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ABSTRACT

Designed to address the major conceptual problems associated with light and vision, appearances of surfaces, and color, this module can be used with high school students or college nonscience majors including those in elementary education. It is one in a series developed by the project "Overcoming Critical Barriers to Learning in Nonmajors' Science Courses." The materials offer guidance to teachers in diagnosing student deficiencies, in creating dissatisfaction with misconceptions, and in providing opportunities for application and practice. This module contains: (1) an introduction (specifying the critical barriers to understanding light and vision, appearances of surfaces, and color and explaining how to use the module to overcome these barriers); (2) diagnostic test and commentary (designed to be used as a pretest and/or posttest); (3) materials for lecture or discussion with commentary (consisting of a series of copy-ready masters for use as overhead transparencies and student handouts on light and color); (4) laboratory activities and commentary (including exercises on shadows, diffraction grating, and color shadows); and (5) problem sets (containing a problem set on light and vision and one on color). All instructional materials for the students are juxtaposed with instructor commentaries. (ML)

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Occasional Paper No. 92

LIGHT: A TEACHING MODULE

Janet Eaton, Theresa H. Sheldon,
and Charles W. Anderson

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Associate Directors: Judith E. Lanier and Richard S. Prawat

Editorial Staff
Editor: Sandra Gross
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Abstract

This module is one in a series developed by the project Overcoming Critical Barriers to Learning in Nonmajors' Science courses, Charles W. Anderson, Director. Each module is self-contained and addresses a specific topic in the physical and biological sciences: respiration and photosynthesis, evolution by natural selection, heat and temperature, and ecology. The modules are appropriate for use with high school students or college nonscience majors including those in elementary education. This module on light is arranged with materials for the instructor on one page juxtaposed by those for the students. A short introductory essay describes the major conceptual problems found among students: light and vision, appearance of surfaces, and color. It then explains how activities in the unit are intended to help students overcome these problems. A diagnostic test, which could be used as a pretest, posttest, or both, is designed to reveal important student misconceptions and provides notes for the instructor to intepret student responses. A set of student handouts and masters for overhead transparencies includes notes for the instructor about conceptual problems each was designed to address. Laboratory activities on shadows, diffraction grating, and color shadows are followed by problem sets on light and vision and color designed to address specific student misconceptions. The first three parts can be used independently or in combination with the laboratory activities and problem sets after students have learned the relevant concepts. The materials help instructors accomplish three tasks essential to overcoming critical barriers to student learning: diagnosing student deficiencies, creating dissatisfaction with misconceptions, and providing opportunity for application and practice.

About the Authors

Charles W. Anderson is director of the project Overcoming Critical Barriers to Learning in Nonmajors' Science Courses. He is a senior researcher at the Institute for Resesarch on Teaching (IRT) and an assistant professor with the Department of Teacher Education, Michigan State University. Janet F. Eaton is a former editor for the IPT. She now works for the Catherine McCauley Health Center in Ann Arbor, Michigan. Theresa H. Sheldon graduated from Michigan State University in 1985 with a degree in Elementary Education. She now teaches kindergarten and lives in Costa Mesa, California.

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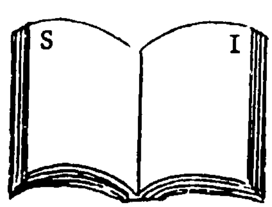

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Preface

We hope that using this module helps you gain insight into your students' understanding, and misunderstanding, of light and vision. One of its main purposes is to provide opportunities for you to learn about your students' thinking. Because of what you discover about your students' thinking, you may have to move more slowly and cover less content than you would like. That may seem like a problem, but we don't think so. It is far better to have students learn to understand a little science than to have them misunderstand a lot.

I. Introduction

How can we best help students learn about science? All science teachers ask this question in one way or another. It seems to have a sensible answer: Students will learn science if scientific content is organized and presented in a logical manner. Anyone who has ever taught science, however, knows that it's not that simple.

Students can seem amazingly stubborn in their inability to comprehend apparently simple and logical presentations. We believe there is a logical reason for that, and we think something can be done about it. Hence this module.

This module is based on extensive investigations of how students think and learn about light. We have given diagnostic tests to several hundred students (in nonmajors', college-level, science courses), both before and after instruction, and analyzed their learning. We have conducted in-depth interviews with some of those students. Several professors and laboratory instructors have field tested the materials in their classes. The result, we believe, is a set of materials that teachers can use to help their students take the first steps toward a scientific understanding of light.

Critical Concepts

This module focuses on the content that we consider most basic: visual perception of ordinary objects. In focusing on this issue, we have ignored topics that are covered in most physics courses and physics textbooks, including light emission, emission and absorption spectra, and the optics of lenses. We omitted these topics not because we consider them unimportant, but because we have found that students cannot understand them until they understand the role of the light in visual perception. This module serves as a base for instruction in these and other topics concerning light.

Based on our research, we consider an understanding of visual perception absolutely fundamental to the study of light. This understanding may seem simple, but it is certainly not trivial. It is the essential foundation on which to base a beginning study of light. Without it, even the best instruction may fall on deaf ears.

Most of the students we've worked with tend to think of visual perception much the same way medieval physicists did, even though many of them were taught beginning optics in high school. They think of seeing in terms of something (e.g., vision, sight, gaze) coming out of the eye. They think of color and light as separate things: Color is a property of objects, and light is colorless. Everyday language, statements such as "That guy's hat is blocking my line of sight" and "I want the red apple," reinforce these ways of thinking and keep students from understanding and correctly applying the instruction they receive about light.

Critical Barriers

You wouldn't expect medieval physicists to understand a lecture on the optics of lenses and eyeglasses until they had first learned a few basic, modern ideas about light: that light is a form of energy and is in constant motion, that cells in the back of people's eyes are stimulated by light, and that people see an object when light reflected off it stimulates the cells in

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their retin You might expect to have a hard time convincing medieval physicists ot these things and making them give up the idea that seeing is an active, rather than a passive, activity.

Medieval physicists' strongly held beliefs would serve as critical barriers (a term we've borrowed from David Hawkins) to their understanding of modern optics. Many of your students have strongly held beliefs--misconceptions--that are serious enough to prevent them from understanding what you teach them. This module is designed to help you break down the critical barriers that stand in the way of your instruction.

The research of others and our own research comparing the ways students and scientific experts deal with scientific problems has helped us identify both the critical barriers that make it hard for students to understand light and ways to overcome them.

We have identified three sets of critical barriers: misconceptions about light and vision, the appearance of surfaces, and color. You will note that all of these are related to perception. That's because students' misconceptions typically are based on their perceptions of the world around them. Unless scientific theories can adequately explain their perceptions, they will tend to discount and disregard the theories.

The materials in this module will help your students overcome all three sets of critical barriers.

Light and vision. "How does light help us to see objects?" We asked our students this question on a diagnostic test. Here are some of the answers we got:

It illuminates the surface to allow us to see.

Light come [sic] to our eyes and we can see the objects from that light.

Makes things brighter so our eyes can focus.

Illuminates an area so we can see it.

Many students think about vision the same way medieval physicists did, in terms of something going from their eyes to an object; and they believe their eyes can only perceive the object if it is illuminated.

Table 1 briefly presents contrasts between the most common student misconceptions (or incomplete conceptions) and the scientific conceptions.

Table 1

Light and Vision

Issue	Misconception	Scientific Conception
Nature of light	The nature of light may vary depending on the type of light or environmental conditions (beams, rays, room light, colored light, etc)	Light is electromagnetic radiation of specific wavelengths.
Function of people's eyes	People's eyes see or focus on on objects.	People's eyes detect the light that enters their pupils.
How people see the shapes of objects	People's eyes see the shape of an object. *or* Light rays that enter people's eyes carry images.	People's eyes detect the shape of an object based on the direction from which the light reflected off it comes to their their eyes.

The materials in this module are designed to help your students (a) articulate their own explanation' f what light is and how it enables seeing, (b) realize that any miscon[illegible]ons they may have are inadequate to explain what light is and how it ena[illegible] seeing, and (3) become convinced that the scientific explanation makes sense and is useful. Any additional content you wish to teach about light and vision will then be easier for your students to understand and learn.

<u>The appearance of surfaces</u>. When we asked our students to tell us what happens when light strikes a piece of wood, we got answers like these: "The light shows up on the wood." "No more traveling occurs. It just lights up the area of concentration on the side of the light." "It will not reflect. It will just put a spot of light on it." "Light appears on the wood."

These students did not ask themselves how they are able to see the wood if the light just stays on it. Even students who say we see reflected light tend to slip back into older ways of thinking when asked this question and give answers like those above. Certainly, if one shines a flashlight on a piece of wood, one will see a spot of light. Most students are satisfied with that and go no further. They need to be convinced that a satisfactory explanation of the appearance of surface requires an explicit statement of *how* people see those surfaces. Many students think an object looks the way it does because of the way it is, not because of the way it interacts with light.

Table 2 contrasts students' common misconceptions about the appearance of various surfaces with scientific conceptions.

Table 2

The Appearance of Surfaces

Issue	Misconception	Scientific Conception
Why people see dark and light colors (e.g., black, gray, and white)	Lightness and darkness are properties of objects (e.g., this book is a darker color than that one).	Lightness and darkness depend on the amount of light absorbed and reflected by an object.
Shiny vs. not-shiny surfaces	Some things are just shinier than others by their nature or shiny things reflect more light than do not-shiny things.	Shiny things (such as mirrors) reflect light coherently; things that are not shiny scatter it.
Transparent objects	Transparent objects are those that people can see through.	People see through transparent objects because light can pass through them to people's eyes.
Translucent objects	People can't really see through translucent objects, but they can see a little light through them.	Translucent objects scatter light as it passes through them.

The materials in this module are designed to help your students critically examine their own thinking about why objects appear the way they do. Students should come to realize that explanations like, "Because that's just the way they look" aren't really explanations of anything. Students should come to understand that science offers them more explicit and more complete explanations of how things work. They should also come to realize that there's more to seeing the appearance of surfaces than they may have first thought. Additional content about the interaction of light with surfaces should then make more sense to them.

Color. Misconceptions about color are among the hardest to overcome because scientific ideas about color are counterintuitive. When we ask our students what color a red pot will look under green light, they generally say it will look brown because that's the color you get when you mix red and green. One student, who we suspect represents many, wrote, "The light is not white it is just brite sic ," when asked how the white light from a flashlight can help us see the green color of a green book.

Table 3 (next page) contrasts students' common misconceptions about color with scientific conceptions.

The materials in this module are designed to help your students recognize that there is a difference between colors of pigment and colors of light, to convince them that their ideas about mixing pigments will not work for mixing colors of light. Your students should also come to realize that the primary colors, of both pigments and light, are determined by the structure of human eyes--the three types of cone cells. The materials are designed to convince your students that color is a property not of objects but of light. Once they are convinced of that (and it will probably take quite a bit of effort to convince them), any additional content you wish to teach about color will be easier for them to understand and learn.

Using This Module to Overcome Critical Barriers

For many students in a beginning physics course, the misconceptions described above are deeply ingrained. We have found that for such students *even the best explanations are not enough*. Replacing easy and familiar misconceptions with more abstract conceptions is a difficult process, requiring sustained effort on the part of the student, corrective feedback from teachers, and many opportunities for practice and application.

The materials in this module are ones that we have developed, field-tested, and found to be useful in helping students to overcome the critical barriers described above. In addition to containing lecture materials providing clear explanations of the role of light in seeing, this module includes a diagnostic test that can be used as both a pretest and a posttest, laboratory activities, and problem sets. These materials can be used either independently or in combination, and they do not need to be used in any particular order, although the laboratory activities and problem sets are designed to be done after students have read or heard explanations of the relevant concepts. The materials are useful because they help you do three things that are essential for enabling your students to overcome critical barriers:

1. Diagnose student difficulties. The diagnostic test, the laboratory activities, and the problem sets all contain questions designed to reveal how well students understand the nature of light and its role in seeing. The commentary for teachers describes specifically what each question is designed to reveal.

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Table 3

Color

Issue	Misconception	Scientific Conception
Nature of ordinary, white light	Ordinary "white" light is pure, clear, or colorless.	White light is a mixture of spectral colors.
Colored objects	Color is a property of objects (e.g., that book *is* red).	*Pigments* in objects differentially reflect and absorb the *colors* in light (and pigments are not colors).
Color vision	Our eyes see the color of an object.	The cones in our eyes are stimulated by different wavelengths of light.
Nature of primary	Primary colors are pure and all other colors are mixtures of them.	Primary colors are the wavelengths of light to which our cones are most sensitive.
Primary colors	The primary colors are red, yellow, and blue.	The primary colors of *light* (additive primaries) each stimulates one type of cone. The additive primaries are red, green, and blue. The primary colors of pigments (subtractive primaries) each absorb light that stimulates one type of cone. The subtractive primaries are magenta, yellow and cyan.

2. <u>Create dissatisfaction with naive conceptions</u>. Many students enter our course expecting to memorize facts and definitions, but we would like them to think scientifically. For those students in particular the process of conceptual change is unexpected as well as difficult. The activities in this module provide students with many opportunities to see that their present ways of explaining and predicting scientific phenomena do not work very well and to understand how their ideas need to be improved.

3. <u>Provide opportunities for practice and application</u>. The scientific conceptions described above are important because they explain many different phenomena in a satisfying way. The activities in this module help students to see the power of these conceptions by encouraging students to apply the conceptions to a variety of phenomena. Since the basic purposes of scientific theories are to explain and to predict, we feel that the questions asking students for explanations and predictions are especially important.

In short, the questions and activities in this module are designed as tools to help you, the instructor, help your students through the process of conceptual change. This module cannot substitute for your personal planning and judgment, but it can inform your plans and judgments and thus help you make them more effective.

II. Diagnostic Test and Commentary

This student test was developed and refined over the course of several terms. It can be used as a diagnostic pretest or as a posttest, and your students should be able to finish it in about 15 minutes. As a diagnostic pretest, it will enable you to (a) assess your students' background understanding of ideas critical to an understanding of light and (b) uncover some of the critical barriers to learning that your students may have.

The test, ready to be photocopied and given to your students, is on the following left-hand pages. On the right-hand pages is commentary describing the purpose of each question and some ways of interpreting student answers.

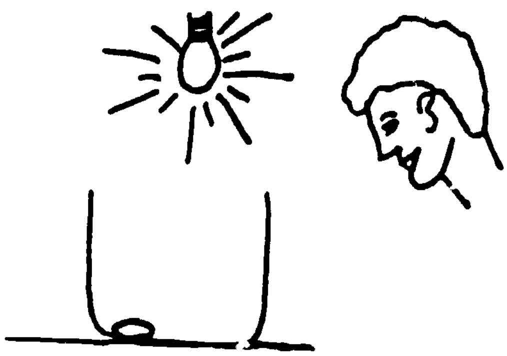
Your students' answers will probably be most revealing and useful if you assure the students their answers will not be graded and if you ask them to try to describe their thinking about each problem, even if they don't know the answer. It will be helpful to you to know what your students do not understand.

Test on Light

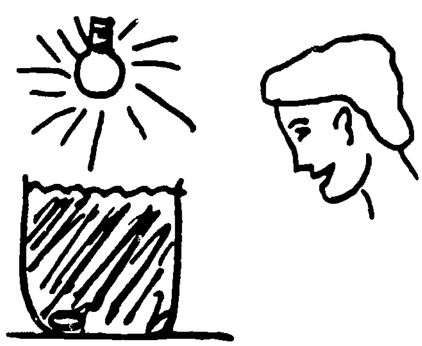
1. How does light help us to see objects?

2. In the diagram at the right, the girl sees the tree. Draw arrows to show how the light from the sun helps her to see the tree.

3.



a. John looks down into a bucket as shown. There is a penny on the bottom. John cannot see the penny. Explain why John cannot see the penny. Explain by drawing, if you like.



b. Now the bucket is filled with water. John can now see the entire penny even though he has not changed his position. The bucket is also in the same place as before. Explain why John can see the penny when the bucket has been filled with water. Explain by drawing, if you like.

Commentary

1. The most common misconception students have is that light is a condition that is necessary for seeing. Students with this misconception will have answers such as "light brightens things," or "without light you can't see." The answer we looked for states that light bounces off objects, enters our eyes and stimulates cells in our retinas. Therefore, we see light rather than the objects. About half of the students in our college nonmajors' courses understand this before the unit begins. The other half either don't know or just think that light illuminates things so our eyes can see them. They tend to think of sight as something that travels to objects.

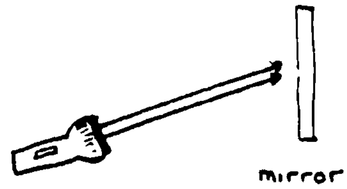
2. Students who believe the most common misconception about light and seeing tend to just draw arrows from the sun to the tree. This seems reasonable to them because it is what their senses tell them is happening. Some students take this a step further and draw lines from the girl's eyes to the tree to represent sight. Students who understand the role of light in seeing will draw arrows from the sun to the tree and from the tree to the girl's eyes.

3a. Most students think it is obvious why John cannot see the penny: The side of the bucket is in his way. This statement, however, is not specific about what the side of the bucket is blocking. Many students think of the bucket as blocking John's "line of sight," rather than blocking light that is reflected from the penny. Even students who answer Question 1 correctly, implying that they understand the role of light in visual perception, may slip back into thinking in terms of the common misconception when asked anything about light but a straightforward, textbook style question about how we see. Some students have learned to answer textbook questions, but are unable to apply the concepts because they don't really understand them.

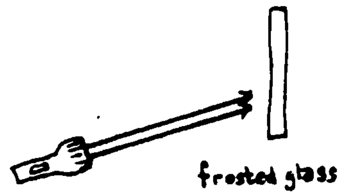
3b. Before the unit begins, most students seem to think that the water allows light to be reflected off the penny or that the water "raises" or "magnifies" the penny or its image. Students who use the word "image" in this context almost invariably think of "image" as a synonym for "picture." They do *not* associate the word with a physicist's definition of a virtual image: the location from which light rays appear to diverge. The best answer in our view, and one that is not common on pretests, describes how light reflecting off the penny is refracted downward as it leaves the water. Even students who are aware that refraction plays a role often concentrate on the light entering the water, rather than leaving it. The issue of refraction is one that does not seem to come easily to students. Therefore, it needs to be carefully and thoroughly addressed.

Draw arrows on the following pictures to show what would happen to light from the flashlights after it hits the objects below. If you cannot draw arrows, explain what happens in writing.

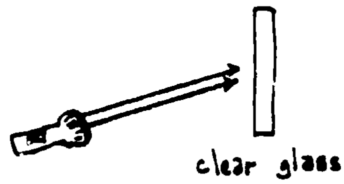
4. A mirror



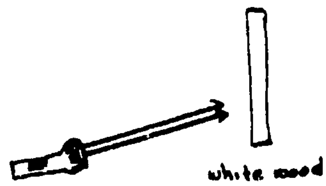
5. A piece of frosted (translucent) glass.



6. A piece of clear (transparent) glass.

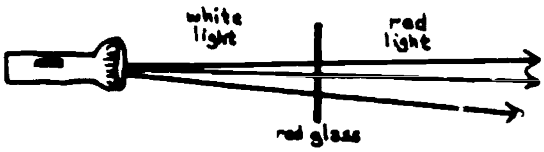


7. A piece of white wood.



8. Why do you think a black object looks darker to us tha a gray object?

9.



When you shine a white light through a piece of red glass, the light looks red on the other side. What does the red glass do to the light?

a) The glass adds red color to the light.
b) The glass lets all the light through, but it stops all the colors except red.
c) The glass lets red light through, but it stops all the other kinds of light.
d) The glass turns the white light into red light.
e) I don't know.

4. Most of the students we have tested know that mirrors reflect light, although some may fail to show the angle of incidence equal to the angle of reflection. When you talk with your students about mirrors, you may find that many students regard mirror images as pictures rather than as patterns of reflected light.

5. Most students will not address the idea of scattered light on the pretest: They will indicate that the light is either coherently reflected or transmitted. Most students explain the blurred nature of images seen through frosted glass by saying that the glass blocks some of the light. When they think of frosted glass, they tend to think in terms of seeing through it, not in terms of light going through it.

6. Most students will have no trouble drawing arrows coming out the other side of the glass on a straight line with those coming in. Although these answers do not account for refraction by the glass, we regard them as essentially correct because we feel the issue of coherent versus scattered reflection is of more importance.

7. Of the four flashlight questions, this is the one that really separates the students with misconceptions from those who understand the photon model of light and seeing. Many students will draw no arrows. They may explain that the light just stays there or that it lights up the wood, making a bright spot. Some students may also say that the wood absorbs the light. Students who know about light will draw arrows coming off the wood and scattering in different directions. Almost none of the students we have tested realize that the wood reflects light. They don't seem to realize that if it did not reflect light, they couldn't see it.

8. Many students consider color to be an innate property of objects rather than a consequence of the way the objects interact with light. For such students this question will seem senseless--either too difficult or too obvious to answer. Students who understand the role of light will note that a black object absorbs (almost) all light, reflecting no (or very little) light to our eyes; the gray object absorbs less light than the black object and reflects more light to our eyes. Once the students understand the concept of reflection and absorption, they usually do not have any problem describing the difference between light and dark objects. Few students taking our pretest, however, have understood this.

9. Students who understand about color will select answer c. The other answers represent typical misconceptions students have about light and color. These misconceptions stem from the belief that white light is pure and colorless rather than a combination of the spectral colors and from the mistaken belief that transparent colored objects add color to light.

10.

Green light is shining on a green plant in a red pot. There are no other lights in the room.
What color will the green plant appear? Why?
What color will the red pot appear? Why?

11. When we see a blue book,

a) the light helps our eyes to see the blue color of the book.
b) the book absorbs blue light and reflects other colors.
c) the book reflects blue light and absorbs other colors.
d) I don't know.

12. Why are there three primary colors of light and not some other number?

13. What are the three primary colors of light?

10. Students who have some understanding of light and color will say that the plant will appear green because green light is striking it, and it can reflect green light. (It would absorb any other color of light). Students who have misconceptions about color and light will say that the green plant will appear green because it is green (and perhaps will add something about the green light.) In conjunction with this line of thinking, students may say the red pot will appear red because that is what color it is. However, predictions about the color of the red pot often involve reasoning about *mixing* of red and green. Students who answer thus are not adequately distinguishing between *color* (a property of light) and *pigments* (substances which absorb certain colors). A theoretically correct prediction is that the pot would appear *black* because the pot reflects only red light while only green light is striking it. The situation is often confused further, however, by students' own prior experience. They have probably never seen a pure green light shining on a pure red object. Impure green light shining on an impure red pigment does in fact produce a brownish color, which could be interpreted as a mixture of green light and the red pot.

11. Students who have some understanding of color vision will realize that the correct answer is c. Students with misconceptions about color vision will typically choose a, believing that color is a property of objects rather than a property of light. Students who choose b probably do not understand that people see by detecting light that is reflected off objects.

12. Students who know about the three kinds of cones in our eyes and how they function in color vision will answer this question by saying that the number of primary colors corresponds to the number of types of color-sensitive cone in our eyes. Students who do not know about the cones in the eye (or who do not connect them with color vision) will be unable to answer this question or will focus on the fact that all other colors can be made from a combination of these three colors without connecting this to the function of the cones in the eye. However, this answer is simply a definition of primary colors--it does not tell *why* we only have three primary colors and why they are red, green and blue. Even students who do not understand what primary colors are can memorize them and regurgitate a definition. This question probes further, allowing you to see whether your students really understand the concept of primary colors.

13. Students with misconceptions may write the three primary colors of *pigment* here (magenta, yellow, and cyan--although based on their school art experience, they may write red, yellow, and blue) instead of the three primary colors of light (red, green, and blue). Students are usually confused at the idea of having separate sets of primaries for pigment and light. Students are not used to making this distinction; they may not realize the distinction exists. We have found that instruction that relates the three primary colors of light to the three types of cones in the human eye helps students to see and understand this distinction.

III. Materials for Lecture or Discussion with Commentary

This section contains three student handouts, eight transparencies you can use with your students, and one demonstration you can do in your class. They are designed to elicit and help overcome you students' misconceptions about light. Use as many or as few as you like.

The materials in this section are intended to reinforce concepts that have already been presented to your students through your instruction. The handouts may be most useful to your students if they receive them either during or after instruction so they may be used as reference material. Students should be encouraged to refer to these materials when they are asked to apply these concepts to a certain situation. Through the repeated use and application of these concepts students should be able to see how well these scientific concepts can be used to explain everyday occurrences.

Contents

Light and Vision--student handout (page 13)
Light and Objects--student handout (page 15)
Seeing Color--student handout (page 16)
Questions to Ask Yourself in Thinking about Color Problems--
overhead transparency (page 18)
Light Pathways--overhead transparency (page 19)
Mirrors vs. Rough Surfaces--overhead transparency (page 20)
Bouncing Light--overhead transparency (page 21)
Objects in White Light--overhead transparency (page 22)
Objects in Red Light--overhead transparency (page 23)
Objects in Green Light--overhead transparency (page 24)
Color is a Property of Light--demonstration (page 25)

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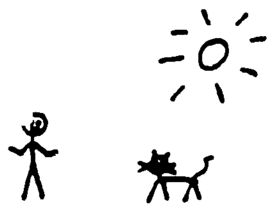
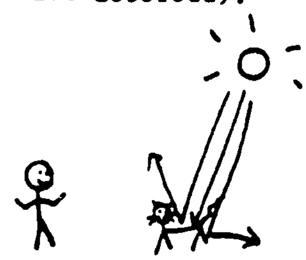
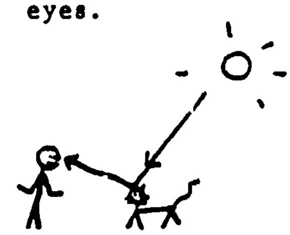
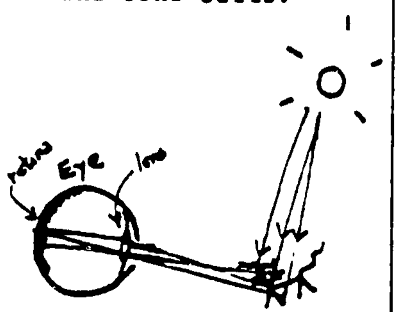
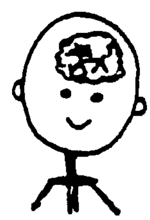
HANDOUT

Light and Vision: Seeing Things

How do people see?

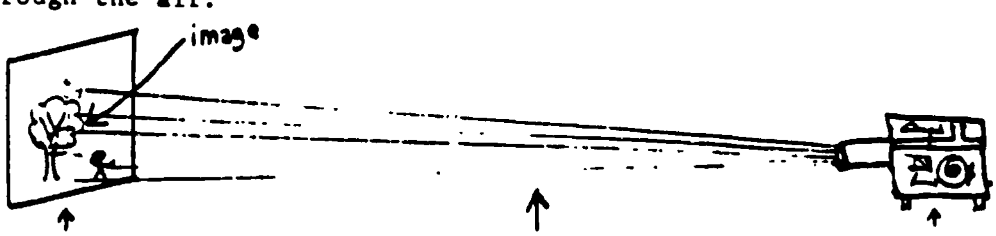
Seeing things is a multistep process that occurs instantaneously.

1. Light (photons) is emitted from a light source (e.g., the sun or an electric lamp) 	2. Some of those photons bounce off objects (others are absorbed). 	3. Some of the photons that bounce off objects enter the pupils of people's eyes. 
4. The lens of the eye focuses the photons so that they form an image on the retina, which contains rod and cone cells. 	5. Millions of rod cells send messages to the brain about the intensity of the light that strikes them. Millions of cone cells send messages to the brain about the wave-length of the light that strikes them (color).	6. The brain integrates these millions of messages to produce visual perception. You "see" what your brain tells you is there. 

What is an image?

Essentially, it's a pattern of light. To a physicist, an image is a pattern created by photons when they strike a surface such as a movie screen or the retina of your eye. An image is not imaginary (in physics). It is a tangible, measurable thing, and it is made up of light. Light does not carry an image. An image <u>is</u> light in a pattern of different wavelengths and intensities.

Images do not travel through the air. Only photons (light waves) travel through the air.



screen — traveling photons (no image here) — slide projector

Commentary

This handout illustrates the process of seeing. It is intended to reinforce the fact that vision is a result of the brain's detection of light waves that have been reflected off an object. It is also intended to clearly contrast the belief some students may have that we see directly.

The second part of this handout explains the concept of an image. It clearly illustrates the fact that an image is not tangible, a misconception that many students may have.

The final portion contrasts real and virtual images. Besides making the distinction between these two types of images, the concept of an image is reinforced.

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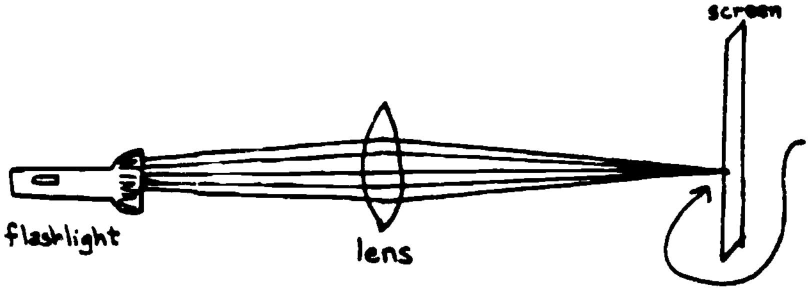
In the picture on the previous page, the image is visible only at the point where the screen is. If you put another screen midway between the screen and the projector, you would see no image on it. The lens in the projector causes the light rays, the traveling photons, to converge on the screen.

What is the difference between real and virtual images?

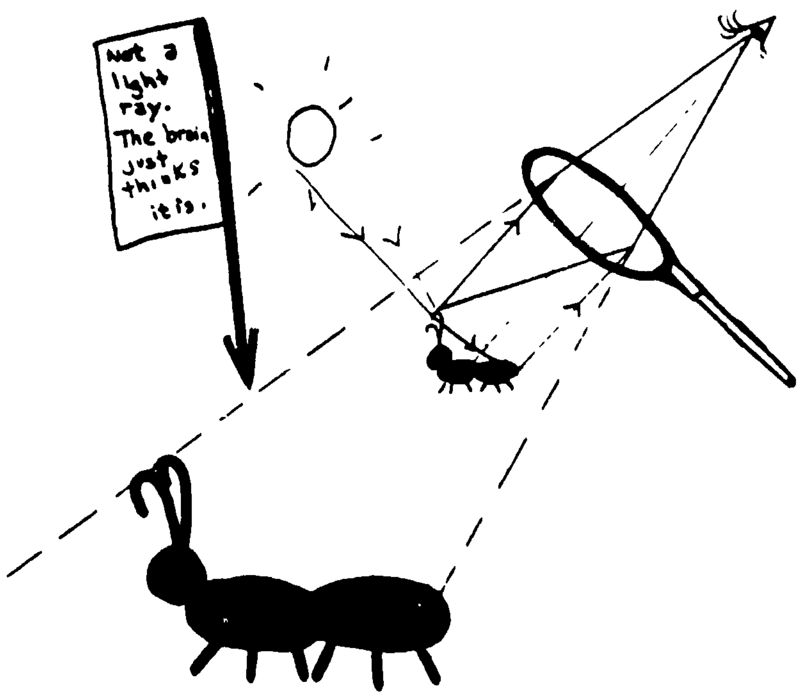
A real image is indeed real. You can see it on a screen. It is the point where actual light rays converge. Real images are upside down.



A real image is formed here, where the light rays converge.

A virtual image isn't really there. You see a virtual image when your brain, which assumes light always travels in straight lines, is tricked by, for example, a lens or mirror. You can see a virtual image through a magnifying glass. Virtual images are right-side up.

There is no light ray here, but your brain thinks there is, because it assumes the light that reaches your retina got there by going in a straight line.

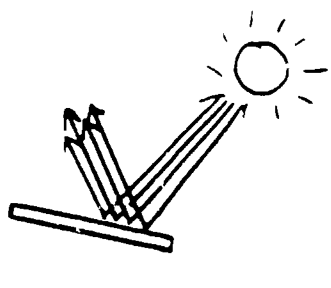


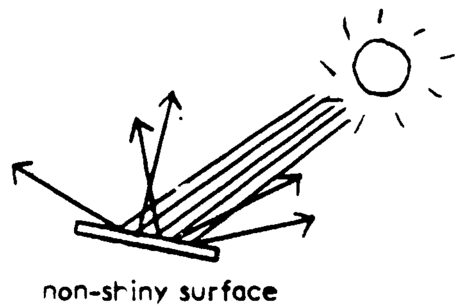
HANDOUT

Light and Objects

What is the difference between objects in which you can see your reflection and objects in which you can't?

Objects you can see your reflection in have extremely smooth (shiny) surfaces that reflect light with virtually no scattering. Thus the pattern of the photons is reflected. Objects you can't see your reflection in have relatively rough (nonshiny) surfaces that scatter most of the light they reflect. (Note that smooth and shiny refer to the surface at the microscopic level. A surface that looks smooth to us may be very rough to a tiny photon.)



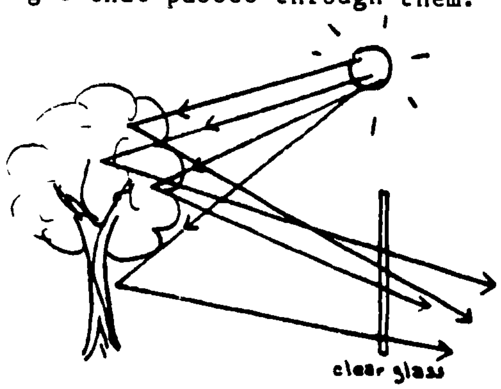


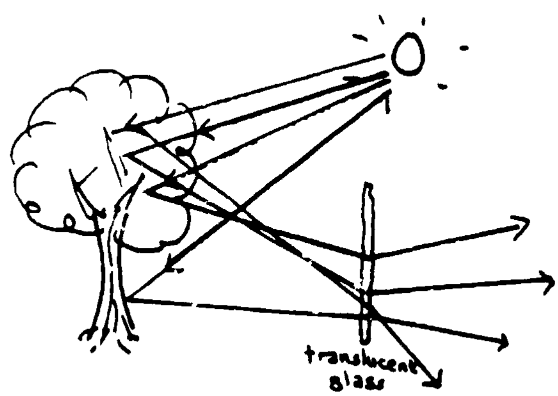
What is the difference between objects that look light and objects that look dark?

These are usually objects with relatively rough (relative to mirrors, that is) surfaces. Light objects reflect (and scatter) most of the light that strikes them. Dark objects absorb most of the light that strikes them. The darkest object you are ever likely to see is black velvet; it absorbs 98% of the light that strikes it.

What is the difference between transparent and translucent objects?

Transparent objects such as clear glass allow light to pass through without scattering it. Translucent objects such as frosted glass scatter the light that passes through them.





What is the difference between tinted glass and clear glass?

Clear glass allows almost all of the light that strikes it to go right on through. Tinted glass (e.g., sunglasses) absorbs some of the light that strikes it and lets the rest go through.

Commentary

This handout illustrates the interaction of light and different types of objects. It deals with pairs of objects and specifically states why they look different to us. Of course, the idea of light being reflected off objects to our eyes is used to explain the phenomenon that allows the students to see how well this conception works. These explanations clearly show that objects look different because of the way light interacts with them not simply because the objects are different. Your students may not have thought of these differences before and may profit from a discussion of these differences.

HANDOUT

Seeing Color

What is color?

Light, as you have learned, comes in a variety of different wavelengths. Your brain interprets the light of different wavelengths that strikes the retina of your eye as different colors.

Where is color?

Color is a property of light. Light is all the colors you see. The objects you see don't actually have color in them; they have pigments. Pigments are substances that tend to reflect some wavelengths of light more strongly than others. Thus a physicist interprets the statement, "The book is red," as follows:

1. The book contains pigments that reflect red light and absorb other colors.

2. When white light (a mixture of all wavelengths) strikes the book, only the red light is reflected.

3. Our eyes detect the red light coming from the book. Thus what we perceive as a property of the book is really a property of the light entering our eyes.

How many colors can we see?

We see only three colors: red, green, and blue. All the other colors that we see are combinations of those three. Here is how it works:

1. In addition to rod cells, which are sensitive to the amount of light striking them, the retina contains cone cells, which are especially sensitive to certain wavelengths of light.

2. There are three kinds of cone cells. One kind is most sensitive to red light, another to green light, and the third to blue light.

3. The brain's perception of color results from integrating nerve signals from all four kinds of cells: rod cells, red-sensitive cone cells, green-sensitive cone cells, and blue-sensitve cone cells. The thousands of different colors that we perceive are actually different combinations of those nerve signals. The chart below gives some examples. You can test your understanding by filling in the missing lines.

Color Seen	Strength of Nerve Signals from Cone Cells		
	Red	Green	Blue
Red	Strong	Weak	Weak
Green	-----	-----	-----
Yellow	Strong	Strong	Weak
Orange	Strong	Moderate	-----
White	Strong	-----	Strong
Black	-----	-----	-----
Pink	Strong	Moderate	Moderate
Gray	-----	-----	-----

Commentary

There is a lot of material contained in this handout regarding our perception of color. The two main points that are continually emphasized are (a) the fact that white light contains all the colors in the spectrum and (b) the color we see is determined by the type of cone cell(s) that is stimulated in our eye. Once your students understand the process that is presented here they should be able to accurately explain why an object appears the color that it does.

Notice that it is possible for different combinations of wavelengths of light to produce the same perception of color. For example, the yellow part of the spectrum comes from a single wavelength that stimulates both red and green cones. However, a combination of red light and green light has exactly the same effect on our cones. In either case we see yellow.

What are the primary colors?

The primary colors are the colors necessary to produce all of our color perceptions. Because our eyes have three types of cone cells, there are three primary colors. There are two sets of primary colors--one for light and one for pigments.

Light--the additive primaries. Physicists refer to the three colors of light that stimulate our cones (red, green, and blue) as the additive primaries. Each one of these three colors of light turns on a different kind of cone cell (red-sensitive, green-sensitive, or blue-sensitive). When all three are added together, the result is white light, which contains all colors. When you mix colors of light, you get more light going to your eyes.

Pigments--the subtractive primaries. Red, yellow, and blue are crude approximations of the subtractive primaries, which are actually magenta, yellow, and cyan. The subtractive primaries are colors of pigments, and pigments selectively absorb light. Magenta pigment absorbs all colors of light except magenta light, which it reflects; yellow pigment absorbs all colors of light except yellow light, which it reflects; and cyan pigment absorbs all light except cyan light, which it reflects. If you mix all three colors of pigment, you subtract the colors you can see, the colors of light, because more of the colors of light are absorbed.

Transparency--Questions to Ask Yourself in Thinking about Color Problems

Which cones are being stimulated?

Is any red light reaching my eyes? How?
Is any blue light reaching my eyes? How?
Is any green light reaching my eyes? How?

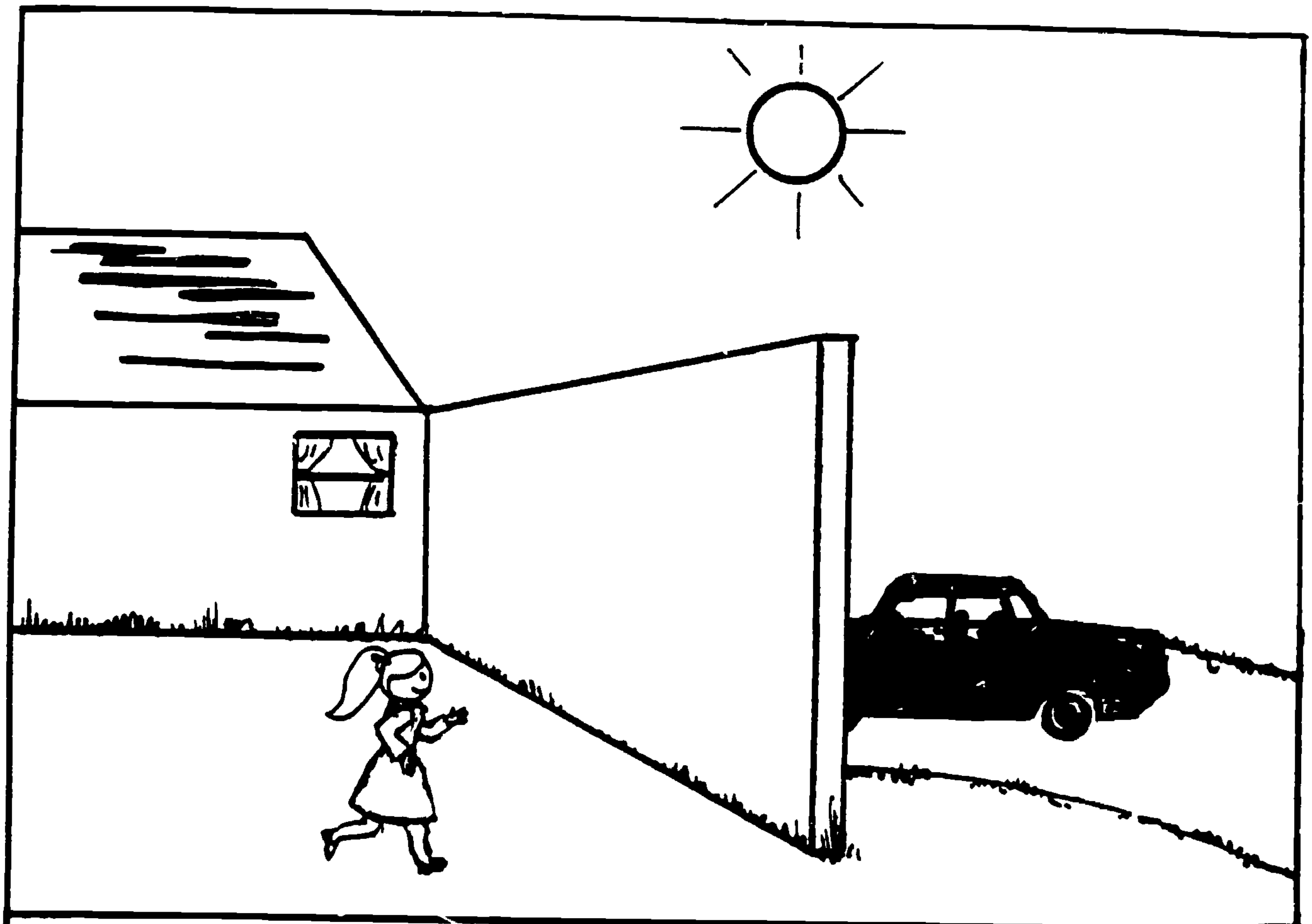
Situation	Cones Stimulated			
	Red-Sensitive	Green-Sensitive	Blue-Sensitive	Color You See

Commentary

Students typically have difficulty answering questions about the color of various objects under various colors of light because there is so much information to consider that they don't know what to think about first. You can use this chart to help them logically break down complex color problems into manageable subproblems. Our students have found it helpful.

Take the following problem, for example: What color would a pure-green book appear under a mixture of pure-red and pure-green light? First ask the students if their red-sensitive cones would be stimulated. If they (incorrectly) say yes, ask them how. Be sure they understand that a pure-green object does not reflect red light; it absorbs it. No red light, therefore, can reach their eyes to stimulate their red-sensitive cones. Ask them likewise, if their green-sensitive cones are being stimulated and if their blue-sensitive cones are being stimulated. When they've answered these questions correctly, they will discover that only their green-sensitive cones would be stimulated, so they would see green.

Transparency--Light Pathways



Why can't the girl see around the wall?

Commentary

Your students will probably say that the girl can't see around the wall because the wall is in her way. The key question is, "What is the wall in the way of?" Most students will say it blocks the girl's line of sight. You may want to use a plastic overlay to draw in the pathways of light for your students. They may need to be shown that the wall is blocking light rays, not the girl's sight.

Transparency--Mirrors vs. Rough Surfaces

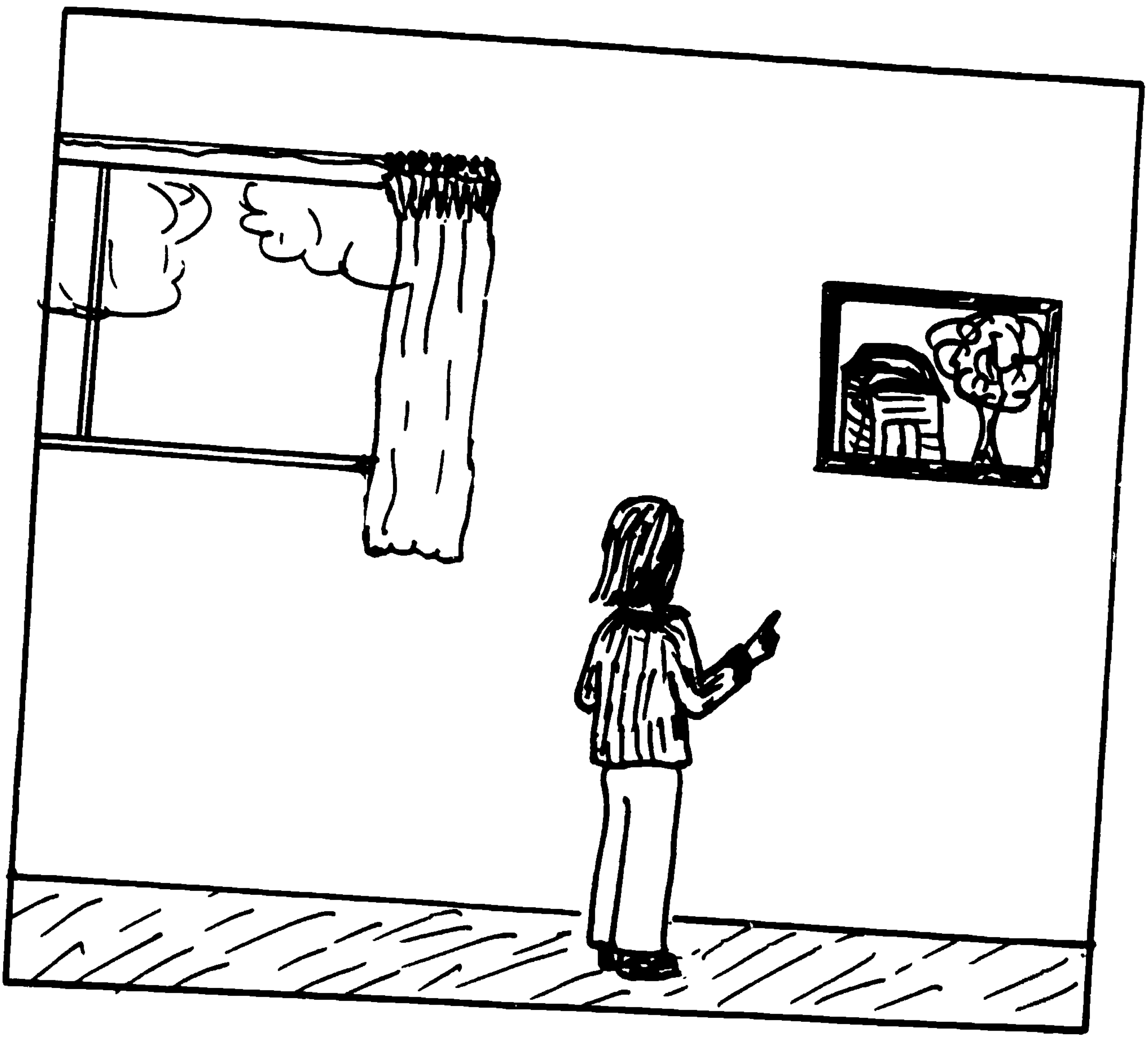
Commentary

Many students will say that the mirror reflects light but the bulletin board doesn't. You can then ask them how the bulletin board can be seen if it doesn't reflect light.

You may want to use a plastic overlay on which to draw in the pathways of light for your students. Many of them will benefit from hearing you explain the difference between the interaction of light with shiny vs. nonshiny surfaces.

Transparency--Bouncing Light

How does light travel so the person can see the picture? (There are no room lights and there is no window on the wall opposite the picture.)

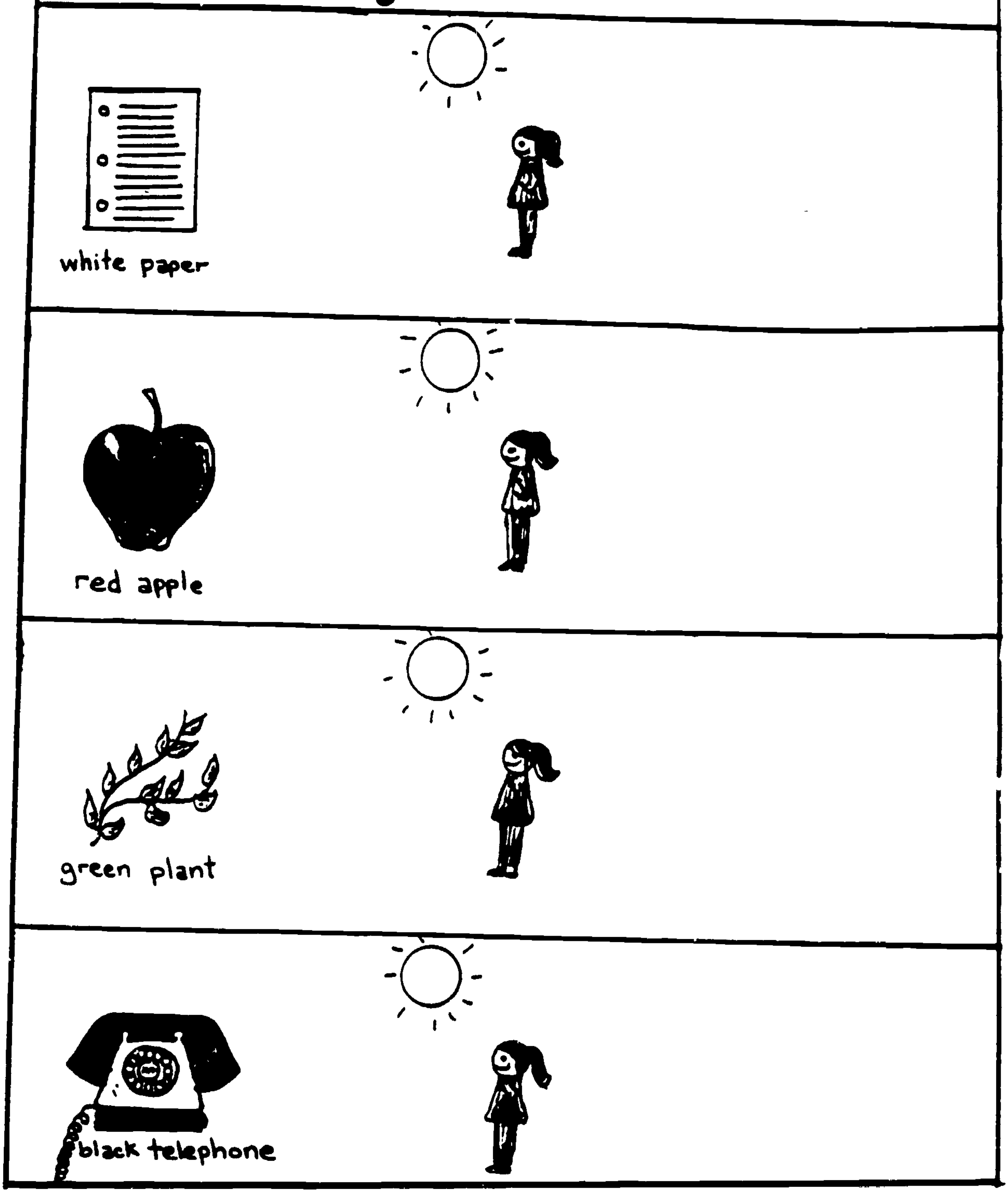


Commentary

Students often lose sight of the way light travels indoors. In an outdoor situation, it is easy to identify the light source (the sun) and draw a straight line from it to an object and then from the object to a person's eyes. Even students who understand that sometimes revert to thinking that light is simply all around us (like heat in a warm room) inside a room. Point out that light travels constantly. It bounces off things back and forth all over the room. Even though the window and picture are on the same wall, enough light eventually reaches the picture and bounces off it to enable the person to see it. The next step is to include artificial lights in the room. Talk about how students see each other in your classroom.

Transparency--Objects in White Light

What color will each object appear in White light?



Commentary

Your students should have no trouble predicting what color the objects will appear, but they may have trouble explaining why. You may want to draw in some light rays, perhaps using different colored markers on a plastic overlay, to help your students understand what's going on. You may want to point out that we see the light reflected to our eyes rather than the object itself.

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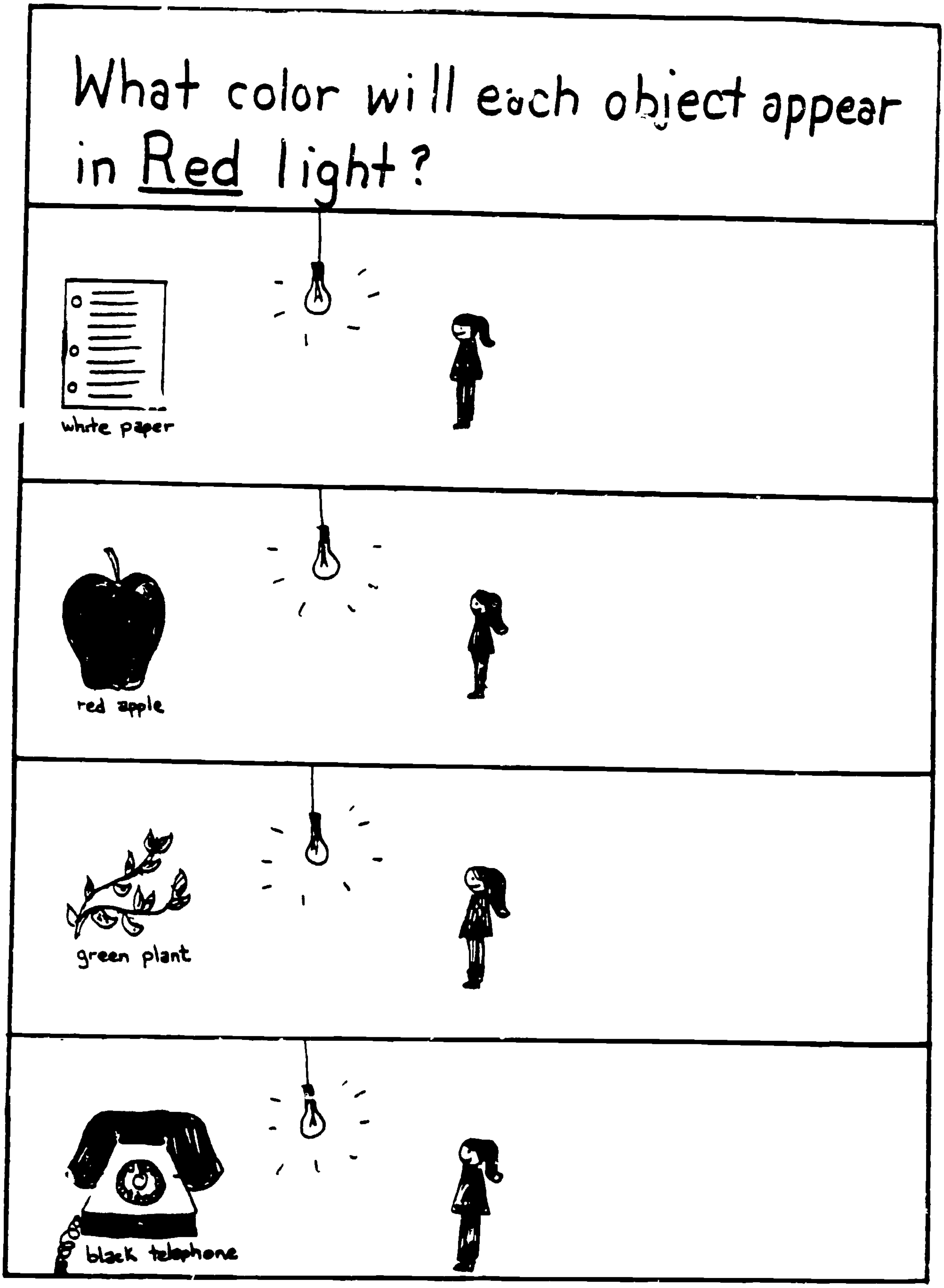
Transparency--Objects in Red Light

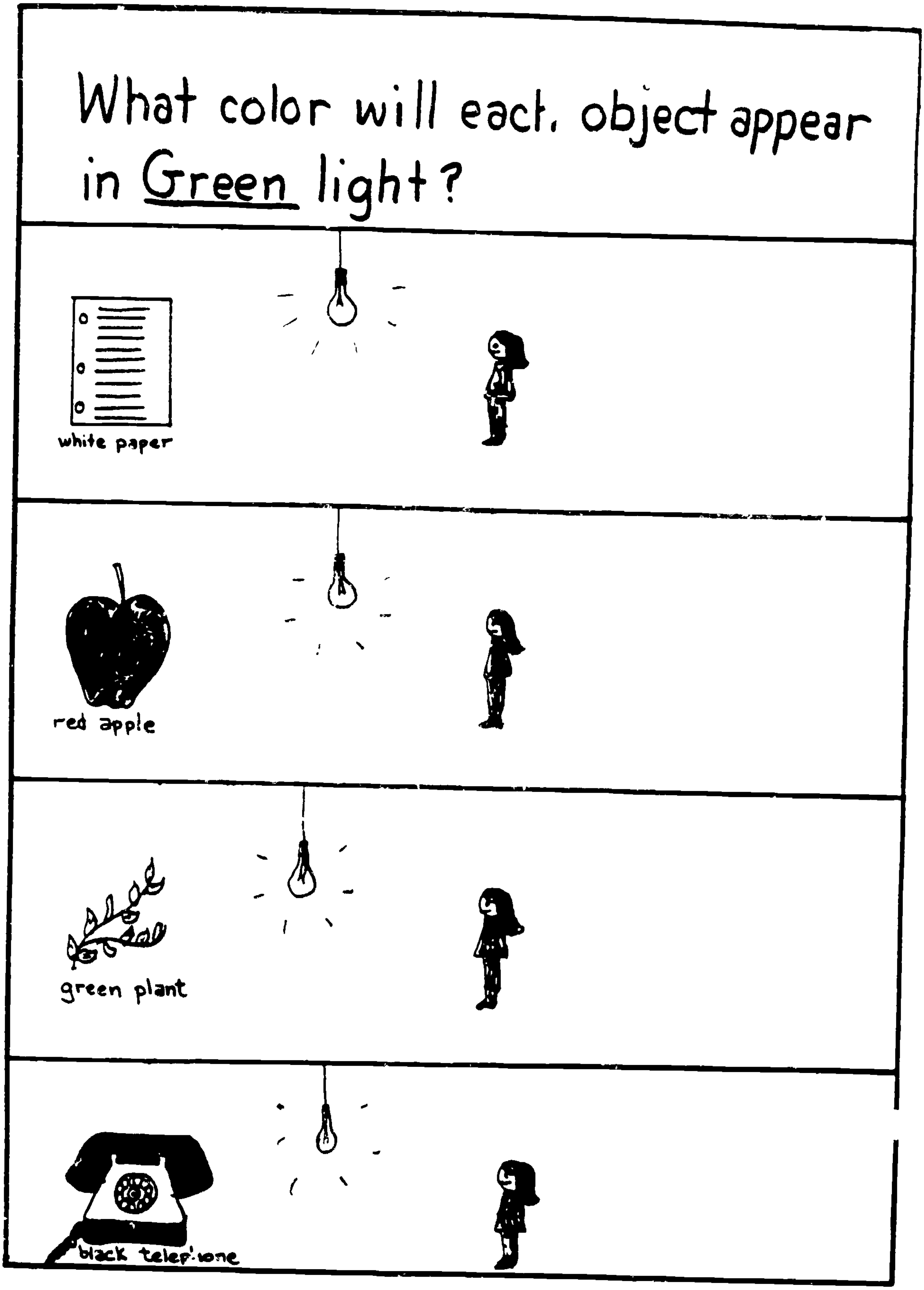


Commentary

Students tend to find questions like these difficult. Focus especially on the question about the plant because this is where student misconceptions will surface. Some students will say that the plant will look green because it *is* green. Others will say it will look red because the light is red. Perhaps the majority will say it will look brown because the red and green mix. Only a few will realize that the plant would look black because there would be no green light for it to reflect, and it cannot reflect red light. You may need to explain the difference between pure, theoretical conditions and those your students are more likely to encounter.

ERIC Full Text Provided by ERIC

Transparency--Objects in Green Light



Commentary

Because students find this kind of question so difficult, we have included a second overhead transparency. Focus especially on the question about the apple because this is where student misconceptions will surface. Many students find it hard to believe that a red apple (with only red pigment) would look black under pure green light.

Demonstration: Color is a Property of Light

Materials

sodium vapor lamp

slide projector with yellow slide

two posts with a line of string connecting them (a clothesline)

clothespins

pieces of cloth of various colors including red, yellow, green, and blue or violet (some with multicolored patterns)

Procedures

Set up the clothesline with clothespins on it, but don't let the students see the cloths. Turn out all the lights. (You will need to be in a room without windows for this demonstration to be effective.) Turn on the sodium vapor lamp so that it shines on the clothesline. Then pin up the cloths and ask the students what colors they are. Next, turn off the sodium vapor lamp and turn on the projector with the yellow slide in it. Again, ask the students what colors the cloths are. They will look different now. Finally, turn off the slide projector and turn on the room lights. Now the students can see what color the cloths "really" are.

Discussion

This is a vivid demonstration of the fact that color is a property of light rather than of objects. Explain to your students that objects can only reflect certain colors, depending on their pigments, and cannot reflect light that does not strike them (i.e., if only yellow light strikes an object that absorbs and therefore does not reflect yellow light, that object will appear black, as do some of the cloths under the sodium vapor lamp).

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IV. Laboratory Activities and Commentary

This section contains some laboratory exercises you may have your students do. The left-hand pages are ready to be photocopied and given to your students. They have complete directions for your students to follow and questions for them to answer. The right-hand pages contain commentary on the labs, pointing out possible areas of student confusion and suggesting some remedies.

It is important that your students think about and try to answer the questions in each lab handout. These questions require them to use their knowledge of light to explain their observations. Students will benefit from postlab discussions of the lab and these questions.

There are three lab exercises:

Shadows Laboratory
Diffraction Grating Laboratory
Color Shadows Laboratory

Each lab will take one to two hours, depending on the speed at which your students work and the amount of discussion you have.

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Shadows Laboratory

Introduction

What is a shadow?
How is one formed?
What determines the size, shape and placement of a shadow?

It will be useful for you to remember a physicist's definition of how we see. That is, we see by receiving light that is reflected off objects. Keep this in mind while you are going through the procedures in this lab. Then you should be able to answer the questions above.

Materials

1. Flashlight or some other small, movable light source
2. A screen
3. A solid cube (preferably 3-5 cm per side)

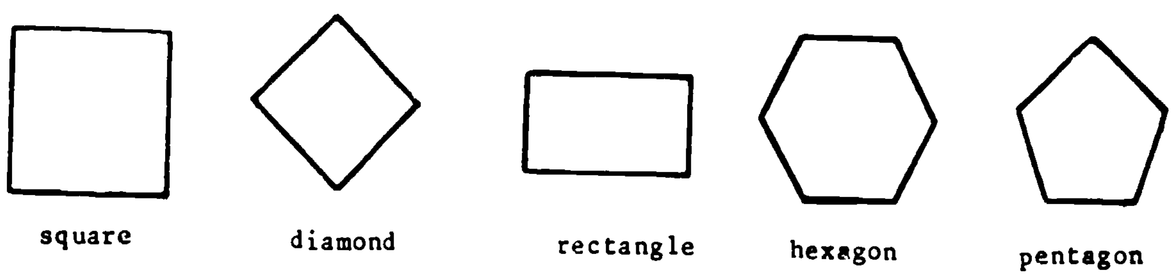
Procedures and Questions

1. Have one person hold the light source and shine it on the screen while another person holds his/her hand between the light source and the screen to cast a shadow.

2. Without moving your hand, how can you
   a. make the shadow move down?
   b. make the shadow move to the left?
   c. make the shadow larger?

3. Without moving the light source, how can you
   a. make the shadow move down?
   b. make the shadow move to the left?
   c. make the shadow larger?

4. Holding the cube between the light source and the screen, which of these shadow shapes can you make with the cube? Which are impossible to make?



Commentary

Introduction. This lab is deceptively simple, and your students may try to rush through it. However, it reinforces and demonstrates some crucial concepts about light, so thoughtful discussion of the lab questions, both during and after the lab, is essential.

In order for this lab to be meaningful for the students, they should have prior knowledge of a physicist's concept of how we see and of the photon model of light. Without this prior knowledge, the student may not be able to understand that the area of a shadow reflects less light to our eyes or be able to determine the placement of shadows. The purpose of this lab is for students to realize the following:

Photons travel in straight lines.

A shadow is dependent on the position of the light source and the size and shape of the object in the path of the light.

A shadow is an area that receives and therefore reflects less light than its surroundings.

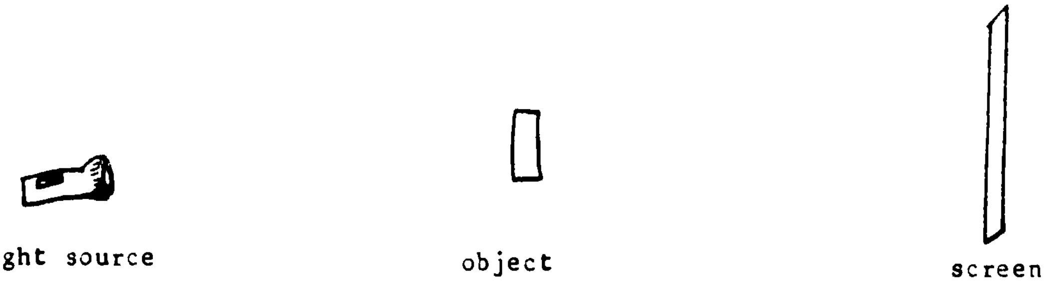
1. Questions 2 and 3 should help the students realize that a shadow is dependent on the position of the light source and the size and position of the object that casts the shadow. This understanding, along with the knowledge that photons travel in straight lines, should help students to predict the placement of shadows (Questions 5 and 7).

2. All the questions in this lab, including this one, attempt to help students understand the photon model of light and focus on the geometric relationships implied by the fact that photons travel in straight lines. Students should recognize here that to make the shadow move in a specific direction, they must move the light source in the opposite direction; to make the shadow larger, they must move the light source closer. Students can easily figure how to make the shadow move, but they may not understand or think about the optics involved. As you go from group to group, you may want to ask students why the shadow moves the way it does when they move their hand. Ask them to explain why in terms of photon movement.

3. Students should recognize here that the shadow will move in the same direction as their hand and that it will get larger if they move their hand closer to the light source. They can easily figure this out from trial and error, but may benefit from having you explain it to them (in their groups) in terms of photon movement if they do not already understand.

4. Students should recognize that by changing the position of the cube, it is possible to make all the shadow shapes except the pentagon. This is explainable geometrically in terms of light rays or photon paths. You may want to demonstrate how to trace the light path from the light source to the screen so the students can really see and understand why these shapes are possible. Getting students to think about light geometrically is one of the aims of this lab. This question asks students to closely observe a phenomenon (what solid objects do to the path of light) that they usually do not notice.

5. Draw a ray diagram to show where the shadow of the object will fall on the screen.



6. Why does the shadow look darker than the rest of the screen? Explain this in terms of seeing, in terms of the light entering your eyes.

7. Why are people's shadows (assuming the people are outside and it's sunny) longer in the late afternoon than they are shortly after noon? Draw ray diagrams to help you explain your answer.

8. Define a shadow in terms of the photon model of light.

5. Students who do not understand the photon model of light will not be able to draw the diagram correctly. The shadow should fall above the object because the light source is below it. Watch for students who draw the shadow on a horizontal line with the object. Such students tend to go no further in their thinking than to say that an object casts a shadow behind itself. Their answer shows that they are not thinking geometrically in terms of the photon model. They will need help understanding why their answer is incorrect. It may be useful to hold an object in front of the light source and place a meter stick along the path of the light, from the light source to the shadow on the screen. This would show the students that the light is traveling in a straight path.

6. Students should understand that a shadow is an area reflecting less light than the areas surrounding it. Because less light is being reflected from the area of the shadow to your eyes, it looks darker than its surroundings. Watch for students who think a shadow is some sort of image. They will need help reconceptualizing shadows.

7. Students should realize that the length of the shadow depends on the angle of the light source (the sun) in relation to the object casting the shadow (the person). This realization depends on an understanding of the photon model of light. Students should be able to illustrate this by drawing two ray diagrams--one with the sun nearly overhead casting a short shadow and one with the sun closer to the horizon casting a long shadow. Again, referring back to the demonstration using the meter stick along the path should help the students who have trouble with this question.

8. Students should realize that a shadow is an area that receives and therefore reflects less light than its surroundings. Watch for students who think of a shadow as a positive thing, something almost tangible. They will need help in thinking of a shadow as the (relative) absence of light caused by an opaque object in the path of the light that reflects the light that reaches it.

Postlab Discussion

It is natural for people to think of shadows as tangible things. Though students may come to think of shadows in the lab as areas reflecting less light, they may not connect this way of thinking about shadows with shadows in the real world. You may want to help your students make this connection during your postlab discussion by setting up some hypothetical real-world shadows questions (e.g., Where does the shadow of the building fall if the sun is here?). Push your students to talk about shadows in terms of pathways of light.

Diffraction Grating Laboratory

Introduction

What is white light?
Have you ever thought of white or ordinary light as a special kind of light?
How can white light enable us to see colors?
How do white light and colored objects interact?

White light, or ordinary light, is the light that you see from an ordinary light bulb. This white light is made up of all the colors of the spectrum. This makes sense if you think that the reason you see white is because all of the kinds of cones in your eyes are being stimulated. Of course, it would be much easier to believe this if you could actually see the separate colors of light that make up white light. By using a diffraction grating, you will see just that in this lab! A diffraction grating is covered with tiny parallel lines that diffract white light in such a way as to separate the colors of the spectrum.

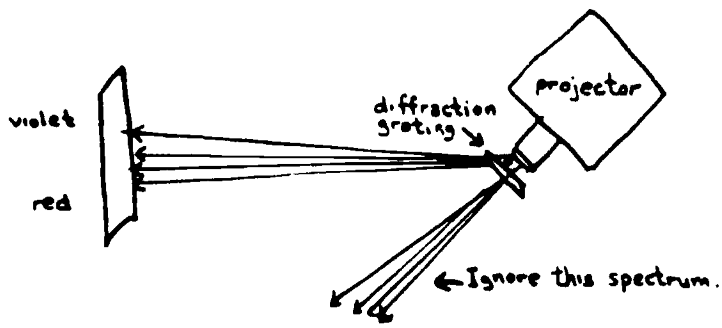
Materials

1. Screen
2. Projector
3. Diffraction grating
4. Slide with a narrow slit in it
5. Colored slides
6. Colored paper

Procedures and Questions

1. Turn on the projector. Put the slide with the narrow slit in the projector and hold the diffraction grating in front of it. Move the projector and/or screen until you have a spectrum on the screen.

Top view of setup:



Note. The diffraction grating will produce two spectra, but your screen should be placed as shown in the diagram so that you are only working with one spectrum. The beam of white light should be positioned so that it is not directly reflecting off your screen. You may need to adjust your screen and/or your projector a few times until you get the best location for each.

Commentary

Introduction. This laboratory exercise is intended to help students form a concept of color perception and come to better understand how pigments interact with light. In order for this lab to be meaningful and make sense for the students, they should understand how light enables seeing. They also need to have prior knowledge about the function of the three types of cone in human eyes. This lab is designed to help students to come to understand the following:

that white light is a combination of all the colors of the spectrum and

that objects differentially reflect and absorb light. That is, objects have pigments--not colors--that allow certain colors of light to be reflected to the cones in our eyes. These colors of light are the colors that we see. If more colors of light than we see are present (e.g., when white light is present) the colors we do not see have been absorbed by the object.

1. Some students seem to have difficulty setting up the equipment. Therefore, a quick demonstration of how to position the slide with a slit in it and the diffraction grating in relation to the projector is helpful if not essencial. You might wish to check each group to make sure the students have located a spectrum and set the equipment up correctly.

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2. Hold different colored slides in front of the projector and record what happens to the spectrum

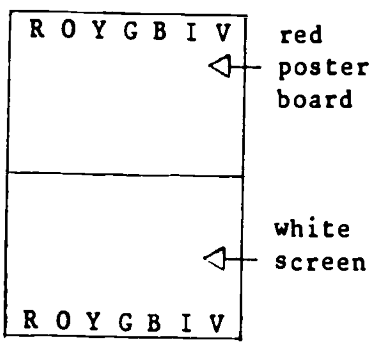
with a red slide . . .

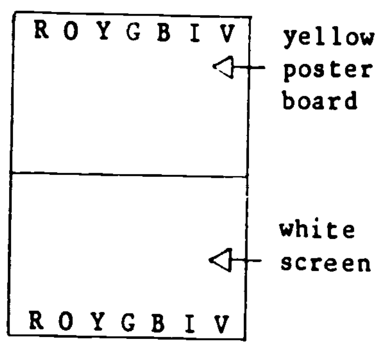
with a blue slide . .

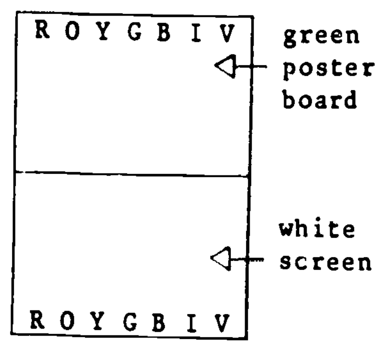
with a green slide . . .

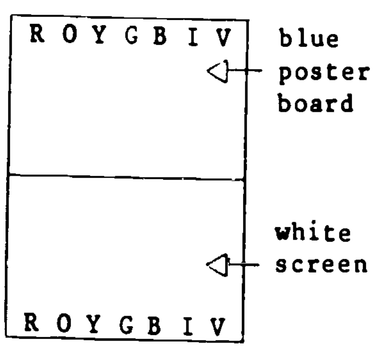
with a yellow slide . . .

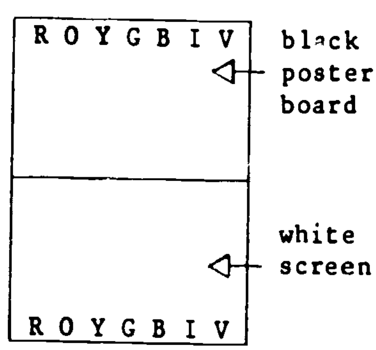
3. Hold different colors of poster board against the screen in the top half of the spectrum so that you can compare the spectrum reflected off of the poster board with the spectrum reflected off the white screen. Complete the illustrations below by circling the letters representing the colors of the spectrum that you see reflected from each color of poster board with the spectrum reflected from the white screen.











2. Students should be aware that whatever color a slide is, it will only let that color of light go through it. For example, a red slide will only allow red light to go through it to the screen and reflect off the screen back to our eyes. The red slide will (ideally) absorb all colors of light except red. Watch for students who talk in terms of seeing through a slide instead of light coming through the slide to the screen and back to their eyes. They may need help in making this important distinction. The students should understand, then, that a red slide will stop (through absorption) all colors of the spectrum except red. A blue slide will stop all but blue, a green all but green. We see yellow when both our red-sensitive and green-sensitive cones are stimulated, so most yellow slides allow red, yellow, and green light to pass through.

3. This procedure works best if artists' poster board is used because the pigment is purer than that in construction paper. However, ordinary construction paper will also work. Regardless of whether poster board or construction paper is used, the pigments will not be pure; therefore, exact answers may vary. So, more bands of the spectrum than just the color of the poster board (or construction paper) may be seen. For xample, some students may be confused as to why a little bit of yellow and blue show up on green poster board (or construction paper). The students should realize that this is due to the impure pigments in the poster board (or construction paper). If they are going to understand the concept of reflection and absorption, they must be made aware of the impurity of most pigments. The students may need an explanation from you regarding pure and impure pigments in order to understand why they see what they do and to be able to answer Question 4 correctly.

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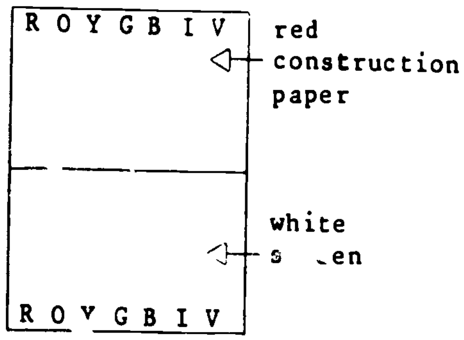
4. Why do you see the green and blue parts of the spectrum on the white screen but not on the red poster board?

Why do you see the red part of the spectrum on both the red poster board and the white screen?

5. Use your answers to Question 4 to explain why red poster board looks red in ordinary white light. Explain in terms of which cones in your eyes are stimulated.

6. Compare the spectrum reflected off the red poster board with the spectrum reflected off a piece of red construction paper. What is the difference between the way the high-quality red pigment in the poster board and the low-quality pigment in the construction paper reflects and absorbs light?



4. It is critical that the students have an understanding of pure pigments (refer to commentary from Question 3) in order to realize that these questions are based on the results they would have seen in Question 3 if pure pigments were present. Based on this, the students should realize that they do not see the green and blue parts of the spectrum on the red poster board because these colors of light are absorbed by the pigments in the red poster board. However, these colors of light are visible on the white screen because white reflects all colors. Similarly, the red part of the spectrum is visible on both the poster board and the white screen because it is reflected by both. The students should be able to generalize from their answers to these questions so they can apply the concept to the other colors of poster board. It may be useful to discuss what happens with another color of poster board with the students to ensure that they understand this concept.

5. With this question, the students are asked to give an explanation of why we see color that goes beyond mentioning reflection and absorption; that is, the students now must realize that their red-sensitive cones are being stimulated by the red light that is reflected off the red poster board; therefore, of course, that is the color they see. The students must first realize that since white light is made up of all colors, red light is present to be reflected. This strategy may seem to be backwards; however, most of the students we have worked with seem to find it easier to begin by thinking about which cones are being stimulated and then realizing that this determines whether or not the color is seen.

6. The students should notice that the red poster board will reflect only the red light (if it is a pure pigment). The construction paper will reflect the red light most strongly, but will also reflect other colors to some extent because the pigment is less pure than the pigment found in the red poster board. Students should realize that pure pigments are rare and that this is why what they see in lab is seldom as distinct as theory would lead one to believe.

Postlab Discussion

You can help your students transfer what they learned in this lab to what they see outside the lab. Ask them questions similar to those asked in the lab, but ask questions about real-world situations. Push your students to talk about color in terms of pigments differentially absorbing and reflecting the various colors of light to their eyes. Watch for students who fall back into thinking of white light as colorless or who talk about light illuminating the color of an object. They may need some additional explanation and examples from you.

Color Shadows Laboratory

In this lab you will further explore the photon model of light and learn to explain the relationship between the color you see and the cones that are being stimulated in your eye. This relationship is the one that physicists use to explain how we see colors. You will discover the result of mixing different colors of light and see what happens when the path of some light, but not all, is blocked. You will discover that the results of mixing colors of light and mixing colors of paints, which you may be more familiar with, are quite different. However, if you continue to relate the colors you see to the cones that are being stimulated in your eye, it should make sense.

Materials

1. Screen
2. 2 projectors set up so that beams of light partially overlap on the screen
3. 6 slides: 1 red, 1 blue, 1 green, 1 yellow, 1 cyan, and 1 magenta
4. A cube for casting shadows.

Procedures and Questions

1. Once the room has been darkened, turn on both projectors and aim the two beams of light at the screen so that there is an area where the two beams of light overlap. Insert slides so that you are mixing light in the following combinations: red & green, red & blue, and green & blue. For each combination, write down the color you see on the screen and explain, in terms of which cones in your eyes are being stimulated, why you see that color.

Red + Green ----▷ ________

Explain:

Red + Blue ----▷ ________

Explain:

Green + Blue ----▷ ________

(You don't need to explain this one.)

Commentary

Introduction. It would be most beneficial to your students if this lab was done after both the Shadow Lab and the Diffraction Grating Lab. This order should allow your students to successfully complete this lab after they have had the opportunity to discover how shadows are formed and to think about colored light.

Prior to this lab, your students should have an understanding of the function of the three types of cones in the human eye. The students should also be familiar with yellow, cyan and magenta. In this lab, students will be exploring the mixing of colors of light and relating the colors they see to the cones of the eye. The purpose of this lab is twofold; it attempts to help the students realize that (a) there is a relationship between the color we see and the cones that are being stimulated in our eye and (b) that the results of mixing colors of light and mixing colors of paint are different.

Students should realize that we have only three types of cones and, depending on how much each type of cone is stimulated, we see a certain color. In order to help students understand why they see the colors they do, it may be useful to refer to pages S-18 and I-18. This strategy allows the students to work backwards and begin to understand why they see a certain color by deciding which cones in the eye are being stimulated.

1. Students should see that red and green light combined look yellow. They should realize that we see yellow when both our red-sensitive and green-sensitive cones are stimulated. They should realize that we do not have special cones for detecting yellow. If the students' explanations do not refer to the cones in our eyes, the students are missing the point of this question and will need some help from you in understanding what they're seeing.

   Students should see that red and blue light combined look magenta. They should realize that we see magenta when both our red-sensitive and blue-sensitive cones are stimulated. They should realize that we do not have special cones to detect magenta. You may need to circulate among the students and talk with some of them to be sure they understand this.

   Students should see that blue and green light combined look cyan. They should realize that we see cyan when both our blue-sensitive and green-sensitive cones are stimulated. They should realize that we do not have special cones to detect cyan.

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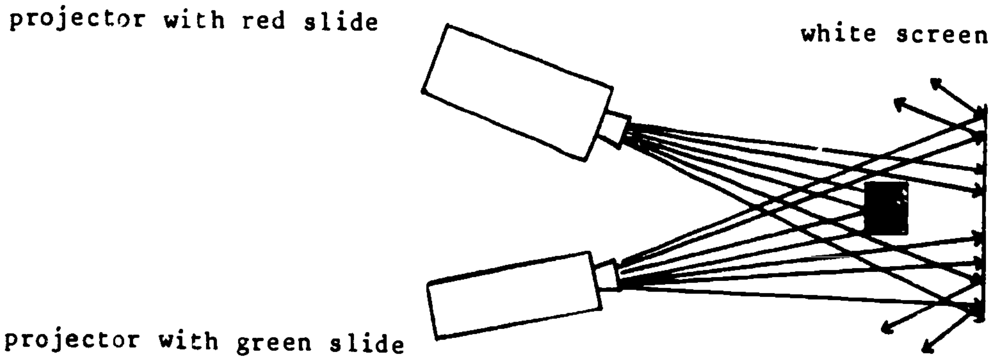
2. For each of the three combinations in Question 1, hold the cube in the beam of light to make shadows. Explain the colors of the shadow you see in the area of the overlap. What colors of light are being reflected off the white screen in the area of the shadows and reaching the cones in your eyes?

Example:



Red + Green: The shadow from the red projector is ______________.

The shadow from the green projector is ______________.

The area where the two shadows overlap is ___________.

Explain each shadow:

Red + Blue: The shadow from the red projector is ______________.

The shadow from the blue projector is ______________.

The area where the two shadows overlap is ___________.

(You don't need to explain this one.)

Green + Blue: The shadow from the green projector is ______________.

The shadow from the blue projector is ______________.

The area where the shadows overlap is ______________.

(You don't need to explain this one.)

2. This is a complex task because it requires students both to analyze a geometrically complex situation and to think of color in terms of the light that reaches our eyes. Something blocking the green beam of light will prevent the green light from going to the screen, bouncing off it, and coming to our eyes. But that doesn't stop the red light from going to the screen, and bouncing off to our eyes. We therefore see a red shadow surrounded by yellow. Similarly, something blocking the red light produces a green shadow surrounded by yellow. Only if both beams of light are blocked does the shadow appear black. Many students will probably need some time to work through their confusion about what they see. (Why are the shadows colored instead of black? Why does the red beam make a green shadow?) As an instructor, you can help by getting the students to work *backwards* from the cones in their retinas:

   -If you see a green shadow, which cones are being stimulated?

   -Show me the path that the green light takes to get to your eyes.

   -Why aren't your red cones being stimulated?

   -Why aren't your blue cones being stimulated?

   This sort of a questioning strategy is presented on pages S-18 and I-18.

3. Get out the yellow, cyan, and magenta slides. Put a yellow slide in one projector and a blue slide in the other in the same set up used for Question 2. What color do you see on the screen? ________ Explain in terms of which cones in your eyes are being stimulated.

Predict which other combinations of slides should also produce this color.

________________ and ________________

________________ and ________________

Check your predictions and correct them if you are wrong.

4. Turn off one projector and hold the yellow slide against the screen. (If no observable difference is seen, try again holding two yellow slides together. One yellow slide may not be thick enough to make an observable difference.)

What color does the yellow slide appear in

red light? ____________

green light? ____________

blue light? ____________

Explain your results:

5. If you shine a pure red light on a pure green plant in a dark room, what color would you expect the plant to appear?

____

Explain:

3. The students should see something close to white. Yellow light stimulates both their red-sensitive and green-sensitive cones. Therefore, when they combine yellow and blue light and that light gets to their eyes, it will stimulate all three kinds (red-sensitive, green-sensitive, and blue-sensitive). When all three kinds of cones are stimulated, we see white. Students should be able to predict that magenta and green light together and cyan and red light together will also result in something close to white. It should be pointed out to the students that there may be some problems due to the intensity of the colored slides. Because of an intensity problem the students may not see pure white when overlapping complementary colors. However, encouraging them to determine which cones are being stimulated should help them see that only exactly equal intensities of the three primary colors will product pure white. It should be clear to students that the rules for mixing colors of light are quite different from the rules for mixing pigments.

4. The light that we see must pass through the yellow slide, bounce off the white screen, then pass back through the slide. Because the slide allows red and green light to pass through, it will appear red under the red light and green under the green light. However, the slide absorbs blue light, so it will appear black in the blue light. Watch for students who expect the pigment of the slide to "mix" with the color of the light producing colors such as orange or yellow-green. Students with these expectations need to reason through a sequence of questions about which cones are being stimulated.

   You should test your slides in advance to make sure this procedure works. It is common for both yellow and blue slides to allow some transmission in green wavelengths. If this is the case with your slides, then the yellow slide will appear green, rather than black, in the blue light. Doubling slides may help, or you can use another color of slide against the screen, or you can discuss with the class why the predictions are wrong.

5. This is the key question for this lab. It tests whether students have learned enough about color to transfer their knowledge and understanding to a hypothetical situation. Students should realize that a green plant can only reflect green light. If only red light shines on it, it won't reflect any light and will appear black. It is common for students to make other predictions, often based on the expectation that the green pigment will somehow "mix" with the red light, producing an intermediate color such as brown. These students will need some additional instruction and discussion.

Postlab Discussion

This lab intends to help students relate color that is seen to the stimulation of cones in our eyes. It may be most useful to your students to work backwards in order to understand why they are seeing the color they are; that is, the students could begin by deciding which cones are being stimulated and then decide upon the outcome of such combinations of stimulated cones. Discussing questions 1, 2, 4 and 5 may be most useful in order to ensure understanding of this relationship.

Your students may need some help making connections between light projected on screens in the lab and light in real-life situations. They may also need help understanding what they saw in this lab. You may want to pose some hypothetical questions to them about lighting in the theater to help them think through and apply what they have learned in this lab.

V. Problem Sets

This section includes two problem sets, one on light and vision and one on color. You may assign these problems as homework, do them with your students during class, assign them as study guides, or use them in your exams.

For students using newly acquired scientific conceptions to solve problems and answer questions, instructor feedback is crucial. These problem sets work best when you discuss individual questions in class after students have tried to answer them.

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Problem Set 1: Light and Vision Problems

1. What is light?

2. What do our eyes do when we see?

3. What is a shadow? How do we see shadows? (Use a drawing to explain your answer.)

4. Does light carry images? Explain.

5. How does light enable someone who is inside a house to see a tree outside through a window?

6. How does light travel to let you see yourself in a mirror?

7. Why can't we see things clearly through frosted glass?

8. Why does a black object look darker than a gray object?

9. Shiny things and white things reflect all colors of light, yet they look different from each other. Why?

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Commentary

1. This is basically a recall question. Some students may simply write that light is a form of energy. When you discuss this question, push them, asking what form of energy it is. The answer we look for is that light is electromagnetic radiation of specific wavelengths.

2. Our eyes, of course, detect light. This question gets at whether students still think of their eyes as actively doing something--sending out sight, perhaps--or whether they realize that our eyes receive and analyze patterns of light.

3. This question draws on what students learned from the Shadows Lab. A shadow is an area that reflects less light to our eyes than the surrounding areas because something is between it and the light source.

4. Some students think that light does indeed carry images. If some of your students do, they will benefit from hearing you explain that an image is just a pattern of different wavelengths of light. They will need to be told that an image is light and that therefore light does not carry an image (it *is* the image).

5. A good answer will explain that the light from the sun bounces off the tree and goes through the window into the person's eyes. Watch for students who write about the person seeing through the window rather than about light going through it.

6. A good answer will explain that light comes from some light source, hits you, bounces off and goes to the mirror, and then bounces off the mirror and goes to your eyes. Watch for students who write just that the mirror reflects your image. In discussion of this question, help students understand where the light comes from and what happens to it.

7. Watch for students who write in terms of frosted glass being too cloudy to see through. Also watch for students who simply write that we can't see through frosted glass because frosted glass scatters light. Ask such students where the light that is scattered came from. A good answer will explain that the light bouncing off whatever is being looked at gets scattered by the glass before it reaches the person looking at it.

8. Watch for students who write that a black object looks darker because black is a darker color than gray. You may, in your discussion, need to remind them to think in terms of light. You may need to tell some of them that a black object absorbs more (and reflects less) light than a gray object; that's why it looks darker.

9. If it has not occurred to students that both white things and shiny things reflect all colors of light, this question will at least prompt them to think about it. Students may need some help with this one, but a good answer would state that a shiny object reflects light in the same pattern the light was in when it hit. A white object scatters the light that it reflects. The essential difference then, is in the way the light is reflected rather than in the kind or amount of light reflected.

Problem Set 2: Color Problems

1. What is the difference between a spectrum and ordinary white light?

2. When you see a red book, where does the color you see come from?

3. a. What is a cone cell?

   b. How many kinds of cone cells do we have? To what colors of light are they sensitive?

   c. How do we see colors other than red, blue, and green?

4. If you shine pure red, pure green, and pure blue light on the same spot on a white screen in a completely dark room, what color will the screen appear?

5. What color will a pure blue book appear if it is in a dark room with only a pure blue light shining on it?

6. What color will that same blue book appear under a pure red light?

7. What typically happens to the light energy that is absorbed by an object?

8. If a lamp shines on two pillows, one white and one black, for the same amount of time, which pillow will be warmer? Why?

9. Why are red, green, and blue the primary colors of light?

Commentary

1. This question gets at whether or not students realize white light contains all the colors of the spectrum. Students who do will say that a spectrum is just white light broken down into its component parts or that white light is just the colors of the spectrum all mixed together. Students who do not understand this will say the difference is that the spectrum has colors and white light doesn't.

2. Watch for students who write that the color comes from the book. The correct answer is that the color comes from the light the book reflects to our eyes. The color is a characteristic of the light, not the book.

3. a This is a straightforward recall question. A cone cell is a cell in the retina of the eye that is sensitive to particular wavelengths of light.

   b. Another recall question. Humans have three kinds of cone cells. Some are sensitive to blue light, some to red, and some to green.

   c. Yet another recall question. The purpose of these questions is to remind students about cone cells before they answer the questions that are to follow. We see other colors when some combination of cone cells are stimulated.

4. The screen will appear white because each of our three kinds of cone cells will be stimulated; when that happens, we see white. Some students may need you to explain this to them.

5. It will appear blue. The crucial part of the question is, "Why?" A good answer will state that the book can reflect only blue light, and since blue light is hitting it, it can reflect that light to a person's eyes.

6. The book will now appear black because there is no blue light for it to reflect; it absorbs the red light. Your students may have trouble believing this and may need you to explain why it is so when you discuss the questions.

7. It is converted to heat energy. Students must know this in order to answer the next question.

8. The black pillow will be warmer because it absorbs (and therefore converts into heat) more light than the white pillow. This question is designed to help make students aware that once an object absorbs light, the energy does not simply disappear. When you discuss this question with your students, you may want to go further and talk about what happens to the heat energy in the pillow.

9. They are the primary colors for us because of the three kinds of cone cells in our eyes: red-sensitive, green-sensitive, and blue-sensitive. Your students will have an easier time understanding the concept of primary colors, not to mention memorizing them, if they know and understand this.