# BioOptics Corporation: An Investigative Interdisciplinary Case Study on the Eye

***Christopher C. Barney[1], Catherine Mader[2], Kathy A. Winnett-Murray[1], Lori Hertel[1] and Alan DeWeerd[3]***

[1] Department of Biology
Hope College
Holland, MI 49423
*barney@hope.edu*
*winnetmurray@hope.edu*
*hertel@hope.edu*

[2]Department of Physics
Hope College
Holland, MI 49423
*mader@hope.edu*

[3]Department of Physics
University of Redlands
1200 East Colton Ave.
Redlands, CA 92373
*alan_deweerd@redlands.edu*

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## Introduction

Physics is often required for biology majors, but rarely integrated into biology laboratories. The BIO2010 report states that "to successfully participate in theinterdisciplinary research of the future, biomedical scientists must be well versed in scientific topics beyond the range of traditional biology. Beginning exposure to these topics early is one key to educating biomedical researchers who deal easily with interdisciplinary research projects." (NRC 2003:13). This case study on vision was designed by an interdisciplinary team with the goal of exposing introductory biology students to the importance of physics in solving biological problems. In the laboratory portion of this exercise, students manipulate an optics bench apparatus equipped with various lenses, mirrors, and measurement devices, to investigate the effect of pinhole designs, lenses, and mirrors on the formation of images, the image quality, and the effect of distance between image and lens on vision. Each of these structural "designs" is related to a species that is equipped with a similar visual system. Newly equipped with these basic physical principles, student groups representing research teams of an imaginary company, BioOptics Corporation, are then challenged to explore scientific literature in order to solve one of three biological "problems": improving visual acuity, improving visual (light) sensitivity, or expanding the range of wavelengths detected in animals with color vision. Student teams give an oral presentation on the solution to their optics problem which includes additional information on visual systems of vertebrates. Included at the end of this exercise are data directed at assessing the goals driving the development of this lab – that students would better appreciate the integration of physical and biological concepts.

## Student Outline

**BioOptics Corporation: An Investigative Interdisciplinary Case Study on the Eye**

**Objectives**

- To learn about different approaches animals use to focus light on receptors cells.
- To learn the basics of image formation through experimentation.
    - Pinhole effects
    - Convex lenses
    - Concave mirrors
- To learn about biological photochemistry in light receptive cells.
- To learn about color vision.
- To learn about visual sensitivity and visual acuity.
- To learn about the dual nature of light.
- To further learn to integrate information from various sources and areas of science.
- To develop an approach to solving a complex scientific problem.
- To learn to find information needed to solve a scientific problem.
- To use what you have learned to suggest solutions to a scientific problem.
- To learn about the similarities and differences in how physics and biology approach a scientific

problem.
- To communicate what you have learned to others in an oral format.

**Introduction – The Case Study**

Welcome to BioOptics Corporation, the company that provides solutions to problems in biological optics. We are pleased that you have accepted our offer to join the first team of scientists to work for BioOptics. We believe that with our financial, scientific, and personnel resources, we can offer both private and public organizations time- and cost-effective solutions to their problems in biological optics. We have indicated in our initial publicity material that we can help enhance visual acuity, sensitivity and color perception in humans and other animals in both terrestrial and aquatic environments and that we can provide biological corrections to such problems as presbyopia, myopia, hyperopia, astigmatism, night blindness, color blindness, cataracts, diabetic retinopathy, glaucoma and traumatic injury to the eye. Unlike our competitors, we offer solutions based on genetic engineering using cloned cells with stem cell-like potentiality.

You have been assigned to the Basic Optics Division of BioOptics. As you know, the primary responsibility of the Basic Optics Division is to provide our other Divisions - Genetic Engineering, Biomaterials, Product Development, Manufacturing, and Client Relations - with background information on the complete range of biological optics applications ranging from Snell's law to the photochemistry of vision. Thus the Basic Optics Division is our primary research division in the area of optics. The management of BioOptics expects the Basic Optics Division to have the capability to respond to any question or need of our other divisions.

There are two initial tasks for the scientists of the Basic Optics Division. The first is to explain the geometrical optics of different types of optical systems used in the animal kingdom to focus light on photoreceptor cells and to provide an assessment of the advantages and disadvantages of each system. The second task is to explain the way in which photoreceptors transduce light energy into bioelectrical energy and how different animals arrange the photoreceptors and other components of their visual systems to optimize visual acuity, visual sensitivity, and color perception. This information will be used by the other Divisions at BioOptics to begin designing biological optical systems to optimize various visual abilities and to correct for various visual defects. Currently BioOptics has a contract with the U.S. Air Force to develop a biological system which will enhance visual acuity (the ability to see clearly/distinguish objects at far distances) in humans by 50%, a contract from Ophthalmology Solutions Inc. to develop recommendations for an approach to improve visual sensitivity (ability to see in low light levels), and a contract with EuroColor Associates to find a way to expand the range of wavelength sensitivity to either the infrared or ultraviolet in sheepherding dogs so that "invisible" dyes can be used to mark different sheep. As scientists in the Basic Optics Division you will provide our other Divisions with recommendations as to which systems in use by animals might be best modified to meet the needs of these clients. In six weeks, you will make a presentation to the other scientists of the Basic Optics Division on what you have learned and recommendations for approaches to solve the needs of one of these clients. You will need to bring to their attention questions for further study. You will be evaluated on the quality of the data you obtain from your experiments on optics and how you relate those data to a biological system, your understanding of photoreceptors, the rationale/information you use to support your recommendations, the quality of any questions you indicate still need to be answered by the Basic Optics Division, your ability to communicate with the rest of the Basic Optics team and your ability to

answer questions about your work.

For these initial Basic Optics problems, the Division has been divided into 5 or 6 teams of 4 members each; each team has been assigned a number from 1-6. First, all teams will perform experiments using the optical benches available in the Basic Optics Laboratories to investigate how pinholes can be used in optical systems. Pinholes are used in the visual systems of the chambered nautilus (F. Nautiliidae). Then groups 1, 3, and 5 will investigate the optics of lenses. Lenses are used by mammals and arthropods. Groups 2, 4, and 6 will investigate the optics of mirrors. Mirrors are used by animals such as clams and scallops. Following your laboratory work on optics, each team will use scientific literature and related internet sources to obtain information on various aspects of visual systems. Teams 1 and 2 will report on the advantages and disadvantages of the nautilus visual system. Teams 5 and 6 will report on the advantages and disadvantages of the scallop visual system. Teams 3 and 4 will report on the advantages and disadvantages of the vertebrate visual system. Each team should refer to the data obtained using the optical benches in its report. In addition, each team will learn about and be ready to answer questions regarding the basic functions of photoreceptors. Finally, teams 1 and 4 will report on the ways in which animals can perceive color and will suggest ways to expand the range of color sensitivity (The EuroColor Project). Teams 2 and 5 will report on how factors that determine visual sensitivity and suggest ways to maximize visual sensitivity (The Ophthalmology Solutions Inc. Project). Teams 3 and 6 will report on how animals control visual acuity and suggest ways to increase visual acuity (The U.S. Air Force Project). It should be stressed that these enhancements in visual ability must be of a biological nature not solely technological. Once you recommend a biological approach, our Genetic Engineering Division will start working on approaches to genetically modify visual systems. A summary of your assignments is given in table 1.

**Table 1. Basic Optics Division Team Assignments**

| Team/Lab Group | Optic Bench Task 1 | Optic Bench Task 2 | Visual System to Analyze | Basic Optics Division Problem |
|---|---|---|---|---|
| 1 | Pinhole | Lenses | Nautilus | EuroColor |
| 2 | Pinhole | Mirrors | Nautilus | Ophthalmology Solutions |
| 3 | Pinhole | Lenses | Vertebrate | U.S. Air Force |
| 4 | Pinhole | Mirrors | Vertebrate | Eurocolor |
| 5 | Pinhole | Lenses | Scallop | Ophthalmology Solutions |
| 6 | Pinhole | Mirrors | Scallop | U.S. Air Force |

**Part 1 – Geometrical Optics of Animal Optical Systems**

As indicated in the introductory material, as members of the Basic Optics Division you need to obtain experimental data that you will use to provide the other employees of BioOptics with an understanding of the optical systems of animals that use lenses, mirrors, or pinholes. You should use your laboratory notebook to draw sketches, to make graphs, and to summarize your findings, using the questions as a guide. Your goal should be to explain the basic principles of optics as observed in your experiments.

1. Setup

a. Position the light source that will serve as the "object" for all activities above the end of the optical bench (see Fig. 1). This will make it easier to measure distances. The scales on the benches are in centimeters.
b. Place the screen about 60 cm from the light source. Look at the screen from behind (the opposite side from the light source). What do you observe?


**Figure 1.** Position of optical bench and object light source.

c. Light goes out in all directions from each point on the object, as indicated in the diagram above. What light rays from the source actually strike the screen at the point P? How does this explain what you observed on the screen in step 1b?

P

2. Pinholes

a. Place pinhole #3 about 30 cm from the light source (Fig. 2). Sketch the image that appears on the screen. If the object looks as shown, what does the image look like? Identify points ***T*** and ***B*** on your sketch.

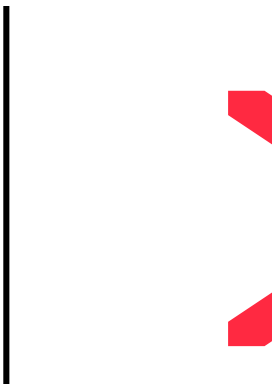

**Figure 2.** Top (T) and Bottom (B) of the light source.

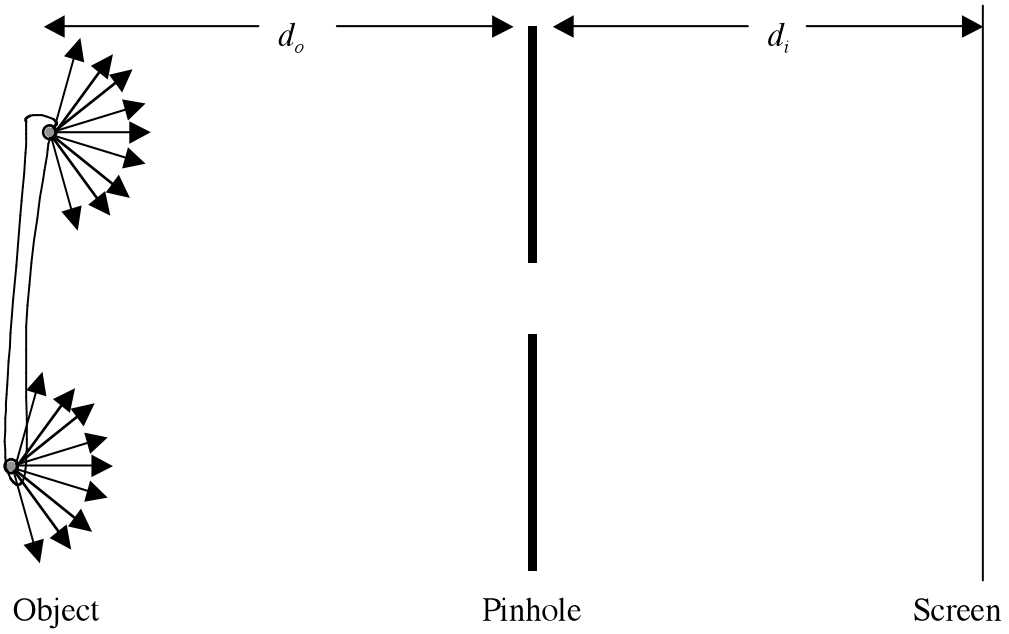


**Figure 3.** Draw how light rays from the object pass through the pinhole.

b. Sketch how the image gets formed. Concentrate on a point at the top of the object (point T) and one at the bottom (point ***B***). Which of the light rays make it through the pinhole and where do they strike the screen? Why do we see a clear image of the bulb on the s screen when this pinhole is present but not when the pinhole is removed?

c. Change the location of the screen. Does the image remain or vanish? How does the image change as you move the screen forward and backward? How is the size, brightness and sharpness (clarity) of the image affected by moving the screen? Look at the

sketch above and use it to describe your observations about how the image changes as the screen moves.

d. Now explore the image size quantitatively. The ratio between the image and object heights is called the magnification ($M=h_i/h_o$). How does the magnification depend upon the object and image distances? The object distance ($d_o$) is measured from the object to optical element (a pinhole, lens, or mirror) and the image distance ($d_i$) is the distance between the image and optical element. Measure the object distance and height as well as the image distance and height and record these data in your laboratory notebook. Calculate the magnification and record it as well. Repeat these measurements 4 times to obtain five measurements. Can you find a mathematical relationship between magnification, object distance and image distance? What is that relationship?

e. Return to object and image distances of about 30 cm. Try the other pinholes and record your observations about the image that is formed. How does the image change with the size of pinhole? Why? Explain with diagrams why the image changes. What are the advantages and disadvantages of a small pinhole? What are the advantages and disadvantages of a large pinhole?

f. With the largest pinhole in place, hold lens #3 just after the pinhole. Move the screen around. What are the advantages and disadvantage of using the lens? Draw several rays coming from one point on the object and passing through the lens onto the screen. What happens to those rays as they pass through the lens so that a clear image is formed?

**Lab teams 1, 3, and 5 should carry out the following investigations of lenses.**

3. Lenses
   a. Replace the holder for the pinhole with the clamp. Place lens #3 in the clamp.
   b. Position the lens and screen so that a clear image is produced.
   c. Cover up the bottom half of the lens with an index card. What happens to the image? Describe the size, brightness and clarity. Try covering other parts of the lens. Is there any particular part of the lens that produces a particular part of the image? What does each part of the lens do? You may find that the diagram you drew in step (2f) is helpful when trying to understand these observations.
   d. Change the object distance and adjust the screen so that a clear image is formed. Record the object distance ($d_o$), image distance ($d_i$) and image height ($h_i$). Repeat this process for five object distances. Make sure that images are in focus each time and be sure to measure the distances and heights each time. What happens when the object distance gets very small?
   e. Repeat step (3d) with two additional lenses. Make sure that images are in focus each time and be sure to measure the distances and heights each time. Record the lens number and note any differences in their shapes. How does the shape of a lens (e.g. thickness, concavity) affect the image distance and magnification for a given object distance?
   f. Borrow data from another lab group so that you have a full set of data for all five lenses.
   g. Graph the image distance (y axis) as a function of object distance (x axis) for each lens. Include the data for all lenses on a single graph. Be careful to use different colors and/or symbols to represent each lens so that you can look for patterns in the data.

**Lab teams 2, 4, and 6 should carry out the following investigations of mirrors.**

4. Mirrors

a. Replace the holder for the pinhole with a clamp. Place mirror #3 in the clamp.
b. Take the holder for the screen off of the track and place it beside the track between the object and mirror. The screen should be right next to the track, but should not block the light from the object as it travels to the mirror. Position the mirror and screen so that a clear image is produced on the edge of the screen close to the track. You may have to twist the mirror slightly as well as moving the screen.
c. Cover up the bottom half of the mirror with an index card. What happens to the image? Describe the size, brightness and clarity. Try covering other parts of the mirror. Is there any particular part of the mirror that produces a particular part of the image? What does each part of the mirror do? A diagram similar to the one you drew in step (2f) will be helpful when trying to understand these observations.
d. Change the object distance and adjust the screen so that a clear image is formed. Record the object distance ($d_o$), image distance ($d_i$) and image height ($h_i$). Repeat this process for five object distances. Make sure that images are in focus each time and be sure to measure the distances and heights each time. What happens when the object distance gets very small?
e. Repeat step (4d) with two additional mirrors. Record the mirror numbers and note any differences in their shapes. Make sure that images are in focus each time and be sure to measure the distances and heights each time. How does the shape of a mirror affect the image distance and magnification for a given object distance?
f. Borrow data from another lab group so that you have a full set of data for all four mirrors.
g. Graph the image distance (y axis) as a function of object distance (x axis) for each mirror. Include the data for all lenses on a single graph. Be careful to use different colors and/or symbols to represent each mirror so that you can look for patterns in the data.

**All teams should answer the following questions in your lab notebooks.**

5. In order to see an object clearly, a sharp image of it must be formed on the back of your eye, the retina. If you have "normal" vision, you are able to see objects clearly over a wide range of distances. Consider how you might design an eye using a lens if you did part 3 or a mirror if you did part 4. Refer to the data you took in part 3 or 4 (especially the graph you made in part 3g or 4g) to answer the following questions. If you have problems with these questions, see your lab instructor for some hints.

a. Suppose the shape of the lens/mirror is fixed. How could the eye adjust for objects at different distances?
b. Suppose the image distance is fixed (the retina is a constant distance from the lens/mirror). How could the eye adjust for objects at different distances?
c. What are the advantages and disadvantages of the possible eye designs in 5a and 5b?

**Part II – Oral Presentation on your BioOptics Vision Problem**

When you are done with Part I, ask you lab instructor for a handout. The handout contains information about the dual nature of light, links to Web sites on optics, eyes, and photoreceptors and a brief overview of phototransduction. Use the rest of the lab period and time outside of lab during the next weeks to work on your specific assignment for the BioOptics presentation, as given in Table 1. You can use the Web sites provided on the handout, other Web sites, textbooks available in the labs, and books and journals in your campus library to learn more about biological optics, photoreceptors, visual acuity, visual sensitivity, and color vision.

First you should record in your notebooks the general questions you need to answer. Then think of as many specific questions you can that will help you carry out your assigned task. Discuss these and record the ones you are going to work on in you laboratory notebook. Think about where you might find the answers to the various questions and how you will divide up the work in your team. Decide on a timeline for your project, including when you will meet and what you will do at each out-of-lab meeting. At the last of those meetings, you should prepare your PowerPoint presentation, decide who will do which parts of the presentation, and then **practice** giving your presentation several times.

Next, begin finding information about your assigned project. Be sure to share the information you find with your group members as each member should know about all the facets of your project. As you work on your project, make note of what additional optical and photoreception questions would need to be answered in order for the members of the other divisions of BioOp to be able to complete the project.

When you have obtained the answers you need for your project and have formulated recommendations for the other members of BioOptics, you should prepare your PowerPoint presentation. Your presentation is limited to 12 minutes and should include no more than 8 PowerPoint slides. Your first slide should include the title of your presentation, the names of the members of your lab group, the date of your presentation, your lab day and time, and your lab instructor's name. Note that PowerPoint slides are most effective when they contain bullet points and illustrations rather than large amounts of text. Note also that you should not use any font size smaller than 28 pt on your slides. You must send your PowerPoint presentation to your laboratory instructor before the day of your presentation.

Your presentation should include the following (suggested time for each section given at the end):

1. A description of the optical system of your assigned animal/group, the advantages and disadvantages of that system, and how what you learned in your optical bench experiments helps explain how that system works. Consider using data/graphs from your optic bench experiments for this description. (3 min)
2. An overview of the basic functions of photoreceptors and how those functions relate to visual sensitivity, visual acuity, or color vision, *depending on your BioOptics "challenge" assignment*. You should **not** present information on how light is converted into a generator potential in rod and cone cells (that is the role of rhodopsin and photopsin) but you may present information on how different wavelengths of light are sensed by different types of receptors and how the organization of photoreceptors and their connections to bipolar cells affect visual acuity and sensitivity as appropriate for your BioOptics challenge assignment. (3 min)
3. Recommendations on how to either expand the range of color sensitivity, maximize visual acuity, or increase visual sensitivity depending on your BioOptics "challenge" assignment. This

is the most important part of your report and will count the most toward your report grade! You should spend a significant amount of your presentation time on this recommendation and the supporting information. You should present information on two or three ways in which these visual improvements might be made, the advantages and disadvantages of each, which one your team recommends, and why. ( 5 minutes)

4. How physics and biology were involved in understanding vision and in preparing your report. (0.5 min)
5. Questions that still need to be answered. (0.5 min)
6. Sources of your information. (Although you can simply show your sources at the end of your presentation, your instructor will review them for accuracy, based on the copy of the PowerPoint presentation you have previously submitted).

## Materials

*Per group of 2-4 students:*

- one optical bench approximately 7 feet long (Instructions for construction are available from the optical bench pdf file included with this lab).
- one light box with bulb – instructions for construction are available from the light box pdf file included with this lab. For bulbs, asymmetrical shapes with different colors top vs. bottom are ideal (e.g. palm trees green on top and blue on the bottom, or dolphins blue on top, white on the bottom, etc.). We purchased palm tree and dolphin fluorescent bulbs at our local Wal-Mart in the party light bulb section.
- one meter stick and one mm ruler
- set of lenses (Table 2) in plastic box with lid for storage
- set of pinholes (Table 2) in plastic box with lid for storage
- set of mirrors (Table 2) in plastic box with lid for storage

*Per classroom:*

- Extra bulbs
- An extra set of lenses, mirrors and pinholes
- Computer and projection unit for student PowerPoint presentations

**Table 2. List of items needed to construct optical benches and light boxes.**

**Bio- Optics Optical Bench Order Information**
Supplier: Sargent Welch. Ph: 800-727-4368; Quantity is per bench (1 bench per group).

| Quantity | Catalog # | Item | Cost (12/07) |
|---|---|---|---|
| 1 | CP85801-01 | 115cm Advanced Optical Bench | $340.39 |
| 3 | CP85808-00 | Fixed carriage | $79.09 |
| 2 | CP72288-00 | Cenco lens and mirror clamp | $44.09 |
| 1 | WL3520-12 | Mirror concave 50mm dia, 150mm FL | $2.99 |
| 1 | WL3520-13 | Miror concave 50mmdia 200mm FL | $2.99 |
| 1 | WL3520-14 | Mirror concave 50mm dia, 300mm FL | $3.30 |
| 1 | WL3520-10 | Mirror concave 50mm dia 100mm FL | $2.99 |
| 1 | WL3411 | Lens CV 50mm dia 50mm FL | $3.60 |
| 1 | WL3411A | Lens CV 50mm dia 100mm FL | $3.60 |
| 1 | WL3411C | Lens CV 50mm dia 150mm Fl | $3.60 |
| 1 | WL3411D | Lens CV 50mm dia 200mm Fl | $3.60 |
| 1 | WL3413 | Lens CV 50mm dia 250mm FL | $3.60 |
| 1 | WL3413B | Lens CV 50mm dia 300mm FL | $3.60 |

Additional materials:

Screens: These are made from ¼'' foam core board, approx 33 cm wide by 25 cm tall. Our physics shop made metal frames to hold them and insert them into the carriages. Our physics department uses translucent screens so that the image can be viewed through the screen. These are made from translucent sheet protectors and transparency frames.

Pinhole holders: These are also made from ¼'' foam core board, approx 25 cm wide by 20 cm tall. A 26 mm hole is cut into the center. Stick on binder labels cut to about 2 1/2'' by 1 ¾'' to make the actual pinhole holder. Our physics shop made the frame to hold these and insert them into the carriages.

Pinholes: These are made from 3 x 5 blank index cards cut to 2" x 2". The holes in the centers measure 1/16 "(just a hole poked through) for #1, 1/8 " for #2, ¼ " for #3. These may be made with office supply store hole punchers.

Lens key: #1 = 50 mm FL , #2 = 100 mm FL, #3 = 150 mm FL, #4 = 200 mm FL, #5 = 250 mm FL, #6 = 300 mm FL.

Mirror key: #1 = 100 mm FL, # 2 = 150 mm FL, #3= 200 mm FL, # 4 = 300 mm FL

NOTE: See your Physics Lab instructors before buying any of this. They may have equipment that you can use. It does not matter if their lenses and mirrors are not identical to these.

## Notes to the Instructor

This case study can be used in introductory biology courses that focus at the level of the organism and in introductory physics courses, which include a section on geometrical optics. The results of the case study can be presented in written, oral, or poster formats. The case study involves the students working in teams in laboratory and out of laboratory settings. Teams of 2 to 4 students can be used. A single lecture on the eye in the physics course was used to set the stage for the case study in physics. A similar lecture could be used in the biology course. In physics, the student work on the case was performed and assessed in the laboratory; these two laboratory sessions coincided with the coverage of geometrical optics in the lecture portion of the course, which also came after the completion of physical optics (the wave nature of light and interference and diffraction). In anticipation of the case study in biology lab, the biology instructor gave a lecture on the human vision system the day before the case study was done in lab.

**Setting up the Equipment**

Instructions for construction of the optical bench units and associated light boxes are available as .pdf files with this laboratory. Instructors may decide to allow student teams to work through the Part I activities at their own pace, or to stop and monitor progress and understanding of the class periodically. *Lights in the classroom must be turned out* (as much as possible) in order to see images, and important differences in image quality, throughout Part I. We have found that the light provided by the fluorescent bulbs is sufficient for students to record results with all room lights turned out, and this greatly accentuates the images produced by this method. Once constructed and set up for the first time, this laboratory subsequently requires very little preparation – simply double-checking the bulbs and that each set of mirrors, lenses and pinholes is complete is sufficient. Optics benches have scales in centimeters and the bases have holes in the center to read distances, (if not, add or subtract 3 cm from the measurements at the ends of the base). The lighted object (e.g. palm tree bulb) should be centered over the zero mark on the optics bench. The screen can be viewed from either side; sometimes it is easier to view from the side opposite the light bulb. It is useful to demonstrate to students during pre-lab how to operate the clamp for lenses/mirrors (push down to

open it up), and the location of the mirrors, lenses, etc. Pinhole cards with different diameters may be taped to the holder one at a time. If pinhole #1 gets blocked, clear it with a pushpin. There are extra pinholes available in case some get lost.

**BioOptics "Challenge" Problems and Related Tasks for the Presentation**

Students may become confused that there are actually 3 separate tasks for the research that goes into their required presentation. One task is to derive a solution to the BioOptics "Challenge" problem (Table 1; E.g. the EuroColor problem). A second task is to conduct research on the biological mechanisms used by a particular animal group that will exemplify one of the 3 optics activities accomplished in Part I (pinholes, mirrors, or lenses). Students should directly relate the animal model to the optics activities investigated in Part I, but that particular animal's visual system may bring very little to bear on the BioOptics Challenge problem they were assigned. The two are not intended to be directly related. The goal of this part of the assignment is to have students "discover" some of the diversity that exists in visual systems of the animal kingdom, and that not all visual systems have similar costs and benefits. Students should be able to directly relate the 3 different optics systems (pinholes, mirrors, and lenses) to animal examples that use structures that function based on each of these 3 systems, *and/or on a combination of these 3 systems.* Third, all groups will be researching the basic functions of photoreceptors, and then relate that information to their particular BioOptics challenge question. These two aspects of the assignment should be directly integrated with one another. Specific assignments for Table 1 may be modified to suit an individual instructor's goals for the class.

**Supplementary Student Handout**

In our biology course, we distribute a handout entitled "The Dual Nature of Light" to our students *after* completion of Part I. This handout provides additional information on visual systems and includes a list of useful websites:

**Dual Nature of Light** (modified from Krane 1996)

To make sure everyone in the Basic Optics Division is up to speed, we provide below a review of the dual nature of light and basic information about energy transduction in photoreceptors. Remember, the wave nature of light is important in focusing the light on the photoreceptors and for color discrimination and the particle nature of light is important in converting the light energy into bioelectrical energy in the photoreceptor cells.

"Light is an electromagnetic phenomenon, and it is only part of a larger whole – a wide range of electromagnetic waves called the electromagnetic spectrum." The electromagnetic spectrum ranges from very long wavelength electromagnetic waves like radio waves down to very short wavelength electromagnetic waves like x-rays and g-rays. These electromagnetic fields are created by charged particles (for example, protons and electrons in atoms). When the charged particles accelerate, or change their velocities, the electromagnetic fields they produce also change their strength and direction and so if the charged particles vibrate back and forth, the electromagnetic field they produce will vibrate in a wavelike manner and these vibrations in the electromagnetic wave will move outwards from the

charge in all directions. As the waves move outward, they interact with the charged particles that they encounter, which can bend and deflect the electromagnetic waves just like buoys in the water will bend and deflect water waves. Typical sources of visible electromagnetic waves (light) are light bulb filaments in which the atoms in the filament are very hot and thus are vibrating in the solid very rapidly and thus create electromagnetic waves of a variety of wavelengths corresponding to the vibrational frequencies of the atoms in the solid.

Electromagnetic radiation can also be produced or absorbed in discrete packets of energy, rather than in the continuous wave-like pattern described above. For example, when an electron in an atom makes transitions from a higher energy level to a lower energy level, it also emits electromagnetic radiation as it changes its speed. In this case, the radiation produces is not in the classical wave-like form found in light bulbs, but rather in specific packets, called photons. These packets (called photons) are particle-like in nature. Photons have a well defined colors (quantitatively described by a wavelength or frequency), but behave like a particles following a specific trajectory away from the charged particle that produced the specific photon. As with all particles, photons can be deflected when they collide with other particles but they can also be absorbed by the particle.

The perplexing (at times) thing about light is that all electromagnetic waves exhibit both particle characteristics AND wave characteristics. In a sense, this is good. Because of the wave nature of light, electromagnetic waves propagate outward from objects and the light reaches sensory organs that focus the light and produce images of the objects. Because of the particle nature of light, the photons that strike the receptor cells in sensory organs can record that information by absorbing these photons that causes a chemical change in the receptor cell that eventually leads to another electromagnetic signal being transmitted to the brain!

**Photoreceptors**

This conversion of the electromagnetic energy of light into the electrochemical energy of the generator and action potentials in neurons is termed transduction. The cells responsible for this energy transduction are the photoreceptors. The photoreceptors in vertebrates are the rods and cones of the retina. In the rods, the visual pigment is rhodopsin. Rhodopsin is made of opsin, a protein that crosses the membrane of the rod cells seven times (a G-protein receptor) and a chromophore 11-cis-retinal. The retinal is produced from vitamin A. The amount of rhodopsin in the rod cells is increased by having stacks of cell membrane in a protruding outer segment derived from a ciliated cell. When a photon of light is absorbed by the retinal is photoisomerizes from the cis to the trans configuration. The trans-retinal has a lower binding affinity for the opsin than the cis-retinal and thus the trans-retinal dissociates from the opsin. The photoisomerization is reversible so if the retinal absorbs another photon of light before it dissociates it will convert back to the cis-retinal. Thus, all the trans-retinal does not dissociate from the opsin if there are high light levels. However, a bright flash of light can lead to so much trans-retinal being formed that photosensitivity is reduced for some time.

The conversion of cis-retinal to trans-retinal also causes changes in the conformation of the opsin that open up active sites. The active sites activate transducin, a G-protein. The activated transducin causes GTP to bind to one of the subunits of opsin, displacing GDP. That subunit then is freed and activates phosphodiesterase, which in turn inactivates cyclic GMP (cGMP). cGMP is made by guanylate cyclase and builds up in the rod cells in the dark. cGMP acts to open ion channels in the cell membrane which allow positively charged ions (primarily $Na^+$) to diffuse through the membrane. This is called the sodium current. As more of these ions move out of the cell than into the cell, the inside of

the cell becomes more positive. When the cGMP is inactivated by the phosophodiesterase (that was activated when the cis-opsin was converted to trans-opsin), the ion channels close and the sodium current decreases. The inside of the cell then becomes more negative or hyperpolarizes. The steps that cause the hyperpolarization are part of an amplification cascade such that each activated opsin activates about 500 transducins and each transducin inactivates several thousand cGMPs. Thus a single photon of light can greatly alter sodium influx into the cell.

The hyperpolarization of the rods causes the rods to reduce the release of the neurotransmitter glutamate. Normally the glutamate is released from the synaptic terminal of the rods and acts on bipolar cells. The glutamate inhibits bipolar cells. So when the glutamate levels fall, the bipolar cells are activated. Several rods synapse with the same bipolar cell so that the bipolar cell can add/integrate the input. This helps improve light sensitivity since low light levels affecting several rods can be enough to activate the bipolar cell. The bipolar cells then activate the ganglion cells which transmit action potentials into the brain via the optic nerve. In addition, the retina contains amacrine and horizontal cells, which play important roles in increasing contrast and responding to movement.

The effect of light on the output of the rods is terminated by the enzymatic breakdown of the GTP attached to the opsin subunit. When the GTP is converted to GDP the opsin subunit then rebinds to the other subunits and the phosphodiesterase is inactivated. This leads to an increase in cGMP and a reopening of the sodium channels. In addition, an isomerase enzyme in the rods converts the trans-retinal back into cis-retinal (a slow process) which then reattaches to the opsin making the rhodopsin photosensitive. Note that in darkness, the rate of cis-retinal production is greater than the rate of breakdown so more and more rhodopsin is produced leading to increased sensitivity to low light levels.

The cones of the retina work in much the same way as the rods, except that different opsins are used. This leads to differences in which wavelengths are absorbed by the cis-retinal. Some cones are most sensitive to blue light, some to red light, and some to green light. All the colors a person perceives are due to different combinations of cone activation. It takes more photons to activate cones than rods and fewer cones synapse with the same bipolar cells. Thus higher light levels are needed to see colors. This gives rise to the saying "All cats are black at night." On the other hand, cones provide better visual acuity than do rods, particularly at the fovea which consists of tightly packed cone cells.

Photoreception in invertebrates demonstrates several differences from vertebrates. Retinal does not dissociate from opsin in invertebrates when light is absorbed but changes to the opsin still occur. In invertebrates light leads to an influx of positive ions into the photoreceptor cells which causes the cells to hypopolarize rather than hyperpolarize as in vertebrates and this occurs through the use of phospholipase C rather than phosphodiesterase.

**Web Sites You May Find Useful**

**Optics**

http://www.physics.pomona.edu/sixideas/sioptc.html
http://micro.magnet.fsu.edu/primer/anatomy/anatomy.html
http://www.colorado.edu/physics/phet/web-pages/simulations-base.html specifically:
http://www.colorado.edu/physics/phet/simulations/lens/lens.swf and
http://www.colorado.edu/physics/phet/simulations/colorvision3/colorvision3.jnlp

**General and Biological Optics**

http://soma.npa.uiuc.edu/courses/bio303/Ch11b.html
www.iop.org/EJ/article/0031-9120/41/1/F03/pe6_1_f03.pdf
http://ebiomedia.com/gall/eyes/eye1.html

http://www.stanford.edu/group/fernaldlab/pubs/2000%20Fernald%20Evolution%20of%20eyes.pdf
http://www.anu.edu.au/BoZo/BIOL1005/Land%20Optics%20Primer.pdf
http://www.tedmontgomery.com/the_eye/index.html
http://www.maayan.uk.com/evoeyes1.html

**Photoreception Systems**

http://www.chemsoc.org/exemplarchem/entries/2002/upton/start.htm
http://www.cals.ncsu.edu/course/ent425/tutorial/photo.html
http://webvision.med.utah.edu/photo1.html
http://retina.anatomy.upenn.edu/~lance/retina/
http://hyperphysics.phy-astr.gsu.edu/hbase/vision/rodcone.html

**Topics**

Vision, Optics, Comparative Anatomy of Eyes, Graphing, Problem Solving, Optical Benches, Light, Graphing, Oral/Poster Presentations

**Answers and Sample Results for Part I: Geometrical Optics of Animal Optical Systems**

Part I usually requires about 2 hours of a 3-hour lab. We use the remaining hour to allow student teams to begin organizing and creating a plan for the research they will undertake.

1. Setup
    a. Position the light source which will serve as the "object" for all activities above the end of the optical bench. This will make it easier to measure distances. The scales on the benches are in centimeters.
    b. Place the screen about 60 cm from the light source. Look at the screen from behind (the opposite side from the light source). What do you observe?

        *There will be no distinct pattern on the screen. It will look blue-green (diffuse mixture of colors of whatever bulb is used).*

    c. Light goes out in all directions from each point on the object, as indicated in the diagram above. What light rays from the source actually strike the screen at the point P? Discuss how this explains what you observed on the screen in step 1b.

        *The screen looks blue-green because light from both blue (bottom) and green (top) parts of the object get to each part of the screen (see Fig. 4).*

2. Pinholes
    a. Place pinhole #3 about 30 cm from the light source. Sketch the image that appears on the screen. If the object looks as shown, what does the image look like? Identify points ***T*** and ***B*** on your sketch.

        *The image originally shown in Fig. 2 is inverted as shown to the right. Both top & bottom and right and left are reversed.*

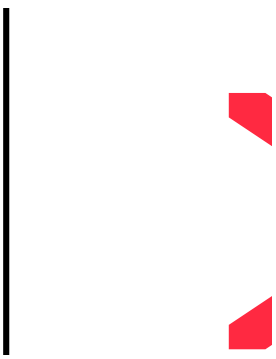

**Figure 2.** Top (T) and Bottom (B) of the light source, reversed in both planes.

*b.* Sketch how the image gets formed. Concentrate on a point at the top of the object (point ***T***) and one at the bottom (point ***B***). Which of the light rays make it through the pinhole and where do they strike the screen? Why do we see a clear image of the bulb on the screen when this pinhole is present but not when it pinhole is removed? *As shown in Fig. 4, the light from the top point that makes it through the pinhole hits the bottom of the screen (and vice versa). Because of the pinhole, light from each point on the object only hits a small area on the screen which is why a relatively clear image is formed.*

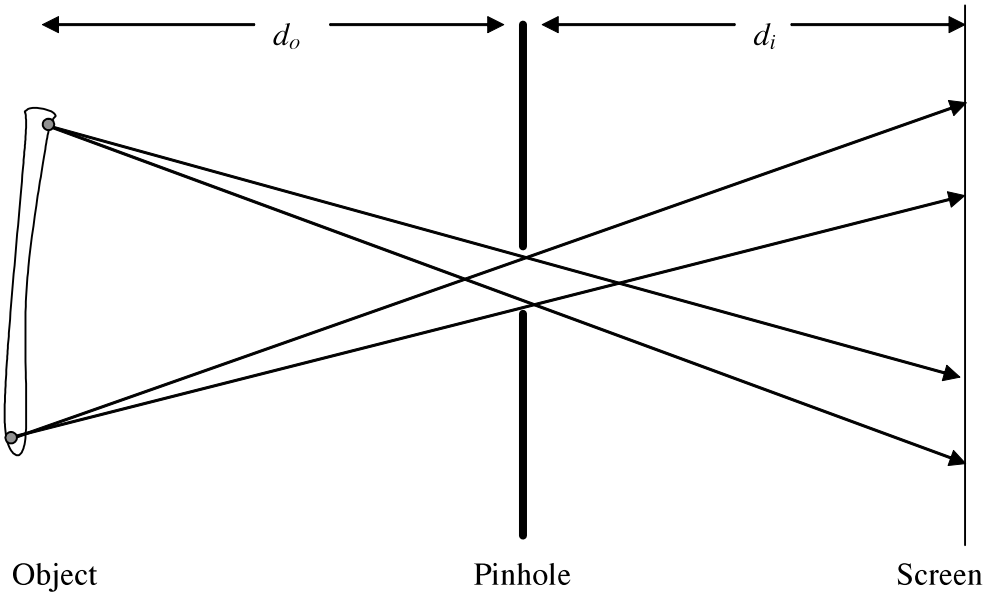


**Figure 4.** Pathway of sample light rays traveling from light source (object) through a pinhole to the screen.

c. Change the location of the screen. Does the image remain or vanish? How does the image change as you move the screen forward and backward? Discuss the size, brightness and sharpness (clarity) of the image. Look at the sketch above and use it to describe your observations about how the image changes as the screen moves.

*The image gets brighter and smaller as the screen gets closer, or dimmer and larger as it gets farther away. The sharpness of the image does not change (even though it gets easier to see when it is brighter). In Fig. 4, if the screen is closer the light from the top and bottom will not have spread out as much before it hits the screen. That explains why the image is smaller and brighter.*

d. Now explore the image size quantitatively. The ratio between the image and object heights is called the magnification (***M=h$_i$/h$_o$***). How does the magnification depend upon the object and image distances? The object distance (***d$_o$***) is measured from the object to optical element (a pinhole, lens, or mirror) and the image distance (***d$_i$***) is the distance between the image and optical element. Measure the object distance and height as well as the image distance and height and record these data in your laboratory notebook. Calculate the magnification and record it as well. Repeat these measurements 4 times to obtain five measurements. Can you find a mathematical relationship between magnification, object distance and image distance? What is that relationship?

*The students should find that the magnification (M=hi/ho) is equal to the ratio of the image distance over the object distance. Students who have take physics before may recall that:*

$$M = \frac{h_i}{h_o} = \frac{-s_i}{s_o}$$

*Technically, the height of the image is considered negative if it is inverted, but this is not important for the current "biology" lab. .*

e. Return to object and image distances of about 30 cm. Try the other pinholes and record your observations about the image that is formed. How does the image change with the size of pinhole? Why? Explain with diagrams why the image changes. What are the advantages and disadvantages of a small pinhole? What are the advantages and disadvantages of a large pinhole?

*The image gets clearer and dimmer as the pinhole gets smaller. If the diagram from step 2b is redrawn with a smaller pinhole, the light from each point reaches a smaller area on the screen. That makes the image clearer because light from different points on the object doesn't overlap as much on the screen. However, the smaller hole lets less light through, so the image is dimmer.*

*A small pinhole gives a clear image, but a large pinhole gives a bright image.*

f. With the largest pinhole in place, hold lens #3 immediately after the pinhole. Move the screen around. What are the advantages and disadvantage of using the lens? Draw several rays coming from one point on the object and passing through the lens onto the screen. What happens to those rays as they pass through the lens so that a clear image is formed?

*The advantage of the lens is that the image can be made both bright and clear at the same time. The disadvantage is that the screen must be in a certain location for the image to be sharp. The light from each point on the object that passes through the lens is redirected to a single point on the image, rather than spreading out (see Figs. 5, 6).*

Figure 5 is a repeat of the original pinhole diagram (Fig. 3) from step (2b). Figure 6 is how the sketch should be modified because the lens is in place. Note that we have only shown the behavior of the top rays to simplify the diagram.

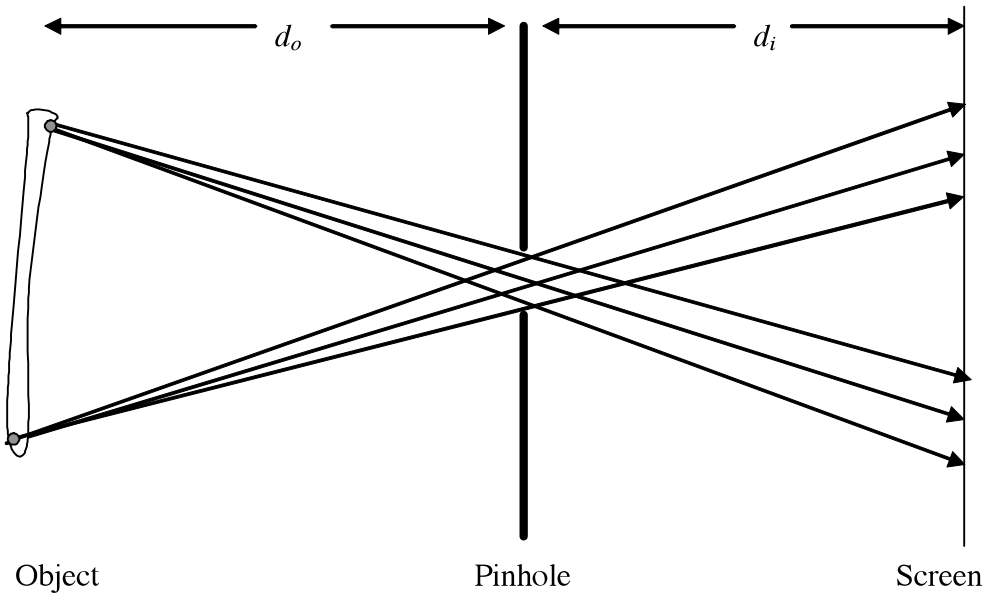


**Figure 5.** Path of light rays from an object to the screen through a pinhole.

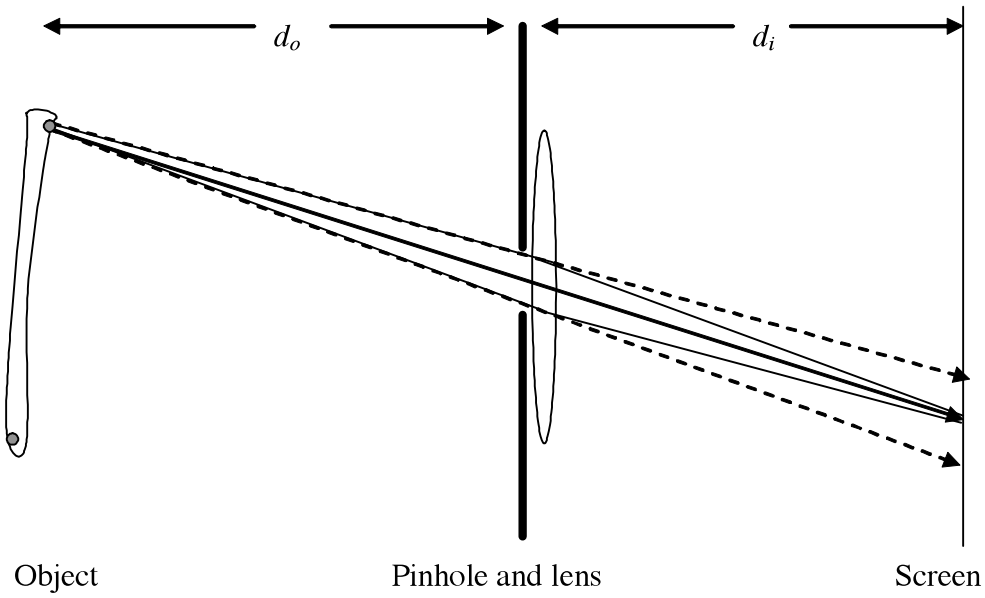


**Figure 6.** Path of light rays originating from near the top of an object as they pass through a pinhole and a lens to a screen.

**Lab teams 1, 3, and 5 should carry out the following investigations of lenses.**

3. Lenses
    a. Replace the holder for the pinhole with the clamp. Place lens #3 in the clamp.
    b. Position the lens and screen so that a clear image is produced.
    c. Cover up the bottom half of the lens with an index card. What happens to the image? Describe the size, brightness and clarity. Try covering other parts of the lens. Is there any particular part of the lens that produces a particular part of the image? What does each part of the lens do? You may find that the diagram you drew in step (2f) is helpful when trying to understand these observations.

        *The image will get dimmer when part of the lens is covered, but the whole image will remain. No part of the lens forms a particular part of the image. As shown in Figure 6 for part 2f, all of the light from a point that reaches the lens gets redirected to a single point on the screen.*

    d. Change the object distance and adjust the screen so that a clear image is formed. Record the object distance (***$d_o$***), image distance (***$d_i$***) and image height (***$h_i$***). Repeat for five object distances. What happens when the object distance gets very small?

        *When the object distance gets too small (less than about 15 cm for lens #3), there is no longer an image formed on the screen.*

    e. Repeat step (3d) with two additional lenses. Record the number of the lenses used and note

any differences in their shapes. How does the shape of a lens affect the image distance and magnification for a given object distance?

*For the same object distance, a more curved lens will form an image at a smaller image distance and it will have a smaller magnification.*

f. Borrow data from another lab group so that you have a full set of data for all five lenses.

g. Graph the image distance as a function of object distance for each lens. Include the data for all lenses on a single graph. Be careful to use different colors and/or symbols to represent each lens so that you can look for patterns in the data.

*Each axis should range from 0 to 100 cm. As distance to the object decreases (near vision), a "fatter", more convex lens (one that decreases the distance between the lens and the image) is required to bring the object into focus on the screen. At greater object distances, a larger distance between lens and image is required to achieve focus.*

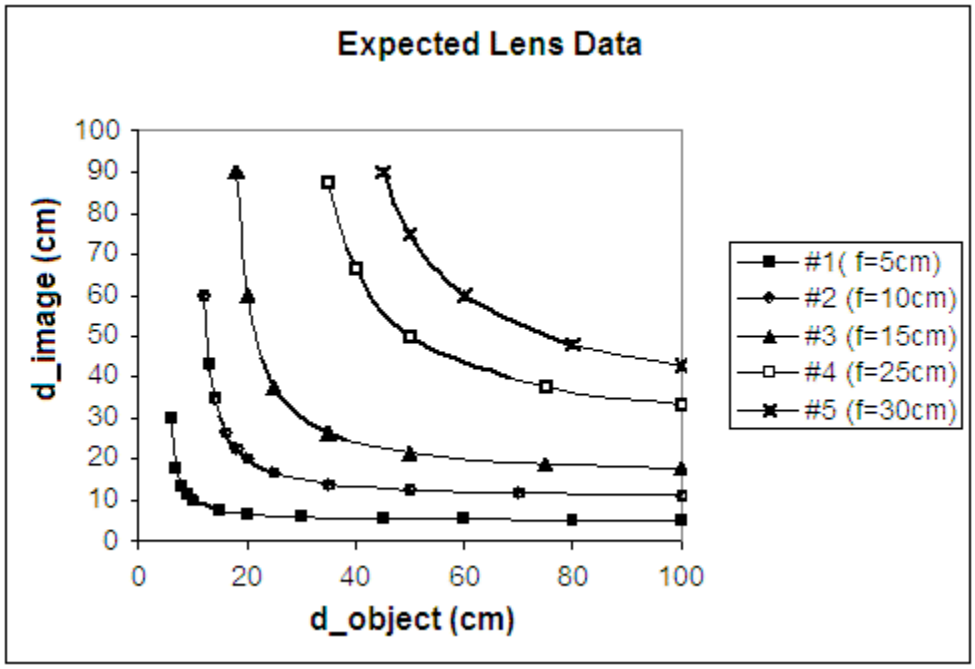


**Figure 7.** Sample data for image distance (y axis) as a function of object distance (x axis) for different lenses.

**Lab teams 2, 4, and 6 should carry out the following investigations of mirrors.**

4. Mirrors
   a. Replace the holder for the pinhole with clamp. Place mirror #3 in the clamp.
   b. Take the holder for the screen off of the track and place it beside the track between the object and the mirror. The screen should be right next to the track, but should not be between the object and the mirror. Position the mirror and screen so that a clear image is produced on the

edge of the screen close to the track. You may have to twist the mirror as well as moving the screen.

c. Cover up the bottom half of the mirror with an index card. What happens to the image? Describe the size, brightness and clarity. Try covering other parts of the mirror. What does each part of the mirror do? Is there any particular part of the mirror that produces a particular part of the image? A diagram similar to the one you drew in step 2f will be helpful when trying to understand these observations.

*The image will get dimmer when part of the mirror is covered, but the whole image will remain. No part of the mirror forms a particular part of the image. As shown in Figure 8, all of the light from a point that reaches the mirror gets redirected to a single point on the screen.*

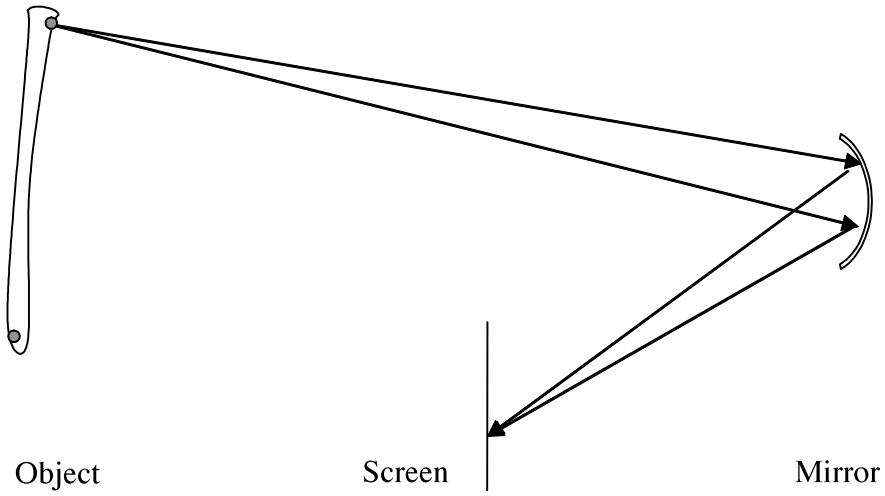


**Figure 8.** Light rays traveling from part of an object that encounter a mirror are reflected

d. Change the object distance and adjust the screen so that a clear image is formed. Record the object distance ($d_o$), image distance ($d_i$) and image height ($h_i$). Repeat for five object distances. What happens when the object distance gets very small?

*When the object distance gets too small (less than about 30 cm for mirror #3), there is no longer an image formed on the screen.*

e. Repeat step (4d) with two additional mirrors. Record the number of the mirrors used and note any differences in their shapes. How does the shape of a mirror affect the image distance and magnification for a given object distance?

*For the same object distance, a more curved mirror will form an image at a smaller image distance and it will have a smaller magnification.*

f. Borrow data from another lab group so that you have a full set of data for all four mirrors.

g. Graph the image distance as a function of object distance for each mirror. Include the data for all mirrors on a single graph. Be careful to use different colors and/or symbols to represent each mirror so that you can look for patterns in the data.

*The axis for the object distance should range from 0 to 100 cm. The axis for the image distance may go slightly higher that 100 cm, depending on the data.*

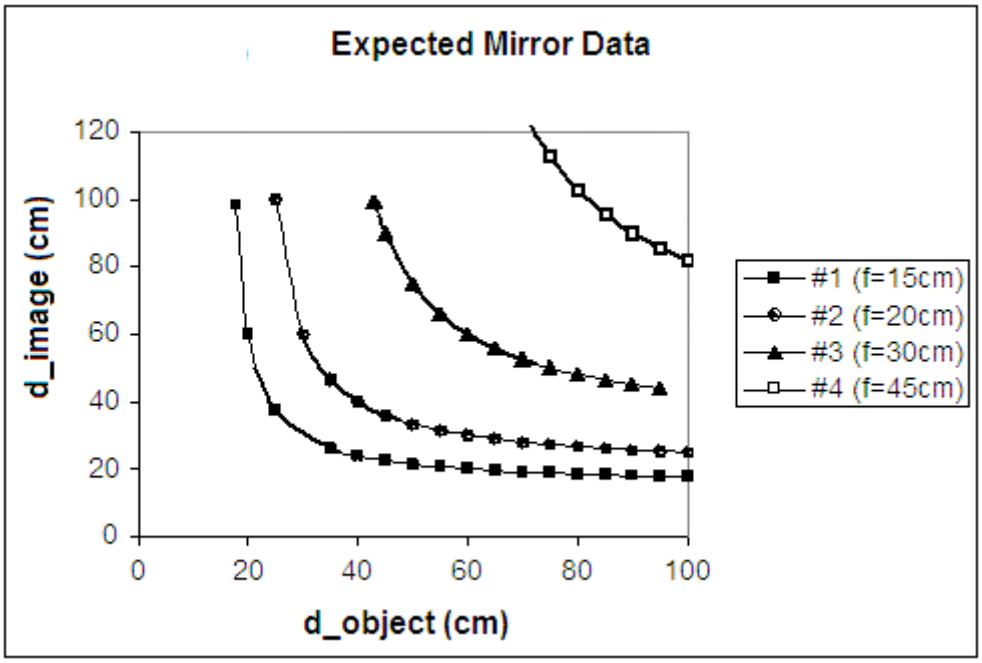


**Figure 9.** Sample data for image distance (y axis) as a function of object distance (x axis) for different mirrors.

All groups should do the following part:

5. In order to see an object clearly, a sharp image of it must be formed on the back of your eye, the retina. If you have "normal" vision, you are able to see objects clearly over a wide range of distances. Consider how you might design an eye using a lens if you did part 3 or a mirror if you did part 4. Refer to the data you took in part 3 or 4 (especially the graph you made in part 3g or 4g) to answer the following questions.

   a. Suppose the shape of the lens/mirror is fixed. How could the eye adjust for objects at different distances?

   *For a fixed lens/mirror shape, consider the data for a single lens/mirror. As the object distance changes, the image distance (from the lens/mirror to the retina) would also have to*

*change to keep the image clear.*

b. Suppose the image distance is fixed (the retina is the same distance from the lens/mirror). How could the eye adjust for objects at different distances?

*Draw a horizontal line (fixed image distance) on the graph from 3g or 4g. For different object distances, a different shaped lens/mirror is required to form a clear image.*

c. Discuss the advantages and disadvantages of the possible eye designs in 5a and 5b.

**Assessment**

This laboratory was first implemented in Biology 260 (Organismal Biology, second introductory course for biology majors) and in Physics 106 (College Physics II) at Hope College. In the biology course, students were assessed for their conceptual/content understanding in three ways. The first was an assessment of their laboratory notebook pages in which they responded to the questions in Part I and sketched graphs and diagrams of their findings as they manipulated the components of the optical bench set-up. The second assessment was of the students' oral presentations (Part II). A sample gradesheet for that assessment follows in Table 3.

**Table 3. Sample Gradesheet for Biology 260: BioOptics Presentations**

Names: _____
Time and Instructor: _____
Topics/Problem: _____

**Oral Presentation Grading Sheet**

| Category | Pts. | Score | Comment |
|---|---|---|---|
| Clear statement of question – **problem** to be solved | 1 | | |
| 1**. Background information** was cited appropriately & was thorough; background information clearly presented and put into context of the problem to be solved | 2 | | |
| 2. Presenters **understand the integration of biology and physical science** in the background information and convey that understanding clearly and in an integrated manner. | 2 | | |
| 3. Presenters demonstrate **effective use of overheads/powerpoint** to convey important/complex ideas. | 1 | | |
| 4. **Overheads/slides** are clear, organized and easy to understand. | 1 | | |
| 5**. Presenters connect** animal part of presentation to data actually collected in lab, where appropriate. | 3 | | |
| 6**. Presenters demonstrate understanding of comparative animal visual systems**. | 2 | | |
| 7. Presenters use background research to **propose a plausible, novel case study solution** and demonstrate excellent understanding of how the research of others provides a framework for the novel solution they propose. | 3 | | |
| 8. The solution proposed is **realistic**, given the current state of knowledge in biology, physics, other science. | 2 | | |
| 9. Presenters demonstrate an understanding of how both **biological and physical principles interact in their** | 2 | | |

| | | | |
|---|---|---|---|
| **proposed solution.** | | | |
| 10**. Presenters demonstrate excellent understanding of what the limitations** of their proposed solution might be, & how they might anticipate, trouble-shoot, or solve these. | 2 | | |
| 11**. Clarity of presenters and adherence to time limit.** | 2 | | |
| 12. Ability of presenters to **respond to audience/instructor questions** thoroughly. | 2 | | |
| **Total** | 25 | | |

The third assessment method consisted of questions on a lab practical exam. Those questions were as follows:

1. Multiple "solutions" for the case study problems tackled by BioOptics Corporation were presented by teams of scientists a few weeks ago. Listed below are 6 different solutions for potential optical problems. On your answer for each question, write one letter that corresponds to the problem that would best be solved by that solution. (More than one correct answer was accepted for some questions).

A. Enhance visual acuity in humans
B. Improvement
C. Expand the range of wavelength sensitivity in sheepherding dogs

1a. Bio-engineer subjects/patients with additional types of photopsins.
1b. Use laser eye surgery to reshape the cornea to assist in focusing light onto the retina.
1c. Increase the concentration of cones within the fovea.
1d. Bioengineer/selectively breed for a longer eye (anterior to posterior aspect).
1e. Addition of mirror-like reflective structures or surfaces behind the retina.
1f. Fill in the fovea centralis with rods.

2. Examine the optical set up in front of you. Then answer the following questions.

a. Explain why the image on the retina (the screen) is inverted, in terms of light rays passing through the pinhole. You may include a labeled sketch if you wish.

b. What anatomical structure functions as a pinhole in the human eye?

3A. What animal was investigated because it demonstrated the type of image-making system modeled in this set up?
3B. In that animal, what specific structures are the "mirrors"?
3C. What physical property of the mirror is associated with the ability to focus on objects that are closer to the eye?

In addition to the evaluation of the students' work on the BioOptics case study, we carried out a Student Assessment of Learning Gains (SALG) survey in both courses during the first year. The results of that survey are included as a .doc file entitled "BioOptics SALG 2007.doc".

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## Further Reading

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