Name: ____________________________
Partner(s): ____________________________
Date(s): ____________________________

Polarization and Wave Plates

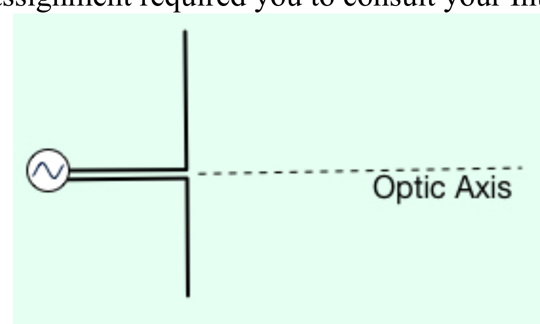
Objectives:

- **To motivate use of Jones vectors and Jones matrices to describe the net effect of a *series* of "polarization optics."**
- To consider the action of polarized waves incident upon matter, particularly (cheap) ***absorbing*** polarizers and (expensive) ***transparent*** waveplates.
- To explicitly think about anisotropic media where the index of refraction is not the same in all directions (hinting at the radiative *back action* of matter).
- To motivate *later*, in-class discussion of the "Polarization Ellipse"
- To motivate *later*, in-class discussion of trajectories on the Poincaré Sphere.

Review: [Partially cribbed from UVA's 241W and AJP **82**, 876 (2014)]

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 (more or less) a single wavelength.

Your *pre-lab* reading assignment required you to consult your Intro Physics text:



In any old-school pen & paper lab notebook, you would need to leave a few blank pages at the front, for your Table of Contents. In *any* lab notebook (including electronic versions) ensure that you include a sketch of your prediction for the E-Field **along the Optic Axis**, followed by your written thoughts about polarization (*and* about propagation delays, or "time lags"). [If we look significantly *off* the optic axis then the story would be more complex, but we will later discuss decomposing complicated waves into a superposition of ideal plane waves, so let's start *simple*.]

At left is a photo of an older piece of instrumentation that I found while cleaning: a microwave **half-wave** dipole transmitter (which many people simply refer to as a dipole antenna). The information that I have on the oscillator isn't very clear, but given that we refer to it as a *half-wave* antenna, I'm hoping that a very simple measurement might allow you to *estimate* the wavelength output by this device, and that you will:

Record your estimate into your lab notebook, <u>along with the independent measurements of at least three classmates.</u>

(Maybe one of you will, as a demonstration of *initiative*, find a way to provide a more exact result.)

Of course, when we refer to something as a transmitter, we're expecting that a wave is radiated from the device. Your pre-lab exercise required you to think about the orientation of the electric field at different points along the device "axis of symmetry" which we have labeled as the "optic axis." The **polarization** of an electromagnetic wave is determined why the direction of the *electric* field vector **E**. Of course, the *magnetic* field **B** encircles the current in the antenna (as charge is pumped onto or off of the wire), and so emanates in the orientation *perpendicular* to **E**.

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 antenna** on a classic radio or (non-cable) television set works. [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 Fig. 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.

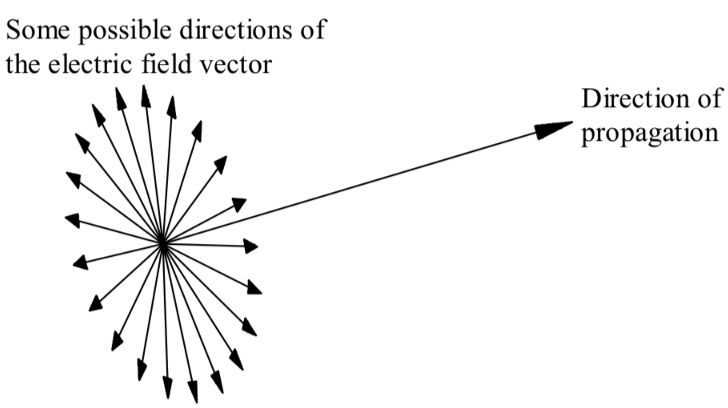


Fig. 3. There are infinitely many possible polarization orientations.

Polarized electromagnetic waves can be obtained in two ways:

1. by using sources, such as certain lasers, that (to a good approximation) 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 characterized by one particular plane of polarization pass through.

Butterflies, bees, octopus, salmon, and *more* have the ability detect the polarization of light, but this is something that mammals have *lost*. So, we require assistive technology to allow us to explore this "vector nature of light." Before implementing the second strategy described above, you should first examine the output of the transmitter, in an effort to assess the *degree* to which it is already polarized, through the use of a polarization-sensitive **receiver** tuned to these microwave frequencies.

Examine (but do not turn on) the receiver and ***write down*** **a protocol** for its use in determining the polarization of the transmitter, which utilizes only the transmitter and the receiver, and no other equipment.

[Explicitly mention placement with respect to the Optic Axis of the transmitter. Why?]

Prediction 1-1: With what relative orientation of the transmitter and receiver do you expect to find *minimum* intensity? If your prediction is validated, what could you conclude about the emissions of this transmitter?

Always, before you turn things on, be mindful: allowing a detector to go beyond the maximum on-scale value ("pegging the meter") *can* cause damage! So, it is wise to start out by first adjusting the settings on a meter to whichever scale can tolerate the the largest input. For this set-up, you may also wish to begin with the detector reasonably *far away* from the transmitter (*i.e.*, across the long dimension of a slate table).

a) By the way, why am I suggesting that you set up on a slate table, rather than atop one of our metal tables? Would it make a difference to switch tables?
b) Is it reasonable to believe that the signal will *decrease with distance*, given that the antenna on the transmitter is located at the focal point of a parabolic dish?
c) If the electric field undergoes a change in phase of 180° upon reflection from a metal surface, under what condition will the reflected wave arrive back at the antenna *in phase* with the antenna emissions?

Prediction 1-2: With the generator and receiver oriented the same way, predict what will happen if we insert an array of parallel metal wires (of the sort shown in class) in between the source and detector: what orientation (relative to the generator) of the wire grid will give the *maximum* received intensity?

The reason for using microwave equipment is simply because the wavelength is so large that the diameter of the metal wires in a cooking shelf (such as the one shown in class) is negligible in comparison.

For visible light, an analogous experiment requires wires that are much, much thinner. **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 *molecular* "wires". This process was a breakthrough in affordability, …but does it seem likely to you that it would yield absolute perfection? What are some likely shortcomings? In a Polaroid filter, the conductivity of these wires is quite low (and so the resistive losses are quite high). Given the thicknesses of the Polaroid filters that we will use for our **visible** light experiments, the component polarized parallel to the direction of stretching might be absorbed, say, 100 times more strongly than the perpendicular component. The light emerging from such a filter would then be better than 99% linearly polarized. [An idealized polarizing filter would absorb 100% of one polarization and transmit 100% of an orthogonal polarization. Real experiments have to make do with (and ***characterize***) non-ideal filters.]

> You should write in your lab notebook an introduction to the notion of resistive losses, and should highlight key differences between our **microwave** experiment with the wire grid, and what you expect to observe with **visible** light using Polaroid filters.

Our understanding of optics is governed by Maxwell's wave equation:

$$\nabla^2 \vec{E} = \mu_0 \epsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2} \tag{1}$$

One of the *simplest* solutions is that of a ***plane*** wave propagating in the *z* direction:

$$\vec{E}\left(x, y, z, t\right) = E_x \hat{x} \cos\left(\omega t - kz + \phi_x\right) + E_y \hat{y} \cos\left(\omega t - kz + \phi_y\right) \tag{2}$$

where E_x and E_y are the electric field amplitudes for the x-polarization and for the y-polarization, respectively, and ϕ_x and ϕ_y are phase shifts.

Mathematically, it is far more convenient to represent the amplitude and phase of a wave using complex exponential notation, where it is understood that only the real part of any complex representation is *physically* real. (That is, the complex representation is only a computationally efficient *shorthand* of sorts.)

> Use complex exponential notation to express the plane wave solution shown in Eqn. 2. (Again, the real part of this complex expression should match Eqn. 2.)

In this week's investigations of different polarization states, we are not concerned with the direction the light is propagating, or the spatial shape of the beam, or the wavelength. So, stripping away, from Eqn. 2, all details that we *currently* consider extraneous, we can model the polarization state of light as a 2×1 "Jones vector:"

$$E_0 e^{i(\omega t - kz)} \left[\cos\theta e^{i\phi_x}\hat{x} + \sin\theta e^{i\phi_y}\hat{y}\right] \rightarrow \begin{pmatrix} \cos\theta e^{i\phi_x} \\ \sin\theta e^{i\phi_y} \end{pmatrix} \tag{3}$$

In this way, for light purely polarized along the x- or the y-direction, we get:

$$\hat{x} \rightarrow \begin{pmatrix} 1 \\ 0 \end{pmatrix} \text{ and } \hat{y} \rightarrow \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{4}$$

Write a Jones vector in the form of Eqn. (3) for light that is linearly polarized with a polarization angle of 45° between the two states shown in. Eqn. (4).

The action of an idealized polarizer oriented along the x-axis would be to keep the x-component unchanged, while eliminating the y-component (via absorption). In the Jones formalism, this is modeled by a 2×2 matrix (with coefficients a, b, c, d) which acts upon the generalized input beam described in Eqn. 3:

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} \cos\theta e^{i\phi_x} \\ \sin\theta e^{i\phi_y} \end{pmatrix} = \begin{pmatrix} \cos\theta e^{i\phi_x} \\ 0 \end{pmatrix} \tag{5}$$

a) What a, b, c, d values would describe an *ideal* polarizer oriented along the x-axis?
b) How about if the polarizer were oriented along the y-axis?

Again, real polarizers are not ideal: they do not transmit 100% of any polarization, and tend, in practice, to let a little bit of the orthogonal polarization get through. *Then what?*

c) What is the physical meaning of the diagonal elements a and d ?
d) Can you think of any possible physical meaning of the off-diagonal elements c and b?

In-Lab ***Experiments with Visible-light Absorbing Polarizers***

NEVER LOOK DIRECTLY INTO A LASER BEAM OR ITS MIRROR REFLECTION

To get accurate results, it is important to have the laser carefully ***aligned***. Before you begin taking data, be sure to align the laser as described below.

One end of a **fiber-optic bundle** is inserted into the center hole in a 3D-printed mount that should be placed on the optical breadboard in a way that allows a little bit of adjustment, to optimize the position the bundle in the beam, while the other is connected to a **photometer**. The photometer will measure the relative intensity of the light that enters into the optical fiber. Your lab notebook should include comments about how *light* incident upon the photodetector is converted to a measured output, including principles of operation and key operating parameters and limitations (*e.g.*, significant noise levels on the output) associated with the particular model used.

Adjust the position of the fiber bundle mount (or the laser) so that the laser beam lands squarely on the fiber optic bundle.

Shutter the laser and set the photometer to the highest sensitivity. Adjust the knob labeled "Zero Offset" until the photometer reads as close to *zero* as possible. This defines a zero intensity that includes all of the background light.

You are now ready to begin this lab. Be careful that you **avoid doing anything that might move the optical fiber *out* of alignment** with the laser.

Part 1: Testing whether or not you have a light source that is "polarized"

Mount a polarizer (we'll call this one "A," which stands for "**analyzer**") in front of (but not touching) the mount for the fiber optic bundle, …and open the shutter on the laser. *Rotate* the polarizer through 360 degrees. As you do this, observe the intensity on the photometer. Be careful not to block the laser beam accidentally.

Is the intensity *constant* as you rotate the polarizer aside, say, from the sorts of intensity fluctuations that are present when you aren't rotating the polarizer, *and* the relatively minor effects of dust or scratches? (It is a good idea to adjust your polarizer mount, so that the laser will avoid any *obviously* damaged areas.) Describe whatever it is that you observe in your lab notebook, including the *max and min detected levels*. [Note: **with PASCO polarizers, the *transmitted* light is polarized with the electric vector parallel to the 0° - 180° axis of the polarizer**.]

Based on your observation, is the light emitted directly by the laser polarized? If it is, describe how you can tell. In what *direction* is the beam polarized? Does this ***drift*** much? Is there any way for you to tell whether your photometer responds equally well to all polarizations of light? If so, test that, too!

Input State Preparation: whether or not your laser beam appears to *already* be polarized, *just to make sure* we want you to place a polarizer (let's call this polarizer "*P*") between the laser and the "downstream" polarizer that we named the "analyzer."

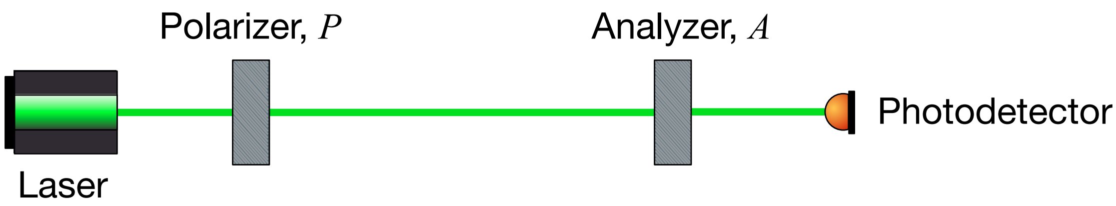


Figure 1

Doing so will (further) extinguish any light from the laser that is not polarized in the direction defined by polarizer *P*. **For the remainder of the day**, we will refer to *combination* of (the laser and polarizer *P*) as "the light source." On the other hand, we'll always refer to any polarizer that comes just before a detector as an "analyzer." Verify that the laser beam *now* (with polarizer *P* added) has a fixed polarization (that does not drift a lot over the time it takes to do measurements). Discuss, in your notebook, how you did this and what you saw.

Part 2a: Examining the Polarization of the Light Source

Carefully rotate the **analyzer** until you find the **maximum intensity** and note the orientation of the analyzer. This is your reference angle. You may, if you wish, adjust the knob labeled "***Variable***" until the intensity on the photometer is a nice number (though some of us think that *all* numbers are nice).

Carefully rotate the analyzer through a full revolution in increments of 10°, recording the intensity at each increment. You may need to adjust the sensitivity as you rotate the analyzer. You can record your data into an Igor Pro spreadsheet, but be sure to include a clearly labeled printout in your lab notebook.

It is fine to consult an online source, for the math, but please be sure that you, yourself, can describe the basic *physics* of Malus's law (and that you do so, in your lab notebook).

Include your **analysis** in your lab notebook. Do your data (and, separately, your fitting parameters) make sense? — At this point, you certainly do *not* expect the agreement between model and data to be perfect! In fact, given what you know about the process for creating Polaroids, you may be surprised by the degree to which they do a pretty good job! **What aspects of the data *are* accurately represented by your predictions? Which aspects of the data *cannot* be accurately represented by your predictions?** Closely examine your results and discuss both what you did and what you think it all means, in your lab notebook, following your tabulated data and analyzed graph.

Part 2b: ***Refining* your apparatus model** (for at least one part of it), to be more realistic:

Idealized polarizing filters transmit 100% of one polarization and 0% of any orthogonal polarization. Is this a good model of the real (***cheap***) absorbing polarizer sheets you have used today?

A) Note that the measured power in an optical beam is proportional to the *square* of the electric field amplitude:

$$P \propto \left|\vec{E}\right|^2 = \left|\begin{pmatrix} E_x \\ E_y \end{pmatrix}\right|^2 = \left|E_x\right|^2 + \left|E_y\right|^2 \tag{6}$$

From your analysis of various readings you have recorded in your lab notebook, estimate the maximum and minimum ***transmission coefficients*** for a PASCO polarizing filter? (These are values that can range from zero to one.)

B) Referring back to Eqn. (5), **write a matrix for a *more realistic* model of the *non-ideal* analyzing filter** measured in your lab work today. — Did that matrix operate on the field or on the power? Which coefficient (a, b, c, or d) represents partial absorption of the "transmitted" polarization? Which coefficient represents additional leakage through, of the "blocked" polarization? What might be the physical meaning of the off-diagonal elements in the Jones matrix?

C) Do the polarizing filter characteristics depend on where, on the sheet, the laser strikes the analyzing filter?

Armed with our model of the polarization of light and our (refined) model of the analyzing filter, then you should be able to derive Malus's law in the case of non-ideal polarizing filters. The following section will guide you through the necessary modeling steps.

When we have either rotated a polarization state (*e.g.*, by using a half wave plate of the sort introduced later in this lab) or when we have rotated an optical element (such as the analyzer), the Jones formalism will use, for describing ***rotation*** through an angle of θ, the following rotation matrix:

$$R(\theta) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \tag{7}$$

If you plan on taking (or have already taken) our course in "Scientific Imaging," I recommend you use *Mathematica*, where one way of entering such a matrix is to use the PALETTES menu item "Basic Math Assistant." Alternatively, *MATLAB* originally meant "Matrix Laboratory," and so can be useful as we predict the combined action of multiple matrix elements. On the other hand, if you are already familiar with Python, look up the Numpy.matrix data type, for examples of how to do matrix math in the Numpy package. With *Mathematica*, you can use the following syntax:

```
r[th_] := { {Cos[th], Sin[th]}, {-Sin[th], Cos[th]} }
```

If you want more details on **defining** functions in *Mathematica*, there is a YouTube screencast, and a Wolfram tutorial available. *Mathematica* also has many capabilities for handling vectors and matrices, which are documented in the built-in help or on the Wolfram website. In particular, a vector (such as a Jones vector) can be represented as:

```
a = { a1, a2 }
```

A matrix (such as the Rotation matrix) is represented by:

```
b = { {b11, b12}, {b21, b22} }
```

Finally, for multiplication between matrices and vectors or matrices and other matrices, you need only type a period between the two:

```
b.a
```

Let's put this all to use! You should have already constructed a matrix to describes the Analyzer filter when it is oriented so as to transmit $\hat{x}$. Let's call. That matrix P_x. Now, when the Analyzer is rotated by an angle θ, the rotated polarizer has a matrix given by:

$$P(\theta) = R(\theta) P_x R(-\theta) \tag{8}$$

Discuss.

Armed with our model of the polarization of light and our (refined) model of the analyzing filter, then you are now in position to be able to derive Malus's law in the case of non-ideal polarizing filters.

A) Use computational software (*e.g.*, *Mathematica*) to express the matrix $P(\theta)$. — Does $P(\theta = \pi/2)$ agree with your expectations?

B) Use the Jones formalism computational model to predict the transmission between two successive polarizing filters oriented at angles different by θ. Does it agree with Malus's law, *i.e.*, $P_{trans} = P_{inc} \cos^2 \theta$?

C) Use your model of Malus' law for non-ideal polarizers to fit your experimental data. Do you get agreement within measurement uncertainties?

Part 3: Adding polarizer "X"

Carefully rotate the analyzer until the intensity is a minimum, *i.e.* at an angle of 90° relative the direction of polarization for your light source. Insert *another* polarizer (we'll call this one "*X*") in front of the analyzer at an angle of 45° relative to the direction of polarization of your light source. Your lab notebook should contain a sketch.

Is the intensity still at a minimum? Try to make sense of your observations: by writing your best <u>*guess*</u> as to what's going on, ***physically***, in your lab notebook (!).

Part 4: 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. Examples of such materials include quartz as well as calcite ($CaCO_3$). 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 medium that is characterized by one index of refraction, n_e, along, say, the x-axis (which might, physically, correspond to the long direction of the rod-like molecules in a highly oriented liquid crystal solution) and a different index, n_o, along the y- and z-axes. Such a material is said to be "uniaxial" in that only one directly is "different." (By convention, the subscript on the index of refraction characterizing the other two directions indicates that they are "ordinary," while the subscript on the other characterizes it as "extraordinary.")

Uniaxial crystals can be used for wave plates if the optic axis is contained in the plane defined by the front surface of the device. In this case a beam polarized in the direction of the optic axis will see a different index of refraction (the extraordinary index n_e) from a beam polarized orthogonally to it (which sees the ordinary index n_o). The result is that the two waves will propagate at different speeds and, after propagating a distance, d, inside the crystal, have accumulate a phase difference of:

$$\Delta\phi = \frac{2\pi}{\lambda_0} d\left(n_o - n_e\right). \tag{9}$$

If $\Delta\phi = \pi$, the two waves will be out of phase, and we call this device a **Half-Wave Plate** (HWP). Such a device can be used to *rotate* the plane of polarization of a linearly polarized beam.

If $\Delta\phi = \pi/2$, the device is called a **Quarter-Wave Plate** (QWP). It can be used to convert a linearly polarized beam into a circularly polarized one. Using the Jones formalism, we can write a matrix M_{QWP} describing an ideal QWP as:

$$M_{QWP} = \begin{pmatrix} e^{i\pi/2} & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} i & 0 \\ 0 & 1 \end{pmatrix} \tag{10}$$

It is almost the same as the identity matrix, but for a quarter-wave plate, the x-polarization exits with an additional $\pi/2$ phase shift relative to the y-polarization.
Does the QWP change the total power in the beam?

Represent the quarter-wave plate matrix in computational software (*e.g.*, *Mathematica*). Use Jones formalism to *predict* the outgoing state of light when the input polarization has an angle of:

A) 0° with respect to the x-axis
B) 30° with respect to the x-axis
C) 90° with respect to the x-axis

The Wolfram site has a simple applet on Circular and Elliptical Polarization that is worth exploring, and another on light passing through Absorbing Polarizers and Transmissive Wave Plates. The use of interactive visualizations strongly complements our work in the lab, by providing clear mental models for phenomena what occur far too rapidly for our detectors to *directly* measure. Check them out!

In Eqn. (3), we wrote an arbitrary polarization state as:

$$\psi = E_0 \begin{pmatrix} \cos\theta e^{i\phi_x} \\ \sin\theta e^{i\phi_y} \end{pmatrix}$$

This can be re-written in a way that highlights the importance of the phase *difference*:

$$\psi = E \begin{pmatrix} \cos\theta e^{i\Delta\phi} \\ \sin\theta \end{pmatrix} \tag{11}$$

where $\Delta\phi = \phi_x - \phi_y$, and $E = E_0 e^{i\phi_y}$. Thus, elliptically polarized light is characterized by three parameters: E, θ, and $\Delta\phi$.

Predict the power transmitted through a polarizing filter, as a function of θ_{pol} (the filter's orientation) for the arbitrary polarization state given by Eqn. (11). Explore how the prediction changes as you vary the elliptical parameters θ and $\Delta\phi$ (*e.g.*, by utilizing *Mathematica*'s Manipulate function)

Example guidance from a student report:

A) Once you have calibrated the zero of the angles for the incident polarization, the QWP, and the analyzing polarizer, *convince* yourself, experimentally, that, for incident light that is linearly polarized, a $\lambda/4$ birefringent plate can produce circularly polarized light (for <u>*what*</u> input polarization angles?), and that a $\lambda/2$ plate can *rotate* the polarization of linearly polarized light by up to 90°. Show your work in your lab notebook. (You are allowed to tape printouts into physics lab notebooks, but make sure that you work contains sufficient comments to ensure clarity!)

B) Design simple tests to distinguish between $\lambda/2$ and $\lambda/4$ retardation plates. One method might be to put two crossed polarizers in the path of the laser beam (completely blocking the light leaving the second polarizer). If an unknown retardation plate is next placed between them and rotated until all light is once again blocked, then, at this point, the plate is aligned with either its fast or slow axis and is having no effect on the relative phase between components of the incident light beam (as there is only one component). If the sample is rotated 45° from this orientation, then it will either be producing circular or 90° shift linear light at its other side (assuming that it is either a $\lambda/2$ or a $\lambda/4$ retardation plate). These two types of light can be distinguished by rotating the second polarizer. If the light is linear, then the intensity of the beam coming out of the second polarizer (the analyzer) will go from zero to full intensity as the polarizer is shifted. If the light is circular, then no change of intensity will be noticed. In the event that an oddball waveplate is used (*i.e.*, one that is neither a $\lambda/2$ nor a $\lambda/4$ retardation plate), then elliptical light would produce a series of minima and maxima of intensity.

C) Use the procedures developed to test a series of unknown samples and determine whether they are $\lambda/2$, $\lambda/4$, or oddball retardation plates, likely intended to be used at a different laser. (Waveplates are chromatic, meaning that the relative phase shift imparted depends on the wavelength of the beam. For example, the PASCO retardation plate causes one wave to lag behind the other by 140 nm, which corresponds to $\lambda/4$ only if the input beam's wavelength is 560 nm.)

D) Take one of the oddball waveplates and determine what type of waveplate it is

Attempt to explain your observations.

Another student's approach:

a) Find the axis of a λ/2 plate. To do this, first orient an analyzer (glass/film polarizer) in front of the detector and adjust for maximum extinction (that is, the laser polarization and analyzer are crossed). Then insert the waveplate between the laser and the analyzer and adjust the waveplate rotation angle until the transmission is again minimized. Now the waveplate is aligned with the beam polarization.

b) Find the analyzer angle that gives maximum transmittance; call this the reference angle. Using the analyzer, **measure the ellipticity and polarization angle** at waveplate angles of 0°, 22.5°, and 45°. The "polarization angle" in this case is found as the difference between the new analyzer angle for max transmittance relative to the reference angle.

c) Repeat (a) and (b) for a λ/4 plate.

Questions to address in your lab notebook:

Discuss the basic physics ideas behind the notion that the absorbing polarizer (*i.e.*, **Polaroid filter**) "only absorbed one polarization"?

Your readings this week all emphasize the **Jones formalism**, both because it is something you can apply, right away, to the simplest experiments involving a single polarizer, and because it provides needed power as you move on to more sophisticated experiments involving multiple polarizers and waveplates at variable angles, as well as (soon) experiments integrating Liquid Crystal on Silicon (LCoS) Spatial Light Modulators. The Jones formalism also provides a good segue into modeling two-state quantum systems, as in our course on "The Momentum of the Photon."

You should now be able to predict the power transmitted through the analyzing filter as a function of the that filter's orientation, for an arbitrary incident elliptical polarization state: such a predicted form can then be used as a fit function for your real data of photodetector *signal level* as a function of analyzing polarizer angle (allowing you to **estimate the parameters of the elliptical polarization state** incident upon the analyzer).
— Be sure to pay attention to the order of optical elements in the beam path, as this dictates the order of matrix multiplication in the Jones formalism.
— By the way, what do you think might be the most effective way of *conveying*, in a document such as your lab notebook, your results for the elliptical polarization state of a beam?

At the end of the third part of this lab, you saw that by inserting a polarizer at an arbitrary angle between a polarized light source and an analyzer that is oriented at an angle of 90° to the direction of the light's polarization, light *was* able to pass through the analyzer. **Is it *possible*** to construct a system where **most** (say 99%) of the polarized light can pass through a polarizer that is crossed? If so, explain *how* you could do this; if not, explain *why* not. In either case, support your idea with any relevant calculations.

Discuss what makes a quarter-wave plate different from glass.

This question explores *systematic* error effects limiting your ability to produce light that is *purely* circularly polarized. (a) Predict how small violations of the idealized *apparatus* would change the result. (b) Do you think that systematic errors of these sorts impacted your results? (c) Are your results within the tolerances of your ability to measure angles and the specifications on the quarter-wave plate? (d) Would it be possible to distinguish between different systematic error sources? (e) Which error source, if any, is most likely impacting *your* results?

Puzzler: It is possible to rotate polarization from horizontal to vertical just with two mirrors. How should the mirrors be oriented?

Opportunities for Initiative:

(Some possibilities are below; your own ideas may be better!)

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Return of the Microwaves:

Additional microwave optics are available in the lab, for which you could try out sections of interest from UCLA's PHYS 6C Experiment 2. You can also explore, with microwaves, the studies that you have, above, only performed with visible light

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Polarization by Reflection

Replace the X polarizer with the **angle table** and place the observing screen on the movable arm. Align the *glass* plate, Slide 9128, on the angle table so that the ***front*** edge of the glass plate is flush with one of the scored lines, as seen in Figure 2.

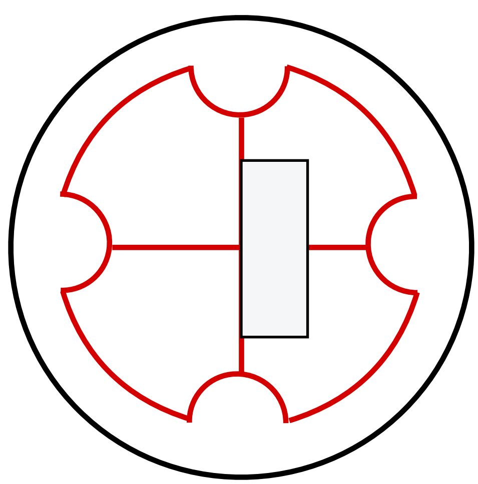

Figure 2

Determine the incident angle by rotating the angle table till the laser beam is reflected back to the laser. Record this angle (along with enough prose and clear drawings to make it clear what it refers to).

For this next part, you will not be using the fiber optic detector. Instead, you will view the reflected beam on an "observing screen:" begin by rotating the angle table clockwise and, as you do so, ***track*** **the reflected beam on the observing screen**. Describe, in you notebook, what you see.

Try to *explain* your observations. (Reminder: the *incident* light from your light source is polarized.)
The reflected angle where the **intensity** of the beam on the observing screen is at a **minimum** is known as **Brewster's Angle**. Your experimental result for Brewster's Angle can be used to ***calculate*** **the index of refraction for glass**. Your text, or the web, can help you to work this out in your lab notebook.

Does your result seem "reasonable," given the index of refraction values typically quoted for common glass?

Repeat this experiment using the *acrylic* plate, Slide 9129 – including full analysis (*i.e.*, calculation of the **index of refraction** and *assessment* of your result)

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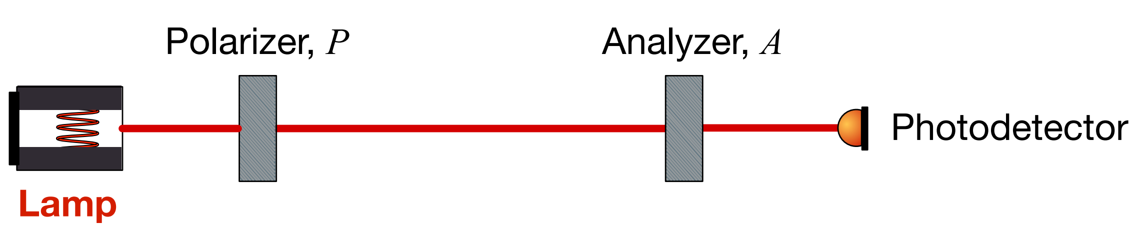
Polariscope *examination of transparent and semi-transparent materials*

A polariscope is system of two crossed polarizers. Since they are crossed, no light will pass through. The arrangement is much like Figure 1, but with the laser replaced with an incoherent lamp.



If you insert various objects, in the middle, you can observe a wide variety of neat, and practical, effects. Play around and discuss what you observed [**Ray's "goodies" are needed here, with light source & large polarizers**]. — For guidance, see Section 4 of UVA's PHYS 241W Lab 11.

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*The Optical Rotary Power of a **Chiral** Medium*

An optically active medium is one that *rotates* the plane of polarization of linearly polarized light passing through it. Linearly polarized light can be thought of as a superposition of a right and left circularly polarized beam of light. In the active medium, these two beams travel at different speeds. This causes one of the beams of light to be delayed, relative to the other. When these polarized waves leave the medium, the superposition of these waves is a linearly polarized wave. However, the right and left circularly polarized light undergo a relative phase shift while in the medium, which manifests itself as a rotation of the linear polarization.

To examine this effect, we place a sample of optically active material (*i.e.*, **corn syrup** or sugar water) after the “input state preparation” optics, and before the “output state analyzer,” as seen in Figure 3. The fiber optic bundle should still be connected.

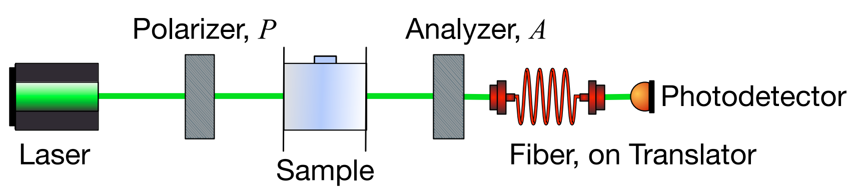

Figure 3

Obtain the chiral fluid sample from your instructor and arrange it between the analyzer, A, and your polarized light source (which may have required the addition of polarizer P). Adjust the light source and the location of the fiber optic cable such that the laser beam lands squarely on the fiber optic cable. Now remove the optically active sample and adjust the analyzer so that it is oriented perpendicular to direction of the incident beam’s polarization. The signal from the photometer should be a minimum when the analyzer is oriented at 90° (“crossed”) with respect to the polarization of your light source; and it is a good idea to adjust the photometer setting as to increase the sensitivity. Now, place the sample back in between the polarizers. Is the intensity still a minimum? If not, adjust the polarizer so that the intensity is again a minimum. ***How much* was the plane of polarization of the incident light (the electric field vector) rotated?**

Attempt to explain your observations.

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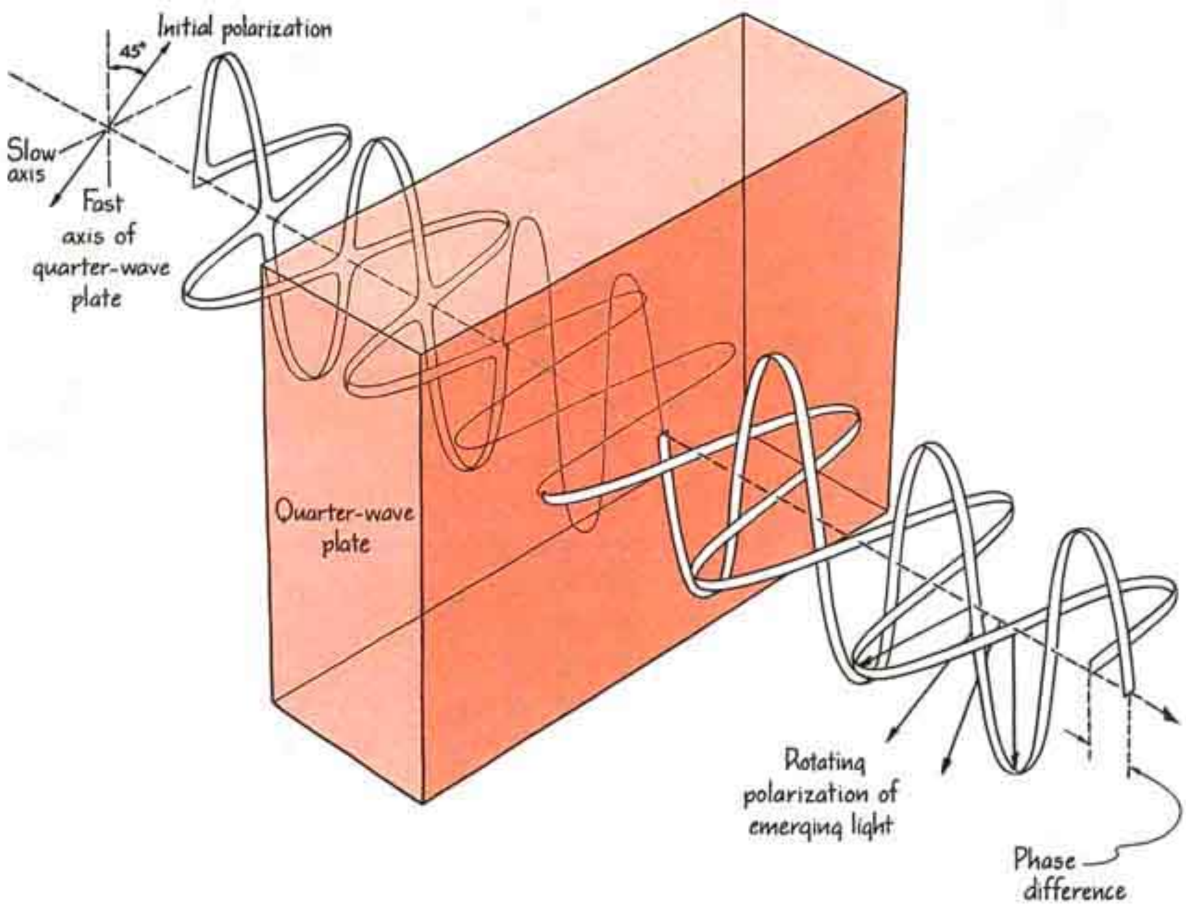
Here's a classic note by Jearl Walker, about how to make your own birefringent waveplates.



[Or, if you prefer, here's a searchable text version of the same article.]

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Spend time writing CONCLUSIONS in your lab notebook!!

Gabe's musings on this *first draft* attempt:

Given that students should have already read both Beck Chapter 2 as well as Sect. 6.1 - 6.6 of Peatross & Ware, is what I have provided here a sufficient (and *complementary*) discussion?

A) Jones Vectors, and
B) Jones Matrices, and an appropriate set-up for in-class discussion of:
C) Polarization Ellipse (to be discussed during a class that follows this lab), and
D) **Liquid Crystal**-based SLMs (to be discussed during a class that follows this lab), and
E) Poincaré Sphere (to be discussed during a class that follows this lab). — Math and constructs such as the Poincaré Sphere should only be introduced AFTER the *motivation* is made manifest! — And ideally the STUDENTS would be the ones creating the mathematical metrics / forms of analysis, wherever possible! The lab's goal is to create a *context* where the Poincaré Sphere is needed!

Students need to be CRYSTAL CLEAR on the notion that a HWP will rotate the polarization, and that a 45° input will be rotated by 90°, so that when analyzed with an exiting polarizer, the result is detected as intensity modulation.