Intermediate Optics labs using matrix modeling, 2019 AAPT Adv. Lab Workshop W44

AUTHOR/
PRESENTER

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COURSE

At F&M, we require an intermediate-level optics lab course for our major, with the following overall curricular goals:

- to introduce several mathematical tools: complex exponential notation in the context of wave optics, matrix methods for modeling polarization and imaging, and Fourier series and transforms as they apply to wave optics and Fourier optics.
- to develop student understanding of several optics concepts beyond that of introductory physics, some of which are coupled with multi-week, scaffolded lab activities.
- to help students acquire experimental skills, like optical alignment, experimental design, error analysis
- to help students develop communication skills, like presentation of data in graphs, creating figures, integrating evidence into a narrative argument for a lab writeup

CONTENTS

Lab handouts for activities for four different, ~ 3-hour lab meetings, along with corresponding Instructor notes that include Parts lists, learning objectives, context of how the lab activities are integrated in the course, and advice about student difficulties. Sample data are also included.

- Polarizers and Quarter-Wave Plates
- 3D Glasses Investigation
- Lenses
- Modeling the Galileoscope

A sample rubric and guidelines for the Lab Reports. ("Characteristics of a Good Lab Report" borrowed from the College of Wooster Physics Department website.)

Polarization and Quarter-Wave Plates

Goals

In this lab, you will explore two optical components that are used to manipulate the polarization of light: linear polarizers and quarter-wave plates. The specific goals of this lab include:

- Using photodiode detectors to make relative measurements of light power.
- Verifying Malus' Law for polarizers.
- Use a quarter-wave plate to change the polarization state of light and observe evidence of these states.
- Construct an optical isolator.

Experiment 1: Malus' Law

You have already used a linear polarizer in the previous lab. They work by absorbing all light except that with an electric field oscillating along the polarizer's transmission axis (TA). Malus' Law describes how much the intensity of an initially linearly polarized light beam is attenuated, due to a linear polarizer whose TA is oriented at an angle θ with respect to the polarization of the incident light.

$$I_{trans} = I_0 cos^2\theta$$

In this experiment, you'll verify this law using a photodetector to measure the relative irradiance of incident light. The detector works by measuring the current of photoelectrons, which is proportional to the irradiance of the light on the diode's sensor. This current is converted to a proportional voltage across a fixed resistance. This voltage is read by the digital multimeter and can be used as a measure of the irradiance.

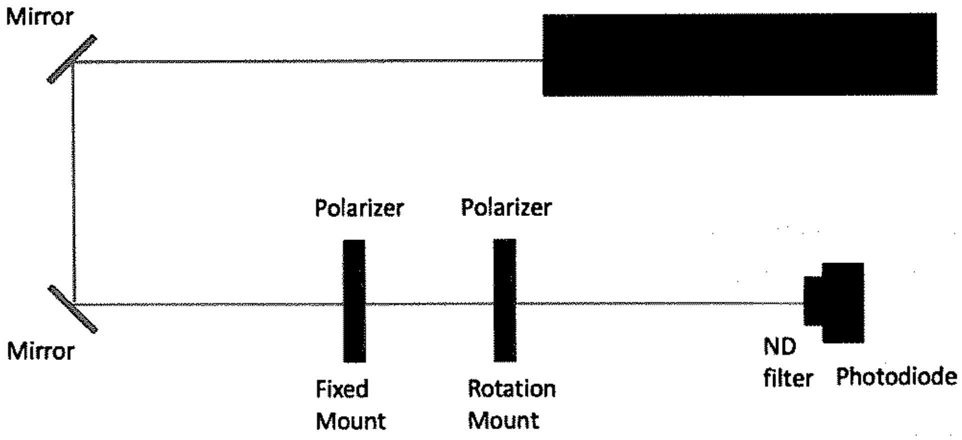
Initial setup:

1. Align the beam at 4" and along a row of holes using the two mirror/ two pinhole method.
2. Mount the photodetector but do not turn on the bias switch on the side. Secure the detector to the breadboard so that the beam is incident on the diode element. Attach the neutral density (ND) filter to the front of the detector.

3. In the previous lab, you used Brewster's angle to set the orientation of one of your linear polarizers in a fixed mount so that its TA is horizontal. Do not adjust this polarizer, but place it after the two mirrors in your aligned beam.

4. Place the other linear polarizer in a rotation mount and place it after the first polarizer in the aligned beam.

5. Connect the multimeter to the detector, set it to measure DC voltage, and switch on the bias for the detector. (Hint: the maximum voltage output of the diode is around 10-12 V. If you see this voltage unchanging even though you are changing the amount of light incident on the diode, this means you have saturated the diode and must further attenuate the beam.)



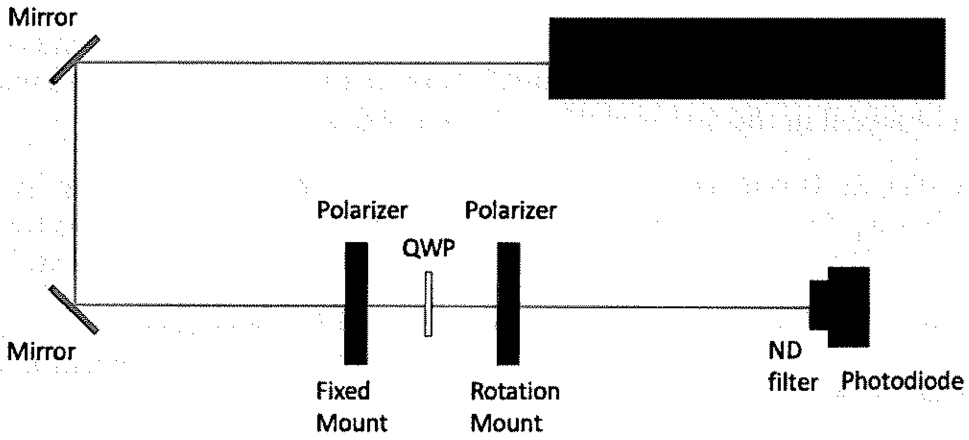
Vary the angle between the TAs of the two polarizers, while recording the transmitted intensity to test Malus' law. Collect points through at least 180 degrees rotation for at least every 10 degrees. Create a plot of your data as a function of relative angle between the TAs of the two polarizers, including error bars. Include on your plot the predicted values of transmission according to Malus' law for the same range of angles, calculating for 2 degree steps (this is a quick way to create a theoretical "curve" for comparison).
To turn in, you should record **at least** the following:

- A large, clearly labelled table with several columns, where you can record angles, voltages, uncertainties, and calculated values and uncertainties. (Handwritten or printout are both OK.)
- Error propagation calculations.
- A printout of your final plot.
- Identify the most significant source(s) of random error and systematic error.

Experiment 2: Quarter-Wave Plates

Quarter-wave plates (QWPs) are often used for converting linearly polarized light to circularly polarized light and vice versa. They can also create elliptically polarized light, however, depending on the relative orientation of the waveplate's fast axis (FA) and the polarization of the incident light.

Initial setup:



1. Rotate the second polarizer so that it extinguishes all light passing through it. The TA of the second polarizer is perpendicular to the TA of the first polarizer, so that the second polarizer is now absorbing all the incident light.
2. Place the QWP in a rotation mount and place it between the two polarizers.

You will likely see that some light now passes through the second polarizer, because the waveplate has changed the polarization state of the light, so that now there is a component of its electric field parallel to the TA of the linear polarizer. Rotate the QWP until you get maximum transmission of the light through the second polarizer. At this point, the light that has passed through the waveplate and is incident on the second polarizer is circularly polarized. (In fact, you have built a circular polarizer by placing the TA of the first linear polarizer and the FA of the QWP at the correct relative orientation.) The second polarizer allows you to probe the polarization state created by the QWP, and so is called an "analyzer."
Plot 1: With the QWP at maximum transmission through the second polarizer, rotate the second polarizer through 180 degrees, recording the irradiance at the photodetector for 10 degree steps. Plot these data (no need for error bars or propagation here). Also record the orientation of the FA of the QWP with respect to the horizontal.
Plot 2: Next, set the QWP to an arbitrary orientation of your choice, where the irradiance is somewhere between minimum and maximum. Rotate the second polarizer through 180 degrees, recording the irradiance at the photodetector for 10 degree steps. Plot these data (no need for error bars or propagation here). Record the orientation of the FA of the QWP with respect to the horizontal.

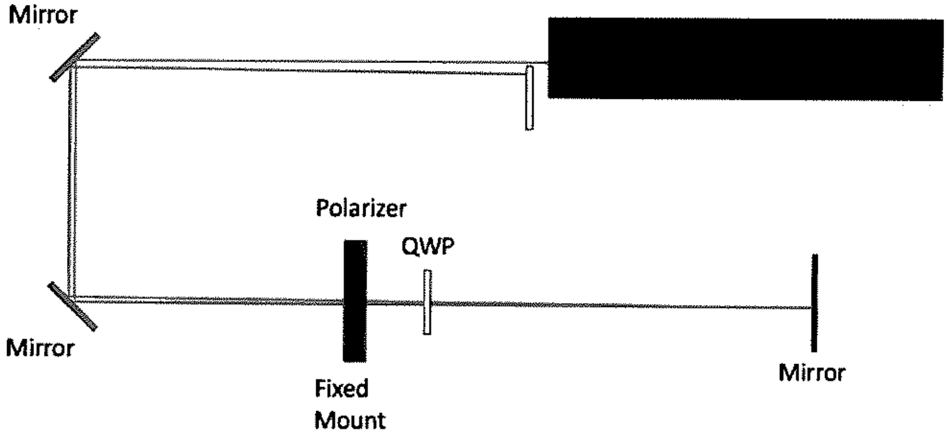
Plot 3: Now, remove the QWP and reset the TA of the second polarizer perpendicular to the first. Replace the QWP and rotate it through 180 degrees, recording the transmission through all three elements for 10 degree steps. Plot these data (no need for error bars or propagation here).

Answer the following questions to turn in:

- Include printouts of all three plots.
- For Plot 1: Why does the brightness of the beam not change (or change only slightly) when the second polarizer is rotated? How and why is this very different from what you observed in the first part of the lab on Malus' Law?
- For Plot 2: Given the orientation of the FA of the QWP, and the behavior of the irradiance, describe the polarization state. It's elliptical, but in which way does it rotate, and why? What are the vertical and horizontal amplitudes of the electric field?
- For Plot 3: Identify on the plot for which angles the light is circularly polarized after the QWP, where it is linearly polarized after the QWP, and where it is elliptically polarized after the QWP.
- Also Plot 3: Why is there a specific orientation of the QWP for maximum transmission and hence a specific orientation for creating circular polarization? What is the orientation of the "fast axis" marked on the QWP, relative to the incoming polarization?

Experiment 3: Optical Isolator

In the final part of the lab, you'll construct an optical isolator. These devices are very useful in combination with interferometers, by preventing light from reflecting backward into the laser cavity and destabilizing it.



1. Remove the QWP temporarily and replace the second polarizer with a metal mirror in a kinematic mount, and direct the beam back on itself toward the laser. You should be able to place an index card just to the side of the laser aperture and see this back reflected beam.
2. Replace the QWP. If its FA is still at 45 deg with respect to the horizontal, the back reflected beam should be strongly absorbed by the polarizer. You can verify that the beam reflected back by the mirror is still there by rotating the QWP.

Answer the following questions to turn in, showing the mathematical expressions for the electric field, as well as the Jones vectors, as the light passes through each optical element, assuming it starts immediately after the first linear polarizer as:

$$\vec{E} = \hat{x}E_{0x}e^{i(kz-\omega t)} \qquad \begin{pmatrix}1\\0\end{pmatrix}$$

- What is the polarization state of the light after passing through the QWP? (You can assume the beamsplitter does not change the polarization.)
- What must happen to polarization state of the light upon reflection from the metal mirror? (Hint: Light reflecting from a metal mirror behaves in a similar way to that reflecting from a higher index material interface.)
- What happens to the polarization state of the light once it passes back through the QWP, and then what happens when it passes back through the linear polarizer?

Polarization and Quarter-Wave Plates: Instructor Notes

Parts list

- Optical breadboard or rail
- Polarization stabilized HeNe laser
- Photodiode (Thorlabs DET36A2)
- Mounted ND filter, OD = 3.0 (Thorlabs ND30)
- Silver mirrors (3)
- Mirror mounts (3)
- Rotation mounts for 1" dia. optics (Thorlabs LM1-A and LM1-B) (3)
- Linear polarizers (2)
- Quarter-wave plate (1)
- Beam blocks/ index cards

Learning objectives

1. Practice experimental skills: optical alignment, understanding of linear polarizers.
2. Practice communication skills: creating a scatter plot, error propagation, identifying experimental error
3. Apply theoretical ideas discussed in class: Jones vectors, Malus' Law, complex exponential notation, polarizers and retarders.
4. Develop an intuition for how the irradiance changes with relative orientations of the transmission axis of a polarizer and the fast axis of a quarter-wave plate.
5. Use Jones vectors and complex exponential notation to model a series of polarizers and waveplates that change the polarization state of light.

Context of this lab

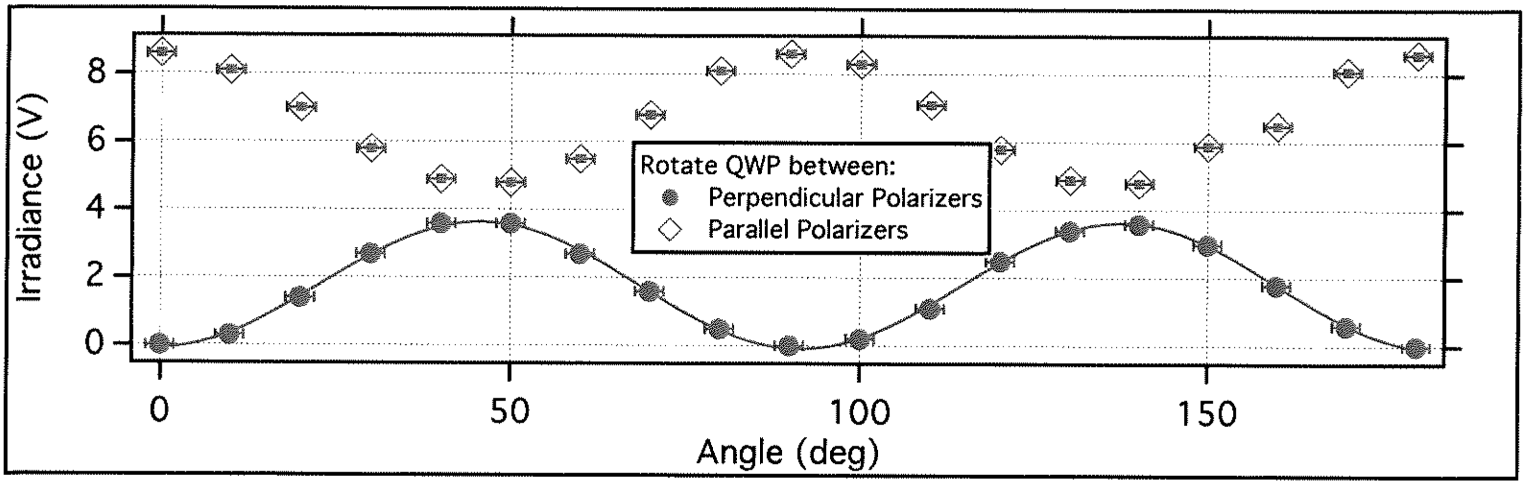
In the previous lab, the students have investigated Fresnel reflection and the Brewster angle, as well as linear polarizers. They should also be familiar with how to align a beam to an optical breadboard by using an iris at two locations along a row of holes on the breadboard, and adjusting with two mirrors on kinematic mounts. The HeNe laser needs to be polarization stabilized for the data to be consistent.

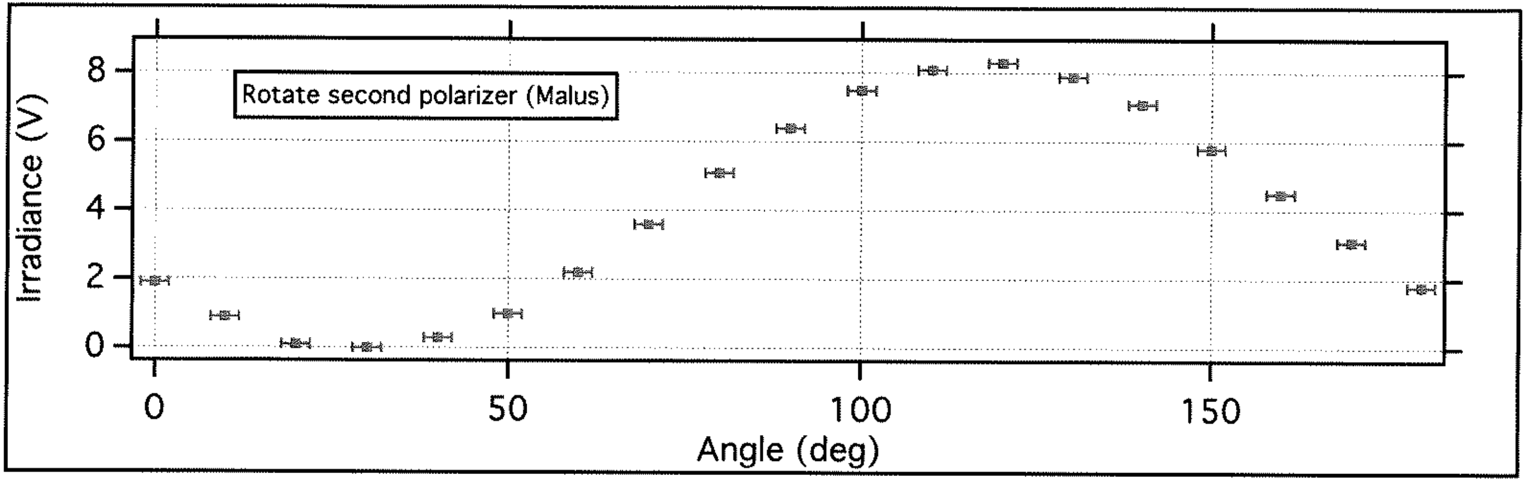
In class, students will deal with the theoretical side of these ideas: polarization states of light, complex exponential models of harmonic plane waves, Jones vector representations of polarization states and polarization-altering optics. This lab is meant to provide hands-on experience with the behavior of these optics along with practical observations that allow students to interpret and, importantly, model mathematically what is happening to the polarization states.

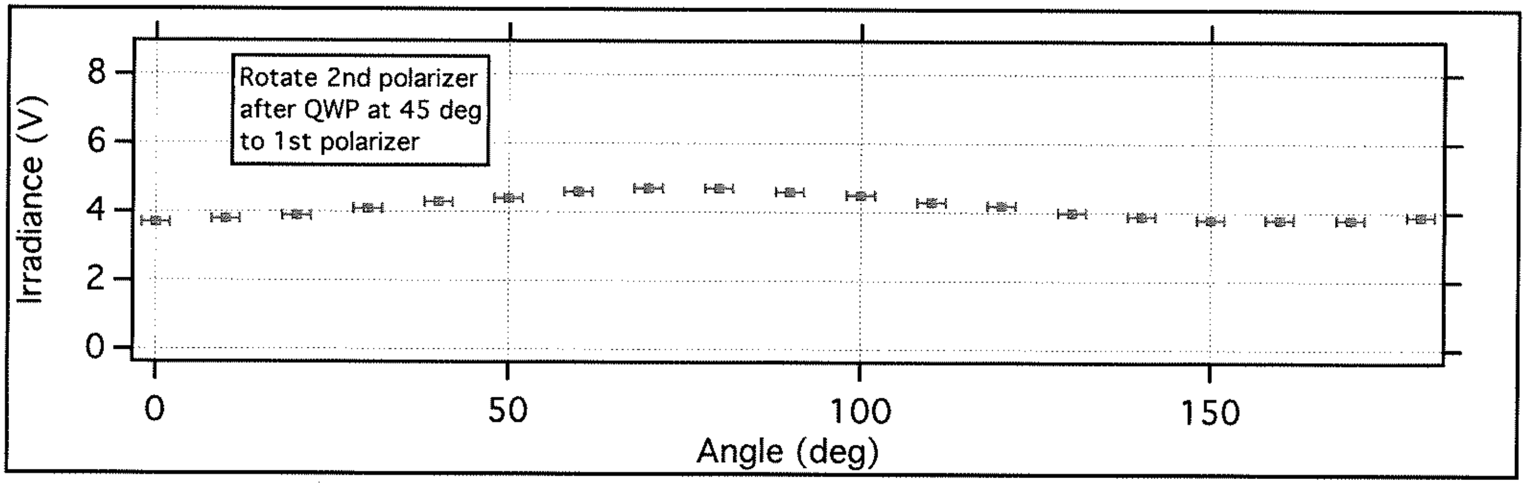
In the next lab, students will use the skills and ideas developed here to then investigate an optical system they may have encountered in real life: RealD 3D glasses. The lab is open-ended and students must collect data that shows how the glasses are constructed and can be used for 3D movie viewing.

Sample Data

A few of these are attached.


Irradiance (V)
0
2
4
6
8
0
50
100
150
Angle (deg)
Rotate QWP between:
● Perpendicular Polarizers
◇ Parallel Polarizers


Irradiance (V)
0
2
4
6
8
0
50
100
150
Angle (deg)
Rotate second polarizer (Malus)


Irradiance (V)
0
2
4
6
8
0
50
100
150
Angle (deg)
Rotate 2nd polarizer
after QWP at 45 deg
to 1st polarizer

3D Glasses Investigation

In this week's lab, you need to design and carry out experiments to determine how 3D glasses (like those at movie theaters) work. You'll write a formal 5-7 page report on your experiment and results. (Rubric and explanation of requirements separate.)
You may research online as you start exploring but you must experimentally verify any explanation you find or hypotheses you come up with. You will need to use several of the techniques we have developed since the beginning of the semester.
You must design your own experiment and determine what measurements you should perform. You don't need to have a completely well-formed plan before you start, but it will definitely be worth taking careful, systematic measurements, and keeping detailed notes so that you can include the appropriate amount of detail in the report. You'll need clearly labeled schematics for each of the measurements you do, along with details of the procedure and explanations of any theory or calculations you rely on. Remember that, as for the other labs, each measurement should have accompanying uncertainty measurements or estimates.

Hints:

- Each "lens" is not a real lens in the geometric optics sense. Instead, it is made of two different optical elements (both of which you've studied this semester) layered together.
- The right and left "lenses" in each pair are slightly different from each other.
- Start all your measurements with horizontally polarized light by using one of your linear polarizers set with its transmission axis parallel to the breadboard.
- You should use the rotation mounts for many of your measurements, using the remaining polarizer, the quarter-wave plate, and the right and left "lenses". You can use double-stick tape to attach each "lens" to the rotating part of the mount.
- You should collect most of your data using the photodiode, supplementing with qualitative descriptions.
- In your report, you'll need to describe which optical element is the front of the "lens", which is the back, and how the right and left lenses are different. All of these should be backed up with experimental evidence.
- *You'll need enough data and types of measurements to show unambiguously that the glasses are what you say they are.* This means considering alternative explanations for how the 3D glasses might work, and using your data to eliminate them.

3D Glasses Investigation: Instructor Notes

Parts list

- Optical breadboard
- Polarization stabilized HeNe laser with mount to 4" height
- Photodiode (Thorlabs DET36A2)
- Mounted ND filter, OD = 3.0 (Thorlabs ND30)
- Silver mirrors (2)
- Mirror mounts (2)
- Rotation mounts for 1" dia. optics (Thorlabs LM1-A and LM1-B) (3)
- Linear polarizers (2)
- Quarter-wave plate (1)
- RealD 3D glasses, lenses separated, taped to lens tube (2)
- Beam blocks/ index cards

Learning objectives

1. Practice experimental skills: designing measurements.
2. Practice communication skills: writing a full lab report, constructing a narrative argument around experimental evidence, introducing an experimental investigation with appropriate context and theoretical background, using figures to clearly support arguments.
3. Apply theoretical ideas discussed in class and experimental ideas developed in the past two labs.

Context of this lab

In the previous lab, the students have investigated linear polarizers, quarter-wave plates, created various polarization states and tested them experimentally using an analyzer linear polarizer and a photodetector. Students will also have done practice with creating figures, propagating error, and discussing sources of experimental error.

One of the main learning objectives of this lab are for students to transfer knowledge from previous labs and from class to designing an experiment to test an authentically unknown optical system. While they can look up how 3D glasses are designed, this lab requires them to come up with measurements that provide evidence for what type of filter the glasses are made of, which, due to manufacturing tolerances, doesn't look exactly the way they might expect.

A second learning objective is to practice synthesizing information into a clear lab report, transferring knowledge from earlier exercises in creating schematic diagrams, scatter plots and captions, and constructing arguments to make a claim about new data.

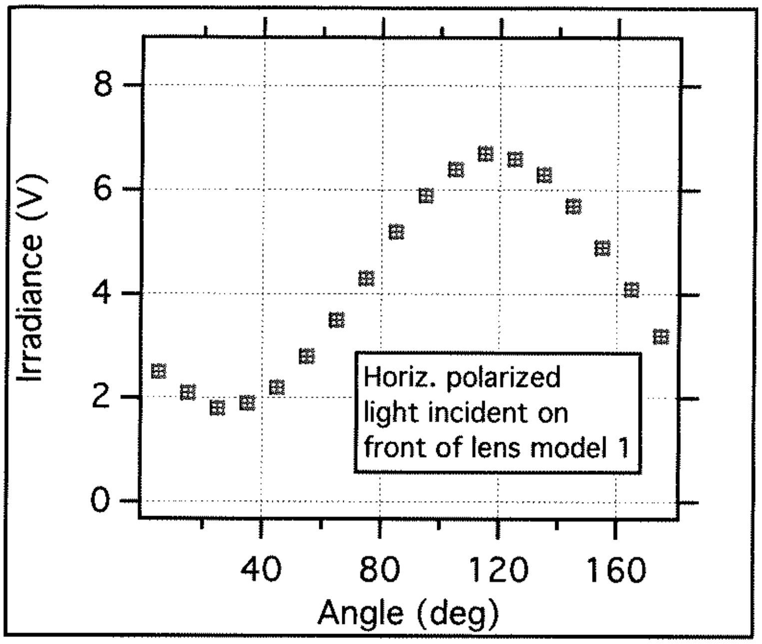
Sample Data

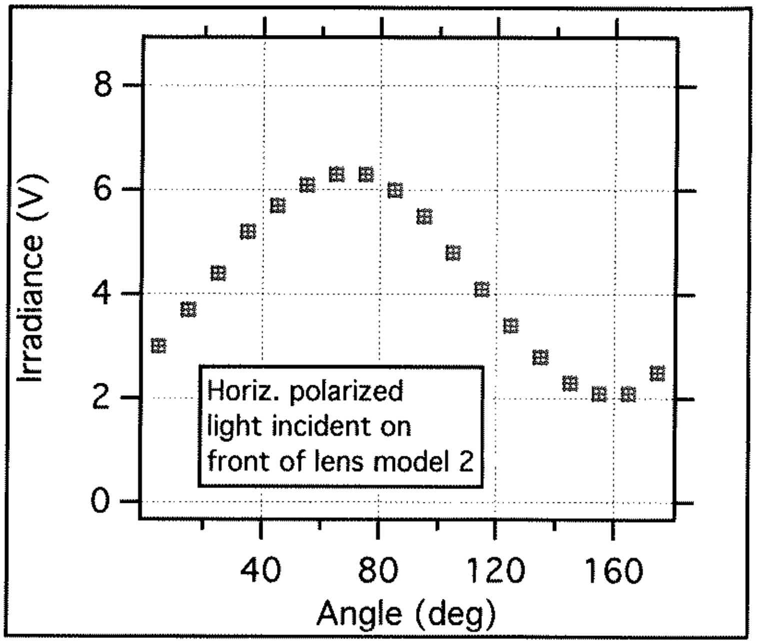
The actual configuration for the 3D glasses lenses are that they are circular polarization filters (QWP with FA at 45 deg in the front, linear polarizer in the back). One strongly transmits right-circular polarized light while strongly absorbing left-circular polarized light, and the other vice versa.

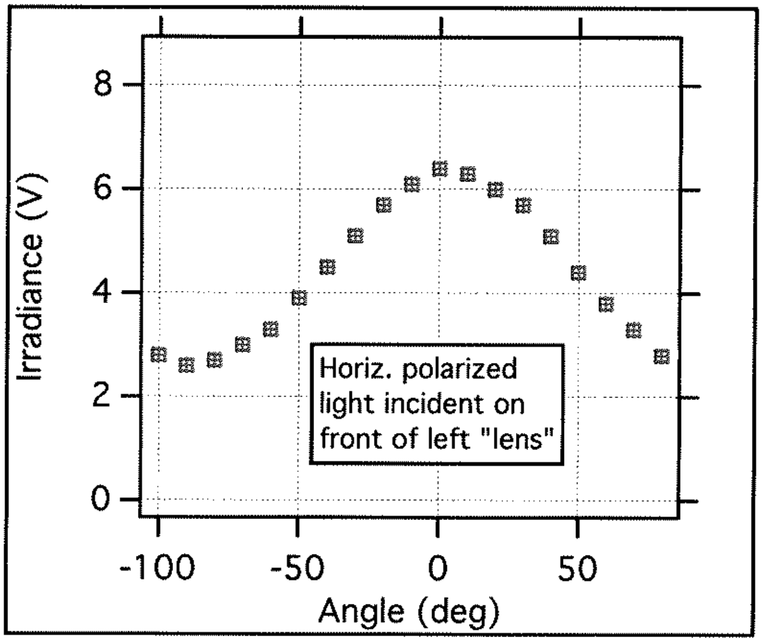
Students can try and explore a number of different measurements and different subsets of these measurements can be used as sufficient evidence. For example, students might measure:

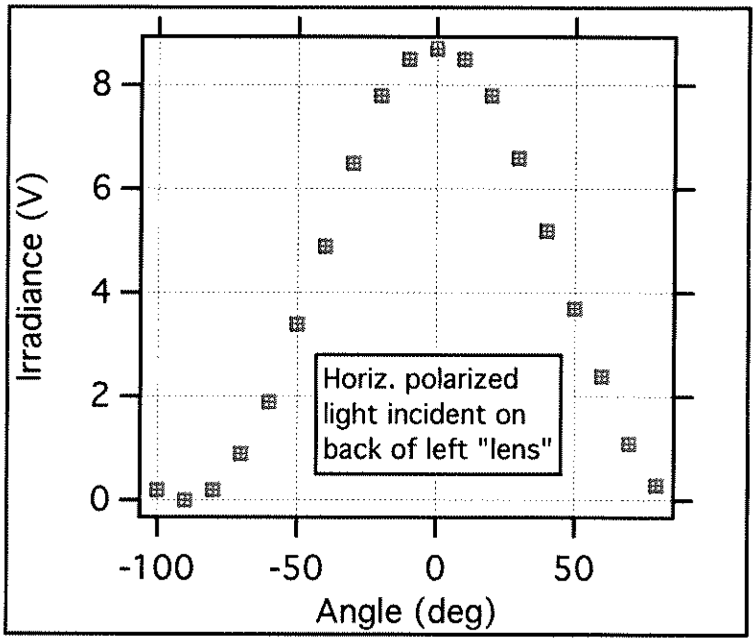
- Irradiance of horizontally polarized light through the front and back of each lens, as a function of lens orientation angle
- Irradiance of circularly polarized light through the front and back of each lens, as a function of lens orientation angle
- Irradiance of horizontally polarized light through a QWP, then the front and back of each lens, as a function of orientation angle of the QWP FA
- Irradiance of horizontally polarized light through a model of each lens, made by putting a QWP and linear polarizer together with the correct orientation, as a function of the orientation angle of the pair

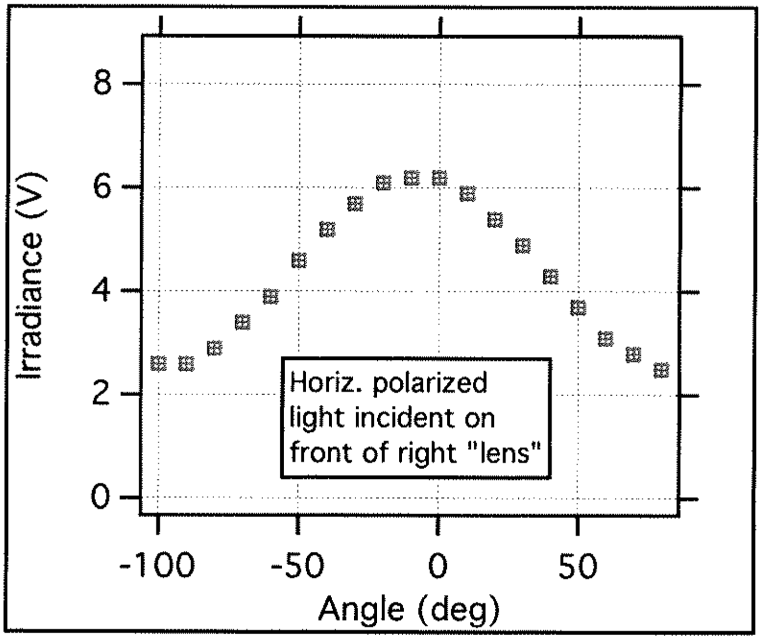
A few of these are attached.

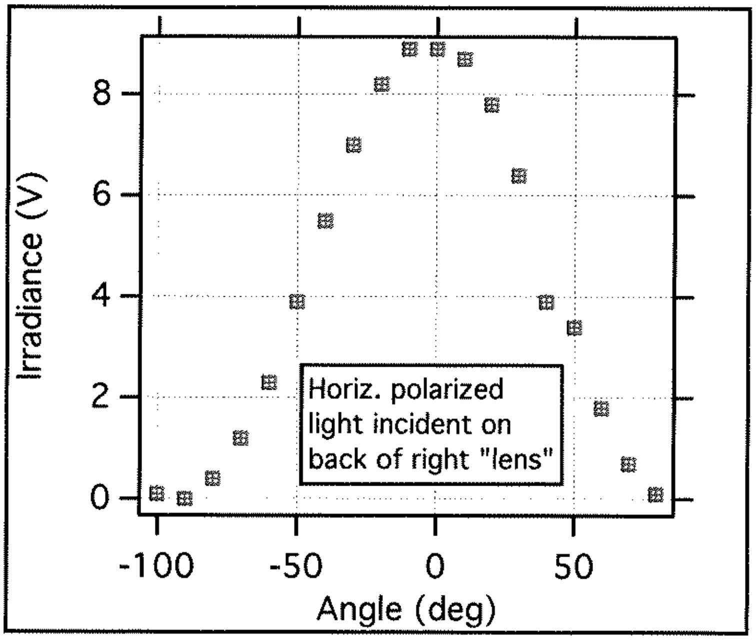

8
6
4
2
0
Irradiance (V)
40
80
120
160
Angle (deg)
Horiz. polarized
light incident on
front of lens model 1


8
6
4
2
0
Irradiance (V)
40
80
120
160
Angle (deg)
Horiz. polarized
light incident on
front of lens model 2


8
6
4
2
0
Irradiance (V)
-100
-50
0
50
Angle (deg)
Horiz. polarized
light incident on
front of left "lens"


8
6
4
2
0
Irradiance (V)
-100
-50
0
50
Angle (deg)
Horiz. polarized
light incident on
back of left "lens"


8
6
4
2
0
Irradiance (V)
-100
-50
0
50
Angle (deg)
Horiz. polarized
light incident on
front of right "lens"


8
6
4
2
0
Irradiance (V)
-100
-50
0
50
Angle (deg)
Horiz. polarized
light incident on
back of right "lens"

Lenses

Goals

In this lab, you will explore image formation with spherical lenses by designing experiments to achieve three different goals:

- Verification of the thin lens equation and measurement of the focal length of a lens.
- Design of a corrective lens for a model eye with near- or far-sightedness.

Experiment 1: Measuring focal lengths

In Physics 112, you learned that the image created by a thin spherical lens obeys the simple (approximate) model, called the lens equation: $\frac{1}{f} = \frac{1}{o} + \frac{1}{i}$, where f is the focal length of the lens, o is the distance from the lens to the object, and i is the distance from the lens to the image. You can use this relationship to determine the focal length of an unknown lens.
You have three lenses with unknown focal lengths. For this part of the lab, you must design and carry out experiments to measure their focal lengths, with uncertainty.

1. For one of the lenses, you should perform enough independent measurements to determine the correct focal length within 5% of its value. (There is more than one equally valid way to do this.)
2. For the other two lenses, you can stick to one independent measurement or set of measurements, but you should be able to determine the correct focal length within 10% of its value. (Hint: At least one of the lenses is a diverging lens, which cannot create a real image on its own!)

To turn in, you should record **at least** the following:

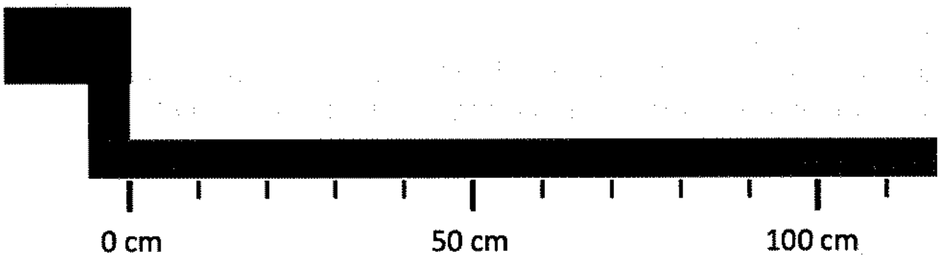
- The focal lengths of all three lenses, with uncertainty.
- A large, clearly labelled table of your raw and calculated data.
- Sample error propagation calculations.
- If relevant, a printout of any plots, with error bars.
- Identify the most significant source(s) of random error and systematic error.

Experiment 2: Corrective lenses

When the eye lens cannot adjust its focal length enough to form a sharp image on the retina, corrective lenses, either eyeglasses or contact lenses, are used to compensate. Proper vision now requires a two-lens system. In this part of the lab, you'll find the proper corrective lenses to compensate for either nearsightedness or farsightedness. You'll need to choose one of the two initial setups (Seup A and Setup B) so that we have enough of each kind of lens for all groups to do this part of the lab.

Place the f = +10 *cm* in front of the light source, 35 cm away for Setup A and 48 cm away for Setup B. Find the real image created by the lens, and place the screen there. This is a model of a properly focused eye, where the screen represents the retina at the back of the eye, and the distance between the lens and screen is the length of the eye.

- Record the positions of the lens and screen/ retina on the figure below, along with uncertainty.



Now replace the f = +10 *cm* with a f = +12.5 *cm* lens for Setup A and a f = +7.5 *cm* lens for Setup B. Since the new lens has a different focal length, it will no longer form an image at the "retina." Use a sheet of paper to locate the image (you may not be able to find it easily at first: if so, stop to think why).

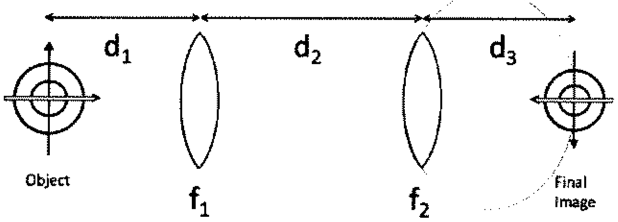
- Record the new location of the image on the figure above, along with uncertainty.
- Is this eye nearsighted or farsighted? Explain.

Now use the lens equation to determine what focal length lens you must place in front of the eye model (meaning between the light source and the eye lens) to form an image at the retina. Assume that you're designing glasses that sit about the same distance in front of the eye that the eye lens is from the retina. (This is roughly true to scale: human eyes are about 2 cm in diameter, and glasses typically sit about 2 cm in front of the eye.)

Find the lens in the kit closest to that focal length, and test your glasses by placing it in front of the eye model. Since we likely do not have the exact focal length you calculated, you'll have to adjust the position of the corrective lens by a centimeter or two to form a real image on the retina screen.

- Record here which corrective lens worked along with its focal length and whether it is converging or diverging. Record its location on the figure above.

Using the lens equation for multiple lenses can be confusing, since you must keep track of several different distances relative to different lenses, and also keep track of the sign conventions for object and image distances. A more computationally straightforward but less intuitive way to do this calculation is with matrices. You'll learn more about where these come from in class, but for this lab you'll use Mathematica to help with your calculations. Operationally, you can model an imaging system with ABCD matrices by representing each optical element and distance by a single matrix. For our setup, from the object to the image there is a translational distance, d_1, a thin lens f_1, a translational distance d_2, a thin lens f_2, and a translational distance d_3 (see figure below).



You can create a model of how these elements transform how the light behaves by multiplying them together. **Note carefully the order of the matrices.** The first matrix, on the left hand side, is the last thing the light encounters before forming the final image, d_3. Multiplying the matrices in the reverse order will not work, since matrix multiplication is not commutative in general!

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & d_3 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f_2 & 1 \end{pmatrix} \begin{pmatrix} 1 & d_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f_1 & 1 \end{pmatrix} \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix}$$

You can use Mathematica to multiply these together by using the MatrixForm function:

$$\text{In[7]:=}\ \mathbf{MatrixForm}\left[\begin{pmatrix} 1 & d3 \\ 0 & 1 \end{pmatrix} . \begin{pmatrix} 1 & 0 \\ -1/f2 & 1 \end{pmatrix} . \begin{pmatrix} 1 & d2 \\ 0 & 1 \end{pmatrix} . \begin{pmatrix} 1 & 0 \\ -1/f1 & 1 \end{pmatrix} . \begin{pmatrix} 1 & d1 \\ 0 & 1 \end{pmatrix}\right]$$

(Of course, you can also multiply these by pencil and paper if you wish.) Once you have your final ABCD matrix, you can solve for any unknown quantities (in this case, f_1) by setting the expression for B equal to zero and solving. Verify that this gives you the same value for f_1 that you found by solving the lens equation.

To turn in, you should put together:

- Answers to the above questions along with clearly presented calculations.
- A printout of your Mathematica worksheet, if used.

Lenses: Instructor Notes

Parts list

- Optical breadboard or rail
- Lens mounts for 1" dia. lenses (2)
- Pasco Basic Optics light source
- Lens kit, including +10 cm, +12.5 cm, +7.5 cm, +250 cm, and -7.5 cm lenses
- Tape measure or ruler
- Screen/ index card

Learning objectives

1. Practice experimental skills: designing and plan measurements, learn various methods for measuring the focal length of an unknown lens.
2. Practice communication skills: error propagation, presentation of data in tables or plots.
3. Apply theoretical ideas discussed in class: ABCD matrices, thin lenses, image formation, vision.
4. Develop an intuition about how lenses alter the behavior of light, and how lens systems can create a desired image.

Context of this lab

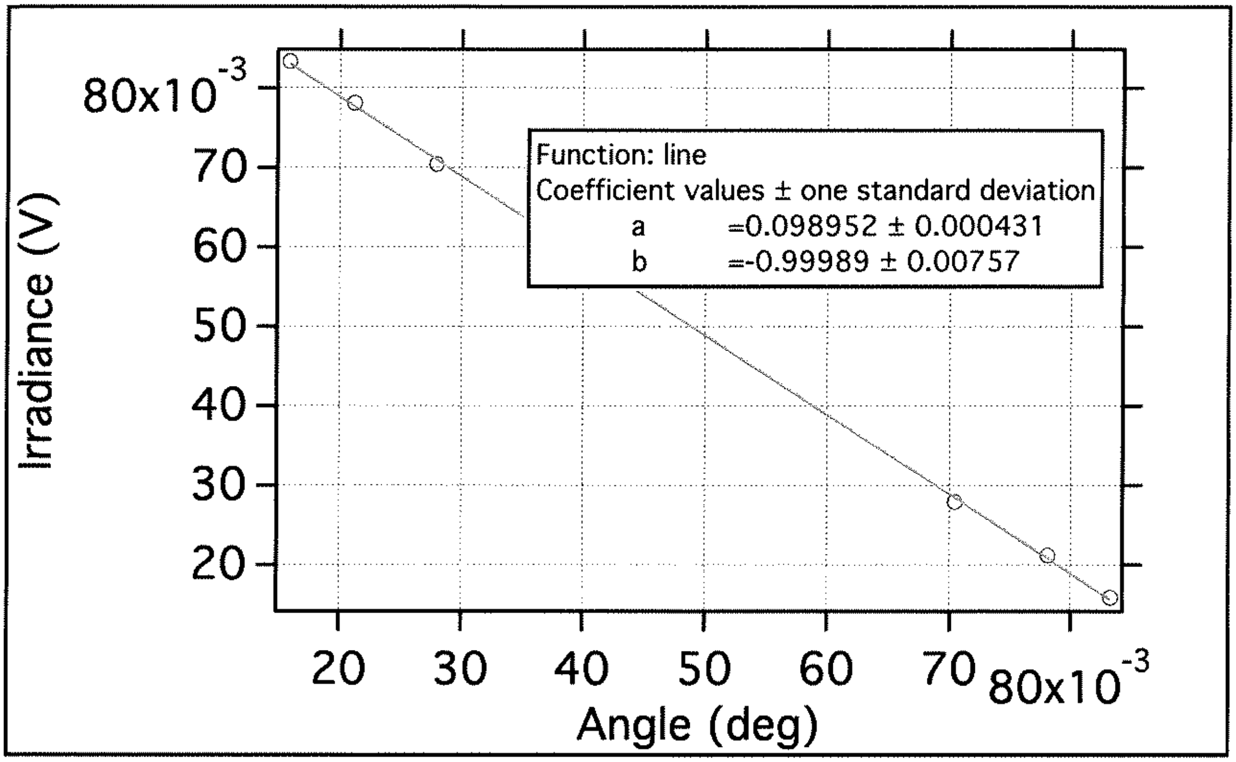
In a previous course, students will have seen and verified the lens equation experimentally. This lab is intended to give them agency in figuring out (or remembering) how to measure the focal length of a lens, including that of a diverging lens, which cannot form a real image alone. Now they must also meet a restriction in the error tolerance. Once they have figured out how to measure the focal length of a lens, they create a model of an eye that exhibits near- or far-sightedness, and must design a corrective lens to compensate. This lab also introduces the basics of using ABCD matrix analysis, contrasting it with using the lens equation, which is more familiar and intuitive, but can be difficult to implement for a multiple-lens system.

In the next lab, students will take the skills developed here to investigate a different optical system: a refractive telescope that they can assemble themselves and model using the ABCD matrix methods.

Sample data

The attached graph shows 1/o vs 1/i for a +10 cm lens.

Corrective lenses for the two eye models are:
Setup A: +25 cm lens located 14.5 cm in front of the +12.5 cm "eye lens."
Setup B: -7.5 cm lens located 14.5 cm in front of the +7.5 cm "eye lens."



Function: line
Coefficient values ± one standard deviation
a =0.098952 ± 0.000431
b =-0.99989 ± 0.00757
Irradiance (V)
80x10^-3
70
60
50
40
30
20
20
30
40
50
60
70
80x10^-3
Angle (deg)

```
In[3]:= d3 = 13.8
        f2 = 12.5
        d2 = 13.8
        d1 = 21.2

Out[3]= 13.8

Out[4]= 12.5

Out[5]= 13.8

Out[6]= 21.2
```

In[7]:=

$$\mathrm{MatrixForm}\left[\begin{pmatrix} 1 & d3 \\ 0 & 1 \end{pmatrix} . \begin{pmatrix} 1 & 0 \\ -1/f2 & 1 \end{pmatrix} . \begin{pmatrix} 1 & d2 \\ 0 & 1 \end{pmatrix} . \begin{pmatrix} 1 & 0 \\ -1/f1 & 1 \end{pmatrix} . \begin{pmatrix} 1 & d1 \\ 0 & 1 \end{pmatrix}\right]$$

Out[7]//MatrixForm=

$$\begin{pmatrix} -0.104 - \frac{12.3648}{f1} & 12.3648 + 21.2\left(-0.104 - \frac{12.3648}{f1}\right) \\ -0.08 + \frac{0.104}{f1} & -0.104 + 21.2\left(-0.08 + \frac{0.104}{f1}\right) \end{pmatrix}$$

In[10]:=

$$\mathrm{Solve}\left[12.365 + 21.2\left(-0.104 - \frac{12.365}{f1}\right) == 0, f1\right]$$

```
Out[10]= {{f1 → 25.8005}}
```

Modeling the Galileoscope

You are provided with a Galileoscope, and a choice of lens combinations that produce different magnifications. Your job is to determine the angular magnification of the Galileoscope experimentally in two ways: by direct observation and by modeling the lens system with matrices, using measured values for lenses of unknown focal length. You'll write a formal 5-7 page lab report on your observations and findings. You must describe, as fully as possible, how the Galileoscope works, backing it up as much as possible with *measurements* and *observations.*

Use the following list as a starting point for making your observations.

- Measure the focal lengths of the component lenses of the telescope. For "doublet" lenses, that is, when a convex and concave lens are held in contact, you can treat the pair as a single thin lens.
- Construct the Galileoscope as indicated for one of the configurations and measure the angular magnification directly. You will construct the 25x version of the telescope using steps 1-15 from the manual. (25x is an approximate angular magnification, but you'll need to measure it directly.) You'll need to measure the separation distances of the lenses very carefully!
- Construct a ABCD matrix model of the lens system, including only the lenses and the distance between the lenses. You can assume thin lenses for all of the optics. Element D gives the angular magnification of the telescope.
- Compare the angular magnification predicted by the ABCD matrix to the measured angular magnification. To measure the angular magnification:
    1. Align the telescope to observe a colored piece of paper at the end of the corridor, using one eye.
    2. With your other eye, observe a second piece of paper of the same size and in the same orientation held by a partner.
    3. Have your partner move toward you or away from you until both pieces of paper are the same apparent size. (This is tricky to do, since you need to view one paper through the telescope, and one directly! But it can be done.)
    4. The angular magnification is given by the ratio of the distance from your eye to the far sheet of paper to the distance from your eye to the near sheet of paper.

Modeling the Galileoscope: Instructor Notes

Parts list

- Optical breadboard or rail
- Lens mounts for 1/2" and 2" dia. lenses
- Galileoscope kit
- Camera tripod
- Long tape measure

Learning objectives

1. Practice experimental skills: designing measurements.
2. Practice communication skills: writing a full lab report, constructing a narrative argument around experimental evidence, introducing an experimental investigation with appropriate context and theoretical background, using figures to clearly support arguments.
3. Apply theoretical ideas discussed in class and experimental ideas developed in the past two labs.

Context of this lab

In the previous lab, the students have investigated lenses, measuring focal lengths, and simple modeling with ABCD matrices. In class, they will see the theory behind modeling with ABCD matrices. Students will also have done practice with creating figures, propagating error, and discussing sources of experimental error.

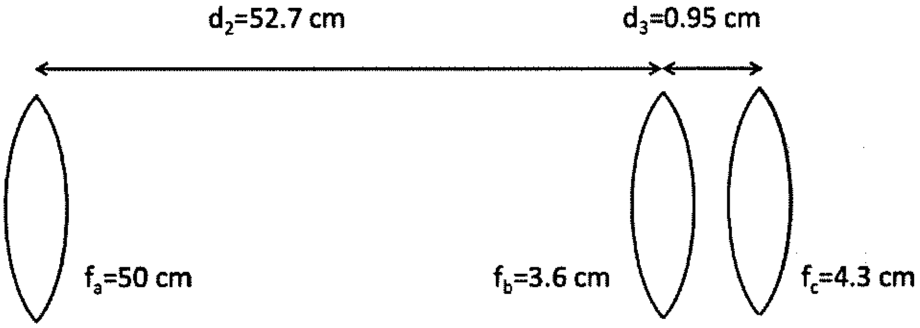
One of the main learning objectives of this lab are for students to transfer knowledge from previous labs and from class to designing an experiment to model an authentic optical system. A second learning objective is to practice synthesizing information into a clear lab report, transferring knowledge from earlier exercises in creating schematic diagrams, scatter plots and captions, and constructing arguments to make a claim about new data.

If they are careful in their measurements, students can get very close numbers for the angular magnifications, but it's easy for them to be careless in determining distances between lenses and focal lengths. It may be worth requiring that the numbers match within a certain error (10-20%, perhaps) or within propagated uncertainty.

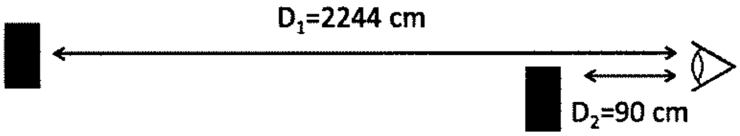
Another tricky aspect to this lab is that students will need to be able to determine the apparent magnification of the telescope, which is done by comparing the apparent size of a sheet of paper viewed at a long distance through the telescope to the same size sheet of paper viewed to the side of the telescope. You can do this by looking through the telescope with one eye and directly at the near paper with the other eye.

Sample Data

Below is a sample set of measurements for the focal lengths and distances between lenses in the Galileoscope:



The distances for the angular magnification of the telescope are:



$$angmag = \frac{2244cm}{90cm} = 24.93$$

The matrix modeling calculations are attached.

In[1]:= $$\text{MatrixForm}\left[\begin{pmatrix}1 & 0\\ -1/\text{fc} & 1\end{pmatrix}\cdot\begin{pmatrix}1 & \text{d3}\\ 0 & 1\end{pmatrix}\cdot\begin{pmatrix}1 & 0\\ -1/\text{fb} & 1\end{pmatrix}\cdot\begin{pmatrix}1 & \text{d2}\\ 0 & 1\end{pmatrix}\cdot\begin{pmatrix}1 & 0\\ -1/\text{fa} & 1\end{pmatrix}\right]$$

Out[1]//MatrixForm=

$$\begin{pmatrix}1-\frac{\text{d3}+\text{d2}\left(1-\frac{\text{d3}}{\text{fb}}\right)}{\text{fa}}-\frac{\text{d3}}{\text{fb}} & \text{d3}+\text{d2}\left(1-\frac{\text{d3}}{\text{fb}}\right)\\ -\frac{1-\frac{\text{d3}}{\text{fc}}}{\text{fb}}-\frac{1+\text{d2}\left(-\frac{1-\frac{\text{d3}}{\text{fc}}}{\text{fb}}-\frac{1}{\text{fc}}\right)-\frac{\text{d3}}{\text{fc}}}{\text{fa}}-\frac{1}{\text{fc}} & 1+\text{d2}\left(-\frac{1-\frac{\text{d3}}{\text{fc}}}{\text{fb}}-\frac{1}{\text{fc}}\right)-\frac{\text{d3}}{\text{fc}}\end{pmatrix}$$

In[2]:= $$\text{mag[d2\_, d3\_, fb\_, fc\_]} = 1+\text{d2}\left(-\frac{1-\frac{\text{d3}}{\text{fc}}}{\text{fb}}-\frac{1}{\text{fc}}\right)-\frac{\text{d3}}{\text{fc}};$$

In[3]:= $$\text{ERd2[d2\_, d3\_, fb\_, fc\_]} = \partial_{\text{d2}}\,(\text{mag[d2, d3, fb, fc]});$$

In[4]:= $$\text{ERd3[d2\_, d3\_, fb\_, fc\_]} = \partial_{\text{d3}}\,(\text{mag[d2, d3, fb, fc]});$$

In[5]:= $$\text{ERfb[d2\_, d3\_, fb\_, fc\_]} = \partial_{\text{fb}}\,(\text{mag[d2, d3, fb, fc]});$$

In[6]:= $$\text{ERfc[d2\_, d3\_, fb\_, fc\_]} = \partial_{\text{fc}}\,(\text{mag[d2, d3, fb, fc]});$$

In[7]:= $$\text{error[d2\_, d3\_, fb\_, fc\_]} = \sqrt{\left((\text{ERd2[d2, d3, fb, fc]}\ \delta\text{d2})^2+(\text{ERd3[d2, d3, fb, fc]}\ \delta\text{d3})^2+(\text{ERfb[d2, d3, fb, fc]}\ \delta\text{fb})^2+(\text{ERfc[d2, d3, fb, fc]}\ \delta\text{fc})^2\right)};$$

In[8]:=
```
d2 = 52.7;
fb = 4.3;
d3 = 0.95;
fc = 3.6;
δd2 = 0.5;
δd3 = 0.5;
δfb = 0.5;
δfc = 0.5;
```

In[16]:=
```
mag[d2, d3, fb, fc]
```

Out[16]=
```
-22.9244
```

In[17]:=
```
error[d2, d3, fb, fc]
```

Out[17]=
```
2.49424
```

Characteristics of a Good Lab Report

Abstract and Title

1. The title is informative. **The abstract clearly and concisely describes the purpose and methods of the experiment and gives the final results or conclusions.**

Introduction

2. **The introduction introduces the concepts and ideas associated with the experiment. It provides sufficient context to identify the purpose of the research and sets an appropriate tone.**
3. The introduction includes interesting information and isn't simply a stale rewording of the information in the lab manual or text.

Theory

4. **The theory section develops the equations needed to understand the experiment starting from a foundation of knowledge common to peer students. The theory is presented clearly with appropriate level of detail.**
5. Equations are correctly formatted and treated appropriately as part of a sentence.
6. Derivations are clearly explained and are not simply a duplication of the lab manual.

Procedure

7. **The procedure provides sufficient detail to allow another advanced student to duplicate the results. The procedure should identify the sources of all data that are collected.** Novel methods or techniques should be explained in more detail than routine techniques.
8. **The procedure is logically and concisely organized,** so that it provides a summary of the activities rather than a step-by-step chronology.

Data and Results

9. **The student has measured all needed experimental factors or quantities.** The intervals or ranges over which data are taken are appropriate.
10. **The student has selected the appropriate information and performed calculations correctly.** A sample calculation should be shown.
11. **The data and results are presented to the reader in a thoughtful, coherent way,** so that the reader can easily understand their significance and implications.
12. When needed or helpful, the student has displayed the results in graphs. All graphs are correctly formatted and contain appropriate labels and units.
13. All data tables and graphs are referred to and discussed in the text.
14. Tables and graphs are captioned with informative but concise text.
15. Uncertainty and error analysis are presented and are correct.

Conclusion

16. **The student summarizes the purpose and findings of the research accurately and concisely.**
17. The student explains the expected results and offers explanations and/or suggestions for further research to clarify any unexpected results.
18. The student draws inferences consistent with the data and avoids over-generalizing.
19. Numeric results are presented with proper formatting (units, uncertainty, sig figs, etc.).

Overall

20. The quality of writing is good. The student uses a variety of sentence structures and is careful when selecting words. **The report is interesting to read.**

The following categories correspond to the document "Characteristics of a Good Lab Report." Please refer to that document for guidance on details expected in each section. Below, along with each category are specific expectations for this lab report.

Abstract and Title ____/10 pts

(For this report, your abstract should include your ultimate claim about how 3D glasses are constructed, and thus how they work. Whatever you claim here, you must back up with the rest of the report.)

Comments:

Introduction ____/10 pts

(Here you are welcome to pique the reader's interest however you'd like (3D technology, history, etc.).)

Comments:

Theory ____/10 pts

(In this section, you'll want to lay out the theory or ideas behind your plan for showing that the construction of the 3D glasses is what you will claim it is. Here's where you will begin to set up an understanding of why you've done the specific measurements you've done.)

Comments:

Procedure ____/20 pts

(There should be a detailed (but not necessarily step-by-step!) procedure and schematic for each investigation or experiment performed, unless it is easy to include multiple experiments into one description (i.e., "We performed the same measurements with the right and left lenses."). You may also choose to lump the Procedure and Data and Results sections together for each individual investigation, rather than all procedures first, then all data and analysis second.)

Comments:

Data and Results ____/30 pts

(This is the most substantial part of the report. Here is where you'll present the experimental evidence in the form of the raw data, calculated data, models, and plots. You'll also need to analyze your data, meaning you should describe what your data are showing and how they are convincing of your ultimate claim. Uncertainties and thoughtful discussion of random and systematic errors are a must.)

Comments:

Conclusion

____/10 pts

Comments:

Overall writing style

____/10 pts

(Your writing should logical and consistent and should “flow” in a readable and interesting way. Pitfalls to avoid: wordiness, excessive passive voice, technical-sounding words or jargon.)

Comments: