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ABSTRACT

This booklet is a teacher's manual in a series of booklets that make up the core of a Physical Science course designed for the freshman year of college and used by teachers in the 27 colleges participating in the Thirteen College Curriculum Program. This program is a curriculum revision project in support of 13 predominantly Negro colleges and reflects educational research in the area of disadvantaged youth. This unit approaches the topic of light by reviewing historical theories of light and waves and wave-particle duality. Geometrical optics is discussed in terms of reflection, refraction, and instruments which utilize light, such as the camera and the microscope. Physical optics is discussed in terms of color, interference, and diffraction. Experiments are provided to illustrate the major concepts. (MLH)

LIGHT

TEACHER'S CURRICULUM GUIDE

For The

THIRTEEN COLLEGE CURRICULUM PROGRAM

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ABOUT THE INSTITUTE FOR SERVICES TO EDUCATION

The Institute for Services to Education was incorporated as a non-profit organization in 1965 and received a basic grant from the Carnegie Corporation of New York. The organization is founded on the principle that education today requires a fresh examination of what is worth teaching and how to teach it. ISE undertakes a variety of educational tasks, working cooperatively with other educational institutions, under grants from government agencies and private foundations. ISE is a catalyst for change. It does not just produce educational materials or techniques that are innovative; it develops, in cooperations with teachers and administrators, procedures for effective installation of successful materials and techniques in the colleges.

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From 1967 to the present, ISE has been working cooperatively with the Thirteen-College Consortium in developing the Thirteen-College Curriculum Program. The Thirteen-College Curriculum Program is an educational experiment that included developing new curricular materials for the entire freshman year of college in the areas of English, mathematics, social science, physical science, and biology and two sophomore year courses, humanities and philosophy. The program is designed to reduce the attrition rate of entering freshmen through well thought-out, new curricular materials, new teaching styles, and new faculty arrangements for instruction. In addition, the program seeks to alter the educational pattern of the institutions involved by changing blocks of courses rather than by developing single courses. In this sense, the Thirteen-College Curriculum Program is viewed not only as a curriculum program with a consistent set of academic goals for the separate courses, but also as a vehicle to produce new and pertinent educational changes within the consortium institutions. At ISE, the program is directed by Dr. Frederick S. Humphries, Vice-President. The curricular developments for the specific courses and evaluation of the program are provided by the following persons:

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The curriculum staff is assisted in the generation of new educational ideas and teaching strategies by teachers in the participating colleges and outside consultants. Each of the curriculum areas has its own advisory committee, with members drawn from distinguished scholars in the field but outside the program.

The number of colleges participating in the program has grown from the original thirteen of 1967 to nineteen in 1970. The orginal thirteen colleges are:

Alabama A. & M. University	Huntsville, Alabama
Bennett College	Greensboro, North Carolina
Bishop College	Dallas, Texas
Clark College	Atlanta, Georgia
Florida A. & M. University	Tallahassee, Florida
Jackson State College	Jackson, Mississippi
Lincoln University	Lincoln University, Pennsylvania

Norfolk State College	Norfolk, Virginia
North Carolina A. & T. State University	Greensboro, North Carolina
Southern University	Baton Rouge, Louisiana
Talladega College	Talladega, Alabama
Tennessee State University	Nashville, Tennessee
Voorhees College	Denmark, South Carolina

A fourteenth college joined this consortium in 1968, although it is still called the Thirteen-College Consortium. The fourteenth member is

Mary Holmes Junior College	West Point, Mississippi

In 1971, five more colleges joined the effort although linking up as a separate consortium. The members of the Five-College Consortium are:

Elizabeth City State University	Elizabeth City, North Carolina
Langston University	Langston, Oklahoma
Southern University at Shreveport	Shreveport, Louisiana
Saint Augustine's College	Raleigh, North Carolina
Texas Southern University	Houston, Texas

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The Ford Foundation
The Carnegie Corporation
The ESSO Foundation

Thirteen College Consortium
Physical Science Teachers

	1967-68	1968-69	1969-70	1970-71
Alabama A & M:	Army Daniel	Army Daniel	Army Daniel	Army Daniel
Bennett:	Perry Mack	Perry Mack	Dorothy Harris	Dorothy Harris
Bishop:	Burtis Robinson	Burtis Robinson	Burtis Robinson	Burtis Robinson
Clark:	Arthur Hannah	Arthur Hannah	Arthur Hannah	Arthur Hannah
Florida A & M:	Ralph Turner	Lewis Allen	Robert Flakes	Melvin Gadson
Jackson State:	Dennis Holloway	Dennis Holloway	Dennis Holloway	Dennis Holloway
Lincoln:	Sabinus Christen-sen	Sabinus Christen-sen	Julian McCreary	Julian McCreary
Mary Holmes:	----------	Thomas Wirth	Thomas Wirth	William Royal
Norfolk State:	Melvin Smith	Melvin Smith	Leon Ragland	Leon Ragland
North Carolina State:	Curtis Higgen-botham	Vallie Guthrie	Vallie Guthrie	Vallie Guthrie
Southern:	Thomas Wirth	Charles Osborne	Charles Osborne	----------
Talladega:	Harban Singh	Harban Singh	Aleyamma George	Aleyamma George
Tennessee State:	Berry Hempstead	Berry Hempstead	Wil Cumming	Wil Cumming
Voorhees:	Bernie Dingle	Bernie Dingle	Bernie Dingle	Donald Volz

Five College Consortium
Physical Science Teachers

1970-71

Elizabeth City State College	Kumar Chatterjie
Langston University	Jimmie White
Saint Augustine's College	Ramesh Mathur
Southern University at Shreveport	Margaret Knighton
Texas Southern University	Edward Booker

Eight College Consortium
Physical Science Teachers

1971-72

Alcorn A. & M College	Newtie Boyd
Bethune-Cookman College	Walter Floyd
Grambling College	Thomas Williams
Jarvis Christian College	Adell Mills
Lemoyne-Owen College	Charles Phillips
Southern University at New Orleans	Charles Scott
University of Maryland (Eastern Shore)	Leon Punsalan
Virginia Union University	James Fennessey

PREFACE

This booklet is one of a series of seven that make up the core of a course in Physical Science designed and used by teachers in the twenty-seven colleges participating in the Thirteen-College Curriculum Program.

The course has several unique features. Especially important is its balanced emphasis on effective teaching methodology and basic concepts in the physical sciences. The two are closely woven into the fabric of the course. Consequently, in order that a teacher gain maximum use of these materials which were designed especially for the TCCP course it is essential that he understands the purposes it was designed to serve and the style and techniques chosen to accomplish them.

Course Objectives

The basic goal of the course is to make clear the nature of science as an enterprise and illustrate by numerous examples how science really proceeds. Exercises are chosen according to their potential to bring students into working contact with the essential aspects of the scientific experience. In these experiences the students develop concrete ideas about the operational meaning of, and the association between observation, experiment, measurement, hypothesis, theory, the nature of evidence, test, modification, formulating questions, accuracy of language, the role and value of schematic language in general and mathematics as an appropriate language in particular, the role of the observer, prediction, and the residual mystery of unanswered questions.

Secondly we strive to develop an appreciation for the features of science that distinguished it from the other major disciplines, namely, the ability to establish a clear and testible criterion for the value of concepts and the role of experimentation as the sole criterion for the scientific truth. "Facts" and theories are never presented without a description, at least, of the experiments which support them.

By the use of a judicious choice of problems in the course we seek to divulge the peculiar nature of physical science that distinguished it from other sciences. The course stresses the use of mathematics as a major analytical took and the use of numerical patterns to describe physical phenomena.

Finally we are concerned with developing an appreciation for the value of "rigor" as a quality measure of a scientific study. A natural part of this is an exposure to the development of the analytical tools and skills to deal with scientific problems.

Pedagogical Priorities

High on our list of priorities in the course is the requirement that a substantial amount of learning take place in the classroom. Attention is given to creating learning situations where students collect information firsthand, consider its implications, and draw conclusions all within the same class period. The classrooms learning experiences are constructed so that they closely approximate real life situations where one has to search for clues and insights from a variety of sources, from reference materials, the teacher, as well as other students. The student must acquire the habit of weighing carefully the value of the information obtained from each.

Because of the variety of learning styles among the students, a mechanism is established for generating a variety of models of information integration. By encouraging students to actively participate in classroom exercises and develop ideas from the evidence that is presented for class inspection, the students themselves provide a range of models of learners. Students are encouraged to seek information from one another and teach themselves while the teacher supervises. This setting generates a number of dramatic experiences in a process of vital intellectual interaction.

The role of the teacher in the classrooms described above differs from that in a more traditional lecture oriented classroom where he is the central figure in the classroom and the prime source of information. In the settings described above the teacher becomes a coordinator. It is his responsibility to assist the students in seeking information and judging the value of what they find. He asks students the questions he would ask himself when he is in search of answers to crucial questions, displays the criteria he uses to reach conclusions, and thus allows the students themselves to make the crucial steps in the learning process. In order to be effective in this role, a teacher must accept as legitimate a wider base of student experiences, priorities, intellectual styles and range of abilities.

It has been our experience that if these things are given proper attention, students develop an attitude about learning, where the learner is active, aggressive, and effective.

The Scope and Structure of the Course

The course is based upon five topics:

1. The Nature of Physical Science
2. Light
3. Inorganic and Organic Chemistry
4. Conservation principles

5. Gas Laws and Kinetic Theory

Each unit is self-contained, starting with a fundamental concept and developing in a spiral fashion through a hierarchy of levels. Each level contains the development of at least one fundamental idea from empirical data obtained in the laboratory, the demonstration of the utility of the concept, and a natural termination point that permits a study to end at a variety of levels always with a sense of completion. By virtue of their self-containment, a given unit may be interchanged in a course sequence with almost any other; consequently, a teacher may construct his course around the sequence of units that best suits h s own interests and the background of his students.

FORMAT OF THE UNIT

This booklet has been designed to serve as a guide to assist the teacher in creating a successful classroom in a laboratory oriented course. As such it contains a number of hints, suggestions, and procedual instructions. When questions are presented in the text as a part of the development of a concept, answere are also given. These special features of the unit are unique to the teacher's version and do not appear in the companion student workbook.

There is a basic uniformity to the structure of each chapter. Each chapter is built around experimental activities that are designed to develop one or more fundamental physical concepts. The structure of the chapters are usually divided into four parts. First, to set the stage, we suggest a discussion session with the class to examine their intial ideas and attitudes about the problem to be studied and to establish a base of reference with which to compare the ideas that are developed in the course of the investigation. Secondly, we move to extablish the rationale for beginning a particular experiment - or set of experiments - and design the experiment. Thirdly, experiments are carried out, data gathered, and the search for physical patterns begins. Once these patterns are identified and a useful description is constructed we move to an examination of its applications and implications.

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We wish to thank Miss LuCinda Johnson for doing an excellent job of drawing the diagrams and other illustrations for this unit.

CONTENTS

I. HISTORY

A. Ancient Views

Since man necessarily approaches nature through sensory experiences, it is not surprising that in the earliest theories concerning light, the sensory (physiological) process of seeing was not clearly separated from the external phenomena of light. The Pythagoreans believed in an emission theory supposing that objects emitted particles which bombarded the eye. The Platonic school explained that vision was produced by an interaction among rays emitted by the sun, particles emmited by the object, and the eye itself emitting rays of "streams of vision". Euclid, believing that the eye emits rays which travel in straight lines, applied his geometry to problems of perspection by drawing divergent straight lines from the eye toward the object. Thus began the use of the idea of a ray of light as a fundamental concept in what one calls "Geometrical Optics".

Among the many scientific speculations, there seems to have been only one real scientific law. Hero of Alexandria (AD100) furnished a simple and beautiful proof that for reflection from a plane surface, the light must travel along the shortest path between the eye and the object in order to make the angle of incidence equal to the angle of reflection. It has become a basic law, one that governs the phenomenon of the reflection of light rays and enables us to understand the operation of mirrors.

The second great theoretical advance was the discovery of the law of refraction by Snell (1621) which asserts that when a ray of light passes from one medium to another, it is bent or refracted by an amount that depends only on the angle of incidence and the relative optical properties of the two media - the one it is leaving and the one it is entering. These two laws comprise the basic framework for the theory of Geometrical Optics - which is the body of knowledge used in the design and study of optical instruments such as; eye glasses, the eye itself, the telescope, and the microscope.

B. The Age of Newton

Of all the founders of the theory of light, undoubtedly the greatest were Sir Isaac Newton and Christian Huygens. Newton discovered the theory of the spectrum. It had already been known that white light could be resolved into colors on passing through glass or water and based on it the rainbow had been explained, but it was supposed that the medium had produced a definite alteration in the light. Newton showed that if the light passed through a glass prism, the white light would be reformed from the colors, and also if a single color from the spectrum is treated similarly it remained unchanged, which facts led to the currently accepted explanation of white light would be reformed from the colors, and also if a single color from the spectrum is treated similarly it remained unchanged, which facts led to the currently accepted explanation of white light as being composed of all the colors. Newton also investigated the colors exhibited by thin plates and films such as soap bubbles. He placed a slightly convex lens on a flat piece of glass and observed it under white light. At the central point of contact, it appears dark, but around this point where the surfaces are separated by a very thin wedge of air, there appears a succession of brilliantly colored rings first black, then faint blue, strong white, orange, red, dark purple, violet, blue faint green, vivid yellow and so on. These rings are found to become invisible. These are not the colors of the spectrum. Their origin is better understood by considering the case where the illumination is monochromatic (of a single spectral color). This produces a dark center surrounded by a large number of rings of the color used.

The rings in white light, then can be explained as a super-position of all the colors. Not very far from the center so many of the colored rings overlap that they become blurred.

Newton attributed the rings to "fits" of reflection and transmission an idea that is quite similar to the notion of phases in wave theory. He criticized the wave theory as failing to explain rectilinear propagation and adopted a complete corpuscular theory of light which held the field for more than a century. It supposed that light consists of minute particles or corpuscles and attempted to explain all of its behavior in terms of varying corpuscular properties. The theory implies that the velocity of light must be proportional to the refractive index and act inversely proportional as in the wave theory. This distinction later provided a critical test which condemned Newton's theory.

C. The Wave Theory

Early in the 17th century, Grimaldi had observed the shadow cast be an opaque body placed in the path of a cone of light formed by a hole admitting sunlight into a darkened room. He found the shadow to be larger than that predicted by drawing straight lines from the edges of the illuminated hole past those of the opaque ogject. Moreover, there were colored bands of light parallel to the edge of the shadow (phenomenon of diffraction). Similarly, when a circular hole was larger than it should have been by simple geometry. Grimaldi hinted that light seemed to behave like waves in a liquid which could spread out into the shadow of objects in their path.

A much stronger argument for the wave nature of light came from

Christian Huygens who is the real founder of the wave theory of light. He based his belief primarily on the idea that if a beam of light were like a flight of arrows, then when two beams cross, there should be collision among the arrows. The general idea he developed is that light is a disturbance in a medium. Any disturbance acts as a center that propagates a spherical wave disturbance which expands at a constant speed. When the initial disturbance is not confined to a single point, each point is regarded as a source and the subsequent disturbance is the geometrical envelop of the spheres surrounding all these sources. Refraction is explained by supposing that the velocity of light varies in different media.

D. Interference of Light

The second great period of discovery in the field of wave theory of light in the beginning of the 19th century was by Thomas Young. He adopted the wave principles of Huygens, but extended its application. In forming his theory, Huygens had considered only waves of the form that we should now call "pulsed", but Young made use of continuous periodic waves, which enabled him to explain Newton's rings. He stated the general principle of superposition "When two undulations from different origins coincide, either perfectly or very nearly in-direction, their joint effect is a combination of the motions belonging to each." This principle is quite general, but Young perceived that interesting results would follow only when the two sources are coherent, that is to say when two beams from the same source are brought to superposition, for only then could the irregularities in the process of emission be the same for both. He set up what proved to be one of the classical experiments underlying optical theory, namely Young's Double Slit experiment.

II. A CLOSER LOOK AT WAVES AND PARTICLES

Each of us has a perception of the differences between waves and particles. We generally think of particles as having the property of being well localized and must obey certain laws of mechanics (e.g. Newton's laws). We also recall that two particles cannot occupy the same space at the same time. These laws of mechanics (particle mechanics) can not only predict the motion of particles we can see but also of those we cannot see. Our concept of localizing particles may have to be altered, however, when we consider very small particles. This fact can be illustrated in a discussion of the role of probability in producing interference patterns with electrons.

We are probably most familiar with wave motion through the observation of the wave patterns of water. We observe the waves rushing in to the shore and the circular pattern of waves when we throw a rock into a pond. Although many waves patterns seem very complicated, they too can be explained by a few simple laws which govern their behavior as was seen in the case of particle motion. These laws which govern wave motion are called wave mechanics.

The study of wave mechanics is very necessary since all things cannot be described by particle mechanics. The description of the nature of light is one of those things which is difficult to explain by particle motion alone or wave motion alone. It is not surprising then that on the basis of their observations and experimentation Newton proposed that light consisted of beams of particles while Huygens, a Dutch physicist, suggested that light consisted of waves. Almost a hundred years later, Young, through his double slit experiments, demonstrated that light obeyed the laws of wave mechanics. Still after another hundred years, Einstein's explanation of the photoelectric effect showed that this phenomenon could best be described by particles of light energy called photons.

It is fairly clear then that in our study of the properties of light, both theories involving particles and waves will be necessary for various experimental and theoretical descriptions. We will probably want to ask ourselves in each case what theory best explains a particular example and why.

III. GEOMETRICAL OPTICS

Definition: The study of optics is usually divided into physical and geometrical optics. Physcial optics is generally concerned with the nature and properties of light itself. Geometrical optics deals with the properties of optical instuments such as the telescope, microscope; mirrors and prisms from which they are constructed.

Objectives: A study of geometrical optics is important partly because of the simplicity with which it explains many of the essential properties of optical instruments.

Concepts: The basic concept in the theory of geometrical optics is the ray of light. It is assured that the ray of light continues in the same straight line while it travels in the same homogeneous medium.

Reflection - Refraction: When a ray of light meets a surface separating one medium from another such as the surface between air and water, the light flux divides, in general, and follows two paths, one of wnich remains in the original medium while the other passes into the second. Both of these paths continue as straight lines in so far as the media are homogeneous. At each surface, the original light path (incident ray), the light path in the second medium (refracted ray), and the path that returns to the original medium (reflected ray) are determined by simple geometrical laws, and the laws of reflection:i.e.

a. The incident ray, the reflected ray and the normal to the surface at the point of reflection lie in one plane.

b. The incident and reflected rays lie on opposite sides of the normal.

c. The angles made by incident and reflected rays with the normal are equal.

Laws of Refraction:

a. The incident ray, the refracted ray and the normal to the surface at the point of refraction lie in the same plane.

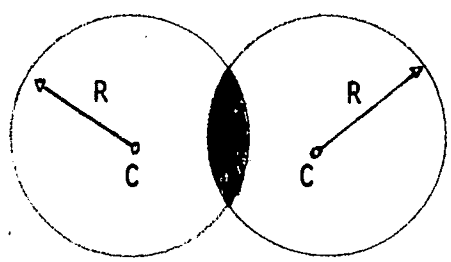
b. The incident ray and the refracted ray lie on opposite side of the normal.

c. The sine of the angle of incidence (angle between incident ray and normal) bears a constant ratio with the angle of refraction (angle between refracted ray and normal). This ratio depends on the composition of the two media and is known as the relative index of refraction.

Demonstration Experiments: The purpose of the set of experiments herein dealt with is mainly to acquaint the students with the basic concepts and simple laws embodied in geometrical optics, in accordance with the rectilinear propagation of light in a homogeneous medium. Without taking actual elaborate measurements, the student can be made to visualize the phenomena of reflection, refraction, despersion, etc. which would be sufficient for a basic understanding of the technique involved in the construction of optical instruments and other related studies.

In demonstrating the experiments the use of a light ray box is emphasized in most cases. Thus the student is introduced to the concepts through experiments he can manipulate and inspect himself.

In the study of lenses there are certain basic principles related to their construction which will aid in the analysis of images. If we let two circles, each of radius R and center C intersect we observe:



assuming now that the shaded area is a lens of small thickness, R is the radius of curvature and C is the center of curvature. This particular lens is called a converging lens since it will tend to converge light rays passing through it. We now consider three principal rays of light passing through the lens: (1) one ray parallel to the axis; (2) another ray through the center of the lens; and (3) the other through the principal focus F (the principal focus is the point on the axis where incident parallel rays entering on one side of the lens converge at the principal focus on the other side of the lens).

If we adjust a ray box so that it gives parallel rays of light and place a convex lens in front of these rays we can show by adjusting the lens the results shown in figure 1.

Parallel ray from ray box:

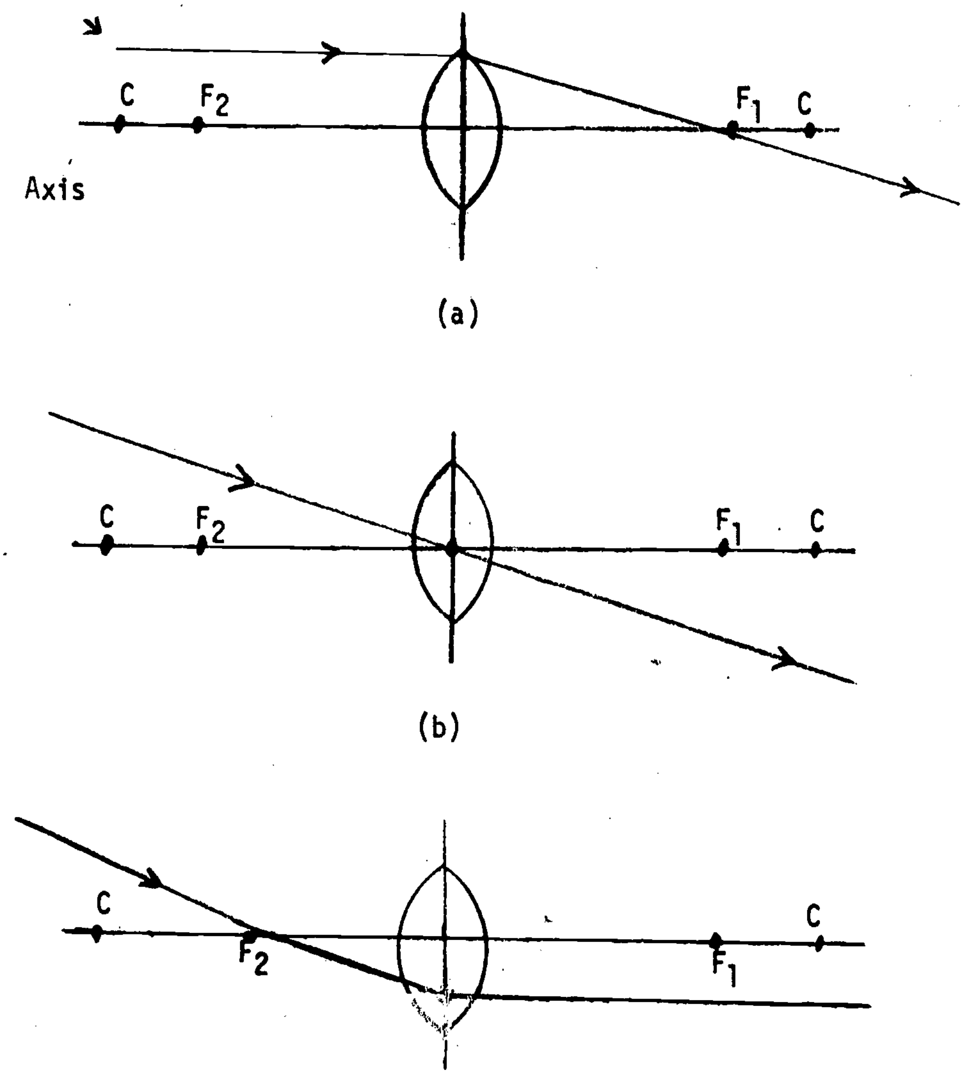


Figure 1

In (a) the ray parallel to the axis is bent by the lens so as to pass through the principal focus F_1; In (b) the ray passing through the center of the lens is not deviated from its straight line path; and in (c) the ray passing through F_2 emerges parallel to the axis containing F_1.

Many kinds of images can be found by placing the object at various distances from the lens, i.e. outside the principal focus, between the principal focus and the lens, etc. Figures (F) and (G) illustrate two possible positions for the objects and the subsequent images. In general, a real image is formed by the conveying lens when the object is on one side of a lens and the image is formed on the opposite side by intersecting principal rays. The virtual image is formed on the same side of the lens as the object and arises because of an "apparent" intersection of principal rays.

A. Reflection: Let a beam from the ray box fall on a plane mirror in a known direction. Catch the beams reflected image on a surface and verify the laws of reflection quantitatively.

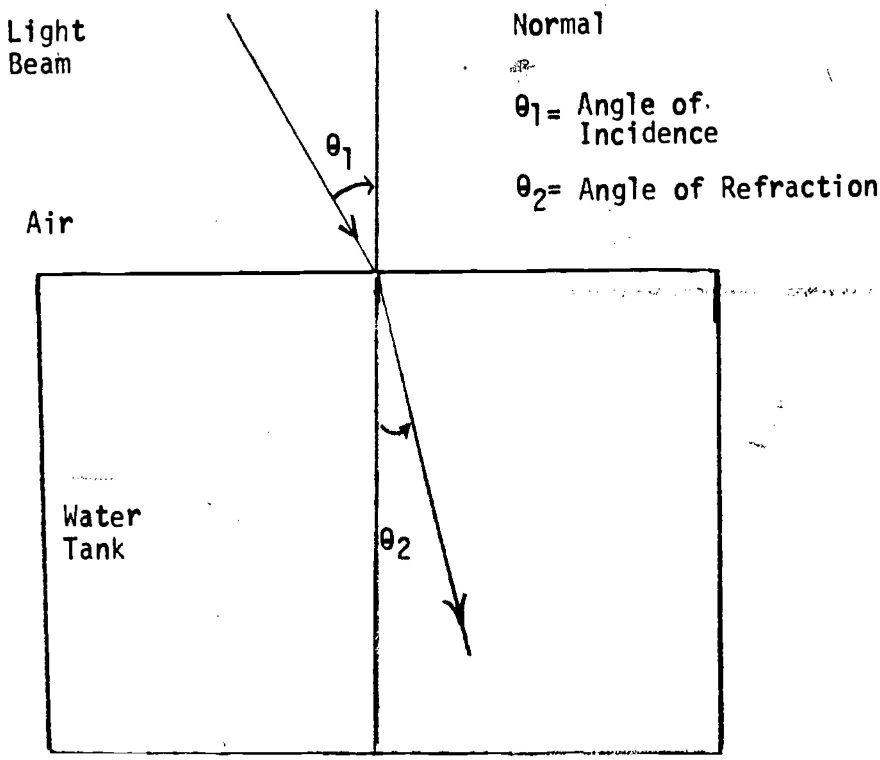
B. Refraction: Let the beam fall at an angle at the air-water boundary in a trough. Catch its direction on a ground glass inside water and also emerging from water to air.

An experiment should be performed to emphasize the empirical relationship of the incident angle to the angle of refraction as light travels from one medium which has certain properties into another medium of different properties (e.g. from air to water; from air to glass; from glass to water, etc.) using suitable apparatus (i.e. water tank, see figure 2) to measure the angles at different interfaces, we shall call the incident angle θ_1 (which we shall measure in air first) and the refracted angle θ_2 (measured in glass, water, etc.). This experiment is done in lieu of a direct introduction to Snell's law in its familiar form.

(a) The data can be recorded in the following form using table 1. Figure 2 illustrates the data technique.

TABLE 1

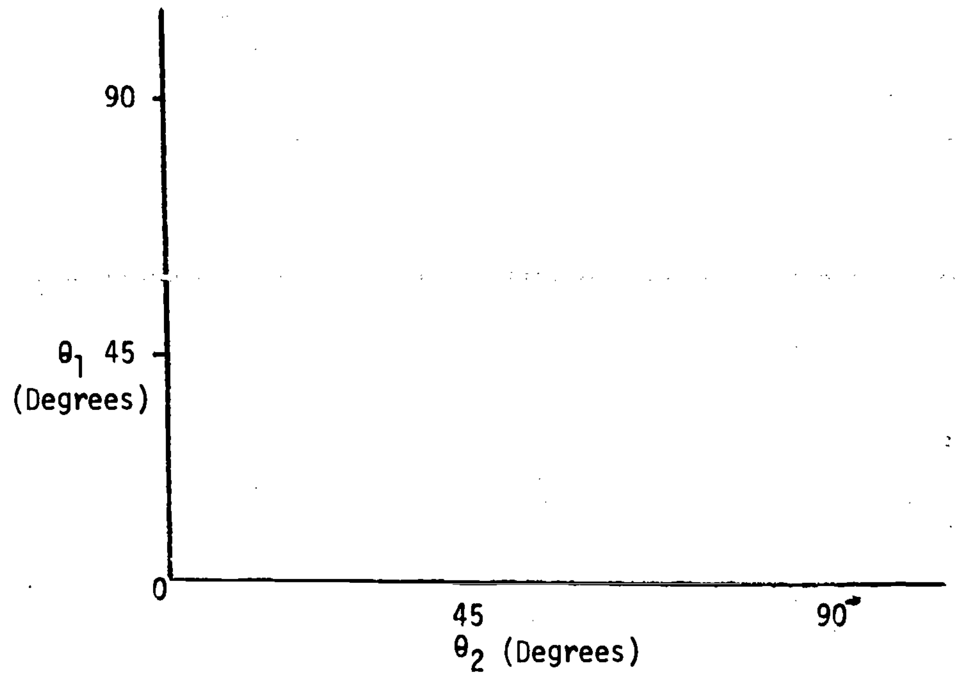
θ_1 (Degrees)	$\theta 2$ (Degrees)	$\theta 1/\theta_2$
5		
10		
15		
20		
25		
.		
.		
.		
.		
.		
85		
90		



Light Beam
Normal
θ_1= Angle of Incidence
θ_1
θ_2= Angle of Refraction
Air
Water Tank
θ_2

Figure 2

(b) Make a plot of θ_1 versus θ_2 with θ_1 on the vertical axis and θ_2 on the horizontal axis and connect the points in order to form a curve.



(c) Make a second plot using additional values of θ, as 3°, 4°, 5°, 6°, 86°, 87°, 88°, 89°.

Analysis Questions for a-c:

1. Is there some kind of relationship between the ratio θ_1/θ_2? (i.e. Is the ratio a constant?)

2. How do the ratios of the small angels $\frac{\theta 1}{\theta 2}$ compare? (i.e. with 1°, 2°, 3°, etc. for θ_1).

3. How do the ratios of the large angles $\frac{\theta 1}{\theta 2}$ compare? (i.e. with 80°, 81°, 82°, 83°, etc. for θ_1)

4. Can you now predict from your curve the values of any θ_2 (<90°) once you know the value of θ_1? (Assuming of course that you consider the same two media).

(d) Using table 1 and a trigonometry text or mathematics handbook and find the sine of each θ_1 and θ_2 and form table 2.

TABLE 2

$\sin \theta_1$	$\sin \theta_2$	$\frac{\sin \theta_1}{\sin \theta_2}$

Analysis questions for d:

1. How do the values of the ratio $\frac{\sin \theta_1}{\sin \theta_2}$ compare?
2. Can you make any conclusion(s) concerning the θ_1/θ_2 ratio as compared to the $\frac{\sin \theta_1}{\sin \theta_2}$ ratio?

In general it has been determined that for two media (i.e. air and water, air and glass, etc.) $\sin \theta_1/\sin \theta_2$ is a constant. In fact we can now write a relationship:

$$\frac{\sin \theta_1}{\sin \theta_2} = \text{constant} = \frac{n_2}{n_1} = n_{12}$$

where the constant is equal to the relative index of refraction of the two media (n_{12}). This is called Snell's Law. n_1 and n_2 are the index of refraction of light passing from air into each of the two media respectively. As an example:

$$\frac{\sin \theta \text{ air}}{\sin \theta \text{ glass}} = \frac{n \text{ glass}}{n_{\text{air}}} = n_{\text{glass}}$$

For this case n glass is almost equal to the index of refraction of glass since n_{air} is about 1.

Snell's law is a very valuable relationship. For now if we wish to find how light will be bent on entering any substance from air, we need only to have initially the index of refraction of the substance.

C. Total Reflection: In the above experiment, catch the image on a screen emerging from the water inside the beaker. Change the direction of the indident beam increasing the angle of incidence. Demonstrate the change of position of the emergent beam. Increase the angle of incidence further and further until the beam is suddenly found to disappear and to appear in a different direction altogether by total internal reflection, following the laws of reflection.

D. Deviation and Dispersion Produced by a Prism

Direct a beam of white light on to the face of a prism and catch the spectrum on a screen on the other side. Note the order of colors.

Let the emergent light from the second face of the prism fall on a similar prism kept in the reverse position to the first. The emergent light will be found to give white light again.

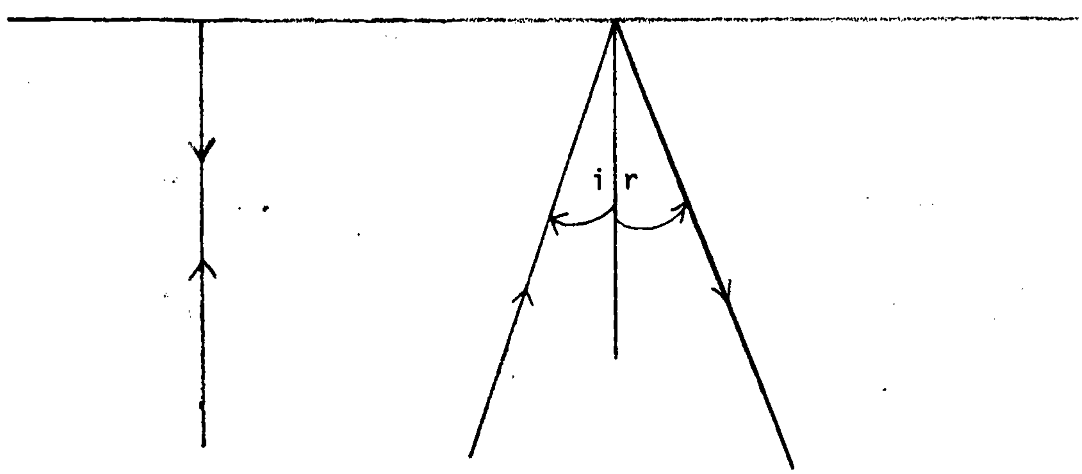
E. Image Formed by Lenses

With an illuminated slit serving as the object on an optical bench, catch the position of its image formed by a convex lens with the object at various distances from the lens (that is, object at infinity, just beyond 2f, at 2f between f and 2f between f and 0 etc.). Explain with illustrative diagrams why the image cannot be caught on the screen at certain positions of the object - the difference between real and virtual images.

F, G, H. Illustrate diagramatically the formation of images by concave lens. Demonstrate the working of the (F) camera, (G) microscope and (H) telescope in the classroom.

Note: The Demonstration experiments can be shown first and the principles and laws deduced thereafter, by general class discussion.

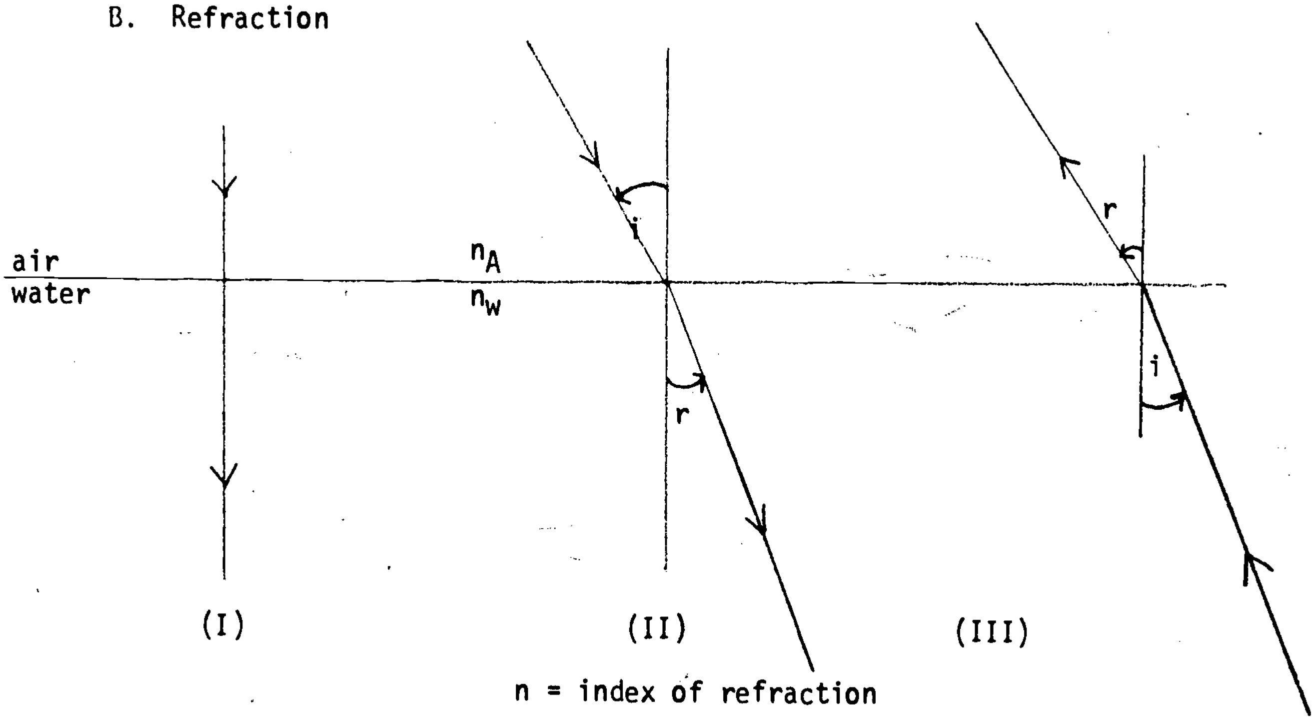
A. Reflection at a plane surface



i = Angle of incidence
r = Angle of reflection

i = r

B. Refraction



n = index of refraction

i = Angle of incidence
r = Angle of refraction

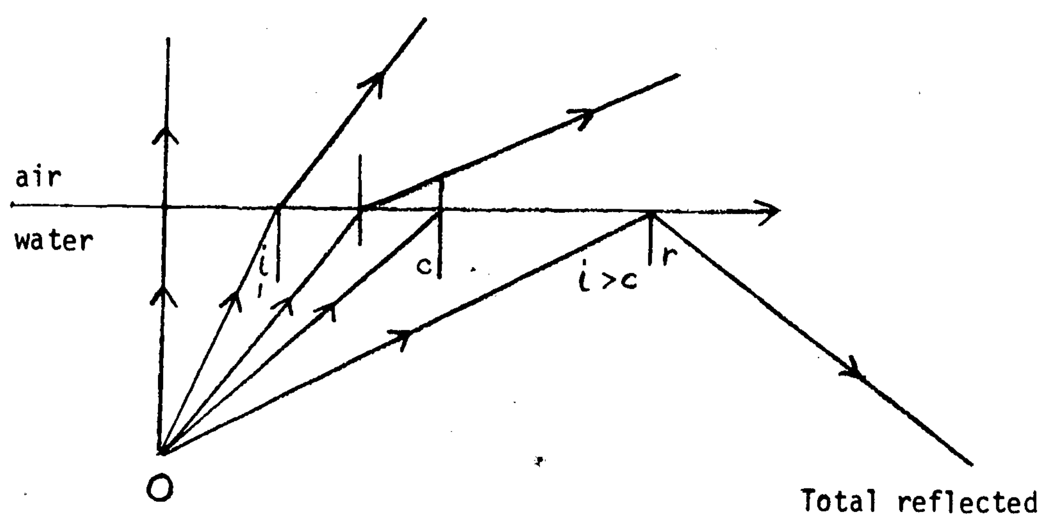
(I) Normal incidence from air to water
(II) Oblique incidence from air to water

$\frac{\text{Sin } i}{\text{Sin } r}$ = Refraction index of water with respect to air.

$= \frac{n_{water}}{n_{air}}$

(III) $r < i$ Refracted ray is bent towards normal when a ray of light passes from a rarer (Air) medium to a denser (water) medium as shown in (III)

C. Total Internal reflection

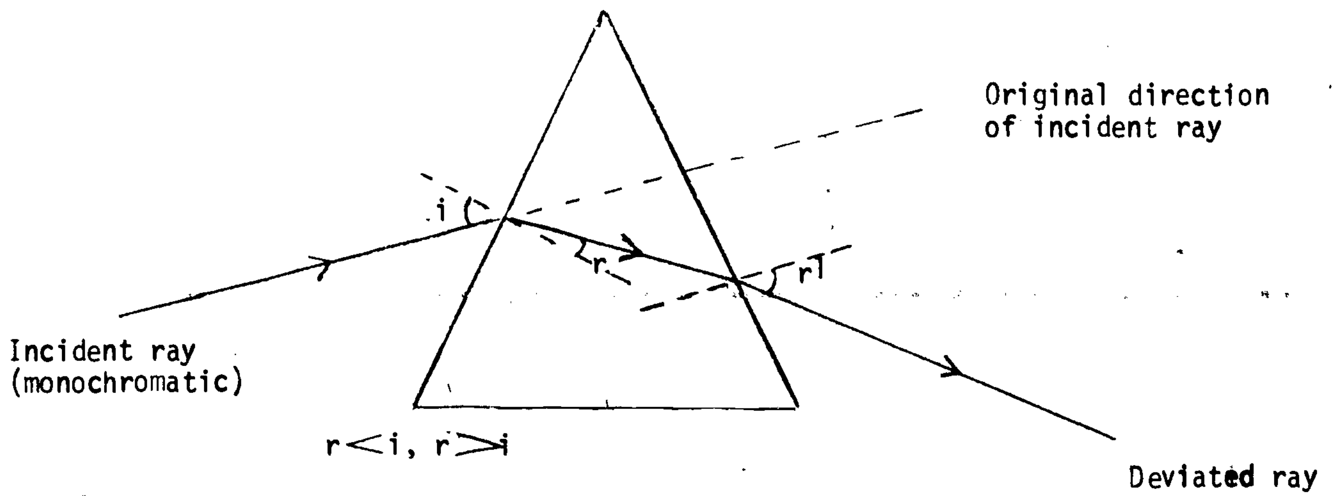


c = angle of incidence (critical angle) for which angle of refraction is 90°

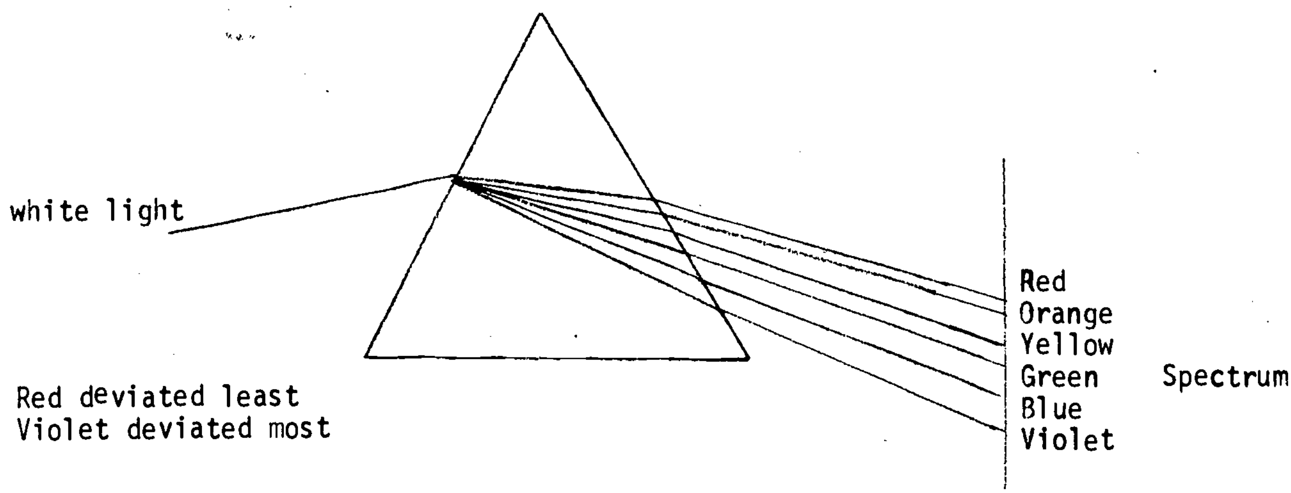
D. Deviation and dispersion produced by a prism.

1. Refraction through a prism.

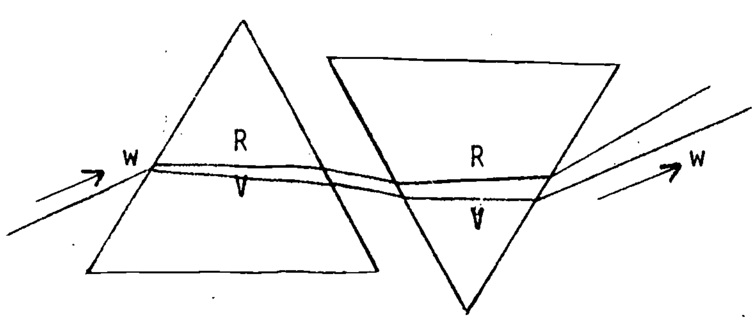
2. Deviation by a prism



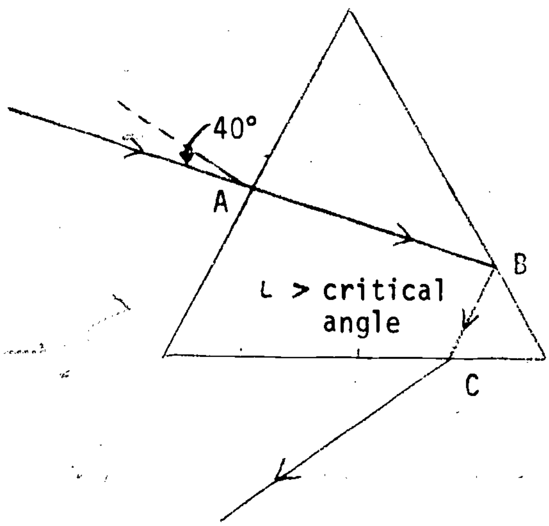
3. Dispersion by a prism



4. Recombination of white light by a prism

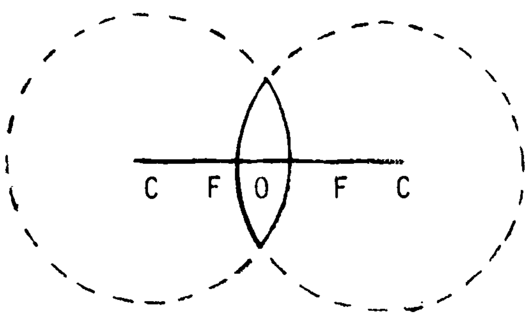


5. Total reflection by a prism

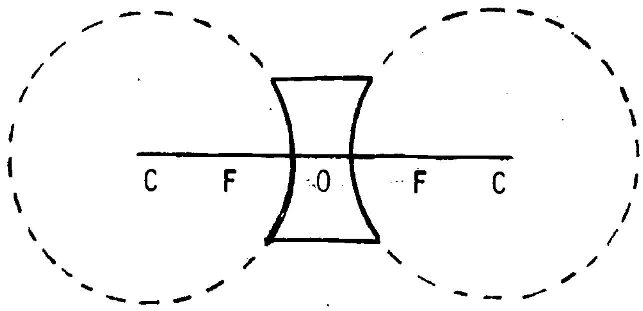


Ray totally reflected at B since angle of incidence at glass-air surface is greater than critical angle for glass (≈ 42°)

E. Lenses - Image formation



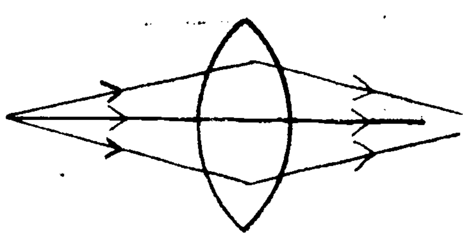
Convex Lens



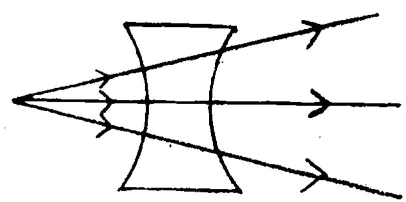
Concave Lens

c - center of curvature
F - focus of lens
O - Optic center
COC - Principal axis

<u>Principle underlying formation of images</u>



object

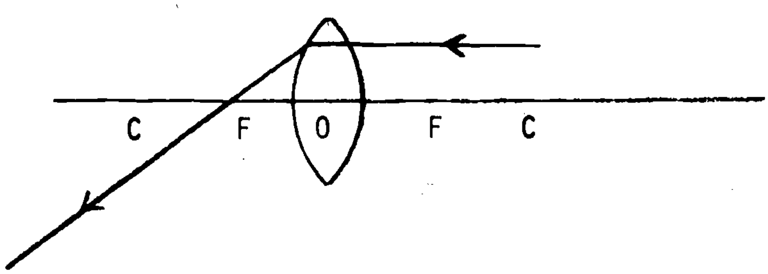


1. Illuminated object

Convex lens - gives convergent beam

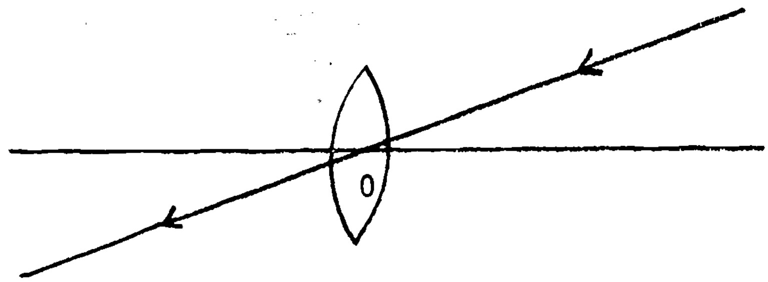
Concave lens - gives divergent rays

2.



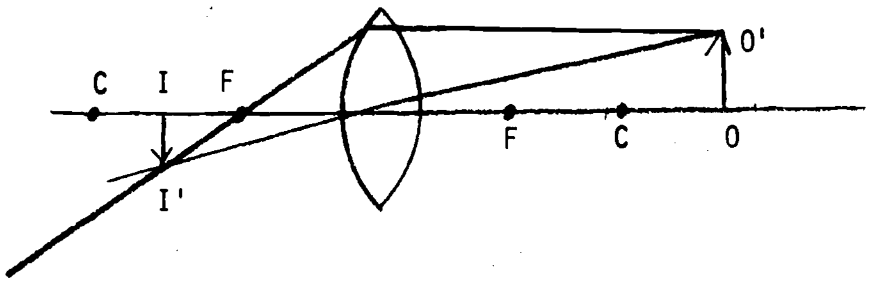
Ray parallel to principal axis passes through focus after refraction

3.



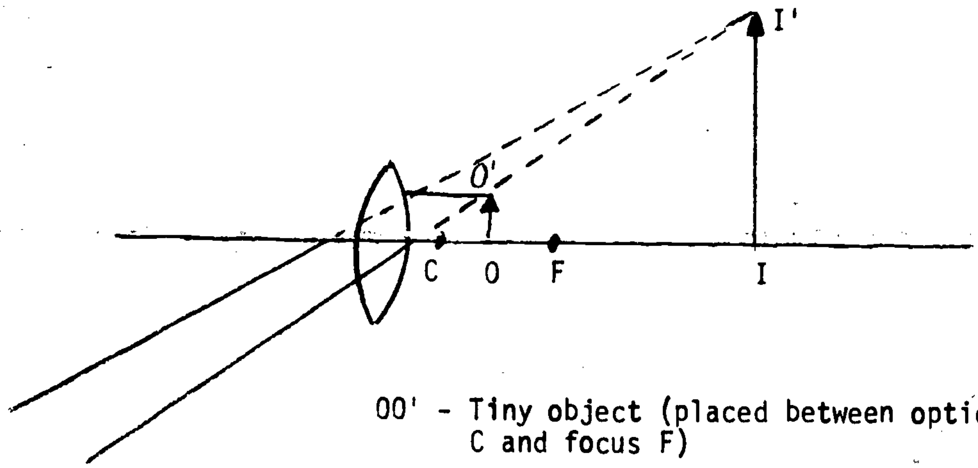
Ray passing through the optic center passes undeviated

F. Principle of the camera



00' - Object in front of lens (beyond C)
II' - Real diminished image on screen (photographic plate) formed between F & C

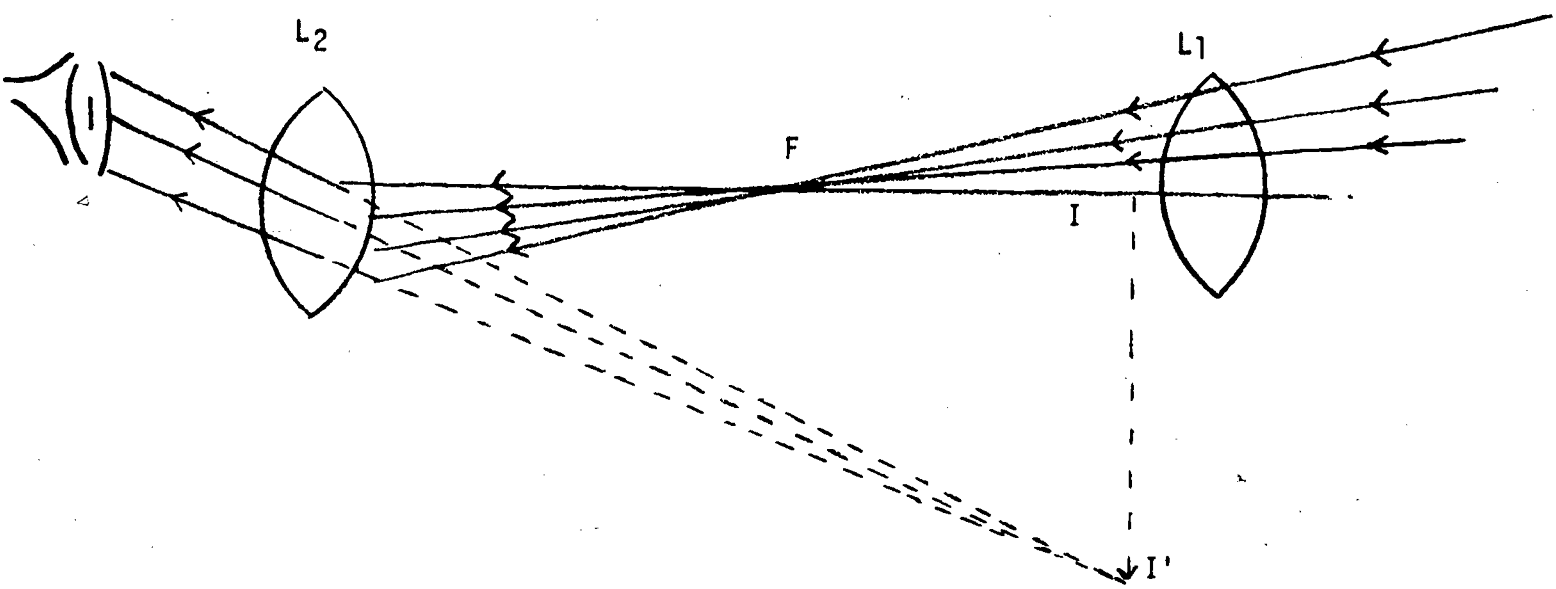
G. Principle of the microscope



OO' - Tiny object (placed between optic center C and focus F)

II' - Virtual enlarged image formed beyond C at the least distance of distinct vision.

H. Principle of the telescope



First image I formed by lens L_1 of
the distant object is adjusted to be within the focus
of the second lens L_2 so that an enlarged image II' is obtained.

Note: (1) Steps (A) to (E) can be demonstrated easily in class by using a narrow laser beam and appropriate prisms, lenses, mirror etc. (If a compact laser kit is available all the equipment necessary are provided for demonstrating the above experiments).

(2) It would be of interest to the students to go a little further in the play of mirror and lenses and demonstrate to students the formation of images by multiple reflections and by curved mirrors (concave and convex) and illustrate the difference between real and virtual images.

I. Problems for class discussion

1. When a straight stick is placed in water at an oblique angle to its surface the part under the surface appears as though bent upwards. Explain the effect with the help of a diagram.

2. A pool appears more shallow than what it really is. Explain diagramatically.

3. "You see the sun after it sets in the horizon" and the duration of daylight is extended to a small extent owing to the refraction of sunlight by earth's atmosphere. Illustrate this effect with a diagram.

4. Flint glass and carbon disulphide have almost the same index of refraction. How does this explain the fact that a flint glass rod immersed in carbon disulphide is nearly invisible?

5. Why is a beam of white light not dispersed into its components colors when it passes perpendicularly through a pane of glass?

6. Explain why a cut diamond held in white light shows flashes of color. What would happen if it were held in red light?

7. Why do stars twinkle?

8. Explain diagramatically the optical illusion - "Mirage."

9. How is the rainbow formed?

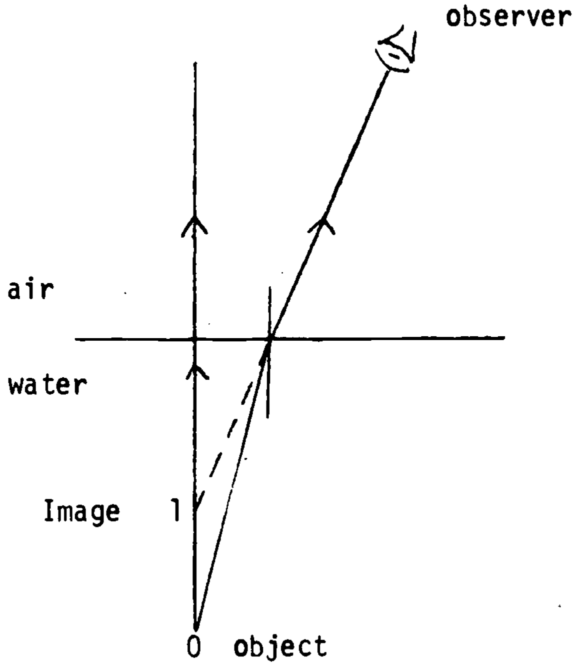
10. You see yourself enlarged or diminished or inverted in curved mirrors. Illustrate the effect with diagrams.

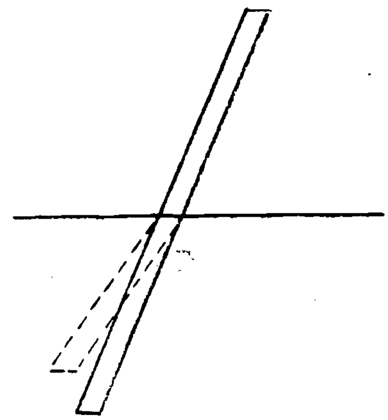
11. What optical principle is made use of in the design of the periscope of the submarine?

12. How many images of yourself can you see between mirrors inclined at 90°, parallel to each other.

Hints to the answers of selected problems.

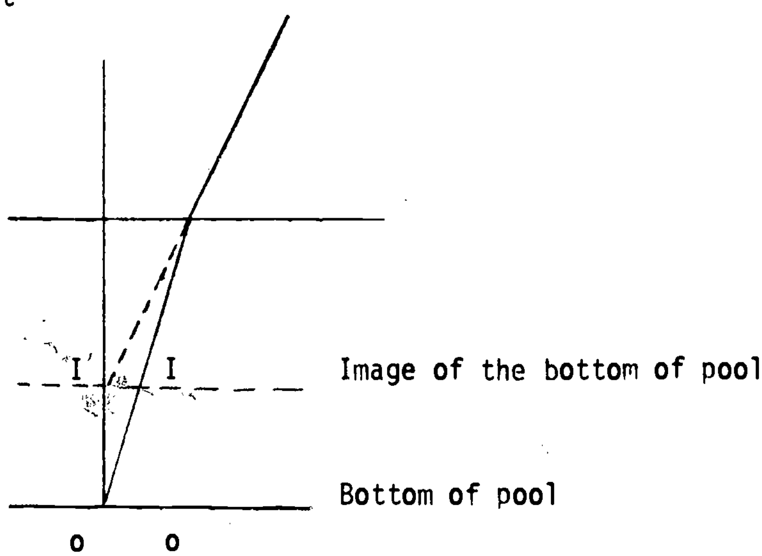
1.



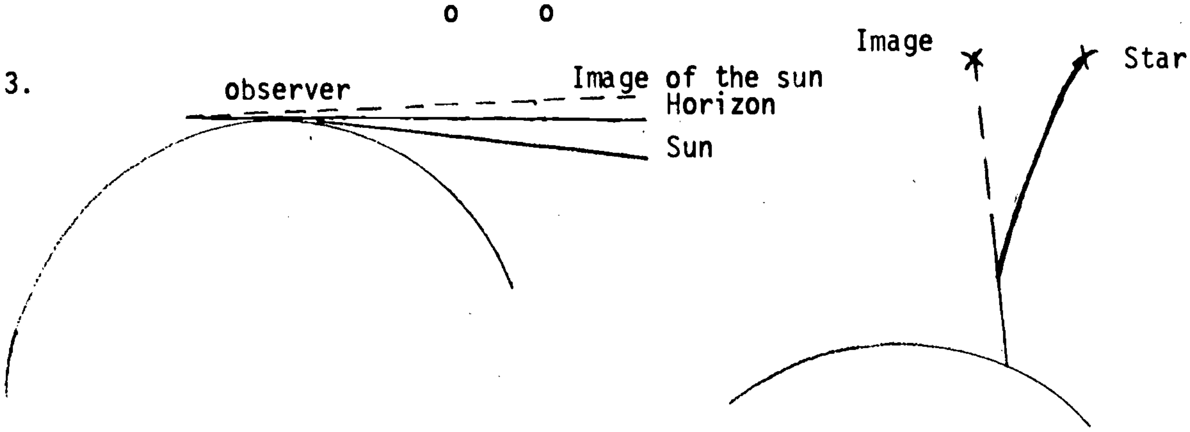


Every point on the stick under water appears to be raised.

2.

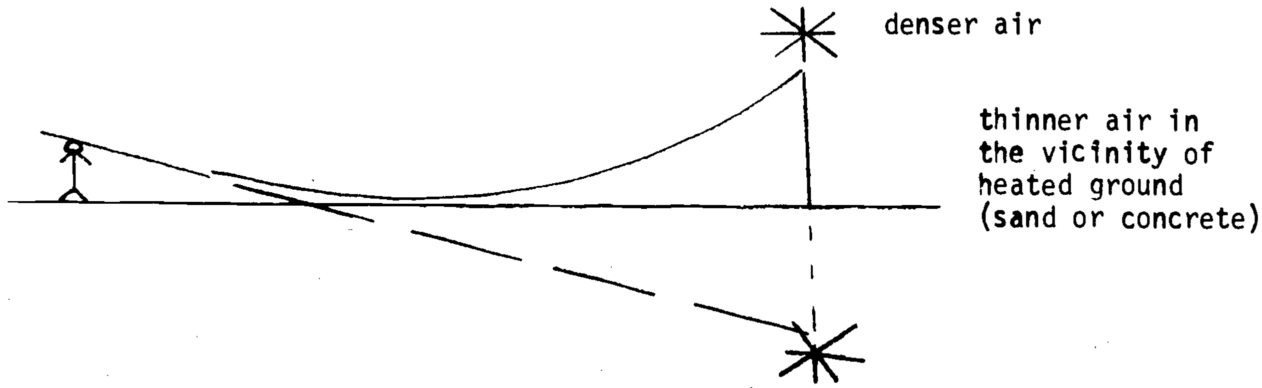


3.



In light entering the earth's atmosphere from heavenly bodies such as the sun or star, refraction takes place from rarer to denser atmosphere, and the ray is continously bent towards the normal. In such astronomical refraction, it has the effect of making the heavenly bodies appear higher above the horizon than they really are, and even after the sun goes below the horizon, for a short while the light from it reaches the earth.

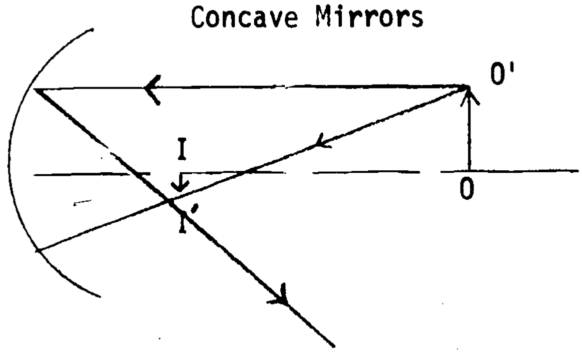
8.



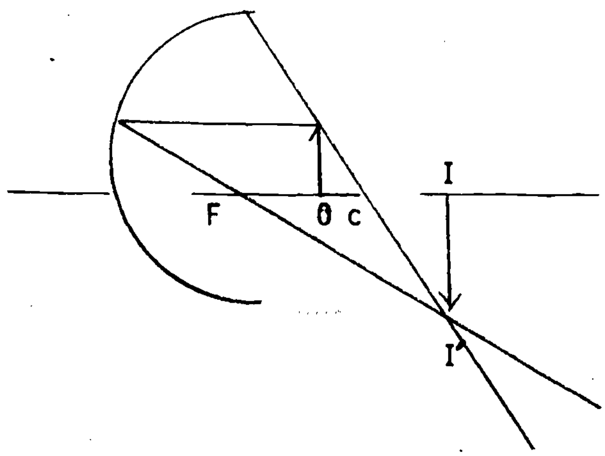
Refracted rays away from normal till far an angle of incidence (at a lower layer of air) greater than critical angle, total reflection occurs and the rays reach the observer at a distance whereby he sees the inverted image of the distant object as if reflected on the surface of water.

10.

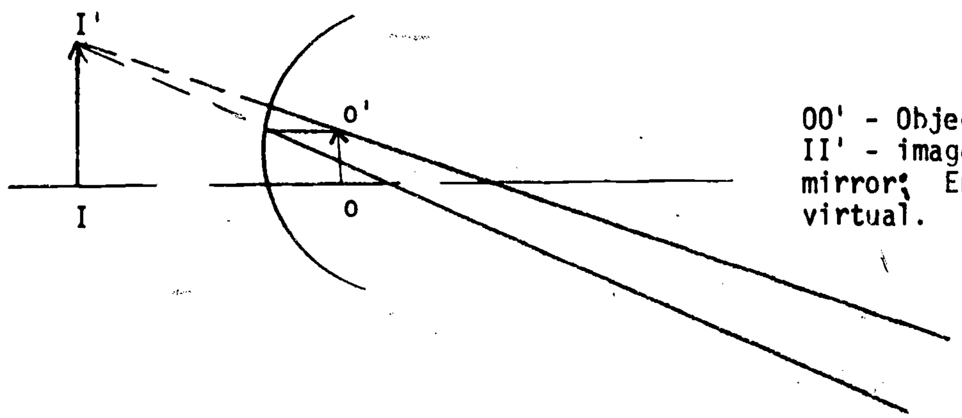
Concave Mirrors



00' - Object beyond C
II' - Image between F & C; diminished, inverted real.

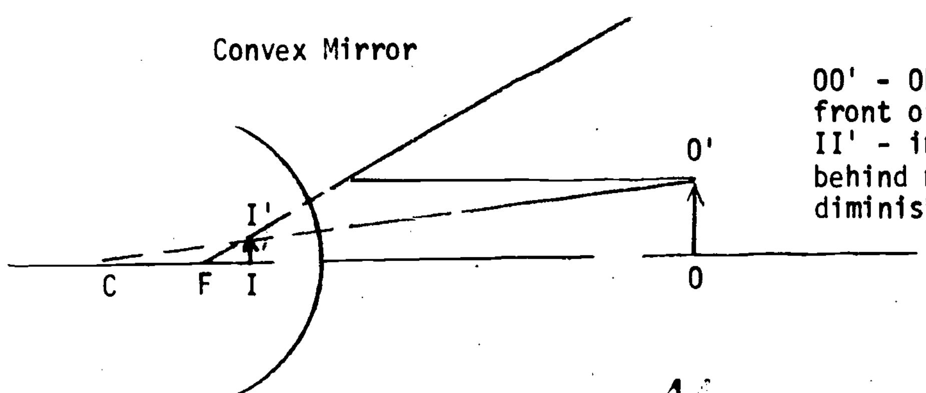


00' - Object between F & C
II' - Image beyond C; enlarged, inverted real.



00' - Object focal length
II' - image formed behind mirror; Enlarged, erect, virtual.

Convex Mirror



00' - Object anywhere in front of mirror.
II' - image always formed behind mirror; diminished, erect, virtual.

PHYSICAL OPTICS

A. Introduction

In general, Physical Optics deals with the nature and properties of light and how they are manifested in the different phenomena in exhibits in its interaction with itself and with matter. The main topics dealt with in this section are finding answers to some of our observations and experiences in nature, as for example,

1) Why does an object appear colored?
2) Does light possess energy?
3) What is a wave?
4) What are the different types of waves and what are their properties?
5) Is light a wave motion and does it exhibit the same wave properties as mechanical waves, water waves, sound waves?

Objective

In finding answers to these and other such questions, the student should be able to grasp the main ideas about waves and their general behavior. He could then more easily apply his knowledge to the abstract idea of light waves and the effects the waves produce. These topics are dealt with in detail in the later sections of this unit.

B. Color and Dispersion

In the earlier experiments on refraction we observed light as it passed through glass having two parallel sides. Our observations showed that the emerging rays of light were parallel to the entering rays. However, when two faces are not parallel, the light will emerge in a different direction than it entered.

Suppose we take two prisms and arrange them first with two bases together and shine parallel beams of light through them.

Figure 3 shows the results.

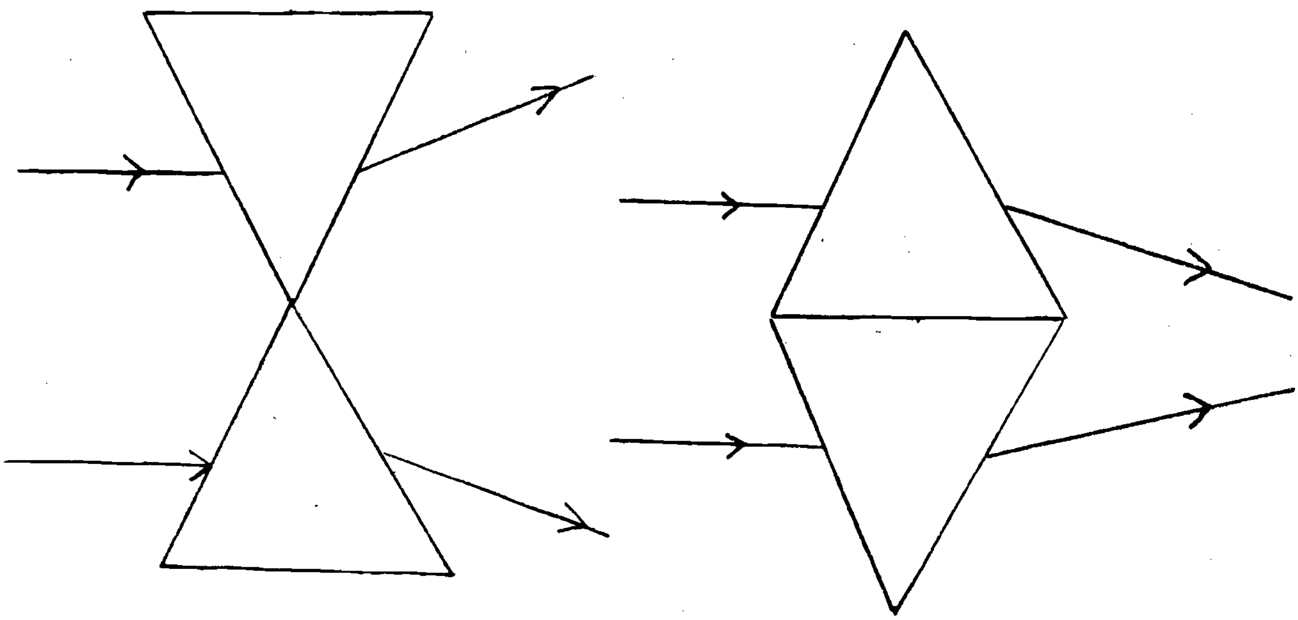


Figure 3

In each case the light beams are seen to emerge in a direction toward the base of the prisms. Figure 3a shows the emerging beam spreading out or dispersing while figure 3b shows the emerging beams converging.

1. Experiment - White Light Dispersion

Let us shine a beam of white light from the ray box through a prism and observe the dispersed light on a screen (Figure 4).

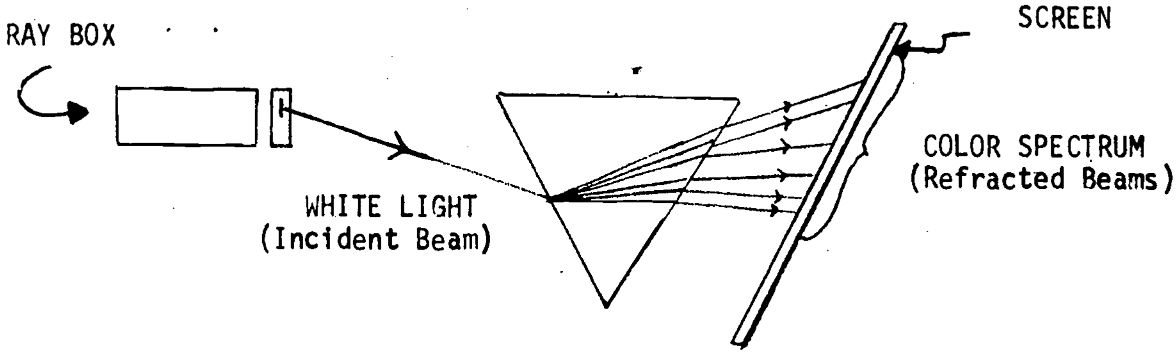


Figure 4

Analysis Questions:

1) In what direction do the emerging rays appear to be bent toward the vertex (the pointed end) or the base?
2) How many colors do you observe?
3) Can you tell which color deviates most from its original direction?
4) Can you make any conclusions about the make-up of white light?

We may conclude now that from the previous demonstration that white light is passed into the prism and the prism does something to it (namely disperses it). A logical question now might be, "why do objects appear colored"? A further question may very well be "Do colored objects take white light and do something to it that makes the objects appear colored"? Since we see things by the light that comes from them, we may ask, "does an apple appear red because the skin of the apple absorbs all of the colors of white light except the red which is reflected"? The following experiment will help us examine this possibility. This experiment is taken from the PSNS text (PSNS/ An Approach to Physical Science, John Wiley & Sons, Inc., 1969, p. 47.)

2. Experiment - Colored Objects

Make red, blue, and black marks on a piece of white paper. Use the red and blue crayons which are supplied for you and a regular black pencil. Now look through the red filter (the piece of red transparent material) at the marks on the sheet of white paper.

(a) Describe the appearance of each mark as viewed through the red filter.

(b) Is the first hypothesis in agreement with your experimental results? The second? Discuss the evidence.

(c) Can you explain why there is so little constrast between the red mark and the white paper when both are viewed through the red filter?

This experiment seems to show that white light is made up of many colors, some of which are absorbed by colored objects while others are reflected or transmitted. If this is really true, why doesn't white light look many colored? The answer to this involves the combined operations of the eye and the mind which enable us to see a many-colored beam of light as white. If white light is composed of many colors, can it be separated into those colors? Have you ever seen a little rainbow formed by light passing through a piece of glass? You can demonstrate this for yourself.

3. The Appearance of Ordinary Things

A Summary

The theories of light are not much concerned with the appearance of ordinary things. In the objects seen around, one distinguishes between the luminous and the non-luminous.

a. Colored Objects

The non-luminous objects are visible only by light reflected from some luminous source as the sun or a lamp and their difference in appearances are attributable solely to the different ways in which they reflect light. Thus a black object is one that reflects relatively very little light. A colored object is one which reflects some colors but not others.

Example

Illuminate a piece of red paper with light passed through a green glass. The result is that the red paper will appear black because there is no red light for it to reflect. On the other hand, being a mixture of all colors, a white object is one that reflects all colors about equally, and so it looks colored if illuminated only by a colored light.

b. Mixing Colors

When two pigments of colors are mixed, the resulting color will be that which they both can reflect, and may be quite different from the color seen when the colored lights are superposed on a white screen.

Example

If light from red and green lamps is compounded this way, the result is a brilliant yellow. But red and green paints when mixed, give a dark muddy color because there is little light that they can reflect in common.

4. Opaque Objects

A Test

One easy test of whether a substance is opaque is to see whether it is of the same color for reflected and transmitted light.

Example

A sheet of red paper looks red whether we look at it under a light or through it at a light. In both cases, each reflection in the tangle fibres reduces the amount of green and blue light by absorption so that only the red emerges. On the other hand if a substance is truly opaque, the result will be quite different.

Example

Gold reflects yellow light more effectively than other colors and thus appears yellow with reflected light. With a very thin sheet of gold, the transmitted light will be bluish green.

C. Experiment - A Chemical Reaction Produced by Light

The purpose of this experiment is two fold. First it is a graphic proof of the fact that light interacts with matter in such a way as to cause changes in that matter. The second purpose of this experiment is that the students will gain additional experience in laboratory techniques and observations. This experiment is taken from the PSNS text. (PSNS/An Approach to Physical Science, John Wiley & Sons, Inc., 1969, pp. 44-45.)

You will need a solution of silver nitrate and a solution of sodium chloride (table salt) for this experiment.

Place about 10 to 20 ml of the sodium chloride solution in a shallow container, such as a watch glass or small dish. Pour a few milliliters of the silver nitrate solution into a small container so that it can be easily withdrawn with a medicine dropper. Cut out a small piece, approximately 3 cm X 8 cm, of absorbent white paper, preferably filter paper, and place it on a paper towel. Thoroughly moisten about half of this paper with the silver nitrate solution, using the medicine dropper. (If, by accident, you spill any silver nitrate on your hands, wash if off immediately with water, or a dark stain will result that will take a few days to disappear.) Pick up the piece of paper by the dry end and submerge the wet portion in the sodium chloride solution for about 20 sec. Do you notice anything happening on the surface of the paper? Is there any change in the appearance of the solution?

Remove the paper and place it between two paper towels for about 10 minutes. Then take off the top towel and quickly place some object such as a coin, key, or paper clip on the piece of treated paper. Place the paper and object in direct sunlight or close to a bright light bulb. What happens to the exposed portion of the paper? The exposure time under the Sun should be about 5 minutes, but under a light bulb 10 or 15 minutes will be needed. Remove the object and record your observations. Keep this paper for a day or two and record your further observations. Have you produced a permanent record of the shape of the object? If not, can you think of ways to make it permanent?

The experiment you have just performed is a photographic experiment. The prefix "photo" refers to light; the suffix "graphic" refers to the record on the paper. The action of the light on the substance with which you impregnated the paper caused it to become dark, and thus the record was made.

It is clear that light does indeed have an effect on the substance you exposed to it. This tells us something about the substance, but it also tells us something about light. Light produced a chemical change; therefore it has energy and can transmit that energy to objects in its path. Let us see what knowledge we can add to what we have just learned.

We see objects because they either reflect light or, like the Sun emit their own light. From each visible bit of an object, rays of light reach our eyes, bringing us information about each particular spot on the object. The light has intensity - one spot may be brighter or fainter than others, light has color - that spot may be red; and light has direction - we can see the object so we know where it is. The mind pieces together all these bits of information to form a concept of the object from which the light comes. Light is essential to our investigation of solids and of the world in general. Since our investigations sometimes depend upon its less familiar properties, we need to examine light and the nature of its interaction with solid matter in more detail.

D. Interference

1. Objective

After acquiring an idea of wave motion in general, you can proceed on to an abstract line of thinking when you deal specifically with the two phenomena exhibited by light waves, namely, interference and diffraction. However, for a better understanding and application of an abstract phenomena the analogous behavior of mechanical waves, expecially water waves, are first studied, and the knowledge applied to the light waves of microscopic dimensions. This method of generalization and application is essential to the scientific approach.

Moreover, by engaging in a few lab experiments where actual measurements are taken to determine the wavelength of light, an introduction to microscopic dimensions and to a quantitative determination of their methods are done. This approach is very revealing in that it gives one an idea of how scientists work and arrive at their important results many times by simple methods.

2. Introduction

Newton's experiments and his logic theory established the particle model of light and it was not questioned until the Dutch scientist Huygens put forward the idea that light might be a form of wave motion. A stronger evidence for the wave nature of light was brought up by Thomas Young (1801) in his double-slit experiment which proved to be one of the classical experiments underlying optical theory. The experiment is simple and can be performed in the lab and from the observations, interesting and enlightening conclusions can be arrived at regarding the behavior of light waves.

3. Young's Double-Slit Experiment

Apparatus

a. Source of light - An incandescent lamp with a long straight filament.

b. Slit-System - Take a microscope slide that has been painted with a suspension of graphite in alcohol. Hold two razor blades tightly together and using a second microscope slide as a guide, draw the razor blades lightly across the graphite-coated surface so that the slits are parallel to the short edge of the slide.

Experimental Procedure

Place your eye close to the slits, and look at the lamp as shown, making sure that the slits are parallel to the filament of the lamp.

Light from a lamp source passes through two parallel slits and into the observer's eye.

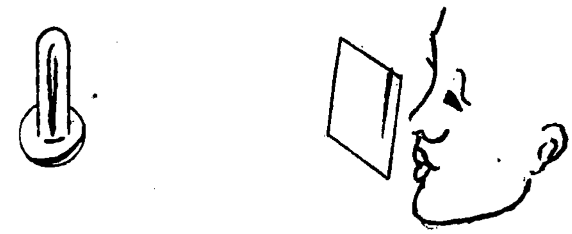


Figure 5

1. <u>Observations</u>

You see several bands of colors in a direction parallel to the slits.

<u>Inference</u>

The bands of light seen spreading out to the right and to the left can result only if the light does not pass through a narrow slit as a single narrow beam, but spreads out in either direction. This will result in the light from one slit being superimposed on the light from the other slit. Hence it is possible that these two beams of light will interfere with each other in some way, and the pattern formed is called an "Interference Pattern."

If light were composed of particles that behave as marbles do, one would probably expect to find two bands of light with perhaps a slight overlapping but certainly with no band of colors.

2. The central part of the band (for a white light source) is found to be white.

3. On either side of the central white band, the order of colors range as in a continuous spectrum starting from red and ending with violet.

4. Observe the lamp bulb through a red filter (cellophane) so that only red light passes through the slits. You see only red and black bands equally spaced.

5. Cover the upper half of the light source with a red filter and the lower half with a blue filter and observe the pattern.

The blue bands are found to be more closely spaced than the red bands.

6. Increase the separation between the slits by using a third razor blade as a spacer between the two razor blades while cutting the double slits, and observe the interference pattern with this slit system.

The pattern is found to have the bands more closely spaced with wider separation of the slits.

To understand the origin of these bands, we must first discuss in detail the principle of superposition which is one of the fundamental laws governing wave behavior.

Principle of Superposition

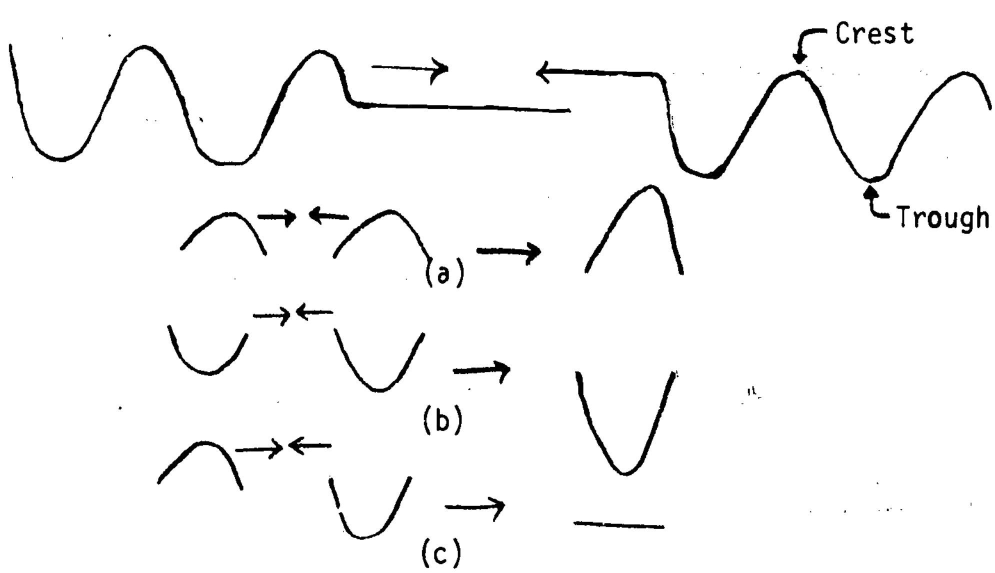
a. Water Waves

Experiments with the Ripple Tank

Generate two trains of parallel water waves of the same amplitude from opposite sides of the tank and observe what happens to the surface of water as the various waves pass by.

Observation

The surface responds to both sets of waves, with each set acting as though the other did not exist. If two crests simultaneously pass a given point, the water level there rises to a height equal to the sum of the individual heights of each crest. Similarly, if two troughs simultaneously pass the point, the water level then falls to a depth equal to the sum of the individual depths of each trough. In the event that a crest belonging to one wavetrain meets a trough belonging to the other and if the amplitudes of both are the same, there is exact cancellation and the water level neither rises or falls. The diagrams in figure 6 illustrate the result.

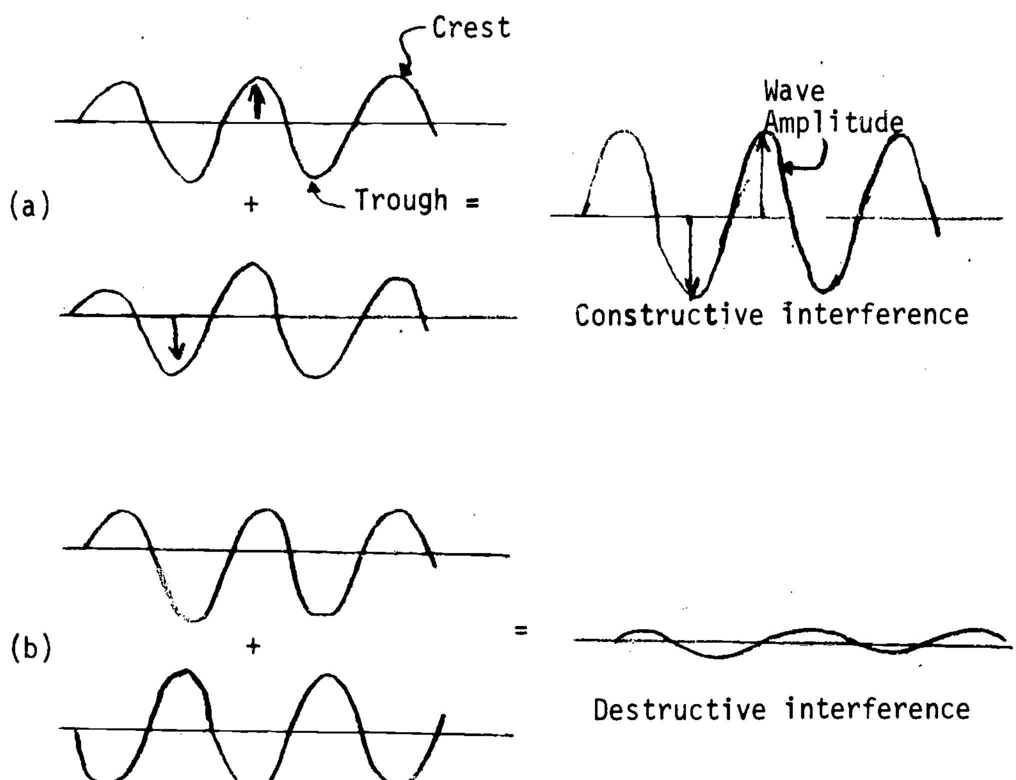


The principle of superposition

Figure 6

The principle of superposition is a statement of the above behavior and applies to all wave motion. The principle can hence be stated as "when two or more waves of the same nature travel past a given point at the same time, the amplitude at that point is the sum of the instantaneous amplitudes of the individual waves."

When the waves come together in such a way that crest meets crest and trough meets trough, the resultant composite wave has an amplitude greater than that of either of the original waves, and the waves are said to interfere constructively with one another. Should the waves come together in such a way that crest meets trough and trough meets crest, the composite wave has an amplitude less than that of either of the original waves, and the waves are said to destructively interfere with one another as shown below.



Waves can interfere with each other even if their wavelengths differ.

Figure 7

Example: Beats in Sound Waves

Take two tuning forks whose frequencies are slightly different and strike them at the same time. The sound you hear fluctuates in intensity. At one instant, you hear a loud tone, then virtual silence, then a loud tone again, then virtual silence and so on. The original of this behavior is shown schematically.

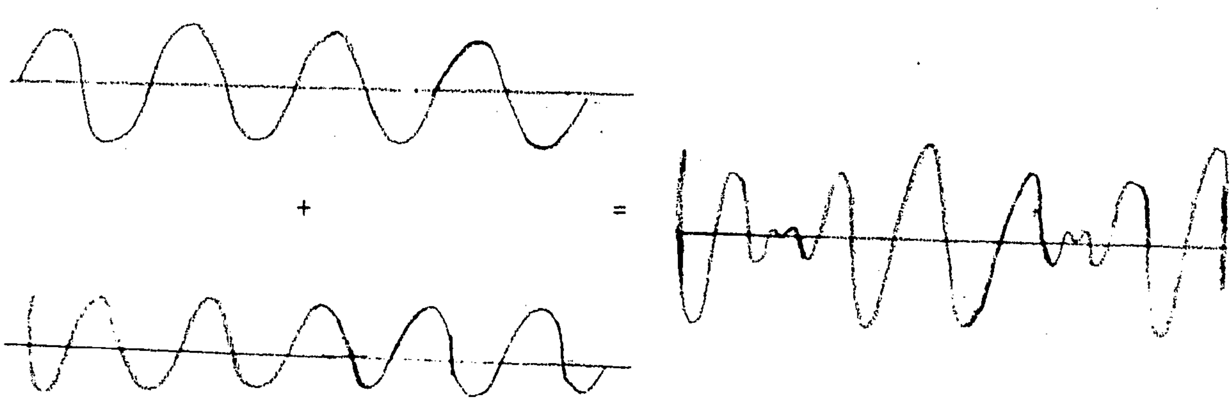


Diagram illustrating the origin of beats

b. Waves in a Coil Spring

Experiments

By striking one end of a fairly taut long spring held between two students, generate a pulse and observe the motion of the pulse down the spring. Let us suppose that the pictures in figure 8 were taken with a motion picture camera, showing the shape of the coil spring at intervals of $\frac{1}{24}$ sec.

[A ribbon tied at one position is found to bob up and down as the pulse goes by, but it does not move in the direction of the pulse which shows that the points on the spring transmitting the wave move in a direction perpendicular to or transverse to the motion of the wave. The wave is called a transverse wave whose motion is similar to the wavemotion on the surface of water.

1. Determine the speed of the wave pulse for various time intervals

Ribbon

TIME (Sec)

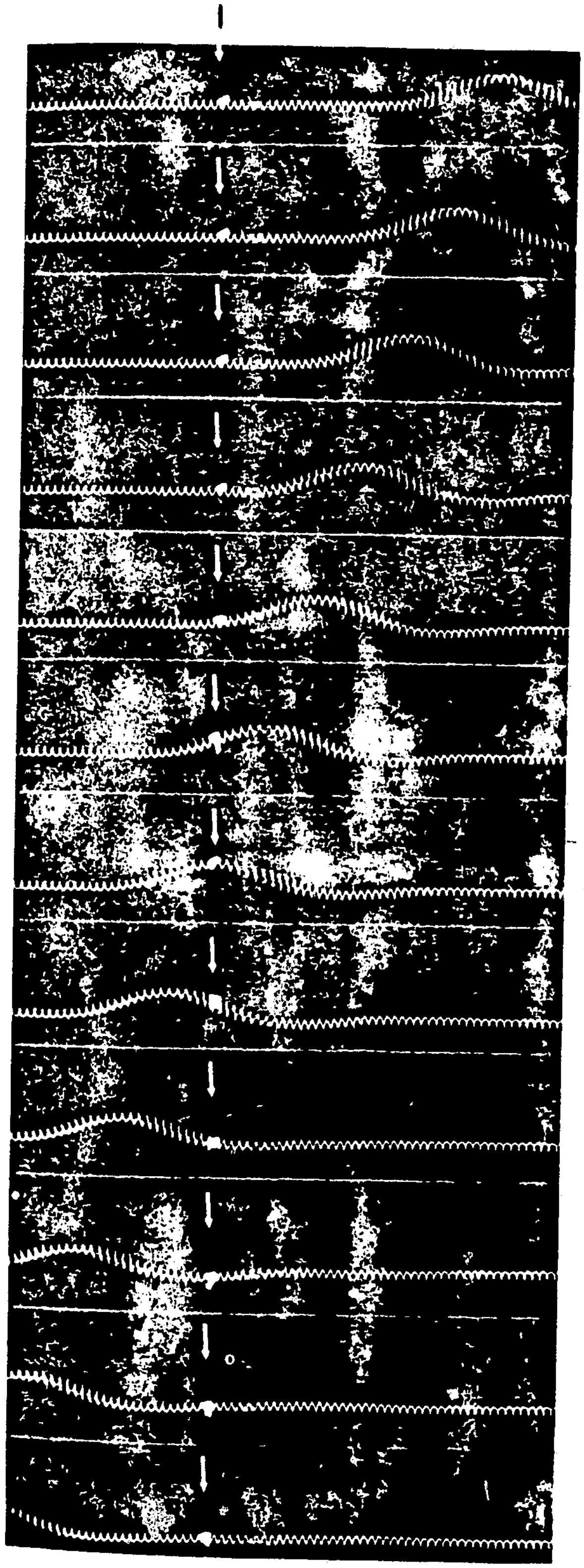


Figure 8

The motion of a pulse from right to left along a spring with a ribbon around one point. The ribbon moves up and down as the pulse goes by, but does not move in the direction of motion of the pulse.

experimentally as well as from the camera pictures by measuring the distances the wave moves in a certain interval of time (by laying a straight edge along corresponding maximum height points on each wave)

Question: Is the speed of the pulse constant?

2. Determine from the pictures in figure 8 if the amplitude changes with time.

Question: Although there may be no appreciable decrease during the small interval of time, can one conclude that ultimately such a pulse would die out? If so, why?

3. Determine the effect when two wave pulses each generated from each end of the coil spring (in the same manner) travel through the same point at the same time. The motion camera pictures in figure 9 illustrate the effects.

i. The frame after 6/24" shows the maximum overlap of the two pulses, with the result that the amplitude is greater than the amplitude of either of the original pulses.

From the pictures in figure 9 measure the amplitude of each pulse at 4/24" and the amplitude of the combination of these two pulses at 7/24".

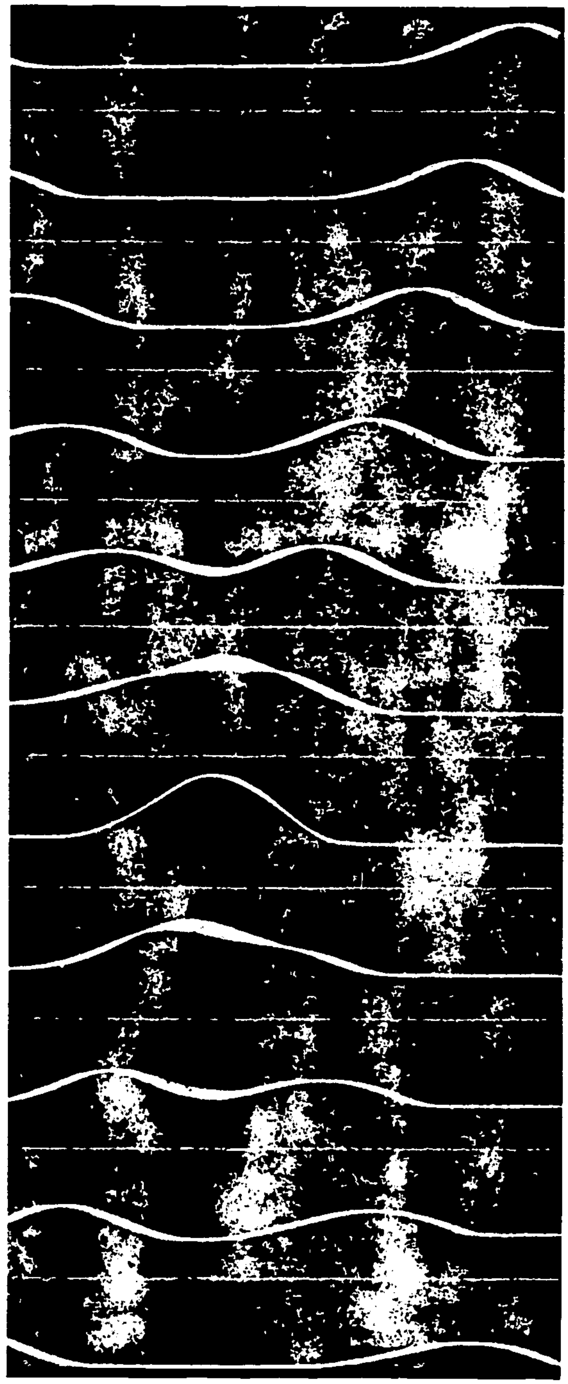
Question: How does the sum of the amplitudes of the individual pulses compare with the amplitude of the combination of the two pulses?

ii. In the last four frames of figure 9, the wave pulses pass through one another apparently unchanged in shape and the one which began on the right continues on to the left and vice versa.

Questions: How do the amplitudes of the two pulses compare before and after the "crossing over?" Is there an increase or decrease in amplitude of either pulse before and after the "crossing over?" Does this phenomenon demonstrate that one fundamental property of waves is that

Interference of Light

TIME
(Sec)



0

$\frac{1}{24}$

$\frac{2}{24}$

$\frac{3}{24}$

$\frac{4}{24}$

$\frac{5}{24}$

$\frac{6}{24}$

$\frac{7}{24}$

$\frac{8}{24}$

$\frac{9}{24}$

$\frac{10}{24}$

Figure 9

Two pulses crossing each other. Notice that the two pulses have different shapes. Thus we can see that the one which was on the left at the beginning is on the right after the crossing, and vice versa.

two wave pulses can pass through one another without being altered? (Figures 8 and 9 are from: PSSC Physics, D. C. Heath and Company, Third Edition, pp. 93-94, 1971)

It is probably instructive to point out here that the distance between two adjacent points in the same state of displacement on a wave pulse is called the wavelength and is usually represented by the Greek symbol lambda, λ. i.e.,

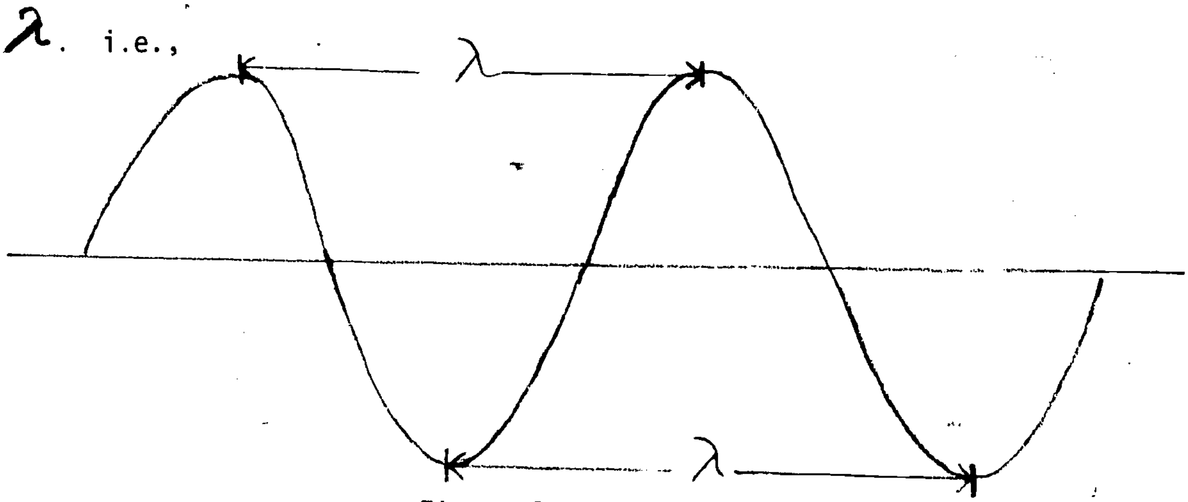


Figure 9

This means that the distance between the maximum point of any two adjacent crests or between the minimum points of any two adjacent troughs is a wavelength. If the frequency of the plunger causing the waves in the ripple tank is known and the wavelength is known for a particular wave, the velocity of the wave pulse can be found. In fact that relationship is:

Velocity (v)	=	f (frequency)	x	λ (wavelength)
(distance travelled in centimeters/sec)		(per second)		(centimeters)

this equation of velocity can be generally applied to all types of waves.

E. Light Waves - Analogy with Water Waves

We became aware of some general characteristics of wave motion in chapter IV which can now be applied to the study of light and its properties. It was seen that waves in a coil spring obey the principle of superposition. As they move through each other, the waves add together to form a total wave that is the sum of the amplitudes or heights of the individual waves.

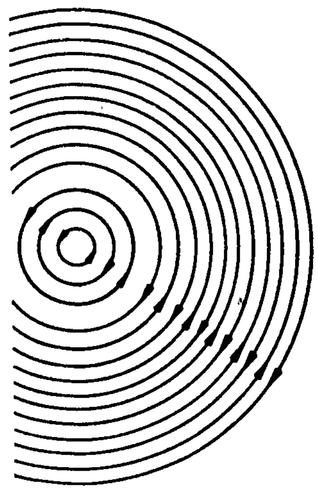
This denotes that when two crests meet, they form a higher crest; when two troughs meet, a deeper trough is formed; and when a crest and a trough of equal amplitude meet, they cancel each other leaving the coil spring with no displacement.

This idea can be used to predict the wave pattern formed when two plungers that are side by side cause wave patterns by bobbing up and down. A set of circular waves is produced by each plunger. These circular waves consist of alternate crests and troughs. Figure 10a shows a picture of the circular water wave patterns produced by a plunger in a ripple tank. (The crests and troughs are represented by light and dark areas respectively).

Water waves obey the principle of superposition as seen with the coil spring. Suppose we let two plungers bob up and down in a ripple tank. Figure 10b will allow us first to visualize graphically the resulting wave pattern and later observe an actual ripple tank demonstration. The high crests will appear where both arrows point upward and the deep troughs will appear where both arrows point downward.

Figure 11a shows an actual ripple tank photograph of an interference pattern. In this photograph, the flat water or lines of destructive interference appear dark and the crests or constructive interference are represented by the light areas (this could be vice versa). Figure 11b demonstrates a further analysis of this pattern and shows the beams of waves.

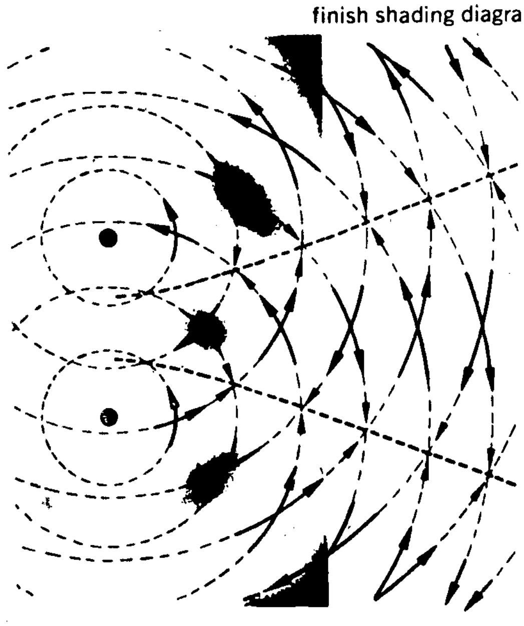
In our later actual physical experiments performed with light, we can interpret the bright bands of light as rays of constructive interference while the dark regions are rays of destructive interference: Thus, we can expect alternate bright and dark bands on a screen if we place it anywhere across superimposed light waves.



To diagram the circular wave pattern we will use arrows to distinguish between crests and troughs.

Figure 10a

finish shading diagram

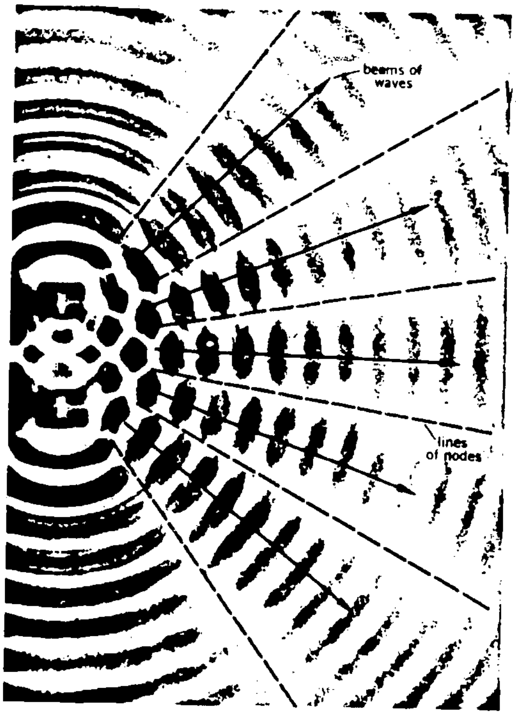


To visualize the resulting wave pattern, we have started to shade the flat water (lines of nodes) pale gray and the deep troughs (where both arrows point downward) dark gray. The high crests (where both arrows point upward) have been left white. Use a pencil to finish this shading, and compare the result with the photograph (c) of the aetual ripple tank pattern.

Figure 10b

Ripple tank photograph of interference pattern. As in our shaded diagram (b), the flat water or lines or lines of nodes appear dark and the crests light (or vice versa).

Figure 11a



Where the waves cancel, lines of nodes appear. Between the nodes are the beams of waves.

Figure 11b

F. Interference Pattern in Young's Double-slit Experiment

A Thought Experiment

In figure 12, light waves from slits S_1 and S_2 travel identical distances in reaching the central position O on the screen, and consequently they interfere constructively there.

The reason for having the light reaching S_1 and S_2 come from the same source S is now evident, for, a light wave leaving S_1 is always in exactly the same part of its cycle as that leaving S_2 at the same time, so that when a crest leaves S_1, a crest also leaves S_2, and when a trough leaves S_1, a trough also leaves S_2, and so on.

1. At point 0.

When waves from the two slits meet at 0, they reinforce one another to produce a bright line. If different sources of light were used to illuminate S_1 and S_2 the light waves leaving S_1 and S_2 would be independent of one another, and when they meet at 0, they would usually be different parts of their cycles, (i.e. they would be out of phase). No interference patterns of light and dark lines would result although diffraction (bending of light) at the slits would cause the screen to be weakly illuminated. Hence, interference phenomena are possible only when a single original light beam is split into two or more parts which travel along different paths and later recombine.

2. At point P_1

Consider the point P_1 on the screen located to one side of 0. The distance S_2P_1 is longer than the distance S_1P_1 by the amount S_2Q_1.

i.e. $S_2P_1 - S_1P_1 = S_2Q_1$ = path difference.

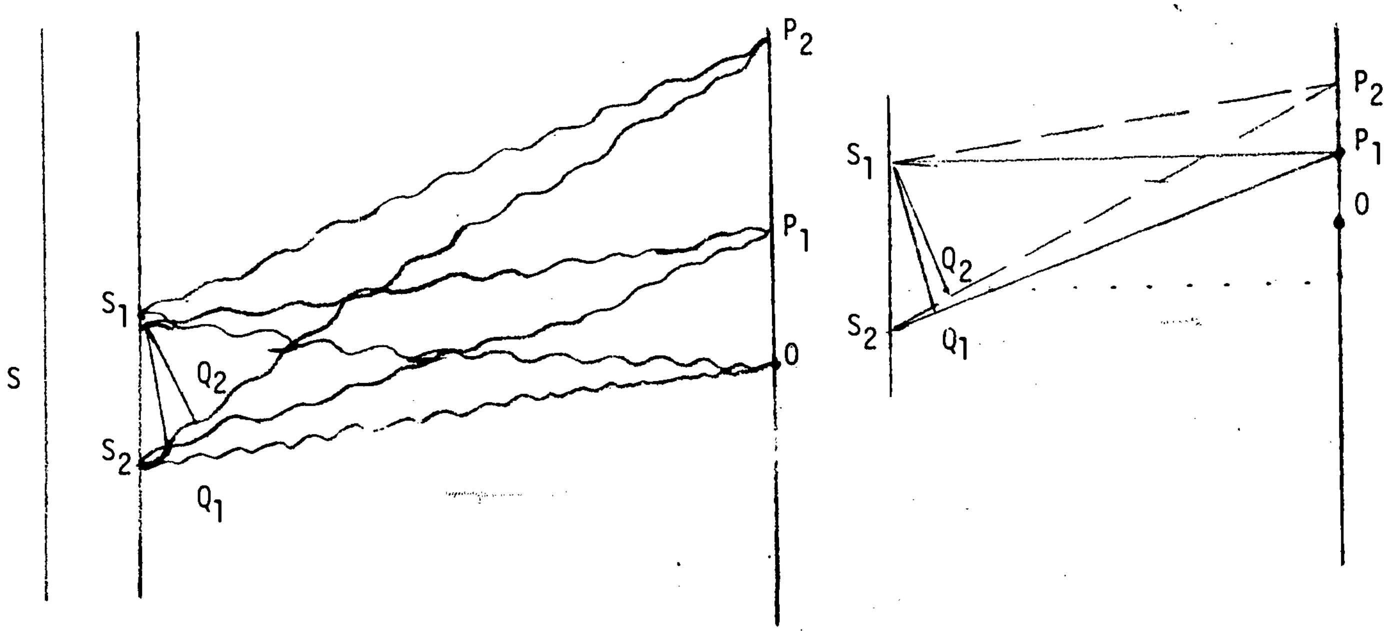


Figure 12

The Origin of the Double-slit Inteference Pattern

Suppose S_2Q_1 = 1/2 λ, where λ = wavelength of light used (of s) then, when a crest from S_1 reaches P_1, this difference in path length means that a trough from S_2 arrives there at the same time (since 1/2 λ separates a crest and a trough in the same wave). The two cancel each other out, and the light intensity at P_1 is zero. Therefore, a dark line results on the screen at P_1.

[At the point 0, the path lengths from S_1 and S_2 are equal and this gives rise to constructive interference. At the point P_1, the difference of 1/2 λ in path length gives rise to destructive interference]

3. At point P_2. On the screen at the point P_2, suppose the distance S_2P_2 is greater than distance S_1P_2 by exactly one wavelength.

i.e., The path difference between S_2P_2 and S_1P_2 = S_2Q_2 and S_2Q_2 = 1λ

Consequently, when a crest from S_1 reaches P_2, a crest from S_2 also arrives there.

Since S_2Q_2 = λ , waves arriving at P_2 from both slits are always in the same part of their cycles, and they constructively interfere to produce a bright line at P_2.

By continuing the same analysis, we find that the alternate light and dark lines observed on the screen correspond respectively to locations where constructive and destructive interference occur .

Thus, in general, at points on the screen where the path difference is equal to a whole number of wavelengths (λ, 2λ, 3λ, etc.) constructive interference occurs and at such points will be a bright line.

At points on the screen where the path difference is equal to an odd number of half wavelengths ($1/2\lambda$, $3/2\lambda$, $5/2\lambda$, etc.) constructive interference occurs and at such points there will be a dark line.

At intermediate locations on the screen, the interference is only partial, so that the light intensity on the screen varies gradually between the bright and the dark lines.

Conclusion. The double slit experiment demonstrates that both diffraction and interference occur in light. Since both are phenomena characteristic of waves, this experiment is further evidence for the wave nature of light.

G. Experiment - The Determination of the Wavelength of Light Using the Double-Slit Interference Method

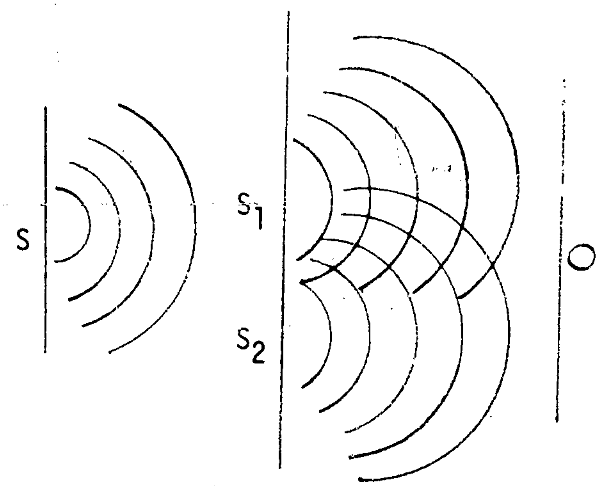
1. Introduction

The physical science course is built around one main topic, namely "solid matter" and this line of thought is pursued in the subject matter dealing with light. In order to make an investigation on the structure of solids and to form an idea of intermolecular distances in a solid based on X-ray diffraction experiments, a study of the behavior of waves in general is dealt with initially. The phenomena of superposition of waves, interference and diffraction are made intelligible to the student by experimental demonstration with a coiled spring and waves in a ripple tank. You can proceed to a microscopic outlook and you discover for yourself the magnitude of the wavelength of light in the laboratory using simple equipment. The present experiment consists of applying Young's technique of using double slits to study the interference pattern with light waves and in determining the wavelengths of the different colors of light.

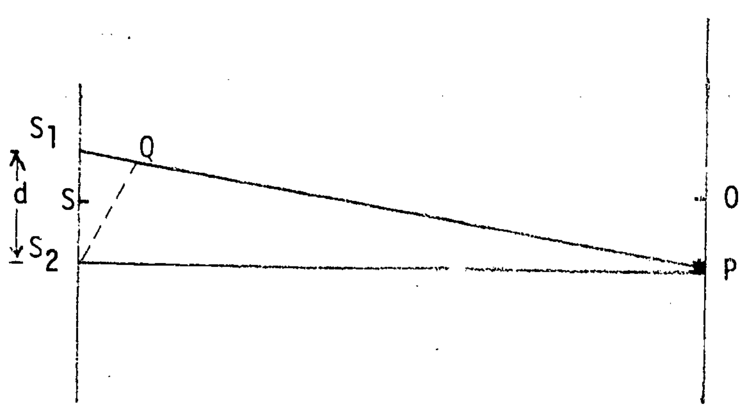
An opportunity to gain experience in computer programming is also given. This is done by using the computer to calculate the wavelengths from the observations made in the experiment at the end.

2. Principles of the Method

When waves spreading out from a slit S pass through slits S_1 and S_2, they emerge from each slit as circular waves. By the principle of superposition for the waves traveling outward from slit S_1 and S_2, when two crests are superimposed (or two troughs are superimposed) a reinforcement occurs, which is termed constructive interference. When a crest and a trough superimpose, cancellation or destructive interference occurs. With regard to light waves emenating from the slit S and spreading out from slits S_1 and S_2, the bright rays of light are rays of cancellation. Thus a screen placed anywhere across the superimposed waves will show alternate bright and dark bands on it.



3. <u>Theory of the Method</u>



Let S_1 and S_2 represent the two slits. Let P be a point on the screen placed at a distance of about a meter from the slits where you observe the interference bands which consist of alternate bright and dark bands equally spaced, on either side of the central bright bend at O. The point O will be always bright since it is equidistant from S, the midpoint of S_1 and S_2 and only constructive interference can take place there. Let us now consider a point P on the screen, a small distance away from the central point O. Point P will be bright or dark depending on the fact that the waves starting from S_1 and S_2 reach there to form constructive interference or destructive interference, and this happens when the difference in the path length which the waves from S_1 and S_2 travel (i.e. S_1Q) corresponds to any multiple of the wavelength of the light for constructive interference or any odd multiple of half a wavelength for destructive interference. i.e. P will be bright when $S_1Q = n\lambda$ and P will be dark when $S_1Q = (n+1)\ \lambda/2$ where n is any integer and λ = wavelength of the incident light.

In forming a quantitative expression relating the wavelength the slit separation d, and the distance of point P from O (i.e. OP) and the slit system (SP), one has to take in to consideration certain theoretical aspects with regard to the magnitudes of λ, d, and SP and make certain assumptions. Figure 13 explains the situation.

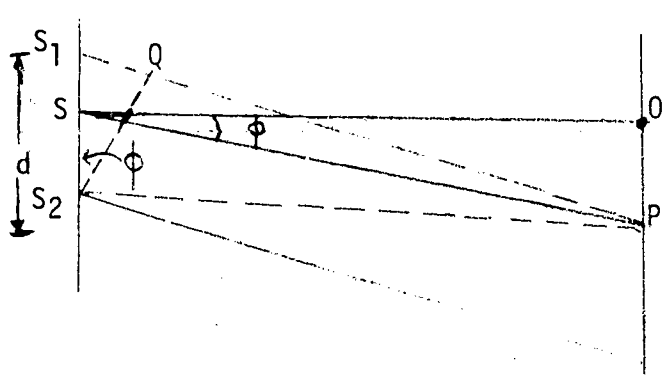


Figure 13

The slit separation d is very small compared to the distance of the screen from the slit system, and therefore we can assume that the lines S_1P and SP in Fig. (13) are nearly parallel to each other, and make the same angle ϕ with the horizontal. If S_2Q is drawn perpendicular to S_1P, $\angle S_1S_2Q$ is also = ϕ and S_1Q represents the path difference between wavelets from S_1 and S_2 reaching the point P. Hence by theory if $S_1Q = n\lambda$ point P will be bright and if $S_1Q = (n+1)\ \lambda/2$ the point P will be dark (n = 0, l, 2 ...).

$$\text{Now}\quad \frac{S_1Q}{S_1S_2} = \text{Sin}\ \phi$$

i.e. path difference $S_1Q = d\text{Sin}\ \phi$

$\therefore$ If $d\text{Sin}\ \phi = n\lambda$ the point P is bright

and if $d\text{Sin}\ \phi = (n+1)\ \lambda/2$ point P is dark

Again, in an actual laboratory experiment, with a double slit system, the theoretical diagram of Figure 13 and thus the midpoint of the slit system S becomes indistinguishable from S_1 and S_2 on account of the extremely small dimensions. Hence angle OSP measures the angle and Sin ϕ is numerically equal to $\frac{OP}{SP}$. Hence in an experiment if P corresponds to the n^{th} bright band from O,

$$d \times \frac{OP}{SP} = n\ \lambda$$

where all the quantities except λ can be experimentally determined, and hence λ can be easily calculated.

The double slit used in the experiment is constructed as follows. A glass microscope slide coated with an opaque film of graphite, made by painting the surface with a suspension of graphite in alcohol is the screen on which the narrow slits can be produced by drawing a razor blade over the graphite surface. For making a double slit, as is needed in this experiment, the slits should be very narrow and very close together. Two razor blades are held together tightly and using a second microscope slide as a guide, the razor blades are drawn lightly across the graphite coated surface. The two lines form two narrow slits separated from each other by the thickness of a blade.

Now placing tour eye close to the slit system, look at a lamp placed about a meter from the eye. The schematic diagram of the experiment is shown in Figure 14.

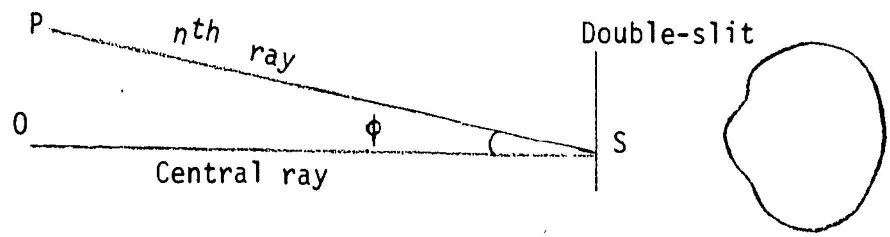


Figure 14

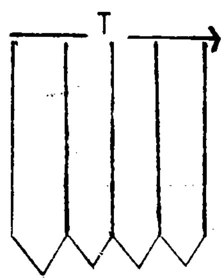
One observes a series of bands of different colors with a central white band when white light is used, and if the light is interrupted by a red filter, one observes a series of red and black bands in accordance with the theory of formation of bands by constructive and destructive interference. The retina of the eye serves as the screen here.

To make quantitative measurements the following experimental procedure is adopted.

Using a red filter over the lamp, look at the lamp through the double slit. Locate the best section of this double slit which gives the clearest pattern and scratch a small window just above or below it. A meter stick clamped above the lamp horizontally will enable measurements to be made.

The microscope slide is so held that one can look through both the double slit and the window at the same time. The band resulting from the central ray will be seen in line with the filament of the lamp. Clamp the meterstick in position directly above the filament of the lamp. Now count the number of bands between the filament (zero band) and the farthest band. This number gives n in the equation. From Figure 13 Sin ϕ is given by $\frac{OP}{SP}$. OP can be determined by noting the distance of this n^{th} band from the zero band along the meter stick and SP, the distance between the n^{th} band and the slits on the slide S can be directly measured.

Finally to determine d, the slit separation, or the distance between the cutting edges of two razor blades held together, a stack of razor blades is taken and its thickness determined accurately, from which dividing it by the number of blades, the value of d will be obtained. Figure 15 explains the method of finding d.



$d = T/4$

Figure 15

Now, knowing all the terms in the equation $d \sin \phi = n\lambda$ the wavelength of light can be calculated. The experiment can be repeated using the same slit for various values of n and SP, and in each case measuring OP.

Use of the Computer in the Calculation

$$\lambda = \frac{d \sin \phi}{n}$$

$$\sin \phi = \frac{OP}{SP} = \frac{x}{y}$$

Program

```
100    INPUT    D, X, Y, N
110    LET      X = (D * (x/y) )/n.
120    PRINT    Z
130    END
```

Data for X, Y, and N can be supplied for the same value of D, and the wavelength of light (Z) can be computed. For each set of data, using different color filters, the wavelength of each light can be easily computed.

Comment

The experiment with the double slit in determining the wavelength of light serves as a pedagogical device for introducing and discussing the wave theory of light. To carry out this experiment successfully demands careful observation, for in repeating the experiments with different color filters, for example, only careful observation will make one realize that the red interference pattern spreads out more than the blue which makes it possible to generalize observations that as the wavelength gets larger, for the same slit separation, the band width becomes greater and the pattern spreads out.

The experiment with its theoretical background also gives training in applying simple mathematics to interpret observations from a theoretical point of view.

Above all, to an interested person it will be a revelation that microscopic dimensions as the magnitude of the wavelength of light could be almost accurately determined in a laboratory by using simple techniques and simple equipment.

One will be fascinated in getting the computer to solve programs and make calculations by designing simple programs.

Other Materials to be Used

a. Film Loops

The film loops that can be shown to describe the nature of wave formation and its physical behavior are:

1. Formation and reflection of waves in a ripple tank - straight

waves, circular waves, waves reflected from straight barrier, circular barrier, elliptical barrier.

2. Superposition and interference of waves from two vibrating sources in a ripple tank.

3. Interference bands formed by a double-slit for white light and colored lights, and the nature of the pattern as the wavelength of the incident light is gradually increased from violet to red and vice versa.

4. Interference bands with monochromatic light and how the pattern changes with increasing slit widths and also with increasing separation between slits.

b. Movie Projector

A half hour sound film explaining the wave propagation in a coiled spring, reflection, superposition, etc. can be shown thus enlightening one on wave behavior in general.

Extensions of the Experiment

The experiment can be extended to include:

1. Determination of slit separation using light of a known wavelength.

2. Determination of band width for various slit separations for a known wavelength of incident light.

H. DIFFRACTION

1. An Approach to the Phenomenon of Diffraction

Earlier considerations have demonstrated to us how individual waves add together to produce interference patterns and this was one of the basic principles of wave motion. Another basic principle of wave motion is one which allows us to predict the motion of individual waves. This principle was discovered by a contemporary of Isaac Newton, Christian Huygens, a Dutch physicist. Huygen's principle states that:

> If the position of the front of a wave is known, the future position of the wavefront can be determined by assuming that each point on the wavefront serves as the source of a new wave.

Figure 16 shows how the future position of a wavefront can be predicted by making the above assumption.

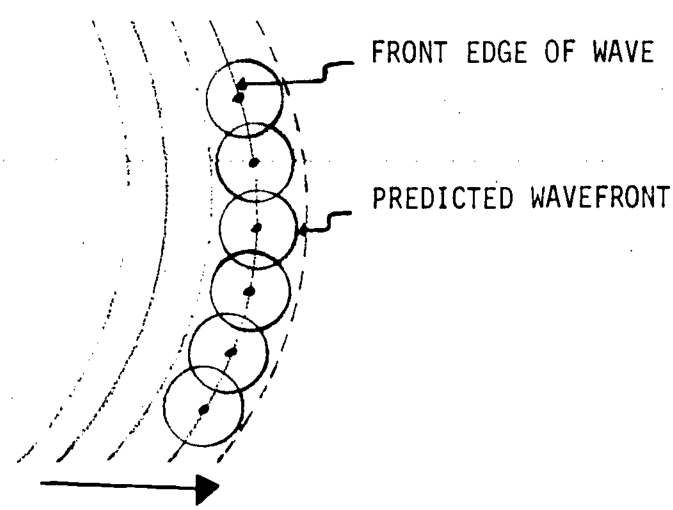


Figure 16

As a consequence of Huygen's principle, one often observes a bending of waves around sharp edges or through narrow slits as demonstrated in Figure 17.

The bending of a wave around the edge of an obstacle in their path is termed "Diffraction."

Examples

(a) We can hear sounds that originate around the corner of a building from where we are standing. These sound waves cannot have traveled in a straight line from their source to our ears, and refraction cannot account for their behavior. The sound waves in face, have vent around the corner, by their property of diffraction.

(b) Waterwaves also diffract as it has been observed in the ripple tank experiments in the previous section.

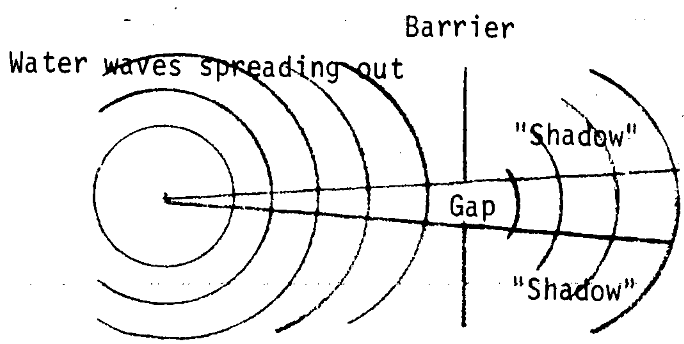


Figure 17

Figure 17 illustrates the diffraction of water waves at a gap in a barrier - It will be found that the waves on the far side of the gap spread out in to the geometrical "shadow" of the gap's edges, though with reduced amplitude. In the absence of diffraction, no waves would be present in the shadow region. The diffractioned waves spread out as though they originated at the gap.

(c) A large rock in the path of the ocean waves permits most of the waves to pass, but the waves beyond the rock are altered by its presence.

(d) Diffraction of Light

Sharp looking shadows result when a light beam is partially obstructed by an object. Hence Newton ascertained that light must be corpuscular in nature. However, the phenomenon of diffraction is pronounced only when the dimensions of an obstacle or opening are comparable to the wavelength of waves striking them.

An ordinary audible sound wave might have a wavelength of perhaps 1 meter, and a typical ocean wave might have a wavelength of perhaps 100 meters. Hence with obstacles of comparable dimensions, it is not hard to observe diffraction effects with these types of waves. But visible light, however, contains wavelengths smaller than 10^{-6} meters, and so light waves exhibit diffraction only with slits or obstacles of dimensions comparable to the wavelength of light which are in its path, and so it is quite an unusual occurrence.

In Young's double-slit experiment, light from S passes through both slits S_1 and S_2 and then to the viewing screen. If light were not a wave phenomenon, one would expect to see the viewing screen completely dark, since no light ray can reach it from the source along a straight line path. Instead, owing to the diffraction of light, the entire screen is illuminated. Even the point O separated from S by the opaque barrier between slits S_1 and S_2 turn out to be bright, and not dark! Hence, if the width of the opening through which light waves, water waves, or sound waves pass, is about the same as the wavelength of these waves, then these waves will spread out as if the opening were a point source of waves -- which property is termed "diffraction."

2. Diffraction - Interference - A distinction

There is no basic difference between diffraction and interference, but only a difference in emphasis. Thus the term diffraction is used for phenomena connected with the spreading of waves on passing through a slit, shadow formation etc, explained as the joint effect of the interference of all the secondary waves emanating from the exposed part of the wave front. The term interference is usually applied to simpler cases as in Young's experiment, where waves from a finite number of separate but coherent sources one superimposed. When we describe Young's experiment, we consider the two holes on the screen as secondary sources of light emitting sperical waves, but having been illuminated by a single (coherent) source.

3. The Nature of Diffraction

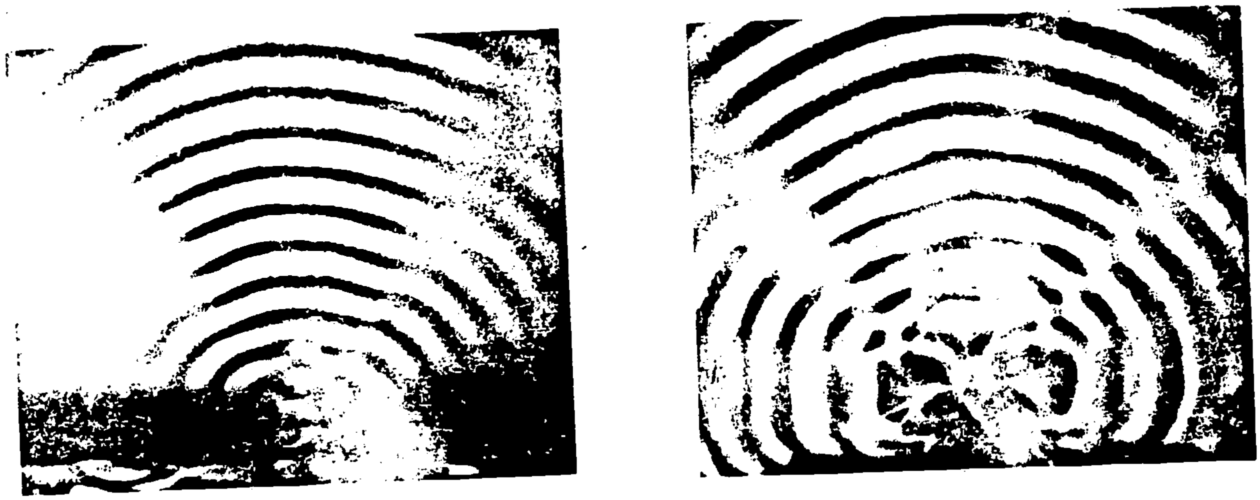
We have dealt with the interference of light coming from two slits. The effect of increasing the number of slits keeping their spacing and wavelength of the waves constant is illustrated in figure 18 with regard to water waves.

With light, similarly, the experiments can be performed using a series of equally spaced slits, each with an exceedingly narrow width. Such a system of slits is called the "Diffraction grating." It is constructed by the laborous process of scribing parallel lines very close together on a metal base using a special ruling engine, and there may be about 13,000 to 20,000 lines per inch, which means that the slit separation is of the order of nearly 2×10^{-4} cms (20,000 Å) or less. Usually replica gratings are made from this original grating, and it consists of a thin transparent film which has grooves and ridges forming thinner and thicker parts acting in the same way as slits do.

Experiments and Demonstrations

a. You can repeat the experiments with the water waves in the ripple tank and observe for themselves the results illustrated in figure 18 .

b. With replica gratings, and simple spectrometer tubes, you can observe the effect of diffraction of light from various sources as Hg, Ne, He, Ar, Na, H_2, O_2, etc., and form an idea of the various diffraction patterns exhibited by these different gases in their incandescent form.



(a) (b)

Figure 18

A diffraction pattern of straight waves passing through a single slit (a) and in (b) an interference pattern of a line of equally spaced point sources (many slits) extending across the slit. Near the sources, separation leads to some difference in the patterns. Far away the two patterns are the same. (Courtesy of PSSC, D.C. Heath and Company, Third Edition, 1971).

At this stage you may wish to be introduced to the terms "emission spectra", "absorption spectra", Fraunhofer line and solar spectra etc., and in this connection, the working of an actual spectroscope may be demonstrated.

c. Film loops showing the various types of emission spectra may also prove to be an interesting demonstration item.

QUESTIONS

1. Why do some objects appear "colored"?
2. Would you consider "white" to be a color? Explain your answer.
3. Would you classify "black" as a color? Explain.
4. How would you define the frequency and wavelength of a wave? Illustrate the wavelength of a wave by a diagram.
5. Compare the wavelengths of visible light, radio waves, infrared and ultraviolet rays, and x-rays. Which one has the shortest wavelength? Which one has the longest wavelength?
6. Give a complete description of Young's double slit experiment. What conclusion can you make from this experiment regarding the nature of light (i.e. particle or wave nature)? Explain your conclusion.