Active Learning in Optics and Photonics

Training Manual

United Nations
Educational, Scientific, and
Cultural Organization

The International Society
for Optical Engineering

ACTIVE LEARNING IN OPTICS AND PHOTONICS

TRAINING MANUAL

Edited by

David R. Sokoloff
University of Oregon, USA

Contributing authors

Zohra Ben Lakhdar
University El Manar, Tunisia

Ivan B. Culaba
Ateneo de Manila University, Philippines

Vasudevan Lakshminarayanan
University of Missouri-St. Louis, USA

Joel T. Maquiling
Ateneo de Manila University, Philippines

Alex Mazzolini
Swinburne University of Technology, Australia

David R. Sokoloff
University of Oregon, USA

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FOREWORD

The International Year of Physics 2005 brought the issue of physics teaching to the attention of the public. The importance of physics education for sustainable development was emphasized at the World Conference on Physics and Sustainable Development (31 October to 2 November 2005, Durban, South Africa). In order to address the situation in university physics teaching in many countries, especially in the developing world, UNESCO has organized trainers' training activities promoting innovative approaches to teaching and student learning, in particular activity-based methods that engage students in the learning process. In order to communicate the excitement and joy of physics discoveries, UNESCO workshops foster the use of laboratory work and hands-on activities in physics classes. Teacher participants in the workshops are offered not only the opportunity to learn about innovative modes of content delivery but also the chance to improve their conceptual understanding of physics. Women physics instructors are especially encouraged to participate. In particular, the UNESCO project in optics education, *Active Learning in Optics and Photonics (ALOP)*, aims to better equip university and high school teachers to teach optics in the introductory physics course. The project focuses on an experimental physics area that is relevant and adaptable to research and educational conditions in many developing countries. This training manual was designed as an accompanying material to the ALOP workshop and is available for distribution free of charge. The international team of resource persons who facilitate the workshops developed the modules and the hands-on activities. The activities use simple and inexpensive materials, and materials that can be fabricated locally, whenever possible. The manual also includes a complete Teacher's Guide and an assessment instrument, the *Light and Optics Conceptual Evaluation* that has been developed to measure student learning of optics concepts.

This foreword provides me with the opportunity to express deep gratitude, on behalf of UNESCO, to the international team of resource persons who has made this endeavour possible. Sincere thanks to the International Society of Optical Engineering and the Abdus Salam International Centre for Theoretical Physics for believing in and supporting the project since its inception.

W. Erdelen
Assistant Director-General for Natural Sciences
UNESCO

Project Working Group:

Minella Alarcon, Eugene Arthurs, Zohra Ben Lakhdar, Ivan Culaba, Gallieno Denardo, Vasudevan Lakshminarayanan, Joel Maquiling, Alex Mazzolini, Joseph Niemela, David Sokoloff

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Introduction

INTRODUCTION

Improvement of science education is a significant need that has received considerable attention throughout the world. The challenges, while great in the developed world, are even greater in the developing world where well-trained teachers, effective materials and even the most basic scientific equipment and supplies are often in short supply. In its efforts to promote creativity and innovations in the way introductory physics is taught at the university level, UNESCO has supported activities in different developing countries to address the need for teacher upgrading and to introduce innovative learning approaches.[1-3] In recent years, the focus in workshops for teacher trainers has been on the *active learning* approach. This has included the development of teaching and learning materials that incorporate this approach. The introduction of active learning in physics in developing countries is especially encouraged by UNESCO because it fosters hands-on laboratory work, promotes conceptual learning and encourages instructors to do research in physics education that may lead to a significant improvement in their students' learning. The goal of these active learning UNESCO projects is to foster the implementation of student-centered, minds-on, hands-on learning as much as possible in introductory physics courses.

Why Active Learning?

Active learning in physics, developed over the last decade, has been demonstrated in the United States and other developed countries to enhance student understanding of basic physics concepts. In this learning strategy, students are guided to construct their knowledge of physics concepts by direct observations of the physical world. Use is made of a learning cycle including predictions, small group discussions, observations and comparison of observed results with predictions. (This learning cycle can also be represented as *PODS*—*P*rediction, *O*bservation, *D*iscussion and *S*ynthesis.) In this way, students become aware of the differences between the beliefs that they bring into the introductory physics classroom, and the actual physical laws that govern the physical world. An evolving product of many years of physics education research, the active learning method has been demonstrated to measurably improve conceptual understanding.[4-10] It reproduces the scientific process in the classroom and aids in the development of good physical reasoning skills. Table I-1 compares the characteristics of active learning environments to traditional (passive) environments.

Table I-1: Passive vs. Active Learning Environments

Passive Learning Environment	Active Learning Environment
Instructor (and textbook) are the authorities--sources of all knowledge.	Students construct their knowledge from hands-on observations. Real observations of the physical world are the authority.
Students' beliefs are rarely overtly challenged.	Uses a learning cycle in which students are challenged to compare predictions (based on their beliefs) to observations of real experiments.
Students may never even recognize differences between their beliefs and what they are told in class.	Changes students' beliefs when students are confronted by differences between their observations and their beliefs.
Instructor's role is as authority.	Instructor's role is as guide in the learning process.
Collaboration with peers often discouraged.	Collaboration and with peers is encouraged.
Lectures often present the "facts" of physics with little reference to experiment.	Results from real experiments are observed in understandable ways.
Lab work, if any, is used to confirm theories "learned" in lecture.	Laboratory work is used to learn basic concepts.

Of critical importance is the change in the role of the instructor when active learning materials are introduced into the classroom. In both the developed and developing worlds, it can be challenging for a physics instructor to pull back from her/his traditional role of explaining everything as the authority, to a role as guide through active learning materials. For this transition to be successful requires acceptance of the evidence that introductory students often do not learn effectively even from the most logical explanations by their instructors, and faith in the effectiveness of active learning materials in teaching concepts. The ease of this transition is dependent not only on a willingness to give up the role of authority, but also on a number of cultural factors that differ from country to country. This is the ultimate challenge in presenting active learning training workshops in different parts of the developing world, and is one important reason why recruitment and training of local trainers has been incorporated into this project.

Active Learning Labs and Interactive Lecture Demonstrations

Examples of active learning materials in the developed world include materials from the *Physics Suite*, published by John Wiley and Sons.[11] These include hands-on laboratory materials like *RealTime Physics*[12] (from which parts of Module 1 in this Training Manual are adapted). In their original forms, these materials make heavy use of technology, especially microcomputer-based tools and modelling software. With such tools and curricula, it has been possible to bring about significant changes in the laboratory learning environment at a large number of universities, colleges and secondary schools in the developed world, without changing the lecture/laboratory structure and the traditional nature of lecture instruction.[4-5] In addition, workshop materials, like *Workshop Physics*[10,13] have also been developed. While *Workshop Physics* has been demonstrated to be very effective, its implementation requires a complete restructuring of the introductory course (including the elimination of lectures). Therefore, its use is somewhat limited in both the developed and developing worlds.

While laboratory-based active learning approaches have been demonstrated to be successful in the U.S. (and parts of the developed world), and there is considerable evidence that traditional approaches are ineffective in teaching physics concepts,[4-10] most physics students in the world continue to be taught in lectures, often in large lectures with more than 100 students. To improve learning without significantly changing the structure of the introductory course, it is also necessary to design a strategy to make learning in large (and small) lectures more active. Physics education research work, primarily at the University of Oregon and at Tufts University (in the United States), has led to the development of a teaching and learning strategy called *Interactive Lecture Demonstrations* (*ILDs*) to improve conceptual learning in lectures.[14-15] A procedure for *ILDs* has been formalized that is designed to engage students in the learning process and, therefore, convert the usually passive lecture environment to a more active one. Table I-2 lists the eight steps of the procedure.

Student involvement in understanding these simple conceptual demonstrations is obvious from observations in the classroom. Most students are thoughtful about the individual prediction called for in step 2, and the small group discussions (step 3) in a large lecture class are initially quite animated and "on task." In time, however, the prediction will be made and the discussions may begin to stray into extraneous matters. The instructor must observe the students carefully, and pick an appropriate time to move to the next step.

Step 4 is facilitated by using a transparency made from the Prediction Sheet, and sketching student predictions using different colored pens. This is a brainstorming activity, and no commentary should be made as to whether a prediction is correct or incorrect. If no students volunteer predictions that represent the common misconceptions for a demonstration, the instructor may want to record these, saying that “a student in my last class made this prediction." The purpose of this step is to help validate all the predictions made by students in the class. It can also be supplemented by taking a vote after all predictions are recorded. When time is short, the instructor may skip this step.

Table I-2: The Eight Step Interactive Lecture Demonstration Procedure

1. The instructor describes the demonstration and—if appropriate—does it for the class without measurements displayed.
2. The students are asked to record their individual predictions on a Prediction Sheet, which will be collected, and which can be identified by each student's name written at the top. (The students are assured that these predictions will not be graded, although some course credit is usually awarded for attendance and participation at these *ILD* sessions.)
3. The students engage in small group discussions with their one or two nearest neighbors.
4. The instructor elicits common student predictions from the whole class.
5. The students record their final predictions on the Prediction Sheet.
6. The instructor carries out the demonstration with results clearly displayed.
7. A few students describe the results and discuss them in the context of the demonstration. Students may fill out a Results Sheet, identical to the Prediction Sheet, which they may take with them for further study.
8. Students (or the instructor) discuss analogous physical situation(s) with different "surface" features. (That is, different physical situation(s) based on the same concept(s).)

Notice that in steps 7 and 8 it is the instructor's task to get *students* to give the desired answers. The instructor must have a definite "agenda," and must often guide the discussion toward the important points raised by the individual *ILDs*. The instructor should *avoid lecturing to the students*. The discussion should use the experimental results as the source of knowledge about the experiment. If students have not discussed everything that is important, then the instructor may need to fill in the gaps.

This manual includes some materials that are intended for use as active learning laboratory activities, some that are intended as *ILDs*, and some that can be used in either way. More details will be found in the section *Contents and Use of this Manual,* below.

History of the UNESCO Active Learning Projects

As of early 2006, the time of writing of this Training Manual, the following international active learning activities have taken place under the auspices of UNESCO:

January, 1999, initial active learning short course presented to Asian Physics Education Network (ASPEN) participants in Australia

February, 1999, meeting and workshop in Laos

November, 1999, workshop in Vietnam

July, 2000, workshop in South Korea

February, 2001, trainers' workshop in the Philippines

February, 2001, workshop in Sri Lanka

June, 2001, workshop in Malaysia

October, 2001, workshop in Laos

December, 2002, meeting and workshop in Sri Lanka

September, 2003, workshop in Ghana

November, 2004, optics workshop in Ghana

March, 2005, optics workshop in Tunisia

Active learning strategies were introduced to the participants in the January, 1999 ASPEN workshop by David Sokoloff (University of Oregon), Priscilla Laws (Dickinson College) and Ronald Thornton (Tufts University). Several participants from this workshop were chosen as trainers for future workshops. These educators have served as trainers in the workshops held since that time. They, in addition to other trainers recruited along the way, are the authors of the modules that make up this training manual.

Active Learning in Optics and Photonics

The original set of active learning activities in these UNESCO sponsored programs covered a range of physics topic areas, including mechanics, heat and thermodynamics and electricity. The Active Learning in Optics and Photonics (ALOP) project was conceptualized and begun by UNESCO in 2003. UNESCO coordinates and funds the project, with additional support from the Abdus Salam International Center for Theoretical Physics (ICTP), and the International Society for Optical Engineering (SPIE). The focus of the project is on one of the experimental physics areas that is relevant and adaptable to research and educational conditions in many developing countries. Optics has been termed an "enabling science" as it is the basis of many modern advances in high technology. It is hoped that improving optics and photonics education will result in a viable and well-educated workforce for emerging industries in African countries and other developing nations where specific skills in this area will be needed.

Contents and Use of this Manual

This Training Manual is intended for university and senior high school physics teachers from developing countries, and aims to train and better equip them to teach the optics part of the introductory physics course by using active learning with hands-on activities and by drawing examples from local research activities. The modules contained in the manual are curricular materials for use with introductory physics students at these levels.

This Training Manual contains an activity-based curriculum including the following six Modules:

Module 1: Introduction to Geometrical Optics

Module 2: Lenses and Optics of the Eye

Module 3: Interference and Diffraction

Module 4: Atmospheric Optics

Module 5: Optical Data Transmission

Module 6: Wavelength Division Multiplexing

Each module includes student sheets that can be copied and used in class. Permission is granted for users to make as many copies as they need for their students. These modules have been prepared by the trainers who have presented the ALOP workshops. Some of the materials have been developed expressly for the ALOP workshops, while some have been used previously in the courses that the trainers teach at their home institutions. An attempt has been made to develop activities that use simple and inexpensive materials, and materials that can be fabricated locally, whenever possible. Some of the activities in these modules have been developed expressly for hands-on work in the laboratory, and some are more appropriate for use as *ILDs* in lecture. Others can be used either in a lab or lecture environment, depending on the availability of equipment. Regardless of how the materials are used, teachers are encouraged to make their classroom environments more active by including the characteristics described in Table I-1.

Module 1 includes lab activities adapted from *RealTime Physics*, sets of *ILDs* on Reflection and Refraction and Image Formation with Lenses and a set of *Optics Magic Tricks* designed to stimulate small group discussions. Some of the *ILDs* are similar to the lab activities, thus providing teachers with materials appropriate to both environments.

The materials in Module 2 will work best in a laboratory environment in which students work in groups of 2 to 4. However, some of these could be done as demonstrations with large lenses, e.g., with some form of blackboard optics kit. The activities in Module 3 were also designed primarily for use in the laboratory, but most of them could be adapted as *ILDs*. The activities in Modules 4, 5 and 6 were designed as *ILDs*, but most of them could also be done as lab activities if enough equipment is available.

There is a separate, complete Teachers' Guide for each of these modules. The Teachers' Guides give information on the apparatus and supplies needed for each of the activities (including sources, and in some cases fabrication instructions), photos and diagrams of the apparatus, directions on how to carry out the experiments, sample results and answers to the questions. The goal is to provide teachers with all the information they need to use these activities with students at their home institutions.

Also included in this manual is an assessment instrument, the *Light and Optics Conceptual Evaluation* that has been developed to measure student learning of optics concepts. Teachers can use this assessment to carry out action research in their classes. The ability of teachers to carry out action research has been instrumental in making teachers in the developed world aware of the difficulties their students have in learning physics concepts, and has led to the advancement of Physics Education Research. More information is provided in the *Action Research* section of this manual.

The entire Training Manual is also available in electronic form on a CD. This may be useful for users who want to print the student sheets directly from the electronic files. These files also have the advantage that they are in color. Copies of the CD are available from the project coordinator, Minella Alarcon, at UNESCO, Paris (m.alarcon@unesco.org).

Examples of *ILDs* in Optics and Assessment of Learning Gains

As an example, we will describe a sequence of *ILDs* designed to teach the concepts of image formation with lenses. (This set is included in Module 1 of this manual.) Physics education research suggests that students have difficulties with the way image formation is usually taught. For example, students have conceptual difficulty with the beautiful ray diagrams we draw that only show the special, principal rays.[16] Students do not understand that in order for a sharp image to be formed, *all* of the rays that leave a point on the object and are incident on the lens must be focused to a unique, corresponding point on the image. In these *ILDs*, in order to reinforce this idea, point sources of light are placed at the head and foot of the object arrow, and a cylindrical lens is used to focus these to image points.

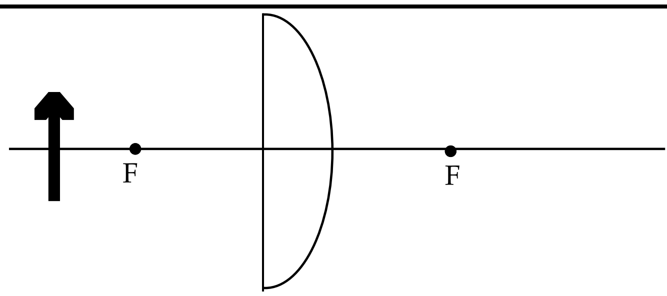
Figure I-1 shows the first page of the Prediction Sheet for the Image Formation with Lenses *ILDs*. Figure I-2 shows the experimental setup. In addition to the three demonstrations illustrated here, there are four other demonstrations asking for predictions of what will happen (a) if the lens is removed, (b) if the object is moved further away from the lens, (c) if the object is moved closer to the lens, and (d) if the object is moved closer to the lens than the focal point. As with all *ILDs*, the eight steps in Table I-2 are carried out for each of these demonstrations. (More details on this set of *ILDs* will be found in Module 1.)

INTERACTIVE LECTURE DEMONSTRATIONS
PREDICTION SHEET—**IMAGE FORMATION WITH LENSES**

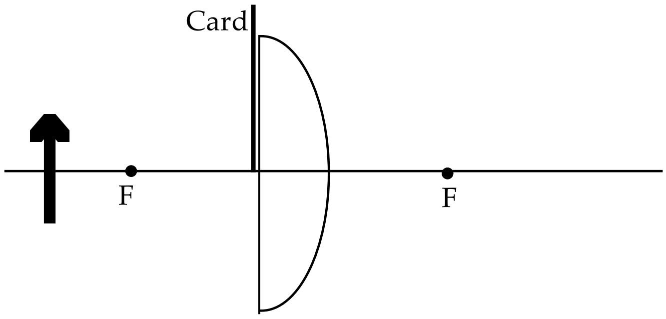
Directions: This sheet will be collected. Write your name at the top to record your presence and participation in these demonstrations. Follow your instructor's directions. You may write whatever you wish on the attached Results Sheet and take it with you.

Demonstration 1: You have a converging lens. An object in the shape of an arrow is positioned a distance larger than the focal length to the left of the lens, as shown in the diagram on the right. Draw several rays from the head of the arrow and several rays from the foot of the arrow to show how the image of the arrow is formed by the lens.

Is this a real or a virtual image?



Demonstration 2: What will happen to the image if you block the top half of the *lens* with a card? Answer in words and show what happens on the diagram on the right by making any changes needed in the rays you drew in Demonstration 1.



Demonstration 3: What will happen to the image if you block the top half of the *object* with a card? Answer in words and show what happens on the diagram on the right by making any changes needed in the rays you drew above for Demonstration 1.

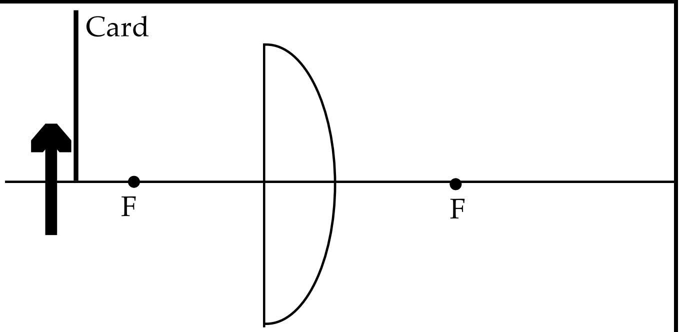


Figure I-1: Excerpt of Prediction Sheet for Image Formation with Lenses *ILDs*.

Figure I-3 shows the introduction to the image formation questions on the *Light and Optics Conceptual Evaluation (LOCE)*. Six of the questions were included in a research study of student understanding of image formation concepts in the University of Oregon (USA) General Physics course in 1997-1998. These questions ask what would happen to the image if (a) the stamp were twice as large, (b) the lens were replaced with one of half the diameter but the same focal length, (c) if the top half of the lens were covered, (d) if the center of the lens were covered, (e) if half of the stamp were covered, and (f) if the lens were removed. (The entire test is included in the *Action Research* section of this manual, and is described in more detail there. The questions used in this study were numbers 25, 26, 28, 29, 30 and 34.) Figure I-4 shows the results on these questions before traditional lecture instruction, after traditional lecture instruction, and then after an additional lecture that included these *ILDs*. As can be seen, the normalized learning gain from all lecture instruction is only 20%, while that with the *ILDs* is 80%! (Normalized gain is defined as actual improvement divided by maximum possible improvement.)[11]

Figure I-5 shows the results on one additional short answer question on the *LOCE*. Here students are asked to continue two rays from the head of the object and two rays from the foot of the object to show how the real image is formed. Only 33% of the students were able to draw this ray diagram correctly after traditional instruction, while 76% drew it correctly after experiencing the *ILDs*—a 64% normalized gain.

This set of *ILDs* is a good demonstration of the fact that significant learning gains can be brought about with low-cost materials. The cylindrical lens can be fabricated with a transparent plastic jar filled with water. In addition to this, only two flashlight bulbs in sockets and a 9 V battery are needed. The cost is under $10 (USD) to present these *ILDs* to a large lecture class.

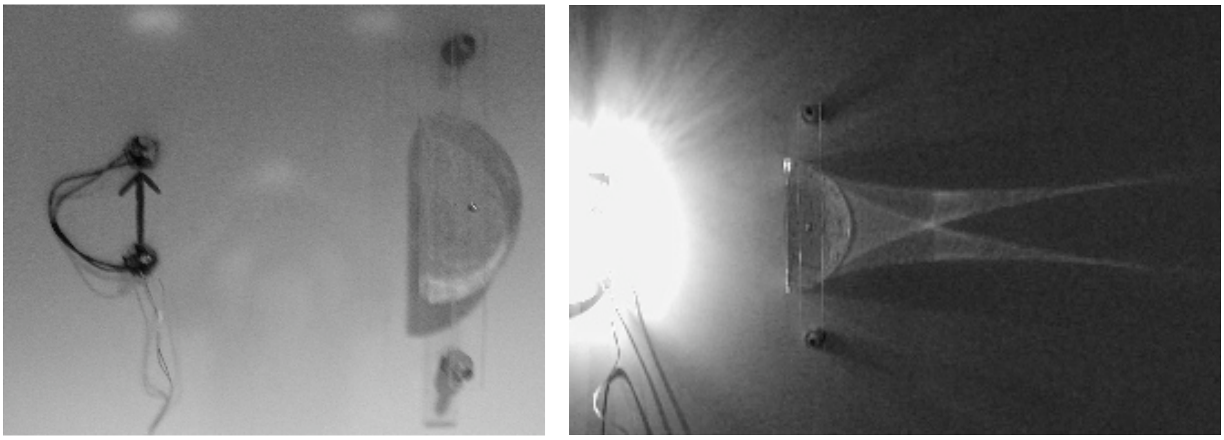


Figure I-2: (a) Setup for Image Formation with Lenses *ILDs* with object arrow, light bulbs and cylindrical lens. (b) Focusing of light by cylindrical lens.

Why do *ILDs* work? The eight-step *ILD* procedure is designed to engage students in the learning process. Students are asked to make predictions based on their beliefs on a sheet that will be collected. They are forced to contemplate each demonstration in terms of the models they commonly use. Students are then asked to defend their predictions to their peers. After these two steps, most students care what happens in the demonstration. They are engaged by these steps. Since the results they observe often disagree with their naïve predictions—often based on incorrect models—there is a chance for their models to be changed by the discussion that follows.

We have used three basic guidelines in designing the short, simple experiments that make up *ILDs* for these modules. First, the order and content of the sequences are based on the results of research in physics learning. If the sequences are to be successful, they must begin with what students know and lay the basis for additional understanding. Secondly, the *ILDs* must be presented in a manner such that students understand the experiments and "trust" the apparatus and measurement devices used. Many traditional exciting and flashy demonstrations are too complex to be effective learning experiences for students in the introductory class. Finally, the *ILDs* must make use of materials that are readily available in developing countries, or inexpensive enough that they can be purchased or supplied by the workshop team. As part of workshops, it has been worthwhile to have a brief session on putting together simple teaching materials to be used in the workshop, including some instruction and practice on soldering simple circuits.

Questions 25-34 refer to the picture on the right. A stamp is placed to the left of the lens, and its image is formed on a screen to the right of the lens, as shown.

Choose the correct answer for each question.

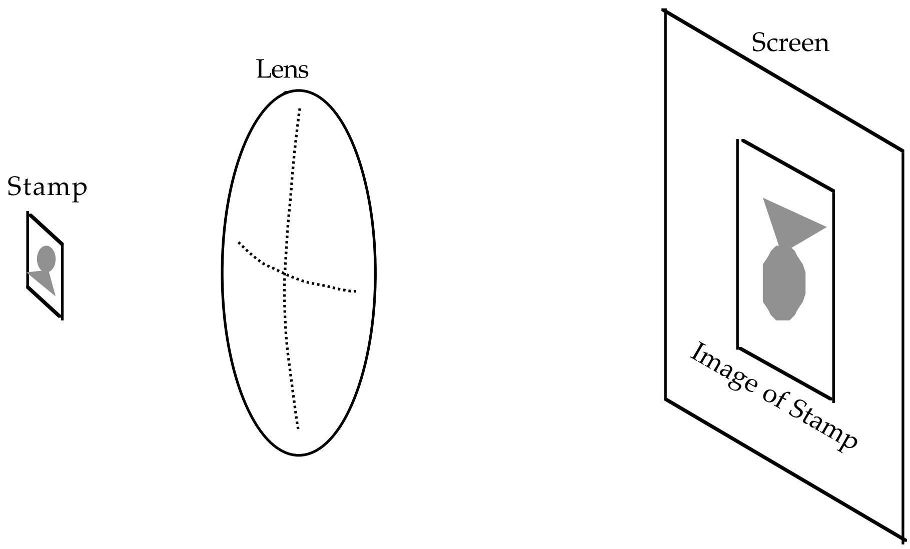


Figure I-3: Introduction to the image formation questions on the *Light and Optics Conceptual Evaluation*.

How do *ILDs* fit into the introductory physics course? The topic areas of the *ILD* sequences in this manual are distributed over the optics concepts covered in most introductory physics courses, with the addition of simple applications in photonics. However, taken together, they do not constitute an introductory optics curriculum. Instead, they are designed to supplement the other components of the course with an efficient way for students to learn physics concepts in lecture. They have been used in a number of different ways, for example: 1) as introductions to important concepts at the appropriate moment in the course schedule, 2) as reinforcement activities for concepts already taught, 3) as weekly active learning sessions scheduled on the same class day each week and 4) as summaries and bridges between active learning laboratory activities. The instructor must decide how they best fit into her/his overall plan for the course.

One last crucial question: why should we care if students understand physics concepts? We believe that this is fundamental to a real understanding of our discipline. Students cannot hope to be able to do more than algorithmic solutions to simple physics problems without a sound grasp of the fundamental concepts.

Active Learning Workshops

The training workshops already presented have generated a high level of interest in active learning by the participants. The consensus appears to be that active learning can be a very successful strategy for improving physics education outcomes in developing countries. A goal of UNESCO and its regional physics education networks is to develop a large group of local active learning resource persons or trainers to coordinate and run regional active learning workshops in the developing world. The strategy is to recruit these trainers from participants in the series of training workshops to be presented in the future. It is thought that faculty who might be good active learning trainers would have the following qualities: high degree of enthusiasm, rich experience as physics teacher, good physics knowledge, young of body and mind (i.e., able to take on new ideas and develop them further), good with their hands, resourceful (able to set up equipment in strange environments and easily adapt when things go wrong), keenly interested in physics education practice and research, from a supportive home university (i.e., that will help in building equipment for workshops and allow leave to run several workshops per year), not too overloaded with administration and basic research, and genuinely wishing to help colleagues in developing countries (and at their home university). In general, faculty with the following characteristics would not make good trainers for this program: inflexible in their ideas, too busy to devote adequate time to this

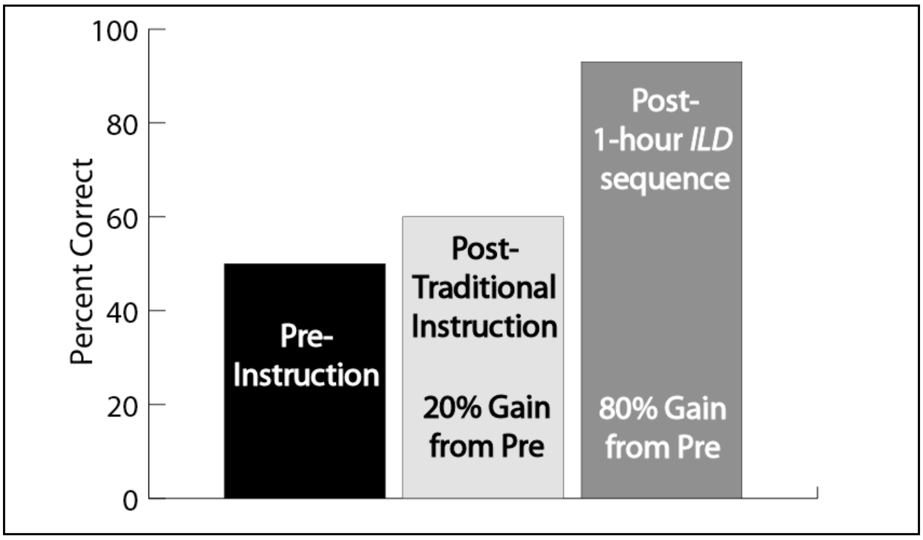
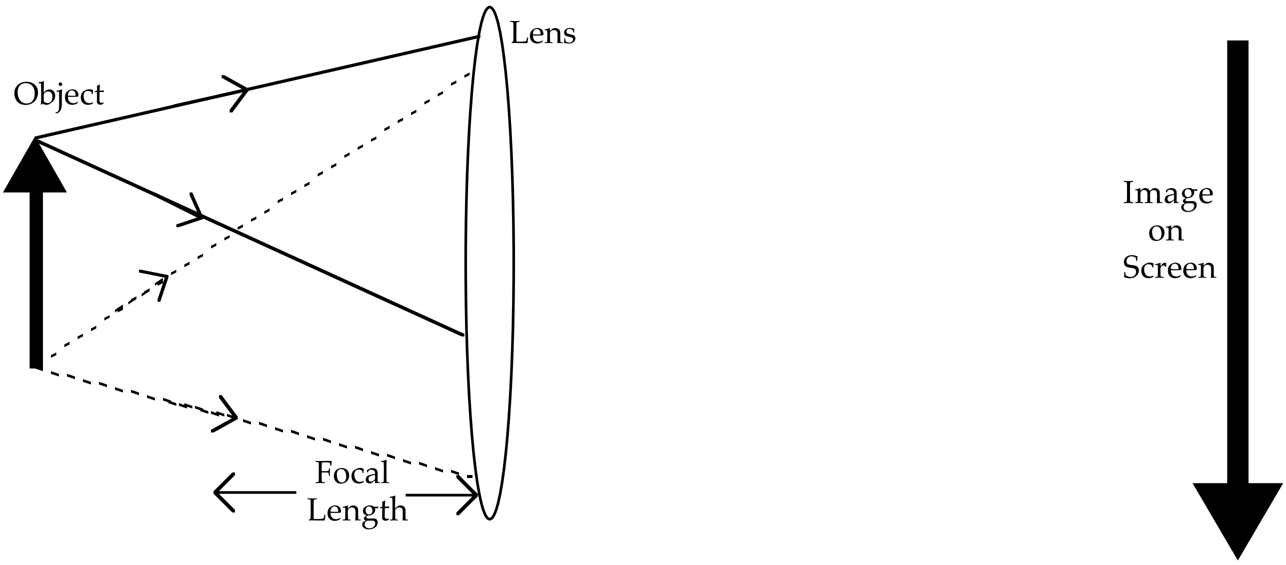


Figure I-4: Pre-, post-traditional instruction and post-*ILDs* results on six image formation questions on the *LOCE* for general physics students at the University of Oregon, 1997-98.

51. In the picture below, the object is to the left of the lens, at a distance from the lens that is larger than the focal length. The image is formed on a screen to the right of the lens as shown. Four rays of light are shown leaving points on the object. Continue those four rays through the lens to the screen.



After traditional instruction	33% correct
After ILDs	76% correct
Normalized gain	**64%**

Figure I-5: Ray diagram question on the *Light and Optics Conceptual Evaluation*, and the results post-traditional instruction and post-*ILDs*.

activity, valuing their basic physics research way above their teaching development and not from a supportive university.

In general, we have found the following structure for a 5-day ALOP workshop to be successful:

1/2 day for touring both teaching and research facilities.

1/2 day for introductions—both participants and resource people. (Everyone should come well prepared with a report on physics education at her/his home institution.)

1/2 day for introduction to workshop goals and active learning, pre-test, and a brief session to prepare workshop materials.

3 days for hands-on work with the modules.

1/2 day for wrap-up discussions and post-test. Issues for discussion in the wrap-up might include the needs for improvement of physics teaching in home countries, how good teaching practices can be encouraged, what resources are available in home countries and how can these be used most effectively, and how can participants help solve implementation issues in their countries.

Acknowledgments

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16. F. Goldberg and L.C. McDermott, "An investigation of student understanding of the real image formed by a converging lens or concave mirror," *Am. J. Phys.* **55**, 108-119 (1987).

Laser Safety

LASER SAFETY

The Human Eye

A schematic diagram of the eye is shown in Figure LS-1. The cornea is the clear film that covers the surface of the eye. The iris controls the amount of light entering the eye. The cornea and lens are the elements that focus the incoming light onto the retina, where light sensitive cells detect the light. Ultraviolet light tends to be absorbed by the cornea. Although corneal cells can regenerate (to an extent), UV radiation in sunlight can permanently damage the cornea if the eye is exposed to excessive bright sunlight over many years. This is one reason why it is a good idea to wear UV-blocking sunglasses during summer.

Visible and near infrared optical radiation is focused onto, and absorbed by the retina. Exposure to high intensity light from a source of optical radiation will cause instantaneous damage to the retina because the light source will be focused onto a small number of cells. The damage will be permanent, because retinal cells do not regenerate.

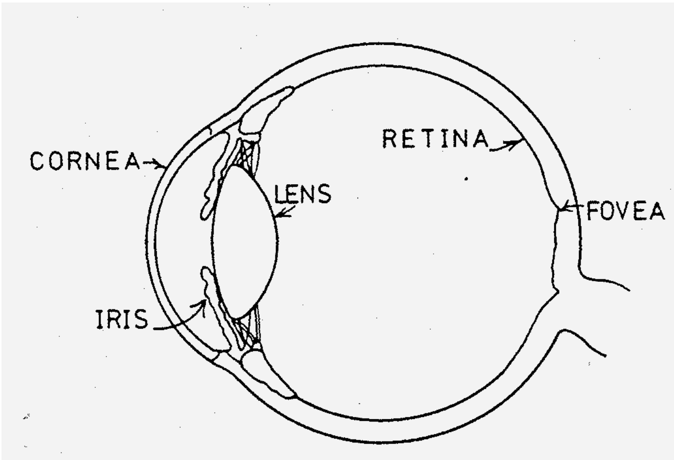


Figure LS-1: Schematic diagram of the eye

With a normal light source (like an incandescent light bulb), the optical energy spreads evenly in all directions. If you double the distance between your eye and the bulb, then the optical energy entering your eye falls by a factor of four. Thus, distance from the light source offers a level of protection.

The Danger of Laser Light

Looking directly into the beam of a low power (1 mW) visible laser can cause considerably more retinal damage than looking directly at the sun! With a laser, the optical energy is contained in a very narrow beam that does not spread out much. Even at relatively large distances, the laser beam spot can still be very small and, thus, the optical energy entering the eye can still be very high.

In addition, the almost parallel laser light irradiating the eye is focused to a very sharp point on the retina. This means that most of the energy emitted by the laser will be concentrated onto only a few cells on the retina causing maximum damage to those cells.

Minimizing the Danger

How can we minimise the exposure risk when dealing with a laser (even a laser pointer)? Try to always follow the following safety procedures:

- **Terminate the beam** at the end of its useful path (i.e., with a photodetector and/or a non-reflective beam stop behind the detector). A large piece of dark-colored cardboard mounted vertically in a slotted wooden base makes a good beam stop.

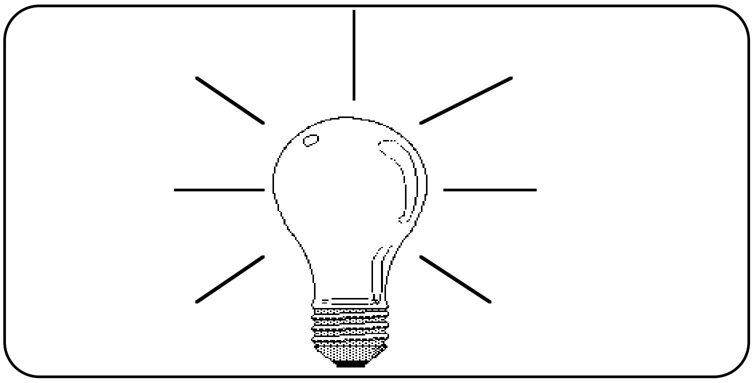
- **Avoid specular reflection** from polished or shiny surfaces (including watches and jewelery), as these will reflect the laser beam around the lab or classroom in an uncontrolled manner.
- **Use the lowest practical intensity** when you align the laser beam. Use partially crossed linear polarisers to temporarily reduce (attenuate) the beam intensity. (The two polarized plastic lenses of cheap Polaroid sunglasses can be used.)
- **Never look directly into the laser beam.** Construct your laser beam path as low as practical to the table or bench top, and then always try to keep your head well above the level of the laser beam. When aligning, move your eye **slowly** when near the beam path. The bright halo associated with the beam gives an early warning of impending disaster (as your eye approaches a direct line of vision with the beam).
- **Avoid darkened rooms**. Do not set up your laser beam in a darkened room, as your pupils will enlarge and therefore potentially will let more of the laser beam energy onto the retina.
- **Always use laser warning signs** to alert others to the potential laser radiation hazard. You should print copies of laser warning signs like those shown below, and display them prominently close to any laser experiment.

Module 1:
Introduction to Geometrical Optics

David R. Sokoloff
Department of Physics
University of Oregon
Eugene, Oregon, USA
sokoloff@uoregon.edu

Hands-on Labs

MODULE 1: INTRODUCTION TO GEOMETRICAL OPTICS



For the rest of my life I want to reflect on what light is.

Albert Einstein, 1916

OBJECTIVES

- To discover how light spreads out from a point source
- To examine quantitatively how the intensity of light varies with distance from a point source
- To discover how light rays can be used to represent light as it spreads out from a point source
- To discover the origin of parallel rays of light
- To observe qualitatively the interaction of light with the surface of a transparent object
- To examine the reflection of light at a surface between two transparent materials quantitatively
- To understand the law of reflection
- To understand Snell's law of refraction
- To observe total internal reflection, and discover under what circumstances it occurs
- To examine dispersion of light and the formation of rainbows
- To explore how a lens forms images

OVERVIEW

Our ability to see the objects around us depends on light traveling from the objects to our eyes. Newton was a strong believer that light was made up of particles, and that it could be described by straight line rays drawn in the direction of motion. He could not conceive of light as waves. In the 19th century, a number of observations of light interference firmly established that light propagated through space as waves. Strangely, Einstein's theory of the photoelectric effect, early in the 20th century, again established light as particles called photons.

We now know that light can be considered from both of these points of view—as particles or waves. When light interacts with objects much larger than its wavelength, it can be described by either waves or straight line *rays*. When it interacts with small objects—near the size of its wavelength—then a *wave* model is needed to accurately describe the interactions. Since optical elements like lenses, mirrors and prisms are generally much larger than the wavelengths of light (which are of the order of half a millionth of a meter), the ray model—usually called *ray optics* or *geometrical optics*—is quite adequate. This module will deal only with such situations.

The spreading out of light from a point source, and the use of rays to represent light will be explored in Investigations 1 and 2.

Many optical elements like mirrors and prisms are made of transparent materials—like glass or Lucite®—with smooth surfaces. When light is traveling in air and comes upon the surface of a transparent material, some of the light is reflected and some of it is transmitted. In order to understand how optical elements work, it is important to have a *quantitative* understanding of *reflection* and *refraction* at a surface. You will examine these in Investigation 3.

There is one circumstance in which light traveling in a dense transparent material is only reflected and not transmitted at a surface with a less dense transparent medium on the other side. This phenomenon of *total internal reflection* will be explored in Investigation 4.

You are well aware from your everyday observations of the separation of white light into its component colors by prisms, and by water droplets to form rainbows. Investigation 5 will explore this process of *dispersion*.

Finally, lenses are essential elements in most optical instruments from eye glasses, to a simple magnifier, to binoculars, optical telescopes and microscopes. In Investigation 6, you will explore how images are formed by lenses. You will see that in order for a sharp image to be formed, it is essential that *all* the rays leaving each point on the object are focused by the lens to a corresponding, unique point on the image.

INVESTIGATION 1: A THOUSAND POINTS OF LIGHT

APPARATUS AND SUPPLIES

- Miniature light bulb
- Power supply (or battery)
- Holder for light bulb
- Light intensity meter
- Meter stick
- Laser ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Blackboard eraser and chalk dust
- Transparent ruler
- Small paper disk
- Graphical analysis software or graph paper

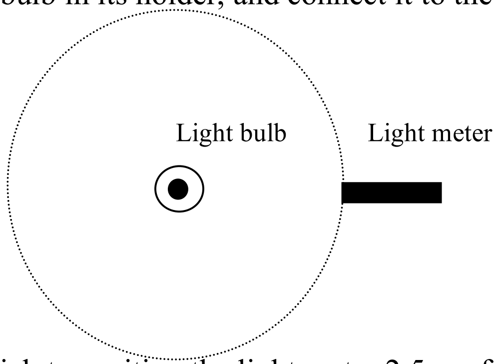
When light is emitted or reflected by an object, each point on the object serves as a source of light. Let's explore how the light from a point source spreads out in space. The filament of a tiny light bulb while not exactly a point source of light is small enough to be a good approximation.

Prediction 1-1: Light from a point source spreads out in every direction. Based on the definition of *light intensity* as the *light power per unit area perpendicular to the direction in which the light is propagating*, how do you think the light intensity from a point source will change as you increase your distance from the point source. Be as quantitative as you can.

Activity 1-1: Light intensity around a point source

Let's look at light coming from a point source at different positions around the point source. To do this, you can use a light intensity meter that measures the light *intensity* incident on the surface of its light detecting element (called a photodiode or phototransistor). Light *intensity* is associated with the *brightness* of the light.

1. Mount the light bulb in its holder, and connect it to the power supply (or battery).



2. Use the meter stick to position the light meter 2.5 cm from the light bulb filament, pointed straight towards it. Move the meter slightly side to side until you get a maximum reading. Then, record the intensity reading in the table below. Now repeat this for four other positions around the bulb, all 2.5 cm away. Record these values in the same column.
3. Repeat for 5.0 cm away, 10.0 cm away, 20.0 cm away and 40.0 cm away. At each position, move the light meter slightly until you get a maximum reading.

	Distance from light bulb filament, *R*				
Measurement	2.5 cm	5.0 cm	10.0 cm	20.0 cm	40.0cm
1					
2					
3					
4					
5					
Average Intensity					

4. Plot a graph of average intensity vs. distance from the bulb filament using the graphical analysis software or paper.

Question 1-1: Describe qualitatively how the intensity measured by the light meter appears to vary as the distance from the light bulb filament increases. Does the intensity increase, decrease or remain the same?

Question 1-2: Try to explain your observations in words based on the way the light spreads out after it leaves the light bulb filament. (Remember that light intensity is light power per unit area perpendicular to the direction in which the light is traveling. Over what area does the light from a point source spread?)

5. If you used graphical analysis software to plot your graph, find the mathematical relationship between Intensity and Distance (R) from the light bulb using the fit routine in the software. If you don't have a fit program, look at the graph and guess at the relationship. Then plot other graphs to verify your guess.

Question 1-3: What mathematical relationship did you find between Intensity and Distance (R) from the light bulb filament? Try to explain this based on the way light spreads out from the filament of the bulb. (**Hint:** the surface area of a sphere is $A = 4\pi R^2$, where R is the radius of the sphere.)

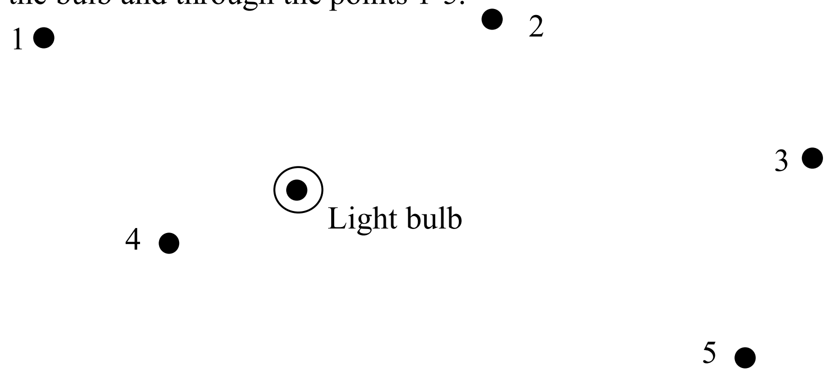
Now let's examine how light can be represented by *rays*.

Activity 1-2: Diverging and parallel rays of light

In geometrical optics, light propagating in space is represented by straight lines called *rays*, drawn in the direction in which the light waves are propagating. Light *wave fronts* are always perpendicular to rays.

In the previous activity you examined the intensity of light from a point source. Now let's look at how rays can be used to represent the light from a point source propagating through space.

1. In the diagram below, sketch 5 light rays beginning on the filament of the bulb and through the points 1-5.



Question 1-4: Describe these rays in words. How are they drawn as the distance from the filament increases?

WARNING: ***The laser beam should never be directed toward anybody in the room. The laser beam is damaging to the eye.***

Now observe the light from a laser shining across the room. It may be helpful to suspend some chalk dust in the path of the laser by pounding a blackboard eraser close to the path of the laser beam.

Question 1-5: Can you see the laser beam very well without the chalk dust in the air? Why does the chalk dust make the beam more visible? Are you actually viewing the light coming from the laser directly, or is something else happening?

Question 1-6: List all the ways in which the light from the laser appears different from the light from the small light bulb.

Question 1-7: In particular, compare how the light from the laser spreads out as compared to the light from the light bulb.

2. Based on your observations, sketch below some rays of light leaving the laser.

Question 1-8: Would you expect to find any rays through points like 1, 2 and 3? In what ways are the rays you drew different than those you drew from the point source in (1)?

Comment: The rays from a point source are radii spreading out from the source. These are called *diverging* rays, and the light is said to be composed of *diverging spherical* waves. (The wave fronts are spherical surfaces.) The rays from a laser are essentially parallel—they hardly spread out at all. They are called *parallel* rays, and the light is said to be composed of *plane* waves. (The wave fronts are planes.) Are there any other situations in which the light from a source can be represented by parallel—or *nearly parallel*—rays?

Prediction 1-2: Imagine a circle 10 cm in diameter on the ground. It is a clear day, and the sun is high in the sky. Are the rays reaching the circle from the sun more like the rays from the small light bulb or like the rays from the laser?

Test your prediction.

Activity 1-3: Rays from a distant source of light

1. Set up the small light bulb and its holder across the room.
2. Measure the distance from the light bulb to your table:_______m.

Question 1-9: How does this distance compare to the diameter of the paper disk?

3. Hold the paper disk up with its surface facing the light bulb.
4. In the diagram below, use the ruler to carefully draw several rays from the filament of the bulb to the disk.

Question 1-10: Was your Prediction 1-2 correct? When light from a very distant source of light is incident on a relatively small object, is it best represented by approximately parallel rays (and plane waves) or by diverging rays (and spherical waves)?

INVESTIGATION 2: UNDERSTANDING LIGHT WITH RAYS

Much of geometrical optics deals with optical elements like lenses, mirrors and prisms. Many optical elements are constructed of transparent materials. Here we want to observe *qualitatively* what happens when parallel rays (plane waves) and light diverging from a point source (diverging rays) are incident on a flat (plane) surface between two transparent materials, for example, air and glass. In the next investigation, you will examine these interactions quantitatively and arrive at the laws of *reflection* and *refraction*.

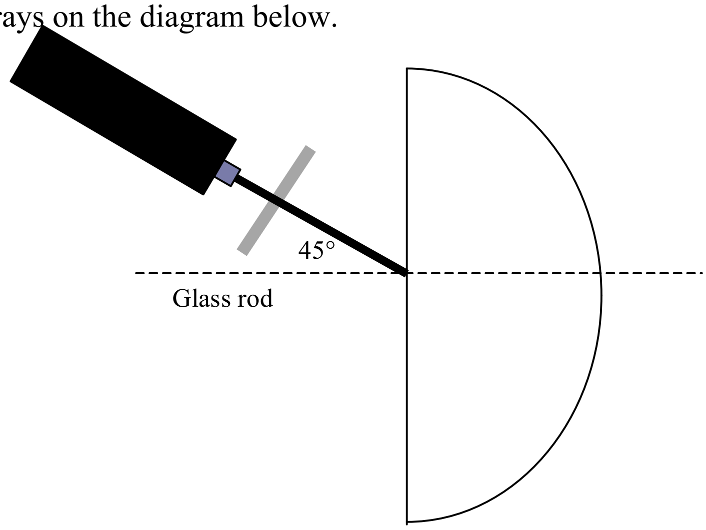
APPARATUS AND SUPPLIES

- Laser ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Glass rod
- Miniature light bulb
- Power supply (or battery)
- Holder for light bulb
- Semicircular transparent chamber filled with a slightly cloudy liquid

- Blackboard eraser and chalk dust

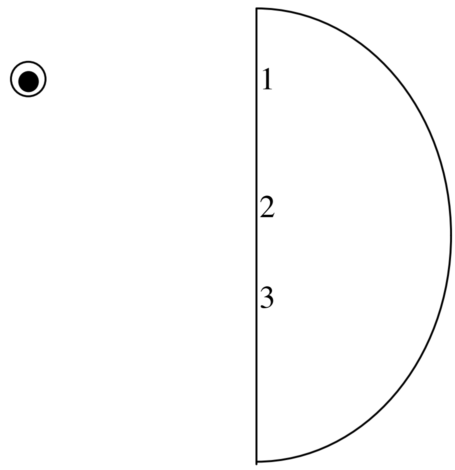
Activity 2-1: Interaction of parallel rays with a transparent surface

1. Set up the laser, glass rod and transparent chamber so that the light is incident on the flat surface of the transparent chamber at an angle around 45°, as shown below. (The only function of the glass rod is to spread out the laser beam vertically so that it is more easily seen on the paper.)
2. Observe the light after it strikes the surface, both the light reflected from the surface (the chalk dust will be helpful for this observation) and the light transmitted through into the liquid.
3. Sketch both rays on the diagram below.



Question 2-1: Describe what happens to light rays when they are incident on the surface between two transparent materials.

Prediction 2-1: What will happen to light from a point source when it is incident on the surface of the transparent chamber? Sketch your prediction for three rays from the point source incident on the flat surface at the three different points indicated on the diagram below. Show both transmitted and reflected rays.



Test your predictions.

Activity 2-2: Interaction of diverging rays with a transparent surface

1. Tape the miniature bulb so that it is pointing up from the paper. Place the transparent chamber in front of the bulb, as shown above.
2. Observe the reflected and transmitted light.
3. Sketch several rays on the diagram in a different color from your predictions. (Label which are your predictions and which your observations.)

Question 2-2: Did your observations agree with your predictions? If they didn't agree, explain why.

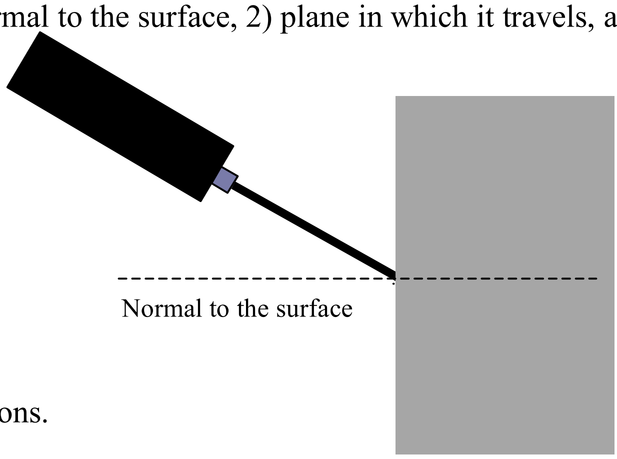
Question 2-3: How could you use the beam from a laser to predict what will happen to just one of the diverging rays from a point source?

INVESTIGATION 3: LAWS OF REFLECTION AND REFRACTION

APPARATUS AND SUPPLIES

- Laser ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Glass rod
- Semicircular clear chamber filled with a slightly cloudy liquid
- Blackboard eraser and chalk dust
- Sharp pencil
- Clear plastic ruler
- Protractor
- Graphical analysis software or graph paper

Prediction 3-1: Light from a laser is incident as shown on the flat surface of a transparent material. Sketch the direction of the reflected ray, and in words compare it to the incident ray in terms of the following 1) angle made with the normal to the surface, 2) plane in which it travels, and 3) intensity.

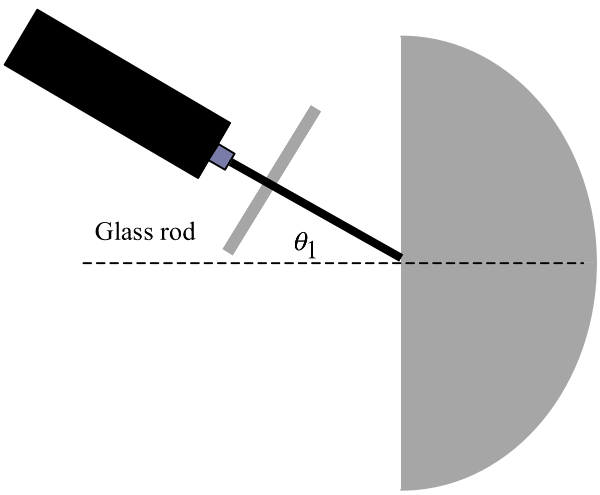


Test your predictions.

WARNING: ***The laser beam should never be directed toward anybody in the room. The laser beam is damaging to the eye.***

Activity 3-1: Law of reflection

1. Place the chamber on a separate piece of paper, as shown in the diagram that follows. Outline the chamber on the paper with a pencil.
2. Position the laser and glass rod as shown. The laser beam should be as close to the paper as possible, and should hit the chamber near the center of the flat surface.
3. Mark two points on the paper along the incident beam using a sharp pencil.
4. Mark the point where the laser beam hits the surface.
5. Use the chalk dust to observe the reflected beam. Then *carefully and precisely* mark two points on the paper along the reflected beam using the pencil.
6. Rotate the laser to change the angle of incidence but have the beam hit the surface at the same point. Again *carefully and precisely* mark the incident and reflected rays with two points for each.
7. Remove the paper, and draw in the incident and reflected rays for both cases, using the ruler. Carefully draw the normal to the surface using the protractor. Save this paper and attach it to these sheets.



8. Measure the angle of incidence, θ_1 and the angle of reflection, θ'_1 for each case. Note that these are conventionally measured from the normal to the surface as shown in the diagram (not from the surface). Record these in the table below, along with an estimate of how precisely you can measure these angles given the thickness of the beams, the thickness of the lines, etc.

	θ_1	θ'_1	Estimate of precision
Case 1			
Case 2			

Question 3-1: What do you conclude about the relationship between the angle of incidence and the angle of reflection?

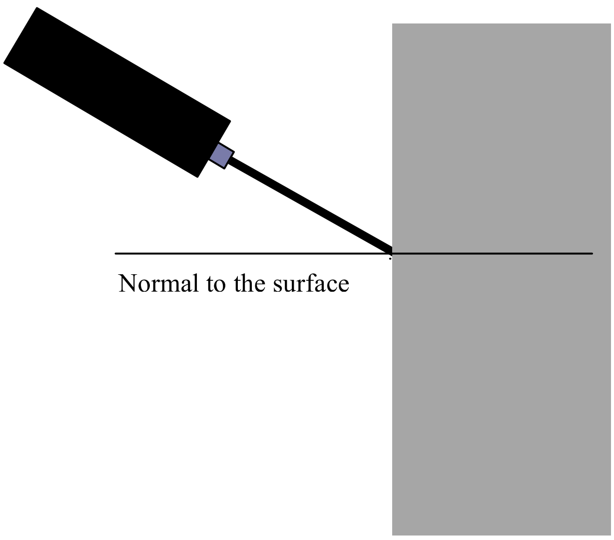
Question 3-2: We can define the *plane of incidence* as the plane defined by the incident beam and the normal to the surface of the clear chamber. Based on your observations, is the reflected beam also in this plane? Explain how you reached your conclusion.

Question 3-3: The *law of reflection* describes the direction of the reflected beam given the direction of the incident beam. Based on your answers to Questions 3-1 and 3-2, state the law of reflection in words.

Question 3-4: Compare the reflected intensity with the incident intensity. Where did the rest of the light go?

What about the transmitted light? In what direction does it travel in the liquid in the clear chamber?

Prediction 3-2: Light from a laser is incident as shown on the flat surface of a transparent material. Sketch the direction of the ray transmitted through the first (left) surface, and in words compare it to the incident ray in terms of the following 1) angle made with the normal, 2) plane in which it travels, and 3) intensity.



Test your predictions.

Activity 3-2: Snell's Law of refraction

1. Set up the chamber, laser and glass rod on a piece of paper as in Activity 3-1. The laser beam should hit near the center of the flat surface.
2. Use the pencil to outline the chamber on the paper.
3. Mark two points on the paper along the incident beam using the pencil, and label them with an A.
4. Mark the point where the laser beam hits the surface.
5. Now look at the light transmitted through the flat surface, and mark the point where the ray hits the curved surface. Label this point with an A.
6. Rotate the laser to change the angle of incidence, but make sure that the beam still hits the flat face of the chamber at the same point that you marked previously on the paper.
7. Mark two points on the new incident ray as before, and label them with a B.
8. Again see where the transmitted ray hits the curved surface, and mark that point. Label it with a B.
9. Repeat 6, 7 and 8 until you have six different angles of incidence, including 0° (i.e., the laser beam perpendicular to the flat surface).
10. Remove the paper and use the ruler to carefully draw in the six incident rays, the six transmitted rays and the normal. Save this paper and attach it to these sheets.

Question 3-5: Compare the angles of incidence and the angles the transmitted rays make with the normal. If one is always smaller, describe which one.

Comment: The "bending" of light rays as they move from one transparent material (e.g., air) into another (e.g., the fluid in the clear chamber) is known as *refraction*. The transmitted light is said to be *refracted* at the surface, and the angle measured with the normal is called the *angle of refraction.*

11. For each case, measure the angle of incidence, θ_1, and the angle of refraction, θ_2. Enter the values in the table that follows, along with an estimate of the precision of the measurements.
12. Enter the values of $\sin\theta_1$ and $\sin\theta_2$ in the table.
13. Plot a graph using the graphical analysis software or a piece of graph paper. Use the fit routine in the software to find the relationship between $\sin\theta_1$ and $\sin\theta_2$ (or find it graphically). Attach a copy of your graph to these sheets.

	θ_1	$\sin\theta_1$	θ_2	$\sin\theta_2$	Estimate of precision
Case A					
Case B					
Case C					
Case D					
Case E					
Case F					

Question 3-6: Based on your analysis, what is the relationship between $\sin\theta_1$ and $\sin\theta_2$? Write this as a mathematical equation.

Comment: Snell's Law of Refraction states the relationship between θ_1 and θ_2. It says $n_1\sin\theta_1 = n_2\sin\theta_2$, where the numbers n_1 and n_2 are quantities called the *indexes of refraction,* that describe the optical properties of the two materials.

Question 3-7: Based on your graph, and given that the index of refraction of air is 1.00, what is the index of refraction of the liquid in the clear chamber? Be sure to use data from your graph rather than individual values from the table. Show and explain your calculations.

INVESTIGATION 4: TOTAL INTERNAL REFLECTION

APPARATUS AND SUPPLIES

- Laser ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Glass rod
- Semicircular clear chamber filled with a slightly cloudy liquid
- Blackboard eraser and chalk dust
- Sharp pencil
- Clear plastic ruler
- Protractor
- Graphical analysis software or graph paper

Today, most of the phone calls in the world travel for at least part of their journey as light signals on fiber optic cables. Because of the high frequencies of light waves compared to microwave and radio waves, these cables are able to carry many more phone messages than metal wires.

But, how is it possible for light to travel along a transparent glass fiber without "leaking" out? In this investigation, you will explore *total internal reflection*, the phenomenon that allows light to travel long distances inside a light fiber.

In Activity 3-2 you collected data for light traveling in air, which has an index of refraction of 1.00 (n_1 = 1.00) and being refracted by water (n_2 = 1.33). In other words, $n_2 > n_1$.

Question 4-1: Based on your data for Activity 3-2, which angle is always greater, θ_2 or θ_1? Explain your answer based on Snell's Law, $n_1\sin\theta_1 = n_2\sin\theta_2$. (**Note**: Remember that the angles are measured *from the normal not from the surface*.)

Comment: When it is refracted at the boundary with a medium with a larger index of refraction than the one the light is originally traveling in (what we call *a more optically dense medium*) we say that the light is bent *closer to the normal*.

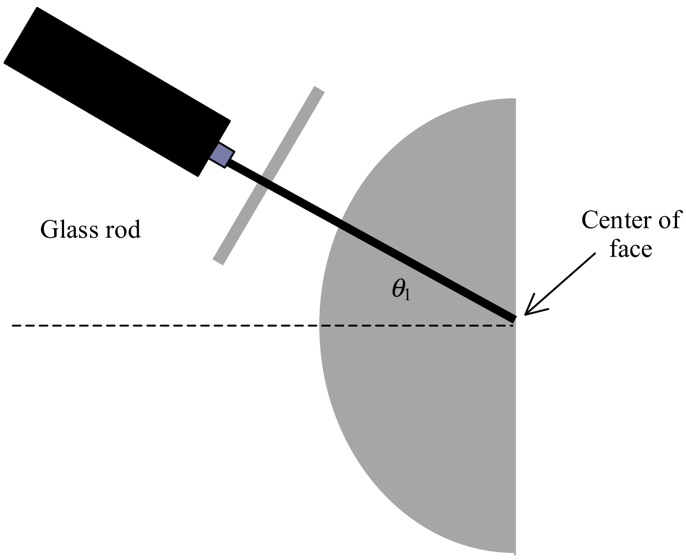
Prediction 4-1: Suppose that the laser light is originally traveling in the water, and is refracted at the surface with the air. (That is, the light is refracted at the boundary with a *less optically dense medium*, $n_1 > n_2$.) Which angle do you think will now be larger, θ_2 or θ_1? (**Note**: Again, remember that the angles are measured *from the normal not the surface*. **Hint**: look at Snell's Law.)

Test your predictions.

Activity 4-1: Refraction at a less dense medium

1. Set up the laser, glass rod and clear chamber on a separate piece of paper as shown in the diagram below. Choose an initial θ_1 of 20-30°.

   This time the laser beam enters the chamber through the curved face. In this activity, be sure that the beam always travels along a radius, and, therefore, always strikes the center of the flat surface for every incident angle, θ_1.



Question 4-2: Why is it important that the laser beam travel along a radius? (**Hint**: In this case, what are the incident and refracted angles at the curved face according to Snell's Law?)

2. Observe the direction of the refracted beam.

Question 4-3: Qualitatively compare θ_2 to θ_1. Which is larger? Does this agree with Prediction 4-1? Explain.

Prediction 4-2: Suppose that you move the laser and increase the angle of incidence, θ_1. What will happen to θ_2?

Prediction 4-3: Is there an angle of incidence for which no light is transmitted from the water into the air? If so, what is that angle? (**Hint**: remember that θ_2 cannot be greater than 90°. Calculate the corresponding θ_1.)

3. Increase θ_1 by moving the laser. Be sure that the beam always travels along a radius. Observe the refracted ray as you increase θ_1 slowly up to about 60°.

Question 4-4: Describe what happened to θ_2 as θ_1 was increased.

Question 4-5: What about Prediction 4-2? Is there a value of θ_1 for which there is no transmitted ray—for which all of the light is reflected back into the water?

Activity 4-2: Disappearing transmitted ray—a more quantitative look

1. With the same setup as in Activity 4-1, use the method of Activity 3-2 to measure θ_1 and the corresponding θ_2 for several different incident angles. Record your values in the table below.
2. Carefully locate and measure the smallest incident angle for which there is no transmitted ray. Record this angle in the table.

	θ_1	θ_2	Estimate of precision
Case 1			
Case 2			
Case 3			
No trans-mitted ray			

Question 4-6: How does your value for θ_1 when there is no transmitted ray agree with the value you calculated in Prediction 4-3?

Comment: The incident angle for which there is *total internal reflection* is called the *critical angle*. Note that no energy is lost when light is totally internally reflected. Virtually all of the incident intensity is reflected back into the optically denser material.

Question 4-7: Explain how total internal reflection enables the design of light "pipes" or optical fibers, through which light can be transmitted over long distances without leaking out. Make a sketch to illustrate your ideas.

INVESTIGATION 5: REFRACTION, DISPERSION, TOTAL INTERNAL REFLECTION, AND THE RAINBOW

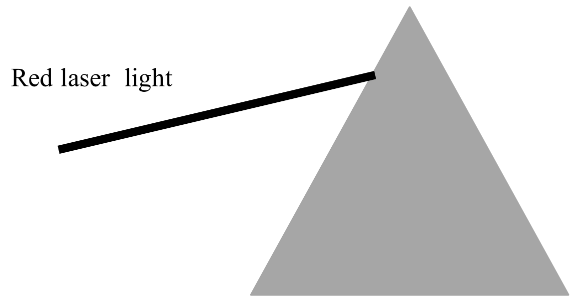
APPARATUS AND SUPPLIES

- Laser ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Flashlight with a narrow slit
- Prism
- Solid clear cylinder

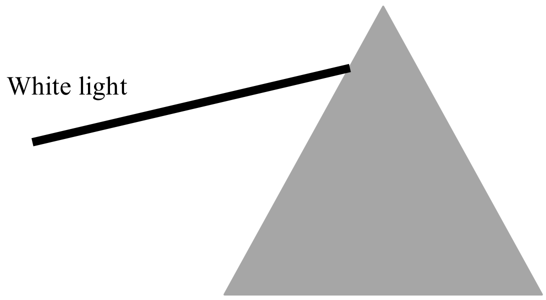
White light from the sun or other white light source includes all of the colors from violet (shortest wavelength) to red (longest wavelength). The index of refraction for most materials is slightly different for the different colors (wavelengths) of light. This phenomenon is called *dispersion*.

Prediction 5-1: Based on Snell's Law, if the index of refraction of a material varies with wavelength, what effect would this have on the refraction of different colors of light?

Prediction 5-2: Suppose that red laser light is incident on a prism—a triangular shaped slab of glass—as shown below. Sketch and describe the refracted light that comes out the other side of the prism.



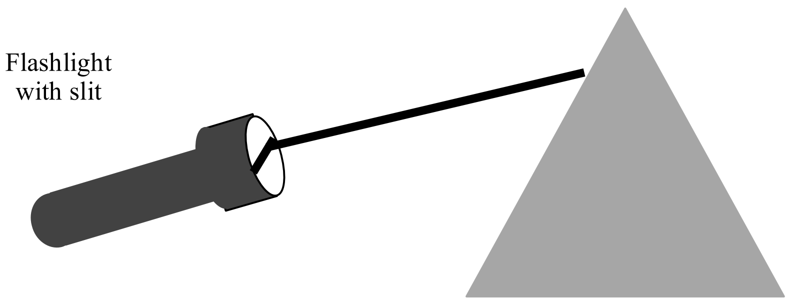
Prediction 5-3: Suppose that a narrow beam of white light is incident on a prism as shown below. Sketch and describe the refracted light that comes out the other side of the prism. (**Note**: because of dispersion, the index of refraction is different for each color of light. Make a guess whether the index is largest for red light or for violet light. State your guess, and base your predictions on it.)



Test your predictions.

Activity 5-1: Dispersion of white light by a prism

1. Set up the flashlight, slit and prism as shown in the diagram below.



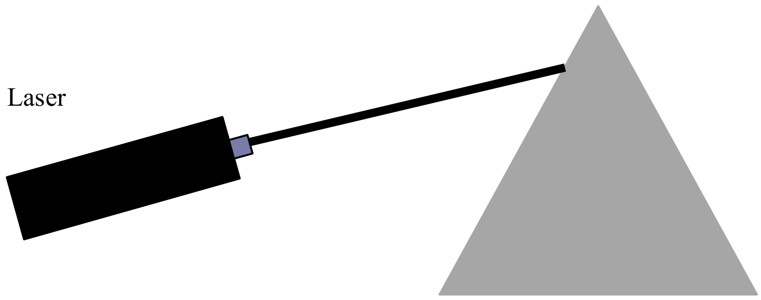
2. Observe the light coming out from the right side of the prism. Be sure to look back into the prism, and move your eye up and down to observe everything.
3. Make a sketch to the right of the prism above of the pattern of the refracted light that you observed. Be sure to label the color(s).

Question 5-1: Compare your observations to Predictions 5-1 and 5-3. Do you see a rainbow of colors? Which color is refracted the most by the prism and which the least?

Question 5-2: Based on this observation, is the index of refraction larger for red or violet light?

Activity 5-2: Dispersion of laser light by a prism

1. Set up the laser and prism as shown in the diagram below.



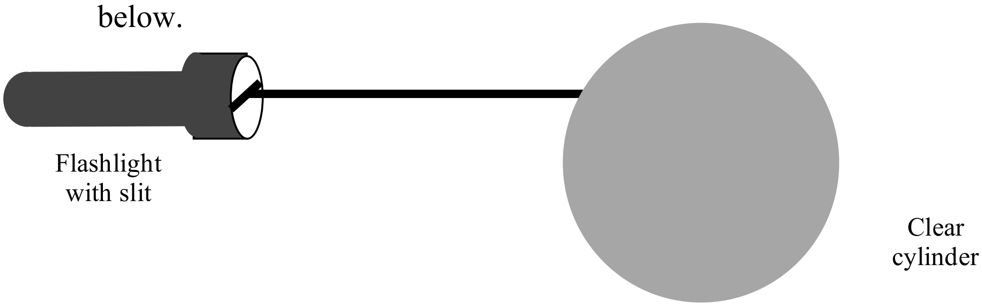
2. ***Do not look back into the laser light with your eye!*** Observe the light coming out from the right side of the prism with a piece of paper. Be sure to move the paper up and down to observe everything.
3. Make a sketch to the right of the prism above of the pattern of the refracted light that you observed. Be sure to label the color(s).

Question 5-3: Compare your observations to Prediction 5-2. Do you see a rainbow of colors? Explain any ways in which your observations are different than for the white light from the flashlight.

Activity 5-3: The rainbow

Now you are ready to explore how *refraction*, *dispersion* and *total internal reflection* in spherical water droplets result in the beautiful rainbows we observe in the sky.

1. Set up the flashlight, slit and clear cylinder as shown in the diagram below.

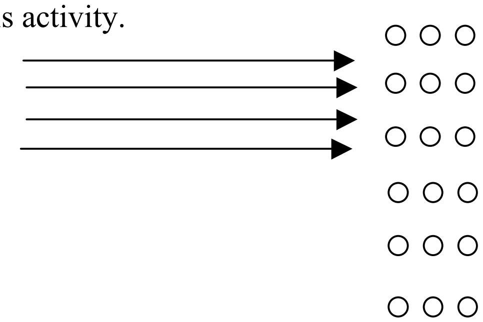


2. Move a piece of paper all the way around the clear cylinder, and observe the color(s) of any transmitted light, and also the direction in which it is observed. (You may also want to look into the cylinder with your eye.)
3. Sketch your observations on the diagram, indicating clearly the direction in which light leaves the cylinder. Be sure to label the color(s).

Question 5-4: Describe what you observed. Did you see a rainbow? If so, in which direction?

Question 5-5: Try to explain what you observed based on what you know about *refraction*, *dispersion* and *total internal reflection*. Draw a diagram and sketch rays inside the cylinder.

Question 5-6: In the diagram below, the circles represent water droplets in a cloud. The arrows represent rays of light from the sun. Where should you stand to observe the rainbow? Explain based on your observations in this activity.



Question 5-7: In this activity you used a clear *cylinder*, but rain droplets are actually *spherical*. Try to explain why rain droplets arranged as shown in Question 5-6 produce a semi-circular *bow* of colors.

INVESTIGATION 6: HOW ARE IMAGES FORMED BY LENSES?

APPARATUS AND SUPPLIES

- Two miniature light bulbs
- Power supply (or battery)
- Hair comb
- Cylindrical lens
- Green filter

When light is emitted or reflected by an object, each point on the object serves as a source of light. The light from each of these points spreads out in all directions in space. To understand what we see or what image is formed by a lens or mirror, we must first see what happens to the light from each of these point sources. The filament of a light bulb while not exactly a point source of light is small enough to be a good approximation.

To simplify matters, in this activity you will focus on the rays coming from only two points on an object.

Activity 6-1: A simple real image

Imagine that the arrow drawn in the picture on the following page is lighted. (It is either a source of light, or light is reflecting off of it.) Every point on the arrow sends out rays in all directions. To simulate this, you


Bulb 2
Bulb 1

will put small light bulbs at the head and foot of the arrow. These bulbs will represent points of the arrow that are emitting light.

1. Tape one of the miniature bulbs to the top and one to the bottom of the arrow, so that both bulbs are pointing up from the paper. (Do not place the cylindrical lens on the paper yet.)
2. Connect bulb 1 to the power supply and turn it on. Describe what the light from bulb 1 does. Then disconnect bulb 1 and connect bulb 2. Describe what the light from bulb 2 does.
3. Place the cylindrical lens in the semicircular outline on the diagram. Sketch on the diagram the beam of light that comes out of the lens with only bulb 2 turned on.
4. Place the comb midway between the bulb and the lens, parallel to the flat face of the lens, so that the beam is divided up into rays.

Question 6-1: Describe what the lens does to the rays from bulb 2. What is their direction when they leave the bulb (diverging, parallel or converging), and what is their direction when they leave the lens?

5. Place an X at the point where the image of bulb 2 is formed (where the rays from bulb 2 are converged to the smallest point by the lens).

Question 6-2: Are rays from bulb 2 hitting only part of the front surface of the lens or all of the front surface?

6. Disconnect bulb 2, connect bulb 1 and repeat (5).
7. Now turn both bulbs on at the same time. Put the green filter in front of bulb 2 so that you can distinguish the light from the two bulbs. Draw an arrow on the paper at the location where the image would be formed by the lens.

Question 6-3: Would the image of the arrow be upright or inverted? How do you know?

Question 6-4: Is the image of the arrow enlarged or reduced in size compared to the arrow itself?

Prediction 6-1: Suppose that you moved the lens further away from the arrow. How would the image be changed?

Prediction 6-2: Suppose that you moved the lens closer to the arrow. How would the image be changed?

Test your predictions.

8. Move the lens further away from the bulbs.

Question 6-5: Describe what happens to the image. Is it now larger or smaller? How do you know?

9. Move the lens closer to the bulbs.

Question 6-6: Describe what happens to the image. Is it now larger or smaller? How do you know?

Question 6-7: Is there a position of the lens closer to the bulbs beyond which an image is no longer formed? Experiment and explain.

Prediction 6-3: Suppose that you covered half of the side of the lens facing the arrow with a card, i.e., cover the top or bottom half of the lens *as seen in the diagram above*. How would the image be changed? Would the whole image of the arrow still be formed?

10. Move the lens back on the outline. Block half of the lens (top or bottom as seen in the diagram above) with a card.

Question 6-8: Carefully describe what happened to the image. Explain your observations based on what happens to rays from each of the bulbs that hit the unblocked half of the lens.

Prediction 6-4: Suppose that you covered the center of the lens facing the arrow with a piece of paper. How would the image be changed? Would the whole image of the arrow still be formed?

11. Block the center of the lens with a piece of paper.

Question 6-9: Carefully describe what happened to the image. Explain your observations based on what happens to rays from each of the bulbs that hit the unblocked portions of the lens.

Prediction 6-5: Suppose that you cover the top half of the arrow with a piece of paper. How would the image be changed? Would the whole image of the arrow still be formed?

12. Block the top bulb (bulb 1) with a card.

Question 6-10: Carefully describe what happened to the image. Explain your observations based on what happens to rays from each of the bulbs.

Prediction 6-6: Suppose that you removed the lens. How would the image be changed? Would the whole image of the arrow still be formed?

13. Remove the lens.

Question 6-11: Carefully describe what happened to the image.

Question 6-12: Carefully describe the function of a lens in forming an image. Describe what the lens does to the light coming from each point on the object.

Module 1:
Introduction to Geometrical Optics

Interactive Lecture Demonstration
Student Sheets

Hand in this sheet Name_____________________________

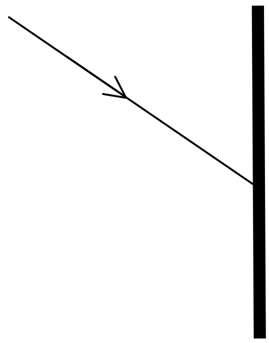
INTERACTIVE LECTURE DEMONSTRATIONS
PREDICTION SHEET—**REFLECTION AND REFRACTION OF LIGHT**

Directions: This sheet will be collected. Write your name at the top to record your presence and participation in these demonstrations. Follow your instructor's directions. You may write whatever you wish on the attached Results Sheet and take it with you.

Demonstration 1: Light is incident as shown on a plane mirror, like the one in your bathroom. The light ray is in the plane of this paper.

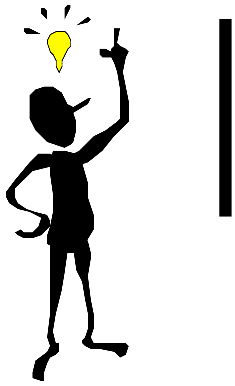
Sketch the normal to the surface of the mirror at the point where the light ray hits the mirror.

Predict the direction of the reflected ray, and sketch it on the diagram. Must the reflected ray be in the plane of the paper?



Demonstration 2: You are standing fairly close to the front of the mirror in your bathroom, and you see your image in the mirror. Sketch a stick figure prediction of your image on the diagram. Be sure to carefully show

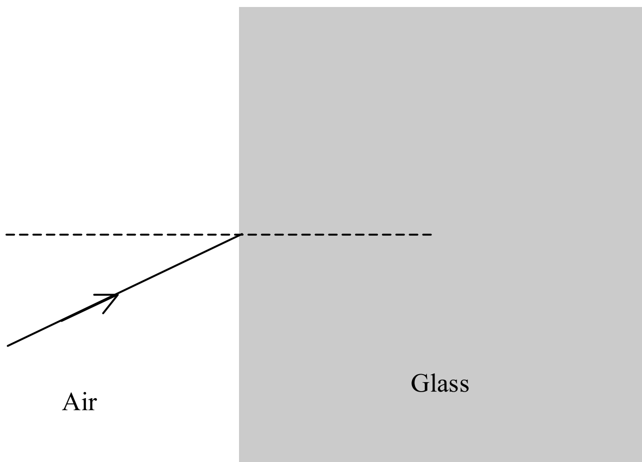
- The position of your image
- The direction your image is facing
- The height of your image
- Mark with arrows on your image about how much of your body you will actually be able to see



Demonstration 3: A light ray is incident on the surface of a slab of glass.

Which has a larger index of refraction—air or glass?

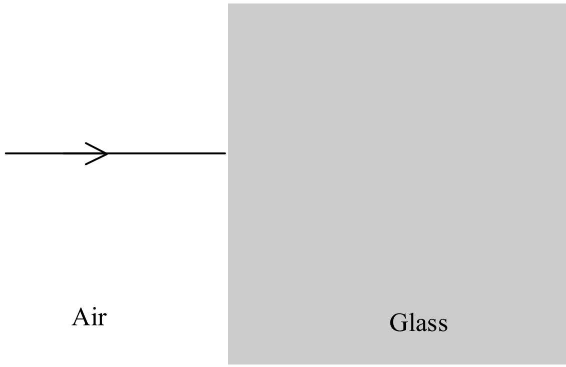
Sketch predictions of the reflected ray and transmitted ray on the diagram.



Demonstration 4: A light ray is incident normally on the surface of a slab of glass.

Predict approximately what percentage of the incident light is reflected (close to 100%, close to 50% or much smaller than 50%).

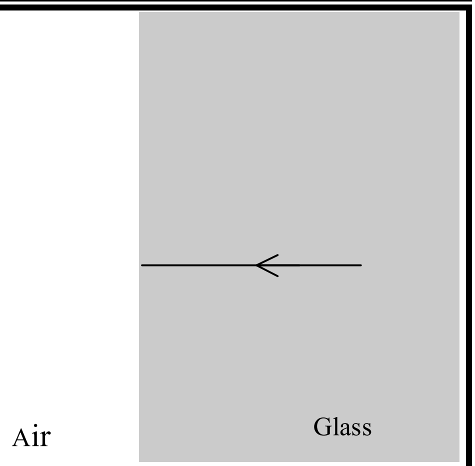
Predict approximately what percentage of the incident light is transmitted (close to 100%, close to 50% or much smaller than 50%).



Demonstration 5: Suppose that the light ray is traveling in the glass and incident normally on air.

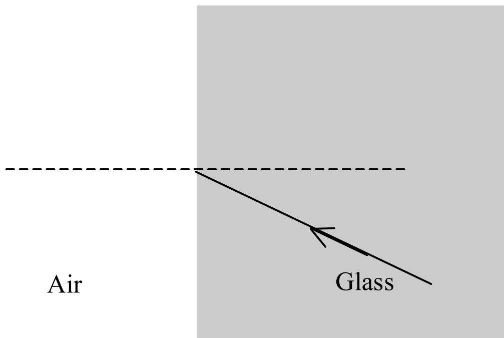
Predict approximately what percentage of the incident light is reflected—the same as in Demonstration 4, or, if different, how much?

Predict approximately what percentage of the incident light is transmitted—the same as in Demonstration 4, or, if different, how much?

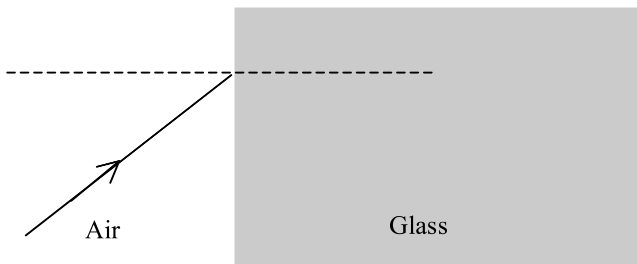


Demonstration 6: A light ray is traveling in a slab of glass, and is incident on air.

Sketch predictions of the reflected ray and transmitted ray on the diagram.

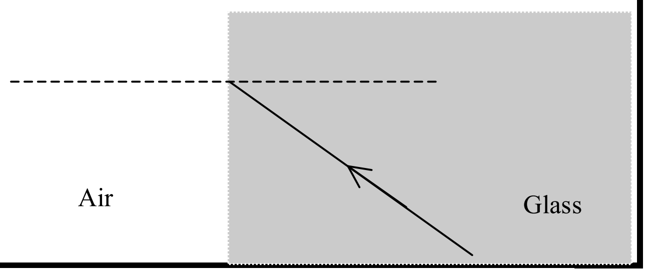


Demonstration 7: Based on your observations in Demonstrations 3 and 6, predict in which case on the right is it possible for there to be no transmitted ray (i.e., transmitted ray *along the surface*). Sketch this case on the diagram.



In this case, what percentage of the incident light is transmitted?

What percentage of the incident light is reflected?



Keep this sheet

INTERACTIVE LECTURE DEMONSTRATIONS
RESULTS SHEET—**REFLECTION AND REFRACTION OF LIGHT**

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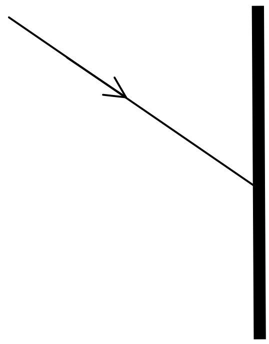

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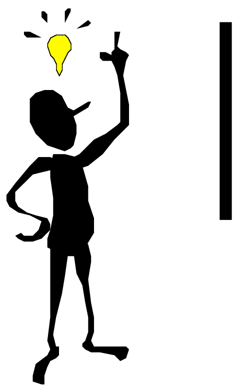

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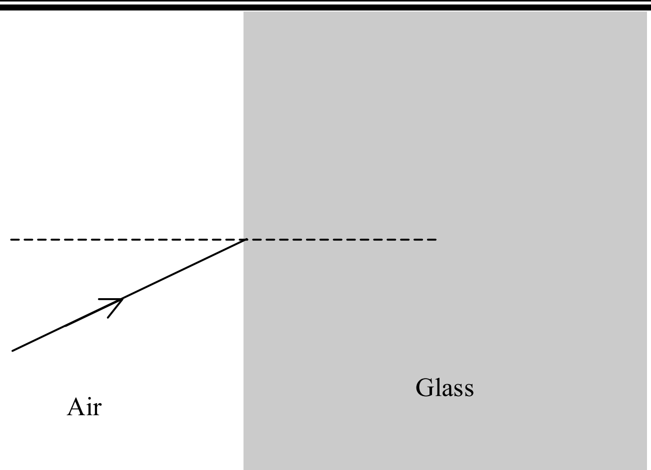
Which has a larger index of refraction—air or glass?

Sketch predictions of the reflected ray and transmitted ray on the diagram.



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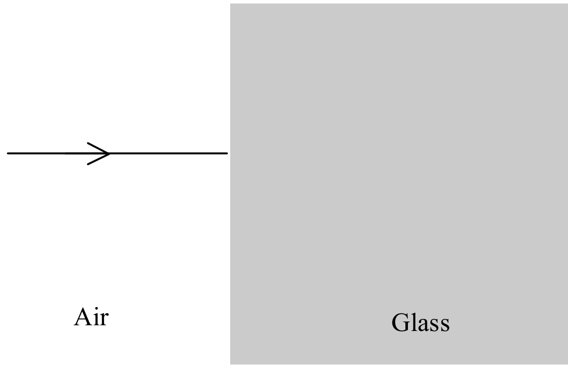
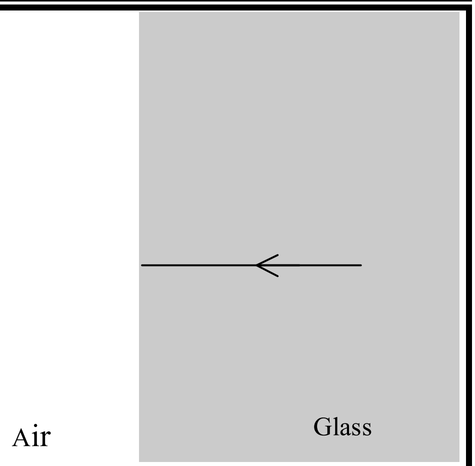
Predict approximately what percentage of the incident light is transmitted (close to 100%, close to 50% or much smaller than 50%).



Demonstration 5: Suppose that the light ray is traveling in the glass and incident normally on air.

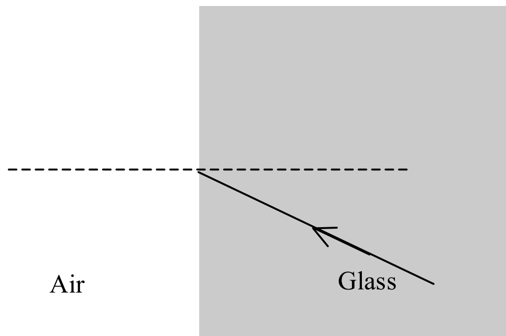
Predict approximately what percentage of the incident light is reflected—the same as in Demonstration 4, or, if different, how much?

Predict approximately what percentage of the incident light is transmitted—the same as in Demonstration 4, or, if different, how much?



Demonstration 6: A light ray is traveling in a slab of glass, and is incident on air.

Sketch predictions of the reflected ray and transmitted ray on the diagram.



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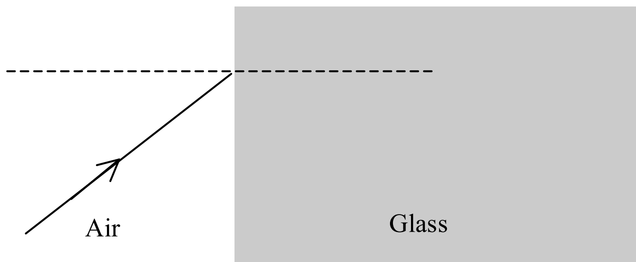
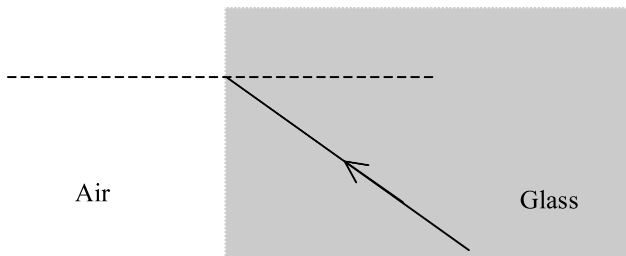


In this case, what percentage of the incident light is transmitted?

What percentage of the incident light is reflected?



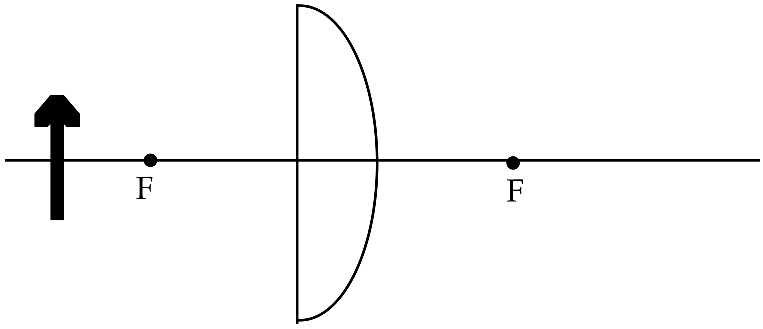
Hand in this sheet Name____________________________

INTERACTIVE LECTURE DEMONSTRATIONS
PREDICTION SHEET—**IMAGE FORMATION WITH LENSES**

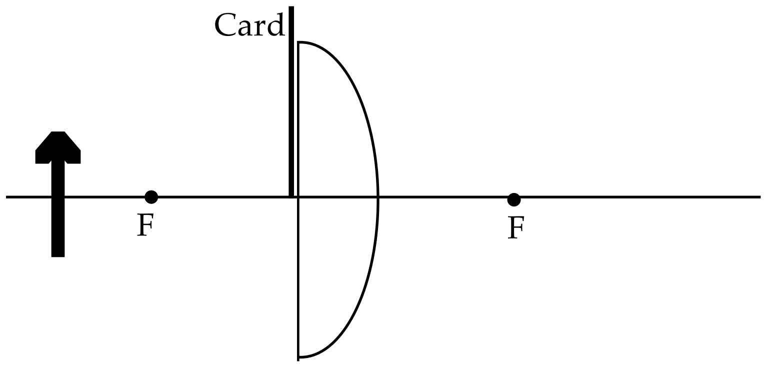
Directions: This sheet will be collected. Write your name at the top to record your presence and participation in these demonstrations. Follow your instructor's directions. You may write whatever you wish on the attached Results Sheet and take it with you.

Demonstration 1: You have a converging lens. An object in the shape of an arrow is positioned a distance larger than the focal length to the left of the lens, as shown in the diagram on the right. Draw several rays from the head of the arrow and several rays from the foot of the arrow to show how the image of the arrow is formed by the lens.

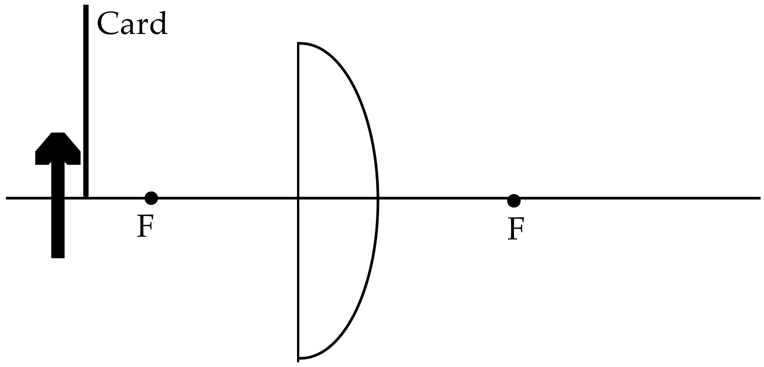
Is this a real or a virtual image?



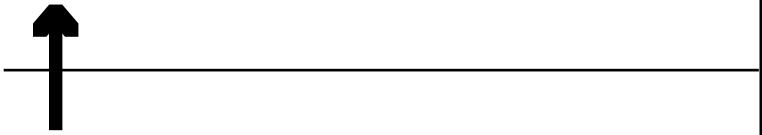
Demonstration 2: What will happen to the image if you block the top half of the *lens* with a card? Answer in words and show what happens on the diagram on the right by making any changes needed in the rays you drew in Demonstration 1.



Demonstration 3: What will happen to the image if you block the top half of the *object* with a card? Answer in words and show what happens on the diagram on the right by making any changes needed in the rays you drew above for Demonstration 1.



Demonstration 4: What will happen to the image if you remove the lens? Answer in words and show what happens on the diagram on the right by making any changes needed in the rays you drew above for Demonstration 1.



Demonstration 5: What will happen to the image if the object is moved further away from the lens? Will the position of the image change? If so, how?

Will the size of the image change? If so, how?

Will the image be real or virtual?

Demonstration 6: What will happen to the image if the object is moved closer to the lens (but is still further away than the focal point)? Will the position of the image change? If so, how?

Will the size of the image change? If so, how?

Will the image be real or virtual?

Demonstration 7: What will happen to the image if the object is moved closer to the lens so that it is closer to the lens than the focal point? Will the position of the image change? If so, how?

Will the size of the image change? If so, how?

Will the image be real or virtual?

Keep this sheet

INTERACTIVE LECTURE DEMONSTRATIONS
RESULTS SHEET—**IMAGE FORMATION WITH LENSES**

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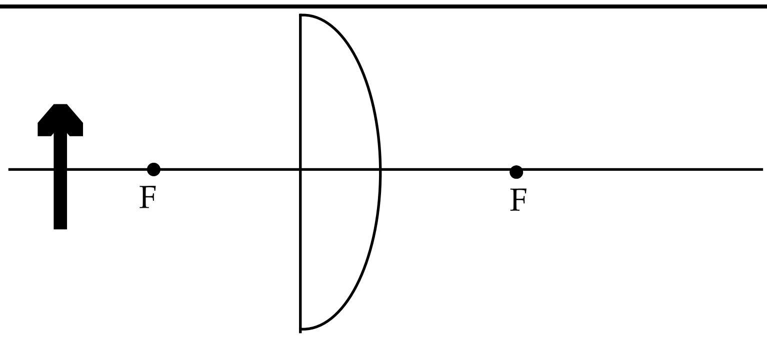
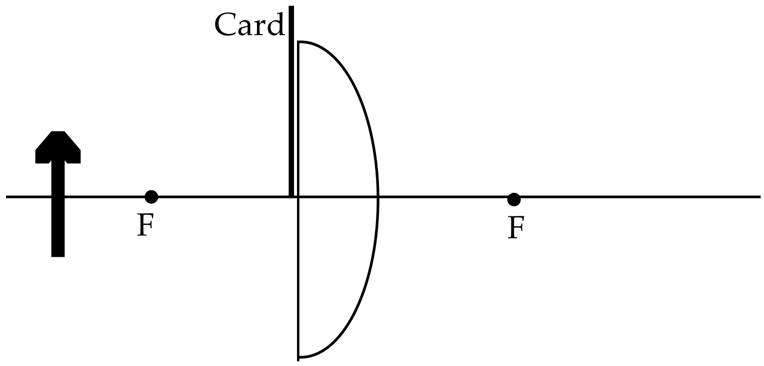


Is this a real or a virtual image?

Demonstration 2: What will happen to the image if you block the top half of the *lens* with a card? Answer in words and show what happens on the diagram on the right by making any changes needed in the rays you drew in Demonstration 1.



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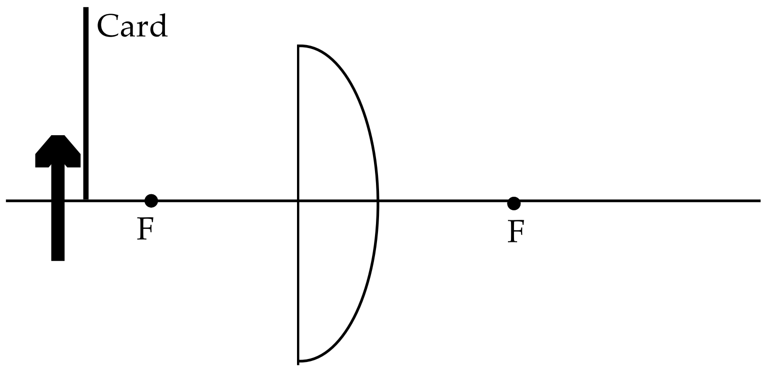

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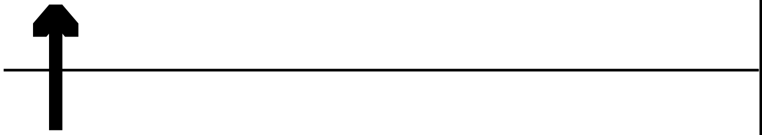

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Will the size of the image change? If so, how?

Will the image be real or virtual?

Demonstration 6: What will happen to the image if the object is moved closer to the lens (but is still further away than the focal point)? Will the position of the image change? If so, how?

Will the size of the image change? If so, how?

Will the image be real or virtual?

Demonstration 7: What will happen to the image if the object is moved closer to the lens so that it is closer to the lens than the focal point? Will the position of the image change? If so, how?

Will the size of the image change? If so, how?

Will the image be real or virtual?

Module 1:
Introduction to Geometrical Optics

Discussion Questions for Optics
Magic Tricks

Discussion Questions for Optics ***Magic:*** *Reappearing Test Tube*

1. How do you think that the test tube was made to reappear?

2. Why can you see a test tube in air or in water, but not in the magic fluid? What is special about the magic fluid?

3. What property of transparent media determines whether reflection takes place at the boundary between them? What has to be true about this property for the two materials in order for reflection to take place?

4. What about the light that is transmitted through the test tube? How is it affected when the test tube is in the magic fluid and when the test tube is in air?

Discussion Questions for Optics ***Magic:*** *Candle Under Water*

1. How do you think that it was possible for the candle to burn under water?

2. Describe the image of the candle formed by the glass (acrylic) mirror. Is the image real or virtual? Define both of these types of images.

3. Is the image upright or inverted compared to the candle? Compare the size of the image to the candle.

4. Compare the "handedness" of the image in a plane mirror to that of the object. That is if the object is a right hand, is the image a right or left hand?

5. What property of the glass (or acrylic) allows the sheet to act as a mirror?

Discussion Questions for Optics ***Magic:*** *Carbon to Silver*

1. How do you think that the carbon ball was made to appear like silver?

2. What could cause the carbon ball to become a reflecting surface when it is submerged in water?

3. Compare the index of refraction of the air layer around the ball to the index of refraction of the water. What special name is given to the reflection at this air layer?

4. Why is the surface of the ball not a “perfect” mirror?

Discussion Questions for Optics ***Magic:*** ***Falling Laser Beam***

1. What caused the laser beam to curve around and stay within the water stream?

2. Compare the index of refraction of the water to that of the air around it.

3. What special name is given to the reflection of the light at the surface of the water stream?

4. What practical devices work on the same principle?

Teachers' Guide for Module 1: Introduction to Geometrical Optics

TEACHERS' GUIDE FOR MODULE 1: INTRODUCTION TO GEOMETRICAL OPTICS

General Introduction

This module contains activities in three formats. The first section is meant to be implemented in a hands-on laboratory in which there is enough equipment for students to work in small groups of 2-4. The second section includes two sets of Interactive Lecture Demonstrations that duplicate the hands-on activities on 1) reflection and refraction at the interface of two transparent media, and 2) image formation with lenses. These topics may be presented to the students in either format, or through a combination with some activities done hands-on, and others done as ILDs. The third section includes four optics magic tricks that are to be presented as classroom demonstrations. The student sheets contain discussion questions. The class (even a large lecture class) can be broken down into small discussion groups of 2-3 students, and these questions can be used to stimulate discussion around these entertaining and informative "tricks."

This teachers' guide contains information on how to implement each of these sets of materials. Together they comprise an introduction to the treatment of light using rays, reflection and refraction, dispersion, total internal reflection, and the basics of image formation by lenses.

HANDS-ON LABS

Module 1 Hands-on Labs Apparatus and Supplies List

- Miniature light bulb
- Power supply (or battery)
- Holder for light bulb
- Light intensity meter
- Meter stick
- Laser ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Blackboard eraser and chalk dust
- Transparent ruler
- Small white disk
- Glass rod
- Semicircular transparent chamber filled with a slightly cloudy liquid
- Protractor
- Sharp pencil
- Flashlight with a narrow slit
- Prism
- Solid clear cylinder
- Two miniature light bulbs
- Hair comb
- Cylindrical lens

- Green filter

Equipment Notes

Miniature light bulb: It is important to use a very small bulb, and one with a glass envelope that produces minimal distortion. The Radio Shack (www.radioshack.com) #272-1141 is a miniature bulb with wire leads that operates at 12 V.

Light meter: Any light intensity meter with ranges appropriate to the sources used will be fine. A meter with a separate small sensor is preferable.

Laser: Please read the LASER SAFETY section of this manual. *The laser beam should never be directed toward anybody in the room. The laser beam is damaging to the eye.* Either a low-powered (0.5 mW) He-Ne laser or a laser pointer will work just fine.

Glass rod: A short piece of glass rod around 0.5 cm in diameter is used to broaden out the laser beam in the vertical direction to make the rays more visible on the paper.

Small white disk: This is just a circular disk of white paper, about 4 cm in diameter.

Semi-circular transparent chamber: This is a common item available in most physics departments. Such chambers are available from Sargent-Welch (www.sargentwelch.com), Refraction Cells #WL3502. The water inside can be clouded very slightly by adding a drop or two of milk.

Flashlight with a narrow slit: An ordinary flashlight (2D batteries) can be used. A slit about 1 mm or so wide can be fashioned from two strips of opaque tape (e.g., duct tape) taped over the lens.

Prism: Small glass or acrylic prisms are generally available in Physics departments. Ones with 25 mm faces will work fine for these activities. They are available from Edmund Scientific (http://scientificsonline.com), e.g., #3031800, Pasco Scientific (www.pasco.com), e.g., SE-9021A or SE9022A or Sargent Welch (www.sargentwelch.com), e.g., WL3487, CPP85506-05.

Solid clear cylinder: Cylinders about 25 mm thick can be cut from a Lucite rod 35-50 mm in diameter. The end faces do not need to be polished.

Cylindrical lens: The Pasco Scientific (www.pasco.com), #OS-8492, shown in Figure TG1-1, works perfectly. Any similar glass or acrylic lens that focuses the light from a bulb in the geometry shown in Figure TG1-3 within the boundaries of the page should be fine.

Figure TG1-1: Pasco #OS-8492 Cylindrical Lens.

Green filter: Any green filter that is not too dark should be fine.

Hair comb: Any plastic hair comb will work fine.

INVESTIGATION 1: A THOUSAND POINTS OF LIGHT

Investigation 1 Apparatus and Supplies List

- Miniature light bulb
- Power supply (or battery)
- Holder for light bulb
- Light intensity meter
- Meter stick
- Laser ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Blackboard eraser and chalk dust
- Transparent ruler
- Small paper disk

Overview

These activities are designed to introduce the students to point sources and how to represent the light from sources using rays. While the first activity is semi-quantitative, the others are qualitative exercises to get students to think about light propagating from a source.

Activity 1-1: Light intensity around a point source

Some care is necessary to do these measurements well, and to observe the $1/R^2$ drop off of intensity with distance from the point source. Five measurements at different locations around the bulb are included for each distance from the bulb in order to average out any variations caused by the envelope of the bulb and the aiming of the light meter.

Question 1-1: The intensity clearly decreases as the meter is moved further from the bulb.

Question 1-2: The light spreads out in all directions around the bulb. The power falls on a spherical surface centered on the bulb. The area of this surface increases as its radius increases, and therefore, the intensity of light incident on it (power per unit area) decreases.

Question 1-3: Since the area of a spherical surface is $4\pi R^2$, the intensity varies inversely with R^2.

Activity 1-2: Diverging and parallel rays of light

Based on Activity 1-1, students should be able to draw rays from the point source as radially diverging.

Question 1-4: The rays are straight lines drawn diverging radially from the filament of the bulb.

Question 1-5: As observed, the light from the laser propagates essentially in a straight line. Therefore, unless your eye intercepts this line, you cannot see the laser light. The chalk dust scatters some of the laser light towards your eye so that you can see it.

Question 1-6: The light from the laser doesn't spread out, while that from the small light bulb spreads out radially. In addition, the light from the laser is red, while that from the light bulb is white.

Question 1-7: The light from the laser does not spread out appreciably. It can be represented by parallel rays in a very narrow beam. The light from the bulb spreads out radially and is represented by diverging rays.

Question 1-8: There would only be a ray through 2, but not through 1 or 3. If the laser were replaced by a point source, there would be radially diverging rays through all three points.

Activity 1-3: Rays from a distant source of light

This activity is designed to help students appreciate why the light from the sun (or any distant source) can be represented by parallel rays.

Question 1-9: The distance from the bulb to the disk is much larger than the diameter of the disk.

Question 1-10: The light is best represented by parallel rays.

INVESTIGATION 2: UNDERSTANDING LIGHT WITH RAYS

Investigation 2 Apparatus and Supplies List

- Laser ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Glass rod
- Miniature light bulb
- Power supply (or battery)
- Holder for light bulb
- Semicircular transparent chamber filled with a slightly cloudy liquid
- Blackboard eraser and chalk dust

Overview

This investigation is a qualitative introduction to the interaction of light with the surface of a transparent medium. It is a prelude to Investigation 3 in which the laws of reflection and refraction will be examined quantitatively.

Activity 2-1: Interaction of parallel rays with the surface of a transparent object

Question 2-1: Some of the light is reflected at the surface and some of the light travels through the surface into the water.

Activity 2-2: Interaction of diverging rays with a transparent surface

These observations are more difficult to make. However, it is possible to see that the rays reflected from the surface are still diverging, as are the rays that are transmitted through the surface into the water.

Question 2-2: The rays diverging from the point source are still diverging after they are reflected from the surface.

Question 2-3: You could put the laser at the position of the light bulb, and aim the beam at one of the three marked points on the surface of the transparent chamber. Since the laser beam is like one ray, you could trace its path after it is reflected or transmitted.

INVESTIGATION 3: LAWS OF REFLECTION AND REFRACTION

Investigation 3 Apparatus and Supplies List

- Laser ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Glass rod
- Semicircular clear chamber filled with a slightly cloudy liquid
- Blackboard eraser and chalk dust
- Sharp pencil
- Clear plastic ruler
- Protractor
- Graphical analysis software or graph paper

Overview

These activities are designed to introduce the students to the laws of reflection and refraction.

Activity 3-1: Law of reflection

The glass rod should be positioned in the laser beam so that the beam is spread out vertically. This will make it much easier to see on the paper below. Care must be taken in making all marks on the paper, in drawing in the lines with the pencil, and in measuring the angles with the protractor. It is important that for each incident angle of the laser beam, the beam hits the flat face of the chamber at exactly the same point.

Students usually have trouble estimating precision, so a little help here will be appreciated, and will be valuable for the remainder of the lab.

Question 3-1: The angles should be equal within the precision of the measurements.

Question 3-2: The reflected beam is in the plane of incidence. If it were not in this plane, it would either rise away from the paper or move down into the paper.

Question 3-3: When a ray of light is incident from one transparent medium on the flat surface of a different transparent medium (with different index of refraction), the reflected ray is in the same plane as the incident ray and the normal to the surface, and the angle of incidence equals the angle of reflection (both angles measured from the normal to the ray).

Question 3-4: The reflected intensity is smaller than the incident intensity. The rest of the light was transmitted through the front surface of the chamber into the liquid.

Activity 3-2: Snell's law of refraction

Only a small amount (a few drops) of milk is needed to cloud the water in the chamber sufficiently to see the transmitted beam. If you cloud the liquid too much, you will not be able to see the beam coming out of the curved side of the chamber. The same care in making marks on the paper as in Activity 3-1 should be taken here. Because of scattering in the cloudy liquid, the transmitted beam is not as bright as the reflected one, and is also more diffuse, making it more difficult to see.

The graphical analysis software should allow the data for sin θ_1 to be plotted vs. sin θ_2. If it is not available, plot the graph manually on graph paper.

Question 3-5: The angle of the transmitted ray with the normal is always smaller than the angle of the incident ray with the normal.

Question 3-6: There should be a proportional relationship between sin θ_1 and sin θ_2. That is, the graph should be a straight line that passes through the origin.

Question 3-7: According to Snell's law, if $n_1 = 1.00$, the slope of the graph of sin θ_1 vs. sin θ_2 should be the value of n_2.

INVESTIGATION 4: TOTAL INTERNAL REFLECTION

Investigation 4 Apparatus and Supplies List

- Laser ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Glass rod
- Semicircular clear chamber filled with a slightly cloudy liquid
- Blackboard eraser and chalk dust
- Sharp pencil
- Clear plastic ruler
- Protractor

Overview

In this investigation the same apparatus is used to look at refraction when light travels from a more optically dense medium to a less optically dense one. Then total internal reflection is possible.

Question 4-1: When the light originates in the air and is refracted by the water, θ_1 is always greater than θ_2. This can be seen from Snell's law solved for

$\sin\theta_2 = (n_1/n_2)\sin\theta_1$. Since $n_2 > n_1$, $\sin\theta_2 < \sin\theta_1$, and $\theta_2 < \theta_1$.

Activity 4-1: Refraction at a less dense medium

This activity is a qualitative observation of total internal reflection. More quantitative observations are made in Activity 4-2.

Question 4-2: Radii are perpendicular to the circular surface of the chamber. Pointing the laser beam along a radius assures that no refraction takes place as the light enters the chamber at the circular surface.

Question 4-3: Now θ_2 is always greater than θ_1.

Question 4-4: As $\theta_1$was increased, θ_2 also increased, and always remained greater than θ_1.

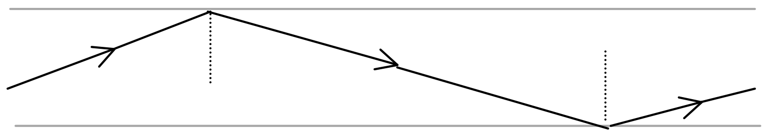
Question 4-5: Yes, there is an incident angle for which no light is transmitted into the air. In this case, all of the light is reflected back into the water.

Activity 4-2: Disappearing transmitted ray—a more quantitative look

The same care in making marks on the paper as in Activity 3-2 should be taken here. Again, because of scattering in the cloudy liquid, the transmitted beam is not as bright as the reflected one, and is also more diffuse, making it more difficult to see.

Question 4-6: The measured value should agree with the one calculated by substituting 90° into Snell's law for θ_2. The calculated value for θ_1 is 48.8°.

Question 4-7: If the light traveling inside an optical fiber made of a transparent material is incident on the surface with air on the outside, it will be totally reflected back into the fiber whenever the angle of incidence at the surface is greater than the critical angle. Therefore, the light will just keep bouncing back and forth within the fiber, without "leaking out."



INVESTIGATION 5: REFRACTION, DISPERSION, TOTAL INTERNAL REFLECTION, AND THE RAINBOW

Investigation 5 Apparatus and Supplies List

- Laser ***CAUTION: Do not point the laser into or near anyone's eyes***
- Flashlight with a narrow slit
- Prism
- Solid clear cylinder

Overview

Dispersion explains the different amounts of bending for different wavelengths (colors) of light in refraction. This is the origin of the spectrum of colors produced by a prism when white light is shone on it. The combination of dispersion and total internal reflection explains the origin of rainbows. These phenomena will be explored qualitatively in this investigation.

Activity 5-1: Dispersion of white light by a prism

The flashlight and slit are described above. The slit should be parallel to the horizontal edges of the prism, in the position shown in the diagram. It is necessary to tilt the flashlight to various positions until an optimum rainbow is observed.

Question 5-1: There should be a rainbow of colors with red on top (bent the least) and violet on the bottom (bent the most).

Question 5-2: According to Snell's law, if n_2 is larger, θ_2 is smaller. Since θ_2 is measured relative to the normal to the surface, smaller angle means greater bending. Therefore the index of refraction appears to be largest for violet light and smallest for red light.

Activity 5-2: Dispersion of laser light by a prism

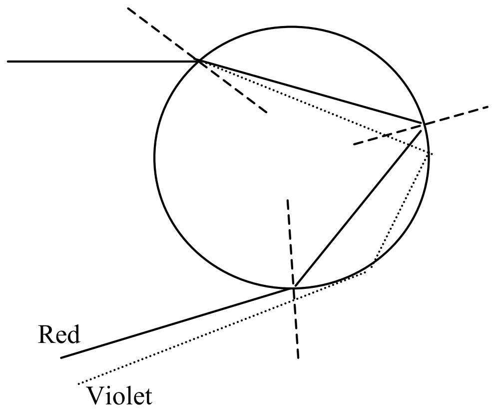
Question 5-3: There is no rainbow of colors this time. The laser light has only a very narrow range of wavelengths (it is essentially one color), rather than all of the visible wavelengths in white light. Therefore, the laser light cannot be spread out into a rainbow by a prism.

Activity 5-3: The rainbow

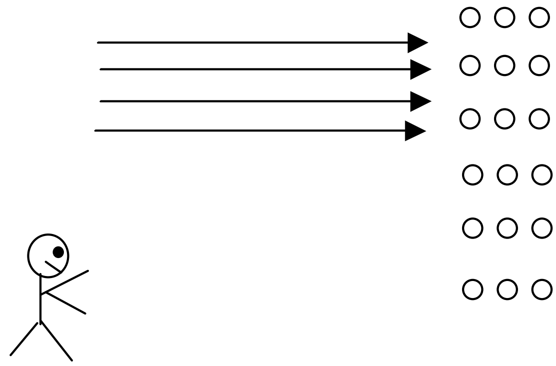
As in Activity 5-2, it will take some experimenting to find exactly where to aim the narrow flashlight beam.

Question 5-4: A narrow rainbow was observed. It was necessary to look into the portion of the cylinder below where the flashlight beam entered the cylinder, toward the right and a little upward.

Question 5-5: As the light enters the cylinder from air, it is refracted and spread out into a rainbow of colors by dispersion. Then, it strikes the back surface of the cylinder and is totally internally reflected. It strikes the lower face of the cylinder, is refracted and transmitted back into the air, while being dispersed still further.



Question 5-6: You should stand below the rays facing the droplets, as shown below.



Question 5-7: If you imagine a sphere instead of a cylinder, you can see that the angle made with the incident beam by the light coming out of the rain droplet must always be the same (actually 42°). So, the light coming out from all parts of all droplets will form a cone of light. As you look at

it, you can see only the top half (the bottom half would be below the ground), so you see a semi-circle.

INVESTIGATION 6: HOW ARE IMAGES FORMED BY LENSES?

Investigation 6 Apparatus and Supplies

- Two miniature light bulbs
- Power supply (or battery)
- Hair comb
- Cylindrical lens
- Green filter

Overview

In most introductory presentations on image formation with lenses, emphasis is placed on "simple" ray diagrams drawn with special, principal rays. Physics education research shows that with this approach a significant number of students fail to understand what it means to form an image, and do not appreciate the role of a lens (or mirror) in the image formation process. The activities in Investigation 1 examine ALL of the light emanating from two different point sources on the object. Research

shows that this helps students to appreciate that all the light from a single point on the object that strikes the lens must be focused to the same image point if a sharp image is to be formed.

Figure TG1-2 shows the setup, Figure TG1-3 shows what is observed with one bulb lighted, and Figure TG1-4 shows both bulbs lighted.

Activity 6-1: A simple real image

The lens should be placed on the outline on the page, and the two bulbs should be taped to the page on top of the sketches of the bulbs. The wires attached to the bulbs should be bent so that the bulbs point vertically up from the paper and are about 5-10 mm above the page. (See Figure TG1-2.) It is easiest to observe the results if the bulbs are lighted as brightly as possible. Therefore, the bulbs should be lighted with a battery or power supply that supplies the full operating voltage (usually 12 V).

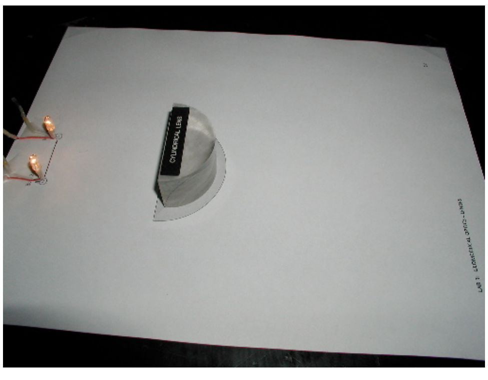


Figure TG1-2: Layout for Activity 6-1 with the bulbs taped so that they point upward.

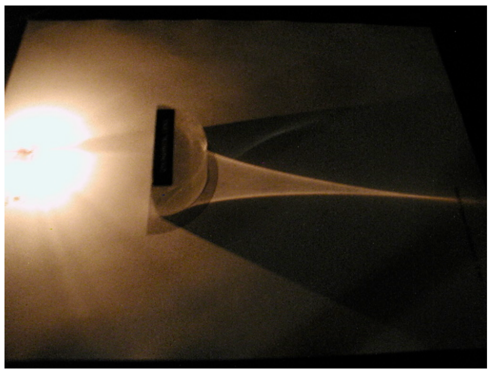


Figure TG1-3: Bulb 1 lighted at head of object arrow in Activity 6-1.

Question 6-1: The light from each bulb spreads out (diverges) equally in all directions.

Question 6-2: The rays are diverging from bulb 2 when they leave the bulb and when they reach the lens. After leaving the lens, they are converging to a point beyond the lens.

Question 6-3: Rays from bulb 2 hit all parts of the front surface of the lens.

Question 6-4: The image of the arrow is inverted. The light from bulb 1 (the head of the arrow) is focused below, while that from bulb 2 (the tail of the arrow) is focused above.

Question 6-5: The arrow is enlarged. The two focus points are further apart than the head and tail of the object arrow. (Of course, this depends on the actual cylindrical lens that is used.)

Question 6-6: The image gets smaller when the lens is moved further away. You can see that the two image points move closer together.

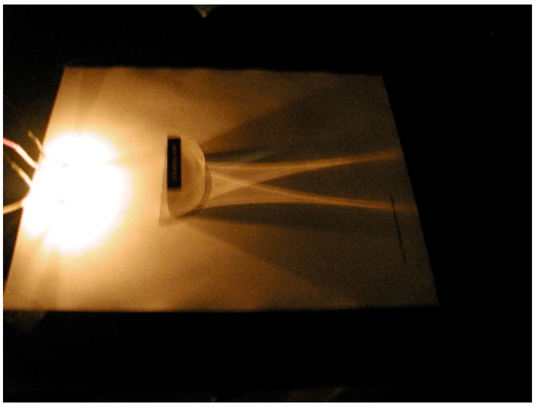


Figure TG1-4: Bulbs 1 and 2 lighted at head and tail of object arrow in Activity 6-1.

Question 6-7: The image gets larger when the lens is moved closer. You can see that the two image points move further apart.

Question 6-8: If you move the lens close enough to the bulbs, the light from the bulbs is diverging when it leaves the lens. Therefore the light from bulb 1 never converges to a point, and likewise for the light from bulb 2. Therefore an image is no longer formed beyond the lens.

Question 6-9: It is clear that the light from each bulb that hits the uncovered portion of the lens is focused to the same image point as before. Therefore the entire image is still formed. However, the light that hits the covered portion of the lens (half of the light) never reaches the image points. Therefore, the image is in the same location, is the same size and is still inverted, but it is dimmer. (See Figure TG1-5.)

Question 6-10: Again the image is in the same location, is the same size and is still inverted. It is dimmer for the same reason as in Question 1-9.

Question 6-11: No light from bulb 1 reaches the lens at all. Likewise no light from the top half of the object would reach the lens, and the top half (arrow head) of the image would disappear. (See Figure TG1-6.)

Question 6-12: The image disappears. There is nothing to focus the rays of light to image points.

Question 6-13: The lens focuses ALL of the light from each point source on the object (that reaches the lens) to a unique image point on the image. Without the lens, no image can be formed.

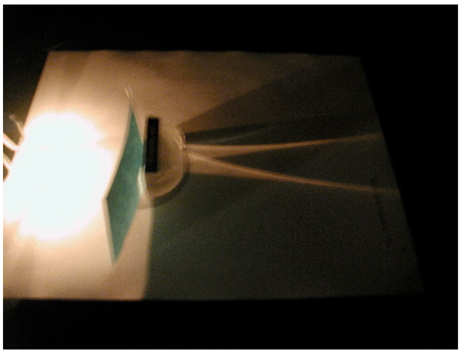


Figure TG1-5: Bulbs 1 and 2 lighted with bottom half of lens blocked by card in Activity 6-1.

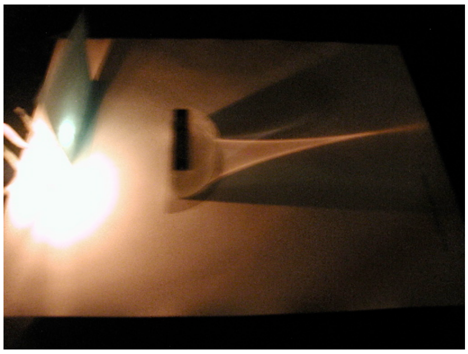


Figure TG1-6: Bulbs 1 and 2 lighted with Bulb 1 blocked by card in Activity 6-1.

INTERACTIVE LECTURE DEMONSTRATIONS

PART 1: REFLECTION AND REFRACTION OF LIGHT

APPARATUS AND SUPPLIES

- Large plane mirror with horizontal mount
- Large sheet of glass or Lucite
- Cloth to cover mirror
- Laser ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Blackboard eraser and chalk dust
- Cylindrical Lucite lens (semi-circular)
- Rotating mount for the Lucite lens
- Ruler

EQUIPMENT NOTES

Plane mirror: The mirror should be the size of a bathroom mirror. It should be mounted vertically facing the class, with the bottom at about waste level. It should be covered by a cloth at first, so that the students cannot see it.

Sheet of Lucite: The size of the sheet of Lucite should be appropriate to the size of the class. A sheet about 0.6 m x 0.6 m should be adequate.

Laser: Please read the LASER SAFETY section of this manual. ***The laser beam should never be directed toward anybody in the room. The laser beam is damaging to the eye.*** The laser doesn't need to be too powerful. A laser pointer will work fine.

Cylindrical Lucite lens (semi-circular) and mount: The Lucite lens should be large enough for the class to see—at least 10 cm radius. Its cross-section should be semi-circular, and it should be at least 5 cm thick. (See the photograph in Figure TG1-7.) If you have a blackboard optics kit (for example PASCO (www.pasco.com) SE-9193 or SE-9194), it probably includes a lens like this. You can attach the lens to a black or whiteboard. It is most convenient to mount the lens so that it can rotate about an axis perpendicular to its cross-section. Some blackboard optics kits include such a mount for the lens, or you can construct one.

DEMONSTRATIONS AND SAMPLE RESULTS

<u>Demonstration 1:</u> Law of reflection. After the prediction and discussion steps, shine the laser at the flat side of the cylindrical lens, so that it is incident on the surface as shown in the diagram on the student sheets. Use chalk dust to view the paths of the incident and reflected rays. The ruler may be used to show the normal to the surface.

Discussion after observing the results: Ask students to describe the direction of the reflected ray. Is the angle of the reflected ray measured from the normal (the angle of reflection) the same as the angle of the incident ray with the normal (the angle of incidence)? Are the incident ray, the normal and the reflected ray all in the same plane? Have a volunteer summarize the law of reflection.

<u>Demonstration 2:</u> Image in a plane mirror. The large mirror should be covered and facing the class. Stand in front of the covered mirror—as shown in the diagram—and ask students to make their predictions. After the prediction and discussion steps, uncover the mirror. For a large class, you will probably need to describe what you can see. For a small class, at least some students could come up and view their images in the mirror. Also let seated students view their images in the mirror, since all but the last prediction can be analyzed based on these observations.

Discussion after observing the results: Ask students to describe their images in the mirror. Where does the image appear to be? Is it upright or inverted? Does it appear to be larger, smaller or the same size as the object? Can you see most of your body, or just the part equal to the height of the mirror? Ask students to explain why you can see your whole body (or most of it). It will be helpful to sketch several rays leaving the character in the diagram and reflected from the surface of the mirror.

<u>Demonstration 3:</u> Refraction at the surface of a more dense medium. After the prediction and discussion steps, shine the laser at an angle with the flat face of the Lucite lens, as in the diagram. This time focus attention on the ray transmitted through the surface and coming out through the curved surface. Chalk dust will again be helpful. If the laser beam is incident at the center of the flat face, it will be refracted at this surface, but not at the curved surface. (The refracted ray will be along a radius and perpendicular to the curved surface.)

Discussion after observing the results: Ask students to describe the direction of the refracted ray. Is the ray bent at the surface? Is the angle of refraction greater than or less than the angle of incidence (both measured with the normal to the surface)? Are the incident and refracted rays and the normal in the same plane? Ask for volunteer(s) to state the law of refraction qualitatively.

<u>Demonstration 4:</u> Percent reflection at the surface of a more dense medium. After the prediction and discussion steps, shine the laser at a small incident angle with the flat surface of the Lucite lens. Use chalk dust to show the incident and reflected rays. It will also be helpful to hold up the large sheet of Lucite, and let the students observe their reflections in it.

Discussion after observing the results: Ask students to compare the incident and reflected intensities (brightness of the beams). If you used the Lucite sheet, ask students to describe how bright their image was. Was very much light reflected from the Lucite to form an image? (Actually, only about 4% of the incident light is reflected by one surface of Lucite or glass.) Why does the mirror in your bathroom reflect more than this?

<u>Demonstration 5:</u> Percent reflection at the surface of a less dense medium. After the prediction and discussion steps, shine the laser through the curved surface of the Lucite lens along a radius so that it strikes the flat surface at the center. The light was moving in the more dense medium, and is now reflected by the less dense medium (air). It is probably easier to use chalk dust to look at the transmitted ray, and compare its brightness to the ray incident on the curved surface. This is not an easy comparison to make.

Discussion after observing the results: Ask students to compare the incident and reflected intensities (brightness of the beams). Is there any reason why the percentage reflected should be different because of the different direction of the incident beam? Actually, the same percentage—only about 4% of the incident light—is reflected by one surface of Lucite or glass in this case as well.

<u>Demonstration 6:</u> Refraction at the surface of a less dense medium. After the prediction and discussion steps, shine the laser through the curved surface of the Lucite lens, along a radius so that it strikes the flat surface at its center. Focus attention on the ray transmitted through the flat surface. Use chalk dust to make the transmitted ray visible.

Discussion after observing the results: Ask students to describe the direction of the refracted ray. Is the ray bent at the surface? Is the angle of refraction greater than or less than the angle of incidence (both measured with the normal to he surface)? How does this result differ from Demonstration 3?

<u>Demonstration 7:</u> Total internal reflection. After the prediction and discussion steps are finished, shine the laser first as in Demonstration 3, rotating the lens to demonstrate that there is always a transmitted ray. Then shine the laser as in Demonstration 6, rotating the lens until there is no transmitted ray and all of the light is reflected back into the Lucite.

Discussion after observing the results: Ask students if there is an angle at which there is no transmitted ray in the top diagram? In the bottom diagram? Ask for volunteer(s) to describe what total internal reflection is.

PART 2: IMAGE FORMATION WITH LENSES

APPARATUS AND SUPPLIES

- Cylindrical Lucite lens (semi-circular)
- Mount for the Lucite lens
- Arrow about half the diameter of the lens, either drawn on the white (black) board, or on a card
- Two small, bright light bulbs, sockets and connecting leads
- Mounts for bulbs
- Power supply (or battery)
- Green filter
- Hair comb
- Index card

EQUIPMENT NOTES

Cylindrical Lucite lens (semi-circular) and mount: The Lucite lens should be large enough for the class to see—at least 10 cm radius. Its cross-section should be semi-circular, and it should be at least 5 cm thick. If you have a blackboard optics kit (for example PASCO (www.pasco.com) SE-9193 or SE-9194), it probably includes a lens like this. You can attach the lens to a black or whiteboard. Some blackboard optics kits include a magnetic or suction mount for the lens, or you can construct one. Figure TG1-8 shows an inexpensive alternative, a smooth-walled plastic jar filled with water. The pictured jar is a Nalgene one with diameter around 15 cm. This is a common item available from chemistry supply companies. If you use such a jar, the positioning of the jar and separation of the bulbs is more critical if you wish to get the desired effect when half of the lens is covered. (See below.)

Light bulbs: The bulbs should be fairly bright, but any 6 V flashlight bulbs and sockets should work. The sockets should be wired in parallel with enough wire to reach the battery or power supply. If you glue ceramic magnets to the bottoms of the sockets, you can easily mount the bulbs on a white board or black board that has an iron backing.

DEMONSTRATIONS AND SAMPLE RESULTS

Demonstration 1: Ray diagram. Figure TG1-7 shows the setup with the lens, arrow and bulbs. Figure TG1-8 shows an alternative to the Lucite lens. Figure TG1-9 shows the setup with the bulbs lighted. Begin by showing students the setup with the bulbs off. These first predictions will obviously be easier for students who have already studied image formation in lecture, and who have had some practice drawing ray diagrams. (This does not mean that they will necessarily draw the diagram correctly!) The idea behind this sequence of demonstrations is that students will better understand the function of a lens in forming images if they see what happens to *all* the light rays from a point on the object incident on the lens.

After the prediction and discussion steps, tell the students that the two bulbs represent point sources of light at the head and foot of the arrow. Turn on both bulbs. Then put the green filter in front of the top bulb. Put the comb in front of the two bulbs to give the illusion of multiple rays.

Discussion after observing the results: Ask students to describe where the image points are for the top and bottom bulbs. What does the lens do to all of the rays from a point on the object that are incident on the lens? Where are the image points of each bulb? What does image formation mean? Is this a *real* or *virtual* image? Have students define each of these. Is the image upright or inverted?

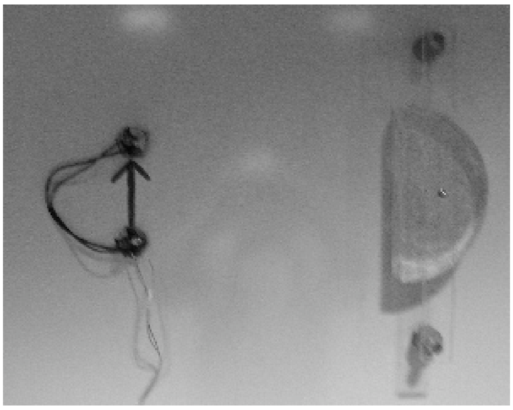


Figure TG1-7: Setup for observing image formation in these demonstrations.

Figure TG1-8: Alternative, inexpensive cylindrical lens—a smooth-walled plastic jar filled with water.

Demonstration 2: Blocking top half of the lens. After the prediction and discussion steps, keep both bulbs lighted, and place the card so that it blocks the top half of the lens. Be sure that students can see clearly that light from both bulbs incident on the bottom half of the lens is still focused to two image points. (The image is whole, at the same location and dimmer.)

Discussion after observing the results: Would the whole image of the arrow still be seen? Would it be in the same location? How would it be changed?

Demonstration 3: Blocking half the object. After the prediction and discussion steps, keep both bulbs lighted and place the card so that it blocks the top bulb (part of the top half of the object). Be sure that students can see clearly that light from the top bulb no longer reaches the lens, and is not focused to an image point. (Only the bottom half of the arrow is now imaged by the lens.)

Discussion after observing the results: Would the whole image of the arrow still be there? Why or why not?

__**Demonstration 4:**__ **Removing the lens.** After the prediction and discussion steps, keep both bulbs lighted and remove the lens. Be sure that students can see that light rays diverge from both bulbs, and there is no focusing element to focus them to image points.

Discussion after observing the results: Would there still be an image? Why or why not? What is an image?

__**Demonstration 5:**__ **Moving lens further away.** After the prediction and discussion steps, keep both bulbs lighted and move the lens further away from the object. Be sure that students can see that there are still two image points that are now closer to the lens and closer together. (The image is closer to the lens and smaller than before.) The rays from each bulb are not diverging as much when they hit the lens, and are focused more effectively by the lens.

Discussion after observing the results: Ask students to describe where the image is now formed. Is it closer or further away from the lens? Is it larger or smaller than before? How do you know?

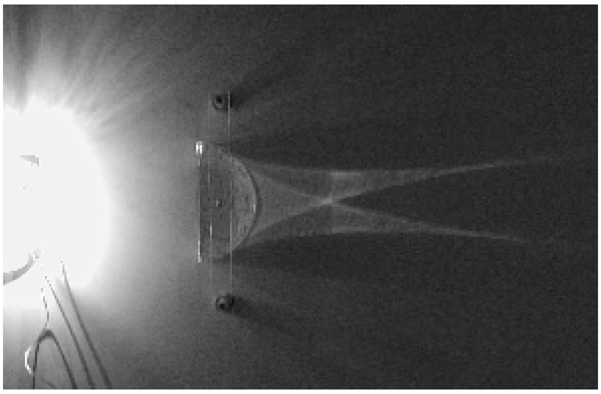


Figure TG1-9: Actual observations of image formation with both point source bulbs lighted.

__**Demonstration 6:**__ **Moving lens closer.** After the prediction and discussion steps, keep both bulbs lighted and move the lens closer to the object (but still further away than the focal point). Be sure that students can see that there are still two image points that are now further away from the lens and further apart. (The image is further from the lens and larger than before.) The rays from each bulb are diverging more when they hit the lens, and are focused less effectively by the lens.

Discussion after observing the results: Ask students to describe where the image is now formed. Is it closer or further away from the lens? Is it larger or smaller than before? How do you know?

__**Demonstration 7:**__ **Virtual image.** After the prediction and discussion steps, keep both bulbs lighted and move the lens still closer to the object, this time closer than the focal point. Be sure that students can see that light rays from each bulb are now still diverging when they leave the lens. (There are no *real* image points formed beyond the lens.) The rays from each bulb are diverging still more when they hit the lens, and the lens isn't strong enough to focus them to image points.

Discussion after observing the results: Ask students to describe what they now observe. Are the rays from an object point converged to a real image point beyond the lens? If you were standing to the right of the lens looking back into it, where would rays appear to be diverging from? What kind of image is this, and where is it located?

OPTICS MAGIC TRICKS

INTRODUCTION

This series of simple demonstrations is designed to introduce students to basic concepts of geometrical optics. Demonstrations 1 and 2 are appropriate as actual introductions to concepts, while Demonstrations 3 and 4 might best be used to reinforce concepts that have already been taught.

These demonstrations were first developed for use at a hands-on science center (the Eugene, OR, USA version of the Exploratorium) in magic shows every Saturday morning. They have been used successfully as part of a college-level general physics course. While most of these demonstrations are not new or original, the context of doing them as magic is new. Students' interest is captivated by presenting the demonstrations in this way, and they are engaged in the learning process.

These demonstrations should be used in an interactive way, including small-group discussions. The Optics Discussion Questions are designed to facilitate these discussions.

Other Optics Magic Tricks on total internal reflection, mirrors, polarization, optical activity, birefringence and scattering are also available. Contact the author for more information.

OPTICS MAGIC TRICK 1: THE REAPPEARING TEST TUBE

OBJECTIVE

- To understand the importance of a difference in optical properties (indexes of refraction) of transparent media in the reflection and refraction of light

APPARATUS AND SUPPLIES

- 2 600 ml clear glass beakers
- 3-4 small clear Pyrex culture tubes (in Europe, Duraglas test tubes)
- Hammer or block of wood
- Envelope
- Vegetable oil or light and heavy mineral oil (in Europe, Paraffin oil)
- Magic wand

PREPARATION

Use vegetable oil or mix the mineral oils to match the index of refraction to the index of the Pyrex culture tubes. (The mineral oils will allow a better match, but the vegetable oil is easier and works pretty well.) Fill one beaker with the oil, and completely submerge one or two culture tubes in it before class. You should not be able to see the submerged tubes. Fill the other beaker with water. It is best if the lights are dimmed somewhat.

THE DEMONSTRATION

Take a dry culture tube and place it in the envelope. Smash it with the hammer or block of wood. Ask a volunteer to look into the envelope to verify that the tube is smashed. Tell the students that the beaker contains a magic fluid that will repair the tube. Drop the pieces of the tube into the beaker with the oil. Say some "magic" work (like "PHYSICS") and/or wave the magic wand. Then reach in and pull out a whole tube! To make it even more dramatic, pull out the second tube!!

Ask the class to break down into small groups of 2-4 students, and have them discuss the Optics Discussion Questions in their groups. After a short time for discussion, ask for volunteer(s) to explain how the trick works.

EXPLANATION

Transparent objects only reflect and refract light when they are in a medium with different optical properties (a different index of refraction). Since the "magic" fluid has the same index as the tube, no light is reflected to your eyes by the submerged tube. Therefore, you cannot see it. You can see the tube in air or water because air and water have different indexes than the tube.

If you have another dry tube, submerge it open side up so that the oil flows over the rim. It will appear to the students to disappear from the bottom. Some students have even described that it seems to disappear in a flash!

OPTICS MAGIC TRICK 2: CANDLE BURNING UNDER WATER

OBJECTIVE

- To explore the properties of the virtual image formed by a plane mirror

APPARATUS AND SUPPLIES

- Candle
- Matches
- 2 600 ml clear glass beakers
- Container of water
- Large (at least 60 cm x 60 cm) Plexiglas or glass sheet supported vertically
- Black (or other dark colored) cloth large enough to cover the sheet
- Magic wand

PREPARATION

Place the candle in one of the beakers in front of the Plexiglas sheet facing the students, and the other beaker an equal distance behind the sheet. The black cloth should be covering the Plexiglas sheet when the students enter the room. It is best if the lights are dimmed.

THE DEMONSTRATION

Light the candle, and pretend to light a candle in the beaker behind the sheet as well. Remove the black cloth. Explain to the students that they are viewing two candles, one in the beaker in front and one in the beaker in back. Say the magic word (and wave the wand), and fill the beaker behind the sheet with water. It will appear to students that there is a candle burning under water in the back beaker. The effect is not all that convincing, and the students' reaction is often laughter!

Ask the class to break down into small groups of 2-4 students, and have them discuss the Optics Discussion Questions in their groups. After a short time for discussion, ask for volunteer(s) to explain how the trick works.

EXPLANATION

The Plexiglas sheet acts as a plane mirror, forming a virtual image of the lit candle in the beaker behind the sheet. Even though the sheet only reflects about 4-8% of the light from the candle, this is enough to have a clear, and somewhat convincing image.

The discussion questions, and classroom discussion will guide the students through the characteristics of the virtual image produced by a plane mirror. Is it in front of the mirror or behind? How far behind? Is it real or virtual? What about the size of the image compared to the lit candle? Is this image like the image in a bathroom mirror? Does any light from your face actually get behind the bathroom mirror? Does the mirror change the image from right-handed to left-handed? (Hold your hand in front of the mirror to demonstrate.)

OPTICS MAGIC TRICK 3: COAL TO SILVER

OBJECTIVE

- To observe total internal reflection at the interface between two transparent media

APPARATUS AND SUPPLIES

- Candle and matches
- Ball (about 5 cm in diameter) made of non-flammable/non-melting material mounted on the end of a rod and covered with soot (carbon) from the candle flame
- 600 ml beaker filled with water
- Magic wand

PREPARATION

Light the candle and rotate the ball in the flame until the ball is covered all over with soot. Fill the beaker with water.

THE DEMONSTRATION

Tell the students that you have discovered how to turn coal into silver. Say the magic word (and wave the magic wand) and submerge the ball in the water. The students will see light reflected off the surface of the ball, and it will appear to have a shiny, silver-like surface.

Ask the class to break down into small groups of 2-4 students, and have them discuss the Optics Discussion Questions in their groups. After a short time for discussion, ask for volunteer(s) to explain how the trick works.

EXPLANATION

The soot traps a layer of air around the surface of the ball. Therefore, light from outside that is incident on this layer can be totally internally reflected back into the water and back to the students' eyes. It appears that the light is being reflected from the "shiny" surface of the ball. Total internal reflection takes place when light is incident from a medium with a larger index of refraction (water) on a medium with a smaller index of refraction (air). Since some of the light is incident at angles smaller than the critical angle, perfect reflection does not take place. The surface of the ball is still visible.

OPTICS MAGIC TRICK 4: FALLING LASER BEAM

OBJECTIVE

- To observe total internal reflection at the interface between two transparent media—the mechanism of fiber optics

APPARATUS AND SUPPLIES

- Clear glass container (e.g., small aquarium) filled with water with a small hole on one wall (about 0.5 cm in diameter) near the bottom, sealed by a stopper
- Laser ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Trough or pan on floor to catch water stream
- Magic wand

PREPARATION:

The laser is shone from the other side of the container through the water so that it is incident on the stopper.

THE DEMONSTRATION

Say the magic word (and wave the magic wand) and remove the stopper. The water streams out along a curved path. The laser beam follows this path, falling downward with the water.

Ask the class to break down into small groups of 2-4 students, and have them discuss the Optics Discussion Questions in their groups. After a short time for discussion, ask for volunteer(s) to explain how the trick works.

EXPLANATION

The laser beam within the stream of water is incident on the interface between water and air, from higher index of refraction to lower index of refraction. Since the light is incident at an angle larger than the critical angle, the beam is totally internally reflected back into the water and seems to be trapped. This is the same mechanism that is exploited in fiber optics.

Module 2:
Lenses and Optics of the Eye

Vasudevan Lakshminarayanan

College of Optometry
University of Missouri-St. Louis
St. Louis, Missouri, USA
vengu@umsl.edu

Module 2: Lenses and Optics of the Eye

OVERVIEW

The eye contains two components that function as lenses, the cornea and the crystalline lens. Therefore, in order to understand how the eye functions to focus images on the retina, it is necessary to explore simple lenses. Once the image is focused onto the receptor cells on the retina, the information is transmitted to the brain along nerve cells, and interpreted. The focus of this module is on the lenses of the eye, and not on this complex nerve brain process. You have already seen in the previous module that the function of a single lens is to take *all* of the rays of light coming from a single point on the object and striking the front surface of the lens and focus them to a single point on the image. Here you will explore further how images are formed by a lens, and how these images are changed by changing the properties of the lens, and the distance of the object from the lens.

OBJECTIVES

1. To learn about the differences between images formed by positive and negative spherical lenses
2. To understand that the human eye is not a fixed focus system, but is capable of varying its focus for far to near objects
3. To understand the basic optics of *mypoia*, and *hyperopia,* and the correction of these refractive anomalies of the human eye
4. To learn about the images formed by cylindrical lenses, and how this is related to astigmatism in the human eye

DEFINITION OF TERMS USED

1. *Positive spherical lenses*: These are lenses that converge the light rays from a distant object (at infinity) to a point image. They are also known as *converging* or *plus* (+) lenses. Both the surfaces of such a lens could be spherical or one surface could be planar while the other spherical. They are always thicker at the center than at the edges**.** They are often biconvex lenses, with both surfaces having the same curvature.
2. *Negative spherical lenses*: These lenses are also known as *diverging* or *minus* (-) lenses. As the name implies, negative lenses diverge the light rays incident on them. These often are biconcave lenses with both surfaces having the same curvature. Both the surfaces of such a lens could be spherical or one surface could be planar while the other spherical. They are always thinner at the center and become thicker at the edges.
3. *Cylindrical lenses:* The surfaces are cylindrical in shape, or one might be cylindrical and one planar. Due to the different shape, the optical properties of a cylindrical lens are different from those of spherical

lenses, and they will be investigated in this lab. Like spherical lenses, they can be positive or negative.

4. *Optic axis:* An imaginary line perpendicular to the surfaces of a lens that runs through the lens center.
5. *Direction of motion:* When the lens is moved perpendicular to its optic axis, the image also moves. When this movement of the image is in the same direction as the lens, it is called *with* motion. Movements in the opposite direction are called *against* motion.
6. *Real image:* An image that is formed by rays of light converging to (and intersecting at) points on the image. A real image can be displayed on a screen.
7. *Real object:* An object, each point of which emits (or reflects) real, diverging rays of light.
8. *Virtual image:* Contrary to a real image, it is an imaginary image formed by diverging rays of light. Each point on a virtual image is the apparent source of divergent light rays. A virtual image cannot be displayed on a screen.
9. *Sign conventions:* It is usual practice when drawing ray diagrams to assume that light travels from left to right. An object to the left of a lens is called a real object and an image to the right of the lens is called a real image. This is a standard convention known as the *Cartesian* convention. The lens is placed at the origin of the co-ordinate system and all distances are measured from the origin. When measuring, when one travels along the direction of light propagation, the sign given is +. On the other hand, if the measurement is opposite to the direction of light propagation, the sign given is -. All heights measured above the axis are given a + sign, while all heights measured below the axis are given a – sign.
10. *Magnification:* The ratio of the image size to the object size (image size/object size). It can be positive (if the image is upright compared to the object) or negative (if the image is inverted compared to the object).
11. *Focal length:* Distance along the axis of a thin lens where the image of a very distant object is formed. For example, if light from a distant light source is focused 1.0 m from the lens, the focal length is 1.0 m.
12. *Thin lens:* A lens for which the thickness along its optic axis is much less than its focal length.
13. *Power:* The inverse of the focal length of the lens: 1/(focal length). Conventionally lens power is given in Diopters (D). The diopter is a unit of inverse meters (1/meters). If light from a very distant source is incident on a lens and the image is formed at a distance of 2.0 m from the lens, then the lens is said to have a focal length of 2.0 m and a power of 0.50 D. The power is physically a measure of the converging (or diverging) ability of the lens. Lens powers are given with a sign (+/-), and a numerical value in D (e.g., +5 D is a converging lens of 5 diopter power, and -7 is a diverging lens of 7 diopters power). A lens

with a greater numerical value of power is considered a lens of higher power when compared to a lens of lower value (i.e., a +7 D lens is of higher power than a +5 D lens).

INVESTIGATION 1: POSITIVE SPHERICAL LENSES

APPARATUS AND SUPPLIES

- Very distant source of light or collimated source of light (to simulate a distant object)
- Light source/object slide (arrow target—non-distant object)
- Collection of positive spherical lenses with refractive powers marked on them
- Optical bench
- Meter stick
- Lens holders
- Screen

Activity 1-1: Qualitative observations with plus (converging) lenses

Pick out a positive spherical lens with power about 5 D. Verify that it is a positive spherical lens by rubbing your fingers along the lens surface—is it thicker at the center and decreasing in thickness toward the edges? Does this feel the same in every direction from the center to the edge?

1. Now hold the lens above this page of typed letters about 30 cm from the page. Your eye should be at least 50 cm above the lens.

Question 1-1: Describe what you observe through the lens.

2. Move the lens from side to side.

Question 1-2: Describe what you observe. Are you observing *with* or *against* motion?

3. Rotate the lens about its axis.

Question 1-3: Do you see any motion? If so, describe the motion.

4. Watch the letters as the lens is lifted from the page and brought up to the eye.

Question 1-4: Do you see any changes in the image viewed through the lens? If so, describe these changes.

5. Hold the lens at least 30 cm from your eye and look at an object down the corridor (a distant object).

Question 1-5: Does the image appear right side up or inverted? Blurred or clear?

Activity 1-2: More quantitative observations with plus lenses

Pick a plus spherical lens with power about the middle of the available range. Set up the lens and screen on the optical bench.

1. Dim the lights in the room and try to find a sharp image of the distant light source on the screen by moving the screen closer and further away from the lens. Is it possible to do this? If so, measure the distance from the lens to the screen. By definition, this is the *focal length* of the lens.

   focal length=

2. Now mount the light source/object slide (arrow target) on the optical bench in front of the lens so that its distance from the lens is about 1.5 times the focal length. Attempt to form an image on the screen by moving the screen backwards and forwards from the lens.

Question 1-6: Can you get a sharp image formed on the screen? If you can, is the image closer to the lens or further from the lens than with the distant object source (as in 1)?

NOTE: Remember that an image formed by real rays of light converging to points on a screen is called a *real image*.

Question 1-7: Is the image *real* or *virtual*? Is it right side up (upright) or inverted? Is its size larger or smaller than the object arrow? Describe the *magnification*. (Is it greater than or smaller than 1? Is it positive or negative?)

3. Repeat (2) with a lens of at least twice the power. Make the lens to light source distance the same as in (2). In order to see the real image you will have to move the screen.

Question 1-8: Is the image formed closer to or further from the lens? Is the image larger or smaller than that produced by the lower power lens (in 2)? (Is the magnification larger or smaller?) Is the image now upright or inverted?

Question 1-9: What can you say about the focusing power of this lens when compared to the previous lens (in 1)?
Try to answer the following additional questions based on your observations:

Question 1-10: What are the characteristics of a real image?

Question 1-11: What can you say about a real image formed using a positive lens—is it always upright or always inverted? Is it always larger than the object or always smaller than the object? Is the magnification always positive or always negative? Is the magnification always greater than 1 or always less than 1?

Question 1-12: How is the ability of a positive lens to converge rays related to the power of the lens? Explain.

Activity 1-3: Image with the object close to a plus lens

1. Take one of the lenses you examined in Activity 1-2, and hold it above this page of typed letters, about 30 cm from the page.
2. Slowly move the lens closer and closer to the page, until it is closer than the focal length from the page.

Question 1-13: Does anything happen to the size of the image of the letters as the lens is brought closer to the page?

Question 1-14: What happens to the image when the lens is brought to a distance from the page less than the focal length? Is the image now upright or inverted? Larger or smaller than the object? Is this a *real* image?

Question 1-15: What common optical device consists of a plus lens with the object closer than the focal length?

INVESTIGATION 2: NEGATIVE SPHERICAL LENSES

APPARATUS AND SUPPLIES

- Very distant source of light or collimated source of light (to simulate a distant object)
- Light source/object slide (arrow target—non-distant object)
- Collection of negative spherical lenses with refractive powers marked on them
- Optical bench
- Meter stick
- Lens holders
- Screen

Activity 2-1: Qualitative observations with minus (diverging) lenses

Pick out a minus spherical lens. Verify that it is a minus lens by rubbing your finger along the surfaces of the lens. Does it go from thin at the center to thick at the edges? Does this change in thickness feel the same no matter in what direction you run your finger?

1. Now hold the lens above this page of typed letters about an arms length from the page.

Question 2-1: Describe what you observe through the lens.

2. Move the lens from side to side.

Question 2-2: Describe what you observe. Are you observing with or against motion?

3. Rotate the lens about its axis.

Question 2-3: Do you see any motion? If so, describe the motion

4. Select a spherical lens with power in the top third of the available minus lenses. Again observe this page of typed letters, this time holding the lens slightly above the page—say about 10-15 cm.

Question 2-4: Are the letters larger or smaller? Upright or inverted? Approximately what is the magnification of the letters?

5. Watch the letters as the lens is lifted from the page and brought up to the eye.

Question 2-5: What changes do you see in the image? Describe.

6. Hold the lens at arm's length and look at an object down the corridor.

Question 2-6: Does the image appear upright or inverted? Blurry or clear? What about its size?

Activity 2-2: More quantitative observations with minus lenses

Pick a spherical minus lens with power about the middle of the available range. Dim the lights in the room and place the lens between the light source/object slide (arrow target) and the screen set up on the optical bench.

1. Attempt to use the lens to form a real image by moving the lens backwards and forwards away from and toward the object.

Question 2-7: Can you get a sharp image formed on the screen? If you can, describe the image. If you cannot, can you guess why you could not do so? Does a minus lens have converging or diverging properties? Explain.

2. Repeat the experiment with a lens of higher power.

Question 2-8: Can you form an image? Why or why not? Are your observations similar to (1)?

Try to answer the following additional questions based on your observations:

Question 2-9: How are negative lenses different from positive lenses? How do negative lenses act differently than positive lenses in affecting the rays that diverge from points on an object source?

Question 2-10: Can you ever form a real image using a negative lens? Explain.

INVESTIGATION 3: MODEL OF THE HUMAN EYE

APPARATUS AND SUPPLIES

- Very distant source of light or collimated source of light (to simulate a distant object)
- Light source/object slide (arrow target—non-distant object)

- Collection of positive and negative spherical lenses with refractive powers marked on them
- Optical bench
- Meter stick
- Lens holders
- Screen

You can construct a relatively simple model of the human eye by setting up the plus lens used in Activity 1-2, step 1 and a screen on the optical rail. The single positive lens simulates the refractive elements of the eye (namely the cornea and crystalline lens) and the screen simulates the retina or the back of the eye, where the light sensitive cells (rods and cones) are located. The length of the eye is fixed—it does not change no matter what you are viewing.

Activity 3-1: Accommodation

As you have seen in Investigation 2, a positive lens forms an image of a distant light source at a smaller distance from the lens than a near light source. But the distance from the lens to the retina of the eye is fixed.

Prediction 3-1: How is it possible that your eyes can form sharp images of distant and near objects on the retina? Any idea?

You have also seen that a higher power lens forms an image of a light source closer to the lens than a lower power lens.

1. Use your eye model to view a distant object source. Adjust the lens to screen (retina) distance to get a sharp image.

Question 3-1: Is this a real image? Is it upright or inverted?

2. Now instead of the distant light source, place a light source on the rail at a distance approximately 1.5 to 2 focal lengths away from the lens. The screen (retina) should be the same distance from the lens as in (1). (Do not move it! Remember that the length of the eye cannot change.)

Question 3-2: What does the image on the retina look like? Is it blurred or sharp?

3. Now, place a second lens in contact with the original one. Again, do not change the lens to screen (retina) distance. Try different powers for this lens until the image comes into focus again on the screen (retina).

Question 3-3: Did you use a plus or minus lens? What is the power of the second lens?

NOTE: The power of a combination of two thin lenses placed against each other is the sum of the powers of the individual lenses.

Question 3-4: What is the total power of the lens combination? Show your calculation.

4. Now, remove the second lens, and move the object closer still to the *eye*, but still further than the focal length away from the lens. Again, do not change the lens to screen (retina) distance.

Question 3-5: Is the image on the screen sharp or blurred?

5. Now, repeat (3) to find a suitable power lens to again bring the image into focus on the screen (retina).

Question 3-6: What is the total power of the lens combination? Show your calculation.

Try to answer the following additional questions based on your observations:

Question 3-7: For what type of object—distant or close—does the power of the optical elements in your eye need to be the largest? Explain why based on your observations.

Question 3-8: Since your eye has a fixed length, in order for you to be able to see both distant and near objects, what must be true about the power of the lens of your eye?

Question 3-9: Based on your observations of the thickness of different power plus lenses in Investigation 1, how can the power of the lens in your eye be increased or decreased? What must be done to its shape? What must be true about the material from which the lens is made?

NOTE: The process of changing the power of the lens in your eye by changing its shape is called *accommodation*.

Activity 3-2: Modeling myopia or nearsightedness

Myopia or nearsightedness is caused by either (a) the eyeball length being too long or (b) the power of the eye's optics being too strong. In both cases, the image of a distant object will no longer be sharply focused on the retina but will instead fall in front of it.

Prediction 3-2: How can you simulate myopia with your lens/screen eye model?

1. With just the single lens used for your eye model in Activity 3-1, set up the lens and screen so that the distant object source is focused to a sharp image on the screen (retina). Now move the screen a little further from the lens. <u>Do not change the lens to screen (retina) distance for the rest of this activity.</u>

Question 3-10: What do you observe?

Prediction 3-3: What kind of lens would you need to bring the image back into focus on the screen (retina)? (Positive or negative?)

2. Experiment with the lenses available to you to find a corrective lens that brings the image on the screen (retina) back into focus when the lens is placed in contact with the eye lens. (You might think of this lens as a "contact" lens.)

Question 3-11: What is the power of the corrective lens that works? (Be sure to include the sign.) How does this compare with your prediction?

NOTE: If you were an eye doctor, this would be the lens prescription to correct myopia for the model eye.

Now try to answer the following additional questions:

Question 3-12: Explain why the type of lens you used was able to correct myopia (nearsightedness). What was the problem with the eye's lens, and what did this corrective lens do to correct that problem?

Question 3-13: If you or your partner are myopic, and wear glasses, take them off and verify for yourself that your eyeglass correction has this type of lens. How can you check this?

Activity 3-3: Modeling hyperopia or farsightedness

Hyperopia or farsightedness is caused by either (a) the eyeball length being too short or (b) the power of the eye's optics being too weak (even when fully accommodated). In both cases, the image of a near object will no longer be sharply focused on the retina but would instead fall beyond it.

Prediction 3-4: How can you simulate hyperopia with your lens/screen eye model?

1. Using a more powerful single lens than the one used for your eye model in Activity 3-1, set up the object source, lens and screen on the rail so that the near object source is focused to a sharp image on the screen (retina). Now move the screen a little closer to the lens.

Question 3-14: What do you observe?

Prediction 3-5: What kind of lens would you need to bring the image back into focus on the screen (retina)? (Positive or negative?)

2. Experiment with the lenses available to you to find a corrective lens that brings the image on the retina back into focus when the lens is placed in contact with the eye's lens.

Question 3-15: What is the power of the corrective lens that works? (Be sure to include the sign.) How does this compare with your prediction?

NOTE: Again, if you were an eye doctor, this would be the lens prescription to correct hyperopia for the model eye.

Now try to answer the following additional questions:

Question 3-16: Explain why the type of lens you used was able to correct hyperopia (farsightedness). What was the problem with the eye's lens, and what did this corrective lens do to correct that problem?

Question 3-16: If you or your partner are hyperopic, and wear glasses, take them off and verify for yourself that your eyeglass correction has this type of lens. How can you check this?

NOTE ON ACCOMMODATION: Typically, the human eye, looking at a distant object (at what is known as optical infinity), has an effective power of about 60 D. However, as was seen in Activity 3-1, when an object is closer to the eye, the total power of the eye has to increase in order to effectively focus the image on the retina. Muscles act on the crystalline lens so that the lens becomes more rounded and its power is increased. This is the process called *accommodation*. In other words, the eye is capable of continually adjusting focus from large distance to near with amazing accuracy. It is precisely this ability to add to the total power of the eye that allows a normal eye to see objects very close to the eye, as close as 25 cm from the eye. The closest distance at which we can see an object clearly is called the *near point*.

The ability to automatically see close objects by changing the effective power of the eye—the accommodation of the eye—is diminished as we get older. That is why, as we enter middle age, additional reading glasses (or bifocals) are needed for seeing close objects, for example to read.

INVESTIGATION 4: CYLINDRICAL LENSES AND ASTIGMATISM

APPARATUS AND SUPPLIES

- Very distant source of light or collimated source of light (to simulate a distant object)
- Collection of positive spherical and cylindrical lenses with refractive powers marked on them
- Optical bench
- Meter stick
- Lens holders
- Screen

Activity 4-1: Qualitative observations with positive cylindrical lenses

NOTE: The axis of the cylindrical lens is marked by a line on the edge of the lens.

1. Pick out a positive cylindrical lens with power about 5 D. As before run your fingers along the surface of the lens.

Question 4-1: Does the lens appear to be curved equally in all directions? Does the shape of a cylindrical lens differ from a spherical lens? If so, how does it differ?

2. Hold the lens about 30 cm above this page of typed letters and note where the mark is.

Question 4-2: How do the letters appear? Pay close attention to the appearance of the letters and the axis (mark). (That is, is there any difference in the image in the direction of the axis and in the direction perpendicular to the axis?)

3. Now move the lens side to side without changing the axis.

Question 4-3: Do you see with or against motion? Explain how you know.

4. Rotate the lens 90 degrees about its axis.

Question 4-4: Do you see any motion of the image during this rotation? If so, describe. How do the letters appear in this new position compared to the old position (in 1)?

Activity 4-2: More quantitative observations with positive cylindrical and spherocylindrical lenses

1. Set up the lens and screen on the optical bench.
2. Dim the lights in the room and try to find a sharp image of the distant light source on the screen by moving the screen closer and further away from the lens.

Question 4-5: Is it possible to do this? Do you get a sharp image at one position? Describe what you observe.

Question 4-6: Are your observations similar to those you made in Investigation 1 with a spherical plus lens? Explain.

Note: We can create a *spherocylindrical* lens by putting in contact a pure spherical lens along with a cylindrical lens. This results in the cylindrical lens having two different powers along two axes, 90 degrees apart.

3. Pick a plus spherical lens with power about 5 D, and place it in contact with the cylindrical lens you have been using.
4. Place this lens combination on the rail, and try to find the image on the screen by moving the screen away and toward the lens.

Question 4-7: Describe what you observe with the spherocylindrical lens? Do you see one clear image, a range of images or two extreme images?

Question 4-8: At what position of the screen is the *best* image? Explain your definition of the *best* image.

Question 4-9: What is the same and what is different about the images formed by positive spherical and cylindrical lenses?

Note on astigmatism: When an eye is astigmatic, its optical elements are not perfectly spherical. Instead, they have a cylindrical component to them. This defect is often combined with myopia or hyperopia. In order to correct such a combination defect, it is necessary to prescribe a spherical lens that has a cylindrical correction as well. But this lens must be chosen so that the best image—as you have seen in Activity 4-2—falls on the retina.

Teachers' Guide for Module 2: Lenses and Optics of the Eye

TEACHERS' GUIDE FOR MODULE 2: LENSES AND OPTICS OF THE EYE

General Introduction

This module is a simple, semi-quantitative introduction to image formation using lenses, with applications to the human eye. The purpose is for students to gain a conceptual understanding of the effects of different lenses, and how these ideas apply to the normal functioning of the eye. Some of the possible abnormalities of the eye are also considered. No attempt is made to develop equations or even ray diagrams.

Module 2 Apparatus and Supplies List

- Very distant source of light or collimated source of light (to simulate a distant object)
- Light source/object slide (arrow target)—non-distant object
- Collection of positive and negative spherical and cylindrical lenses with refractive powers marked on them
- Optical bench
- Meter stick
- Lens holders
- Screen

Equipment Notes

Distant light source: This can just be an incandescent light bulb (clear preferred) at a distance from the lens that is very large compared to the focal length.

Light source/object slide: This should be a lighted arrow or other object that has a distinct top and bottom. It should be possible to position this object securely at a fixed distance from the lens, with a holder on the optical bench. Such object slides can be found at most physics educational supply companies. An object source can also be made by cutting an arrow-shaped slit in opaque cardboard or paper, and placing it in front of a flashlight or other light source.

Collection of lenses: A variety of plus and minus spherical and plus cylindrical lenses is needed. Powers for plus lenses should be in the range +4 to +8D. Powers for negative lenses should be -4 to -8D, and powers for the cylindrical lenses should be +4 to +8D. Any diameter will be okay.

Optical bench and lens holders: Pretty much any optical bench/rail should work. If none is available, blobs of clay could be used to mount the equipment, although this is much less desirable.

Screen: Any white screen mounted in a stable way will work for this.

INVESTIGATION 1: POSITIVE SPHERICAL LENSES

Investigation 1 Apparatus and Supplies List

- Very distant source of light or collimated source of light (to simulate a distant object)
- Light source/object slide (arrow target)—non-distant object
- Collection of positive spherical lenses with refractive powers marked on them
- Optical bench
- Meter stick
- Lens holders
- Screen

Activity 1-1: Qualitative observations with plus (converging) lenses

The lens used in this activity should have focal length less than 30 cm to assure that the page is well beyond the focal point of the lens. The 5D lens specified has focal length 20 cm.

Question 1-1: The letters appear inverted and enlarged.

Question 1-2: Against motion is observed.

Question 1-3: There is no motion of the letters on the page when the lens is rotated about its axis.

Question 1-4: The letters decrease in size as the lens is brought closer to the eye.

Question 1-5: The image appears inverted.

Activity 1-2: More quantitative observations with plus lenses

It is important that students do the first part of this activity with the distant source. The definition of the focal length is the image distance (distance from lens to image point) for parallel rays of light (*light from a distant source*) incident on the lens. Students often confuse this point.

Then in (2), they use the light source/object slide. It is very important that the object slide be placed further from the lens than the focal point. The directions suggest 50% further away than the focal length.

Question 1-6: When the object is not distant, but rather at a distance from the lens somewhat larger than the focal length, the image is formed by the lens with the screen more distant from the lens.

Question 1-7: The image is inverted and larger than the object source. The magnification has a numerical value greater than one, and it is negative.

Note that if you use a lens with twice the power in (3), the focal length will be half as large. Therefore, the object will now be more than 2 times the focal length away from the lens.

Question 1-8: The image is now closer to the lens. It is smaller than the one produced in (2). The numerical value of the magnification is smaller, but it is still negative since the image is still inverted.

Question 1-9: The lens with higher power appears to have greater focusing power.

Question 1-10: A real image is formed by real light rays intersecting at each image point on the image. If a screen is placed at the position of the image, the image is projected on the screen.

Question 1-11: A real image formed by a positive lens is always inverted. It can be larger or smaller than the object. The magnification is always negative (inverted image), but it can have a numerical value greater or less than 1 (larger or smaller than the object).

Question 1-12: The greater the power of a positive lens, the more its ability to converge rays. This was observed in (3) because the image was formed closer to the lens. It is also true that the focal length is smaller for a more powerful lens, i.e., parallel rays from a distant source are focused closer to he lens.

Activity 1-3: Image with the object close to a plus lens

When the object is closer to a plus lens than the focal point, an *upright virtual* image is formed. This image is always larger than the object, and thus the magnification is greater than 1.

Question 1-13: The image of the letters gets bigger and bigger.

Question 1-14: The image becomes upright when the lens is moved closer than the focal length. The image is larger than the object. This is no longer a real image.

Question 1-15: A simple magnifier is just a plus lens held a distance from the object that is smaller than the focal length.

INVESTIGATION 2: NEGATIVE SPHERICAL LENSES

Investigation 2 Apparatus and Supplies List

- Very distant source of light or collimated source of light (to simulate a distant object)
- Light source/object slide (arrow target)—non-distant object
- Collection of negative spherical lenses with refractive powers marked on them
- Optical bench
- Meter stick
- Lens holders
- Screen

Activity 2-1: Qualitative observations with minus (diverging) lenses

Question 2-1: The print appears upright and smaller than its actual size.

Question 2-2: The motion is with, but it is hard to observe.

Question 2-3: There is no motion when the lens is rotated, but this is hard to observe.

Question 2-4: The letters are upright and smaller than without the lens. The magnification is positive and less than 1.

Question 2-5: The image appears small and as you move the lens toward the eye, it gets larger.

Question 2-6: The image is upright and clear. It is smaller than the actual object.

Activity 2-2: More quantitative observations with minus lenses

Of course it will never be possible to form a real image projected on a screen with a minus lens, but it is important for students to observe this themselves.

Question 2-7: It is not possible to get a sharp image focused on the screen. The rays leaving a point on the object are diverging from the point. A minus lens causes them to diverge still more, never converging to a point on the screen.

Question 2-8: An image still cannot be formed, even with the higher power minus lens.

Question 2-9: Positive lenses have converging power. It is possible for them to focus diverging rays from a point on an object to a real image point. Negative lenses diverge rays even more, so they can never focus the rays from an object point to a real image point.

Question 2-10: You can never form a real image with a negative lens for the reasons given in the previous questions.

INVESTIGATION 3: MODEL OF THE HUMAN EYE

Investigation 3 Apparatus and Supplies List

- Very distant source of light or collimated source of light (to simulate a distant object)
- Light source/object slide (arrow target)—non-distant object
- Collection of positive and negative spherical lenses with refractive powers marked on them
- Optical bench
- Meter stick
- Lens holders
- Screen

The actual human eye has two different focusing elements, the cornea and the crystalline lens. (See Figure LS-1 in the Laser Safety section of this manual.) The cornea does the majority of the focusing (higher power) while the lens (lower power) does the fine-tuning to allow the normal eye to see both distant and close objects. A model that ignores this separation into two elements is adequate for the concepts we are teaching here. It is important to note, though, that the length of the eye remains constant whether viewing near or distant objects. Therefore, the distance from the lens to the screen must remain constant throughout these activities.

Activity 3-1: Accommodation

Question 3-1: The image is real and inverted.

Question 3-2: The image is now blurred.

Question 3-3: A plus lens was needed. The rays needed to be converged more. The power depends on the value of the original lens in the eye model.

Question 3-4: The total power depends on the power of the individual lenses used.

Question 3-5: The image is again blurred.

Question 3-6: The total power depends on the power of the individual lenses used.

Question 3-7: The power of the eye needs to be largest for close objects. For close objects, the rays are diverging more when they reach the lens, and thus more converging power is needed to converge them to real image points.

Question 3-8: The power of the lens in your eye must be variable.

Question 3-9: The plus lenses that were thickest at the center had the largest powers. Therefore, if the lens in the eye is made of pliable material, it can be made wider at the center by compressing its edges. This will result in a higher power lens. It can be made thinner at the center by relaxing the edges. This will result in a lower power lens.

Activity 3-2: Modeling myopia or nearsightedness

When the length of the eye has been increased, so that rays from a distant object are focused in front of the screen (retina), this is now a myopic (nearsighted) eye. The lens—screen distance should not be changed for the remainder of this activity.

Question 3-10: The image on the screen is now blurred.

Question 3-11: The actual power of the corrective lens will depend on the student's individual setups. It will, however, be a minus lens.

Question 3-12: It is a negative lens, since the lens of our eye model converges light from a distant object too much to form a sharp image on the retina. The minus corrective lens adds a bit of divergence so that the power of the eye's lens is now just right to converge the rays to a sharp image point.

Question 3-13: You can check whether the lens is plus or minus by feeling whether it is thicker in the center or at the edges. An alternative is to view a distant object as in Investigations 1 and 2.

Activity 3-3: Modeling hyperopia or farsightedness

When the length of the eye has been decreased, so that rays from the light source/object slide would be focused behind the screen (retina), this is now a hyperopic (farsighted) eye. The lens—screen distance should not be changed for the remainder of this activity.

Question 3-14: The image is now blurred because a sharp image would form behind the retina (screen—at the original location of the screen).

Question 3-15: The actual power of the corrective lens will depend on the students' individual setups. It will, however, be a plus lens.

Question 3-16: It is a positive lens, since the lens of our eye model converges light from a close object too little to form a sharp image on the retina. The plus corrective lens adds a bit of power (convergence) so that the power of the eye's lens plus the corrective lens is now just right to converge the rays to a sharp image point.

Question 3-17: You can check whether the lens is plus or minus by feeling whether it is thicker in the center or at the edges. An alternative is to view a distant object as in Investigations 1 and 2.

INVESTIGATION 4: CYLINDRICAL LENSES AND ASTIGMATISM

Investigation 4 Apparatus and Supplies List

- Very distant source of light or collimated source of light (to simulate a distant object)
- Collection of positive spherical and cylindrical lenses with refractive powers marked on them
- Optical bench
- Meter stick
- Lens holders
- Screen

Cylindrical lenses have two different curvatures along two axes that are perpendicular to each other. This produces two different powers along the two principal axes. As a result, a cylindrical lens does not produce a single image. In between these two axes, the powers will vary. As a result, a cylindrical lens will produce a range of images. A *planocylindrical* lens has 0 D power along one axis (which is called the *axis meridian* and is marked by a small line on the lens or lens holder). It has maximum power along an axis at 90 degrees to the axis meridian. Along the axis meridian, the surface is flat. If the lens has positive power, it will be convex along the other axis. A point source object is imaged by a cylindrical lens as a line image, the orientation of which will be parallel to the axis meridian.

Activity 4-1: Qualitative observations with positive cylindrical lenses

Question 4-1: The cylindrical lens is not curved like a spherical lens. While a spherical lens has the same curvature along any axis, the cylindrical lens is curved along one axis and flat along a perpendicular axis.

Question 4-2: Along the direction marked by the axis, there is no change in the letters. Along the perpendicular axis the letters are blurry and elongated or stretched and distorted.

Question 4-3: Against motion is observed. The letters appear to move in the direction opposite to the movement of the lens.

Question 4-4: As the lens is rotated, there are varying levels of distortion and elongation.

Activity 4-2: More quantitative observations with positive cylindrical and spherocylindrical lenses

Question 4-5: It is not possible to get a completely sharp image. Instead there is a range of images of different sharpness over a range of positions of the screen. *You will find a number of images of varying sharpness*.

Question 4-6: With a spherical plus lens, there was one location on the screen where a sharp, real image was focused. The situation with the positive cylindrical lens is different.

Question 4-7: There are a number of images. The two extreme images are clear, but in between there are ellipses.

Question 4-8: For a point object, the best image is the smallest circle seen. This is observed in between the two extreme images.

Question 4-9: For a point object, a line image will be seen when a cylindrical lens is used. With a pure spherical lens, no line image will be seen, only a point.

Module 3: Interference and Diffraction

Joel T. Maquiling
Department of Physics
School of Science and Engineering
Ateneo de Manila University
Quezon City, Philippines
jmaquiling@ateneo.edu

Zohra Ben Lakhdar
Department of Physics
University El Manar
Tunis, Tunisia
zohra.lakhdar@fst.rnu.tn

MODULE 3: INTERFERENCE AND DIFFRACTION

OVERVIEW

In this module we will study the behavior of light when it is incident on very small slits or obstacles. We will see that the geometrical optics model fails to correctly predict the complex light patterns observed. In order to explain the results, it is necessary to think of light as made up of waves. This model of light, called *wave optics* (or *physical optics*) is needed to adequately describe the observed *interference* and *diffraction* effects. In general, *interference* describes the results when a wave-front is divided into parts by passing through two or more distinct holes or slits, while *diffraction* describes what happens when extended light waves are blocked or restricted by a single object or slit. In the latter case, interference takes place between waves originating from different points on the same wave front.

OBJECTIVES

1. To observe and explain the behavior of light when light waves from coherent sources interact each other (interference)
2. To observe and explain the behavior of light when it interacts with material obstacles (diffraction)
3. To deduce the wave nature of light
4. To explain experimental observations using the wave nature of light

INVESTIGATION 1: LIGHT WAVES, SLITS AND OBSTACLES

APPARATUS AND SUPPLIES

- Clear water trough or baking dish
- 2 eyedroppers or syringes
- Overhead projector
- 3 sets of double slits, all the same width but with different separations
- Slit holder
- Ruler or meter stick
- White cardboard screen
- Cylindrical lens
- Laser pointer ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Lump of clay (for mounting the laser)

What are waves and what are their properties? The simplest waves to observe are water waves. Have you ever thrown a rock into still water—a lake or pool? What happens to the water?

Prediction 1-1: In the box on the right, sketch the water pattern that you would expect to observe if a small rock were dropped into a pool of water at the point indicated.

PREDICTION

●

Test your prediction.

Activity 1-1: Waves from a point source

Place the water trough on the overhead projector, and fill it with about 2-3 cm of water. Use an eyedropper or syringe held about 5 cm above the surface of the water to drip drops in the center of the trough at a steady rate, and watch the pattern on the wall or screen. Observe what happens with fewer drops per second and more drops per second.

In the boxes on the right, sketch the observed wave patterns.

OBSERVATION WITH MORE DROPS/SEC	OBSERVATION WITH FEWER DROPS/SEC
●	●

Question 1-1: Describe the water wave pattern you observed, and compare it to your prediction. What is the shape of the water waves from a point source.

Question 1-2: What happens to the spacing between the water wave peaks (and troughs) when the number of drops per second is increased? Decreased?

Note: The number of drops per second is called the *frequency*, and the spacing between the peaks is called the *wavelength*.

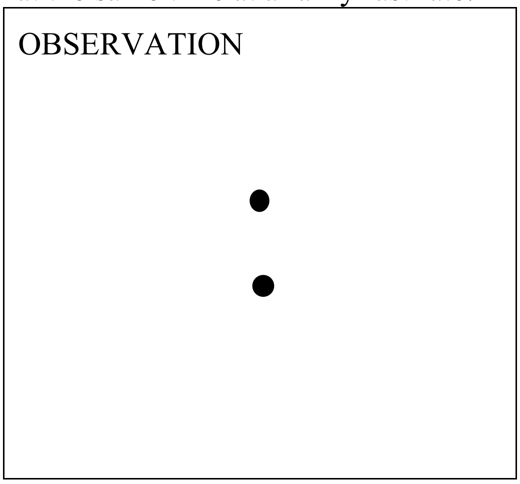
Question 1-3: What is the mathematical relationship between the frequency and wavelength of a water wave? Explain based on your observations.

Prediction 1-2: Suppose that you have two point sources of water waves separated by about 3 cm. Describe in words how the two water wave patterns will affect each other.

Test your prediction.

Activity 1-2: Waves from two point sources

Fill the two eye droppers with water, and hold them about an 3 cm apart and about 5 cm above the surface of the water in the trough. Squeeze the droppers so that drops fall from both at the same time at a fairly fast rate.



In the box on the right, sketch the wave pattern that you observed.

Question 1-4: Describe the wave pattern you observed. Is there any evidence that the waves from one of the point sources are changed by the waves from the other point source when they cross each other's paths? Explain.

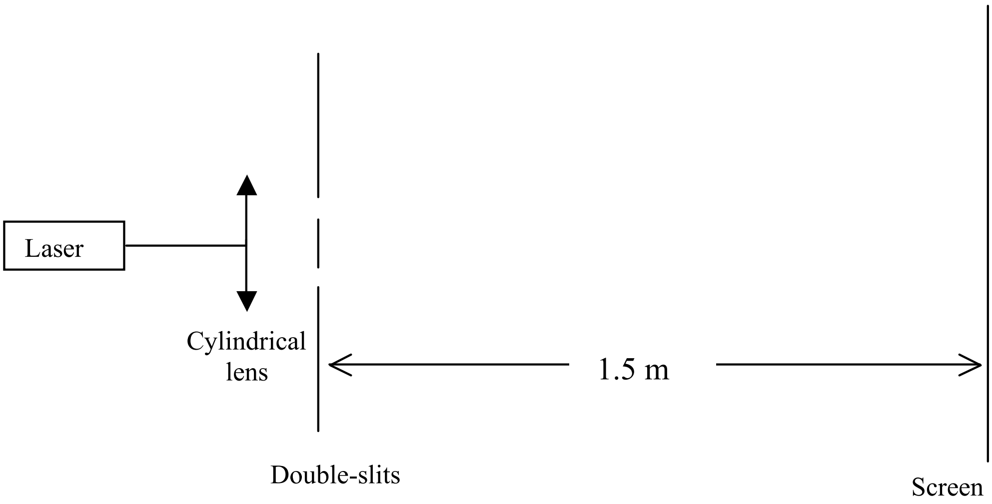
Note: Light from a point source can also be represented as waves. Of course you cannot see the peaks and valleys of these waves with your eyes because the wavelength is so short (and the speed of light is so large). Since the waves move outward from the point source in all directions (in three dimensions), they are spherical waves rather than circular ones (like the water waves in two dimensions).

Prediction 1-3: Suppose that you shine the light from a laser through two very narrow slits that are very close together. (See the diagram below). What will the pattern of light that passes through the slits look like on a screen very far away?

Now test your prediction.

Activity 1-3: Observation of light through two slits

1. Set up the laser, cylindrical lens, double slits with the intermediate size separation and screen as shown below. Observe the light pattern on the screen.



2. Sketch the light pattern you observe on the screen in the box below.

Screen

Question 1-5: What is the purpose of the cylindrical lens?

Note: The bands of light are usually referred to as *fringes*.

Question 1-6: Is there a bright or a dark fringe at the center of the pattern?

Question 1-7: Are the bright fringes of equal width? Are the dark fringes of equal width?

Question 1-8: Can these results be explained by *geometrical optics*? What would geometrical optics predict for the pattern on the screen?

Prediction 1-4: Suppose that you shine the light from a laser through two very narrow slits that are further apart than the original slits. How will the pattern on a distant screen be different?

Test your prediction.

3. Repeat your observations with the pair of slits with a wider spacing.

Question 1-9: Describe how the pattern of light on the screen is different than with the original set of slits. What happens to the spacing between the bright fringes (center to center) when the slits are further apart?

Prediction 1-5: Suppose that you shine the light from a laser through two very narrow slits that are closer together than the original slits. How will the pattern on a distant screen be different?

Test your prediction.

4. Repeat your observations with the pair of slits with a narrower spacing,

Question 1-10: Describe how the pattern of light on the screen is different than with the original set of slits. What happens to the spacing between the bright fringes (center to center) when the slits are closer together.

Question 1-11: What is the qualitative relationship between slit spacing and fringe spacing?

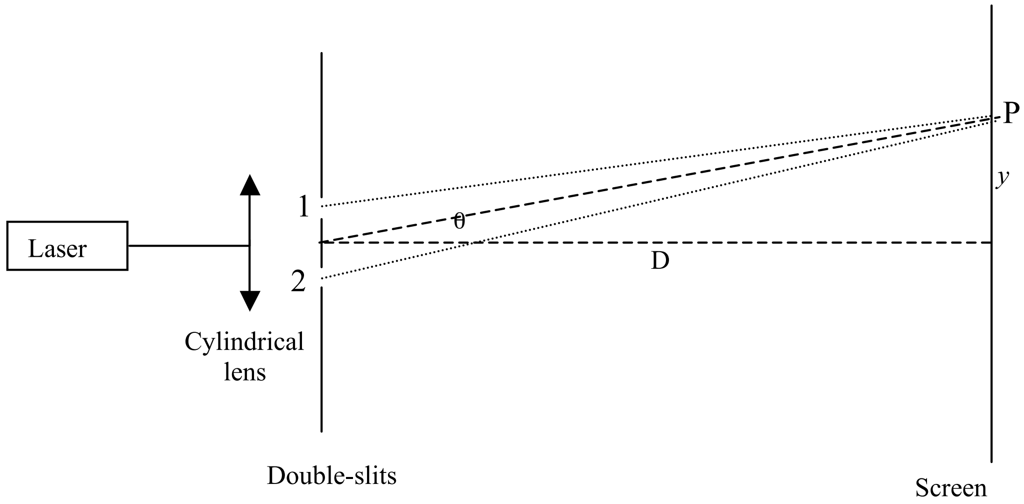
5. Again using the slits with the narrower spacing, observe what happens when the screen is moved further away from and brought closer to the slits.

Question 1-12: What happened to the spacing between the bright fringes (center to center) when the screen was moved further away from the slits? Closer?

In the next activity you will explore how a wave model for light (or *physical optics*) might be used to explain the patterns you observed.

Activity 1-4: Model for light pattern from two slits

If light from the laser goes through both slits, then there are light waves reaching any point on the screen from slit 1 and slit 2.



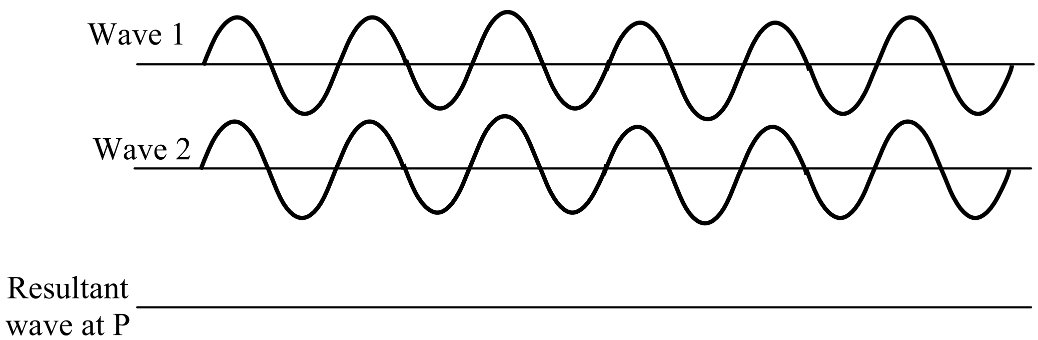
Question 1-13: Do the light waves from slit 1 have the same wavelength as the waves from slit 2 when they leave the slits? Do the waves from slit 1 have the same wavelength as the waves from slit 2 when they reach the screen? Explain.

Question 1-14: Are the waves from slit 1 in phase with the waves from slit 2 when they leave the slits? Are the waves from slit 1 always in phase with the waves from slit 2 when they reach the screen, at every point on the screen?

Note: Light waves from slits 1 and 2 originate from the same source. Therefore, light waves from both slits have the same wavelength, and start out in phase. These are called *coherent* light sources. The slits are like two *coherent* point sources of light.

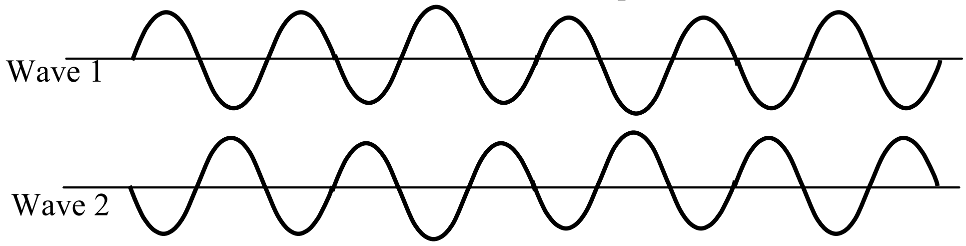
1. The sine waves below represent the light waves from slit 1 and slit 2 when they reach point P on the screen. (The amplitude is related to the light intensity of each wave.) If at P waves 1 and 2 are as shown below, that is, they are in phase at P, draw in the space below the wave that results from the addition of these two waves.

Case 1: Addition of two waves in phase with each other



2. Now suppose that the sine waves below represent the two waves when they reach point P, that is, they are out of phase. Draw in the space below the wave that results from the addition of these two waves.

Case 2: Addition of two waves out of phase with each



Resultant wave at P ______________________________

Question 1-15: Which case results in a bright fringe on the screen at P? Explain.

Question 1-16: Which case results in a dark fringe on the screen at P? Explain.

Question 1-17: What is the origin of the differences in phase for waves reaching the same point on the screen from the two slits?

Question 1-18: Use this model to explain the patterns you observed on the screen in Activity 1-3.

Question 1-19: Use this model to explain why the center fringe in Activity 1-3 is bright.

Question 1-20: Based on your answer to Question 1-16, does the phase difference depend on the wavelength of the laser? How would the fringe spacing in the pattern on the screen be different if a green laser with a shorter wavelength were shone on the same double slits?

Question 1-21: A theoretical analysis shows that the first bright fringe should occur at an angle away from the center of the central bright fringe given by $\sin\theta = \lambda/d$, where λ is the wavelength of the laser light, and d is the spacing between the slits. See the diagram above for the definition of θ. Also, notice that $\tan\theta = y/D$. Are your results, and in particular your answers to Questions 1-11, 1-12 and 1-20, consistent with these equations? Explain.

INVESTIGATION 2: LIGHT THROUGH MANY SLITS

APPARATUS AND SUPPLIES

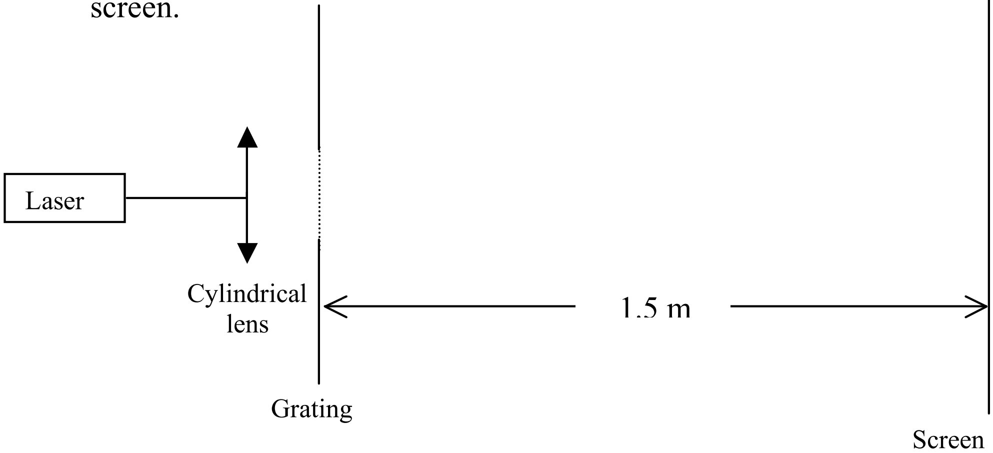
- Slit holder
- Ruler or meter stick
- White cardboard screen
- Cylindrical lens
- Laser pointer ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Lump of clay (for mounting the laser)
- Diffraction grating
- Flashlight with a 1-2 mm cardboard slit

What if coherent light passes through many parallel slits? A *diffraction grating* is a multiple slit device, consisting of many parallel slits that are very close together.

Prediction 2-1: Suppose that you shine the light from a laser through a diffraction grating. (See the diagram below.) What will the pattern of light that passes through the slits look like on a screen very far away?
Test your prediction.

Activity 2-1: Laser light pattern from multiple slits (diffraction grating)

1. Replace the double slits in the setup for Activity 1-3 with the diffraction grating, as shown below. Observe the light pattern on the screen.



2. Sketch the light pattern you observe on the screen in the box below.

Screen

Question 2-1: Describe the light pattern observed on the screen in words.

Question 2-2: Use the model from Investigation 1 to explain why there are bright fringes on the screen resulting from coherent light from many slits.

Question 2-3: Compare the light pattern with many slits (in this activity) to the ones observed with just two slits (in the previous investigation).

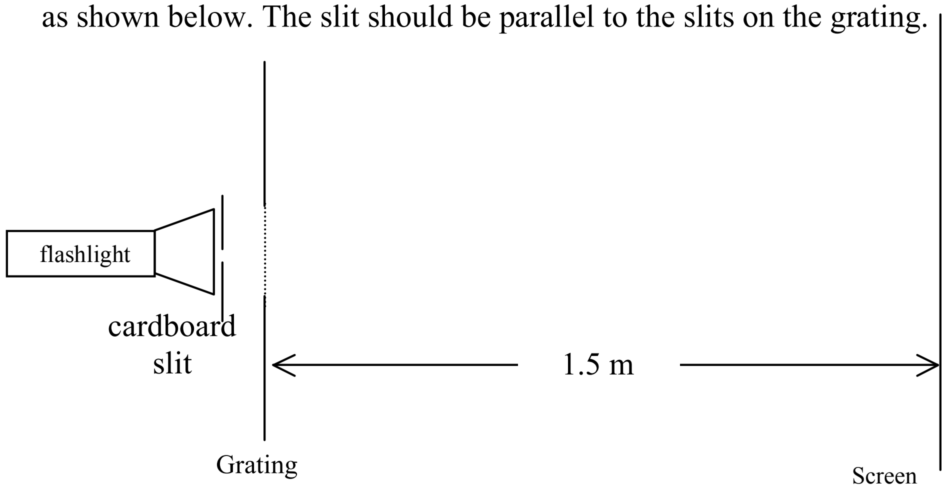
Question 2-4: Try to explain why light from many slits will produce the differences described in Question 2-3.

Prediction 2-2: What will you see on the screen if white light (all visible wavelengths) is shone on the grating? (**Hint:** Use your answer to Question 1-19 to help you make this prediction.)

Test your prediction.

Activity 2-2: White light pattern from multiple slits

1. Set up the flashlight with the slit, the diffraction grating and the screen as shown below. The slit should be parallel to the slits on the grating.



2. Shine the flashlight through the grating, and observe the light on the screen.

Question 2-5: Describe what you observe on the screen.

Question 2-6: Try to use the model from Investigation 1 and the fact that the different colors of light have different wavelengths to explain what you observed.

INVESTIGATION 3: INTERACTION OF LIGHT WITH VARIOUS OBSTACLES

APPARATUS AND SUPPLIES

- Slit holder
- Ruler or meter stick
- White cardboard screen
- Cylindrical lens
- Laser pointer ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Lump of clay (for mounting the laser)
- Button (for clothing)
- Microscope objective
- Small diameter straight wire (not transparent)

In Investigation 1 you observed that shining laser light through two narrow slits that are very close together results in an interesting pattern of bright and dark fringes on a distant screen. Then in Investigation 2 you observed the pattern produced when light is shone through multiple parallel slits. Are interesting patterns of light produced when a laser is shone on any other small obstacles or objects?

In this investigation, laser light will be shone on the hole in a button and a thin piece of wire, and the light patterns will be observed on a screen.

Predictions: Predict the patterns produced on a screen located at different distances from the two obstacles by sketching the patterns produced in the Prediction column in the table below.

Obstacle	**Predicted** Light Pattern	**Observed** Light Pattern
Hole in button		
Straight wire		

Activity 3-1: Laser shone on various obstacles

Using the laser pointer and the above materials, with the screen about 1.5 m away, make your observations and summarize them with sketches in the Observation column of the table.

Question 3-1: Describe and contrast the fringe patterns observed for the two obstacles.

Question 3-2: Can *geometrical optics* explain such patterns?

INVESTIGATION 4: SINGLE SLIT SYSTEM

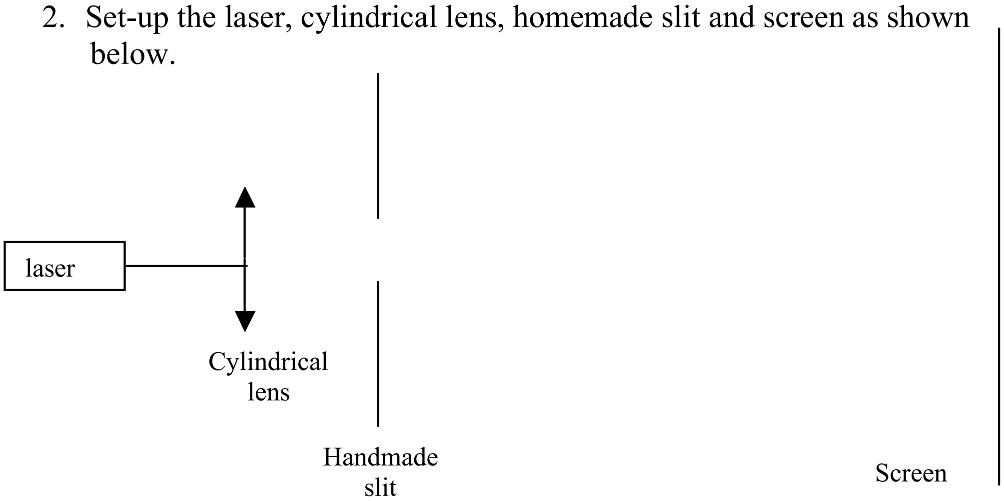
APPARATUS AND SUPPLIES

- Slit holder
- Ruler or meter stick
- White cardboard screen
- Cylindrical lens
- Laser pointer ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Lump of clay (for mounting the laser)
- Mirror with coated surface exposed
- Razor blade
- 3 single slits of different widths—5000 µm (5 mm), 500 µm (0.5 mm), and 50 µm (0.05 mm)
- Tape measure

In this investigation you will examine the pattern created when laser light is incident on a single narrow slit.

Activity 4-1: Creating a single slit system

1. Using the razor blade and ruler, carefully cut a long vertical slit on the coated part of the plane mirror to prepare a homemade single slit.
2. Set-up the laser, cylindrical lens, homemade slit and screen as shown below.



Prediction 4-1: Sketch and describe in the space below the pattern of light intensity that you think will be produced on the screen when the laser beam passes through the homemade slit.

Prediction
Screen

3. Perform the experiment and sketch the intensity pattern you observe in the box below.

Observation
Screen

Question 4-1: Describe the pattern observed in words. Was it similar to any of the patterns observed in Investigations 1, 2 or 3?

Question 4-2: Compare the pattern to that observed in Investigation 1 for two slits. In what ways are they similar and in what ways are they different?

Question 4-3: Based on your comparisons in Question 4-2, and the model examined in Activity 1-4, do you think that the intensity pattern produced when laser light is shone through a single slit is the result of interference of light waves? Explain.

Question 4-4: If the pattern is caused by interference of waves, what do you think is the origin of the different waves that interfere in this case?

Note: In two-slit interference, the origin of the two coherent waves that interfere is clear. In the case of a single slit, the origin is more complicated. As the wave from the laser passes through the slit, each point on the wave front serves as a source of new waves that propagate toward the screen. The idea that points on a wave front can be the sources of new waves is known as *Huygens' principle*, and the interference process is called *diffraction*, in this case, *single-slit diffraction*. The light intensity pattern on the screen is the result of the interference of many waves, slightly out of phase with each other.

Prediction 4-2: How does the width of the slit affect the width of the central bright fringe of the single-slit diffraction pattern? Suppose that you are given three slits a, b and c. a is the narrowest, b is wider and c is still wider. Predict the relative width of the central bright fringes of the diffraction patterns for these slits for a diffraction setup the same as above. Use =, > and < signs below to indicate the relative widths of the central bright fringes on the screen.

Fringe width for slit a   Fringe width for slit b   Fringe width for slit c

Test your predictions.

Activity 4-2: Fringes for different width slits

1. Using the same setup as in Activity 4-2, mount the narrowest slit, and measure the width of the central bright fringe.

   Width of central bright fringe for narrowest slit:__________

2. Replace the slit with the next widest one, and then the widest one, and measure the central bright fringe width for each.

   Width of central bright fringe for next widest slit:__________

   Width of central bright fringe for widest slit:__________

Question 4-5: Compare the widths of the central bright fringe for the three different width slits. State the relationship you observed between slit width and width of the central bright fringe.

Suppose that the orientation of the slit is changed. How will this affect the diffraction pattern observed on the screen?

Prediction 4-3: Predict the diffraction pattern that will be observed on the screen if the orientation of the slit from Activity 4-1 is changed. In each case sketch the pattern you think will be observed in the Prediction column of the table below.

Slit Orientation	**Prediction** Diffraction Pattern	**Observation** Diffraction Pattern
Vertical		
Diagonal		

Horizontal		

Activity 4-3: Changing the orientation of the diffraction slit

Make each of the described changes in the orientation of the slit, and sketch your observations in the Observation column of the table above.

Question 4-6: How is the orientation of the diffraction pattern related to the orientation of the slit? What does this suggest about the nature of light?

Question 4-7: Suppose you used a square hole instead of a narrow slit. What pattern would you expect? Explain based on your observations.

Question 4-8: Suppose you used a round hole instead of a narrow slit. What pattern would you expect? (Recall your observations with a hole in a button in Investigation 3.) Explain based on your observations.

Teachers' Guide for Module 3: Interference and Diffraction

TEACHERS' GUIDE FOR MODULE 3: INTERFERENCE AND DIFFRACTION

General Introduction

With an inexpensive laser pointer, it is possible to observe many interference and diffraction effects. Therefore, simple objects like the hole in a button, or a wire can be used to observe diffraction. A single or double-slit mask can be fabricated from a mirror by using a razor blade to scratch slits into the aluminum coating, or by photocopying a pattern of slits onto a transparency film. Inexpensive diffraction gratings are also readily available, or can be fabricated from CD pieces. Thus it is possible to observe a wide range of phenomena with inexpensive apparatus.

Module 3 Apparatus and Supplies List

- Clear water trough or baking dish
- 2 eyedroppers or syringes
- Overhead projector
- 3 sets of double slits, all the same width but with different separations
- Slit holder
- Ruler or meter stick
- White cardboard screen
- Cylindrical lens
- Laser pointer ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Lump of clay (for mounting the laser)
- Diffraction grating
- Flashlight with a 1-2 mm wide cardboard slit
- Button (for clothing)
- Small diameter straight wire
- Microscope objective
- Mirror with coated surface exposed
- Razor blade
- 3 single slits of different widths
- Tape measure

Equipment Notes

Laser pointer: Please read the LASER SAFETY section of this manual. ***The laser beam should never be directed toward anybody in the room. The laser beam is damaging to the eye.*** Laser pointers are available from many sources, and are very inexpensive. They can be purchased in markets in Asia for under $1 (USD) apiece. Even these very cheap lasers are powerful enough for the activities in this module, but are often not very durable. If these are not available locally, the best advice is to search the web for *laser pointer* to find the best source.

Double and single slits: The slit mask below should be photocopied onto transparent film, and then the slits can be used in these activities.

Diffraction grating: Inexpensive transmission diffraction gratings are available from many sources, e.g., Edmund Scientific (http://www.scientificsonline.com). They offer transmission grating slides with 13,500 grooves/in. (#3001307 and # 3050183) and with 25,400 grooves/in. (#3039502). Diffraction gratings can also be fabricated from pieces of CDs.

Homemade single slit: The homemade single slit should be made by carefully cutting a slit with the razor blade and ruler into the metallic coating of the mirror. This produces a narrow slit that is quite adequate for these activities.

INVESTIGATION 1: WAVES, LIGHT AND INTERFERENCE

Investigation 1 Apparatus and Supplies List

- Clear water trough or baking dish
- 2 eyedroppers or syringes
- Overhead projector
- 3 sets of double slits, all the same width but with different separations
- Slit holder
- Ruler or meter stick
- White cardboard screen
- Cylindrical lens
- Laser pointer ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Lump of clay (for mounting the laser)

Activity 1-1: Waves from a point source

It takes a little practice to be able to produce drops at a constant rate, and to vary the rate. However, it is possible to get nice patterns of circles spreading out from the point where the drops hit the water. These patterns are clearly visible on a screen or wall using an overhead projector. Student observations should be as shown in Figure TG3-1, below.

Question 1-1: The waves are shaped like concentric circles with the point where the drops hit the water as the center.

Question 1-2: When the number of drops per second is increased, the spacing between the wave peaks decreases. When the number per second is decreased, the spacing between the peaks increases.

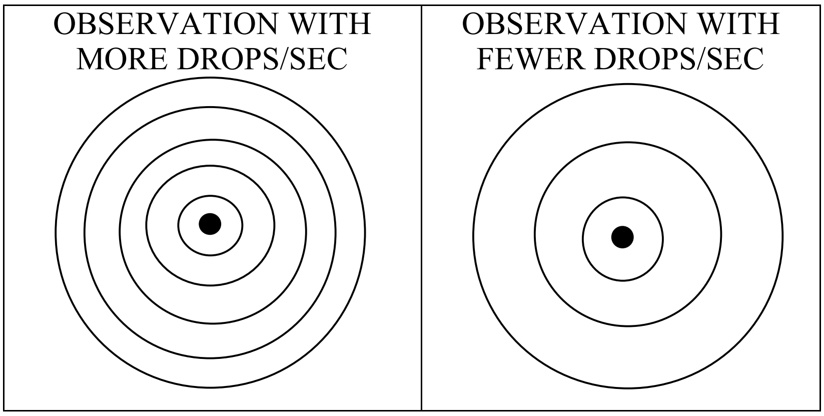


Figure TG3-1: Sketches of water waves produced by water droplets dropped at center point. Left is higher frequency than right.

Question 1-3: The frequency (number of drops per second) and wavelength (spacing between the wave peaks) vary inversely. When one is increased, the other decreases.

Activity 1-2: Waves from two point sources

Without a water wave apparatus that allows relatively high, uniform frequencies for the two point sources, it is not possible to observe interference between the waves. This activity still illustrates two things: 1) the analogy of two point sources for water waves, and how the waves from these two sources spread out as circles and 2) the fact that the two waves are not affected by each other except possibly at the points where they cross each other.

Figure TG3-2 shows an example of a student sketch.

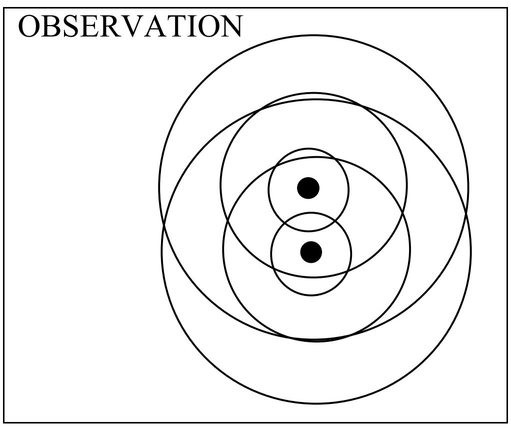


Figure TG3-2: Sketches of water waves produced by two point sources of water droplets displaced from each other.

Question 1-4: Waves from each point source spread out as they did before. There are two sets of circular waves, displaced from each other.

Activity 1-3: Observation of light through two slits

Figure TG3-3 shows the apparatus used. The lump of clay serves quite well as a laser mount. If you don't have a mount for the slits or the lens either, lumps of clay could be used for these as well.

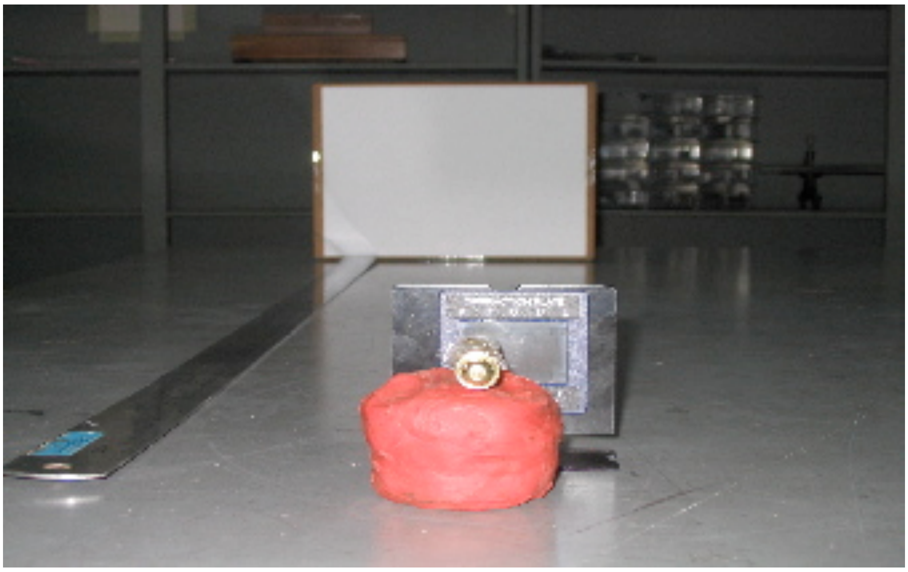


Figure TG3-3 Photo of setup of simple apparatus for observing fringe patterns produced by interference or diffraction.

Figure TG3-4 shows the actual pattern of fringes observed with double slits.

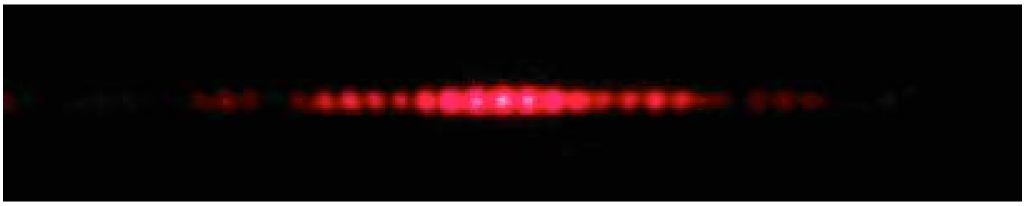


Figure TG3-4 Photo of fringe pattern produced by laser light shone on two narrow slits separated by a small distance.

Question 1-5: The cylindrical lens broadens out the laser beam so that it is incident on both slits, and illuminates them fairly uniformly.

Question 1-6: There is a bright fringe at the center of the pattern.

Question 1-7: The bright and dark fringes appear to be of equal width.

Question 1-8: These results cannot be explained by geometrical optics. Geometrical optics would predict two bright bands on the screen, corresponding to laser light going through he two slits.

Question 1-9: With the slits spaced further apart, the pattern looks similar, but the fringes are narrower and closer together.

Question 1-10: With the slits spaced closer together, the pattern looks similar, but the fringes are wider and further apart.

Question 1-11: There appears to be an inverse relationship—the wider the spacing of the slits, the narrower the fringe spacing.

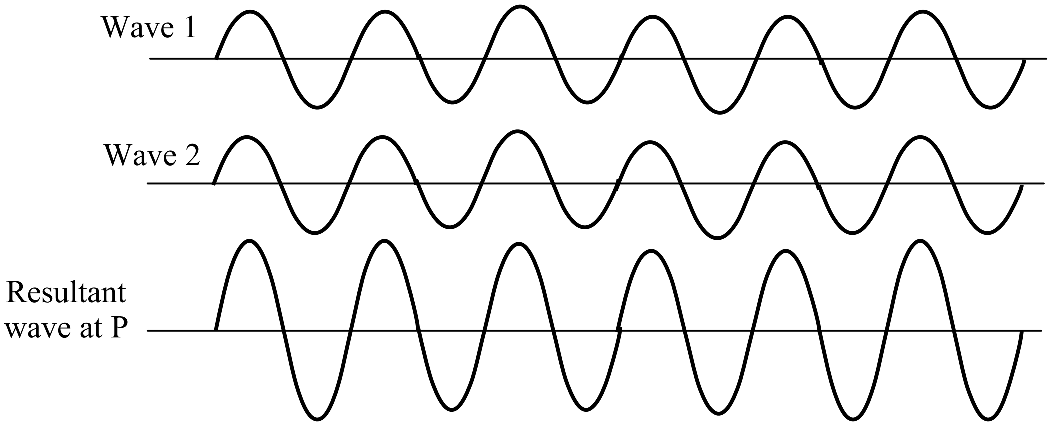
Question 1-12: When the screen is further away, the fringe spacing is larger, and when it is closer, the fringe spacing is smaller.

Activity 1-4: Model for light pattern from two slits

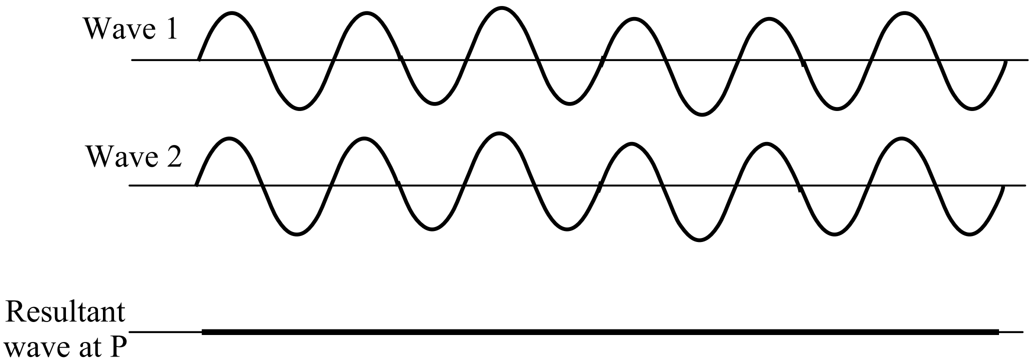
Question 1-13: Since the light waves from both slits originate from waves from the same laser, they both have the same wavelength. This is true at the position of the slits, at the screen and anywhere in between.

Question 1-14: Since the waves leaving the two slits originate on the same wavefront from the laser, they are exactly in phase with each other as they leave the slits. However, these waves do not necessarily travel the same distance to the screen. For example, for point P, waves from slit 2 travel further from the slit than waves from slit 1. Therefore, these waves may be out of phase at some points on the screen.

Case 1: Addition of two waves in phase with each other



Case 2: Addition of two waves out phase with each other



Question 1-15: Case 1 results in a wave at the screen that has a larger amplitude. This means a bright fringe will appear on the screen at this point.

Question 1-16: Case 2 results in a wave at the screen that has zero amplitude. This means a dark fringe will appear on the screen at this point.

Question 1-17: The waves from the two slits travel different distances in reaching point P. These paths are a different number of wavelengths, and the path difference results in a phase difference.

Question 1-18: At points on the screen where the waves from the two slits arrive in phase, there are bright fringes. Anytime the path difference is a whole number of wavelengths, the waves will arrive in phase. At points on the screen where waves from the two slits arrive exactly out of phase, there are dark fringes. As can be seen from the picture for Case 2, this means that the path difference is some number of half wavelengths. In between, the waves are neither exactly in phase nor exactly out of phase, so the intensity is somewhere in between bright and dark.

Question 1-19: The distances from the slits to the center of the screen are the same, so both waves arrive at this point on the screen in phase.

Question 1-20: The number of wavelengths that fit into a path from a slit to the screen depends on how long the wavelength is. Since it is the difference in the number of wavelengths that fit into the path from slit 1 to the screen and the path from slit 2 to the screen that determines the phase difference, this will depend on the wavelength of the light waves. Since green has a shorter wavelength, a smaller displacement along the screen will bring about a difference in path of one wavelength. Therefore, the bright fringes will be closer together and narrower.

Question 1-21: The observations in Activity 1-3 illustrated that the positions (y) are all larger if d is smaller, and smaller if d is larger. This agrees with the equations. Observations also illustrated that increasing D, makes y larger, and decreasing D makes y smaller, again in agreement. The answer to Question 1-20 says that for smaller wavelength, y will be smaller. This also agrees with the equations.

INVESTIGATION 2: LIGHT THROUGH MANY SLITS

Investigation 2 Apparatus and Supplies List

- Slit holder
- Ruler or meter stick
- White cardboard screen
- Cylindrical lens
- Laser pointer ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Lump of clay (for mounting the laser)
- Diffraction grating
- Flashlight with a 1-2 mm wide cardboard slit

Activity 2-1: Laser light pattern from multiple slits (diffraction grating)

Figure TG3-5 shows the fringe pattern on the screen, while Figure TG3-6 shows a comparison of the fringe pattern for double slits and that for a diffraction grating with the same slit separation.

Question 2-1: The light pattern consists of a number of bright red spots, with the area between them dark.

Question 2-2: There are points on the screen for which the waves from all of the slits arrive in phase. At these points, the waves all add together to give a bright fringe.

Question 2-3: With two slits, the bright fringes are wider, and the dark fringes are relatively narrow. For the grating, the bright fringes are narrow, and the dark spacings between them are much wider than the bright fringes.

Figure TG3-5: Photo of fringe pattern produced by laser light shone on a diffraction grating.

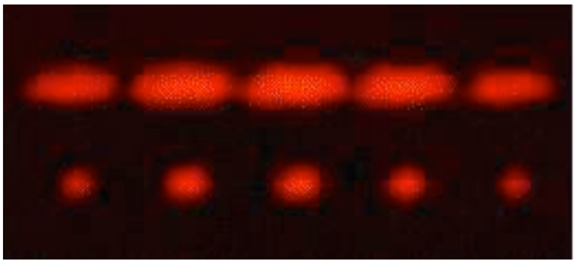


Figure TG3-6: Photo of fringe pattern produced by laser light shone on a pair of slits (top) and on a diffraction grating with the same slit spacing (bottom).

Question 2-4: If you move away from a point where the waves from all the slits are in phase with each other, then the waves from successive slits are slightly out of phase. The condition for a bright fringe is gone, and by moving only a small distance, the waves cancel out and give a dark region.

Activity 2-2: White light pattern from multiple slits

The slit for the flashlight should be about 1-2 mm wide. The flashlight should be held with the slit parallel to the grooves on the grating. The distance from the grating to the screen may need to be adjusted depending on the number of grooves/in. A white line will appear at the center of the screen, and a rainbow pattern will be observed at the same location as the first dot to the right or left in Figure TG3-5. This is known as the first order diffraction pattern. If the flashlight is bright enough, there will be rainbows at the locations of each of the dots in Figure TG3-5.

Question 2-5: A rainbow pattern with all of the colors spread out is observed on the screen. The color closest to the center is violet, and the color furthest from the center is red.

Question 2-6: For laser light with only one color (nearly one wavelength), bright fringes occur on the screen at points where the path difference for waves from successive slits is equal to a whole number of wavelengths. White light is a mixture of all of the wavelengths of visible light. The bright fringes for each wavelength occur at slightly different locations on the screen. Thus the colors are spread out into a rainbow pattern.

INVESTIGATION 3: INTERACTION OF LIGHT WITH VARIOUS OBSTACLES

Investigation 3 Apparatus and Supplies

- Slit holder
- Ruler or meter stick
- White cardboard screen
- Cylindrical lens
- Laser pointer ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Lump of clay (for mounting the laser)
- Button (for clothing)
- Small diameter straight wire

Activity 3-1: Laser shone on various obstacles

Figures TG3-7 and TG3-8 show the light patterns observed on the screen for the two objects.

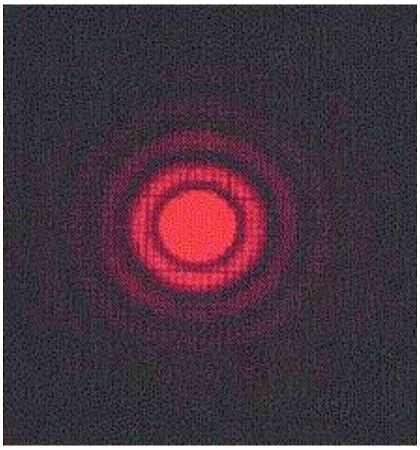


Figure TG3-7: Diffraction pattern for circular hole like that in a button.

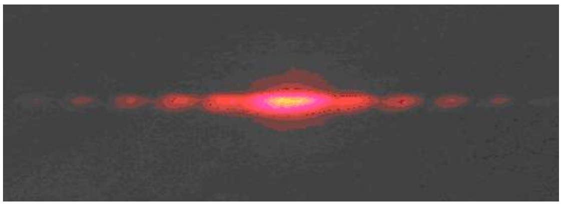


Figure TG3-8 Diffraction patterns for thin wire.

Question 3-1: The pattern for the hole in the button looks like a series of concentric rings around a bright, central circular fringe. The pattern for the straight wire looks like a wide central fringe with a series of narrower fringes on either side of it.

Question 3-2: Geometrical optics definitely cannot explain these fringe patterns. According to geometrical optics, we should just see the shadows of these obstacles.

INVESTIGATION 4: SINGLE SLIT SYSTEM

Investigation 4 Apparatus and Supplies

- Slit holder
- Ruler or meter stick
- White cardboard screen
- Cylindrical lens
- Laser pointer ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Lump of clay (for mounting the laser)
- Mirror with coated surface exposed
- Razor blade
- 3 single slits of different widths
- Tape measure

Activity 4-1: Creating a Single Slit System

Figure TG3-10 shows two examples of the fringe pattern for laser light shone on the single, narrow slit created with the razor blade and mirror. The same setup of the laser, slit, lens and screen as in the previous investigations should work here as well.

Question 4-1: There is a very wide central bright fringe, with a series of dark and bright fringes on either side of it. This fringe pattern is really not similar to any other observed earlier.

Question 4-2: They are similar in that they both have a series of bright and dark fringes. However the widths of the fringes are very different. In Investigation 1, all of the bright fringes are pretty much the same width, and evenly separated. For the single slit, the central bright fringe is much wider than the others. The other bright fringes do appear to be equally spaced.

Question 4-3: It appears that the fringe pattern is caused by interference of light waves, because there are bright and dark fringes—places where waves add together or subtract from each other.

Question 4-4: This question is pretty much speculation for the students. Unless they have studied single-slit diffraction previously, they will likely have no idea. The note that follows this question tries to briefly answer the question.

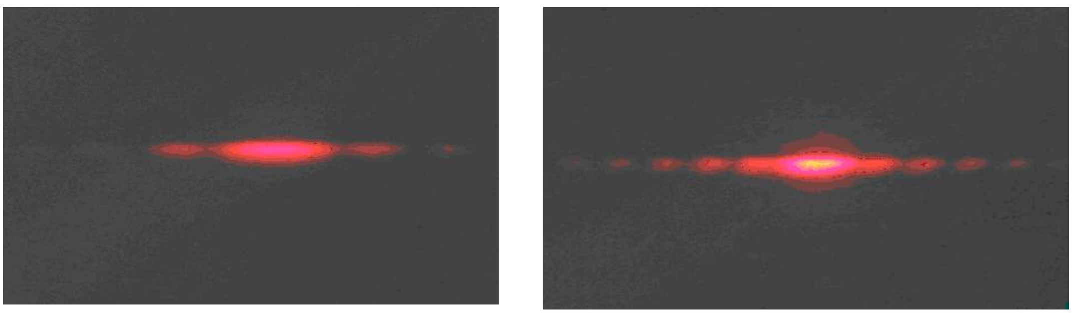


Figure TG3-10: Diffraction fringes produced with laser light shone through a homemade slit, for two different homemade slits.

Activity 3-2: Fringes for different width slits

Figure TG3-11 shows the fringe pattern for three different width single slits.

narrowest slit

intermediate width slit

widest slit

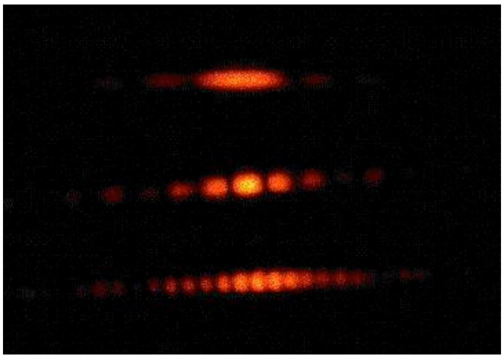
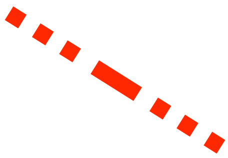


Figure TG3-11: Photos of fringe pattern produced by laser light shone on a single slit, for three different widths of slits.

Question 4-5: The central bright fringe is widest for the narrowest slit, and narrowest for the widest slit. There appears to be an inverse relationship between slit width and width of the central bright fringe.

Activity 3-3: Changing the orientation of the diffraction slit

Typical observations for this activity are shown in the table below.

Slit Orientation	**Observation** Diffraction Pattern
Vertical	
Diagonal	
Horizontal	

Question 4-6: The orientation of the fringe pattern appears to be perpendicular to the orientation of the slit. If the slit is vertical, the fringe pattern spreads out horizontally. If the slit is horizontal, the fringe pattern spreads out vertically. If the slit is diagonal, the fringe pattern spreads out in the perpendicular diagonal direction. It appears from these observations that light has a vector nature.

Question 4-7: With a square hole, the waves are restricted both horizontally and vertically. There should be fringe patterns spreading out both vertically and horizontally.

Question 4-8: With a round hole, the waves are restricted in all directions. Therefore, the fringe pattern should spread out in all directions. That is, the fringe pattern should be circles. This is what was observed with the hole in the button in Investigation 3.

Module 4: Atmospheric Optics

Ivan B. Culaba

Department of Physics
School of Science and Engineering
Ateneo de Manila University
Quezon City, Philippines
iculaba@ateneo.edu

Hand in this sheet **Name______________________________**

INTERACTIVE LECTURE DEMONSTRATIONS
PREDICTION SHEET—ABSORPTION AND MULTIPLE SCATTERING

Directions: This sheet will be collected. Write your name at the top to record your presence and participation in these demonstrations. Follow your instructor's directions. You may write whatever you wish on the attached Results Sheet and take it with you.

Demonstration 1: A piece of clear plastic is placed in front of you. Compare the intensity of the reflection of your face (a) if there is a bright light behind the plastic sheet (Figure 1), to that (b) if a dark board is placed behind the plastic sheet (Figure 2).

Figure 1

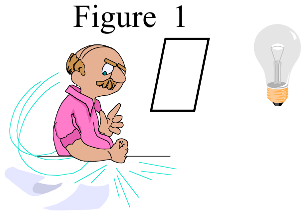
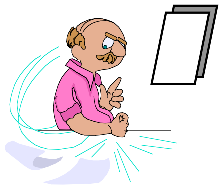
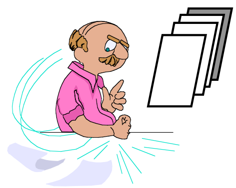


Figure 2

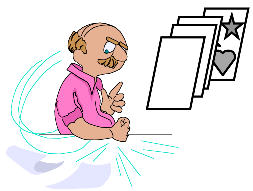


Demonstration 2: (a) Now suppose you add more clear plastic sheets over the dark-colored board. What changes in your image will you observe? Will you still see a single image or multiple images? Will your image be clearer or will it be blurry?



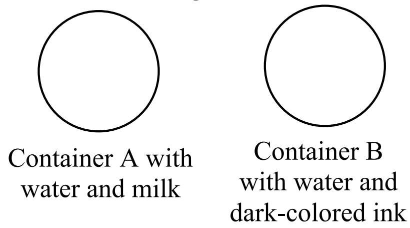
(b) Will the intensity of the reflected light (brightness of your image) increase, decrease or remain the same? Can you explain the reason for any changes?

(c) If you replace the board with a colorful picture, will you be able to see the picture as clearly as with only one sheet of plastic?



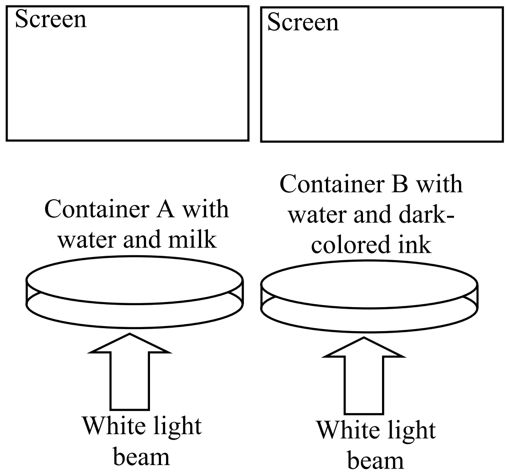
Demonstration 3: Two identical circular transparent containers are filled with water. A few drops of milk are added to container A while the same number of drops of dark-colored ink is added to container B. Each liquid is thoroughly mixed. What color will you observe in the liquid in each container? Illustrate your predictions in Figure 3 using colored pencils.

Figure 3



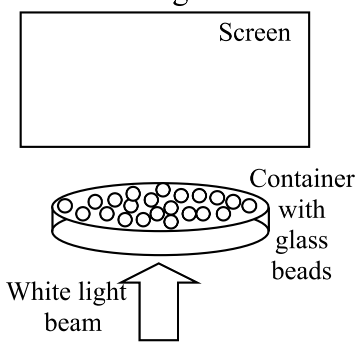
Demonstration 4: Suppose that in Demonstration 3, a white light beam is shone from below each container and a white screen is placed above each container. Describe what you will see on each screen. Illustrate your predictions in Figure 4 using colored pencils.

Figure 4

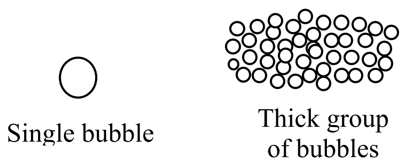


Demonstration 5: Now a transparent container is filled with glass beads. The white light beam is shone from below the container and a white screen is placed above the container, as in Demonstration 4. Describe what you will see on the screen. Illustrate your prediction in Figure 5 using colored pencils.

Figure 5



Demonstration 6: If you form soap bubbles with detergent, compare the color of a single bubble to that of a thick group of bubbles.



Keep this sheet

INTERACTIVE LECTURE DEMONSTRATIONS
RESULTS SHEET— ABSORPTION AND MULTIPLE SCATTERING

You may write whatever you wish on this sheet and take it with you.

Demonstration 1: A piece of clear plastic is placed in front of you. Compare the intensity of the reflection of your face (a) if there is a bright light behind the plastic sheet (Figure 1), to that (b) if a dark board is placed behind the plastic sheet (Figure 2).

Figure 1

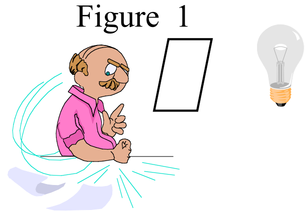
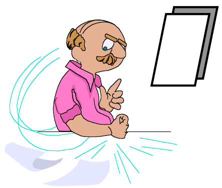
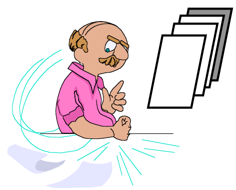


Figure 2

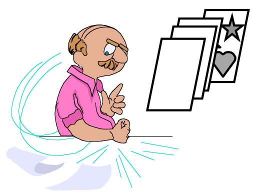


Demonstration 2: (a) Now suppose you add more clear plastic sheets over the dark-colored board. What changes in your image will you observe? Will you still see a single image or multiple images? Will your image be clearer or will it be blurry?



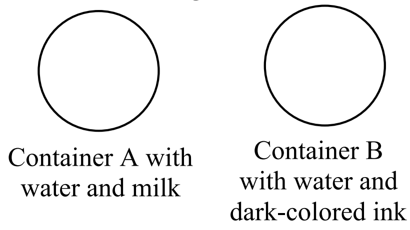
(b) Will the intensity of the reflected light (brightness of your image) increase, decrease or remain the same? Can you explain the reason for any changes?

(c) If you replace the board with a colorful picture, will you be able to see the picture as clearly as with only one sheet of plastic?



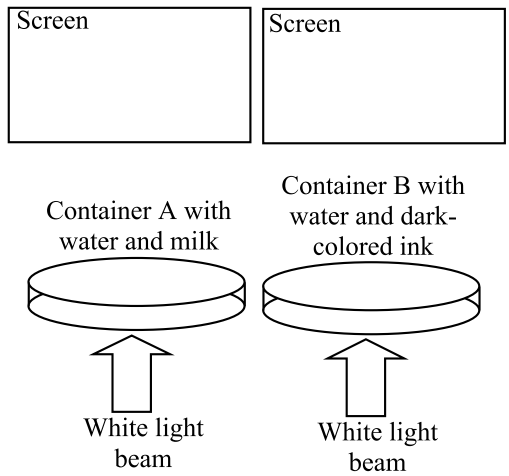
Demonstration 3: Two identical circular transparent containers are filled with water. A few drops of milk are added to container A while the same number of drops of dark-colored ink is added to container B. Each liquid is thoroughly mixed. What color will you observe in the liquid in each container? Illustrate your predictions on Figure 3 using colored pencils.

Figure 3



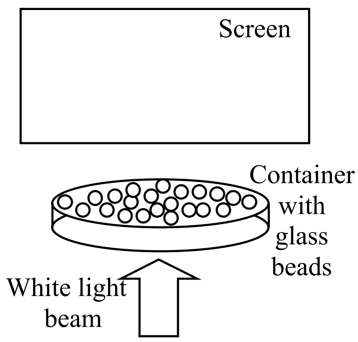
Demonstration 4: Suppose that in Demonstration 3, a white light beam is shone from below each container and a white screen is placed above each container. Describe what you will see on each screen. Illustrate your predictions in Figure 4 using colored pencils.

Figure 4

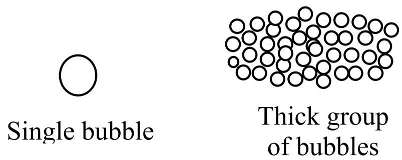


Demonstration 5: Now a transparent container is filled with glass beads. The white light beam is shone from below the container and a white screen is placed above the container, as in Demonstration 4. Describe what you will see on the screen. Illustrate your prediction in Figure 5 using colored pencils.

Figure 5



Demonstration 6: If you form soap bubbles with detergent, compare the color of a single bubble to that of a thick group of bubbles.

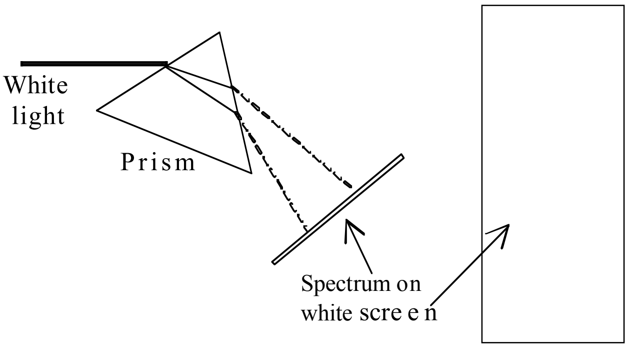


Hand in this sheet **Name____________________________**

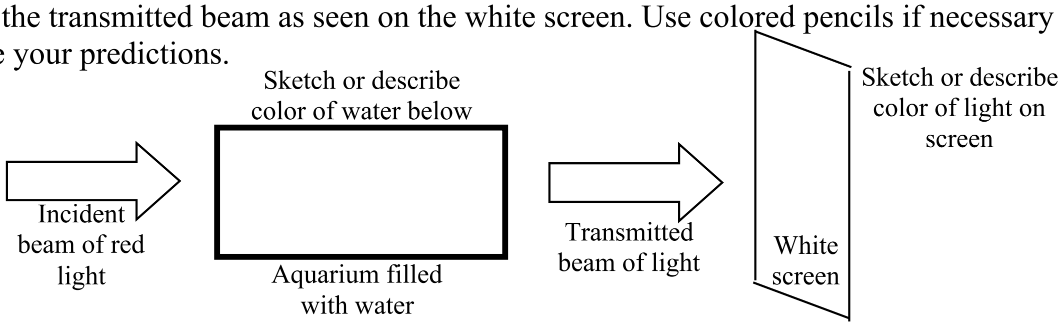
INTERACTIVE LECTURE DEMONSTRATIONS
PREDICTION SHEET—BLUE SKY AND RED SUNSET

Directions: This sheet will be collected. Write your name at the top to record your presence and participation in these demonstrations. Follow your instructor's directions. You may write whatever you wish on the attached Results Sheet and take it with you.

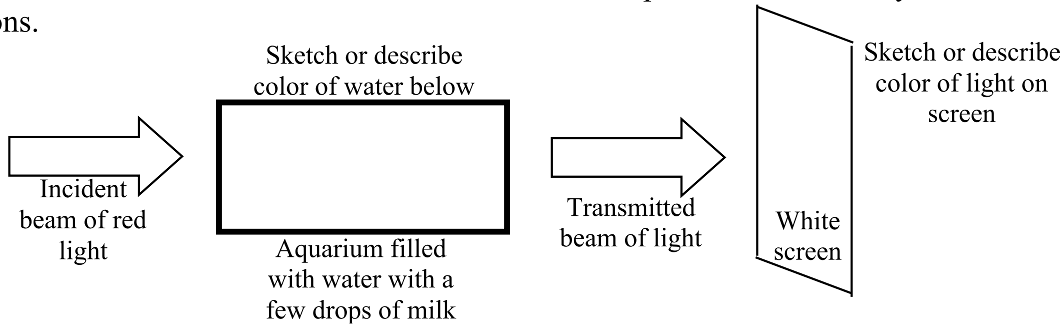
Demonstration 1: Light coming from a strong white light source is incident on a prism. The light undergoes refraction and separates into its component colors as shown in the figure on the right. Using colored pencils sketch the colors (spectrum) that will be seen on the screen.



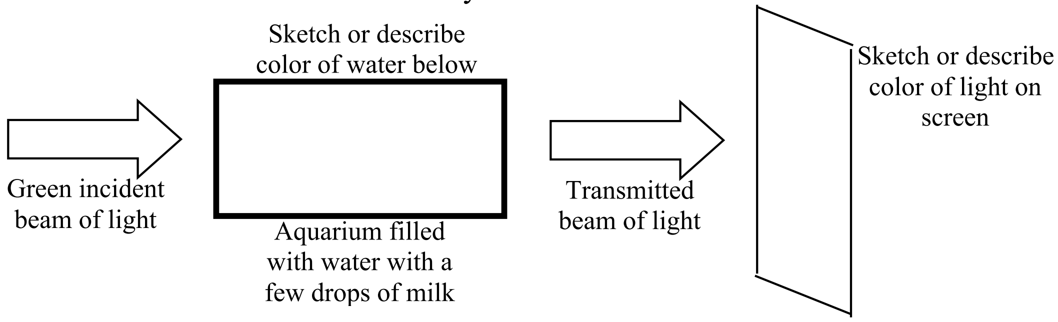
Demonstration 2: The figure below shows a beam of white light incident on an aquarium filled with water. The light that is transmitted through the water strikes a white screen. Predict the color of the liquid, as seen through the side of the aquarium. Also predict the color of the transmitted beam as seen on the white screen. Use colored pencils if necessary to illustrate your predictions.



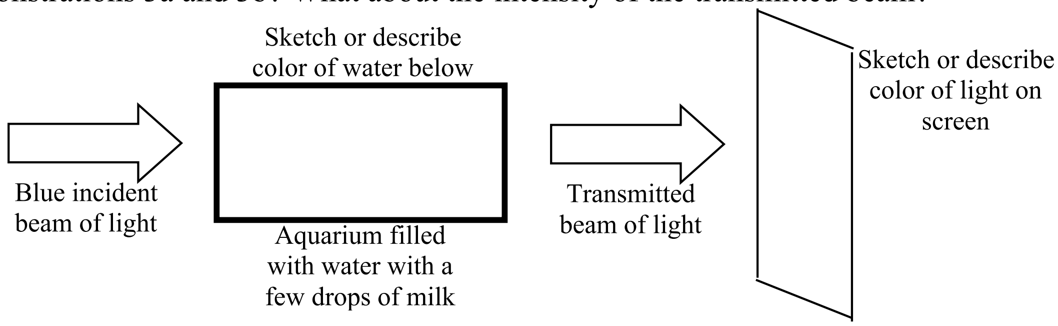
Demonstration 3a: The figure below shows a beam of red light incident on an aquarium filled with water. The light that is transmitted through the water strikes a white screen. A very small amount of milk is added to the water and the solution is thoroughly mixed, so that there are small particles of milk evenly distributed throughout the aquarium. Predict the color of the liquid, as seen through the side of the aquarium. Also predict the color of the transmitted beam as seen on the white screen. Use colored pencils to illustrate your predictions.



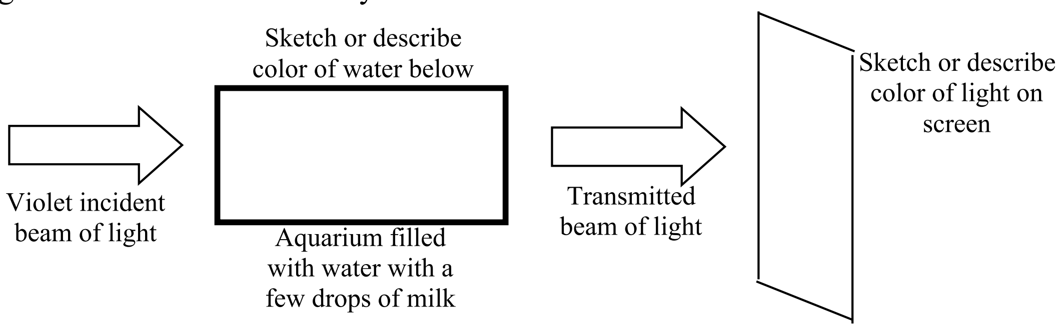
Demonstration 3b: Suppose the incident light has a green color. Predict the color of the liquid and the color of the transmitted beam. Illustrate your predictions using colored pencils. How will the intensity of the light from the water compare to that with the red light in Demonstration 3a? What about the intensity of the transmitted beam?



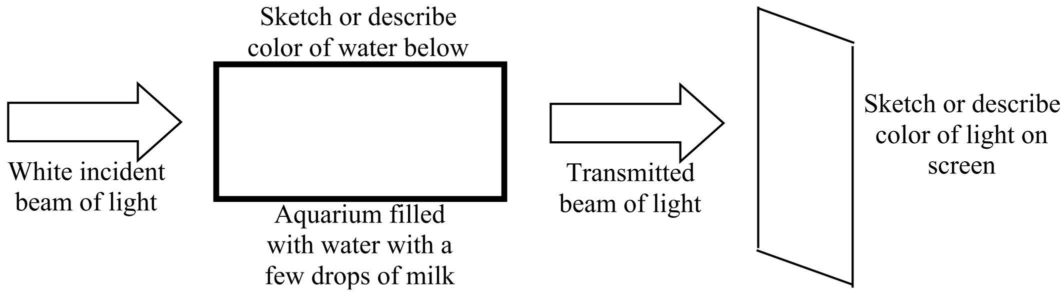
Demonstration 3c: Now, suppose the incident light has a blue color. Predict the color of the liquid and the color of the transmitted beam. Illustrate your predictions using colored pencils. How will the intensity of the light from the water compare to that with the green or red light in Demonstrations 3a and 3b? What about the intensity of the transmitted beam?



Demonstration 3d: Now, suppose the incident light has a violet color. Predict the color of the liquid and the color of the transmitted beam. Illustrate your predictions using colored pencils. How will the intensity of the light from the water compare to that with the green, red or blue light? What about the intensity of the transmitted beam?



Demonstration 4: This time white light, a mixture of all the different colors, is incident on the aquarium. Predict the color of the liquid, as seen through the side of the aquarium. Also predict the color of the transmitted beam as seen on the white screen. Show your predictions in the figure below using colored pencils.



Suppose you examine the color of the liquid using a diffraction grating. Will you observe a pure color or will you be able to observe other colors?

Suppose you examine the transmitted light using a diffraction grating. Will you observe a pure color or will you be able to observe other colors?

Demonstration 5: Now more drops of milk are slowly added to the aquarium, and the water is stirred after each drop.

Will the intensity and/or color of the scattered light viewed from the side of the aquarium change? If so, how will it change?

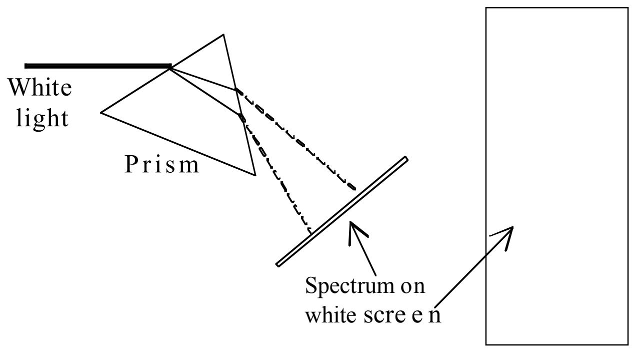
Will the intensity and/or color of the transmitted light viewed on the screen change? If so, how will it change?

Keep this sheet

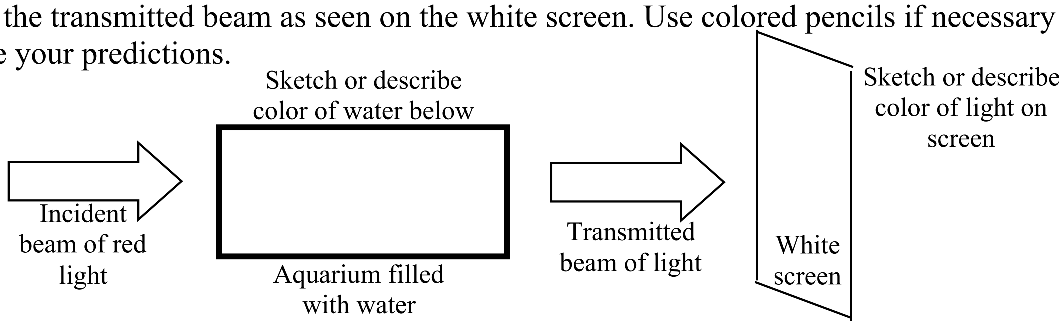
INTERACTIVE LECTURE DEMONSTRATIONS
RESULTS SHEET— BLUE SKY AND RED SUNSET

You may write whatever you wish on this sheet and take it with you.

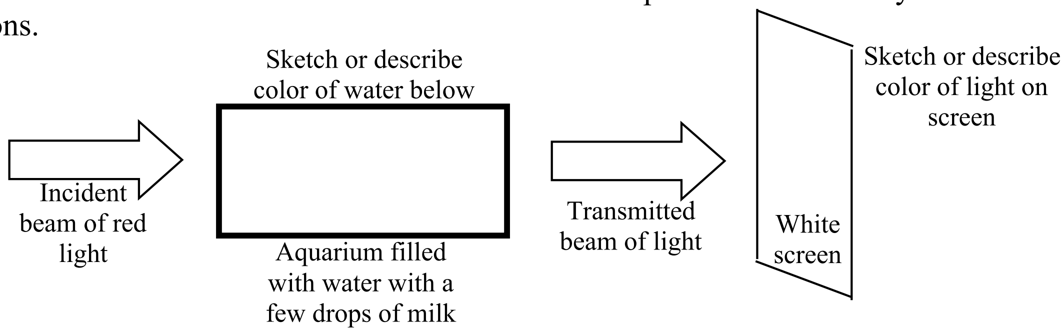
Demonstration 1: Light coming from a strong white light source is incident on a prism. The light undergoes refraction and separates into its component colors as shown in the figure on the right. Using colored pencils sketch the colors (spectrum) that will be seen on the screen.



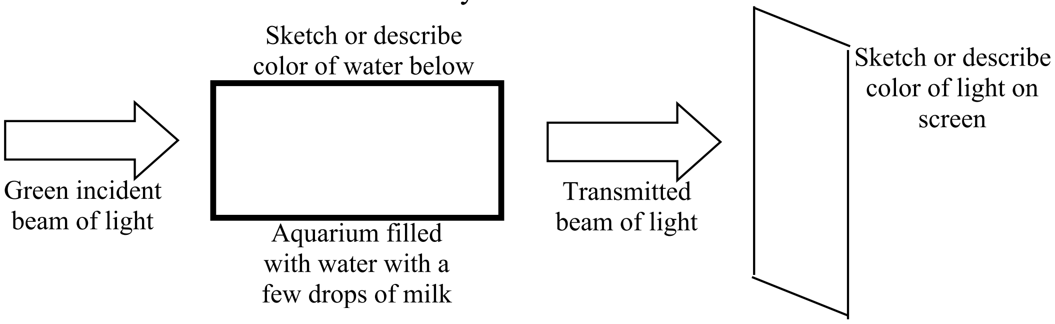
Demonstration 2: The figure below shows a beam of white light incident on an aquarium filled with water. The light that is transmitted through the water strikes a white screen. Predict the color of the liquid, as seen through the side of the aquarium. Also predict the color of the transmitted beam as seen on the white screen. Use colored pencils if necessary to illustrate your predictions.



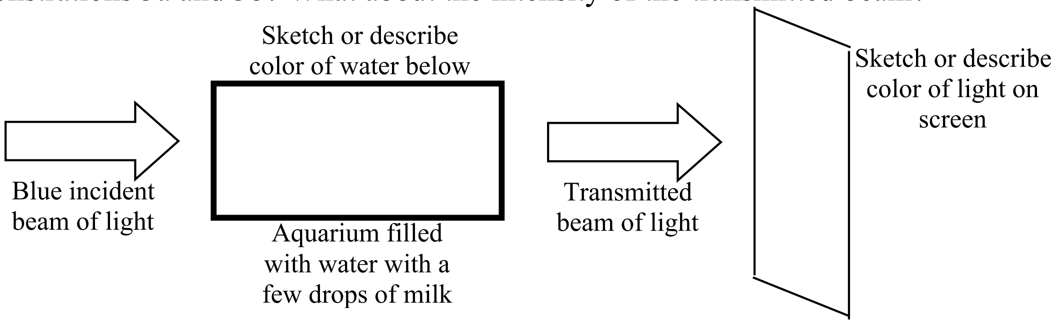
Demonstration 3a: The figure below shows a beam of red light incident on an aquarium filled with water. The light that is transmitted through the water strikes a white screen. A very small amount of milk is added to the water and the solution is thoroughly mixed, so that there are small particles of milk evenly distributed throughout the aquarium. Predict the color of the liquid, as seen through the side of the aquarium. Also predict the color of the transmitted beam as seen on the white screen. Use colored pencils to illustrate your predictions.



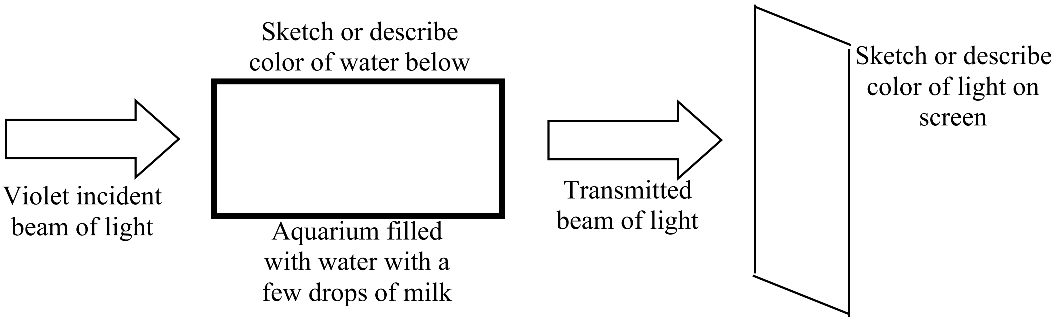
Demonstration 3b: Suppose the incident light has a green color. Predict the color of the liquid and the color of the transmitted beam. Illustrate your predictions using colored pencils. How will the intensity of the light from the water compare to that with the red light in Demonstration 3a? What about the intensity of the transmitted beam?



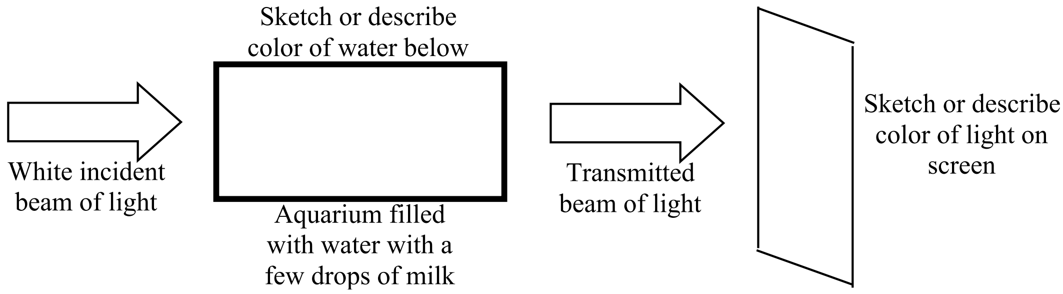
Demonstration 3c: Now, suppose the incident light has a blue color. Predict the color of the liquid and the color of the transmitted beam. Illustrate your predictions using colored pencils. How will the intensity of the light from the water compare to that with the green or red light in Demonstrations 3a and 3b? What about the intensity of the transmitted beam?



Demonstration 3d: Now, suppose the incident light has a violet color. Predict the color of the liquid and the color of the transmitted beam. Illustrate your predictions using colored pencils. How will the intensity of the light from the water compare to that with the green, red or blue light? What about the intensity of the transmitted beam?



Demonstration 4: This time white light, a mixture of all the different colors, is incident on the aquarium. Predict the color of the liquid, as seen through the side of the aquarium. Also predict the color of the transmitted beam as seen on the white screen. Show your predictions in the figure below using colored pencils.



Suppose you examine the color of the liquid using a diffraction grating. Will you observe a pure color or will you be able to observe other colors?

Suppose you examine the transmitted light using a diffraction grating. Will you observe a pure color or will you be able to observe other colors?

Demonstration 5: Now more drops of milk are slowly added to the aquarium, and the water is stirred after each drop.

Will the intensity and/or color of the scattered light viewed from the side of the aquarium change? If so, how will it change?

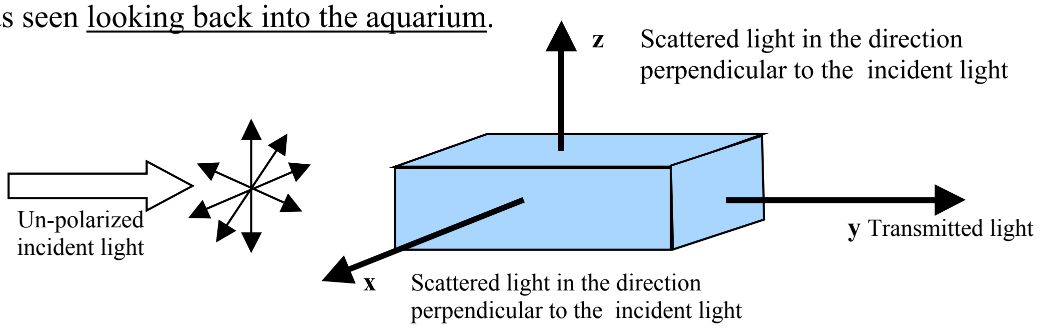
Will the intensity and/or color of the transmitted light viewed on the screen change? If so, how will it change?

Hand in this sheet **Name**________________________________

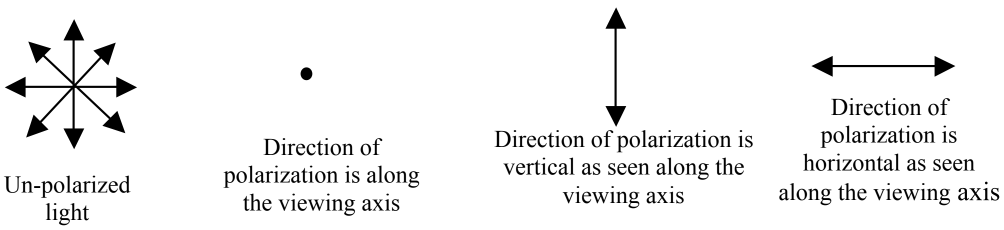
INTERACTIVE LECTURE DEMONSTRATIONS
PREDICTION SHEET—POLARIZATION BY SCATTERING

Directions: This sheet will be collected. Write your name at the top to record your presence and participation in these demonstrations. Follow your instructor's directions. You may write whatever you wish on the attached Results Sheet and take it with you.

Demonstration 1: The figure below shows an un-polarized beam of light moving along the y axis. It is incident on the aquarium filled with water mixed with a very small amount of milk. Light along **x** represents the light scattered by the solution as seen looking into the side of the aquarium. Light along **z** represents the light scattered by the solution as seen looking down into the aquarium from above. Light along **y** represents the light transmitted through the solution, as seen looking back into the aquarium.

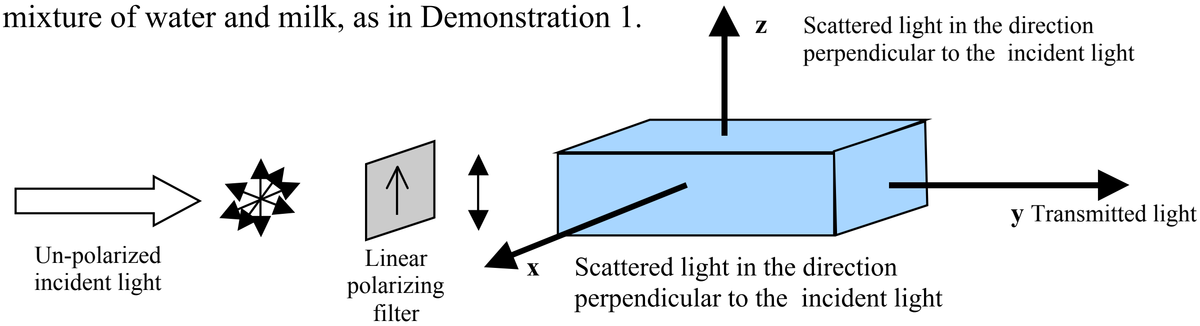


Predict in the spaces below the state of polarization of the scattered light along **x** and along **z** and the polarization of the transmitted light along **y** (all as seen looking into the aquarium). Use the following symbols to denote the different states of polarization.



Predicted polarization along **x** | Predicted polarization along **z** | Predicted polarization along **y**

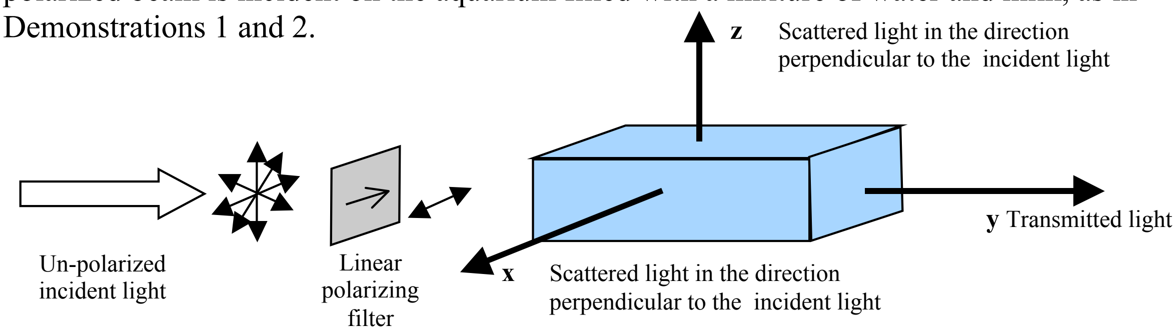
Demonstration 2: The figure below shows an un-polarized beam of light passing through a linear polarizing filter. The vertically polarized beam is incident on the aquarium filled with a mixture of water and milk, as in Demonstration 1.



Predict in the spaces below the state of polarization of the scattered light along **x** and along **z** and the polarization of the transmitted light along **y** (all as seen looking into the aquarium). Use the same symbols for polarized light as in Demonstration 1.

Predicted polarization along **x**		Predicted polarization along **z**		Predicted polarization along **y**	

Demonstrations 3: The figure below shows an un-polarized beam of light passing through a linear polarizing filter rotated by 90° compared to Demonstration 2. The horizontally polarized beam is incident on the aquarium filled with a mixture of water and milk, as in Demonstrations 1 and 2.

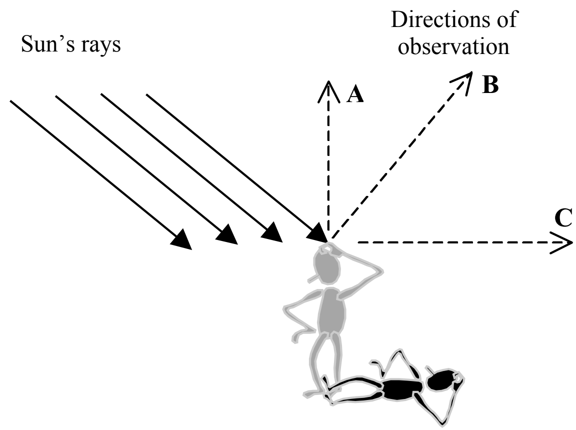


Predict in the spaces below the state of polarization of the scattered light along **x** and along **z** and the polarization of the transmitted light along **y** (all as seen looking into the aquarium). Use the same symbols for polarized light as in Demonstrations 1 and 2.

Predicted polarization along **x**		Predicted polarization along **z**		Predicted polarization along **y**	

Demonstration 4: In which of the three possible directions of observation will the sky appear most blue? Direction **A** is directly overhead, **B** is 90 degrees relative to the direction of the sun's rays, and **C** is straight towards the horizon.

In which of the three possible directions of observation will one see the sky significantly polarized?

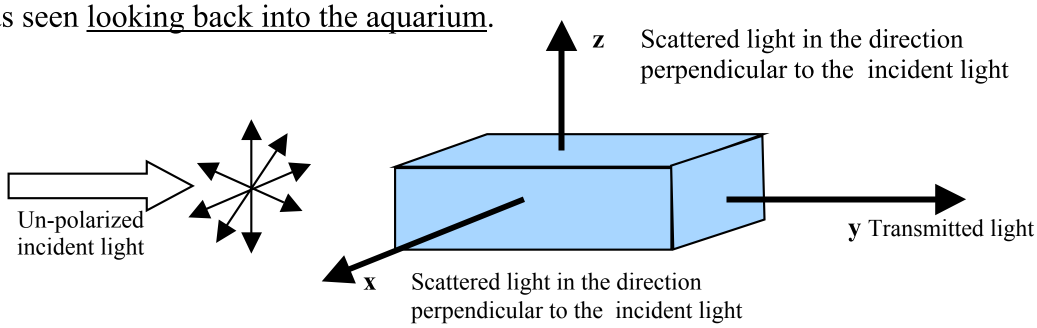


Keep this sheet

INTERACTIVE LECTURE DEMONSTRATIONS
RESULTS SHEET— POLARIZATION BY SCATTERING

You may write whatever you wish on this sheet and take it with you.

Demonstration 1: The figure below shows an un-polarized beam of light moving along the y axis. It is incident on the aquarium filled with water mixed with a very small amount of milk. Light along **x** represents the light scattered by the solution as seen looking into the side of the aquarium. Light along **z** represents the light scattered by the solution as seen looking down into the aquarium from above. Light along **y** represents the light transmitted through the solution, as seen looking back into the aquarium.



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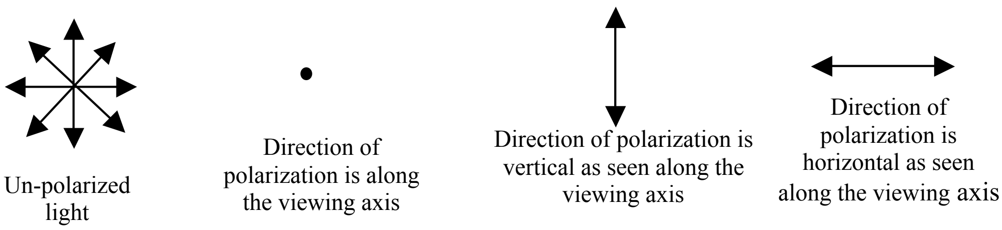
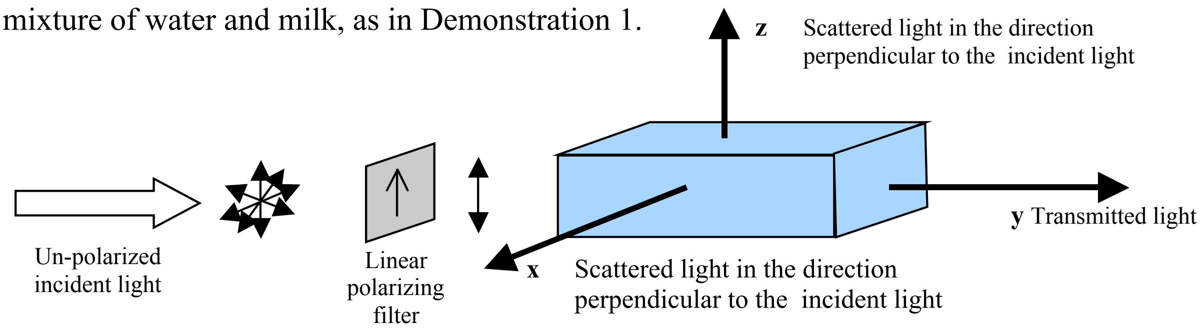


Predicted polarization along **x**

Predicted polarization along **z**

Predicted polarization along **y**

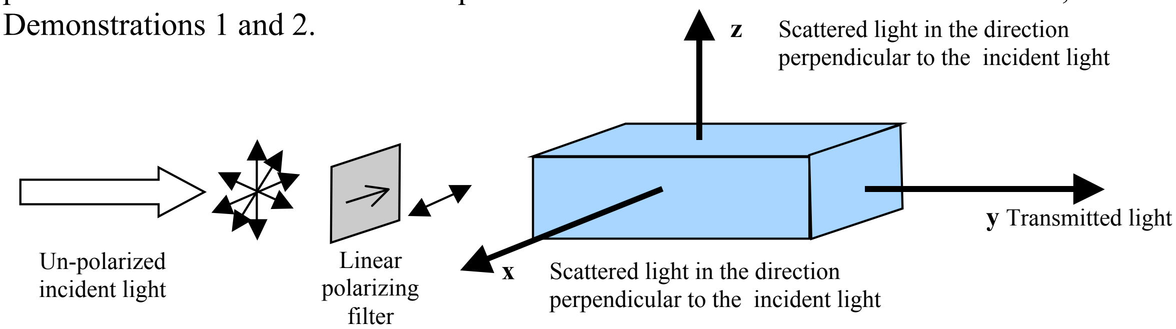
Demonstration 2: The figure below shows an un-polarized beam of light passing through a linear polarizing filter. The vertically polarized beam is incident on the aquarium filled with a mixture of water and milk, as in Demonstration 1.



Predict in the spaces below the state of polarization of the scattered light along **x** and along **z** and the polarization of the transmitted light along **y** (all as seen looking into the aquarium). Use the same symbols for polarized light as in Demonstration 1.

Predicted polarization along **x**		Predicted polarization along **z**		Predicted polarization along **y**	

Demonstrations 3: The figure below shows an un-polarized beam of light passing through a linear polarizing filter rotated by 90° compared to Demonstration 2. The horizontally polarized beam is incident on the aquarium filled with a mixture of water and milk, as in Demonstrations 1 and 2.



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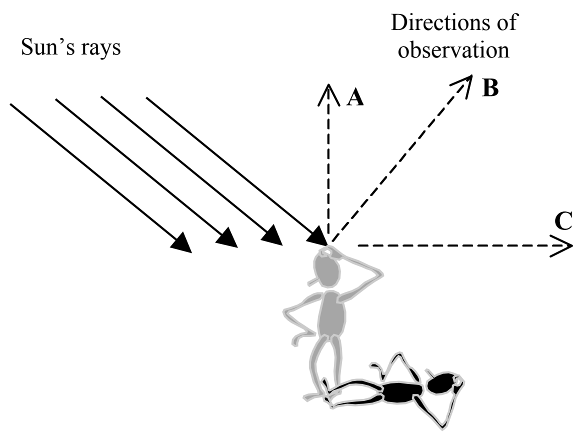
Predicted polarization along **x**		Predicted polarization along **z**		Predicted polarization along **y**	

Demonstration 4: In which of the three possible directions of observation will the sky appear most blue? Direction **A** is directly overhead, **B** is 90 degrees relative to the direction of the sun's rays, and **C** is straight towards the horizon.

In which of the three possible directions of observation will one see the sky significantly polarized?



Teachers' Guide for
Module 4: Atmospheric Optics

TEACHERS' GUIDE FOR MODULE 4: ATMOSPHERIC OPTICS

PART 1: ABSORPTION AND MULTIPLE SCATTERING

OBJECTIVES

1. To demonstrate single and multiple scattering
2. To demonstrate the effect of scattering on the intensity of the transmitted light
3. To demonstrate the difference of absorption and scattering in terms of the change of the intensity of the transmitted light
4. To show—by analogy—that multiple scattering is responsible for the white color of the clouds and the froth formed when water waves break along the shore
5. To show—by analogy—that scattering by particulates and air molecules causes the visible haze that reduces the contrast between the bright sky and mountains on the horizon

INTRODUCTION

The set of Interactive Lecture Demonstrations (*ILDs*) in this module introduces phenomena in nature and in daily life that most students have observed, for example: white (and at times dark) clouds, the white foam formed when waves reach the shore (or when the bow of a ship slices through the water), common white-colored suds when bars of soap of different colors are mixed with water. On the molecular scale, light scattering is a complicated process. Thus, the topic is introduced by analogy using simple demonstrations.

Demonstrations 1a and 1b are analogies—albeit simplistic—to single scattering of light by a particle. They show that a transparent material—a material that has low absorption of visible light—reflects light, but that this may not be obvious if the background light is bright. The objects behind the material are then clearly more visible than the reflected image of the object in front. The focus of the demonstrations is on the reflected light.

Demonstrations 2a, 2b and 2c are analogies to multiple reflections. People normally believe that absorption is the usual cause when light cannot (or can barely) be seen through a material. It will be shown in this demonstration that the decrease in the intensity of the transmitted light may also be due to incident light being scattered by the material. The demonstrations are focused on the relative intensities of the reflected and transmitted light.

Demonstrations 3 and 4 further demonstrate the difference between absorption and scattering. These demonstrations are also the transition toward the discussion of scattering of light by very small particles.

In Demonstration 5, glass beads are used as scatterers of light. This is the analogy of the scattering of light in the water-milk mixture, in the previous two demonstrations. The beads represent the fat globules in milk that act as scatterers of light and make milk appear white.

Demonstration 6 uses air bubbles in soap. It will be shown that observed singly, air bubbles are transparent. But when they cluster together, they appear white. This serves as an analogy for the scattering of light by clouds.

As with all *ILDs*, follow the 8-step procedure outlined Table I-2 in the Introduction section of this manual. To review, after 1) the description of the demonstration to the students, 2) students make their own predictions of the expected result on the prediction sheet, and then 3) discuss these with their immediate neighbor(s). Students 4) may then change their predictions. If you have time, 5) elicit predictions from volunteers in the class. Then 6) show the demonstration with the result clearly visible. 7) Ask for volunteers to describe and explain the result in the context of the demonstration, and 8) to discuss any other analogous physical phenomena that can be explained in the same manner. It is very important to remember that the *instructor should elicit the conclusions from the students through classroom discussion rather than lecturing to the students*.

This guide includes suggested discussion questions that can serve as guides in the discussion.

Suggestions on how to carry out the demonstrations are included below. All observations are made using the eye. Therefore the term *color* rather than *wavelength* is used in these demonstrations. The term *transmitted light*, which normally refers to the un-scattered beam, actually includes the forward scattered light. The light observed along a path different from the path of the incident beam is referred to as the *scattered light*.

A list of references is included at the end of this Teachers' Guide.

APPARATUS AND SUPPLIES

- Overhead projector or any strong white light source
- Ten or more clear plastic sheets (transparencies are highly recommended)
- Two transparent, shallow containers
- Dark-colored board
- A colorful picture
- Small amount of whole milk (with milk fat)
- Small amount of dark-colored ink
- Transparent glass beads (diameter about 5 mm)
- Water
- Detergent
- Laser pointer ***CAUTION: Do not point the laser into or near anyone's eyes!***

DEMONSTRATION NOTES

Demonstrations 1. Demonstration 1 is done in a lighted room where the students' faces are well illuminated. A clear plastic sheet is held in front of a bright background. (Transparency plastic sheets are recommended for use in these demonstrations since they are thin, flat, and have no creases. Any folds in the plastic sheet tend to distort the reflection.) The students are told to observe their reflection from the plastic sheet. Then a dark-colored board is placed behind the plastic sheet. Again the students are told to observe their reflection from the plastic sheet. They compare the two different observations.

In Demonstration 1a the reflection is barely visible if the light behind the plastic sheet is bright. The objects behind the sheet are much more clearly visible when the background light is bright.

With a dark background in Demonstration 1b, the reflection becomes noticeable. The black-colored board doesn't increase the reflectivity of the material. It simply enhances the contrast between the two sides of the transparent material.

Discussion questions:

1. What happens to the light that is incident on the plastic sheet?
2. Why are the objects behind the plastic sheet much more visible than your reflection when the light behind the plastic sheet is bright?
3. Why is your reflection much clearer if a dark-colored board is placed behind the plastic sheet? Does the board increase the reflectivity of the plastic sheet?

Alternate Demonstration 1. An alternate demonstration is to place a clear glass plate vertically on the table. A student sits in front of the glass plate and another student sits on the opposite side. Each student is lighted by a lamp with a dimmer switch. Each student describes what s/he sees reflected from the mirror and looking through the mirror when the lamps are equally bright or when her/his lamp is much brighter than the other lamp. This demonstration should be done in a dark room. Each lamp should be directed to the face of the student. A variac or a dimmer switch may be used to change the intensity of the light. Note that it is even possible to adjust the relative intensities of the lamps so that the two faces (reflected and transmitted) overlap and form an unusual-looking face.

Demonstration 2a. More plastic sheets are stacked in front of the dark-colored board. The students observe the change in the intensity and clarity of the reflection as the number of plastic sheets is increased.

The dark board is replaced with a colorful picture. The picture is placed behind one plastic sheet, and sheets are added until there are ten or more plastic sheets over the picture. The students observe and describe the changes in the visibility of the picture as more sheets are added.

Demonstration 2b. A lighted lamp can be placed in front of the plastic sheet. A group of students observes the changes in the reflection of the lamp as the number of plastic sheets is increased. At the same time another group of students observes behind the plastic sheet. They note down the change in the intensity of the light transmitted as the number of plastic sheets is increased.

Demonstration 2c. A laser pointer is used in this demonstration. **Please read the LASER SAFETY section of this manual.** ***The laser beam should never be directed toward anybody in the room. The laser beam is damaging to the eye.***

To further show the students that each plastic sheet reflects light, the laser pointer is shone on a single sheet and reflected to the ceiling. The students observe the number of laser dots on the ceiling as the stack of sheets is increased. They also observe the intensity of the laser light transmitted through the plastic sheets and projected on a white sheet of paper.

Discussion questions:

1. Why does the reflection increase if more sheets are added?
2. Do there seem to be multiple images of the reflection? Where do these images come from?
3. Why can't the colorful picture be seen clearly through the multiple plastic sheets?
4. Why does the number of laser dots on the ceiling increase with the addition of more plastic sheets on the stack?

5. Why does the intensity of the transmitted beam decrease with increasing number of plastic sheets?

Demonstrations 3 and 4. Two identical shallow transparent containers are placed on the overhead projector. Both containers are half-filled with water. Several drops of milk are added to one of the containers. Several drops of dark-colored ink are added to the other container. The students observe the color of both liquids along the sides and from the bottom of each container. They also observe the shadows cast on the screen.

The water-milk mixture looks bright and whitish while the water-black ink mixture looks dark. Both, however, cast a dark shadow on the screen. A lot of scattering takes place in the milk-water so it appears whitish. The light is scattered in several directions, not only toward the screen thus casting a dark shadow on the screen. The ink-water mixture absorbs light and thus almost no light is transmitted to the screen.

Discussion questions

1. Describe the color of the liquid in each of the containers.
2. Describe the color of the shadow cast by both containers on the screen.
3. Can you explain why both containers cast dark shadows on the screen?

Demonstration 5. A transparent glass container is half-filled with water. The container is placed on the overhead projector. Transparent glass beads are placed in the container. The students observe the light scattered by the beads from the sides and bottom of the container. They also observe the shadow cast by the beads on the screen.

The glass beads will scatter the incident light is evident by the glitters they produce. Therefore there is less light transmitted as shown by the dark shadow on the screen.

Discussion questions

1. How do the glass beads look when observed from the sides and bottom of the container? Can you explain your observation?
2. Why is there a dark shadow cast by the glass beads on the screen?

Demonstration 6. The detergent is mixed with water to form soap bubbles. The transparency of a single soap bubble is compared with a cluster of bubbles.

Discussion questions

1. Why does a single soap bubble appear clear to the eyes but a thick group of soap bubbles appears white?
2. Can you relate this set of demonstrations to the white (and sometimes dark) color of clouds? To the white color of the surf when waves crash on the beach?
3. Can you explain why, even on a clear day, distant mountains appear hazy? Hint: What's in between the mountains and the observer? What happens to the light that travels from the mountains to your eyes?

PART 2: BLUE SKY AND RED SUNSET

OBJECTIVES

1. To observe the spectral selectivity of light scattering
2. To understand the physical explanation for the blue sky and red sunset
3. To explain related phenomena

INTRODUCTION

On a cloudless day, the sky as seen from an observer on the ground is blue in color. Above the clouds the sky is always blue. The shade of blue, however, changes with direction of observation. It appears pale blue when viewed near the line of sight of the sun and goes to deep blue away from this line of site. In space the atmosphere of the earth also appears blue. So why is the sky blue?

During sunrise and sunset, the color of the atmosphere appears yellow, orange, or red. Why is this? The following set of Interactive Lecture Demonstrations will help to answer these questions.

Demonstration 1 may be done outdoors with sunlight (direct or diffuse) as the source of light or indoors using a lamp. The objective of the demonstration is to show, using either a prism or a simple spectroscope, that the white light to be used in the subsequent demonstrations is composed of different colors.

Demonstration 2 shows that pure water—without suspended fat particles from the milk—does not alter white light by scattering.

Demonstration 3 will show that each color undergoes scattering by the milk fat particles suspended in the water, and the transmitted light (assuming that the mixture is not optically dense) also has the same color as that of the incident beam.

Demonstration 4 will show that—when white light is used—the scattered beam is dominated by the color blue.

Demonstration 5 is done to examine the spectral purity of the scattered and transmitted beams using the spectroscope.

As with all *ILDs*, follow the 8 step procedure outlined in the introduction to this manual. To review, after 1) the description of the demonstration to the students, 2) students make their own predictions of the expected result on the prediction sheet, and then 3) discuss these with their immediate neighbor(s). Students 4) may then change their predictions. If you have time, 5) elicit predictions from volunteers in the class. Then 6) show the demonstration with the result clearly visible. 7) Ask for volunteers to describe and explain the result in the context of the demonstration, and 8) to discuss any other analogous physical phenomena that can be explained in the same manner. It is very important to remember that the *instructor should elicit the conclusions from the students through classroom discussion* rather than lecturing them to the students directly.

This guide includes suggested discussion questions that can serve as guides in the discussion. The concluding discussion questions will then link the series of demonstrations to the blue sky and red sunset and other related phenomena.

Suggestions on how to carry out the demonstrations are included below. All observations are made using the eye. Therefore the term *color* rather than *wavelength* is used in these demonstrations. The term *transmitted light*, which normally refers to the un-scattered beam, actually includes the forward scattered light. The light observed along a path different from the path of the incident beam is referred to as the *scattered light*.

A list of references is included in the Reference section at the end of this manual.

APPARATUS AND SUPPLIES

- Slide projector (or any strong collimated source of light)
- Cardboard slit about 1 mm in width

- Prism
- Aquarium or beaker
- Simple grating spectroscope
- Small quantity of whole milk (with milk fat)
- Medicine dropper
- Red, green, blue and violet color filters
- Picture of the moon during total lunar eclipse

EQUIPMENT NOTES

Light source: An intense light source should be used. A slide projector is highly recommended because it is intense, highly collimated, and the halogen lamp approximates white light.

If a flashlight is used, it is strongly recommended that a fresh set of batteries be used. Besides being less intense, if the batteries are weak the light bulb's emission in the shorter wavelengths (blue and violet) is less as compared to the longer wavelengths (red). The scattering will appear yellowish or even reddish rather than bluish. The light beam from most flashlights is not collimated. To form a collimated beam, place a mask with a small round opening in the center of the face of the flashlight. Attach a long cylindrical tube to the opening of the mask. The complete attachment is shown in Figure TG4-1.

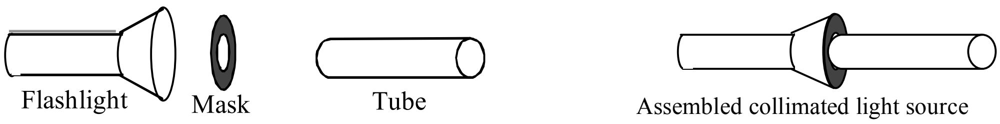


Figure TG4-1: Construction of a collimated light source from a flashlight.

Another alternative light source that is highly recommended is a white light emitting diode (LED). There are super bright ones available and a converging lens can be used to collimate the output. There are actually flashlights using a white LED source with built-in lens for collimation. The scattering appears more bluish with this light source.

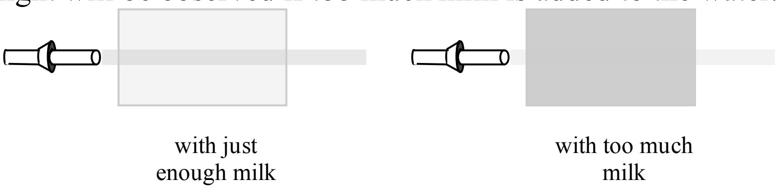
Filters: Colored cellophanes can be used as filters. Note however, that the light transmitted through a piece of colored cellophane may look blue but it is not pure blue as can be verified by using the simple spectroscope. Four to five layers of cellophane placed in front of the white light source may be sufficient to produce the necessary color.

As an alternative to color filters, use blue, green, and red light emitting diodes. The scattered light appears much brighter.

Aquarium: A clear glass or clear acrylic aquarium is best suited for these demonstrations. If one is not available, transparent plastic containers may be used. However, these materials normally exhibit colors, due to internal stress, when placed between crossed polarizers. While a discussion of the source of these colors is interesting, it will divert attention from the discussion of scattering. These demonstrations may also be done using an overhead projector. A beaker may be used in place of the aquarium. It is important that a mask with a circular opening of the same diameter as the beaker be placed on the overhead projector.

Source of scattering particles: In the demonstrations discussed in this module, just like in most of the references, milk (in liquid form or powder form) is the usual material used as scattering particles. There are oils, like the ones used as coolant in lathe and milling machines, which are miscible in water. Fuchs is one example brand name of these types of oil. A few drops of this oil in water will cause the mixture to appear white due to multiple scattering. It's counter intuitive because the oil is yellowish in color. It is therefore a good starting point for a discussion of how multiple scattering produces the white color mixture.

Observations of the scattered light are best made when the propagation of the light beam is clearly visible in the liquid. *Put only a very small amount of milk (or the miscible oil) in the water*. Diffused light will be observed if too much milk is added to the water.



Construction of a simple spectroscope: A simple spectroscope can be used in place of a prism for qualitative observation of the spectrum of a light source. It can be made out of a 30 cm long and 4 cm diameter cylindrical tube. This is typical of an aluminum foil roll. The cardboard cover on one end has a 1 mm width by 2 cm length slit. The cover at the other end has a 1 cm x 1 cm square hole. (See Figure TG4-2). A diffraction grating is attached over this hole. The positions of the slit and grating are adjusted so that the spectral lines are seen parallel to the orientation of the slit. (See Figure TG4-3).

Two orders of diffraction can be observed if a 500 lines/mm grating is used. The end covers should be attached well so that no light enters the tube except that which passes through the slit.

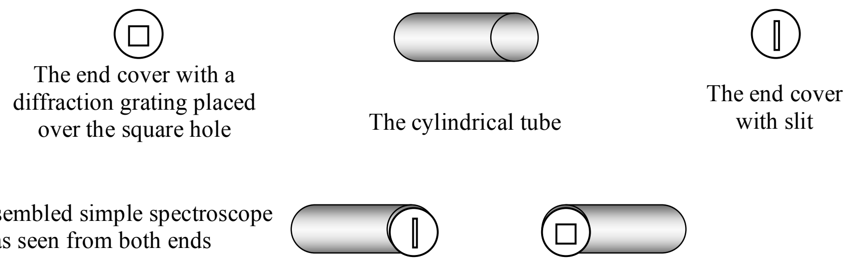


Figure TG4-2: Construction of a simple grating spectroscope.

Figure TG4-3: Spectrum of white light as viewed with the simple spectroscope.

DEMONSTRATION NOTES

Demonstration 1. Hold the prism so that the light is incident at an oblique angle on one of the faces. The spectrum can be seen on a white screen placed behind the prism. See Figure TG4-4.

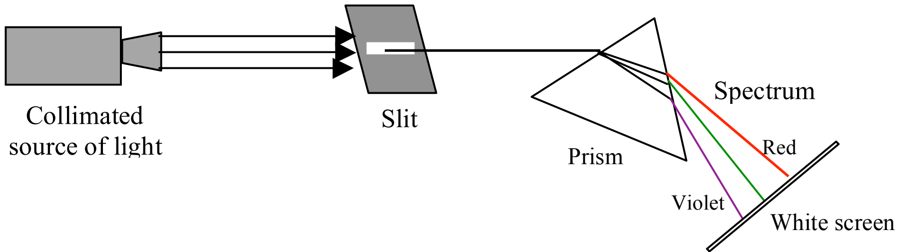


Figure TG4-4: Setup for viewing the spectrum of white light with a prism.

The simple grating spectroscope may also be used to observe the spectrum of white light from the projector. The setup is shown in Figure TG4-5. Alternatively, this demonstration may be done outdoors with the sun replacing the projector as the light source. Both the prism and spectroscope will reveal that the light from the projector (or the sun) is a mixture of different colors. The colors (visible to the eye) appear to be identical as seen using both optical instruments, although their order may be different.

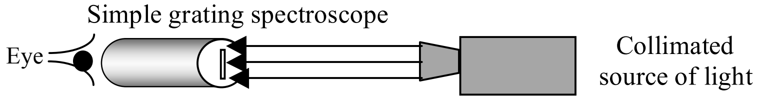


Figure TG4-5: Simple spectroscope positioned to view the spectrum of white light.

Discussion questions

1. Describe what you observe when light passes through a prism or a diffraction grating.
2. Identify the colors that you see on the screen or that you see through the grating?
3. *This question may be asked if observations are done both using the prism and the spectroscope:* Are the colors seen by using the prism similar to the ones seen through the spectroscope?

Demonstration 2. This demonstration can be done indoors using an aquarium filled with tap water. Tap water is preferred since distilled water may not contain enough particles to scatter the light at all. The container with water is placed along the path of the light from a projector (Figure TG4-6). (A smaller container may be used if this is done outdoors using sunlight as the source.) Observations are made on both the light scattered as it propagates in the water and the light that is transmitted through the water to the screen.

The intensity of the scattered light will depend on the quantity of suspended particles in the water. The particles will appear like very tiny shiny objects in constant motion. Neither the scattered nor the transmitted light will show any particular color.

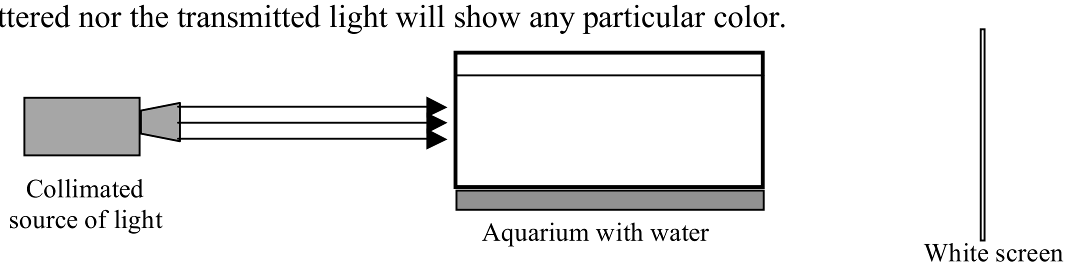


Figure TG4-6: Setup for observing light shone through an aquarium filled with water

Discussion questions

1. Can the light be clearly seen as it propagates through the water? Why or why not?
2. Is there any particular color of the light as it propagates through the water? How about the light transmitted to the screen?

Demonstration 3. This demonstration is best done in a darkened room. A very small amount of milk is added to the water in the aquarium. Light from the intense collimated source of light is incident on one side of the aquarium as shown in Figure TG4-7. A red filter is placed between the light source and the aquarium. The color of the water in the aquarium and the color of the transmitted light projected on the screen are observed. The red filter is replaced by other color filters and the color and relative intensities of the scattered and transmitted light are observed.

The light scattered when the incident light is blue (with the blue filter) appears to be brighter than the other colors. But there can be differences in opinion. If an overhead projector is used, it may be possible to simultaneously observe the scattering due to the different incident colors. This alternative demonstration is described in the section on Alternate Setups. Demonstration 4 is intended to settle these questions.

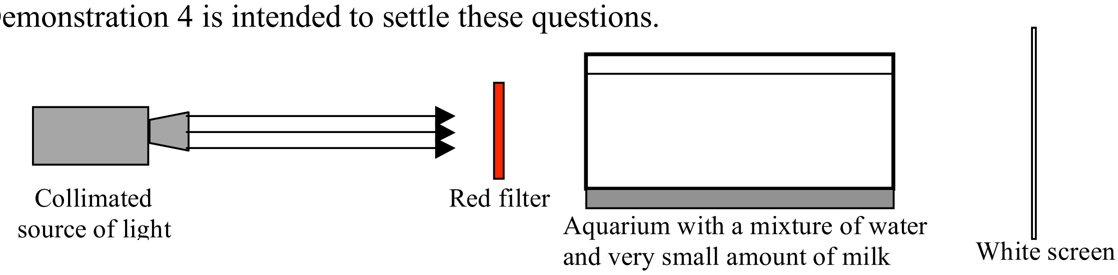


Figure TG4-7: Setup for Demonstration 3

Discussion questions

1. What do you think is the purpose of adding a very small amount of milk to the water?
2. How do the color of the scattered and transmitted light compare with that of the incident light (which entered the aquarium)?
3. For which color incident light does the scattered light seem to be the most intense? The least intense?

Demonstrations 4. In this demonstration, no filters are placed in between the light source and the aquarium as shown in Figure TG4-8. The white light beam, a mixture of the different colors, is incident on the aquarium. A very small amount of milk is added to the water and then thoroughly mixed, as in Demonstration 3.

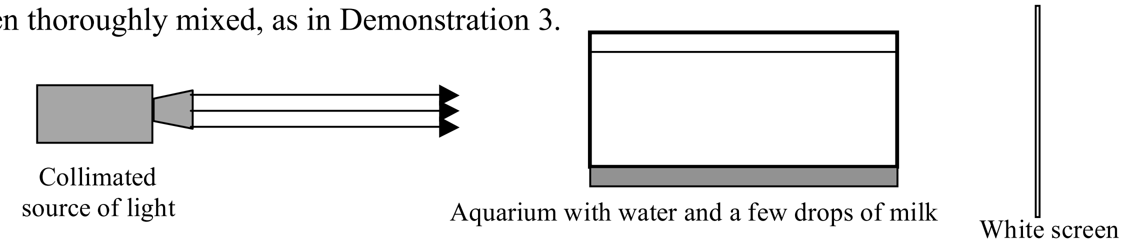


Figure TG4-8: Setup to observe scattering by milk fat particles

Note the color of the scattered light and of the transmitted beam. Use the simple spectroscope to observe the spectrum of colors of the liquid and the spectrum of colors of the transmitted beam.

When only a very small amount of milk is added, the scattered light appears bluish while the transmitted light appears yellowish on the white screen. However, the scattered light is not pure blue and the transmitted light is not pure yellow when viewed through the spectroscope. All of the colors in the visible region are found in both the transmitted and scattered light.

Discussion questions:

1. Describe the color of the scattered and transmitted light.
2. Which color undergoes the most scattering? The least scattering?
3. Can you explain the reason for the color of the transmitted beam?
4. Is the color of the scattered light as seen by the naked eye the same as the color when seen through the simple spectroscope? Can you explain the difference, if any?

Demonstration 5. Slowly add more milk to the water and stir and observe the changes in the intensity and color of the scattered and transmitted light.

As more milk is added to the water the scattered light appears brighter and turns whiter in color. The transmitted beam changes color from yellow to orange then red as more milk is added to the water. Its intensity is diminished more as the amount of milk is increased.

Discussion questions:

1. Describe the changes in the color and intensity of the scattered light as more milk is added to the water.
2. Describe the changes in the color and intensity of the transmitted light as more milk is added to the water.
3. Can you explain why the screen appears dark when a lot of milk is added to the water? Can you explain what happens to the incident light inside the aquarium?
4. Suppose the mixture in the aquarium represents the earth's atmosphere. What does the water represent? What does the milk represent?
5. In what ways is the demonstration similar to the occurrence of the blue sky and the red sunset? Can you explain how these phenomena occur in nature?
6. In Rayleigh's scattering theory, the intensity of the scattering by isotropic, single particles, with dimensions smaller than the wavelength of the incident light is inversely proportional to the fourth power of the wavelength. Explain why blue light is scattered more efficiently than red.
7. Since violet light has a shorter wavelength than blue, why does the sky appear blue rather than violet?
8. How can you explain the bluish color of smoke coming from a cigarette, smoke from the exhaust of a motor vehicle, or smoke produced when cooking on a grill?
9. Describe the color of the moon during total lunar eclipse. Can you explain why it has such a color?
10. When one stands on a hilltop and looks around, the surrounding vegetation appears green, but a distant mountain with trees may appear bluish. But over the horizon, a more distant mountain range appears whitish. Why do you think this is so?

ALTERNATE SETUPS

Using an overhead projector and a beaker: The demonstrations can also be done using an overhead projector, and a beaker may be used in place of the aquarium. It is important that a mask with a circular opening of the same diameter as the beaker be placed over the projector so that only the light that passes through the beaker is shown on the screen.

The relative intensities of the scattered and transmitted light from the incident beams of different colors can be simultaneously viewed using several small transparent containers placed on the overhead projector. They should all have the same milk concentration. There should be a mask with a circular opening for each container. A filter is place underneath each container.

Super bright red, green, and blue light emitting diodes (LED's) can be used in place of the projector and cellophane filters. The LED's have higher spectral purities than the cellophane. A converging lens is needed for collimation. However, using a super bright white LED in place of the lamp or sunlight is tricky since its spectrum is deficient in the red region. The scattered light will therefore appear very bluish.

The Tyndall effect: Another common method of doing the red sunset and blue sky demonstration is by mixing sodium thiosulphate in the water in the aquarium or beaker (if the overhead projector is used) and adding hydrochloric acid to this mixture. The suspended sulfur particles that are released in the chemical reaction with the acid act as the scatterers similar to the milk fat globules. Here are the details:

Equipment and Supplies

- 10 gallon aquarium or large beaker

- Distilled water
- 120 grams of sodium thiosulfate (NaS_2O_3)
- 60 mL of concentrated HCl
- Slide projector with a slide cut to form a circular image on the screen
- Large stirring rod
- White screen

Procedure:
Set up the aquarium or beaker before the class starts. Fill it to about 4 inches below the top. Add 120 grams of NaS_2O_3 and stir to dissolve. Set up the slide projector shining through the aquarium onto the screen. The light on the screen should be viewable from all seats in the audience.

In class, turn the projector on, dim room lights, and pour hydrochloric acid into the aquarium. (DO NOT STIR). Allow 10-15 minutes for color changes to occur. You can use this time to have a discussion with the students about what is happening.

PART 3: POLARIZATION BY SCATTERING

OBJECTIVES

1. To determine the state of polarization of scattered and transmitted light when the light incident on the medium is un-polarized
2. To determine the state of polarization of the scattered and transmitted light when the light incident on the medium is polarized
3. To observe the blue sky and its state of polarization
4. To investigate if clouds exhibit polarization
5. To explain how a linear polarizer is used in photography to improve the contrast between the sky and the clouds

INTRODUCTION

In the previous demonstrations you observed the spectral characteristics of the scattered light. In this set of demonstrations the state of polarization of the scattered light will be investigated. The qualitative results will help the students understand the polarization of scattered light in the sky.

In Demonstrations 1 and 2 you will examine the polarization of the scattered light when un-polarized and polarized light beams are incident on a medium with suspended particles. In Demonstration 3, the results in first two demonstrations are applied to skylight. In Demonstration 4, skylight is actually observed.

There are suggestions on the choice of materials to be used and the preparation of the set-up in the Equipment Notes and Demonstration Notes sections. There is a list of references on scattering and polarization from books and journal articles at the end of this module.

APPARATUS AND SUPPIES

- Aquarium
- Intense collimated white light source
- Water
- Two pieces of linear polarizing filter (Polaroid filters)

- Small amount of whole milk
- Stirring rod

EQUIPMENT NOTES

Light source: Use the same light source as described in the notes for Part 2.

Polarizing filters: Polaroid film has the property of linearly polarizing an un-polarized light source. It was invented 1n 1938 by E.H. Land. It's made of long chain hydrocarbon molecules that are aligned when the sheet is stretched in one direction during the manufacturing process. Micro-crystals of a dichroic material such as quinine iodosulfate are embedded in the plastic sheet so that the long chains become conducting at optical frequencies. When the incident light's electric vector is parallel to the chain, it is absorbed while an electric vector perpendicular to the chain is allowed to pass through. The direction perpendicular to the chain is called the *transmission axis*.

The transmission axis is not usually indicated when one buys a Polaroid filter. But this can easily be determined by looking at the reflected light from a shiny, non-metallic surface through the filter, as shown below. The reflected beam is partially polarized in the direction perpendicular to the plane of incidence of the light. The filter is rotated until the minimum transmission of the reflected beam is observed. At this position the transmission axis of the Polaroid filter is parallel to the plane of incidence of the light. (See Figure TG4-9.)

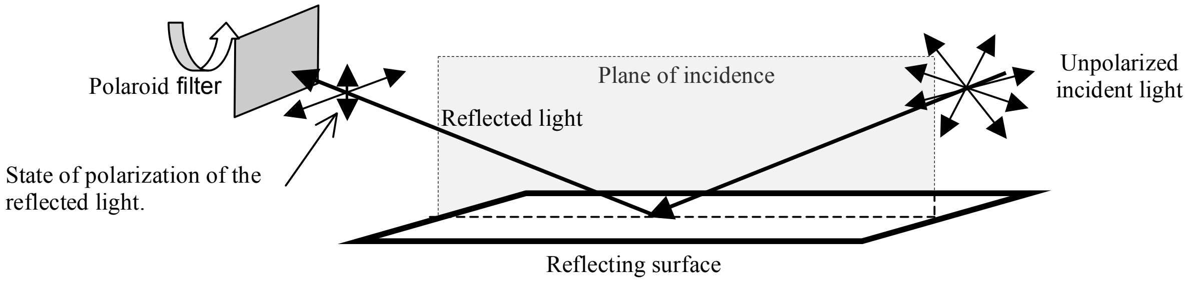


Figure TG4-9: Method to determine the transmission axis of a Polaroid filter

Scattering particles and aquarium: See the Equipment Notes for Part 2.

DEMONSTRATION NOTES

Demonstration 1. An aquarium is filled with water. A very small amount of milk is added to the water, just enough to make the mixture appear whitish, yet still transparent. The globules of fat in milk serve as the scatterers of light. An un-polarized collimated light source is shone through one side of the aquarium.

A linear polarizing filter is used to determine whether the scattered and transmitted light is polarized. The set up is shown in Figure TG4-10, below. The polarizer is rotated. A change in the intensity of the light as seen through the polarizer means that the light is polarized. A maximum transmission indicates that the polarization of the light is parallel to the transmission axis of the polarizer. A minimum transmission indicates that the polarization of the light is perpendicular to the transmission axis of the polarizer. If there is no change in the intensity as the polarizer is rotated, then the light is unpolarized.

The light scattered along the **x** direction is more intense when the Polaroid filter is oriented with its transmission axis vertical than when its transmission axis is horizontal. This means that the light scattered along the **x** direction is polarized in the **z** direction (vertical). Note that the polarization is also perpendicular to the direction of propagation of the un-polarized incident beam.

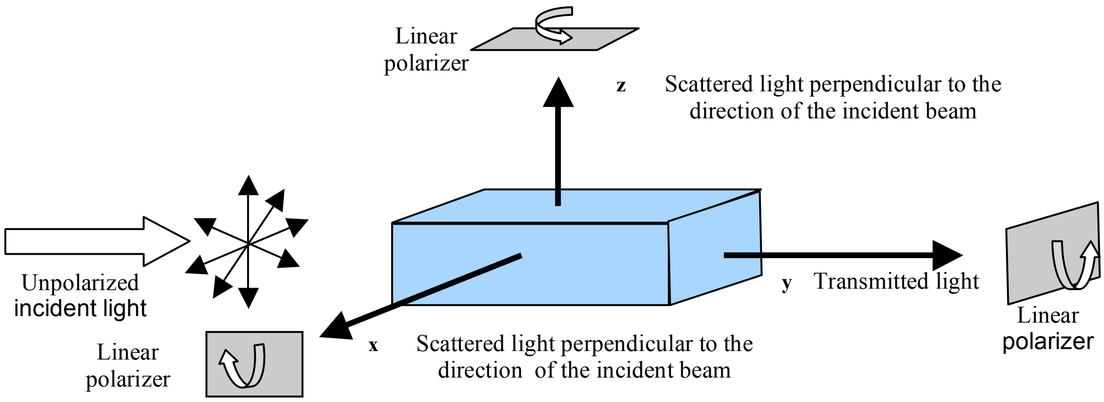


Figure TG4-10: Set up for examining the polarization of light scattered by small suspended particles

The light scattered along the **z** direction is more intense when the Polaroid is oriented with its axis along the **x** direction than with its axis oriented along the **y** direction. This means that the light scattered along **z** is polarized in the **x** direction (horizontal), and also perpendicular to the direction of propagation of the un-polarized incident beam.

There is no change in the intensity of the transmitted light when the Polaroid filter is rotated. This means that the transmitted light is un-polarized (or it could be circularly polarized).

These observations are illustrated in Figure TG4-11 below.

The electric field of light waves vibrates in a direction perpendicular to the direction of propagation of the light. In the process of scattering of light by a particle, this electric field causes the electrons in the particle to oscillate in the direction of the electric field. These electrons re-emit light in every direction perpendicular to the direction of oscillation, but not in the direction of oscillation. Therefore, scattering can never result in light with its polarization along the direction of propagation of the incident light.

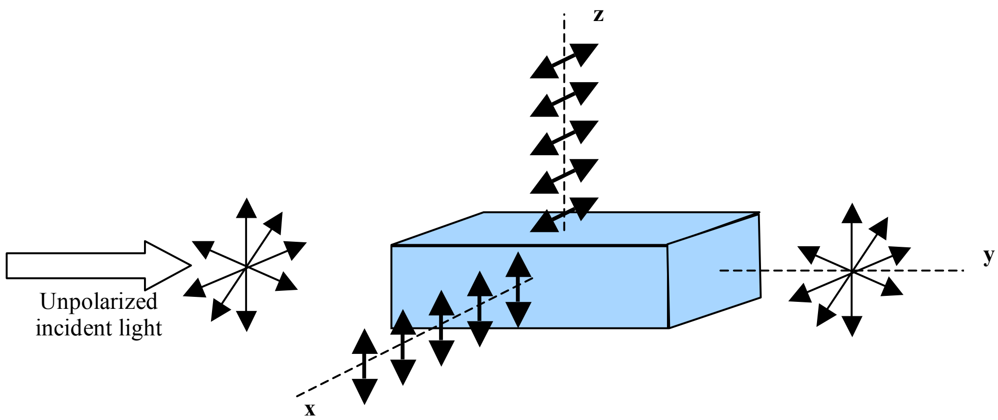


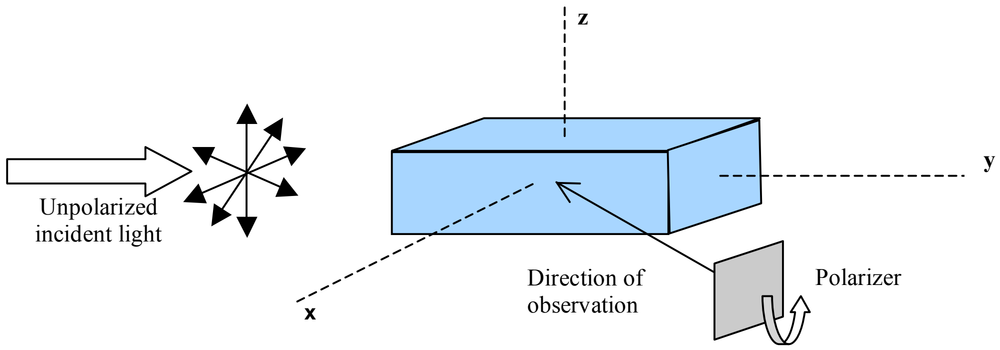
Figure TG4-11: Observed polarization of the scattered and transmitted light for Demonstration 1.

In Rayleigh's theory of scattering by a single isotropic particle, where it is assumed that the size of the particle is small compared with the wavelength of the incident light, the scattered light is un-polarized in the forward and backward directions and completely polarized in the directions perpendicular to the direction of the incident beam. Using a very small amount of milk will approximately show this phenomenon. If too much milk is added then multiple scattering of light will result in just partial polarization of the scattered light.

Discussion questions:

1. Describe the polarization of the scattered light along **x** and along **z**, giving the direction of polarization, and stating whether it is completely or partially polarized? Describe the direction of polarization relative to the direction of propagation of the incident beam.
2. Is it possible for light to be scattered with polarization along the direction of propagation of the incident beam (in this case along the **y** direction)? How does scattering turn un-polarized light into polarized light?
3. Carefully describe the polarization of the transmitted light along **y**, giving the direction of polarization, and stating whether it is completely or partially polarized. Can you explain based on your observations of the polarization of the scattered light?

Optional follow-up demonstration. In this follow up demonstration the scattered light is observed at a different angle and the degree of polarization is compared with the previous demonstration. Ask the following question to the students: If the scattered light along the x direction is polarized and that along the y direction is un-polarized, will there be a change in the degree of polarization if the scattered light is observed from an oblique direction, as illustrated below?



In this follow-up demonstration it will be observed that the scattered light has a higher degree of polarization in a direction perpendicular to the propagating beam than at the oblique angle.

Demonstrations 2 and 3. Demonstrations 2 and 3 are designed to confirm the conclusions reached in Demonstration 1. The same setup is used—the aquarium filled with water with a few drops of milk added and thoroughly mixed. The difference is that the un-polarized collimated light goes through a linear polarizing filter with its transmission axis along the z axis (vertical direction) in Demonstration 2 and along the x axis (horizontal direction) in Demonstration 3 before being incident on the aquarium. Therefore, vertically polarized light is now incident on the aquarium in Demonstration 2, and horizontally polarized light in Demonstration 3.

Another linear polarizing filter is used as before to determine the state of polarization of the scattered and the transmitted light, as shown in Figure TG4-12 below. The polarizations of scattered light along the **x** and **y** directions and the transmitted light along the **z** direction are investigated by rotating the polarizer and observing the light that goes through it.

In Demonstration 2, the light scattered along the **x** direction is more intense when the Polaroid is oriented vertically than horizontally. This means that the light scattered in the **x** direction is polarized along the **z** direction, and perpendicular to the direction of propagation of the un-polarized incident beam.

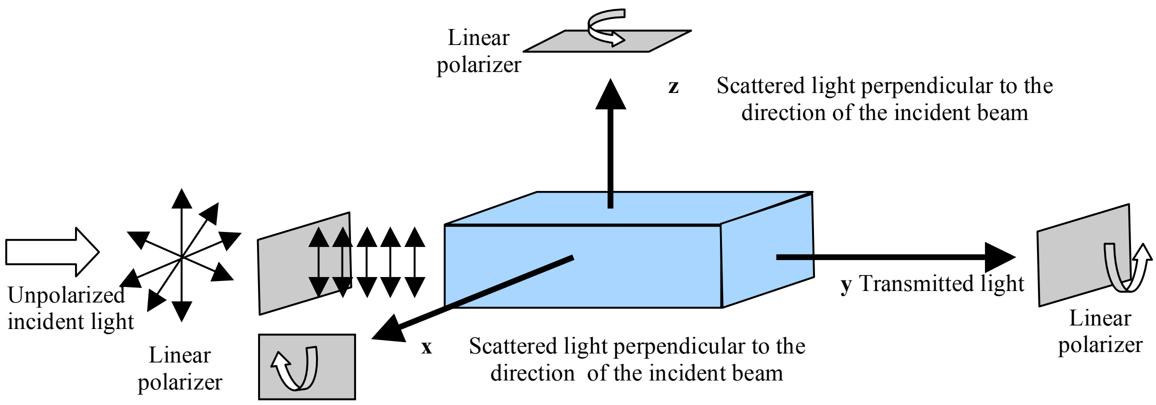


Figure TG4-12: Setup for Demonstrations 2 and 3 (The polarizer in front of the light source is rotated by 90° in Demonstration 3).

The light scattered along the **z** direction has low intensity even without looking through the polarizer. There is very little light scattered in this direction. The transmitted beam has the same polarization as the incident beam. In Demonstration 3, when the linear polarizer in front of the light source is rotated by 90°, the intensity of the scattered light along the **x** axis is diminished while the transmitted beam and scattered light along the **z** axis are enhanced with the same polarization as the incident beam.

Figures TG4-13 and TG4-14 illustrate the expected results.

Discussion questions for Demonstration 2:

1. Compare the intensity of the scattered light observed along the **z** direction and the scattered light observed along the **x** direction.
2. Why is there only very little light scattered in the **z** direction?
3. What do you expect will happen if the polarizer in front of the light source is rotated so that its transmission axis now lies along x axis? Describe the polarization of the scattered light.

Discussion questions for Demonstration 3:

1. Compare the intensity of the scattered light observed along the **z** direction and the scattered light observed along the **x** direction.
2. Why is there only very little light scattered in the **x** direction.

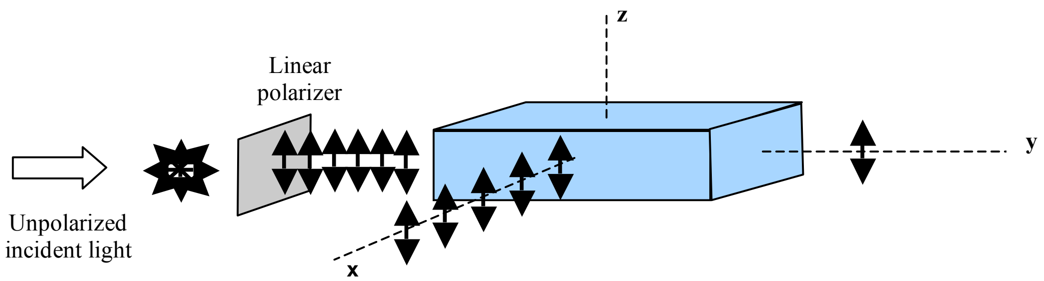


Figure TG4-13: Expected observations of polarization in Demonstration 2.

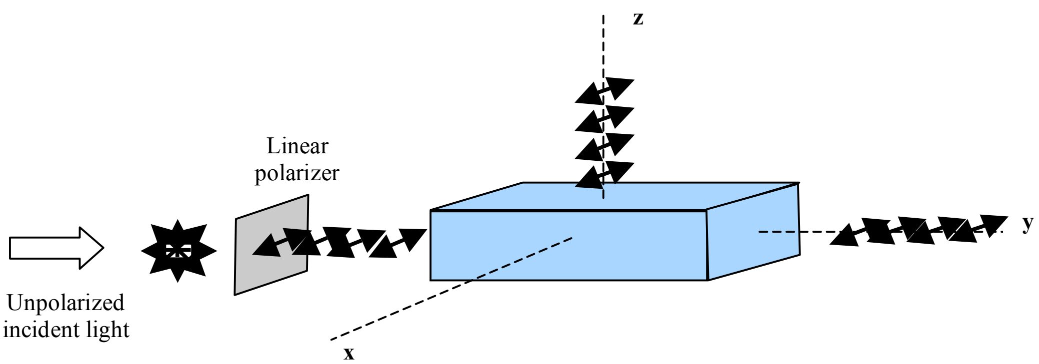
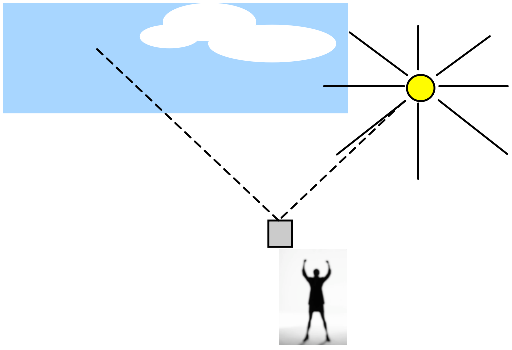


Figure TG4-14: Expected observations of polarization in Demonstration 3.

Demonstration 4. This is an outdoor demonstration where the students now apply what they observed in Demonstrations 1-3 to the scattering of sunlight by the molecules and particles in the atmosphere.



With the sun at your back, hold the polarizer in front of your eye and look at the sky. Rotate the polarizer and observe the state of polarization of the blue scattered light. Look through the polarizer at another direction in the sky. Try to find the direction relative to the sun, where there is maximum polarization. ***Do not look directly at the sun. It may damage your eye.***

Next, look at a patch of clouds through the polarizer. Rotate the polarizer and observe if the light reflected by the clouds is polarized.

Finally look through the polarizer at the portion of the sky where it is partly covered by clouds. Rotate the polarizer and compare the relative change in the intensity of the light from the reflection of the clouds and the blue scattered light.

Additional demonstration. It may also be interesting to observe, through the Polaroid filters, the diffuse reflection of direct sunlight by things (leaves, pool of water, etc.) in the surroundings. The reflected light also shows partial polarization.

Discussion Questions:

1. In which direction, relative to the sun, is the polarization of the blue sky maximum?
2. Is the light reflected by the clouds polarized?
3. How does the polarizing filter provide contrast between the image of the clouds and the sky in cameras?
4. If the sun is about 45 degrees above the horizon, in which part of the sky do you think will you observe maximum polarization?

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Module 5:
Optical Data Transmission

Alex Mazzolini

Faculty of Engineering and Industrial Sciences
Swinburne University of Technology
Hawthorn, Victoria, Australia
amazzolini@swin.edu.au

MODULE 5: OPTICAL DATA TRANSMISSION

OVERVIEW

One very important application of the optics concepts you have studied in Modules 1-4 is optical communication. In this module and the next, you will put these all together, and use some basic electronics to build a simple optical communication system.

OBJECTIVES

1. To explore how information can be transmitted from sender to receiver
2. To explore how information can be transmitted using light
3. To design simple optical source (LED & laser diode) and optical detector (phototransistor) circuits
4. To demonstrate *optical modulation* (that is, converting an electronic signal into an equivalent optical signal, and then converting the optical signal back into an electronic signal)
5. To demonstrate the concept of information coding

INVESTIGATION 1: AN ANALOG TRANSMISSION SYSTEM

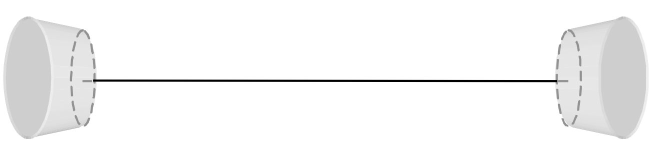
APPARATUS AND SUPPLIES LIST

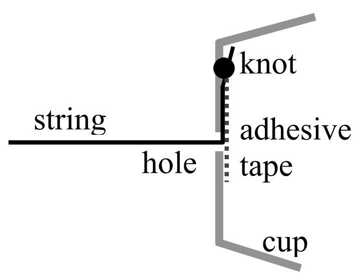
- Two polystyrene or plastic cups
- Toothpick to make a small hole
- Adhesive tape
- Long piece of fishing wire or strong thread

Have you ever built a "string phone?" This is a simple toy device that allows you to communicate voice messages over relatively long distances.

Activity 1-1: Building the string phone

1. Build the "string phone" shown below. You should thread the string through a small hole in the base of the cup as shown. Knot the string and use the adhesive tape to stick the string to the inside of the base of the cup securely.





2. One student should hold one cup inside the room, while another student takes the second cup—which is joined to the first via the string—into another room, separated by a door or window. Partially close the door or window joining the two rooms so the two students can't hear each other through the air. Make sure the string joining the

two cups is free and not touching any other objects (like the door, window or the floor).

3. Keeping the string tight, speak into one cup (transmitter) and see if your friend can hear what you say when she places her ear close to the other cup (receiver).

Question 1-1: What is sound? How does it propagate?

Question 1-2: How do humans make "voice" sounds?

Question 1-3: How do humans hear "voice" sounds?

Question 1-4: What is the sound propagation medium for our "string phone?"

Question 1-5: How does the length and tightness of the string affect the loudness and clarity?

Question 1-6: Why is it important to pass the string through a mostly closed door or window?

Question 1-7: An *analog signal* is defined as a signal that varies continuously over time. Why would the transmission system described above be called an "analog transmission" system?

INVESTIGATION 2: DIGITAL TRANSMISSION SYSTEMS

APPARATUS AND SUPPLIES LIST

- Electronic push-button switch
- Red LED
- Resistors (390 Ω, 1.8 Ω)
- Phototransistor
- DC piezo buzzer
- 9 V battery leads (two sets)
- 1 m of 2 mm diameter plastic optical fiber
- Two 9 V transistor batteries
- Two electronic breadboards or printed circuit boards
- Laser diode module ***CAUTION: Do not point the laser into or near anyone's eyes!***
- Blackboard eraser and chalk dust
- Audio transformer
- Mini-speaker and foam cup
- 3.5 mm mono audio plug
- 1 kΩ resistor, 1 μF capacitor and 0.5 W Amplifier Module Kit (use these items if you do not have access to a HI-FI audio output amplifier and speaker)
- LM317 voltage regulator, 5 kΩ variable resistor, 240 Ω fixed resistor (use these items to construct a variable laser diode voltage supply if you do not have access to a DC voltage laboratory supply that is variable over the range of approx 3-3.5 volt)
- An audio source (tape, MP3 or CD player, etc.)

INTRODUCTION

With the string phone constructed in Investigation 1, if you wanted to convey the information that you needed help, you could shout "HELP" into the transmitter cup (i.e., send an analog voice message). Is there another way that you could transmit the same "HELP" *message* down the string from transmitter to receiver in another information format?

As an alternative to sending an analog signal (i.e., amplitude of the vibration along the string is proportional to the voice signal), you could also send a sequence of digital pulses that could be coded to represent the "HELP" message and this could be transmitted down the string phone. A transmission system that uses coded discrete pulses is called a *digital* transmission system.

In a digital transmission system information may be represented as follows:

- "**no pulse**" usually represents the digital symbol "0"
- "**pulse**" usually represents the digital symbol "1"

The presence or absence of pulses (i.e., “1s” or “0s”) is much easier to detect than a small change in the amplitude of a signal, especially if there is a lot of other “noise” on the line. With digital systems, information can either be sent as a digital code representing each character in the original message, or as a digitized representation of the original analog message.

Question 2-1: In terms of signal identification and decoding, what are the advantages and disadvantages of using an analog or digital transmission system?

Question 2-2: With a mobile *digital* phone system (i.e., one that uses digital pulses to send information) how are *text* messages coded?

Question 2-3: With a mobile *digital* phone system, how are voice messages coded?

Question 2-4: Which system (text or voice messaging) conveys information more efficiently?

Activity 2-1: Exploring the operation of a simple LED “optical telegraph”

A simple “optical telegraph” can be constructed from a light emitting diode (LED) (the transmitter) and phototransistor (the receiver). The circuits are shown below.

Figure 5-1: Light Emitting Diode (LED) circuit (transmitter)

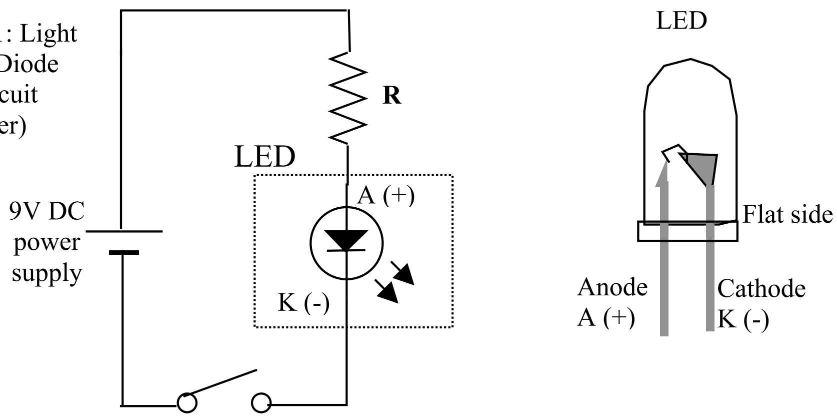
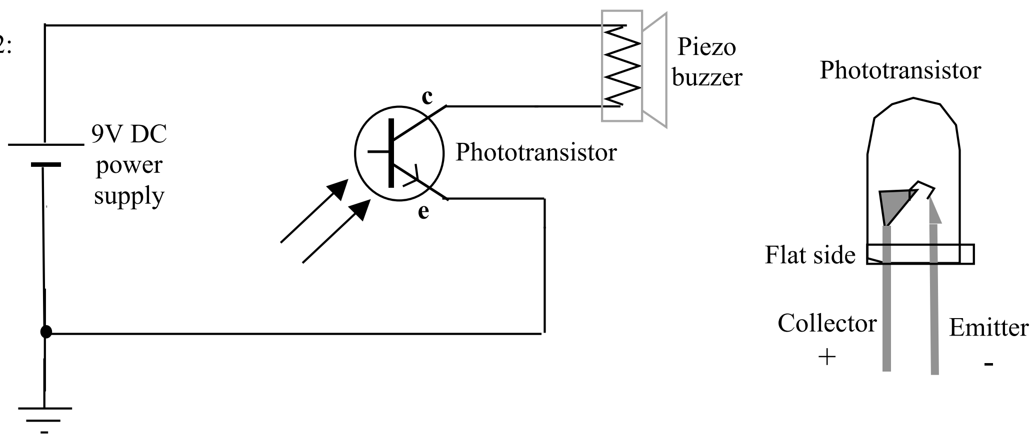


Figure 5-2: Photo-transistor circuit (receiver)



The typical current-voltage (I-V) characteristic curve for an LED is shown in Figure 5-3. For the red LED used in this activity, the normal operating current is 20 mA when the forward bias voltage is approximately 2.0 volts. These normal operating I-V characteristics should never be exceeded.

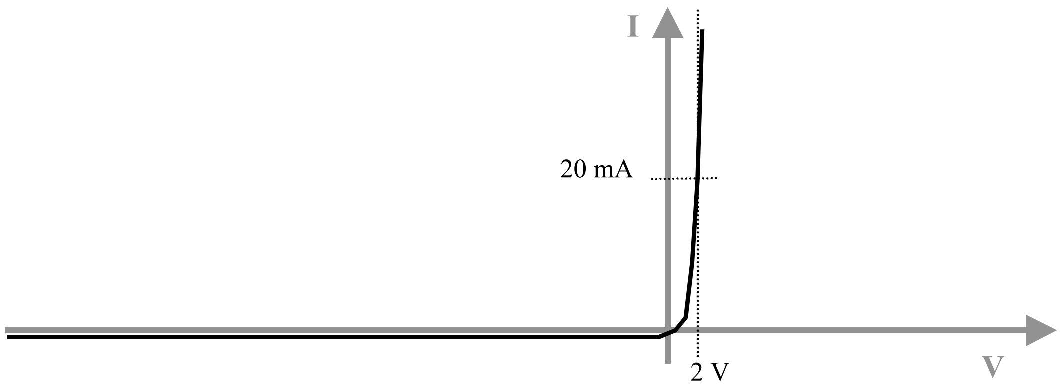


Figure 5-3: Typical LED I-V characteristic curve

1. Determine the value of the current limiting fixed resistor (R) that ensures that the maximum current through the LED will never exceed 20 mA when the 9 V battery is used to power the LED circuit. Show your work below.

Question 2-5: You have been supplied with a 390 ohm resistor. Based on your calculation, is this a safe resistor to use with this LED circuit? Why?

Comment: It can be shown that the light intensity given off by an LED is directly proportional to the current flowing through it. When the switch is open in the transmitter circuit (see Figure 5-1), no current flows through the LED and no light is generated. When the switch is closed, maximum current flows through the LED, and the LED glows brightly. This on-off LED light signal can be detected and amplified by the phototransistor in the receiver circuit (see Figure 5-2). When it is illuminated by the LED, the phototransistor can produce enough current to switch on the buzzer so that it makes a loud noise.

2. Use the Morse code table in Figure 5-4 to send a simple message from the LED transmitter to the phototransistor receiver.

Question 2-6: Is this a digital or analog transmission system? Explain.

Question 2-7: What is the medium that the information travels through?

A	.-	I	..	N	-.	V	...-	0	-----
B	-...	J	.---	O	---	W	.--	1	.----
C	-.-.	K	-.-	P	.--.	X	-..-	2	..---
D	-..	L	.-..	Q	--.-	Y	-.--	3	...--
E	.	M	--	R	.-.	Z	--..	4	....-
F	..-.			S	...			5	.....
G	--.			T	-			6	-....
H	....	**Letter**	**Morse**	U	..-			7	--...
								8	---..
								9	----.

Figure 5-4: Morse Code table

Question 2-8: The information pulses travel via a wave disturbance. In what ways is this light wave different from the longitudinal (sound) wave on the string of the string phone?

Question 2-9: What happens to the intensity of the light at the receiver as you move the LED and photo-transistor further apart? Why?

Question 2-10: Would it be practical to transmit information over large distances in this way? Explain your answer.

Question 2-11: Suppose that you are in one spaceship looking at another unmanned spaceship that is 100 m away, through a window that on earth can usually transmit both sound and light. There is a large explosion on the unmanned ship. Discuss with your neighbor(s) why you can see the explosion but not hear it. Is a medium necessary to transmit sound waves? Is a medium necessary for light waves?

Activity 2-2: An optical fiber communication system

We now want to place one end of an optical fiber close to the LED transmitter and the other end close to the phototransistor receiver to form a simple optical fiber-based optical telegraph.

Prediction 2-1: Will the light level illuminating the phototransistor receiver increase or decrease compared to the case of using just the long air path?

1. The size of the core of the optical fiber is large (approximately 2 mm

in diameter) and its two ends are placed as close as possible to the transmitter and receiver (which themselves are some distance apart).

Question 2-12: Compare the signals received by the receiver with and without the optical fiber in place. Does the detected signal level change?

Note: The optical fiber you are using in this module has a 2 mm diameter plastic core that has an index of refraction of approximately 1.49. A cladding made of a different plastic that has an index of refraction of approximately 1.40 surrounds the core. A cross-sectional view of the fiber is shown in Figure 5-5.

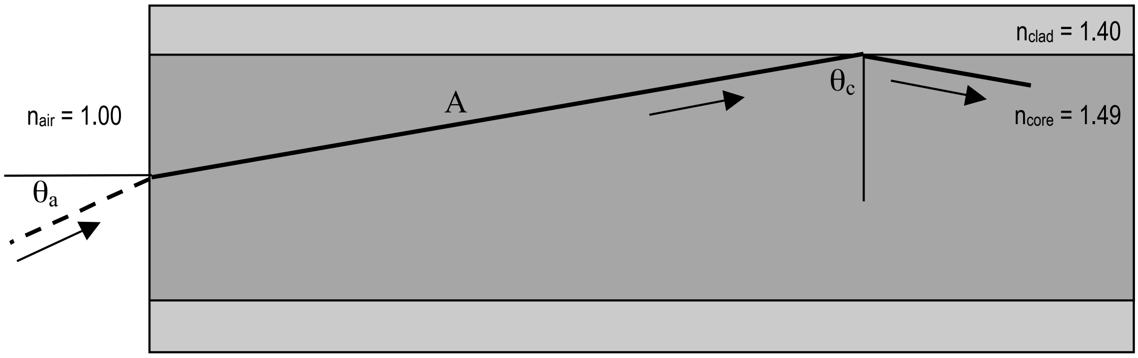


Figure 5-5: Cross-section of a plastic optical fiber

Question 2-13: Using Snell's law ($n_1\sin\theta_1 = n_2\sin\theta_2$), determine the critical angle θ_c for a light ray A (as shown in Figure 5-5) traveling in the fiber core when it meets the boundary between the core and the cladding materials. Show your calculation below. (Recall that the critical angle is the smallest angle (θ_c) for which no light is transmitted into the cladding material, i.e., for which total internal reflection takes place.)

Question 2-14: What happens to any light rays incident on the core-cladding boundary at an angle greater than the critical angle ($\theta > \theta_c$)? What happens to rays incident at less than the critical angle?

Comment: Total internal reflection at the core-cladding boundary of the optical fiber provides a means whereby all light incident at greater than the critical angle is trapped and channeled within the fiber—none of it is transmitted out of the core. (With the particular fiber used here some of the light can also be channeled in the cladding, but this is not very effective as the cladding air boundary has many imperfections, scratches, dust and other sources of light loss.)

Question 2-15: Again using Snell's Law, determine the angle θ_a of the external light ray that enters the fiber core and then is refracted to become the critical angle ray A. This angle is known as the *acceptance angle* (θ_a) of the optical fiber. (See Figure 5-5.)

Question 2-16: What happens to light rays entering the fiber core at angles less than the acceptance angle? At angles greater than the acceptance angle?

Question 2-17: Explain why coupling an optical fiber between the LED and the photodetector gives a stronger signal than just using a long air path.

Activity 2-3: A simple laser diode "optical voice communication system"

WARNING: ***The laser beam should never be directed toward anybody in the room. The laser beam is damaging to the eye.***

A simple laser diode module as is found in inexpensive laser pointers is ideal as a voltage-controlled light modulator. The light output of the laser diode is directly proportional to the current flowing through it, which itself is directly proportional to the supply voltage over a fairly large range. This means that if you add a small, varying modulation voltage (which itself is proportional to an audio signal) onto the supply voltage of the laser pointer, the light output of the laser diode will vary linearly with this varying modulation voltage.

A simple voltage modulation circuit (which acts as the "audio light transmitter") is shown in Figure 5-6 below. For high fidelity (HI-FI) quality sound, you can use a portable tape, MP3 or CD player as your modulation source.

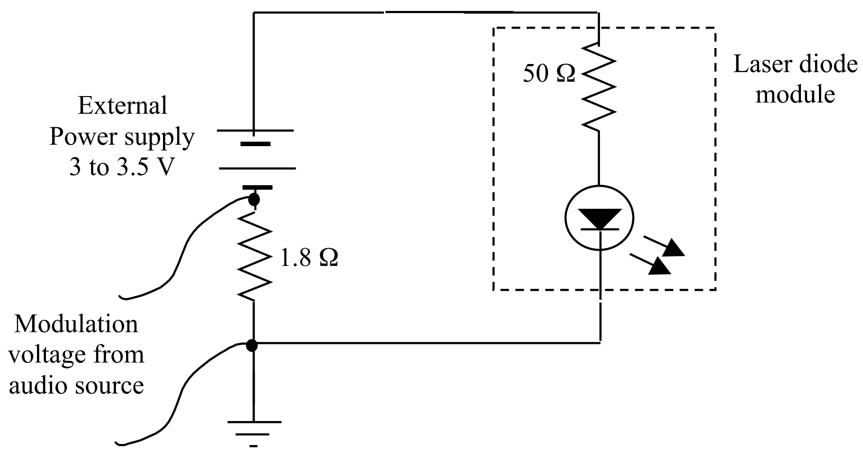


Figure 5-6: Laser Diode (LD) voice modulation source

1. Turn up the variable voltage supply to just above 3 volts. The laser diode first glows weakly then suddenly shines brightly (this indicates that the laser diode is lasing).

Warning: Do not exceed the minimum voltage needed to maintain lasing, as too high a voltage causes overheating and eventual failure of the laser diode.

2. Attach the audio source being careful to connect the signal and ground wires the correct way as shown in Figure 5-6.

The variation in light output from the voltage-modulated laser diode can be converted back into an electrical signal via a phototransistor, which has a high gain and sufficient frequency bandwidth for our audio modulated signal. A suitable phototransistor circuit is shown below in Figure 5-7.

The signal from the phototransistor circuit needs to be amplified and connected to a high quality speaker system. HI-FI quality sound can be obtained by using the amplified speaker system of a computer or audio system, or by constructing an audio amplifier.

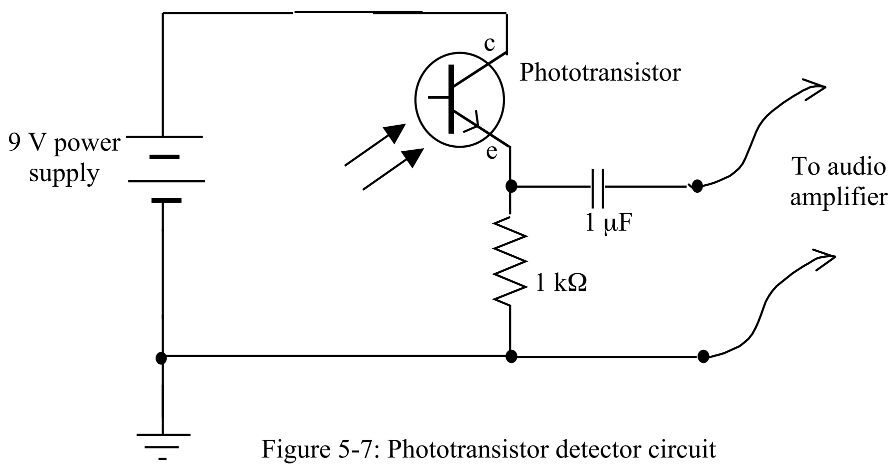


Figure 5-7: Phototransistor detector circuit

Question 2-18: How well does this system work to transmit sound from the audio source to the amplifier?

Question 2-19: Is there any limit to the amount of information that can be transmitted over a system like this? Explain.

Teachers' Guide for Module 5: Optical Data Transmission

TEACHERS' GUIDE FOR MODULE 5: OPTICAL DATA TRANSMISSION

General Introduction

Using the optical principles studied in Modules 1-4, and some relatively simple electronics, it is possible to construct a simple optical communication system.

Module 5 Apparatus and Supplies List

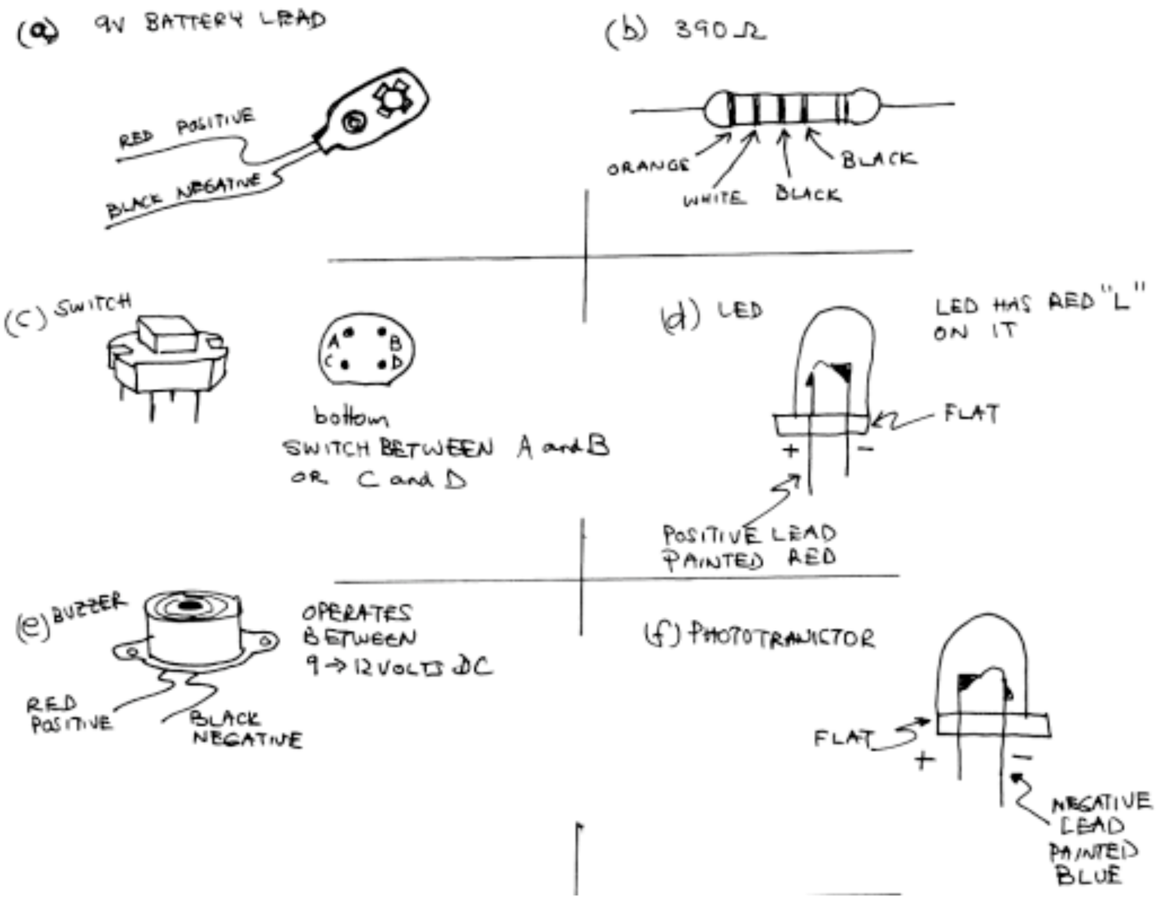
- Two polystyrene or plastic cups
- Toothpick to make a small hole
- Adhesive tape
- Long piece of fishing wire or strong thread
- Electronic push-button switch
- Red LED
- Resistors (390 Ω, 1.8 Ω)
- Phototransistor
- DC piezo buzzer
- 9V Battery leads (two sets)
- 1 m of 2 mm diameter plastic optical fiber
- Two 9 V transistor batteries
- Two electronic breadboards or printer circuit boards
- Laser diode module
- Audio transformer
- Mini-speaker and foam cup
- 3.5 mm mono audio plug
- 1 kΩ resistor, 1 μF capacitor and 0.5 W Amplifier Module Kit (use these items if you do not have access to a HI-FI audio output amplifier and speaker)
- LM317 voltage regulator, 5 kΩ variable resistor, 240 Ω fixed resistor (use these items to construct a variable laser diode voltage supply if you do not have access to a DC voltage laboratory supply that is variable over the range of approx 3-3.5 volt)
- An audio source (tape, MP3 or CD player, etc.)

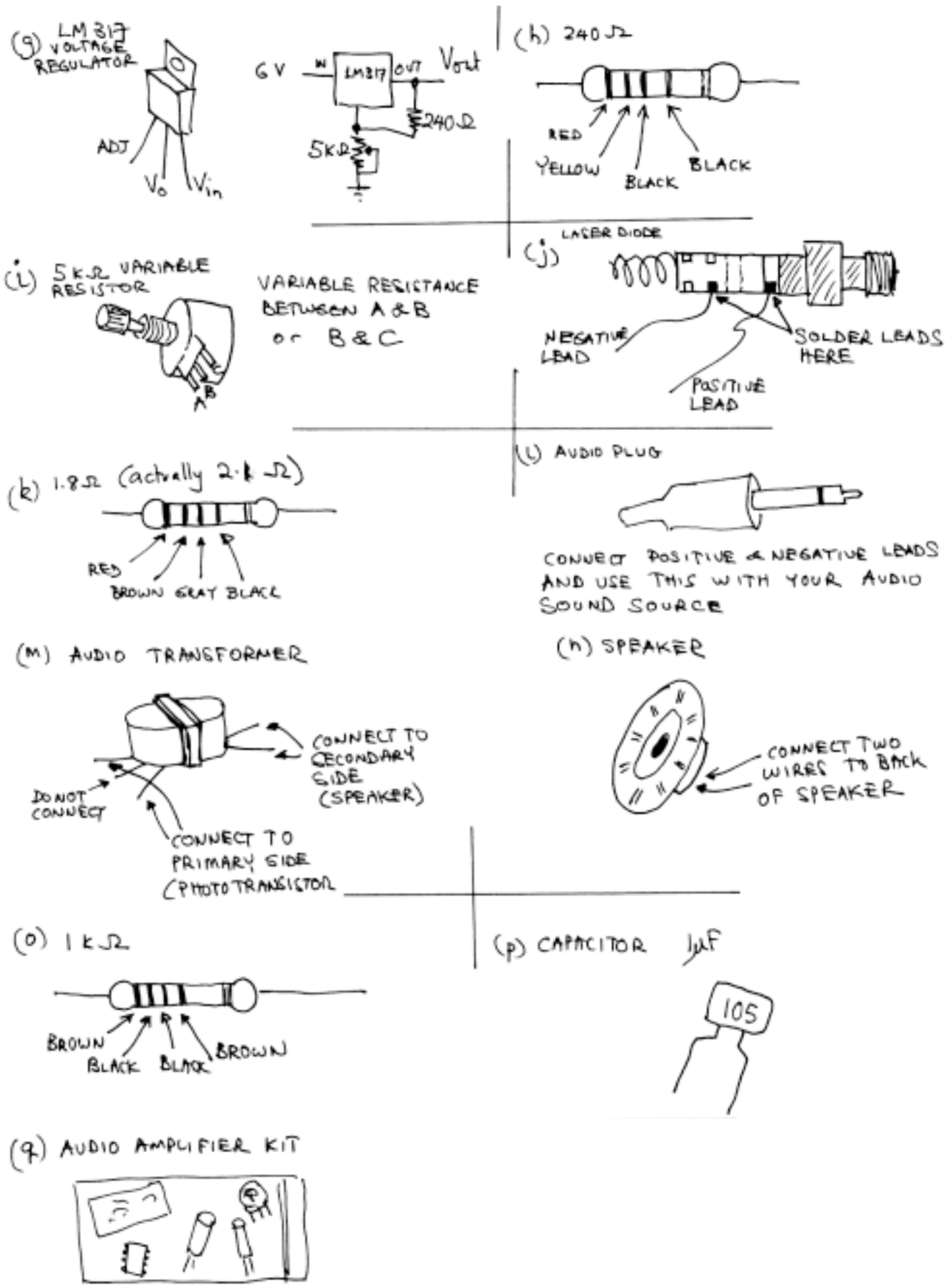
The following table lists information on these items, along with possible suppliers.

Item	Supplier	Part Number	Approx. Cost (USD)	Web reference
5mm super-bright RED LED	LEDsales (Australia)	7000MCD, 15^{O}	$0.75	www.ledsales.com.au/
27 mm mini speaker	Dick Smith Electronics (Australia) or	C2208	$1.50	www.dse.com.au/cgi-bin/dse.storefront

	similar supplier			
Audio transformer	Dick Smith	M0216	$0.75	as above
Electronic push button switch	Dick Smith	P7572	$0.75	as above
3.5 mm mono plug	Dick Smith	P1134	$0.40	as above
16 mm linear 5KΩ potentiometer	Dick Smith	R7553	$0.75	as above
Plastic optical fiber (CK-80, 0.080" diam)	Industrial Fiber optics (USA)	IF-C-U2000	$2.50/m	www.i-fiberoptics.com/
Phototransistor	Electus Distribution (Australia)	ZD1950	$0.75	www.electusdistribution.com.au/
Audio amplifier 0.5 W kit	Dick Smith	K5604	$4.50	www.dse.com.au/
Mini piezo buzzer (3-16 V DC)	Jaycar electronics supplier or similar	AB3462	$2.25	http://www.jaycar.com.au/
5 mW laser diode module	Oatley Electronics or similar supplier	LM1	$3.40	http://www.oatleyelectronics.com/
Voltage regulator, resistors, bread-boards, battery leads, capacitors	Any electronics supplier			

Sketches of components





INVESTIGATION 1: AN ANALOG TRANSMISSION SYSTEM

Investigation 1 Apparatus and Supplies List

- Two polystyrene or plastic cups
- Toothpick to make a small hole
- Adhesive tape
- Long piece of thin fishing wire or strong thread

Activity 1-1: Building the string phone

It is important to be sure that the string between the cups is held tight, while not in contact with anything.

Question 1-1: Sound is vibrations—localized vibrations in the medium (air, water, etc.)—that transmit energy from one point to another. Sound propagates as longitudinal waves, waves with the disturbances along the direction of propagation. In air, these disturbances are pressure changes that propagate through space at the speed of sound. Sound is an example of a mechanical wave (a wave that requires a medium for propagation).

Question 1-2: Air from the lungs passes the vocal chords in the throat causing them to vibrate over a range of frequencies. These vibrations are transmitted to the air stream. The shape of the mouth and the position of the tongue (and teeth) modulate these vibrations to produce the sound that is transmitted out of the mouth and into the air.

Question 1-3: The sound waves enter the ear, and ultimately cause delicate membranes in the inner ear (cochlea) to vibrate. These vibrations are converted into electrical signals that are sent along nerve cells to the brain.

Question 1-4: For the string phone, the sound waves propagate along the string rather than in air.

Question 1-5: The longer the string, the greater the sound energy that will be lost to the air as the waves propagate along the string. The tighter the string, the more efficiently the sound waves propagate along the string. Therefore both length and tightness will affect both loudness and clarity (i.e., signal to noise ratio).

Question 1-6: The mostly closed door or window will block out transmission of sound through the air. This is important in this activity in order to demonstrate that sound is actually transmitted along the string.

Question 1-7: In the string and cup system (and likewise when sound is transmitted through the air), the sound waves can have amplitudes of any value down to zero, depending on the sounds produced at the transmitting cup. Since the amplitude (and intensity) vary continuously, this is an analog system.

INVESTIGATION 2: DIGITAL TRANSMISSION SYSTEMS

Investigation 2 Apparatus and Supplies List

- Electronic push-button switch
- Red LED
- Resistors (390 Ω, 1.8 Ω)
- Phototransistor
- DC piezo buzzer
- 9 V Battery leads (two sets)
- 1 m of 2 mm diameter plastic optical fiber

- Two 9 V transistor batteries
- Two electronic breadboards or printer circuit boards
- Laser diode module
- Audio transformer
- Mini-speaker and foam cup
- 3.5 mm mono audio plug
- 1 kΩ resistor, 1 μF capacitor and 0.5 W Amplifier Module Kit (use these items if you do not have access to a HI-FI audio output amplifier and speaker)
- LM317 voltage regulator, 5 kΩ variable resistor, 240 Ω fixed resistor (use these items to construct a variable laser diode voltage supply if you do not have access to a DC voltage laboratory supply that is variable over the range of approx 3-3.5 volt)
- An audio source (tape, MP3 or CD player, etc.)

Digital systems are very different from analog ones. It is important for students to understand the differences, and why digital systems are preferable for optical communication.

Question 2-1: The main disadvantage of an analog system is that noise outside the signal being transmitted can interfere with the signal. Since an analog signal is represented by the amplitude of the wave, anything that changes the amplitude will change the transmitted signal. The chief advantage of a digital transmission system is that it is much less affected by noise. In a digital system, the signal is transmitted with a code of pulses (a pulse represents the bit "1" and no pulse represents the bit "0"). It is much more difficult for noise to completely mask the presence or absence of such pulses. Of course the circuitry needed to code/decode a digital signal is much more complex than that needed for an analog signal.

Question 2-2: Digital coding is used to represent each letter in the text message.

Question 2-3: The analog voice signal is sampled at various points in time, and these analog signal samples are digitized into an equivalent digital number. This means that there is some loss in the information carried by the analog signal. It is important that the sampling is frequent enough in time so that the voice signal doesn't lose too much quality.

Question 2-4: Text messaging is more efficient and more precise, since there is a limited number of codes needed to represent the limited number of letters in the alphabet. Of course, less information is transmitted (e.g., no changes in loudness or inflections of the human voice). With voice messages the analog voice signal must be sampled many hundreds of times per second, and each sample must be digitized with high resolution. This means that many more bits are needed to represent the same information using voice rather than text messaging.

Activity 2-1: Exploring the operation of a simple LED "optical telegraph"

The figures below show some examples of how you can easily build these demonstrations for students in your own institution. Figure TG5-1 shows an LED transmitter, while Figure TG5-2 shows a phototransistor detector. The LED and phototransistor are fixed on simple mounts that can easily be adjusted vertically.

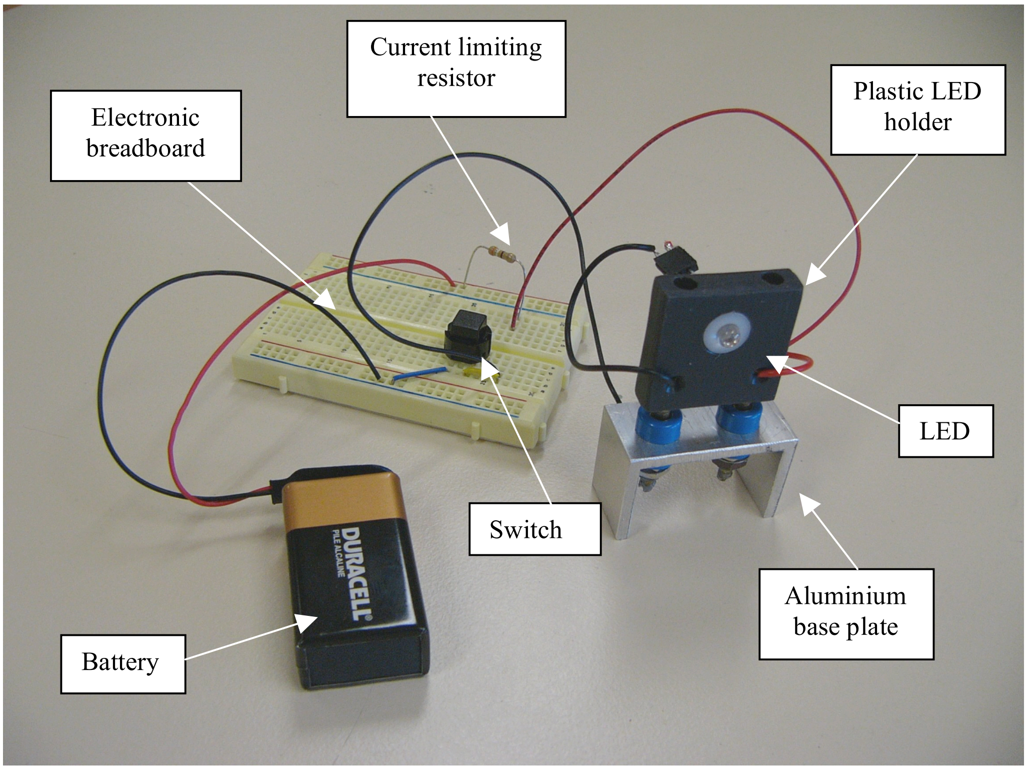


Figure TG5-1: Photograph of sample layout for LED transmitter.

Alternatively, the LED and phototransistor can be simply mounted directly onto electronic breadboards, as shown in Figures TG-3 and TG-4.

Question 2-5: In the circuit in Figure 5-1, the sum of the voltages across the power supply, the resistor and the LED must equal zero. The operating voltage across the LED is 2.0 V. Thus, 9–IR-2=0, I(390)=7, I=7/390=18 mA which is less than the 20 mA maximum. This is a safe resistance to use with this LED.

Question 2-6: This is a digital system, since information is digitally coded i.e., the switch and the buzzer are either on or off. It doesn't matter how loud the buzzer is, the information transmitted (sequence of "1s" and "0s") is the same.

Question 2-7: The information travels through the region between the LED and the phototransistor as light waves. (See Question 2-11.) In this case the region happens to be air, but the system would work equally well if the region were a vacuum.

Question 2-8: Light waves are transverse electromagnetic waves. That is, the disturbance is perpendicular to the direction of propagation, unlike the sound waves that are longitudinal waves. Light waves travel at the speed of light, which is much faster than the speed of sound. Electromagnetic waves (light) do not require a medium (i.e., a light beam can travel in a vacuum), unlike sound waves that do require a medium. In this case, the light waves are able to spread out in space once they leave the LED, while the sound waves were pretty much confined to the string.

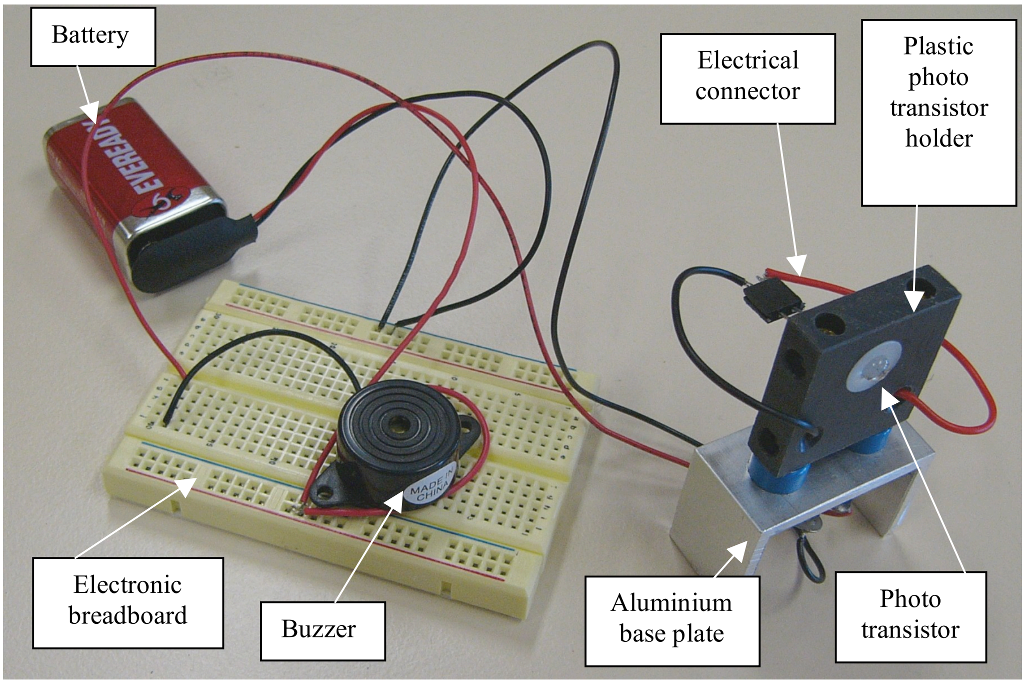


Figure TG5-2: Photograph of sample layout for phototransistor detector.

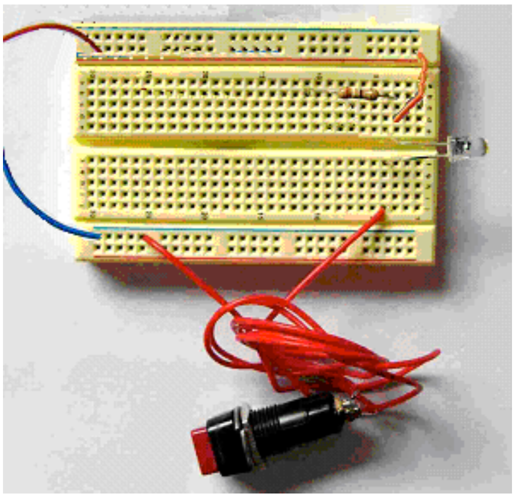


Figure TG5-3: LED mounted on electronic breadboard.

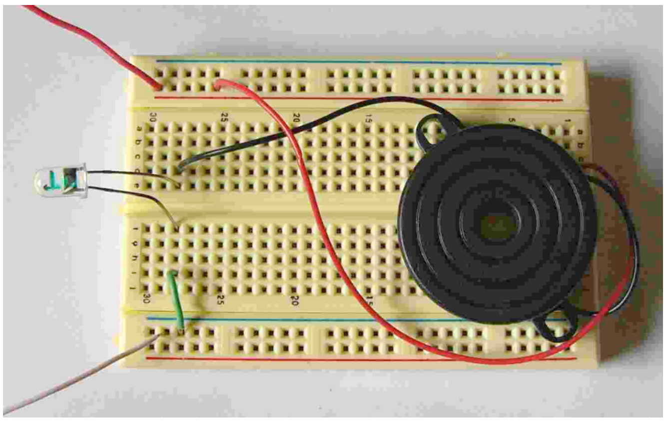


Figure TG5-4: Phototransistor breadboard.

Question 2-9: The intensity of the light wave decreases as the distance from the LED increases. This is because the light waves emitted by the LED spread out in space.

Question 2-10: This would not be practical because eventually the distance would be so big that not enough light would reach the phototransistor from the LED. Then it would no longer be possible to receive the signal. Clearly we need some way of channeling the light energy between source and detector if we want to use this system over a large distance.

Question 2-11: Sound waves need a medium to propagate through, but light waves do not. In the vacuum of space, the sound waves from the explosion will not propagate from the unmanned spaceship to you, but the light waves will. Therefore, you can see the explosion but not hear it.

Activity 2-2: An optical fiber communication system

In this activity, you will need the help of a student to hold one end of the fiber close to the LED source and the other end of the fiber close to the phototransistor. In this way we can get good coupling of the light energy from the LED to the phototransistor by allowing the light to channel along the fiber.

Question 2-12: The signal is much greater with the optical fiber than without it.

Question 2-13: Using n_1=1.49, θ_1=θc, n_2=1.40 and θ_2=90° (no transmitted ray), 1.49 sin θc=1.40 sin 90°, sin θc = 1.40/1.49 = 0.940, θc =70°.

Question 2-14: Light incident on the core-cladding boundary at an angle greater than the critical angle is completely reflected back into the core (via total internal reflection). There is no loss of this light from the core. Light incident at less than the critical angle is partially reflected and partially transmitted. Some of it is lost from the core to the cladding.

Question 2-15: The acceptance angle is the angle at which light is incident on the end of the fiber so that after refraction at this surface, it is incident on the core-cladding boundary at the critical angle. From Figure 5-4, now n_1=1.00, θ_1=θ_a, n_2=1.49 and θ_2=90°- θc= 20°. 1.00 sin θa=1.49 sin 20°, sin θa = 0.510/1.00=0.510. θa = 30.6°.

Question 2-16: Light incident on the endface of the fiber at angles less than the acceptance angle, enters the fiber along rays that are incident on the cladding at angles greater than the critical angle. This light is completely reflected back into the fiber. Light that is incident at angles greater than the acceptance angle is incident on the cladding at angles less than the critical angle. Some of this light is transmitted through the cladding and lost from the core.

Question 2-17: With the air path, the light from the LED spreads out, and only part of it falls on the phototransistor. The fraction incident on the phototransistor can be very small for long distances. With the optical fiber, most of the light coupled into the fiber is channeled down the fiber core, so very little of this light is lost, and most of it reaches the phototransistor.

Activity 2-3: A simple laser diode "optical voice communication system"

Audio Light Transmitter Design: A simple version of the laser diode "audio light transmitter" is shown in Figure TG5-5. This particular HI-FI quality example uses a portable CD player as the modulation source. This example uses a variable laboratory voltage supply to power the laser diode. Alternatively, a simple, inexpensive, variable, battery-operated, voltage source (based on the LM317 voltage regulator chip) can be easily built by following the instructions in the data sheet and application notes . These are obtained at http://www.national.com/pf/LM/LM317.html by clicking on **View Online**.

WARNING: Lasers, like the ones used in this activity, have the potential to cause serious eye injury. Please read the Laser Safety section of this manual.

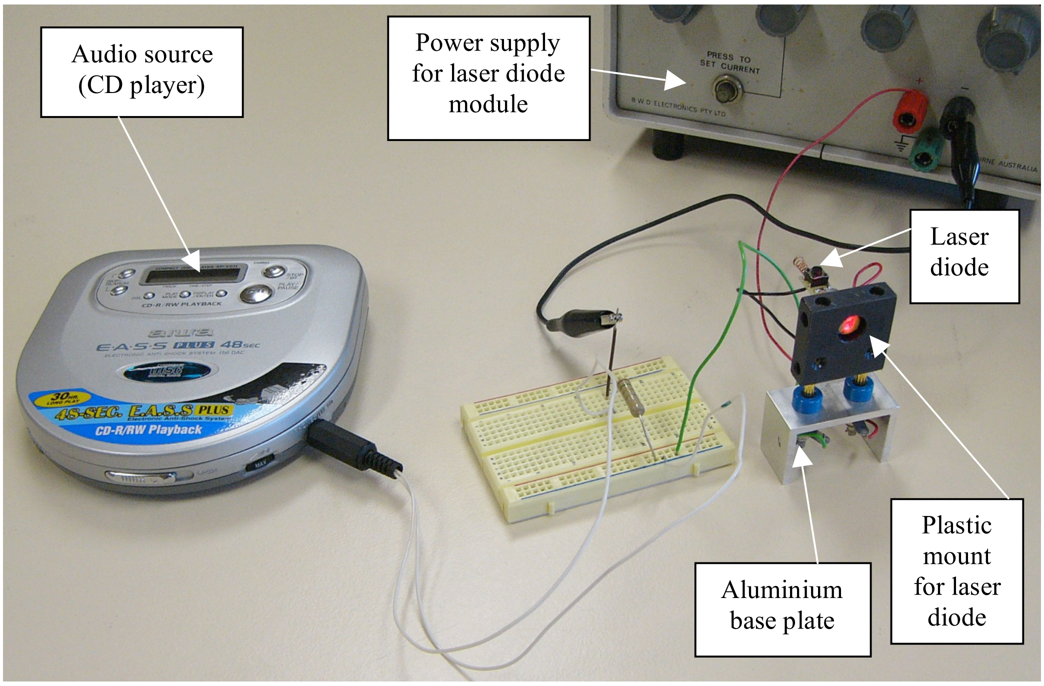


Figure TG5-5: Photograph of audio light transmitter with CD player as audio source.

The leads should be connected to the Laser Diode unit as shown below in Figure TG5-6:

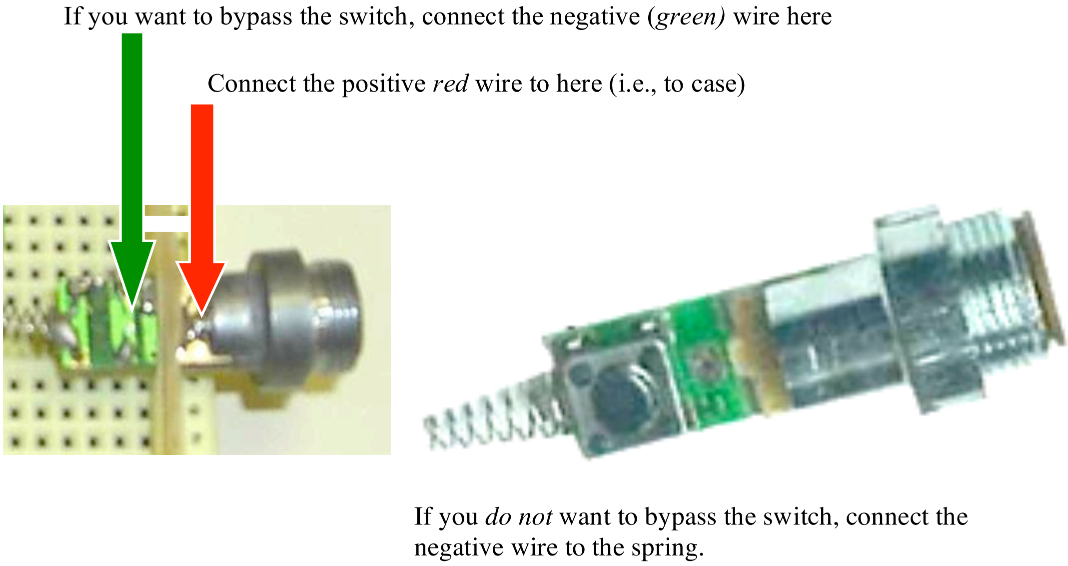


Figure TG5-6: Wiring directions for the Laser Diode.

Alternatively, you may wish to mount the laser diode directly onto an electronic breadboard as shown in Figure TG5-7. An elastic band can be used to secure the laser diode module to breadboard.

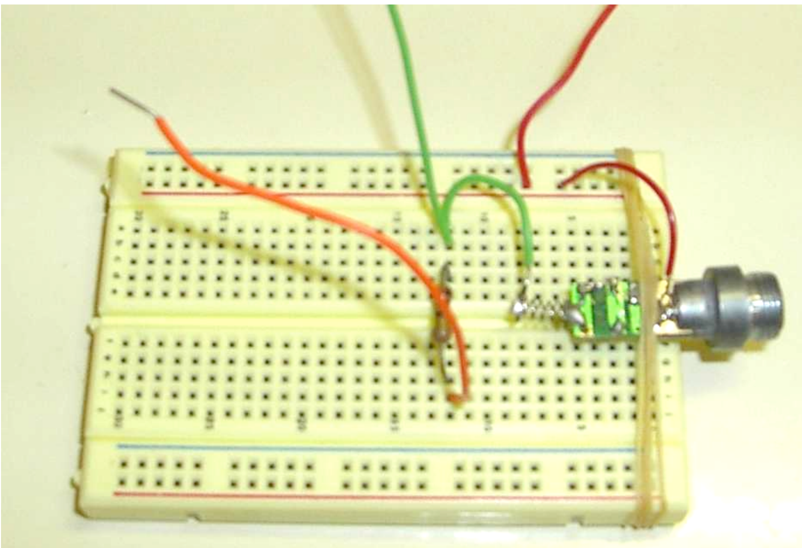


Figure TG5-7: Photograph of method for mounting the laser diode directly onto breadboard.

Phototransistor receiver design: The signal from the phototransistor circuit needs to be amplified and connected to a high quality speaker system. HI-FI quality sound can be obtained by using the amplified speaker system of a computer or audio system. In this case the circuit shown in Figure TG5-6 of can be used. The 1 kΩ resistor acts as the load resistor and the 1 μf capacitor acts to decouple any DC component in the signal (i.e., only the time-varying part of the signal is amplified, as required). Alternatively—if a HI-FI system is not available—a simple and inexpensive audio amplifier (0.5 W) can be constructed from a kit. Details of where to obtain an audio amplifier kit and instructions are given in the Equipment Notes.

Even if audio amplifier is not available, the single stage phototransistor amplifier can be connected to an inexpensive audio transformer and miniature speaker circuit as shown in Figure TG5-8 to reproduce the original audio signal. Although this does not give HI-FI quality sound, it is still sufficient for this simple demonstration. The circuit shown in Figure TG5-8 is very simple and inexpensive to build.

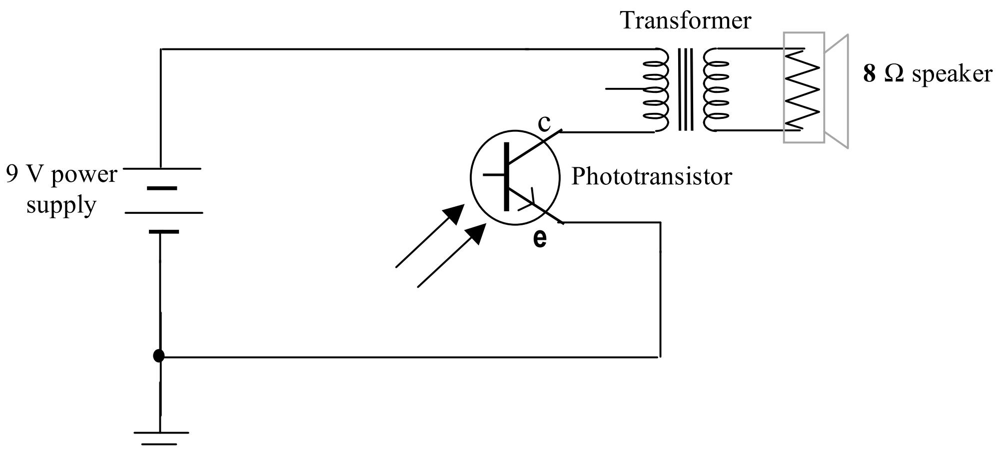


Figure TG5-8: Circuit diagram of connection of phototransistor to a miniature speaker through an audio transformer.

The phototransistor is used to amplify the photocurrent generated by the light. The collector current drives the speaker via the audio transformer. The audio transformer has a primary DC resistance of approx 110 Ω. The transformer is operated as a step down device so that the actual 8 Ω speaker resistance in the secondary coil has an apparent resistance of approximately 1 kΩ in the primary coil at around 1 kHz. The phototransistor can drive this apparent load reasonably well.

Figure TG5-9 shows an example of a phototransistor detector driving a small speaker via s simple audio transformer. A polystyrene cup makes an excellent speaker enclosure, and enhances the loudness of the sound. The connections are as follows:

Phototransistor: The longer lead is the emitter (i.e., connected to the more negative side of the circuit). The lead on the *flat* face of plastic case is the collector.

Transformer: The outer two leads of the three lead side are used as the primary coil.

Speaker: Leads must be soldered to the speaker and the speaker should be mounted facing outwards in a snug fitting hole in the polystyrene cup.

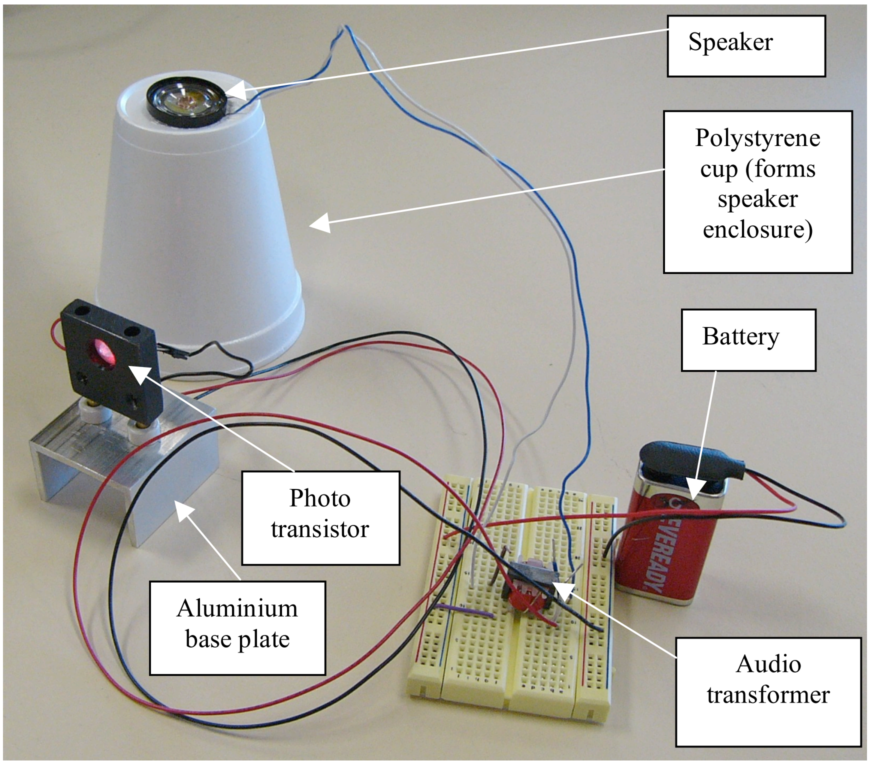
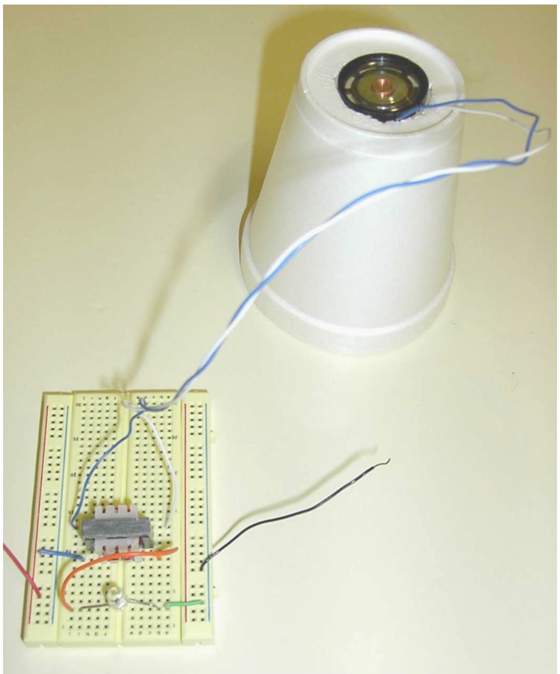


Figure TG5-9: Photograph of phototransistor/speaker connection using audio transformer.

Figure TG5-10 shows another variation where the phototransistor and transformer are both mounted on an electronic breadboard.

Figure TG5-10: Photograph of alternate receiver design with phototransistor and audio transformer mounted on a breadboard.



Module 6:
Wavelength Division Multiplexing

Alex Mazzolini
Faculty of Engineering and Industrial Sciences
Swinburne University of Technology
Hawthorn, Victoria Australia
amazzolini@swin.edu.au

MODULE 6: WAVELENGTH DIVISION MULTIPLEXING

OVERVIEW:

In Module 5, you examined how information can be sent over a fiber optic transmission line. In order to make an efficient communication system, it is necessary to maximize the amount of information that can be sent over such a line. In this module you will look at one important method for doing this, *wavelength division multiplexing*. This is an important component of *photonics*, the optical technology that is at the heart of all optical transmission systems.

This module should be attempted after Module 5. The preliminary considerations in Investigation 1 should be completed before attempting the laboratory activities.

OBJECTIVES:

1. To explore the factors that limit the rate at which information can be transmitted from transmitter to receiver
2. To explore how the amount of information transmitted down an optical fiber can be increased
3. To explore the dispersion of light
4. To explore color addition
5. To investigate the unique properties of light that allow *Wavelength Division Multiplexing (WDM)*
6. To demonstrate *WDM*
7. To explore practical *WDM* systems

INVESTIGATION 1: PRELIMINARY CONSIDERATIONS

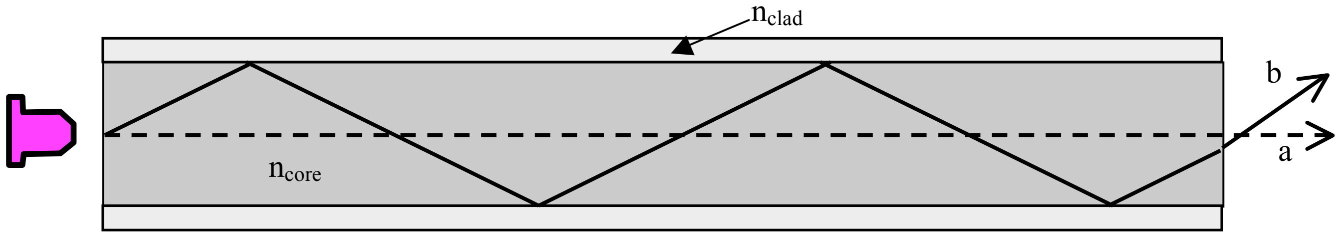
APPARATUS AND SUPPLIES

- Red-Green-Blue LED (known as a white light LED or WLED) and microcontroller driver
- 1 meter of cladded plastic fiber (2 mm outside cladding diameter, 1.96 mm core diameter).
- 4.5 volt (3xAA) battery pack for microcontroller power supply
- Plastic lens (focal length about 25 mm, diameter 25 mm)
- Sheet of Mylar film (used as viewing screen)
- Plastic WLED to optical fiber coupler
- WLED/microcontroller driver holder
- Optical fiber holder
- Lens holder (with variable height adjustment)

Activity 1-1: Pulse spread

Consider an LED that has its light coupled into the core of an optical fiber. The light can travel down the fiber following many possible paths. In Module 1, you examined total internal reflection at the boundary between a medium with a higher index of refraction and one with a lower index of refraction. You applied these ideas to the optical fiber used in Module 5. Total internal reflection will occur as long as the light is incident on the core-cladding boundary at angles greater than the critical angle. Then the light will be channeled down the fiber without loss.

The diagram below shows two of the possible rays for light traveling down a straight length of fiber. The dashed ray (a) is along the optical axis of the fiber. The solid ray (b) follows a zig-zag path through the fiber and undergoes a number of (total internal) reflections.

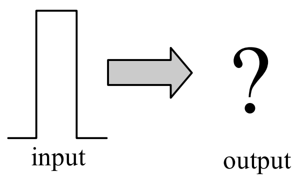


The core of the fiber has a constant index of refraction (n_{core}) which is a little larger than the index of refraction of the cladding (n_{clad}). Such a fiber is called a *step-index multimode fiber*.

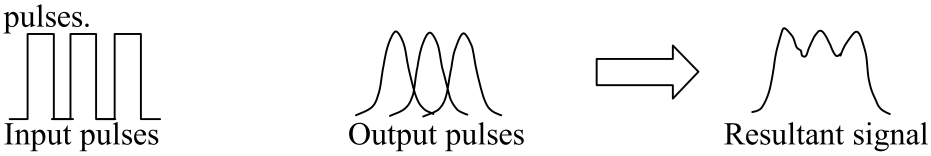
Assume the LED is switched on and off very rapidly giving a very narrow pulse of light. Light from the LED enters the entrance end of the optical fiber along rays at many angles.

Question 1-1: For the two light rays shown—along paths (a) and (b), which light traverses the length of the fiber in the shortest time? Explain.

Question 1-2: If the LED emits short rectangular light pulses (as shown on the right) that illuminate the entrance end of the fiber, what happens to the shape of these pulses after the waves that make up the pulses have traveled to the exit end of the fiber along many different ray paths? Explain.



Comment: The difference in transit times for the two paths (a and b) shown in the previous diagram is very small but will result in some spreading out of the pulses. If the pulses are very narrow and close to each other, the pulse spread may make it difficult to identify individual pulses.



A modern digital optical fiber transmission system uses ultra-narrow pulses of light to convey information. Each pulse or its absence can represent a binary digit or bit (a 1 or a 0). These pulses of light are sent down the fiber from transmitter to receiver.

Question 1-3: With a given fiber, how can we transmit information at a faster rate (i.e., more bits per second) from transmitter to receiver?

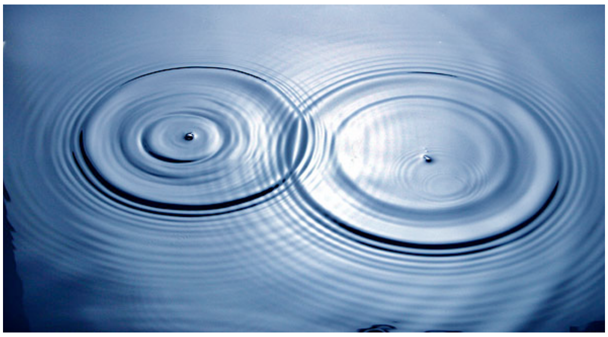
Question 1-4: What will eventually limit the rate of information transfer (i.e., the maximum number of pulses that can be sent down the fiber per second)?

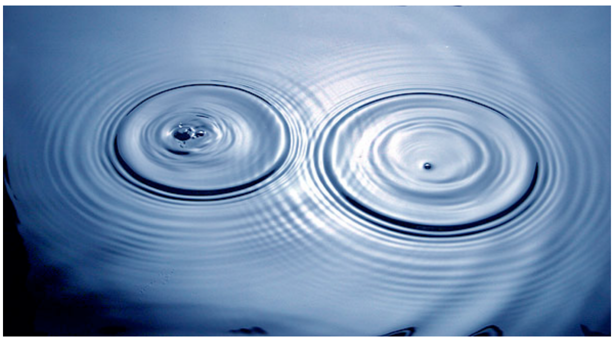
Comment: There are many other causes of pulse spread in optical fibers, so this is a real limitation to high data transfer rates in fiber optic systems!

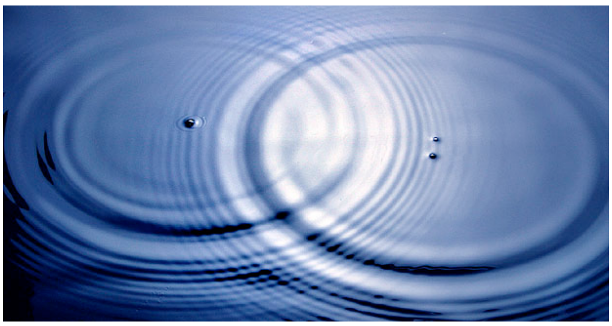
Activity 1-2: Behavior of water waves on a calm pond

As you have seen in Module 3, if you drop a stone into a calm pond a wave disturbance spreads out along the surface of the water (a set of surface ripples all spread out from the point where the stone hit the water). If a second stone is dropped (almost at the same time) into the pond close to the first we would see a ripple pattern as shown in the diagrams below.

Question 1-5: If you were to look at the points where the two waves overlap, what would you see when: (a) a crest (maximum) from one wave overlaps with the crest from the other wave, and (b) a crest from one wave overlaps with the trough (minimum) from the other wave?





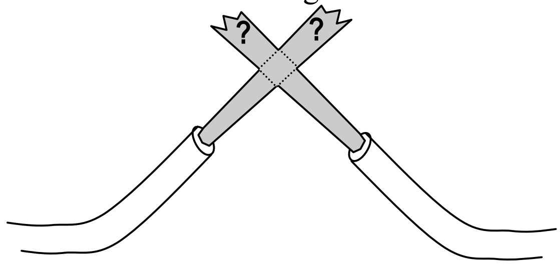


These three pictures were taken by Andrew Davidhazy, and can be found at the following website: www.rit.edu/~andpph/ exhibit-3.html

Question 1-6: What do you see when the two waves have passed through each other? What effect do the ripples of the second stone have on the propagation of the ripples of the first stone?

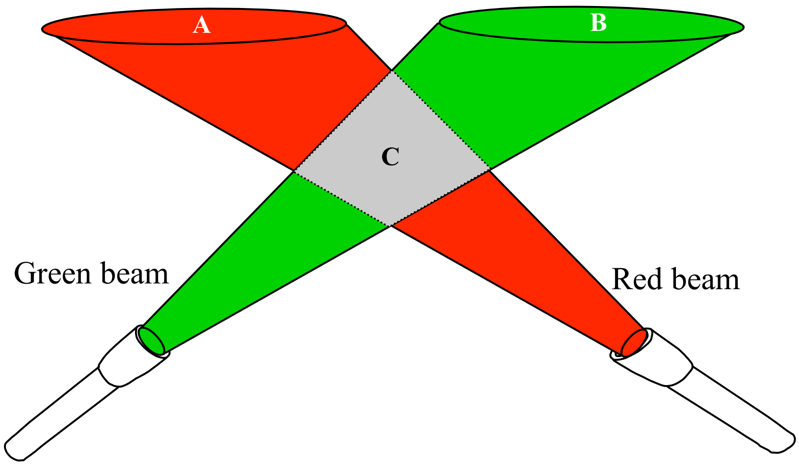
Activity 1-3: Wave behavior of light

1. Suppose water streams from two garden hoses are made to intersect.



Question 1-7: What happens to the streams beyond the intersection region?

2. Now consider two flashlights with differently colored light beams (Red and Green) that pass through each other, as shown below.



Question 1-8: If we could put a piece of white paper at various positions in the light beams, what colors would be seen at point A? Point B? Point C?

Question 1-9: How does the presence of the RED beam affect the GREEN beam beyond the intersection region, C?

Comment: The light beams are behaving like waves, where each wave is unaffected by the other past the intersection region (i.e., each color wave propagates independently of the other)!

INVESTIGATION 2: EXPLORING A WDM SYSTEM

APPARATUS AND SUPPLIES

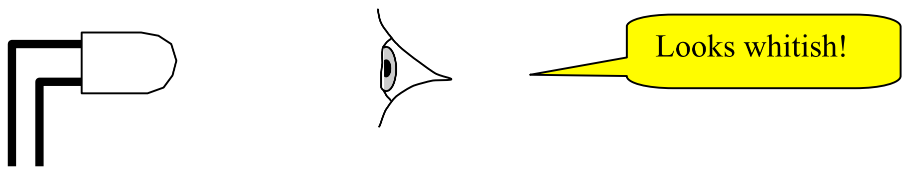
- Red-Green-Blue LED (known as a white light LED or WLED) and microcontroller driver
- 1 meter of cladded plastic fiber (2 mm outside cladding diameter, 1.96 mm core diameter).
- 4.5 volt (3xAA) battery pack for microcontroller power supply
- Plastic lens (focal length about 25 mm, diameter 25 mm)
- Red filter (cellophane sheet)
- 25 mm x 25 mm piece of diffraction grating
- Diffraction grating holder
- Phototransistor holder
- Phototransistor audio amplifier similar to the one developed in Module 5

Activity 2-1: Exploring the Red-Green-Blue (RGB) LED

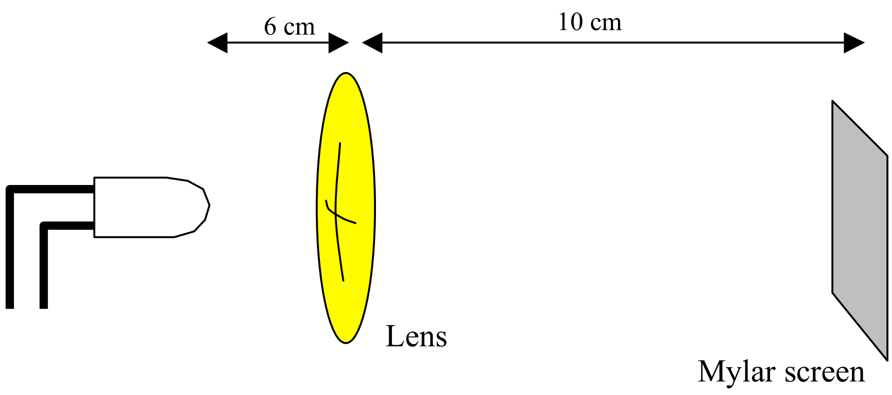
WARNING: The voltage used to power the microcontroller driver in this activity should never exceed 5.5 volts, as this will permanently damage the device. Reversing the polarity of the supply voltage has a similar effect.

Most people have seen red LEDs, but only some have seen green or blue LEDs. An RGB LED has <u>all three</u> colors in one package!

1. Examine the output of an RGB LED. Connect the 4.5V battery power supply to the LED microcontroller. (See the **WARNING** above.) When the power is connected, the LED immediately turns on and the output of the LED appears "whitish" in color.



2. Now you will use the lens to focus the white light from the surface of the RGB LED module to form an image on a screen so we can observe the output of the LED more clearly.



Prediction 2-1: What do you think will be observed on the screen? Draw your prediction in the box on the right.	**Prediction**
3. Set up the plastic lens approx 6 cm from the LED. Make sure the less curved surface of the lens is facing the LED. Place the mylar screen approximately 10 cm from the lens and move it backward and forward until the LED image is clearly visible. What do you observe on the screen? Draw it in the box on the right.	**Observation**

Question 2-1:What colors can be seen in the image?

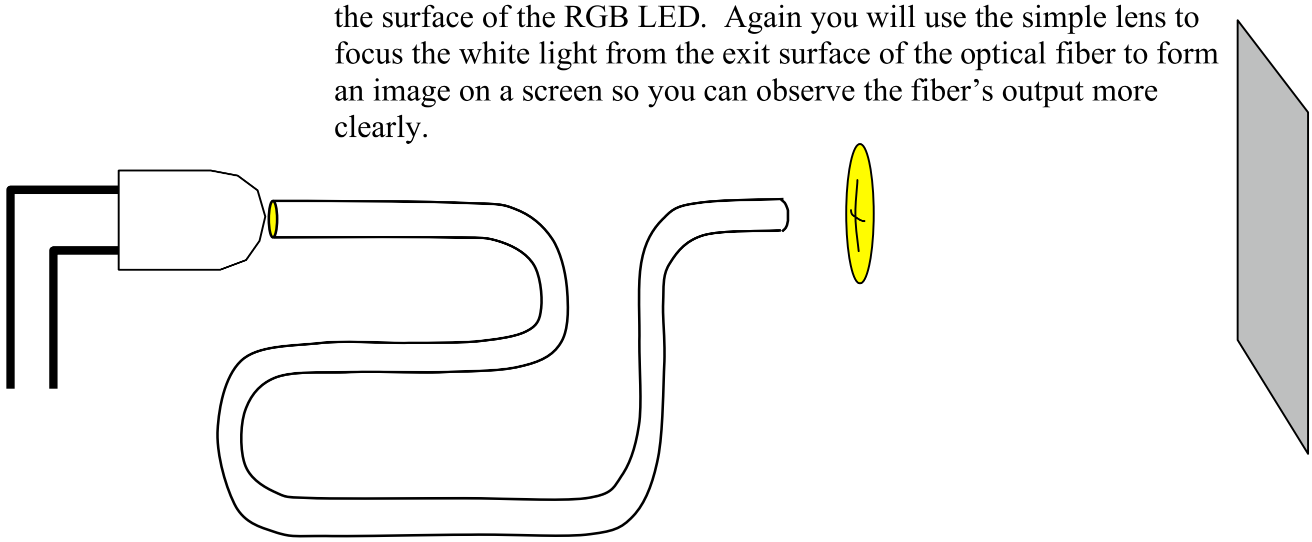
4. Discuss the following questions with your partner(s), and then answer them

Question 2-2: Are all the colors equally sharp? If not, why not? Does scattering have anything to do with it?

Question 2-3: Why does the LED look "white" when we look at it? What process makes it appear white?

Activity 2-2: Sending RGB LED light down an optical fiber

1. You will next position the 2 mm plastic optical fiber on the center of the surface of the RGB LED. Again you will use the simple lens to focus the white light from the exit surface of the optical fiber to form an image on a screen so you can observe the fiber's output more clearly.

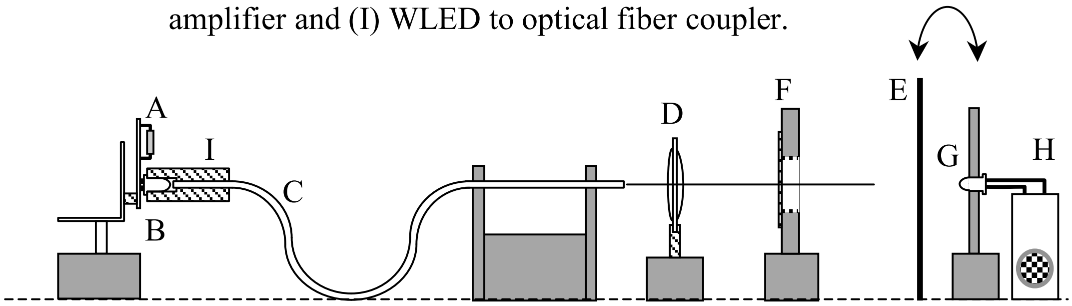


Prediction 2-2: What do you think will be observed on the screen? Draw your prediction in the **Prediction** box on the right.

Prediction	Observation

2. Couple the optical fiber to the LED by using the plastic coupler. Thread the other end of the fiber through the holes in the fiber holder. Position the lens approximately 3.5 cm from the tip of the fiber and the screen approximately 13 cm from the lens. Adjust the position of the screen to obtain a sharp image

   The diagram below is a sketch of the setup. (A) microcontroller, (B) WLED, (C) optical fiber, (D) lens, (E) Mylar screen, (F) red cellophane, (G) phototransistor (replaces Mylar screen), (H) audio amplifier and (I) WLED to optical fiber coupler.



   What do you observe on the screen? Draw it in the **Observation** box above.

3. Discuss the following questions with your partner(s), and then answer them

Question 2-4: Explain why the image on the screen is different from the image in the Activity 2-1 without the optical fiber? Are they not both images of light coming from the same LED!?

Question 2-5: What is happening to the signals from the Red, Green and Blue sources in the LED when they pass through the optical fiber?

INVESTIGATION 3: SENDING INFORMATION DOWN AN OPTICAL FIBER

If we have some information, we can encode it into a sequence of light pulses and send it down the optical fiber. The source of these coded light pulses is called the *transmitter.*

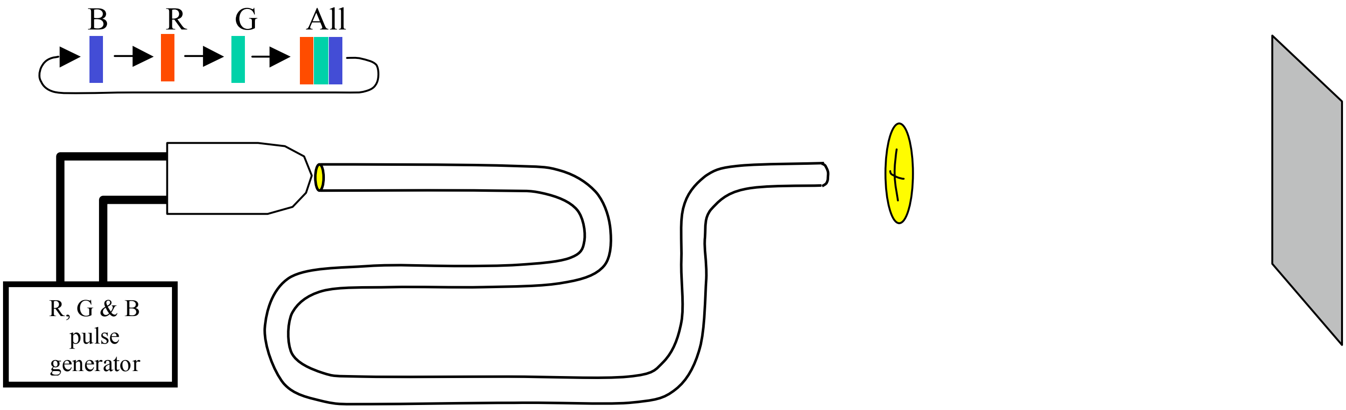
These pulses are channeled down the fiber without loss and can be detected and decoded at the other end. The device that does this is called the *receiver.*

Each of the three tiny sources in the RGB LED can be controlled independently, so we can send various R, G or B pulses of light down the fiber. In this manner information can be sent down any or all of these three different color channels.

We can use the microcontroller to generate different sequences of R, G and B light pulses from the RGB LED. (These represent three different information streams.)

Activity 3-1: Sending a sequence of color pulses down the fiber

Suppose that the microcontroller of the transmitter generates the following input sequence of four color pulses, repeated over and over again: **Pulse 1—Blue, Pulse 2—Red, Pulse 3—Green, Pulse 4—All three colors together.**



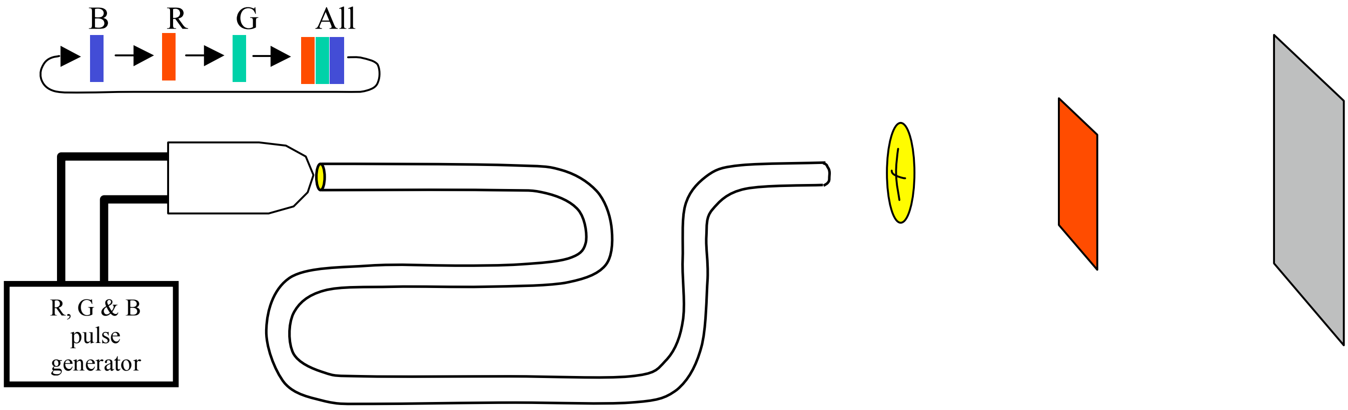
Prediction 3-1: What sequence of colors and shapes do you think would be observed on the screen?

1. Press the push button on the microcontroller ***<u>once only</u>***. This will activate the required sequence—B pulse, R pulse, G pulse, (R+G+B) pulse.

Question 3-1: What sequence of colors and shapes do you actually observed on the screen?

Question 3-2: Why do the pulses have those specific colors? Why is the pulse with all three colors neither red nor green nor blue?

2. Place the red cellophane sheet between the lens and screen as shown in the diagram below.



Prediction 3-2: Continuing to use exactly the same sequence of pulses down the fiber (B pulse, R pulse, G pulse, (R+G+B) pulse), what sequence of colors and shapes do you think will now be observed on the screen?

Question 3-3: What sequence of colors and shapes do you actually observe on the screen?

Question 3-4: What effect does the red cellophane sheet have on the image sequence? Why does this happen? What function does the cellophane sheet perform?

Comment: The optical fiber is combining the information pulses from the R, G and B sources together down one transmission line. This process of combining many input information streams into one output stream is called *multiplexing*.

If "1" represents "light pulse" and "0" represents "no light pulse", then the information sent down the different channels for the sequence of pulses used in previous activities is:

BLUE channel	1001 1001 1001 etc
RED channel	0101 0101 0101 etc
GREEN channel	0011 0011 0011 etc

The red filter allows us to separate out the information on the red channel from that on the other two (green or blue) channels. That is, only the RED channel 0101 0101 0101 reaches the screen when the red filter is in place. We could replace the red filter with a green or blue one and separate out the information streams for these other colors.

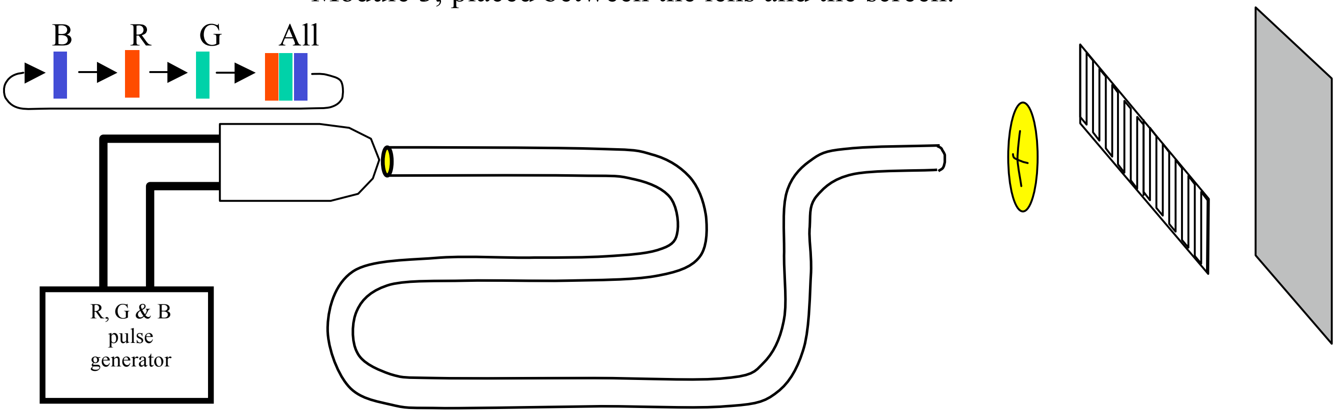
Question 3-5: Would the use of filters (as described above) allow us to increase the information carrying capacity of our optical fiber?

Question 3-6: What could we do to increase the information carrying capacity of our optical fiber by a factor of three?

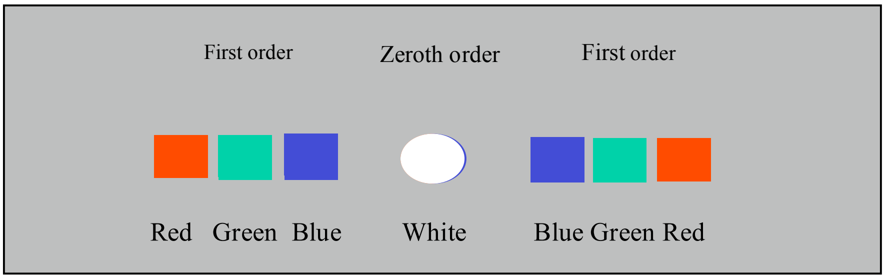
Activity 3-2: Using a diffraction grating to retrieve the information

There are two devices that you can use to spread out (or disperse) the light from the output of the optical fiber into separate R, G and B spots on the screen—a *prism* or a *diffraction grating*. This would allow us to see all the information contained in the red, green and blue pulse streams *simultaneously*.

We will use a diffraction grating, similar to the one you observed in Module 3, placed between the lens and the screen.



If a white light pulse were being transmitted the pattern on the screen would look like the following:



Question 3-7: Explain why the pattern for a white light pulse would look like this. Consider both the position and shape of the various colored patterns.

Prediction 3-3: What sequence of colors and shapes would be observed on the screen for the same sequence of pulses used in the previous activity: Blue pulse, then Red pulse, then Green pulse, then combined (R+G+B) pulse? Sketch below, next to the name of each pulse its position relative to the center of the screen.

Time Sequence ↓		Prediction
	B pulse	
	R pulse	
	G pulse	
	RGB pulse	

1. Now replace the red filter (from the previous activity) with the diffraction grating, and position the grating so that a clear focused image is obtained on the screen.
2. Sketch the sequence of colors and shapes observed on the screen.

Time Sequence ↓		Observation
	B pulse	
	R pulse	
	G pulse	
	RGB pulse	

Question 3-8: In terms of your observations in Module 3, try to explain why in the first order diffraction pattern, the blue spot is closest to the center of the screen, and the red spot is furthest from the center.

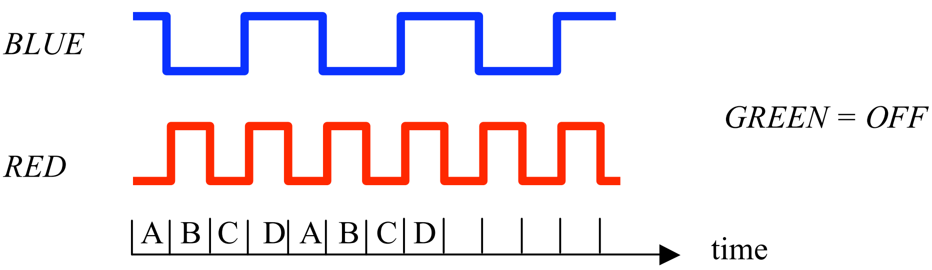
Question 3-9: Why are the zeroth order spots circular but the first order spots non-circular?

Activity 3-3: Wavelength division multiplexing using a diffraction grating

With the grating, we are now able to send different pulse sequences on different color (RGB) channels, carrying independent information. This technique is called *Wavelength Division Multiplexing (WDM)*.

Question 3-10: Does WDM increase the information carrying capacity of the optical fiber? Why or why not?

Prediction 3-4: What would you observe on the screen if the following blue and red pulse sequences were sent down the fiber simultaneously:



Time Sequence ↓	Interval	Prediction
	A	
	B	
	C	
	D	

1. Again press the push button on the microcontroller ***once only***. (This means that this is the **second** time the button has been pushed since the device was turned on). This will activate the microcontroller to generate the required Red-Blue LED sequence shown above.
2. Sketch below the sequence of colors and shapes observed on the screen.

Time Sequence ↓	Interval A B C D	Observation

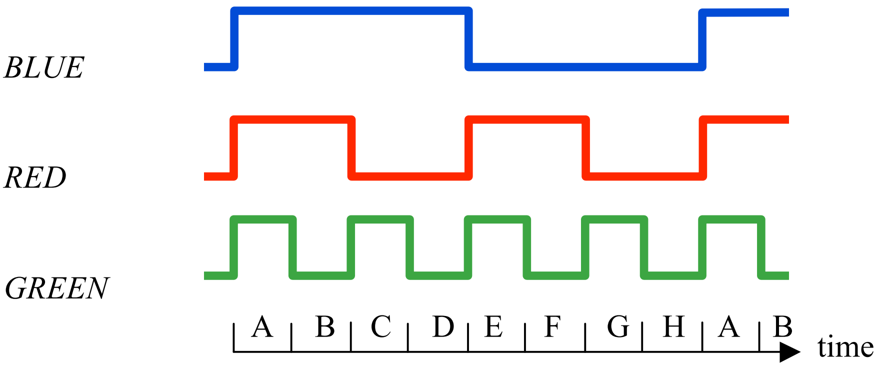
Question 3-11: As well as red and blue, a new color is also observed. What is this color? How is it generated?

Question 3-12: What happens when we add Green and Red? What color results from this addition? (Check this with the next observation.)

3. Again press the push button on the microcontroller ***once only***. (This means that this is the **third** time the button has been pushed since the device was turned on). This will activate the microcontroller to generate a Green-Red sequence that will allow you to observe the addition of these two colors. **Note:** What happens here is that you get the same sequence as shown in Prediction 3-4 except that the blue signal is switched with the green signal.

Time Sequence ↓	Interval A B C D	Observation

Prediction 3-5: What would you observe on the screen if the following red, green and blue pulse sequences were sent down the fiber:



Time Sequence ↓	Interval	Prediction
	A	
	B	
	C	
	D	
	E	
	F	
	G	
	H	

4. Again press the push button on the microcontroller ***once only***. (This means that this is the **fourth** time the button has been pushed since the device was turned on). This will activate the required sequence shown above.
5. Sketch the sequence of colors and shapes observed on the screen.

Time Sequence ↓	Interval	Observation
	A	
	B	
	C	
	D	
	E	
	F	
	G	
	H	

Question 3-13: As well as the primary colors red, green and blue, you also observe additive colors magenta (R+B) and yellow (G+R). What is the third additive color observed? How is it generated?

Activity 3-4: Audio demonstration of WDM

In this demonstration, two separate digital audio codes are sent down the fiber via WDM (one signal is sent in blue light and the other is sent in red light.) The diffraction grating is used to separate out these two signals at the receiver.

When the phototransistor-based audio amplifier is moved from the blue to the red spot, the audio tone changes accordingly.

1. Again press the push button on the microcontroller ***once only***. (This means that this is the **fifth** time the button has been pushed since the device was turned on). This will activate the microcontroller to switch the RED signal off and on at a fast rate, and the BLUE signal on and off at a fast but different rate.

2. Replace the Mylar sheet with the phototransistor detector and audio amplifier system. This system converts the blue and red high frequency light pulses into two distinct audio tones.

Question 3-14: What do you hear as the phototransistor is moved from the first order red diffraction region to the first order blue diffraction region? Explain why you observe this change as you move the detector from one region to the other.

Teachers' Guide for Module 6: Wavelength Division Multiplexing

TEACHERS' GUIDE FOR MODULE 6: WAVELENGTH DIVISION MULTIPLEXING

General Introduction

In order to maximize the amount of information an optical fiber communication system can carry, it is necessary to send information along a fiber in a number of different channels simultaneously. One way of achieving this is *Wavelength Division Multiplexing (WDM)*. A simplified model of WDM is explored in this Module.

Module 6 Apparatus and Supplies List

- Red-Green-Blue LED (known as a white light LED or WLED) and microcontroller driver
- 1 meter of cladded plastic fiber (2 mm outside cladding diameter, 1.96 mm core diameter)
- 4.5 volt (3xAA) battery pack for microcontroller power supply
- Plastic lens (focal length about 25 mm, diameter 25 mm)
- Sheet of Mylar film (used as viewing screen)
- Plastic WLED to optical fiber coupler*
- WLED/microcontroller driver holder*
- Optical fiber holder*
- Lens holder (with variable height adjustment)*
- Red filter (cellophane sheet)
- 25 mm x 25 mm piece of diffraction grating
- Diffraction grating holder*
- Phototransistor holder*
- Phototransistor audio amplifier similar to the one developed in Module 5

* These items may be available locally, or will need to be fabricated. There are many different options. The photos in this guide show some examples.

Equipment Notes

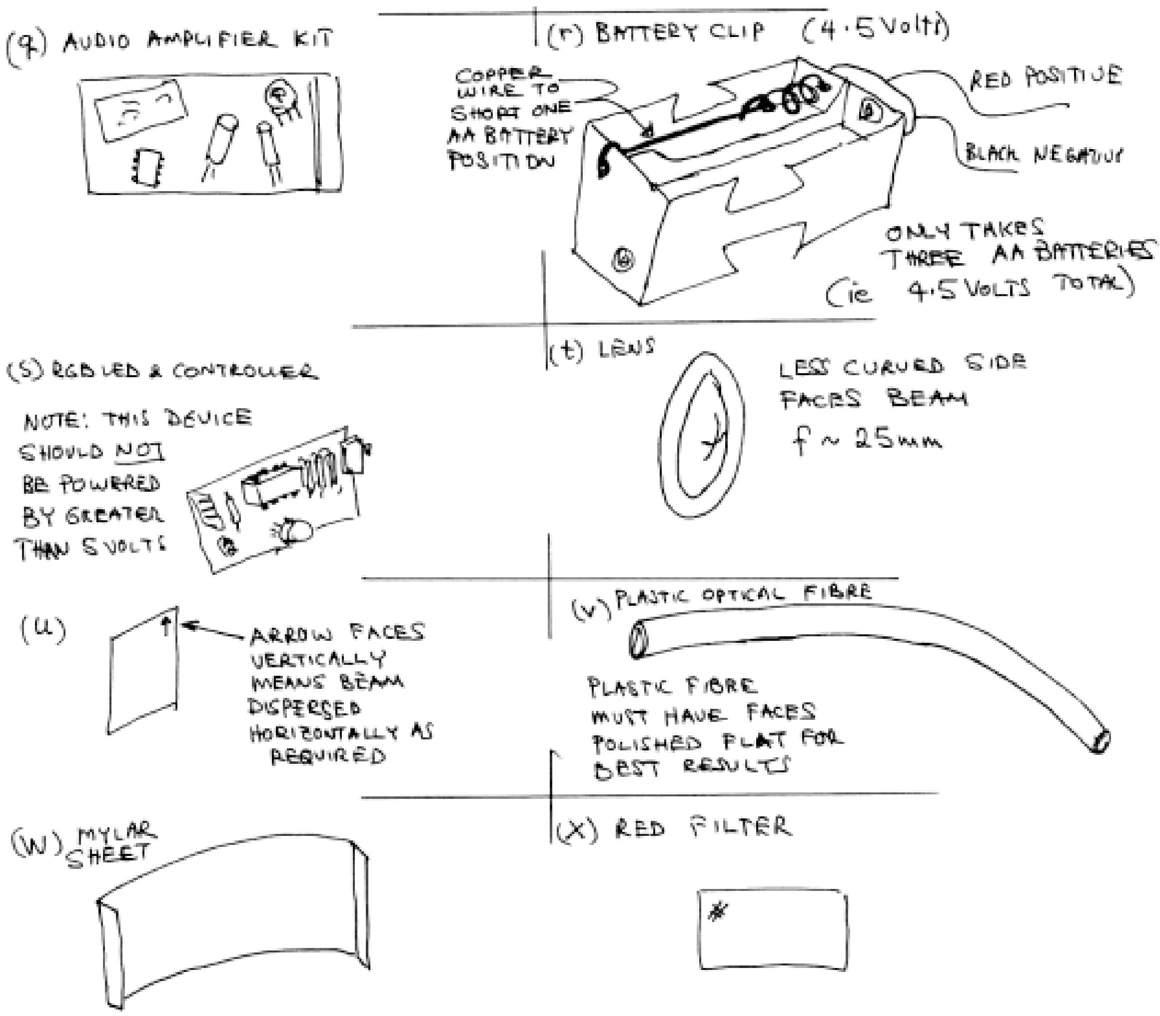
Further background detail concerning the apparatus used for this WDM activity can be found in the two references at the end of this teacher's guide.

The following table lists information on these items, along with possible suppliers.

Item	Supplier	Part Number	Approx. Cost (USD)	Web reference
Audio amplifier 0.5 W kit	Dick Smith Electronics, (Australia) or similar supplier	K5604	$4.50	www.dse.com.au/cgi-bin/dse.storefront

Battery holders (4XAA)	Dick Smith	S6124	$1.15	as above
Phototransistor	Electus Distribution (Australia)	ZD1950	$0.75	www.electusdistribution.com.au/
RGB WLED	LEDsales (Australia)	RGB 5mm 4-pin LEDs	$0.95	www.ledsales.com.au/
PICAXE08M Microcontroller	Revolution Education Ltd (UK)	AXE007M	$3.50	www.rev-ed.co.uk/picaxe/
Plastic optical fiber (CK-80; 0.080” diameter)	Industrial Fiber optics (USA)	IF-C-U2000	$2.50/m	www.i-fiberoptics.com/
Plastic diffraction grating film 1000 lines/mm	Rainbow Symphony Inc. (USA)	01504	$2.50 for 6”x12” sheet	www.rainbowsymphony.com

Sketches of components



Battery pack: A standard 4xAA battery holder can be used in this activity, where a copper wire is utilized to short one of four series AA battery positions. Hence the battery holder connects only three AA batteries in series to give a total voltage of 4.5 volts which is sufficient to power the microcontroller. *Note that 4 AA batteries in series would exceed the maximum voltage allowed for the microcontroller.*

Holders: The simple optical mount for holding the microcontroller printed circuit board is convenient though not essential. Any simple apparatus that holds the device steady at approximately the correct height is sufficient.

The simple optical mounts for holding the optical fiber and diffraction grating sheet are also convenient but not essential. Any simple apparatus that holds these devices steady at approximately the correct height is sufficient. The viewing screen is simply a piece of Mylar sheet bent into the required shape. Grease-proof wrapping paper or white matt-finish cardboard would also be suitable. The WLED to optical fiber coupler is a piece of plastic rod with a 2 mm hole drilled right through it. The optical fiber is a snug (close) fit in one end of the hole. The other end of the hole is enlarged so that the WLED is a snug fit in it. Alternatively the fiber could be attached to the WLED via some adhesive tape, "bluetak" or soft wax. The mount for the lens must allow some vertical movement for fine adjustment of the final image position. In this particular case, a small plastic rod, which is a snug fit into a hole drilled into the wooden base, has been used. Alternatively a piece of "bluetak" or soft wax could be used to hold the lens.

INVESTIGATION 1: PRELIMINARY CONSIDERATIONS

Investigation 1 Apparatus and Supplies List

No apparatus or supplies are needed.

Activity 1-1: Pulse spread

Question 1-1: The light traveling along ray (a) traverses the length of the fiber in the shortest time, because the index of refraction is the same for either path and the straight path (a) is shorter than the zig-zag path (b).

Question 1-2: Depending on which path the waves (and hence their associated rays) traverse, they will be shifted in time when they reach the other end of the fiber. Therefore a sharp rectangular pulse will tend to get wider and Gaussian shaped (i.e., broaden out in time) when it reaches the other end of the fiber.

Question 1-3: More information can be transmitted if it is coded into more pulses with narrower widths that are closer together. The narrower the pulses, the more can be transmitted in a given time interval and hence the more information can be transmitted in that interval

Question 1-4: As the spacing between narrow pulses gets smaller, there comes a point when the pulse broadening will cause significant overlap of pulses. At this point it will be impossible to distinguish whether a "1" or "0" is being transmitted. This will limit the rate of data transmission.

Activity 1-2: Behavior of water waves on a calm pond

Question 1-5: When two crests come together, they add together constructively and give a larger crest. This is just constructive interference as observed in Module 3. When a crest and a trough come together, they subtract from each other (interfere destructively), and give zero displacement of the water surface.

Question 1-6: Once the waves have passed through one another, and reach a region where they no longer overlap, they have the same appearance as if they had not come together at all. This is apparent in the photos.

Activity 1-3: Wave behavior of light

Question 1-7: The streams of water affect each other even beyond the intersection point. Molecules of water crashing into each other mess up (or scatter) both streams.

Question 1-8: At A, the color would be red, the same as if the beams had not intersected. At B the color would be green, the same as if the beams had not intersected. At C, where the two beams overlap, the color would be the mixture of red and green which is yellow.

Question 1-9: Beyond the interaction region, the two beams have no effect on each other, as we would expect for waves. Each is the same as if they had never intersected.

INVESTIGATION 2: EXPLORING A WDM SYSTEM

Investigation 2 Apparatus and Supplies List

- Red-Green-Blue LED (known as a white light LED or WLED) and microcontroller driver
- 1 meter of cladded plastic fiber (2 mm outside cladding diameter, 1.96 mm core diameter).
- 4.5 volt (3xAA) battery pack for microcontroller power supply
- Plastic lens (focal length about 25 mm, diameter 25 mm)
- Sheet of Mylar film (used as viewing screen)
- Plastic WLED to optical fiber coupler
- WLED/microcontroller driver holder
- Optical fiber holder
- Lens holder (with variable height adjustment)

Activity 2-1: Exploring the Red-Green-Blue (RGB) LED

WARNING: the voltage used to power the microcontroller driver in this activity should never exceed 5.5 volts, as this will permanently damage the device. Reversing the polarity of the supply voltage has a similar effect.

Figure TG6-1 (a) and (b) are photographs of the suggested configuration of the battery-powered microcontroller with the RGB WLED.

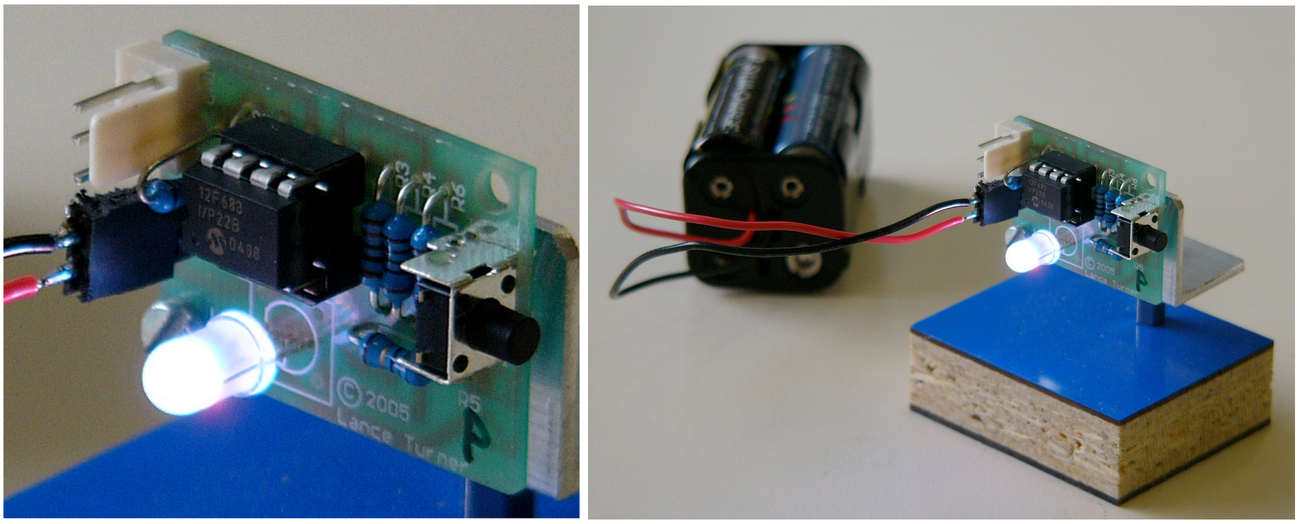
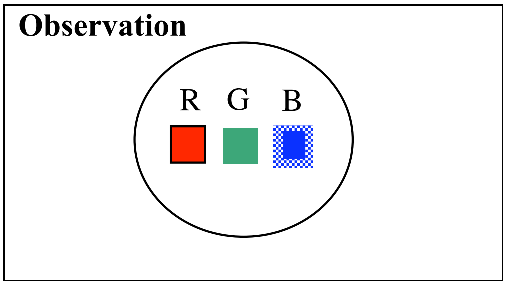


Figure TG6-1: (a) PICAXE08M microcontroller with RGB WLED mounted on circuit board, and (b) battery pack connected to microcontroller and WLED.

A typical observation of the image of the RGB LED on the screen through the lens is shown on the right.



Question 2-1: Three separate sources of light (Red, Green and Blue) can be seen in the image.

Question 2-2: The three colored sources are not equally sharp. The RED source is the sharpest, the BLUE source is the least sharp. The reason is that tiny particles in the cloudy plastic dome over the LED light sources scatters the blue end of the spectrum more than the red end.

Question 2-3: The RED, GREEN and BLUE light from the three color sources inside the WLED enter the eye, adding together to give white light.

Activity 2-2: Sending RGB LED light down an optical fiber

Figure TG6-2 is a photograph of the setup with the coupler attached to the RGB LED, while Figure TG6-3 is a photograph of the entire setup.

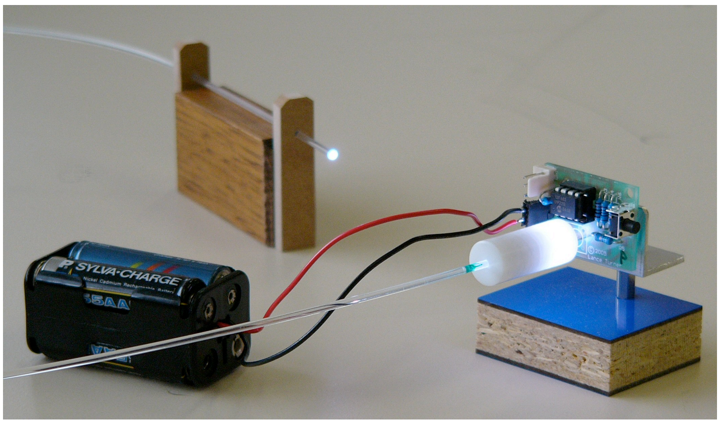


Figure TG6-2: photograph of the setup with the coupler attached to the RGB LED. White light can be seen at the exit end of the fiber.

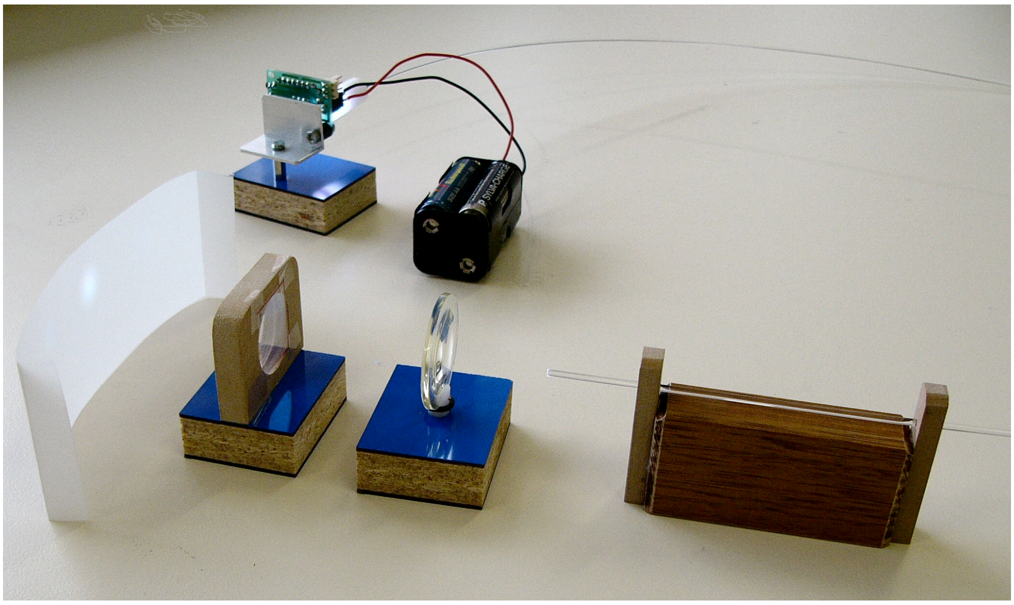
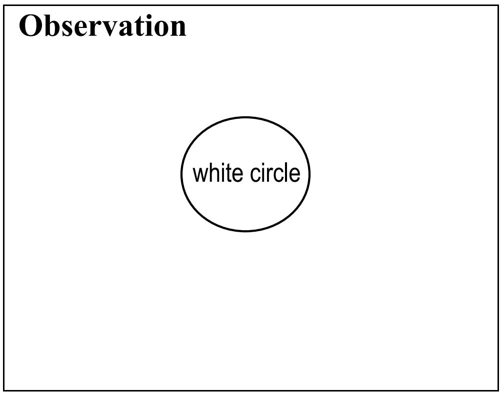


Figure TG6-3: Photograph of the entire setup for exploring information transmission along an optical fiber.



A typical observation of the image of the end of the optical fiber on the screen is shown on the right. The image is circular and white.

Question 2-4: The light rays from the three RED, GREEN and BLUE sources in the WLED are scrambled as they are channeled through the fiber. As the light is completely mixed the image is white.

Question 2-5: The light rays from each source in the WLED can travel down the fiber along many different paths, so the light rays exiting the fiber are completely scrambled. Although the fiber transmits virtually all the incident light (via total internal reflection) it cannot transmit the spatial information of the original three light sources.

INVESTIGATION 3: SENDING INFORMATION DOWN AN OPTICAL FIBER

The order of colors of the light pulses emitted by the LED is controlled by the microcontroller. The sequence is chosen by the number of times the button on the microcontroller is pressed. The directions assume that the transmitter is powered up and not turned off during these activities. The number of pushes on the microcontroller switch is cumulative from the first one.

Activity 3-1: Sending a sequence of color pulses down the fiber

Question 3-1: The sequence of colors observed is blue, followed by red, followed by green, followed by white, then the sequence repeats. The shapes of the images are all circular (i.e., same shape as the fiber endface).

Question 3-2: The white occurs because red, green and blue occur simultaneously and add to give white.

Question 3-3: The sequence of pulses is NO PULSE, RED PULSE, NO PULSE, RED PULSE, repeated over and over again.

Question 3-4: The red cellophane (filter) only allows the red light to pass through completely. Therefore, it lets the red pulses reach the screen, and also lets red light from the pulses with all three colors (white pulses) reach the screen.

Question 3-5: Using filters separates out the pulses by color, but does not allow the receiver to detect them separately. While the red filter is in place, the information on the blue and green pulses is lost. While the blue filter is in place, the information on the red and green pulses is lost, etc. Therefore, it is still not possible to detect independent information along the different colored pulse channels.

Question 3-6: In order to send information independently along each of the three different colored pulse channels, it is necessary to separate the three different colors in space, so they fall on three separate receivers (phototransistors). If we can do this, then the information carrying capacity will be multiplied by three.

Activity 3-2: Using a diffraction grating to retrieve the information

The diffraction grating is now mounted on the holder, between the lens and the screen, with its lines vertical. (See Figure TG6-3.) Figure TG6-4 shows the diffraction pattern on the screen. Both the zeroth order (center) white spot (W) and first order colored spots (R,G and B) can now be observed.

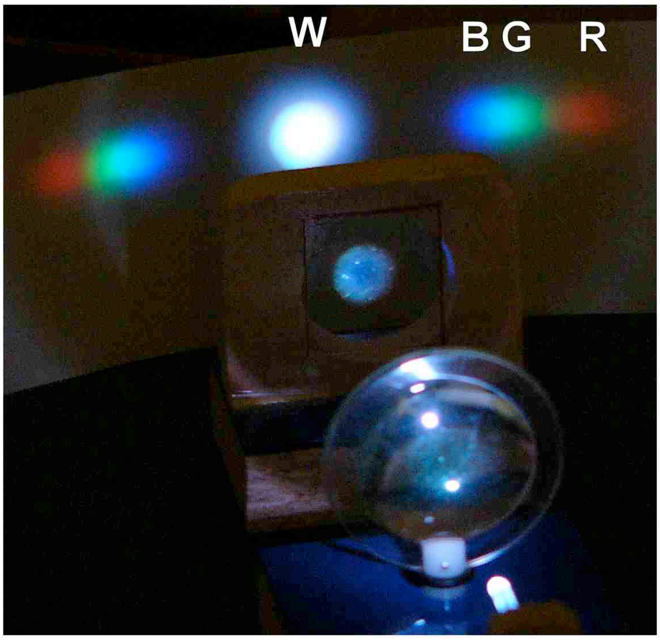
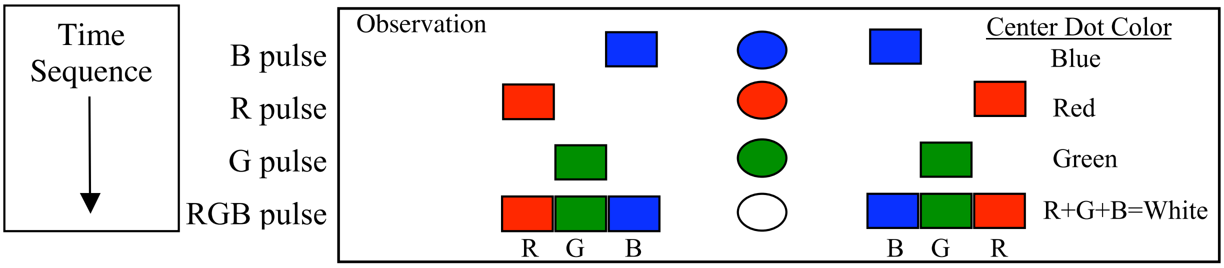


Figure TG6-4: Photograph of the diffraction pattern from the image of the optical fiber endface.

Question 3-7: In the zeroth order of a diffraction grating, all colors (wavelengths) are superimposed on top of each other. Thus the zeroth order of white light from the LED (i.e., RGB light) is white, and at the center. The dispersion of the diffraction grating in first order is larger, the longer the wavelength. Therefore blue light—with the shortest wavelength, is displaced the least from the center, and red light—with the longest wavelength, is displaced the most. This is shown in Figure TG6-4.



Question 3-8: The answer above for the previous question gives a good qualitative answer. For a more quantitative answer recall that for "diffraction from a grating" we have the following relationship:

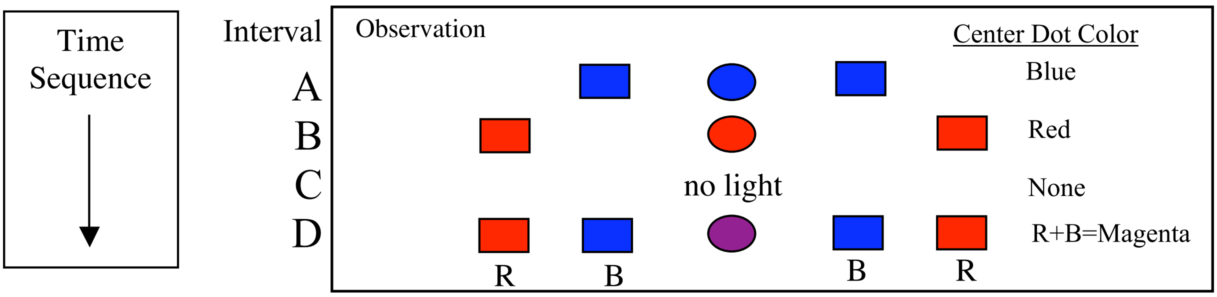
$$\sin\theta = m\lambda/d$$

where m represents the order of the diffraction, d represents the line spacing of the grating, λ represents the wavelength of the light and θ represents the angle through which the light is diffracted. Hence the angle at which the light is diffracted increases with increasing wavelength, as observed.

Question 3-9: The zeroth-order pattern represents light that is not diffracted so we expect the image to be a faithful representation of the circular endface of the fiber. The first-order pattern represents light that has been diffracted by a one-dimensional periodic grating. Hence we expect the light to be spread out in the horizontal direction, and hence the light pattern has an approximately rectangular shape.

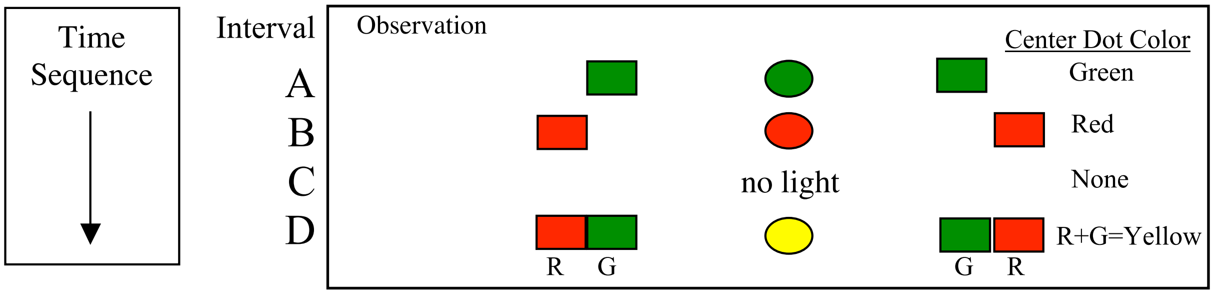
Activity 3-3: Wavelength division multiplexing using a diffraction grating

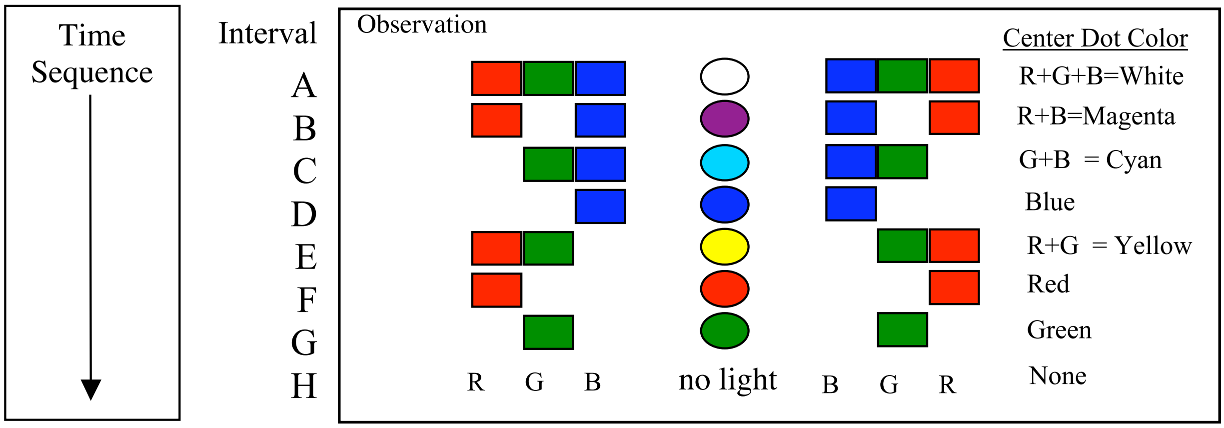
Question 3-10: WDM increases the information carrying capacity of the optical fiber because the three color channels are detected separately in space. Information can be sent independently with each of the three colors, and, therefore, three times as much information can be sent along the same fiber.



Question 3-11: The new color is magenta (purple). It is generated by the mixing of blue and red, and seen in the zeroth-order spot. The blue and red are separated, though, in first order.

Question 3-12: Green and red added together gives yellow. This is what is observed when both the green and red LED channels are on, without the blue.





Question 3-13: The third additive color is cyan (sky blue). It is generated from the addition of blue and green.

Activity 3-4: Audio Demonstration of WDM

The phototransistor detector and audio amplifier system used here is the same as used in Module 5. Some form of audio amplification must be used, as the light signals are not very intense. Certainly the phototransistor-audio transformer-speaker system does not have enough amplification for this experiment. The phototransistor will be moved physically from the red light stream to the blue in the first order of the diffraction grating. In a real optical transmission system, there would be three phototransistors positioned for the three different colored light streams. TG6-5 shows a typical setup.

Question 3-14: The WLED/microcontroller system now generates red and blue signals which have very different audio frequency modulations (tones). As the phototransistor is moved from the red first-order diffraction spot to the blue spot a different tone is heard, indicating that the different colors transmitted simultaneously down the same optical fiber are carrying different information streams.

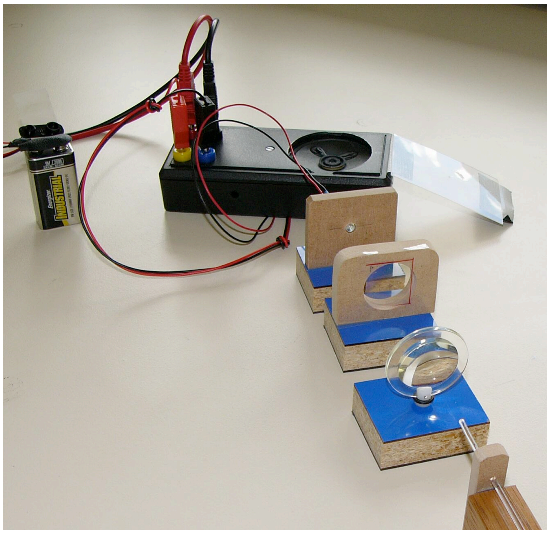


Figure TG6-5: Photograph of the system used for audio multiplexing. The mylar screen is replaced with a phototransistor and audio amplifier.

REFERENCES

1. A.P. Mazzolini and P.J. Cadusch, “A simple low-cost demonstration of wavelength division multiplexing,” *Am. J. Phys.* **74**, 2006.
2. Lance Turner,"Building This tiny microcontoller-driven lightshow,” can be downloaded from: www.ledsales.com.au/kits/8_pin_2.pdf. (Paper explains how the microcontroller-driven WLED operates.)

Action Research and the *Light and Optics Conceptual Evaluation*

ACTION RESEARCH AND THE *LIGHT AND OPTICS CONCEPTUAL EVALUATION*

Conceptual Evaluations

Why should you consider reforming your teaching methods, and implementing active learning strategies like the materials in this Training Manual? A sample of U.S. students' results on the *Light and Optics Conceptual Evaluation (LOCE)* has been presented in the Introduction. But, perhaps you are not convinced that your students share the same difficulties in understanding optics concepts. The best way for you to explore this question is to conduct action research in your own classes. In fact, the interest in Physics Education Research (PER) over the last 15-20 years has been driven by a desire to explore how well students are learning physics in secondary and college physics courses, and to develop new teaching and learning strategies based on this knowledge. This ever-broadening interest in the developing world has been largely driven by the development of easy to use learning assessments that have enabled faculty to conduct action research. The first two of these, the *Force Concept Inventory (FCI)*[1] and *Force and Motion Conceptual Evaluation (FMCE)*[2] were developed in the early 1990's to assess knowledge of Newtonian mechanics. Many physics faculty have administered one or the other of these assessments, only to be shocked by their students' poor results, even at the end of the introductory physics course. Even more shocking are the observations that even many students who earn high grades in an introductory physics course cannot answer basic, simple questions on Newtonian mechanics correctly. And furthermore, these discouraging results appear to be independent of how excellent the lecturer for the course is.[1-2]

Since the development of the *FCI* and *FMCE*, learning assessments have been developed in most other areas of physics. As part of the ALOP project, a *Light and Optics Conceptual Evaluation (LOCE)* is under development. The latest version of the *LOCE* is included at the end of this section.

One reason why physics faculty have been willing to accept the results on these learning assessments is that the tests are research-based. That is, the answers on these multiple-choice tests, both correct and incorrect are based on the common models students use for physical systems. These models are known from previous extensive research based on student interviews and student answers to more open-ended questions. The development and use of multiple-choice assessments has been dictated by several considerations: 1) difficulties in convincing physics professors and high school teachers to give up course time for testing, 2) a desire to make evaluation less subjective, and 3) the effort involved in analyzing the large samples of data from many institutions that is necessary to have a wide-ranging impact on the physics community. Although a more complete understanding of student learning can be gained by an open-ended questioning process, research-based multiple-choice assessments have allowed the gathering of sufficient data at many different institutions to counter the common response that "my students do not have these difficulties you describe." Because all answers— including distractors—are based on research, almost all answers—right or wrong—help to evaluate student models, and contribute to the design of additional research and new curricular materials.

These are specially designed multiple-choice tests, since even when students give the correct answer, that does not necessarily mean they understand why the answer is correct. For this reason, there are several other important design features of the *LOCE* and other conceptual assessment tests:

1. Distractors are carefully chosen so that it is possible to learn what students really think.

2. Because student answers are often context dependent, sets of questions are asked in a number of different contexts and results from these sets are compared with each other.
3. Because the available choices in the questions were derived from students' answers to free response questions and from student interviews, students almost always find an answer that they are satisfied with.
4. Guessing correctly is very difficult because many of the questions require students to choose an answer from six or more choices.

The correlations among questions have been examined and individual questions have been correlated with more open-ended student answers. The use of easily administered and robust multiple-choice tests has allowed tracking of changes in student models and separation of the effects of various curricular changes on student learning.

Conducting Action Research on Optics in Your Classroom

The *LOCE* and an answer sheet follow these introductory remarks in a form that can be copied and administered to your classes. If you decide to conduct action research on optics in your course(s), the answer key and a spreadsheet for evaluating the results may be obtained from David Sokoloff (sokoloff@uoregon.edu) or Minella Alarcon at UNESCO/Paris, (m.alarcon@unesco.org). It is suggested that the *LOCE*, or parts of it, be given to your students as a pre and post-test. Because students must think on each question, and evaluate a number of choices for their answers, the entire test could take as much as an hour to administer.

There are a number of important considerations in the way you administer the test if you want the research results to be valid.

1. The pre-test should be given at the beginning of the course, or at least before the topics are covered at all in class.
2. In order to maximize your sample size, it is best to require students to take the pre-test. One way of doing this is to give some course credit for attending the day of the pre-test. (In that way, you do not need to tell the students in advance that they will have a test that day.) However, the pre-test should never be graded in any way. (Maximizing attendance at the pre-test is not a small problem. If a small number of students miss the pre-test, and a different small number of students miss the post-test, this can affect your sample size significantly.
3. It is important to motivate the students to do the best that they can on the pre-test. Otherwise they may not take it seriously. The best way to motivate students is to tell them that you are assessing their initial knowledge of the topics you will cover in order to help determine what the emphasis of your teaching should be. Ask them to do the best they can, based on their knowledge of optics from before they entered the course.
4. It is best to not say that you are conducting research on the class, or to tell the students this is an experiment. Many students react negatively to being part of an experiment.
5. Do not distribute, post or go over the answers to the questions before the post-test.
6. Students should not be told that there will be a post-test. Telling them that will only raise their anxiety, and increase their desire to see the answers.
7. While it is important to try to effectively teach the material covered on the pre-test, you should not “teach to the test.” The distinction here can be subtle. Your

instruction should be addressed at teaching the basic concepts (e.g., with the materials in this Training Manual). We want students to understand concepts and be able to apply this understanding. However, do not discuss with the students the exact questions, framed exactly as they are framed on the test. It is interesting to note, however, that research has shown that teaching to the test in this way is actually ineffective in improving student results on these learning assessments. Simply telling students the answers—unless they can be memorized—does not help students to apply the correct models to probing questions.

8. Research has shown that the identical test, with the same order of choices, may be administered as both the pre and post-test. In many research studies in which passive, traditional instruction was the only intervention between the pre and post-test, the learning gains were very small. These small gains might be attributed to the ineffective passive instruction, or they might be attributed to taking the same test a second time. Since they are so small, they are not of significance. (This, of course, assumes that (5) above is followed!)
9. The post-test may be give as part of a formal exam (graded). The advantages to this are that students are required to attend, motivated to do well, and no extra class time is needed for the post-test. Furthermore, by putting conceptual questions on your exams, you are demonstrating that you are serious about students learning concepts.
10. It is also possible to administer the post-test as a separate test. In this case you must once again motivate students to attend (perhaps by again requiring attendance and giving credit), and motivate them to do their best (e.g., by challenging them to do better than on the pre-test). It is best to motivate the students to attend without telling them in advance that there will be a post-test.
11. Do not expect improvement on questions that cover topics not taught in the course, or taught in a traditional, passive manner. If you want to assess the effectiveness of the materials in this manual, or other classroom materials, it is best to only include in your research study the questions on the topics covered by the materials you used.
12. Your sample group should be a matched set of students who took both the pre and post-test, and who participated in the learning strategies you are studying.
13. Results on these conceptual assessments are usually quoted as normalized gain (or figure of merit). This is defined as[3]

$$g = \frac{\textit{(class post - test average - class pre - test average)}}{\textit{(100 - class pre - test average)}} \textit{ x 100\%}$$

Defined in this way, g tells the average fraction of the *possible* improvement that was achieved by the class.

Conducting action research in your courses puts you in touch with what your students are actually learning. It is a valuable exercise even before you attempt anything new. Such research results can be strong motivational factors for making significant changes in instruction. They can often be effective in getting the resources (equipment, funding, etc.) to help bring about these changes. More information on action research can be found in Chapter 5 of *Teaching Physics with the Physics Suite*.[3]

References

1 D. Hestenes, M. Wells and G. Swackhamer, "Force Concept Inventory," *Phys. Teach.* **30**,

141-158 (1992).

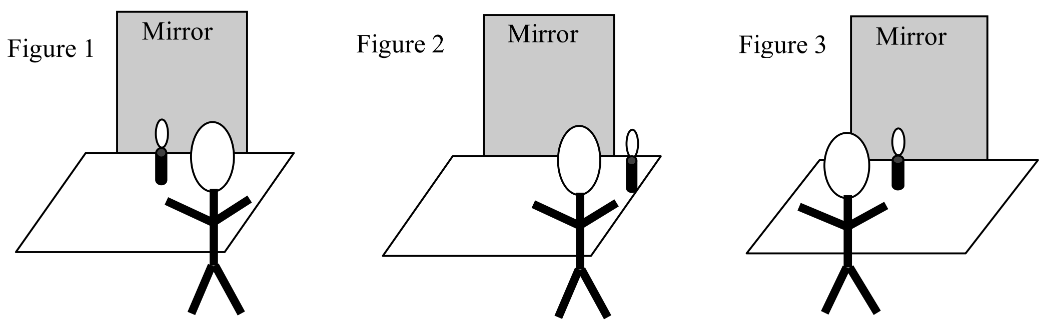
2 R.K. Thornton and D.R. Sokoloff, “Assessing student learning of Newton’s laws: The Force and Motion Conceptual Evaluation,” *Am. J. Phys.* **66**, 338-352 (1998).

3 E.F. Redish, *Teaching Physics with the Physics Suite,* (Hoboken, NJ, Wiley, 2004).

Light and Optics Conceptual Evaluation

DIRECTIONS: Answer questions 1-50 on the answer sheet by writing in the letter corresponding to the best choice. Also include brief written answers for Questions 28, 30, 31, and 34, and sketch your answer for Question 51, all on the answer sheet.

Questions 1-5 refer to the three figures below of a candle on a table in front of a plane (flat) mirror.



1. In Figure 1, a person is standing in front of the table looking into the mirror. The image of the candle is located **A**. In front of the mirror, **B**. On the surface of the mirror, **C**. Behind the mirror, **D**. There is no image of the candle, **E**. Not enough information is given.

2. The height of the image of the candle is **A**. Larger than the candle, **B**. Smaller than the candle, **C**. The same size as the candle, **D.** There is no image of the candle, **E**. Not enough information is given.

3. In Figure 2, the candle is moved to the new location shown. The image of the candle as seen by the person is now **A**. To the left of where it was before, **B**. To the right of where it was before, **C**. In the same location as before, **D**. No image is seen by the person, **E**. Not enough information is given.

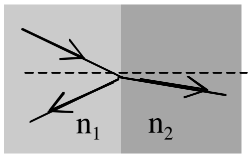
4. In Figure 3, the candle is moved back to its original location, and the person moves to the left to the new position shown. Compared to Figure 1, the location of the image of the candle is now **A**. To the left of where it was in Figure 1, **B**. To the right of where it was in Figure 1, **C**. In the same location as in Figure 1, **D**. There is no image of the candle, **E**. Not enough information is given.

5. The distance of the candle from the mirror is doubled. The height of the image of the candle is now **A**. Smaller than before, **B**. The same size as before, **C**. Larger than before, **D**. There is no image of the candle, **E**. Not enough information is given.

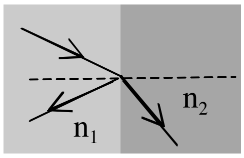
Questions 6-10 refer to a very narrow beam of light (for example, a laser beam) that can be represented by a single ray. The light is initially traveling from left to right in a transparent medium of index of refraction n_1, and incident on a second transparent medium of index of refraction n_2. The reflected and refracted rays are as shown in the diagrams below. (If either is missing, it means there is no reflected or no refracted ray.) Answer each of the questions below with one of the following choices, **A** through **F**.

A. Only if $n_2 > n_1$,	**D.** Can happen with **A** or **C**.
B. Only if $n_2 = n_1$,	**E.** Never possible.
C. Only if $n_2 < n_1$,	**F.** Always possible regardless of the relative sizes of the indexes of refraction.

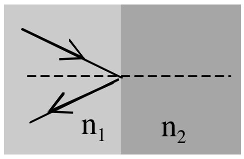
6. For which condition **A** through **F** could the rays be as shown in the figure?



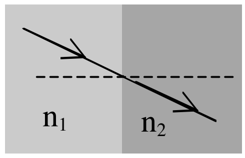
7. For which condition **A** through **F** could the rays be as shown in the figure?



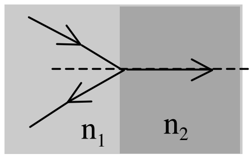
8. For which condition **A** through **F** could the rays be as shown in the figure?



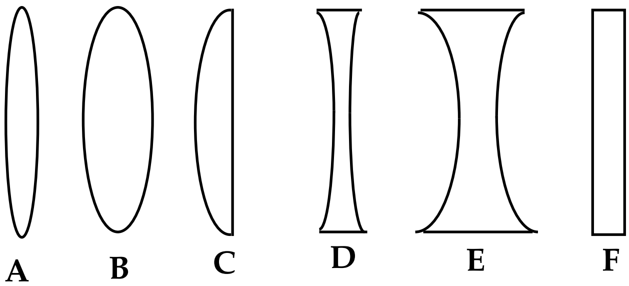
9. For which condition **A** through **F** could the rays be as shown in the figure?



10. For which condition **A** through **F** could the rays be as shown in the figure?



Questions 11-17 refer to the six lenses **A - F** shown on the right. All of the lenses are made of the same glass. Choose the lens that best answers each question below. There is only one correct answer for each question. If you think that none of the lenses is correct, choose answer **G**.

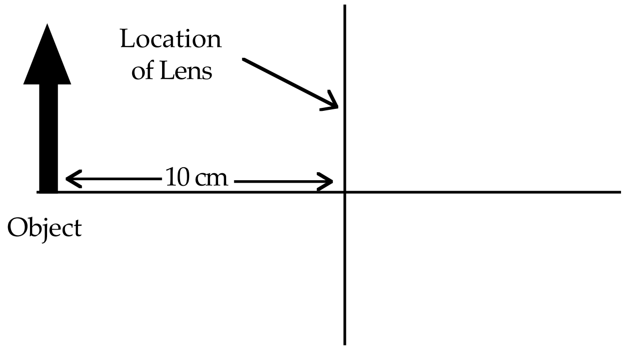


11. Which lens has the shortest positive focal length?
12. Light from the sun is focused by the lens to form a sharp spot on a piece of paper. Which lens must be held closest to the paper?
13. Which lens has the shortest negative focal length?
14. Which lens used as a magnifier would produce the largest magnification?

15. Which lens would give the largest correction to a person who is nearsighted? (Nearsighted people have distant objects focused in front of their retina. They can clearly see objects that are close to their eyes, but objects far away are blurred.)
16. Which lens has no focusing effect on light incident upon it?
17. Which lens would give the largest correction to a person who is farsighted? (Farsighted people have close objects focused behind their retina. They can clearly see objects that are far away from to their eyes, but objects that are close are blurred.)

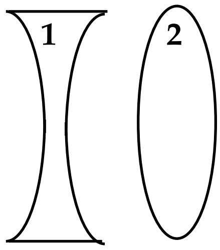
Questions 18-22 refer to an object that is positioned 10 cm in front of a lens. The lens is either shaped like lens 1 or 2 shown below.

For each of the possible lenses in Questions 18-22, choose the one statement **A - D** that correctly describes the image formed by that lens. If none of the descriptions is correct, choose answer **E**.



A. The image is upright and larger than the object.
B. The image is upright and smaller than the object.
C. The image is inverted and larger than the object.
D. The image is inverted and smaller than the object.
E. None of the descriptions of the lens is correct.

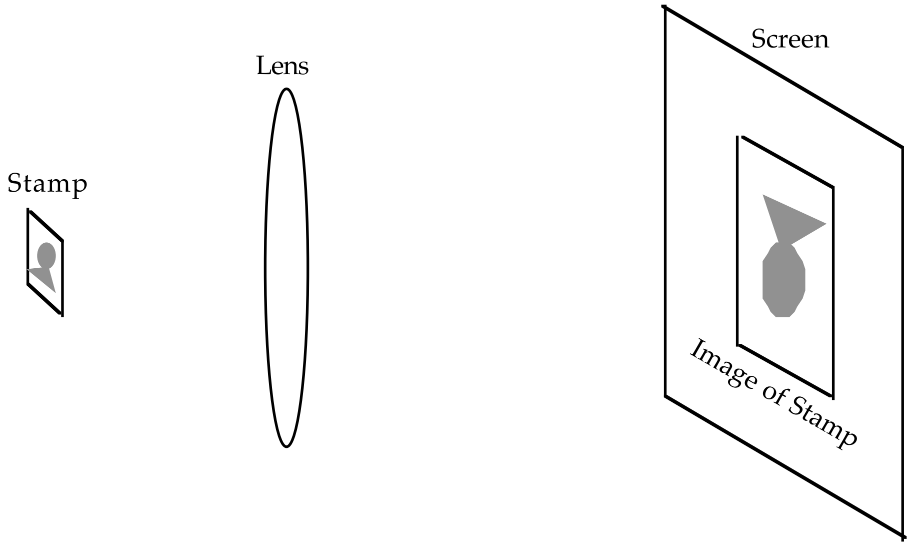
18. The lens looks like 1 with focal length 4 cm.
19. The lens looks like 2 with focal length 8 cm.
20. The lens looks like 2 with focal length 16 cm.
21. The lens looks like 2 with focal length 4 cm.
22. The lens looks like 1 with focal length 16 cm.



23. For a person with myopia (nearsightedness) the cornea and lens focus light from distant objects in front of the retina, causing blurred vision of distant objects. To correct myopia, the person should wear glasses (spectacles) with lenses that have which of the following prescriptions? **A.** A spherical lens with positive power, **B.** A spherical lens with negative power, **C.** A cylindrical lens with positive power, **D.** A cylindrical lens with negative power, **E.** A combination of spherical and cylindrical lenses, **F.** None of the above.
24. For a person with hyperopia (farsightedness) the cornea and lens focus light from near objects behind the retina, causing blurred vision of near objects. To correct hyperopia, the person should wear glasses (spectacles) with lenses that have which of the following prescriptions? **A.** A spherical lens with positive power, **B.** A spherical lens with negative power, **C.** A cylindrical lens with positive power, **D.** A cylindrical lens with negative power, **E.** A combination of spherical and cylindrical lenses, **F.** None of the above.

Questions 25-34 refer to the picture on the right. A stamp is placed to the left of the lens, and its image is formed on a screen to the right of the lens, as shown.

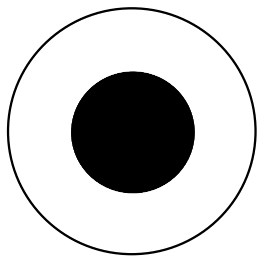
Choose the correct answer for each question.



25. Suppose the stamp is temporarily replaced (only for this question) with one twice as large. Which is true? **A.** The image will be whole but half as large, **B.** The image will disappear, **C.** The image will be dimmer, **D**. Only half of the image will be seen, **E**. The image will be twice as large, **F**. The image will be unchanged, **G**. None of these is correct.
26. Suppose the lens is temporarily replaced (only for this question) by a lens with half the diameter but with the same focal length. Which is true? **A.** Half of the image will disappear, **B.** The image will be whole but half as large, **C.** The image will disappear, **D.** The image will be dimmer, **E**. The image will be unchanged, **F**. None of these is correct.
27. Suppose that the screen is temporarily moved further away (only for this question) with the positions of the stamp and lens unchanged. Which is true? **A.** The image will be blurry, **B.** The image will be sharp but slightly larger, **C.** The image will be sharp but slightly smaller, **D**. The image will be unchanged, **E**. The image will disappear, **F**. None of these is correct.
28. Suppose the top half of the lens is temporarily covered by a piece of paper (only for this question) so that no light can pass through this portion. Which is true? **A.** Half of the image will disappear, **B.** The image will be whole but half as large, **C.** The image will disappear, **D.** The image will be dimmer, **E.** The image will appear on the paper, **F**. The image will be unchanged, **G**. None of these is correct.

Briefly explain your answer:

29. Suppose a circular piece of black tape temporarily covers the center of the lens (only for this question) as shown on the right. Which is true? **A**. The center of the image will disappear, **B**. The image will be whole but smaller, **C**. The image will disappear, **D**. The image will be dimmer, **E**. The image will appear on the tape, **F**. The image will be unchanged, **G**. None of these is correct.



30. Suppose half of the stamp is temporarily covered by a piece of paper (only for this question). What happens to the image of the stamp? **A.** Half of the image will disappear, **B.** The image will be whole but half as large, **C.** The image will disappear, **D.** The image will be dimmer, **E.** The image will appear on the paper, **F**. The image will be unchanged, **G**. None of these is correct.

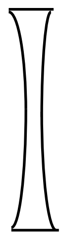
Briefly explain your answer:

31. Suppose that the stamp is temporarily moved slightly further away from the lens (only for this question). The screen is also moved to find the sharpest possible image. Which is true? **A.** The image is now larger than before, **B.** The image is now upright, **C.** The image is now the same size as before, **D.** The image is now smaller than before, **E.** None of these is correct.

Briefly explain your answer:

32. Suppose that the stamp is temporarily moved closer to the lens (only for this question). The screen is also moved to find the sharpest possible image. Which is true? **A.** The image is now smaller than before, **B.** The image is now the same size as before, **C.** If the object is moved close enough to the lens, it is possible that no sharp image will be found on the screen, **D.** The image on the screen will become upright, **E.** None of these is correct.

33. Suppose that the lens is temporarily replaced by one that looks like the one on the right (only for this question). The screen is moved to find the sharpest possible image. Which is true? **A.** The image will be larger, **B.** The image will be the same size, **C.** The image will be smaller, **D**. It will not be possible to find a sharp image on the screen, **E.** The image will be upright, **F.** None of these is correct.



34. Suppose the lens is removed. Which is true? **A.** The image will still be there but a little blurred, **B.** The image will be whole but smaller, **C.** The image will disappear, **D.** The image will be dimmer, **E**. The image will be unchanged, **F**. None of these is correct.

Briefly explain your answer:

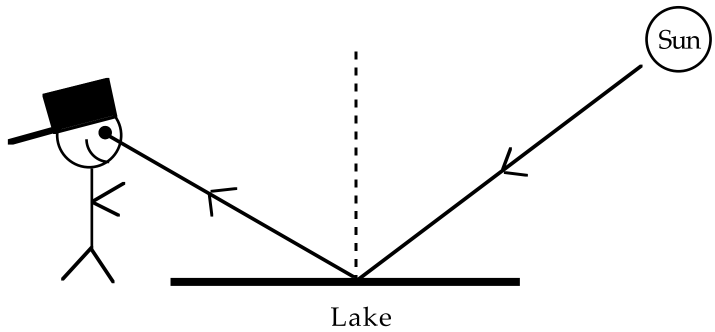
Questions 35-37 refer to a *perfect* polarizing filter that by definition passes 100% of light incident on it that is polarized along its axis, and 0% of light that is polarized perpendicular to its axis.

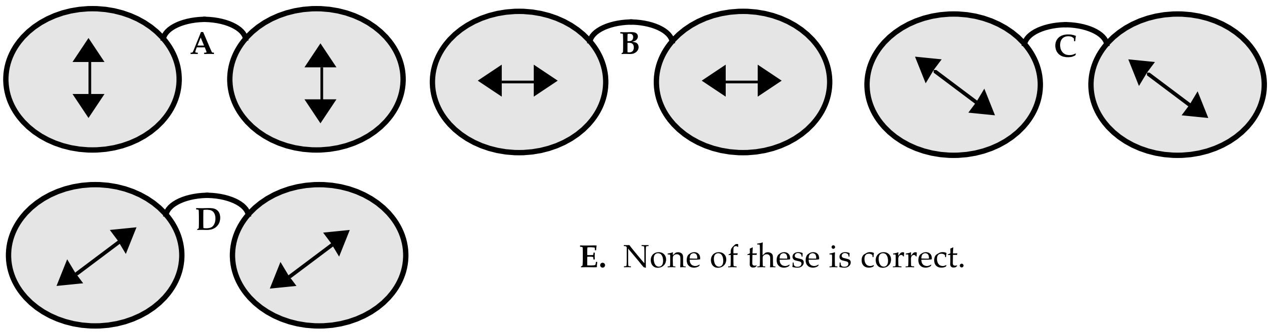
35. The light beam from a particular light source is un-polarized. The light is incident on the *perfect* polarizing filter with intensity 100. The transmitted intensity is **A**. 100, **B**. 75, **C**. 50, **D**. 25, **E**. 0, **F.** None of these is correct.

36. The light beam from a particular light source is linearly polarized with its axis of polarization *vertical*. The light is incident on the *perfect* polarizing filter with intensity 100. If the axis of the polarizing filter is vertical, the transmitted intensity is **A**. 100, **B**. 75, **C**. 50, **D**. 25, **E**. 0, **F.** None of these is correct.

37. Now the *perfect* polarizing filter in question (36) is rotated so that its axis is *horizontal*. The transmitted intensity is now **A**. 100, **B**. 75, **C**. 50, **D**. 25, **E**. 0, **F.** None of these is correct.

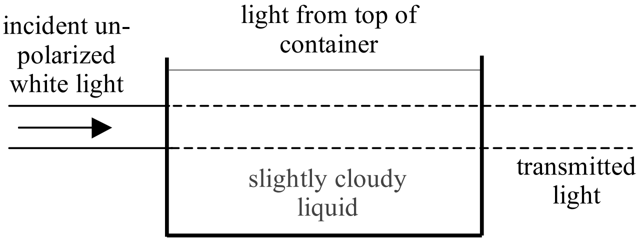
38. Light from the sun can reflect into your eyes off the surface of a lake, as shown on the right. If you wear Polaroid sunglasses (made with polarizing filters), this reflection can be reduced. Which of the pictures below shows the correct direction of the axis of the polarizing filters in the sunglasses for the sunglasses to be most effective in blocking out the unwanted reflection from the lake?





E. None of these is correct.

Questions 39-42 refer to the experimental setup on the right. White, un-polarized light is incident from the left on a container filled with water made *slightly* cloudy by a small amount of dissolved milk. Observations are made on any light transmitted out through the other end of the container, and any light coming out from the top of the container.



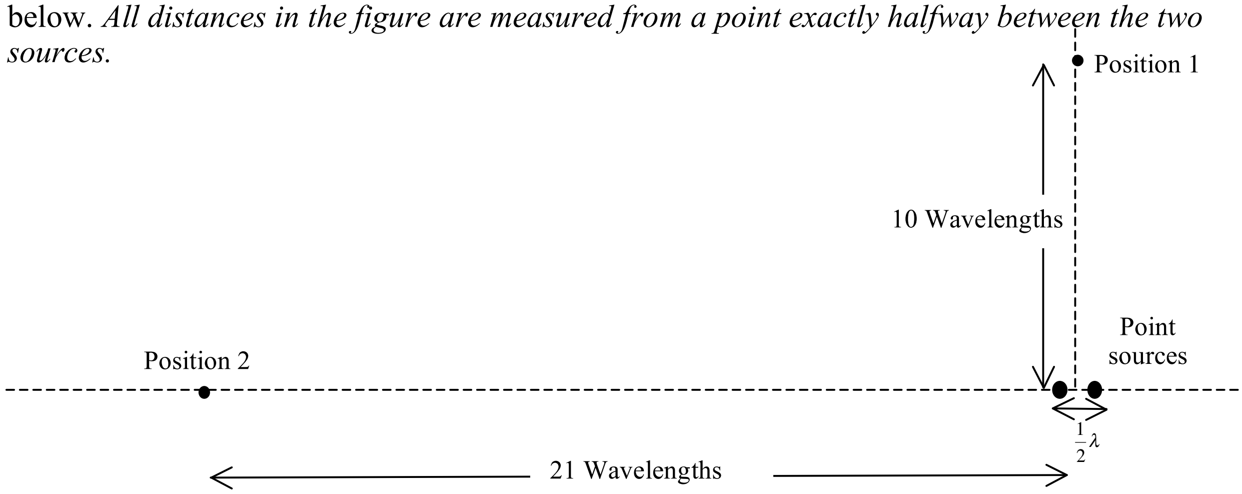
39. The transmitted light is **A.** White, **B.** Yellowish, **C.** Bluish, **D.** Greenish, **E.** There is no transmitted light, **F.** None of these is correct.

40. The light coming out from the top of the container is **A.** White, **B.** Yellowish, **C.** Bluish, **D.** Greenish, **E.** There is no light coming out from the top of the container, **F.** None of these is correct.

41. The transmitted light is **A.** Polarized with its axis vertical, **B.** Polarized with its axis horizontal, **C.** Polarized with its axis diagonal, **D.** Un-polarized, **E.** There is no transmitted light, **F.** None of these is correct.

42. The light coming out from the top of the container is **A.** Polarized with its axis vertical, **B.** Polarized with its axis horizontal, **C.** Polarized with its axis diagonal, **D.** Un-polarized, **E.** There is no light coming out from the top of the container, **F.** None of these is correct.

Questions 43-46 refer to two monochromatic point sources of light that are coherent with each other. They are separated by a distance equal to 1/2 wavelength, as shown in the figure below. *All distances in the figure are measured from a point exactly halfway between the two sources.*



43. When waves from the two point sources reach Position 1, which is directly above the halfway point between the two sources, they are **A**. Exactly in phase with each other, **B**. Exactly out of phase with each other, **C**. Neither in phase nor out of phase with each other, **D**. Not enough information is given.

44. Position 1 is a point of **A**. Completely constructive interference, **B**. Completely destructive interference, **C**. Neither constructive nor destructive interference, **D**. Not enough information is given.

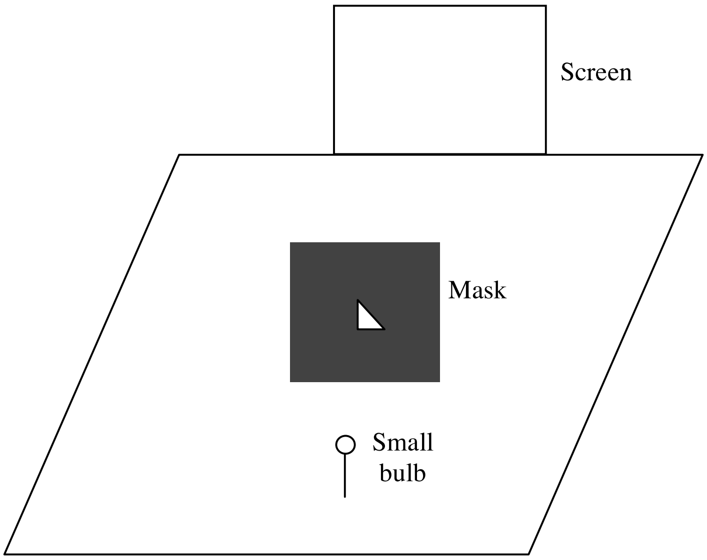
45. When waves from the two point sources reach Position 2, they are **A**. Exactly in phase with each other, **B**. Exactly out of phase with each other, **C**. Neither in phase nor out of phase with each other, **D**. Not enough information is given.

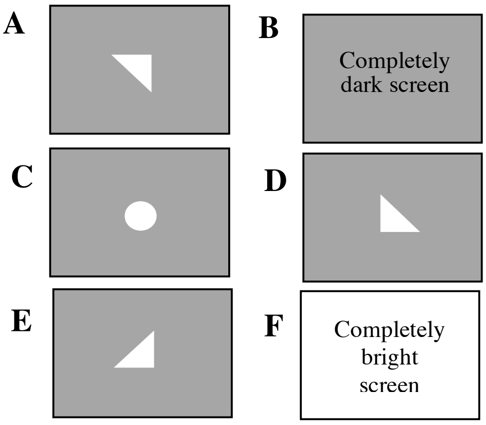
46. Position 2 is a point of **A**. Completely constructive interference, **B**. Completely destructive interference, **C**. Neither constructive nor destructive interference, **D**. Not enough information is given.

47. Laser light of wavelength 633 nm is directed on a narrow slit. A wide bright band of light and narrower bands on either side are seen on a screen a long distance away. Which of the following changes would result in a narrower bright central band on the screen? **A.** The slit is wider, **B.** The screen is further away, **C.** The slit is narrower, **D.** The wavelength is longer, **E.** The laser is closer to the slit, **F.** None of these will make the central band narrower, **G.** Not enough information is given.

48. Laser light of wavelength 633 nm is directed on two narrow parallel slits that have a very small separation. A series of bright and dark bands are seen on a screen a long distance away. Which of the following changes would result in a wider separation between two adjacent bands on the screen? **A.** The two slits are wider, **B.** The two slits are closer together, **C.** The two slits are narrower, **D.** The two slits are further apart, **E.** The screen is closer, **F.** The wavelength is shorter, **G.** The laser is further from the slits, **H.** None of these will make the separation wider, **J.** Not enough information is given.

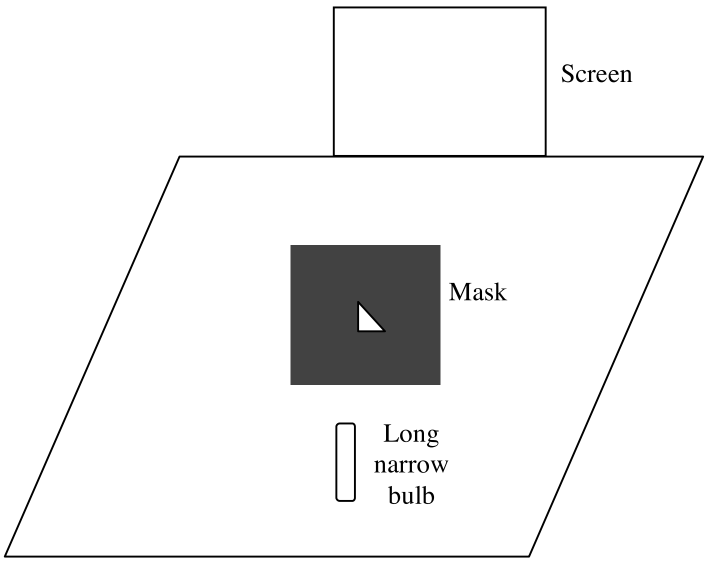
49. A very small light bulb is held in front of a screen. A mask with a triangular hole larger than the bulb is placed between the bulb and the screen as shown on the right. Which picture below correctly shows what will appear on the screen?

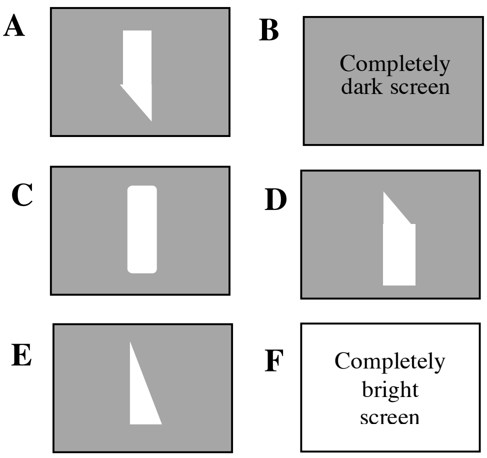




G. None of the above is correct.

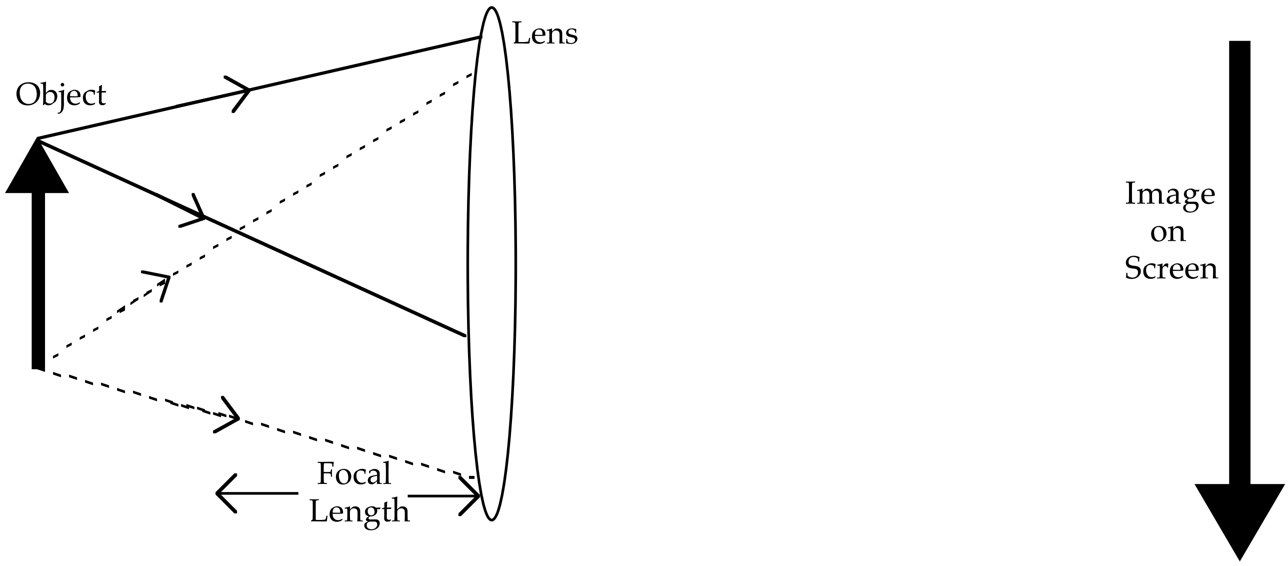
50. The bulb in (49) is replaced by a long, narrow bulb. Which picture below correctly shows what will appear on the screen?





G. None of the above is correct.

51. In the picture below, the object is to the left of the lens, at a distance from the lens that is larger than the focal length. The image is formed on a screen to the right of the lens as shown. Four rays of light are shown leaving points on the object. Continue those four rays through the lens to the screen.



Light and Optics Conceptual Evaluation Answer Sheet

Name____Class______________________________

_____1.	_____7.	____13.	____19.	____25.	____31.	____37.	____43.	____49.
_____2.	_____8.	____14.	____20.	____26.	____32.	____38.	____44.	____50.
_____3.	_____9.	____15.	____21.	____27.	____33.	____39.	____45.	
_____4.	____10.	____16.	____22.	____28.	____34.	____40.	____46.	
_____5.	____11.	____17.	____23.	____29.	____35.	____41.	____47.	
_____6.	____12.	____18.	____24.	____30.	____36.	____42.	____48.	

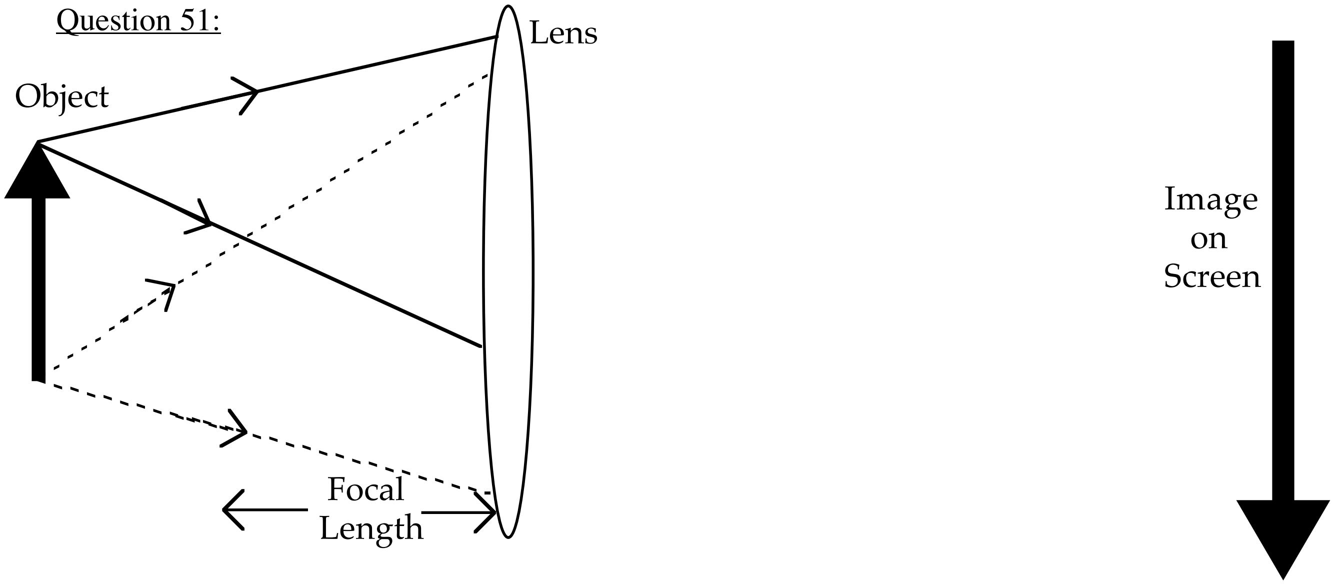
Briefly explain your answer to Question 28:

Briefly explain your answer to Question 30:

Briefly explain your answer to Question 31:

Briefly explain your answer to Question 34:

Question 51:



Errata Sheet for *Active Learning in Optics and Photonics Training Manual*
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Page 70 **Question 6-10:** . . . It is dimmer for the same reason as in Question **6**-9.

Page 83 **Objective 3:** . . . basic optics of ***myopia**,* and *hyperopia* . . .

Page 105 **Question 4-1:** . . . lens is curved along one axis and **has no curvature** along a perpendicular axis.

Page 109 **Objective 1:** . . . waves from coherent sources **are superposed on** each other (interference).

Page 109 **Apparatus and Supplies:** 3 sets of double slits . . . **or 2 razor blades and a mirror with coated side exposed**

Page 110 **Note**: . . . spacing between **two successive** peaks is called the *wavelength*.

Page 111 **Activity 1-2:** Fill the two **eyedroppers** with water, and hold them **about 3 cm** apart . . .

Page 115 **Top**: Case 2: Addition of two waves out of phase with each **other**.

Page 115 **Question 1-18:** Use this **wave** model to explain . . .

Page 115 **Question 1-20:** Based on your answer**s** to Question**s 1-15 to 1-19**.

Page 117 **Prediction 2-2:** (**Hint**: Use your answer to Question 1-**20** to help make this prediction.)

Page 118 **Apparatus and Supplies:** Remove **microscope objective**

Page 122 **Question 4-7:** Suppose you used a **small** square hole . . .

Page 122 **Question 4-8:** Suppose you used a **small** round hole . . .

Page 125 **Module 3 Apparatus and Supplies List**: 3 sets of double slits . . . **or 2 razor blades and a mirror with coated side exposed**

Page 126 **Investigation 1 Apparatus and Supplies List:** 3 sets of double slits . . . **or 2 razor blades and a mirror with coated side exposed**

Page 126 **Double and single slits:** The slit mask below should be photocopied onto **transparency** film, and then the **single** slits can be used in these activities.

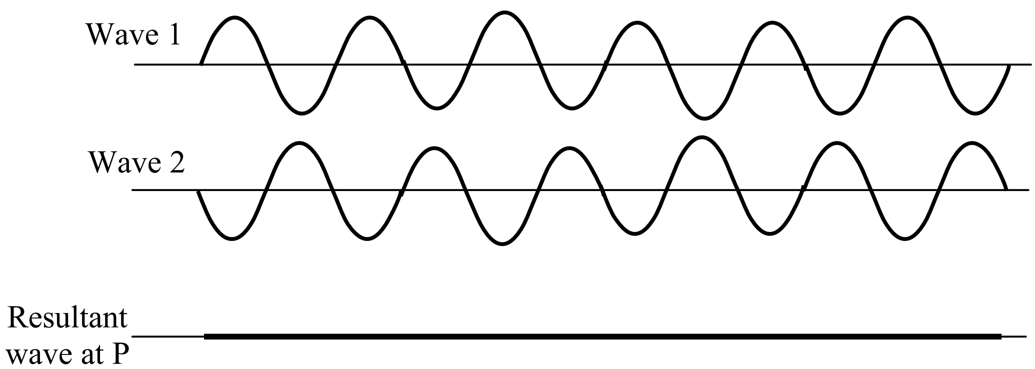
Also add the following paragraph after the "Homemade single slit" paragraph:

Homemade double slits: Double slits can be made in a similar way with two razor blades and a mirror. Put one or more pieces of paper between the two blades, and tape them together. Then carefully use the blades and the ruler to cut parallel slits into the mirror coating. The spacing between the slits may be varied by putting more pieces of paper between the blades.

Page 128 **Question 1-7:** The bright **fringes appear wider than the dark ones**.

Page 129 **Paste the following over the original Case 2:**

Case 2: Addition of two waves out phase with each other



Page 131 **Activity 2-2:** . . . there will be rainbows at the locations of each of the dots in Figure TG3-5 **(except for the center one).**

Page 133 **Question 4-1:** . . . This fringe pattern is **similar to the one produced by the wire in Activity 3-1.**

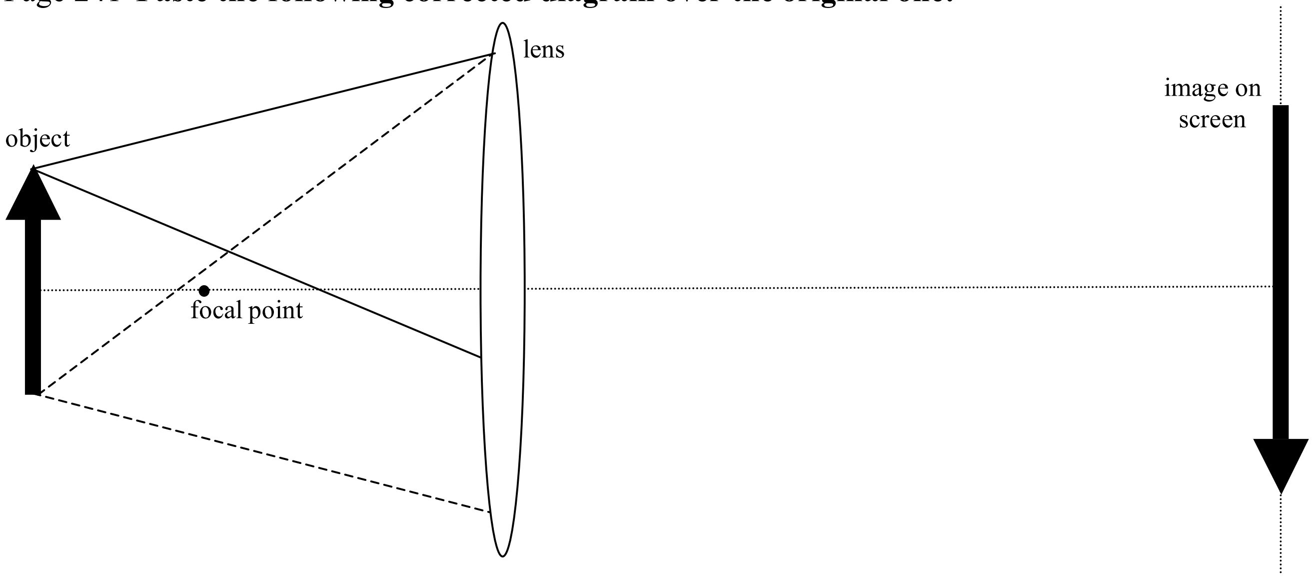
Page 164 **Alternate Setups:** A filter is place**d** underneath each container.

Page 236 **27:** Suppose that the screen is temporarily moved **slightly** further away . . .

Page 238 **Questions 39-42:** . . . light is incident on a **transparent** container filled with water . . .

Page 240 **49:** A very small light bulb is held in front of a **large** screen. . .

Page 241 **Paste the following corrected diagram over the original one:**



Page 243 **Paste the following corrected diagram over the original one:**