over steps 7 – 12 before taking data. You will need to take these data fairly quickly as discussed before, and you need to be familiar with the procedure.

7. When you are ready to take data, press Keep. A box will pop up that asks you the angle of the polarizer. Type in “-90” and press Enter.

8. Change the analyzer to an angle of $-80^\circ$. The voltage output will be shown as before. Press Keep and type in the angle.

9. Adjust the angle of the analyzer in $10^\circ$ steps from $-90^\circ$ to $90^\circ$. Repeat step 8 until all of the values are entered. This can go rather quickly with one person changing the angle and another person operating the computer. Once Keep has been selected, the next angle can be changed by one group member while another is entering the angle into the computer.

10. When you are finished entering data, click on the red square next to Keep to stop data collection. Print out your table for your report. Only print one per group. [You may need to print it twice to include all the data.]

11. At the bottom of the screen, there should be two graphs minimized. Bring up the graph titled I vs. Angle so you can
see the graph of your light intensity plotted versus angle. If you see a fit to your data, you have brought up the wrong graph. Print out this graph for your group report.

**Question 2-6:** What does your graph look like? Does it follow the curve you would expect?

12. Minimize this graph, and maximize the second graph entitled **Fit Malus**. You will see your data plotted along with a fit. You could have easily entered this fit into Data Studio yourself, but we have done it for you to save time. We have fit straight line \( y = mx + b \) to \( I \) versus \( \cos^2 \theta \). Print out your fit for your group report.

13. Record the fit parameters \( m \) and \( b \):

\[
m \quad \quad \quad \quad \quad b
\]

**Question 2-7:** Discuss the physical meanings of \( m \) and \( b \).

**Question 2-8:** Is it possible that \( b \) is not constant? Explain. How could you minimize \( b \)?
INVESTIGATION 3: OTHER METHODS FOR POLARIZING AND DEPOLARIZING

DEPOLARIZATION

To change polarized light into unpolarized light one must introduce random phase differences between the two components of the electric vector. This can be accomplished by interposing a material that is both inhomogeneous and anisotropic across the wave front.

BIREFRINGENCE

Most of the transparent materials that one encounters daily, such as glass, plastics, and even crystalline materials such as table salt, are optically isotropic, i.e. their index of refraction is the same in all directions. Some materials, however, have an optically favored direction. In these materials the index of refraction depends on the relative orientation of the plane of polarization to that preferred direction. Such materials are called birefringent or doubly refracting. The best known example of such materials is calcite (CaCO₃). Optically isotropic materials, such as glass, can be given a preferred direction, and thus made to be birefringent, by stressing or bending them.

Consider a light wave traversing a birefringent crystal, as shown in Figure 10, where the direction of propagation of the wave is entering the crystal perpendicularly. An initially unpolarized light beam will split into two separate linearly polarized beams. One of these is called the ordinary ray or o-ray and the other the extraordinary ray or e-ray. The behavior of the o-ray is essentially that of a ray in an isotropic medium: it is refracted in accordance with Snell’s law, and its refractive index \( n_o \) is independent of the direction of travel.

The e-ray, on the other hand, behaves in a most peculiar way. Its index of refraction \( n_e \) depends on the orientation of the crystal. Moreover, its direction of travel, after entering the crystal is not
consistent with Snell’s law. As Figure 10 shows, it will be refracted even if its angle of incidence is 90°. On leaving the crystal it becomes again parallel to the direction of incidence but displaced with respect to the incident beam. Since the two emerging rays are linearly polarized along mutually perpendicular directions, doubly refracting crystals make very effective polarizers: If one cuts a birefringent crystal so that the e-ray, but not the o-ray, is totally reflected at the exit face one can produce light that is 99.999% linearly polarized.

The wavelength dependence of the index of refraction, although small, lends itself to some pretty demonstration experiments. If one places two Polaroid filters in front of a light source so that their directions of polarization are perpendicular to each other, they will appear dark. If one then places an object made of a birefringent material between the crossed Polaroids, a multicolored image of the object will become visible in the previously dark field. The o-ray and the e-ray have traveled different optical path lengths and their phases, upon leaving the object, will differ, the difference being a function of the wavelength of the light. Since the two rays are polarized in different directions they cannot interfere with each other. The second Polaroid (the analyzer) passes that component of each ray whose plane of polarization is parallel to the direction of polarization of the filter. These components have the same plane of polarization and can interfere. Whether their interference is constructive or destructive will depend on their phase difference and hence on their color.

In this investigation, you will use different objects and materials to both polarize and depolarize light. You will need the following materials:

- Polarized light demonstrator kit
- Optical bench with lens holders
- Desk lamp

**Activity 3-1: Depolarization**

As you will recall from the readings above, random phase differences may be introduced between the two components of the electric field vector to depolarize the light.
1. Set up two polarizers on the optical bench with the desk lamp and heat-absorbing filter as done in Investigation 2 (see Figure 11). Set the polarizer P such that $\mathbf{E}$ is vertical ($0^\circ$).

**Prediction 3-1:** With this setup (without wax paper), what do you expect to see as you vary the angle of the analyzer $P'$ with respect to $P$? (Hint: we did this in Investigation 2).

2. Hold the piece of wax paper from the polarizing kit in between the two polarizers.

3. Rotate the polarizer through all angles and observe (by eye) the transmitted light.

**Prediction 3-2:** With the wax paper added between the polarizers, what do you expect to see as you vary the angle of the analyzer $P'$ with respect to $P$?
**Question 3-1:** Describe the transmitted light intensity as you rotate the polarizer.

**Question 3-2:** What does this indicate about the polarization of the light through the wax paper?

**Activity 3-2: Birefringence by the Calcite Crystal**

Set the calcite crystal from the polarization kit on the dot:

1. Hold a polarizer over the calcite and look through the thickest section of calcite at the dot.

**Question 3-3:** What do you observe with and without the polarizer?

2. Slowly rotate the polarizer until only one dot is seen. Note the orientation of the polarizer.
   \[ \theta_1 \] (choose a relative zero angle)

3. Rotate the polarizer again until only the other dot is seen. Note the orientation of the polarizer.
   \[ \theta_2 \] (use same zero angle as before)
**Question 3-4:** What does this tell you about the relative polarization of the images created by the calcite crystal?

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**Activity 3-3: Interference Caused by Birefringence**

1. Hold the mica sample between two crossed polarizers (set at 90º and 0º, for example) and look through the setup at the lamp.

2. Tilt the mica sample slowly backwards as shown in Figure 12. Also rotate the mica in the plane of the Polaroids.

![Incident light and mica plate](image)

**Figure 12**

**Question 3-5:** What do you see?

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**Activity 3-4: Birefringence Due to Stress**

Replace the mica with the U-shaped piece of plastic between the crossed polarizers. Note that the inside corners of the plastic are cut different: one is sharply cut at 90º; the other side is rounded.

1. Look through the polarizer at the plastic.
**Question 3-6:** What do you observe? Do you see light?

**Question 3-7:** Based on your previous observations, is the light polarized by the plastic? Why or why not?

2. Lightly squeeze the two legs of the U toward each other while looking at the plastic through the polarizer.

**Question 3-8:** What do you observe?

**Question 3-9:** What has changed about the light through the plastic?

**Comment:** The strain partially orients the molecules and makes the plastic birefringent. From such patterns engineers can locate regions of high strain in a plastic model of a structure and then decide whether the structure must be redesigned or strengthened in certain places.
**Question 3-10:** In which corner of your plastic is there the greatest stress?

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**Activity 3-5: Polarization of Scattered Light**

Sunlight is scattered while passing through the atmosphere. Light with a short wavelength is scattered more than light with a long wavelength. This is why the sky appears blue. Light scattered by 90° is strongly polarized. You can verify this on a clear day if you look through a Polaroid filter in the appropriate direction of the sky. A similar observation can be made in the laboratory by passing laser light through a tank of water that has been clouded by suspending some scattering material in it. At the front of the room there should be such a tank of water with a laser beam passing through it.

1. Look down from the top of the tank into the water so you can see the laser beam scattered in the water. Rotate the polarizer while you look at the scattered light.

**Question 3-11:** Record your observations and use them to discuss the polarization of the scattered light especially as a function of the polarized filter.