THE MECHANICAL UNIVERSE

High School Adaptation

A co-production of the
California Institute of Technology
University of Dallas
and
Southern California Consortium

QUAD VII

MODERN PHYSICS

The Wave Nature of Light
Wave-Particle Duality
Models of the Atom
Special Relativity

An Annenberg/CPB Project

National Science Foundation

Materials Development Council

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FOREWORD

Today, scientific and educational leaders are seriously concerned about the quality of science and mathematics education in the United States. It is as though the problems have been rediscovered, 25 years after Sputnik! In addition to those problems which have repeated themselves, today many qualified science and mathematics teachers at the pre-college, college, and university levels are being lured from the classroom by higher-paying jobs in business and industry. Many classrooms, therefore, have become the responsibility of instructors with limited preparation in the subject matter they are called upon to teach. And yet, more than ever the nation's current economic, social, and political needs call for a technologically literate population.

The Mechanical Universe, which served as the basis for the high school materials, addresses one critical need in science education by providing video and print materials that can serve as the basis of a solid, introductory college-level physics course. The video offers an exciting array of audiovisual resources for classroom instruction: close-ups of complicated experiments; extensive computer animation sequences that make abstract concepts and mathematical processes understandable; historical reenact-ments that provide a philosophical fabric for the development of ideas of physics.

The Mechanical Universe, part of the Annenberg/CPB collection, has as its primary purpose the provision of a quality learning experience for those whose lives cannot fit into the traditional campus schedule. This 52-program introduction to physics also offers a partial answer to some of the current problems of science education, for it can be used to upgrade skills of secondary science teachers and to provide supplementary support in the college and university classes.

Through the sponsorship of the National Science Foundation, selected programs of **The Mechanical Universe** have been adapted for use in high school. These materials represent the same quality and innovation as the college series, but they are presented in shorter and less mathematically oriented tapes that can be used in a wide variety of high school curricula. Teachers who find themselves teaching high school physics in spite of limited preparation will discover that, by enrolling in **The Mechanical Universe** course and using the adaptations in their classes, they will enjoy the confident feeling that they are presenting their students with quality instruction.

INTRODUCING

THE MECHANICAL UNIVERSE

High School Adaptation

The adaptations of **The Mechanical Universe** were created by twelve outstanding high school physics teachers (the Materials Development Council) through the generous support of the National Science Foundation. The clear purpose of the Council and the entire staff was to produce quality materials that would be used to improve instruction in physics. No one was satisfied with the goal of producing materials that would simply motivate or fascinate students, or would provide a change of pace. From the start, the challenge was to create materials which could make wise use of the power of television in developing a sound and solid understanding of physics.

Herewith the fruit of these labors: sixteen modules each consisting of a video adaptation from **The Mechanical Universe** with written support materials. Each module stresses conceptual understanding of underlying physical principles. The written materials support the video dimension of the modules. These support materials provide the teacher with additional background information and mathematical derivations, pre-video and post-video questions, applications, demonstrations, and evaluation questions.

The Mechanical Universe was originally developed for lower-division college courses in physics. The materials from **The Mechanical Universe** that have been adapted for use in high schools were field tested in 1984–86 by over 100 high school physics teachers located in schools widely scattered across the county in both urban and rural communities that serve various socio-economic populations. As a result of the assessment of the field testing, the videos were re-edited and the written materials were focused more directly on the videos to provide the best support possible for teachers.

PREFACE

These materials are intended for all teachers of high school physics. Teachers new to the arena of physics will discover rigorous, conceptual video presentations of traditional and not-so-traditional topics in classical physics. We hope that each word of the written materials will be savored. They are your resources and we hope that you tap them to capture the excitement of **The Mechanical Universe**. Experienced teachers will find a different slant to classical physics in the space age: a humanizing, compelling, integrated approach to the greatest revolution in the history of Western civilization. These teachers, too, we hope, will find the written materials continually refreshing resources.

Although **The Mechanical Universe** is a calculus-based course, the excerpts for high school use were selected to focus on concepts. That is not to say that the videos for high school use are not rigorous; they present sound logic at every stage in the development. Mathematics is occasionally used in the high school materials as a language to relate ideas concisely. In many cases the original mathematical derivations have been modified to be appropriate to the high school level. Nonetheless, mathematical derivations go by quickly in the video and we hope that teachers will replay these sections for their students. The mathematical background sections of the modules, we expect, will be read by all teachers even though they may not necessarily present to their classes the same level of mathematics provided in the print materials. We hope that teachers as well as students will gain a better appreciation of the vital role of mathematics in physics.

No laboratory component is currently suggested. The reason is not because we judge a physics laboratory component to be unimportant or uninteresting. On the contrary, we believe that demonstrations and laboratories lie at the heart of a sound education in high school physics. Instead we concentrated on what we could offer best: instruction through television. There are dozens of laboratory manuals which can be appended easily to these materials and we expect that each teacher will decide how best to handle the laboratories. On the other hand, since many demonstrations and applications to everyday life are presented in the video, we identified simple, short, and effective demonstrations that tie into concepts in the video. We hope that all physics teachers will enjoy performing them.

Not all the topics covered in the modules are conventional to high school physics curricula. *Angular Momentum* and *Harmonic Motion*, effectively covered in the videos, are two topics which are not necessarily a part of every curriculum. *Navigating in Space*, on the other hand, represents an exciting application of Kepler's ellipses and Newton's gravity that is not covered in typical curriculum. Other topics, such as *The Fundamental Forces* and *Curved Space and Black Holes*, provide tantalizing looks at twentieth century physics from the perspective of classical physics.

The Mechanical Universe is the story of the Copernican revolution, why it was necessary, and how it unfolded in the work of Galileo, Kepler, and Newton. It is the story of the eventual wedding of the heavens with the earth through the synthesis of mechanics and astronomy. History is presented in the series, not for the sake of historical detail, but for a fuller sense of how scientific thought proceeded through the intellectual searches and triumphs of men who reshaped the society of their times. We hope the infectious spirit of **The Mechanical Universe** will inspire teachers and students and will contribute to a lifelong scientific interest in the workings of the universe.

ACKNOWLEDGEMENTS

The adaptations of these instructional materials for high school use would not have been possible without the assistance of a long list of people who aided through the dedicated use of their diverse and specialized skills.

Heading the list is Professor David L. Goodstein, of Caltech, whose inspiration and guiding force in the creation of **The Mechanical Universe** led to the development of these materials.

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Materials Development Council
Irving, Texas
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STRUCTURE OF THE MATERIALS

The written materials are designed to support and extend the VIDEO presentation of each module. The format and content of the materials are designed to help the user (1) to integrate the concept(s) presented in the VIDEO with traditional high school materials, (2) to supplement and promote conceptual understanding of the phenomena presented in the VIDEO, and (3) to infuse the students with a new spirit of inquiry concerning the mechanics of physics.

Each module is composed of components of written materials. Each component is intended as a resource to promote active engagement of the learner in developing conceptual understanding of the physical phenomena. The five components of the print materials are:

TEACHER'S GUIDE

Pre-Video Activities*

Content and Use of the Video – describes what the VIDEO does and does not cover.

Terms Essential for Understanding the Video – includes the definitions of terms listed in the STUDENT'S GUIDE, discussion of critical elements or relationships.

What to Emphasize and How to do It – includes the objectives of the module, references to demonstrations, possible applications, and suggestions for correcting common misconceptions.

Points to Look for in the Video – includes common misconceptions when relevant; characteristics and questions concerning critical elements presented in the VIDEO. Answers to questions in the STUDENT'S GUIDE are included.

Post Video Activities*

Everyday Connections and Other Things to Discuss – suggests additional questions to promote student participation and discussion. An essential purpose of the questions is to engage students in review and clarification of the concepts.

Summary – reviews the key concepts that have been presented.

STUDENT'S GUIDE

(designed for duplication and distribution)

Introduction – a brief statement about the content or purpose of the VIDEO.

Terms Essential to Understanding the Video – includes terms or critical elements of the VIDEO, with definitions and explanations provided in the TEACHER'S GUIDE.

Points to Look for in the Video – includes common misconceptions when relevant; characteristics and questions concerning critical elements presented in the VIDEO along with figures representative of key points in the VIDEO.

TEACHER RESOURCES

Supportive Background Information – summarizes additional historical, physical, and mathematical information that relate to the topics and content presented in the VIDEO.

Additional Resources – includes demonstrations and applications the teacher may use to extend and enrich the treatment of the topic.

Evaluation Questions – provides ten multiple-choice questions dealing with the objectives of the module and two essay questions that require student's explanations of certain concepts related to the topics.

*The repeated showing of the video (in full and part) is essential to student understanding. The division of activities into prevideo and postvideo activities, therefore, is somewhat artificial. It is likely that most, if not all, prevideo activities will precede the initial showing of the video. Sections of the video will undoubtedly be sprinkled throughout the postvideo activities, with a full showing being used for closure where time permits.

QUAD VII

WAVE NATURE OF LIGHT

WHAT IS LIGHT? Contrary to the notion that light is a stream of particles, scientific rogues such as Huygens, Young, and Maxwell dared to describe light as a wave. The video shows details of this wave nature: properties that light shares with other kinds of waves, the unique characteristics of the electromagnetic spectrum, and the fundamental nature of the interaction between light and matter. Instruments such as refracting and reflecting telescopes, eyeglasses, and radar devices are highlighted.
Running time: 19:42

WAVE-PARTICLE DUALITY

HOW CAN WE RECONCILE BOTH THE PARTICLE AND WAVE DESCRIPTIONS OF LIGHT AND MATTER? Why are both descriptions needed? Classical physics could not accurately describe thermal radiation or the photoelectric effect until a particle description of the behavior of light was formulated. A complementary description of the wave characteristics of matter soon followed. This wave-particle duality of light and matter is reflected in Heisenberg's Uncertainty Principle and is the foundation of quantum mechanics. This video explores in depth wave-particle duality.
Running Time: 18:38

MODELS OF THE ATOM

WHAT IS THE TRUE NATURE OF MATTER? The nature of matter has been a concern of science since the time of the ancient Greeks. Over the last 2,000 years, and particularly the last 200 years, science has developed the concept of the atom to explain matter. Because atoms are too small to be seen, scientists have developed models to assist them in their understanding. This module concentrates on the development of these models starting with Dalton's chemically combining spheres. There were several changes to the atomic models which occurred with Thomson's discovery of the electron and after Rutherford's discovery of the nucleus. Bohr was able to develop a model which combined the ideas of energy levels within atoms. Schrödinger, de Broglie, Heisenberg, and others helped develop the present quantum mechanical view of the atom which involves a nucleus surrounded by an electron cloud.
Running time: 13:15

SPECIAL RELATIVITY

WHAT DOES THE THEORY OF SPECIAL RELATIVITY DESCRIBE? The theory of relativity is clearly one of the major ideas in the development of 20th century thought. This video introduces the postulates of special relativity and how they lead to the failure of simultaneity, time dilation, length contraction, and relativistic mass. Beginning with the problem of synchronizing stationary and moving clocks using an expanding sphere of light, the video extends the argument to space-time diagrams. First Galilean relativity is considered with its assumption of absolute time. Then with the problems of synchronizing moving clocks a new slant is added to the time axis and the space-time diagram evolves. A brief consideration of relativistic mass is given through the use of an animated space billiards game.
Running time: 20:49

TEACHER'S GUIDE TO THE WAVE NATURE OF LIGHT

CONTENT AND USE OF THE MODULE – This module explores the wave nature of light by examining the properties of refraction, reflection, and interference in terms of the electromagnetic character of light waves. The electromagnetic spectrum is presented as a result of the constant speed in free space and varying wavelengths and frequencies of electromagnetic waves. A study of basic wave characteristics (such as presented in the *Introduction to Waves* module) should precede this material. With this background, the first sections of the module can be used at any time. Either the last portion or the entire module can be used after studying electromagnetic induction (refer to the *Electromagnetic Induction* module) to visualize electric fields and the connection between changing electric and magnetic fields. (See Notes to the Teacher in POINTS TO LOOK FOR IN THE VIDEO for suitable divisions of the video.)

See the chart on page 6 for planning suggestions. If portions of the module are used to teach single topics, it is still important that the video be shown more than once to emphasize the logical, scientific, and historical flow of the concepts of *The Wave Nature of Light.*

SECTIONS WHICH FOLLOW

TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO – Since the following terms are introduced in the video, it should be helpful to discuss them with students prior to viewing the video. See the BACKGROUND INFORMATION for sketches to help clarify the meanings of these terms.

wavelength (λ) – for a travelling transverse wave, the distance between successive crests (or troughs).

frequency (f) – the number of crests of a wave that pass a certain point in a unit of time. One hertz (Hz) is defined as one cycle per second.

propagation – the movement of a wave disturbance.

refraction – the change in speed as a wave passes from one medium to another. This leads to a change in direction of the wave in the second medium unless the incident angle is zero.

dispersion – the separation of white light into component colors by different amounts of refraction for different wavelengths of light.

interference – the superposition of waves that arrive at the same point at the same time.

constructive interference – interference in which the waves are reinforced by combining crests with crests and troughs with troughs.

destructive interference – interference of two waves that are not *in step*, causing subtraction of amplitudes.

reflection – the rebounding of a wave at the interface of two media. The incident angle (between the reflected wave's direction of propagation and the perpendicular line to the surface) equals the reflected angle (between the incident wave's direction of propagation and the perpendicular).

electric field – the alteration of the properties of space around a charged body that will affect other charges in the vicinity. Electric field lines indicate the direction of forces exerted by the field on positively charged bodies. (See the *Electric Fields and Forces* module for further explanation.)

electromagnetic spectrum – the collection of all wavelengths (or frequencies of light) that is divided into regions according to the characteristics of the waves. These regions, in order of increasing wavelength, are gamma rays, x-rays, ultraviolet light, visible light, infrared radiation, microwaves, and radio waves. The speed of electromagnetic waves in a vacuum (c) equals 3×10^8 m/s.

WHAT TO EMPHASIZE AND HOW TO DO IT – The video presents the wave nature of light by introducing Young's experiment which is explained with a wave model. The reasons for sharp shadows, reflection, and refraction are discussed from the wave viewpoint. The first four objectives relate to this material. For students to master this material, you should plan to use *several* weeks of class time. Repeated showings of short segments of the video will aid students in understanding the material and, along with the demonstrations, labs, etc., are *necessary* for student understanding.

The second major division of this video shows the Electromagnetic Spectrum, OBJECTIVES 5 and 6. One or two days should be adequate for this portion of the video.

The third division of the video, Interaction of Light and Matter, might pose the most difficulty for students. OBJECTIVE 7 is based on this material. This section of the video is largely for enrichment and for a brief glimpse of the real interaction taking place.

An historical thread runs throughout the video that focuses on the work of Huygens, Young, and Maxwell.

This video can be used most effectively by repeated showings in *several short* segments and then as an overall review of light and waves.

Prior to showing the video, ask the class whether light is a wave *or* a stream of particles. Put two columns on the board: Particle Model and Wave Model. Have students suggest in which column to list common, well-known properties of light; e.g., shadows, reflection, refraction, etc. If room on your blackboard permits, leave this visible during the entire study of light, adding and making changes as prompted by student discussions.

Objective 1: Explain how Young's double-slit experiment provides evidence for the wave nature of light.

This video relies on animation of a ripple tank to present interference from a two-point source. Prior to viewing this portion of the video, do DEMONSTRATION #1, Constructive and Destructive Interference, on the board. DEMONSTRATIONS #2 and #3, Interference of Water Waves and Young's Experiment, could be done either before or after seeing the video. Both DEMONSTRATIONS #2 and #3 can be done as student laboratories if time permits.

Stress the point that Young's experiment with light can be explained only with a wave model.

Objective 2: Reconcile well-defined shadows with the wave theory of light.

How can light be a wave-like vibration and still cast sharp shadows? This is a question which poses difficulties for students. You might pose this to the class *prior* to any detailed discussions of the wave model of light.

The video explains shadows in terms of a wave picture immediately after treating Young's experiment. You will probably need to show this short segment of the video several times. Also, between viewings, do DEMONSTRATION #4, Waves and Shadows. Although the demonstration is very similar to the animations in the video, actually doing the demonstration will allow a few quantitative measurements to be made and various possible sizes of slit openings to be explored. If time permits, this demonstration can easily be extended into the student laboratory.

Objective 3: Recognize that refraction is caused by the change in a wave's speed as it passes from one medium to another.

There are several demonstrations relating the properties of water waves passing from one depth to a different depth, with the properties of light passing from one medium into a different medium. Do DEMONSTRATION #5, Refraction in a Ripple Tank, followed with DEMONSTRATION #6, Penny in a Cup. In comparing these demonstrations, carefully make the connections that the *deep region* in the ripple tank corresponds to *air* and the *shallow region* in the ripple tank corresponds to the *water* in the cup.

The index of refraction is the measure of change in speed or change in direction or propagation of light. Most textbooks introduce this idea with the law of refraction (Snell's law). The video, however, mentions *neither* Snell's law *nor* the index of refraction.

The video stresses the point that the change in direction of the wave front of light in the optically more dense substance (i.e., glass) is due to the reduced speed of light in this material. Showing this portion of the video several times in connection with demonstrations will help your students grasp this concept.

DEMONSTRATION #7, Refraction of Light, allows students to view the change in directions of a beam of light passing from air into water.

Objective 4: Explain the reflection of light.

DEMONSTRATION #8, Reflection of Waves, which uses a ripple tank, will give the students much more of a "hands-on" experience with the reflection of waves than merely viewing the short segment in the video. The direction of propagation of the wave fronts corresponds to *ray diagrams* found in most textbooks, but *ray diagrams* for lenses are not discussed in the video.

Near the end of the video a deeper explanation of reflection is given in terms of the interactions of electromagnetic waves and the electrons in the material. A discussion of this picture will lead to a deeper understanding of light and its interaction with matter.

DEMONSTRATION #9, Reflection of Light, shows the actual reflection of a narrow beam of light. Showing this immediately after the students have seen reflections of waves will strengthen the picture of light as a propagation of wave fronts. DEMONSTRATION #10, Rainbow, provides a demonstration of the interactions of light with a "drop" of water. It involves both reflection and refraction. Also, this demonstration gives an introduction and brief explanation of rainbows. Teaching *dispersion* is not an objective of this video, but this demonstration could serve to introduce the property.

Objective 5: Relate the constant speed of electromagnetic waves to their frequencies and wavelengths.

The video makes a transition from the behavior of waves and various phenomena of light at the point of introducing the equation $c = f\lambda$, the speed of light equals the wavelength multiplied by the frequency. *After* viewing this short segment and *before* seeing the regions of the electromagnetic spectrum, discuss the fact that this equation is just the common equation – applicable to a trip on the freeway – speed equals distance divided by time. (See SUPPORTIVE BACKGROUND INFORMATION for details.)

After viewing the portion of the video on the spectrum, you could have the students calculate the frequencies of various regions of the spectrum. For comparison, remind them that their local power company supplies electricity at 60 Hz. (These calculations provide practice in using exponents.)

If time permits, this discussion could lead to *how* such wavelengths (or vibrations) are generated. The EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS section provides brief answers to several such questions.

Objective 6: Identify the regions of the electromagnetic spectrum.

Either before or immediately after viewing the video dealing with the spectrum, do DEMONSTRATION #11, Electromagnetic Waves. This is a "fun" demonstration which can be used to "fix" in the student's mind the connections between the vibrating electric field, the vibrating magnetic field, and the speed of light.

After the video, have students name various regions of the electromagnetic spectrum which you list on the board; then add various properties of each region (e.g., wavelength, origin, uses, etc.). Stress the *small* region of this spectrum to which the eye is sensitive.

DEMONSTRATION #12, Transmission of Electromagnetic Waves, will demonstrate visibly the passage of something connecting the two coils to the speaker from the Walkman.

A preconception is that sound is "like" electromagnetic waves. DEMONSTRATION #13, Comparison of Light Waves and Sound Waves, shows that while air is necessary for sound, it is not necessary for light.

Objective 7: Describe light as a disturbance in an electric field caused by an oscillating charge.

This objective introduces the students to the connection between light and the electrical nature of matter. It would be well worth re-showing this portion of the video several times, interspersing it with a discussion of students' questions and comments. This is a qualitative introduction to a deeper level of understanding.

Although polarization is not mentioned in the video, DEMONSTRATION #14, Transverse Light Waves, is an excellent demonstration of the transverse nature of light waves. Most students are familiar with Polaroid sunglasses and will have that connection with this demonstration.

SUGGESTED ORGANIZATION FOR PRESENTATION OF INDIVIDUAL TOPICS

WAVE NATURE OF LIGHT

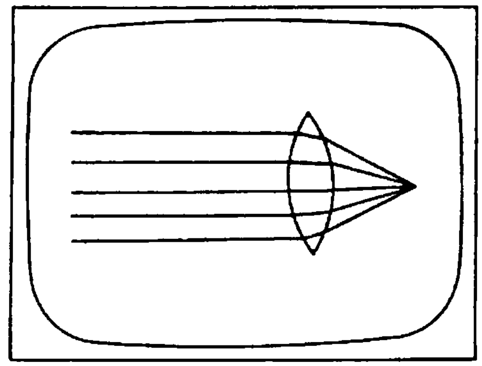
TOPIC	HISTORICAL INTRODUCTION	WAVE PROPERTIES	ELECTROMAGNETIC SPECTRUM	INTERACTION OF LIGHT & MATTER
TERMS	refraction	wavelength frequency propagation refraction dispersion interference constructive interference destructive interference reflection	electric field electromagnetic spectrum	
OBJECTIVES		1 2 3 4	5 6	7
POINTS TO LOOK FOR (STUDENT GUIDE)	Frame # 1	Frame # 2 3 4 5 6	Frame # 7 8	Frame # 9 10 11
EVERYDAY CONNECTIONS	11 14	1 2 3 7 11 12 13 14 16	5 6 8 16	4 9 10 15
ADDITIONAL RESOURCES	Demonstration 6 Demonstration 7	Demonstration 1 through Demonstration 10	Demonstration 11 Demonstration 12 Demonstration 13	Demonstration 14
EVALUATION QUESTIONS		1 3 4 7 8 9 10	2 5	6

POINTS TO LOOK FOR IN THE VIDEO – Several questions are posed in the STUDENT'S GUIDE. Here are those questions along with suggested responses and selected frames from the video. Be ready to stop, replay, or discuss the frames and questions/answers with your class.

I. HISTORICAL INTRODUCTION: Galileo was able to examine the very distant and the very small by using his understanding of refraction to build telescopes and microscopes. For hundreds of years, makers of eyeglasses have corrected imperfections in the refraction of the human eye with lenses.

Name three common devices that utilize refraction.

Three examples might be (1) contact lenses, (2) swimming goggles, (3) telescopes, and (4) prisms.



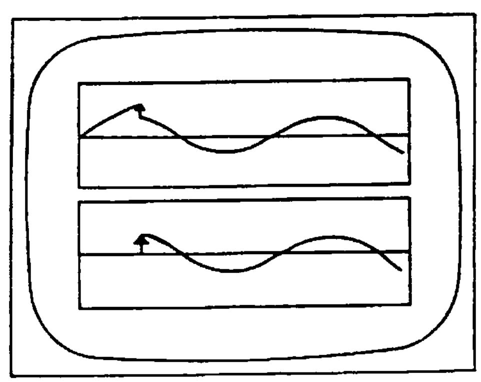
II. WAVE PROPERTIES: Newton's particle theory of light was replaced by a wave description as the result of work by Huygens and Young. Light exhibits wave properties including reflection, refraction, and interference.

Terms for Wave Properties:

wavelength
frequency
propagation
refraction
dispersion
interference
constructive interference
destructive interference
reflection

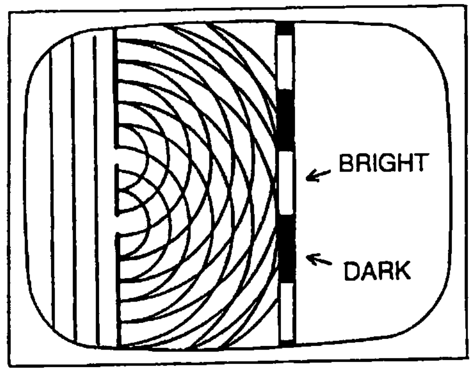
What happens when two waves that are "in step" encounter each other? If they are "out of step," what happens?

If the waves are "in step," they can reinforce each other, creating a wave with larger amplitude than either of the beginning waves. This is called constructive interference. If they are "out of step," they can cancel each other completely, producing destructive interference.



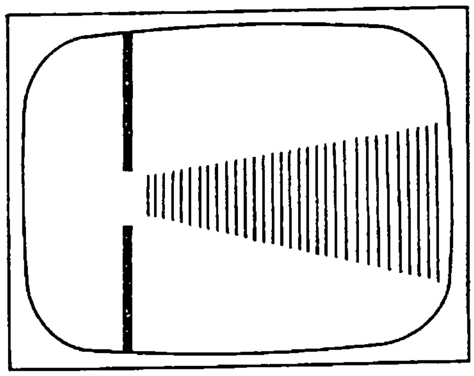
How does the wave theory of light explain Young's experiment?

Constructive and destructive interference of light explains the bright and dark bands on the screen. Bright bands represent constructive interference; dark bands show regions of destructive interference.



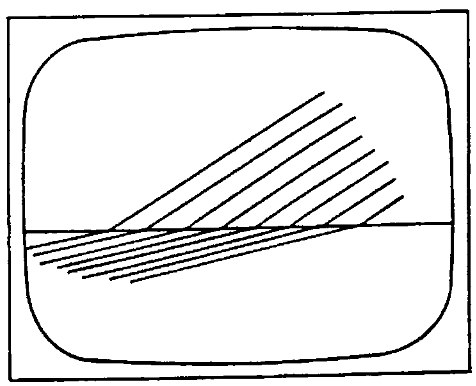
What factors determine the amount of spreading of waves around corners of an opening?

The relative sizes of the wavelength and the opening determine the amounts of spreading of waves.



What happens to a light wave as it enters glass obliquely that causes it to bend?

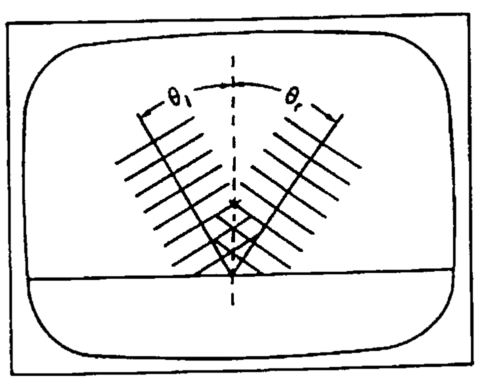
The light wave slows down as it enters the glass, but since parts of the wavefront enter the glass before other parts, the wavefront changes directions.



[NOTE TO THE TEACHER: The discussion of the properties of refraction, interference, and reflection ends with a segment about refracting and reflecting telescopes. This is a good stopping point if the electromagnetic spectrum and electric effects are to be studied at another time.]

What is the relationship between the incident angle of the light wave and the reflected angle?

The angle of incidence equals the angle of reflection.

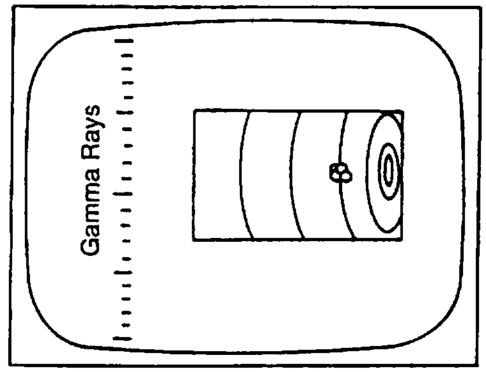


[NOTE TO THE TEACHER: Stop the video when the electromagnetic wave animation appears and point out that the yellow oscillating vectors represent the electric field and the blue vectors represent the magnetic field. Also, remind students that these are traveling waves, not standing waves.]

III. **ELECTROMAGNETIC SPECTRUM:** Light waves are disturbances in the electromagnetic field that propagate at 3×10^8 m/s in free space. Waves of different wavelengths (and thus different frequencies because of the equation $c = f\lambda$) have unique characteristics and are divided into regions according to those characteristics.

Terms for Electromagnetic Spectrum:

electric field
electromagnetic spectrum



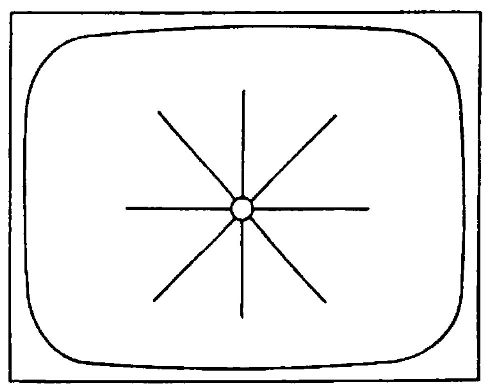
List the regions of the electromagnetic spectrum in order, from shortest wavelength to longest.

Gamma rays, x-rays, ultraviolet, visible light, infrared, microwaves, radio waves.

If gamma rays have the shortest wavelengths in the electromagnetic spectrum, what can be said about their frequencies of vibration?

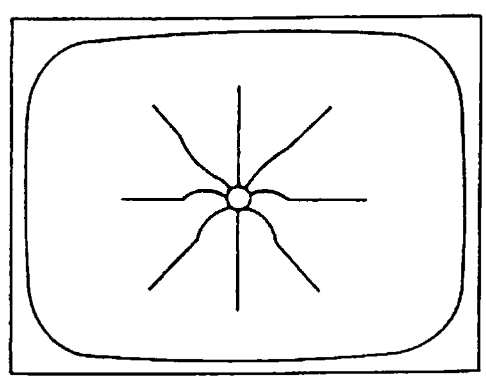
Gamma rays have the highest frequencies because of the relationship $c = f\lambda$, where c is a constant, the speed of light.

IV. **INTERACTION OF LIGHT AND MATTER:** Since all matter is electrical in nature, interactions between light and matter can be explained in terms of the electrons in the matter responding to the oscillating electric field of the incident light.



What do the lines emanating from the charge in this frame represent?

They represent electric field lines.



What condition is necessary to generate a traveling electromagnetic wave?

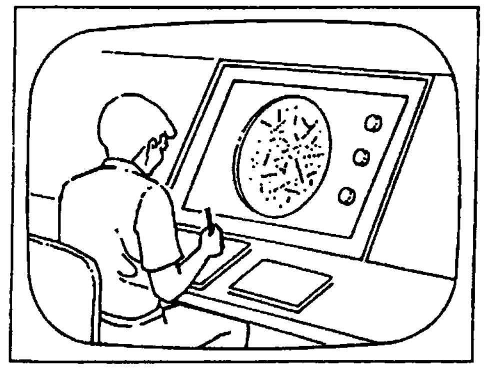
An oscillating electric charge causes ripples in the electric lines of force which, at sufficient distances, become electromagnetic waves.

[NOTE TO THE TEACHER: Point out to the students that all the waves in the electric field lines in this animation sequence actually have the same wavelength. They might appear different because of the distortion caused by projecting a three-dimensional phenomenon onto two dimensions.]

In summary, all electromagnetic radiation, including visible light, exhibits the wave properties of refraction, reflection, and interference. However, differences in the characteristics of the waves comprising the electromagnetic spectrum result in the need for different instruments to detect them.

Why must devices used to detect starlight differ from those used to detect radar waves?

Although they both may use parabolic reflectors, the differences in wavelengths of visible light and radar waves require different sizes of detection components.



TEACHER'S GUIDE TO STUDENT EXERCISES AND ACTIVITIES –

These exercises and activities are for out-of-class work for students as well as a basis for classroom discussions. Some may require extensive answers; some lend themselves to group projects; some to students preparing or describing demonstrations.

I. HISTORICAL INTRODUCTION

1. **Sketch and label three common examples of refraction *not* shown in the video. Identify the materials through which the light travels.**

   This question is to generate student thought about the refraction of light. One example might be light passing from air into a contact lens.

II. WAVE PROPERTIES

1. **Briefly outline the contributions of Newton, Huygens, Young, and Maxwell to the theory of light.**

   A very brief synopsis is:

   Newton—corpuscular, or particle theory
   Huygens—wave theory
   Young—interference experiment (wave evidence)
   Maxwell—electromagnetic waves

2. **Why was Young's experiment extremely important in the history of physics?**

   The importance of Young's experiment could be answered in a few sentences, or it could be the basis of library research. The teacher should specify what depth of answer is expected. Students might use library resources to research in greater detail the contributions of Young and the other scientists.

3. **Describe how well-defined shadows are explained by the wave theory.**

   Explaining well-defined shadows from wave-like motion is Objective 2. This is an important question in the concepts presented in this video. To be able to give a reasonable description, most students will need to use (or at least see) ripple tanks in which various wavelengths and openings are used.

4. **How would you demonstrate interference with sound? Why would such a demonstration be difficult?**

   The following aspects might be considered:

   a. *The relationship between size of opening and wavelength is a vital part of Objective 2. Sound waves are long, so the openings must be large for the waves to pass through.*
   b. *Reflections off walls could hide the sought-for interference effects.*
   c. *Researching the topic of acoustics could reveal other difficulties in such a demonstration.*

5. **Demonstrate the reflection of sound waves.**

   Any echo is a reflected sound wave.

6. **Straight waves in a ripple tank are refracted when they go from one depth to another. Draw a diagram showing deep and shallow regions of a ripple tank and wave crests in both regions. Label carefully all lines and areas of your diagrams.**

   See the video or pictures in a textbook. Better yet, have students set up a ripple tank demonstration upon which to base their drawing.

7. **Explain the directions of travel of the wave crest in your diagram (Question 6).**

   The response to this question should illustrate the reversibility of a ray of light.

8. **Explain how a reflecting telescope works.**

   See EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS #12.

III. ELECTROMAGNETIC SPECTRUM

1. **List the regions of the electromagnetic spectrum. Under each region put several applications or illustrations.**

   Either the video or a textbook could be used in answering this question.

2. **Discuss major events in the 1860's in science and in the history of the United States. Include in your discussion the consequences of those events.**

   This is a question which could lead to extensive library research either by an individual student or by a group of students. Maxwell's mathematical synthesis of electromagnetism brought together all of electricity, magnetism, and light and is the basis of our modern technological society. In the United States the War Between the States preserved our nation as one country.

IV. INTERACTION OF LIGHT AND MATTER

1. **Discuss the similarities and differences between an optical telescope, a radio telescope, and a microwave antenna.**

   Each of these devices is sensitive to electromagnetic radiations but radiation in different regions of the spectrum. Each detector measures wavelengths (or frequencies). The speed of light waves is the same for each telescope.

2. **At amusements parks, hands of the patrons are sometimes marked with ink sensitive to UV light. To re-enter the park their hands are checked. How does this process work?**

   See EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS #15.

3. **Each summer we are warned *not* to leave small children or animals inside enclosed cars with all the windows rolled up – even for a short period of time. On a hot day in the sun, temperatures can soar inside such a closed place. How can this be explained?**

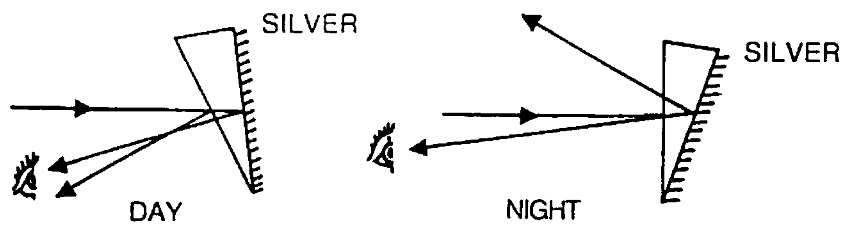
   See EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS #16.

EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS –

To reinforce further the concepts presented in the video, you might pose the following questions to your students for discussion.

1. **Explain how the bright headlight reflection in your rear-view mirror is eliminated by merely *pushing a button.***

   The rear-view mirror is a back-surfaced mirror. Although there is some reflection from the front glass surface, most reflection occurs at the silvered surface.

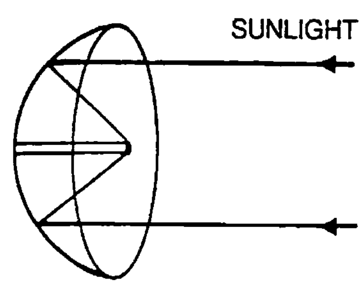


   At night the mirror is tilted so that the large proportion of the reflected light misses the eye and only the small fraction of light reflected from the front surface reaches the eye.

2. **How is a rainbow produced?**

   It is the result of refraction and reflection of sunlight by water droplets in the air. See DEMONSTRATION #10, Rainbow, as well as standard information in textbooks for details.

3. **How does a solar cigarette lighter work?**



   The end of the cigarette (or match) is placed at the focal point of the parabolic dish. Incoming sunlight is reflected from each point of the surface coming together at the focal point of the parabolic dish. This "focusing" of the energy of the light to a point produces sufficient heat to "light" a cigarette or to ignite a match. [CAUTION: The Surgeon General has determined that cigarette smoking is hazardous to your health.]

4. **How does an antenna work to send a radio signal?**

   To send a radio signal an alternating voltage is applied to an antenna. Electrical charges in the wire antenna oscillate in response to the electric field created in the antenna. The oscillating (accelerating) charges generate oscillating electric fields which, in turn, generate oscillating magnetic fields. These electromagnetic fields propagate away from the antenna at the speed of light.

An alternate viewpoint is that the alternating current in the antenna produces an oscillating magnetic field which, in turn, generates an oscillating electric field. The electromagnetic field travels through space at the speed of light.

5. **The wavelength of microwaves is 3 cm (approximately). Find the frequency of microwaves.**

$$c = \lambda f \qquad c = 3 \times 10^8 \ m/s$$

$$f = \frac{c}{\lambda} \qquad \lambda = 3 \ cm = 3 \times 10^{-2} \ m$$

Thus, $$f = \frac{3 \times 10^8 \ m/s}{3 \times 10^{-2} \ m}$$

$$f = 10^{10} \ Hz$$

6. **What is the basic principle in the operation of a microwave oven?**

Microwave ovens generate electromagnetic waves with wavelengths in the range of a few centimeters. These waves have a frequency of approximately 10^{10} Hz, which is in the frequency region for which water molecules are sensitive to vibration. The microwaves generated in your oven induce increased vibrations of the water molecules in the food. The rapid vibrations of the H_2O molecules and the surrounding molecules serve to heat the food from the **inside out.**

7. **Why can you see the food placed in a microwave oven yet not be harmed by the microwaves when the oven is turned on?**

Across the glass plate in the door is a metal shield perforated with small holes having a diameter of approximately 1mm (10^{-1} cm). Visible light has a much smaller wavelength than the size of the holes in the shield and passes through them with little interference. However, microwaves have wavelengths of 3-10 cm (30-100 mm) – much larger than the diameter of the openings. For such wavelengths the openings form an opaque barrier. (This can be demonstrated in the ripple tank. See DEMONSTRATION #4.)

8. **X-rays have a wavelength of approximately 1 nm (10^{-9}m). What is the frequency of x-rays?**

$$c = f\lambda \qquad c = 3 \times 10^8 \ m/s$$

$$f = \frac{c}{\lambda} \qquad \lambda = 10^{-9} \ m$$

$$f = \frac{3 \times 10^8 \ m/s}{10^{-9} \ m}$$

$$f = 3 \times 10^{17} \ Hz$$

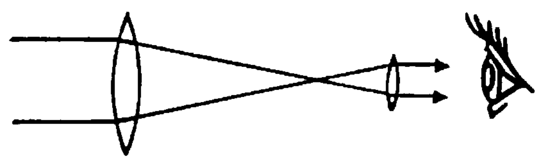
9. **How are x-rays generated by an x-ray machine in a hospital?**

Very high speed electrons are accelerated onto a metal plate. The electrons have sufficiently high energy to penetrate into atoms and to collide with inner electrons, knocking them free from the atoms. Electrons in higher shells of the atom move into the vacancies and emit x-rays in the process.

10. Explain how an x-ray photograph of your hand is made.

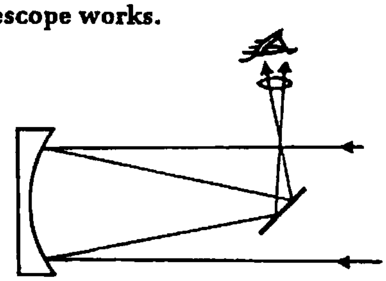
X-rays have a very short wavelength and your skin is almost transparent to such electromagnetic radiation. The film behind your hand will become exposed (darkened) where only soft tissue interrupts the x-rays. Bones are largely calcium and much denser than surrounding tissue, which is largely water; the bones absorb and scatter x-rays. Hence, the film behind bone is unexposed and appears white.

11. Explain how a *refracting* telescope works.



A refracting telescope has two lenses that are separated by the sum of their focal lengths. (This is only one of several varieties of telescopes.) The first lens that the light strikes is called the objective and has the longer focal length; the second lens is called the eyepiece. The eyepiece magnifies the image formed by the objective.

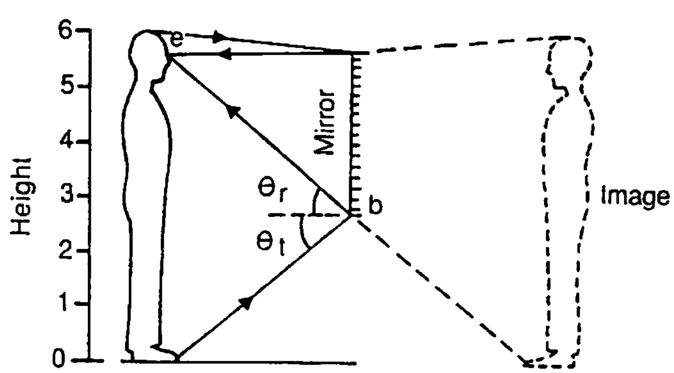
12. Explain how a *reflecting* telescope works.



(The arrangement shown is only one of a variety of reflecting telescopes.) Light strikes a parabolic reflector and is reflected toward the focal point. A small plane mirror reflects the light rays to the side and into the eyepiece, which magnifies the image.

13. What is the shortest length of mirror you need to see yourself from head to toe?

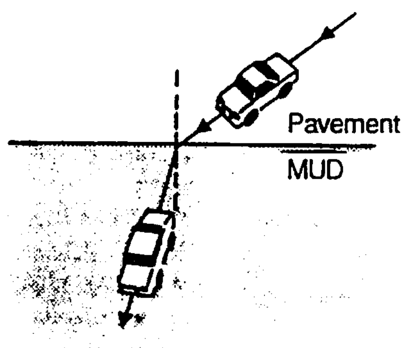
The mirror must be at least half your height. Consider the diagram below.

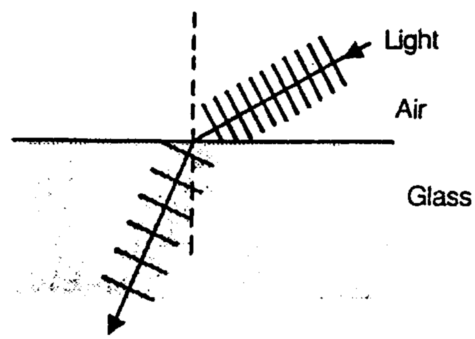


The image of the feet that reaches the eye is a result of the light following the path from the feet to the mirror at Point b, then being reflected to the eye. Since the angle of reflection equals the angle of incidence, the point where the light is reflected will be half the vertical distance between the feet and the eye. Any section of mirror below that point of reflection would be unnecessary. The same argument can be made for determining the top part of the head and being reflected to the eye. Similar diagrams can verify that the distance between the subject and mirror does not matter. (Students may want to experiment with different sizes of mirrors to verify these results.)

14. **What would happen to your speed if, when driving, you ran off the pavement into sticky mud? Would you keep going the same direction if your car hit the mud at an angle; that is, if both the front wheels did not hit the mud at the same time?**

Your car's speed in the mud would be slower than on pavement. If the front wheels did not hit the mud at the same time, the wheel in the mud would be moving more slowly than the wheel on the pavement, so the direction of the car would change. The direction of propagation of the car would be refracted, just like a wavefront of light passing from air to glass. (See diagram below.)





15. **At amusement parks, hands of the patrons are sometimes marked with ink sensitive to ultraviolet light. To re-enter the park their hands are checked. How does this process work?**

When re-entering the park, the ink mark on the hand is placed under an ultraviolet lamp. The UV light excites certain molecules in ink that then emit light in the visible spectrum. The park attendant merely verifies that each returning patron has the correct mark on his/her hand when it passes under a UV lamp.

16. **Each summer we are warned *not* to leave small children or animals inside enclosed cars with all the windows rolled up – even for a short period of time. On a hot day in the sun, temperatures can soar inside such a closed space. How can this be explained?**

The glass in the windows transmits visible light that is absorbed by the upholstery of the interior and the air. The molecules of the interior upholstery then re-emit some of this energy but in a longer wavelength range. The glass does not transmit this infrared radiation; instead, it is reflected back to the air molecules. This process leads to increased energy of the air molecules that rapidly increases the temperature inside the enclosed car. (This is analogous to the "greenhouse effect.")

17. What is the origin of visible light?

Visible light originates from oscillations of the electrons inside the atom. Why each atom produces its own unique fingerprint (spectra) was one of several "clues" to the actual picture and mechanics of the atom. See the Models of the Atom module for more information.

SUMMARY – Thomas Young reinforced Huygens' wave theory of light by demonstrating the interference of light. Light also exhibits other wave properties: reflection, refraction and a relationship between speed, frequency, and wavelength described by $c = f\lambda$.

Maxwell described light as a wave-like disturbance in an electromagnetic field that propagates at a definite speed. Interactions between light and matter can be explained by the interactions between the oscillating electric field (light) and electrons (matter).

Electromagnetic waves form a continuous spectrum, ranging from gamma rays to radio waves. Visible waves make up only a small part of the electromagnetic spectrum.

NOTE OF EXPLANATION REGARDING THE STUDENT'S GUIDE –

The following four pages of the STUDENT'S GUIDE should be duplicated and distributed to the students for use in preparation for viewing the video. The same may be done with the additional page of STUDENT EXERCISES AND ACTIVITIES.

In general, the STUDENT'S GUIDE lists topics, terms, and questions, and the TEACHER'S GUIDE provides definitions, discussion, and answers to the questions. It is very important to have the students receive an appropriate *preparatory set* for viewing the VIDEO and also, following the showing of the VIDEO, to have a systematic discussion, analysis, and summarization of the objectives of the module.

The students should be informed that the INTRODUCTION, TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO, and POINTS TO LOOK FOR IN THE VIDEO should be read and discussed *prior* to viewing the VIDEO. These should also be rediscussed following the viewing.

Answers to the questions listed in the STUDENT'S GUIDE have been included under POINTS TO LOOK FOR IN THE VIDEO in the TEACHER'S GUIDE. The questions which follow this section of the TEACHER'S GUIDE and deal with EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS as well as the SUMMARY should be discussed as a part of the activities that *follow* the viewing(s) of the VIDEO and give closure to the lesson.

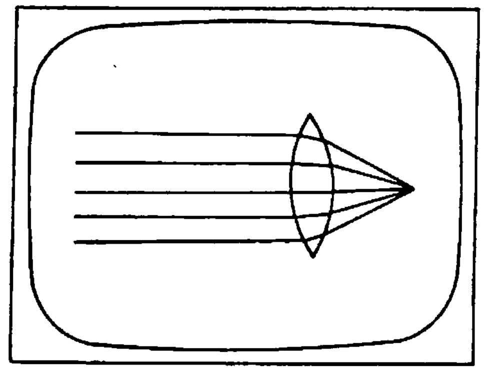
STUDENT'S GUIDE TO THE WAVE NATURE OF LIGHT

****NOTE: Parts of the video, especially mathematical equations, may go by quickly on the screen. If you have questions, you should ask your teacher to replay those sections.****

Points to Look for in the Video

I. HISTORICAL INTRODUCTION: Galileo was able to examine the very distant and the very small by using his understanding of refraction to build telescopes and microscopes. For hundreds of years, makers of eyeglasses have corrected imperfections in the refraction of the human eye with lenses.

Name three common devices that utilize refraction.

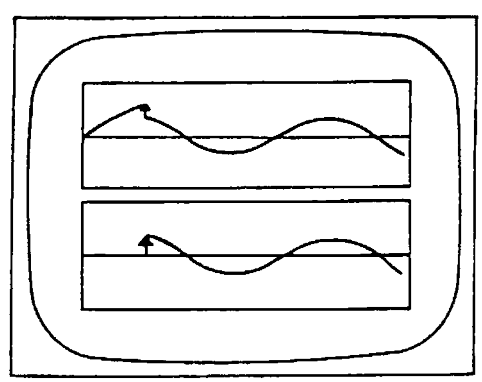


II. WAVE PROPERTIES: Newton's particle theory of light was replaced by a wave description as the result of work by Huygens and Young. Light exhibits wave properties including reflection, refraction, and interference.

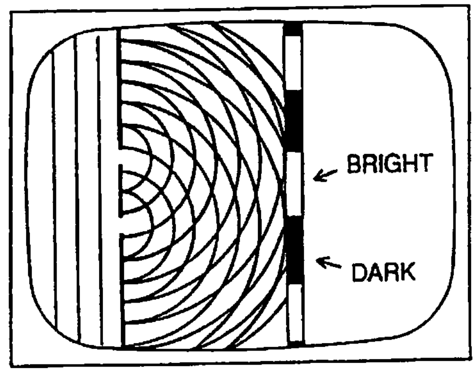
Terms for Wave Properties:

wavelength
frequency
propagation
refraction
dispersion
interference
constructive interference
destructive interference
reflection

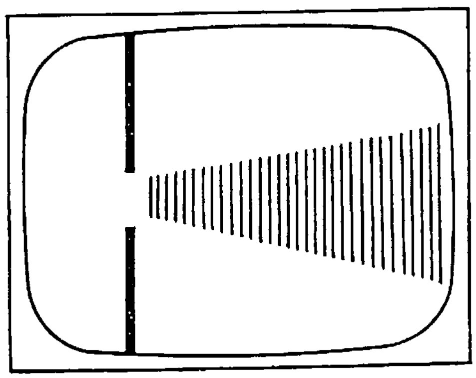
What happens when two waves that are "in step" encounter each other? If they are "out of step," what happens?



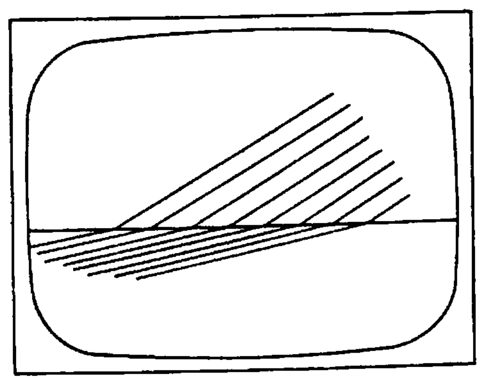
How does the wave theory of light explain Young's experiment?



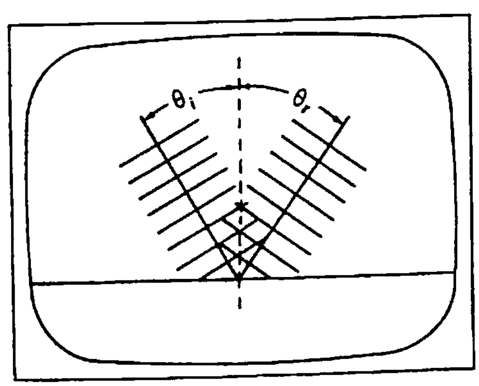
What factors determine the amount of spreading of waves around corners of an opening?



What happens to a light wave as it enters glass obliquely that causes it to bend?



What is the relationship between the incident angle of the light wave and the reflected angle?



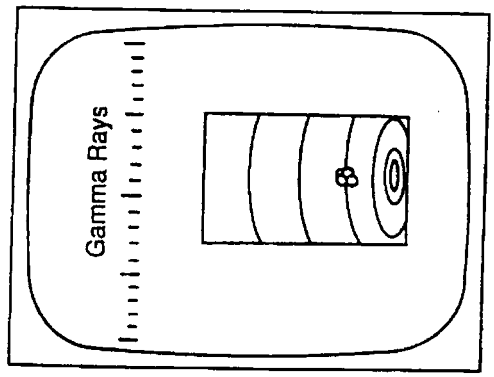
III. ELECTROMAGNETIC SPECTRUM: Light waves are disturbances in the electromagnetic field that propagate at 3×10^8 m/s in free space. Waves of different wavelengths (and thus different frequencies because of the equation $c = f\lambda$) have unique characteristics and are divided into regions according to those characteristics.

Terms for Electromagnetic Spectrum:

electric field
electromagnetic spectrum

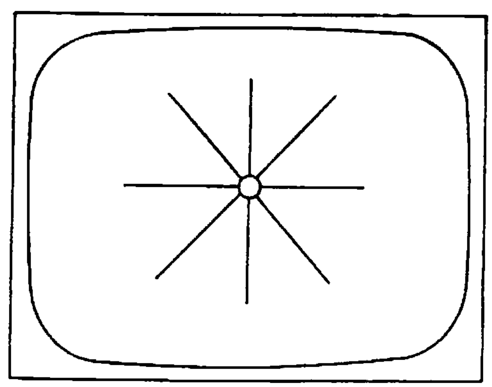
List the regions of the electromagnetic spectrum in order, from shortest wavelength to longest.

If gamma rays have the shortest wavelengths in the electromagnetic spectrum, what can be said about their frequencies of vibration?

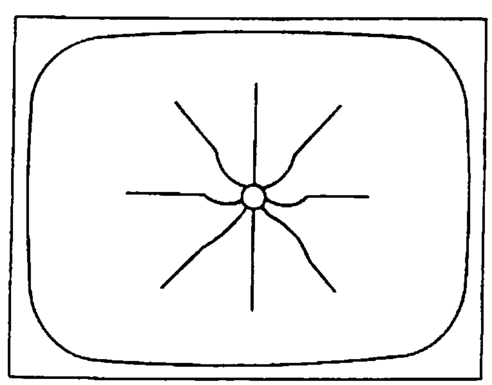


IV. INTERACTION OF LIGHT AND MATTER: Since all matter is electrical in nature, interactions between light and matter can be explained in terms of the electrons in the matter responding to the oscillating electric field of the incident light.

What do the lines emanating from the charge in this frame represent?

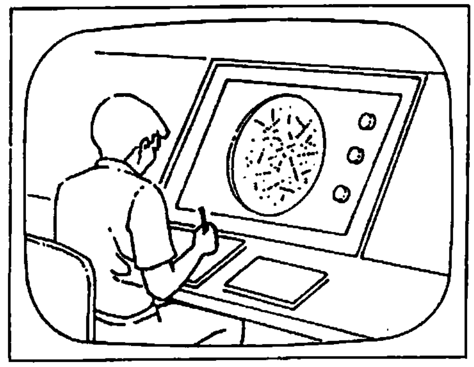


What condition is necessary to generate a traveling electromagnetic wave?



In summary, all electromagnetic radiation, including visible light, exhibits the wave properties of refraction, reflection, and interference. However, differences in the characteristics of the waves comprising the electromagnetic spectrum result in the need for different instruments to detect them.

Why must devices used to detect starlight differ from those used to detect radar waves?



STUDENT EXERCISES AND ACTIVITIES

I. HISTORICAL INTRODUCTION

1. Sketch and label three common examples of refraction (not shown in the video). Identify the materials through which the light travels.

II. WAVE PROPERTIES

1. Briefly outline the contributions of Newton, Huygens, Young, and Maxwell to the theory of light.
2. Why was Young's experiment extremely important in the history of physics?
3. Describe how well-defined shadows are explained by the wave theory.
4. How would you demonstrate interference with sound? Why would such a demonstration be difficult?
5. Demonstrate the reflection of sound waves.
6. Straight waves in a ripple tank are refracted when they go from one depth to another. Draw a diagram showing deep and shallow regions of a ripple tank and wave crests in both regions. Label carefully all lines and areas of your diagrams.
7. Explain the directions of travel of the wave crest in your diagram (Question 7).
8. Explain how a reflecting telescope works.

III. ELECTROMAGNETIC SPECTRUM

1. List the regions of the electromagnetic spectrum. Under each region put several applications or illustrations.
2. Discuss major events in the 1860's in science and in the history of the United States. Include in your discussion the consequences of those events.

IV. INTERACTION OF LIGHT AND MATTER

1. Discuss the similarities and differences between an optical telescope, a radio telescope, and a microwave antenna.
2. At amusements parks, hands of the patrons are sometimes marked with ink sensitive to UV light. To re-enter the park their hands are checked. How does this process work?
3. Each summer we are warned *not* to leave small children or animals inside enclosed cars with all the windows rolled up – even for a short period of time. On a hot day in the sun, temperatures can soar inside such a closed place. How can this be explained?

TEACHER RESOURCES

SUPPORTIVE BACKGROUND INFORMATION – The ancient Greeks thought light was fire – one of the four basic elements. Plato considered light to be streamers or filaments emitted by the eye. The Pythagoreans thought that light traveled from an object to one's eyes in the form of very fine particles, or corpuscles. Since this theory seemed adequate to describe the observations of shadows, reflection, and intensity of light, it remained unchallenged until the seventeenth century.

In 1678, Christian Huygens, a Dutch scientist, formally proposed that light is a wave-like disturbance. His ideas commanded attention because he could describe many properties of light, such as propagation, reflection, and refraction with the wave theory. Still, the particle theory dominated the scientific community, with Isaac Newton being a notable advocate. Huygens and Newton carried on a lengthy dialogue but failed to resolve the controversy, which actually continued into the twentieth century.

The first convincing experimental evidence for the wave nature of light appeared in the classic investigations of interference by Thomas Young and Augustin Fresnel. In 1801, Young designed an experiment in which light passed through two very small slits in a barrier and projected a pattern of light and dark fringes on a screen. Since this phenomenon, constructive and destructive interference, is unique to waves, the particle theory was threatened. However, since Young never worked out a detailed mathematical description of interference, the particle theory remained popular until 1819, when the French physicist Augustin Fresnel synthesized Huygens' wave description with a comprehensive description of the principle of interference.

Forty years later James Clerk Maxwell, with mathematics as his primary tool, predicted that disturbances in an electromagnetic field would travel with the speed of light. He made a bold leap and theorized that light itself is an electromagnetic wave, and he then extended his theory to describe the interaction of light with matter. His theory was verified experimentally ten years after his death.

(Incidentally, the electromagnetic wave theory was not the final word on light. The scientific community presently accepts the wave-particle duality of light – that light exhibits both wave and particle properties. See the module *Wave-Particle Duality* for further information.)

Observations of Wave-Nature Phenomena

Refraction

When a light wave passes from one medium to another of different density, the speed of the wave changes. If the incident wave's direction is not perpendicular to the interface, the direction of propagation is altered as well. If the wave is entering a more dense medium (such as from air to glass), it slows down and is subsequently bent *toward* the normal (perpendicular) line. If the wave enters a less dense medium, it is refracted *away* from the normal, as shown in Figure 1.

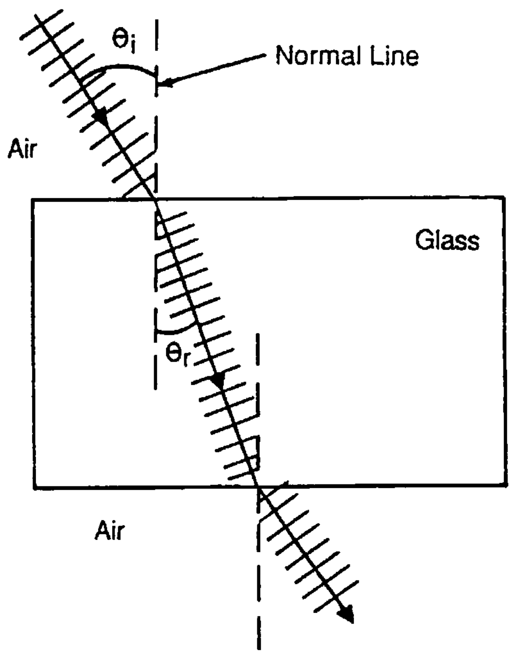


Figure 1

Lenses can be ground into curved surfaces that refract rays so that they focus into a single point. At each point on the surface of the lens, the light is refracted toward or away from the normal to that point on the surface. (See Figure 2.)

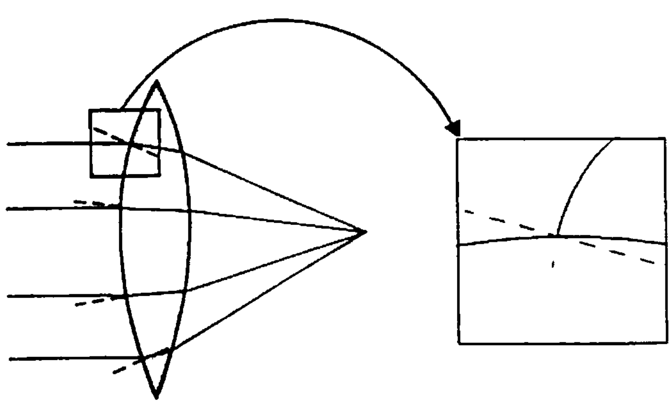
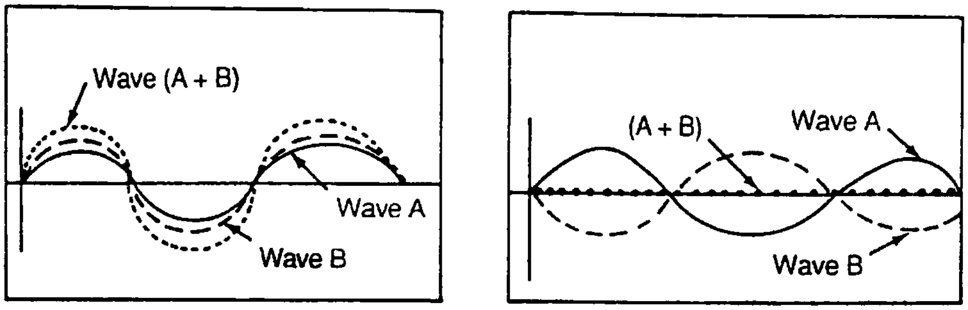


Figure 2

A prism separates white light, which consists of waves with different wavelengths, into a rainbow of colors according to wavelength. Red light, having the longest wavelength is refracted least. This effect is called dispersion.

Interference

When two waves encounter one another, their amplitudes add according to the principle of superposition. If a crest adds to a crest, or a trough adds to a trough, a wave with larger amplitude is produced. This is called *constructive interference.* If a crest arrives on top of a trough (of equal amplitude), they cancel each other completely in *destructive interference.*



a) Constructive Interference b) Destructive Interference

Figure 3

Consider a number of plane waves encountering a barrier with two openings separated by a small distance. In Figure 4, the lines represent the crests of the waves. As the plane waves pass through the slits, the slits act as two sources of circular waves propagating to the right. Every point where the crests intersect represents a region of constructive interference. If this pattern is projected onto a screen, the regions of constructive interference produce bright fringes and the regions of destructive interference produce dark fringes.

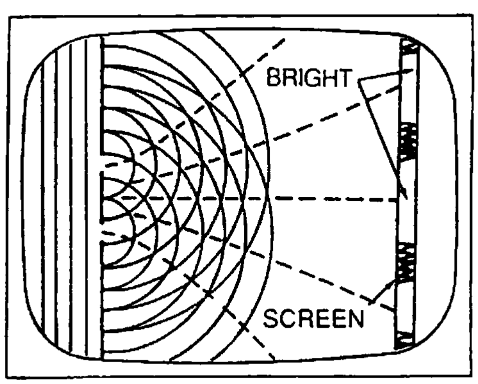


Figure 4

Constructive and destructive interference account for the spreading of any wave as it passes through an opening or past an object. However, the spreading is minimal unless the size of the opening is comparable to the wavelength of the wave (or smaller). Generally, the smaller the opening, the greater the amount of spreading of the wave, and vice versa. Since the wavelengths of visible light are so small, the spreading of the light waves around objects is usually imperceptible.

Reflection

The law of reflection states that the angle of incidence equals the angle of reflection. This means that the incident ray rebounds from the reflective surface so that the outgoing ray makes the same angle with the normal line that the incident ray did. (See Figure 5.)

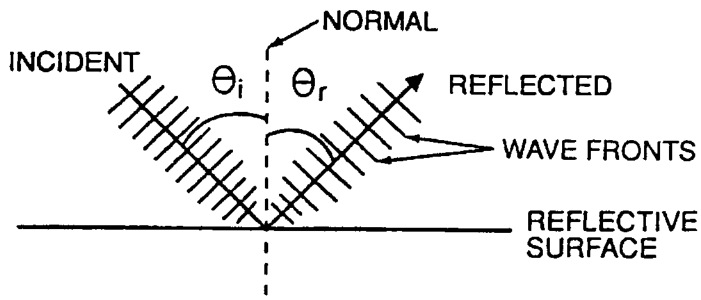


Figure 5

Since the angle of reflection equals the angle of incidence for each point on any surface, a parabolic reflective surface focuses rays to a point as shown in Figure 6.

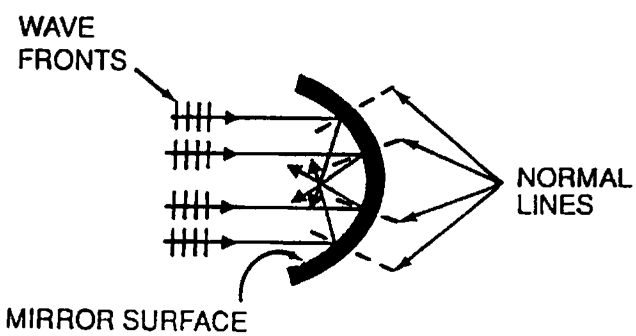


Figure 6

Electromagnetic Wave Propagation

If, indeed, light is an electromagnetic wave that can propagate through free space at a certain speed, how does such a wave get started? The answer lies in an examination of electric and magnetic fields around accelerated charges.

Imagine a single charge at rest in space. Its electric field can be represented by lines of force extending radially outward in all directions. Now suppose that the charge is suddenly accelerated. The field lines will be disturbed, and the disturbance will propagate outward along each of the lines at the speed of light. If the charge is again accelerated, say in the opposite direction, a new disturbance is generated along the field lines. If the charge continues to oscillate, accelerating with simple harmonic motion, the succession of wave pulses constitutes a transverse wave in each field line. These ripples become more parallel farther from the source, coming more and more to resemble plane parallel wavefronts. (See Figure 7.)

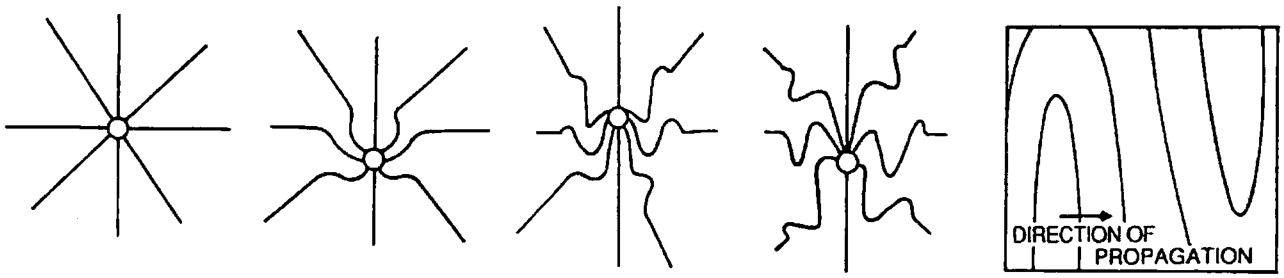


Figure 7

Because any changing electric field creates a changing magnetic field, the waves are actually electromagnetic waves, with the electric field vectors oscillating in one plane and the magnetic field vectors oscillating in a perpendicular plane as shown in Figure 8. THE WAVE DOES NOT TRANSPORT ELECTRIC CHARGE.

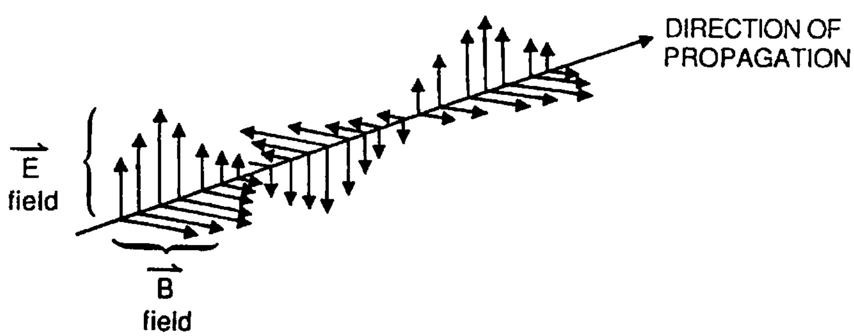


Figure 8

The interactions of electric charges and electric fields are the underlying causes of reflection and refraction of light. When light is incident on the surface of a metal, the mobile electrons at the surface respond to the force of the oscillating electric field. The electrons move in the opposite direction of the incoming electric field. These moving electrons produce electric fields which interfere destructively with the incoming field and, thereby, prevent most of the light from entering the material. That is why metals are usually good reflectors.

In other materials, such as glass or water, the electrons are not mobile enough to cause the light to be reflected entirely. Electrons in these materials respond to the oscillating electric field by oscillating also, but because they are held to their atoms and also because they collide with other electrons, they tend to slow down the transmission of electric field disturbances. The net result is that the electromagnetic wave is bent toward the direction perpendicular to the surface – it is refracted.

The Electromagnetic Spectrum

The collection of all electromagnetic wavelengths (or frequencies) is called the electromagnetic spectrum. Since all types of electromagnetic waves propagate through free space at the speed of light, their wavelengths and frequencies are inversely proportional to each other – the longer the wavelength, the smaller the frequency. The variations in wavelengths and frequencies account for the differences in effects, production, and detection of different types of electromagnetic waves.

The equation relating wavelength and frequency to the speed of light, $c = f\lambda$, is equivalent to a much more familiar relationship – that involving velocity, distance, and time. In $c = f\lambda$, c is the speed of light, the magnitude of a velocity.

$$\begin{array}{lll} c = & f & \lambda \\ \Uparrow & & \\ \Downarrow & & \\ v & & \end{array}$$

And f is frequency, the reciprocal of the period. Since the period of a wave is a measure of the time it takes for one wavelength to pass a point, we have

$$\begin{array}{lll} c = & f & \lambda \\ \Uparrow & \Uparrow & \\ \Downarrow & \Downarrow & \\ v & 1/t & \end{array}$$

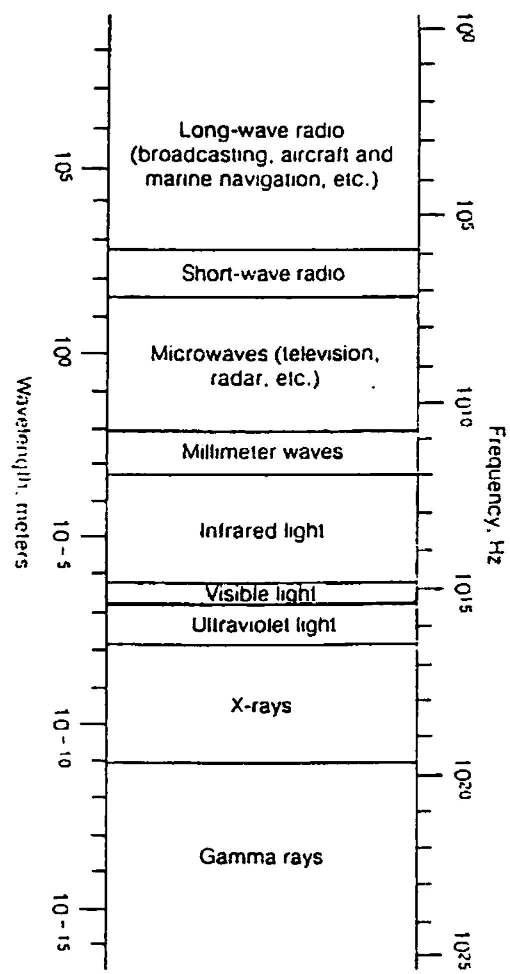
Finally, λ is wavelength, a length or distance.

$$\begin{array}{lll} c = & f & \lambda \\ \Uparrow & \Uparrow & \Uparrow \\ \Downarrow & \Downarrow & \Downarrow \\ v & 1/t & d \end{array}$$

Therefore, these two expressions are equivalent:

$$c = f\lambda \text{ and } v = d/t.$$

Electromagnetic Spectrum



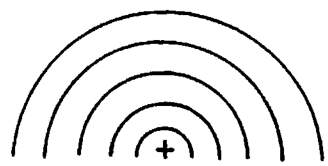
ADDITIONAL RESOURCES

Demonstration #1: Constructive and Destructive Interference

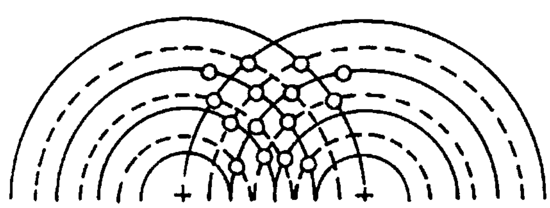
Purpose: To demonstrate constructive and destructive interference.

Materials: String and chalk or chalkboard compass or overhead projector.

Procedure and Notes: Place thumb tightly on string about 10 cm from the chalk and draw a semi-circle on the board with your thumb as the center. The radius of this circle represents one wavelength. Measure two wavelengths and draw a second semi-circle from the same center. Continue in this manner until there are six to ten semi-circles on the board. Each arc represents the crest of a wave.



Draw a second series of semi-circles in exactly the same fashion, but with a center three or four wavelengths to the right. Care must be taken to keep the wavelength constant.



Explanation: The intersection of lines represents the intersection of two crests resulting in a double-crest, which is constructive interference.

Halfway between crests are troughs; these can be drawn in as dotted lines (or use other colors).

This intersection of two dotted lines represents the intersection of two troughs, again constructive interference. But the intersection of solid lines and dotted lines represents destructive interference.

On the board, circle those points where a solid line and a dotted line intersect. These represent calm regions – no disturbance – and they will trace out a series of curves as shown in the video animation. These lines of no disturbance are called nodal lines.

Demonstration #2: Interference of Water Waves

Purpose: To demonstrate the constructive and destructive interference of water waves.

Materials: Ripple tank with either a two-point source generator or a periodic straight wave generator, paraffin blocks.

Procedure and Notes: Details of setting up a ripple tank are found in most physics laboratory manuals.

Reflections from the walls of the ripple tank can make the desired patterns difficult to see. A paper towel lying on the edge of the tank and in the water will weaken these reflected waves.

When using the straight wave generator, barriers such as paraffin blocks must be placed to form two slits for the waves.

Explanation: The regions of calm water represent destructive interference. Compare the similarity of the pattern far from the point sources (or two openings between the paraffin blocks) with the chalk drawing (DEMONSTRATION #1) and with the animation shown in the video. Also, compare with an actual Young's experiment using light or with those frames in the video showing the interference of light. The regions of calm water correspond to regions of no light on the screen in Young's experiment.

Demonstration #3: Young's Experiment

Purpose: To demonstrate the constructive and destructive interference of light.

Materials: A laser or a white light source or microwave apparatus.

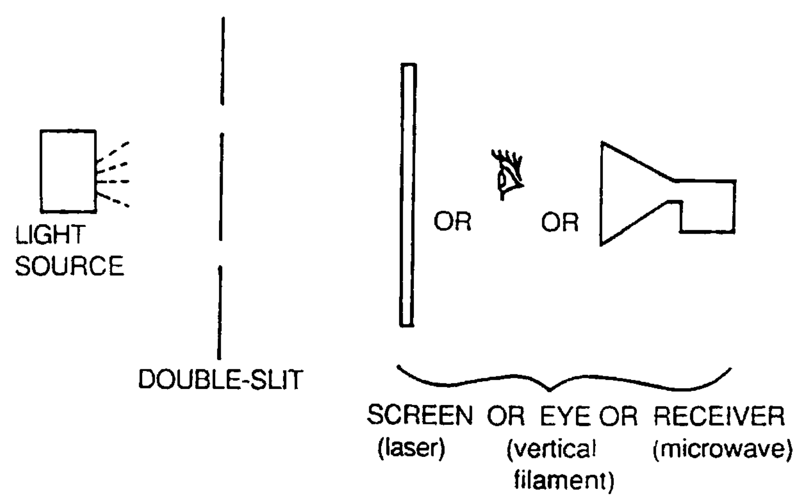
Procedure and Notes: Most laboratory books give complete information about this experiment.

a. Using a laser for your light source is the only means for easily displaying the interference of light on a screen. Care must be taken in the use of every low power laser. Protect your students' eyes.

b. A light bulb with a long vertical filament in a darkened room can be used to see and make measurements of the interference of light. Students hold the double slit in front of their eyes; the interference pattern formed on the retina of their eye appears to be across the room.

c. A microwave apparatus composed of a transmitter and a receiver can be used to demonstrate interference. Since the microwaves cannot be seen, the receiver is moved to detect maximum and minimum reception of radiation by viewing the deflection of the needle on the scale.

Explanation: This experiment conclusively demonstrates the wave-like nature of light. The regions of light are from constructive interference; regions of no light are destructive interference.



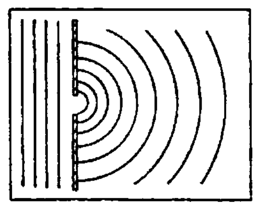
Demonstration #4: Waves and Shadows

Purpose: To demonstrate the condition necessary for waves to cast sharp shadows.

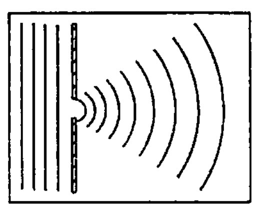
Materials: Ripple tank and paraffin blocks with which various size openings can be formed.

Procedure and Notes: Set up the ripple tank with the straight wave generator sending periodic straight waves across the tank. Using paraffin blocks, form a barrier with the opening between the blocks shorter than the wavelength.

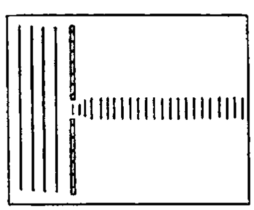
1. Observe the wave pattern after the wave passes through the opening. This pattern will be very circular.



2. Increase the size of the opening until the opening is approximately the same size as the wavelength. Observe the difference in the wave pattern past the opening.



3. Increase the size of the opening once more until this opening is now much longer than the wavelength. Observe the difference in this wave pattern compared to the earlier situation.



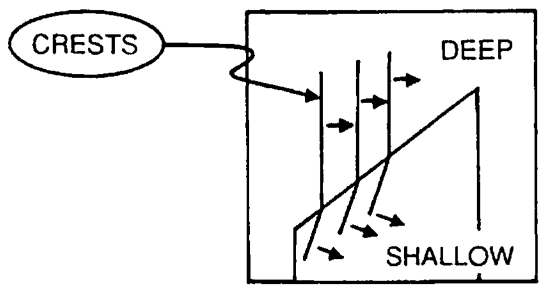
Explanation: When d (opening size) < λ (wavelength), circular waves are generated past the opening. As d becomes longer than λ, very little bending of the waves occurs and shadows are cast on the sides. This phenomenon is explained by the interference of different portions of the wave front as they pass through the opening, a physical process known as diffraction.

Demonstration #5: Refraction in a Ripple Tank

Purpose: To demonstrate refraction in a ripple tank.

Materials: Ripple tank apparatus, glass plate.

Procedure and Notes: Use the straight wave periodic generator to produce straight waves in the deep region of the tank. Observe the direction of propagation in the shallow region. For best effects the shallow region should be as shallow as possible.



Explanation: The speed of water waves depends on the depth of the water–the deeper the water, the greater the wave speed. When the wave crests strike the barrier, they slow in the shallower region and hence the crests change direction.

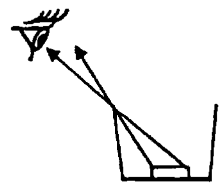
It is also possible to see partial reflection at the interface of the two depths.

Demonstration #6: Penny in a Cup

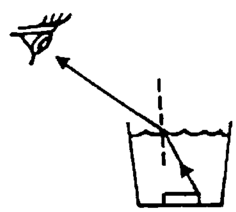
Purpose: To demonstrate the refraction of light in water.

Material: Paper cup, penny, water.

Procedure and Notes: Place a penny in the bottom of an empty cup.



Position the eye so that the penny is just out of sight.



Pour water into the cup; the penny will become visible.

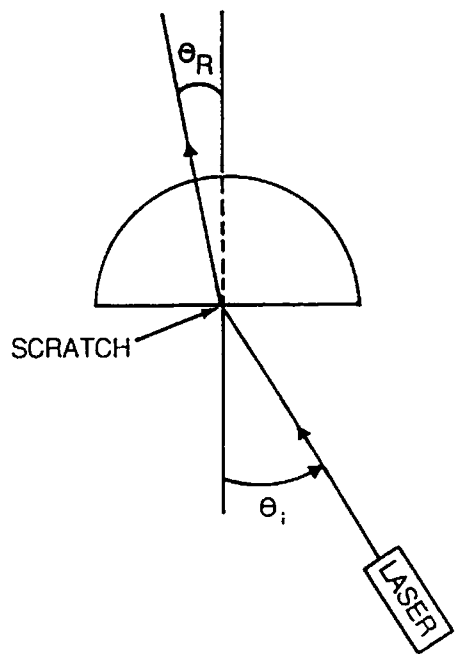
Explanation: The penny is visible because of the refraction of light at the air-water interface.

Demonstration #7: Refraction of Light

Purpose: To demonstrate the refraction of light.

Materials: Laser or well-defined beam of light, semi-circle of clear plastic which can be filled with water or semi-circle of glass, polar graph paper.

Procedure and Notes: Place the center of the semi-circle of water on the center of the polar graph paper. Place the laser at an angle (30°) from the perpendicular to the flat side of the water container. Follow the path of light through the water. Identify the angles of incidence and refraction. (See diagram.)



Move the light source to vary the angle of incidence.

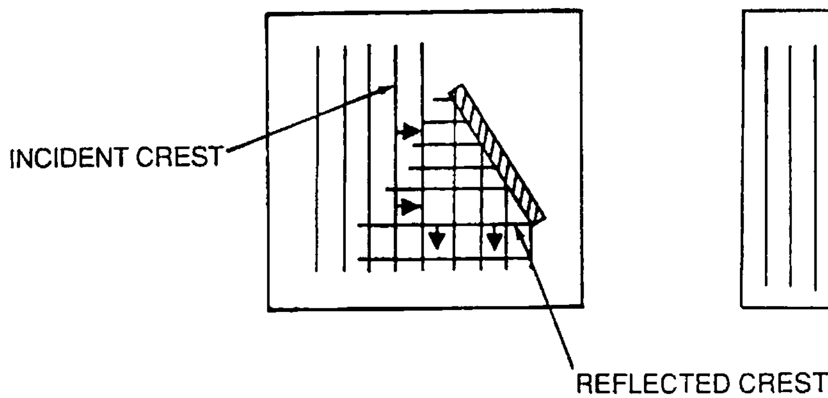
Explanation: The refraction of light can be measured with this arrangement. Polar graph paper makes the measurement of angles very easy.

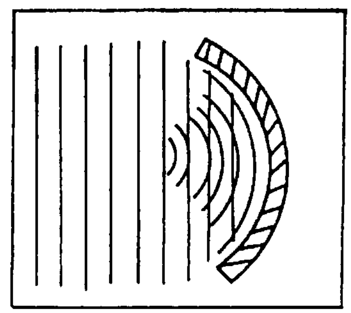
Demonstration #8: Reflection of Waves

Purpose: To demonstrate the reflection of water waves.

Materials: Ripple tank, paraffin block, section of rubber hose.

Procedure and Notes: Generate a series of straight waves at an angle to a paraffin block in the tank.





Hold the rubber hose in a parabolic shape to demonstrate the focusing property of a parabolic reflector.

Explanation: Each section of the wave crest reflects from a barrier building up a reflected crest. The angle between the direction of travel of the incident crest and the normal is the same as the angle between the direction of travel of the reflected crest and normal.

Demonstration #9: Reflection of Light

Purpose: To demonstrate the reflection of light.

Materials: Laser or intense beam of light, plane mirror, chalk dust.

Procedure and Notes: Shine the laser at a plane mirror in a darkened room. By placing chalk dust in the path of the light, its passage across the room can be readily seen. Call attention to the change in direction of the laser beam. USE CAUTION WHEN REFLECTING THE LASER LIGHT!

If a laser is not available, an intense beam of light can be used. It may not be possible to follow this light through space, but its origin, where it strikes the mirror, and its reflection on a screen will be visible. With these points, your students can visualize the change in direction by reflection.

This demonstration can be extended to include reflection from parabolic surfaces.

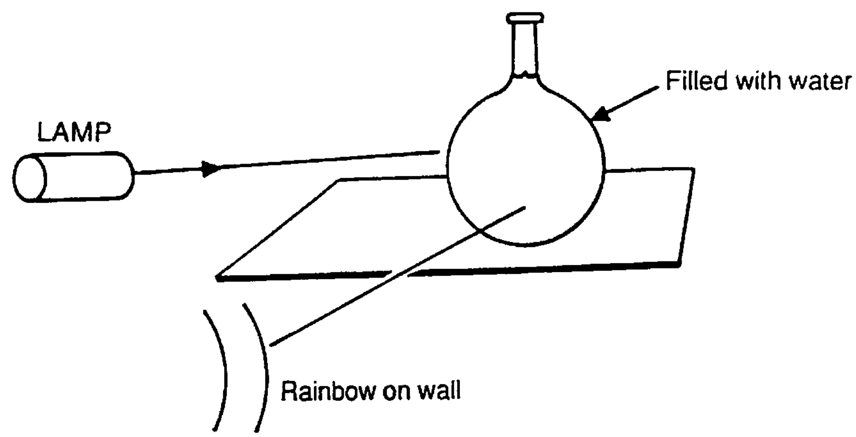
Explanation: For reflection, the angle of reflection equals the angle of incidence.

Demonstration #10: Rainbow

Purpose: To demonstrate refraction, reflection, dispersion of light.

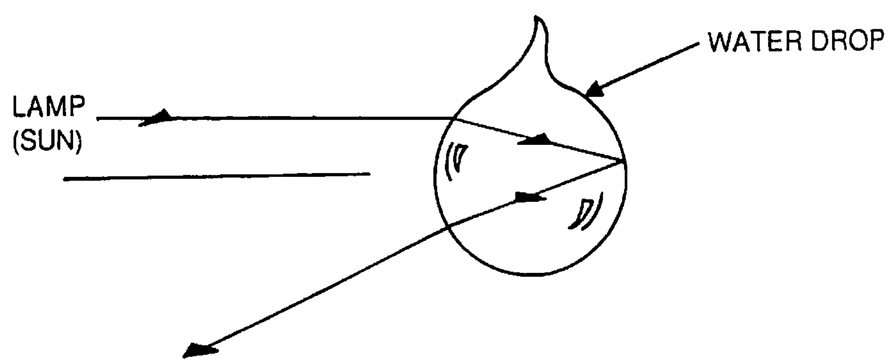
Materials: High intensity lamp, florence flask, dark room.

Procedure and Notes: Set up the apparatus as shown in the diagram.



Explanation: The ray of white light is refracted at the spherical water surface. This ray is reflected at the back surface of the drop and on striking the water-air interface it is refracted a second time. This refraction-reflection-refraction, plus the dispersions of light, leads to the rainbow seen in the classroom and to the rainbow seen in the sky.

In the sky each drop of water is causing a part of the sunlight to undergo the same sequence of events as seen in the diagram below.

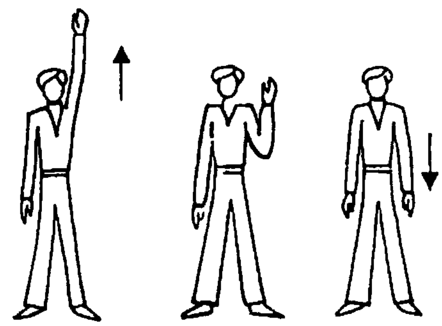


Demonstration #11: Electromagnetic Waves

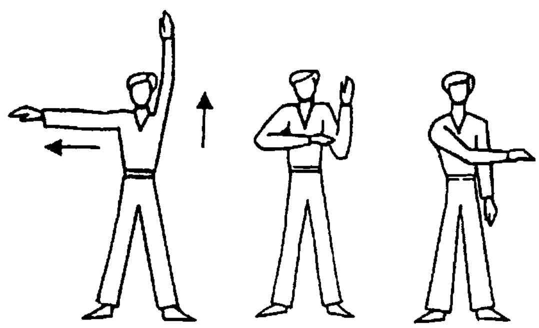
Purpose: To demonstrate the connections between electric and magnetic fields as they propagate through space at the speed of light.

Materials: None

Procedure and Notes: Move your left arm up and down vertically explaining that the tips of your fingers represents the electric field vector.



Now move your right arm horizontally, the tips of these fingers representing the magnetic field vector.



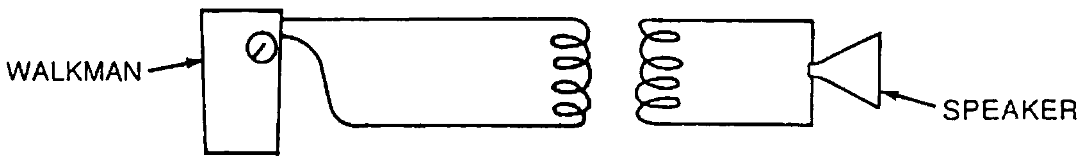
Walk across the room (at the speed of light) continuing to move your left hand vertically (the electric field vector) and your right hand horizontally (the magnetic field vector). Note that if you reverse the *relative* position of arms, you will need to walk backwards since you reverse the direction of propagation.

Demonstration #12: Transmission of Electromagnetic Waves

Purpose: To demonstrate the passage of electromagnetic waves through space.

Materials: Walkman-type radio, two coils (PSSC), speaker.

Procedure and Notes: Cut the wires to the headphones on a walkman and connect these to one of the coils. Connect the second coil to a speaker. The coils must be parallel to one another. Turn on the walkman; sound comes from the speaker. The sound can be dramatically increased by including a small amplifier in the speaker circuit. (A small Radio Shack amplifier works well.)



Explanation: Although the circuits are not physically connected, electromagnetic waves link the two coils, providing the sound from the speaker.

Demonstration #13: Comparison of Light Waves and Sound Waves

Purpose: To show that light can travel through a vacuum.

Materials: Bell jar with vacuum pump, battery-powered buzzer or bell.

Procedure and Notes: Connect the battery to the buzzer (or bell) and ask students to explain why they hear the sound. Place the buzzer (bell) inside the bell jar and evacuate the air. The sound will decrease to a very faint level. Ask the students if they can still *see* the buzzer (bell).

Explanation: Sound can be heard because longitudinal sound waves are traveling from the source to the eardrum. Once the air is removed, the muffled sound, which may remain, is generated by the vibrations of the bell jar and metal plate. Light, on the other hand, needs no medium through which to propagate since it is just a disturbance in the electromagnetic field. The bell can be *seen* because light travels through a vacuum.

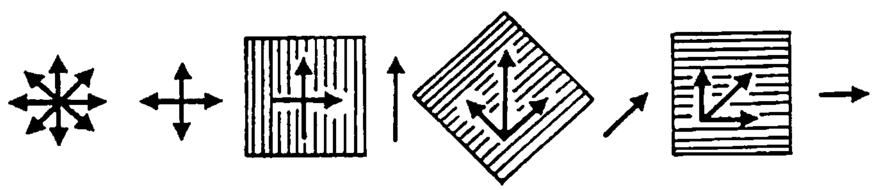
Demonstration #14: Transverse Light Waves

Purpose: To demonstrate the transverse nature of light waves.

Materials: Two pairs of Polaroid® sunglasses or two polarizing filters, light source.

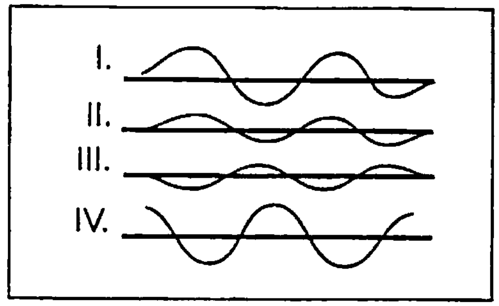
Procedure and Notes: Place two of the lenses of the sunglasses (or the polarizing filters) on top of each other with the same orientation and hold them in front of a light source. (The overhead projector works well.) Then slowly rotate *one* of the lenses until the light is blocked completely.

Explanation: Each filter *polarizes* the transmitted light, allowing only light waves in a certain plane to pass. For instance, if a rope is stretched through one of the cracks in a picket fence, it can be shaken vertically to send waves through the fence, but any horizontal waves would be blocked and not transmitted. If the overlapping filters have the same orientation, they are both transmitting the same plane of light waves. If they are not in the same orientation, however, only the matching components of the waves are transmitted, dimming the light. If they are placed so that their "chosen" planes are perpendicular, they have no components in common, so no light is transmitted. This polarizing effect can be described only by *transverse* light waves.



EVALUATION QUESTIONS

1. **In which of the following pairs of waves could complete destructive interference take place?**

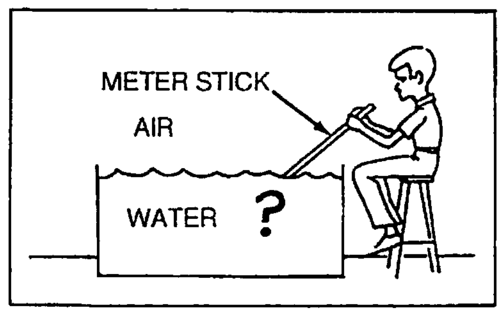


   A. I and IV
   B. I and II
   C. II and III
   D. III and IV

2. **High-energy gamma rays have been detected from a source near the center of the galaxy known as Cygnus X-3. If the wavelength of these gamma rays is 3×10^{-15}m, what is their frequency?**

   A. 1×10^{23} Hz
   B. 3×10^{7} Hz
   C. 3×10^{23} Hz
   D. 1×10^{-7} Hz.

3. **Richard puts a meter stick into a container of water as shown in the figure. The submerged end of the meter stick appears**



   A. above its actual position.
   B. below its actual position.
   C. at its actual position.
   D. to the side of the meter stick.

4. **A microwave generator generates waves with a wavelength of 3 cm. Which of the following is most likely to cause maximum spreading of the microwaves?**

   A. An open doorway
   B. Closed aluminum window blinds with one slat missing
   C. The eye of a needle
   D. The space between two sky-scrapers

5. **In the electromagnetic spectrum, infrared radiation lies between which of the following?**

   A. gamma rays and x-rays
   B. ultraviolet light and visible light
   C. visible light and microwaves
   D. visible light and x-rays

6. **Electromagnetic waves are generated by**

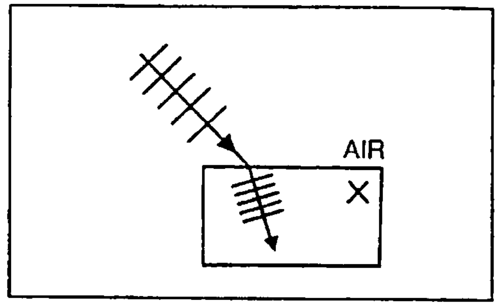
   A. oscillating charges.
   B. electrons travelling with a constant speed in a wire.
   C. the vibration of molecules in the air.
   D. electrons traveling through space at the speed of light.

7. **In Young's double slit experiment, the bright bands on the screen were parallel with the slits and**

   A. equal to the number of slits.
   B. continually changing to dark bands and back again.
   C. were caused by destructive interference.
   D. were caused by constructive interference.

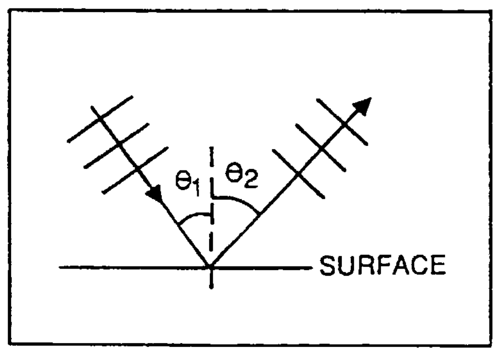
8. **If light passes from air into a transparent material X as in the diagram, which statement is *correct*?**

   A. In material X light travels faster than in air.
   B. In material X light travels at 3×10^8m/s.
   C. Light bends away from the normal in material X.
   D. Light travels more slowly in material X than in air.



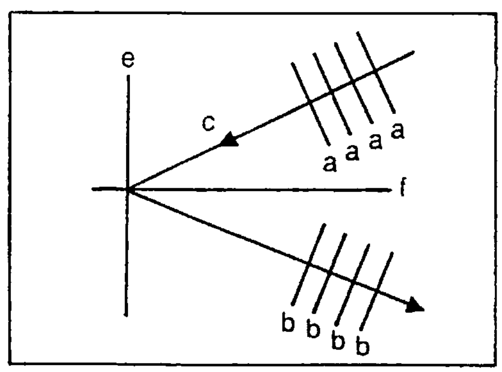
9. **Consider a beam of electromagnetic radiation striking a reflecting surface as shown in the diagram. Which statement is *incorrect*?**

   A. The reflected radiation travels at the same speed as the incident radiation.
   B. The angle θ_2 (the reflected angle) equals the angle θ_1 (the incident angle).
   C. The diagram is correct for visible light but not for radar.
   D. The two media are air and water. Medium 1 can be either of these for the diagram to be correct.



10. **Which of the following statements about the diagram shown is *incorrect*?**

   A. The lines "a" and "b" could represent wave crests.
   B. The arrow head "c" represents the direction of travel of the incident wave crests.
   C. The line "e" represents the interface between two different materials.
   D. The line "f" represents the interface between two different materials.



ESSAY QUESTIONS

11. **List and explain briefly various wave properties of light.**

12. **List several regions of the electromagnetic spectrum in order of increasing wavelength. How are the frequency and speed related in these regions?**

KEY

1. C
2. A
3. A
4. B
5. C
6. A
7. D
8. D
9. C
10. D

SUGGESTED ESSAY RESPONSES

11. Refraction: Light waves passing from air into glass slow down and thus change direction.

    Reflection: Light waves striking an interface *bounce* such that the angle of reflection equals the angle of incidence. These angles are between the normal to the surface and the direction of travel of the wave crests.

    Interference of light: Light passing through two closely-spaced, narrow slits either *add* or *cancel* to produce a pattern of alternating bright and dark bands on the screen.

12. Several regions of the electromagnetic spectrum in order of increasing wavelength are gamma rays, x-rays, visible light, infrared, microwave, radio waves. The speed is constant for all electromagnetic waves. The frequency varies from large to small as you go from gamma rays to radio waves.

TEACHER'S GUIDE TO WAVE-PARTICLE DUALITY

CONTENT AND USE OF THE MODULE – This video focuses on several aspects of modern physics which led to an understanding of the dual wave-particle nature of photons and electrons. The particle nature of light is described in terms of the photoelectric effect, and the wave nature of electrons is also discussed. The works of Planck, de Broglie (de Broy), Heisenberg, and Schrödinger are introduced. Outstanding computer animation helps students to visualize their ideas. This material could follow effectively the study of the module *The Wave Nature of Light*. This video is particularly effective as a summary, showing the interdependence of these developments in physics.

Although not intended this way, some teachers may wish to present the following topics individually:

1. Thermal radiation.
2. The photoelectric effect and its explanation in terms of particles of light and the work function.
3. de Broglie's matter waves.
4. Heisenberg's Uncertainty Principle.

If used to teach single topics, see the chart on page 4 for planning suggestions. It is still important that the video be shown more than once to emphasize the logical, scientific, and historical flow of the concepts of quantum mechanics.

SECTIONS WHICH FOLLOW

TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO – Prior to viewing the video, discuss the following terms with students.

quantum – a discrete or definite amount; in this video, a packet or discrete amount of energy; the plural is quanta.

photon – a particle or quantum of electromagnetic radiation. The energy of a photon is $E = hf$ where h is Planck's constant $= 6.626 \times 10^{-34}$ J s and f is the frequency of the radiation.

photoelectric effect – the emission of electrons from a metal surface by photons of light.

work function – in the photoelectric effect, the amount of work or energy that the electron needs to escape from a particular material, symbolized by φ.

matter waves – waves of probability associated with moving particles, also called de Broglie waves.

uncertainty principle – Heisenberg's principle that a particle's position and momentum cannot be known precisely at the same time:

$$\Delta x \, \Delta p \geq \hbar \, ,$$

Δx, denotes the uncertainty in measuring position,
Δp, denotes the uncertainty in measuring momentum, $(p = mv)$, and

$$\hbar = h/2\pi \, .$$

wave-particle duality – the concept that there is no distinction between waves and particles; sometimes particles may behave like waves, and waves like particles.

WHAT TO EMPHASIZE AND HOW TO DO IT – This module, *Wave-Particle Duality*, traces discoveries in twentieth century physics that led ultimately to quantum mechanics.

The electromagnetic wave theory of Maxwell was inadequate in explaining the radiation of a glowing body, but Max Planck's concept of quanta, with energy proportional to frequency, succeeded. Albert Einstein used this same idea, a particle theory of light, to explain the photoelectric effect. About twenty years later, Louis de Broglie (de Broy) set about deriving a mathematical expression that compares the wavelength of a wave to the momentum of a particle. In the process, he provided a plausible explanation of Bohr's assumption that electrons of atoms exist only in specific orbits. Refining this idea further, Erwin Schrödinger developed the electron-cloud model of the atom. The interaction of wave-particle duality is expressed in Heisenberg's uncertainty principle and the de Broglie hypothesis.

Objective 1: Describe the characteristics of the thermal radiation emitted by a glowing body.

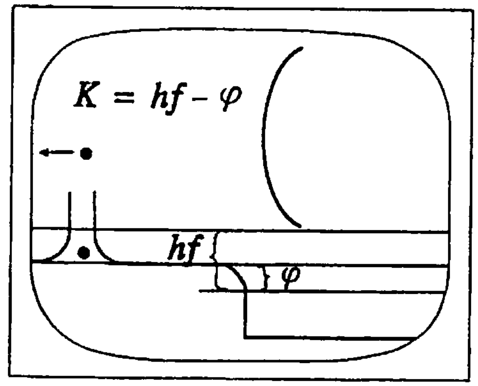
Objective 2: Explain how the particle nature of light is illustrated by the photoelectric effect.

The discussion of Objectives 1 and 2 appears early in the video and should be preceded by a knowledge of the essential terms outlined previously. Questions raised in the STUDENT'S GUIDE should be used to alert students to the importance of these terms. You might want to stop the video to discuss answers to these questions with your class. DEMONSTRATIONS #1 and #2, Incandescent Bulb and The Photoelectric Effect, will reinforce these concepts.

Objective 3: Recognize that the energy of a quantum of light is proportional to its frequency and that the constant of proportionality is a fundamental constant of nature.

The video presents the equation $E = hf$ as well as the photoelectric equation $KE = hf - \varphi$. You will want to solve problems using these equations with your class, as well as treating the concepts of work function and threshold frequency. These are discussed in SUPPORTIVE BACKGROUND INFORMATION. It might help to remind students of other quantities that are quantized, such as charge. (The module *Millikan Experiment* deals with the discovery that electric charge is quantized.)

Student understanding would be enhanced by pausing the video to look at and discuss the diagrams representing the work function, φ, the energy of photons, hf, and the kinetic energy of ejected electrons. The vertical axis represents the electric potential energy of the electron. As you watch the video, notice that the electron slides along the bottom line and slips up the edge to the bottom of the work function line. This represents the most energetic electrons, the ones that will escape from the surface if photons strike the surface with energy equal to or greater than the work function.



Objective 4: Describe and cite examples of wave-particle duality.

Before viewing the video, it might be helpful to remind students of the previous conflicting theories of the nature of light: Newton's particle theory and Huygens' wave theory. The video discusses both light and electrons in terms of their wave and particle characteristics. DEMONSTRATION #3, Circular Standing Waves, will help students to visualize the de Broglie waves for the Bohr atomic model. If your textbook has pictures of electron diffraction or electron interference, it would be helpful to point these out to your students. You might want to discuss the scanning electron microscope, which is explained in EVERYDAY CONNECTIONS. ACTIVITY #1 shows calculation of the de Broglie wavelength.

Objective 5: State Heisenberg's Uncertainty Principle and recognize that it is a consequence of wave-particle duality.

While you are previewing the video, you may want to make sketches from this section to share with your students before they view it. Such sketches are also included in SUPPORTIVE BACKGROUND INFORMATION. Stop the video to discuss the computer graphs of position and momentum with the class. The SUPPORTIVE BACKGROUND INFORMATION will also help you to understand the treatment of uncertainty presented in the module and the application of it to modern theories of atomic structure. DEMONSTRATION #4, Particle or Wave, illustrates that as the measurement of position of a particle becomes more certain, measurement of its momentum becomes less certain. ACTIVITY #2 could be used at this time.

SUGGESTED ORGANIZATION FOR PRESENTATION OF INDIVIDUAL TOPICS

WAVE-PARTICLE DUALITY

TOPIC	THERMAL RADIATION	PHOTOELECTRIC EFFECT	de BROGLIE MATTER WAVES	HEISENBERG'S UNCERTAINTY PRINCIPLE
TERMS		quantum photon photoelectric effect work function	matter waves wave-particle duality	Uncertainty Principle wave-particle duality
OBJECTIVES	1	2 3	4	4 5
POINTS TO LOOK FOR (STUDENT GUIDE)	Frame # 1	Frame # 2 3 4	Frame # 5 6	Frame # 7 8 9 10
EVERYDAY CONNECTIONS	1	2	3	4 5
ADDITIONAL RESOURCES	Demonstration 1	Demonstration 2	Demonstration 3 Activity 1	Demonstration 4 Activity 2
EVALUATION QUESTIONS	1 8	3 4 5 6 11	2 9	7 10 12

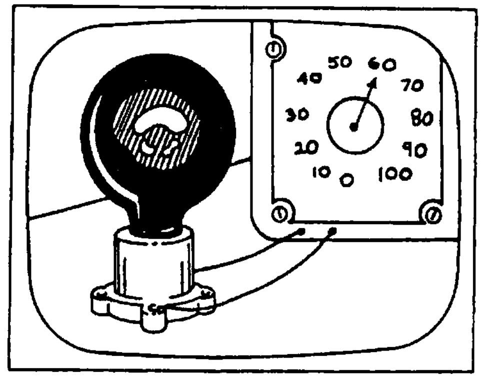
POINTS TO LOOK FOR IN THE VIDEO – Several questions are posed in the STUDENT'S GUIDE. Here are those questions along with suggested responses and selected frames from the video. Be ready to stop, replay, or discuss the frames and questions/answers with your class.

I. **THERMAL RADIATION:** All physical objects radiate energy; hot bodies such as an incandescent bulb can radiate enough visible light to glow.

Upon what physical quantity does the color of any glowing body depend?

Temperature.

[NOTE TO THE TEACHER: If students have studied *Wave Nature of Light*, you might need to indicate that this "light" is not from *atomic levels*. It does not depend on properties of the material of the filament.]



II. **PHOTOELECTRIC EFFECT:** Certain frequencies of light cause electrons to be emitted from certain metal surfaces. Ultraviolet light, for instance, ejects electrons from zinc metal. Einstein was able to explain this phenomenon using Planck's equation.

Terms for Photoelectric Effect:

quantum
photon
photoelectric effect
work function

In Planck's equation $E = hf$, what does each symbol represent?

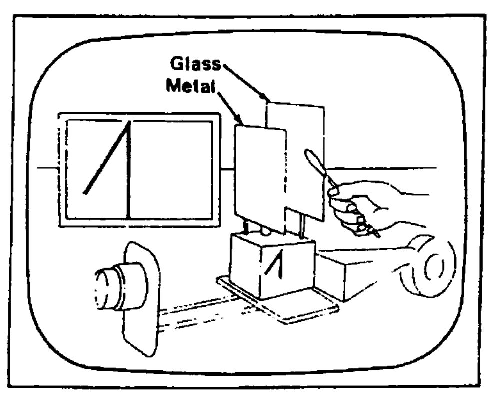
E represents energy.
h is a fundamental constant that equals 6.626×10^{-34} J s.
f is the frequency of the light.

An ultraviolet light discharges a negatively-charged electroscope. The effect is known as____________.

The photoelectric effect.

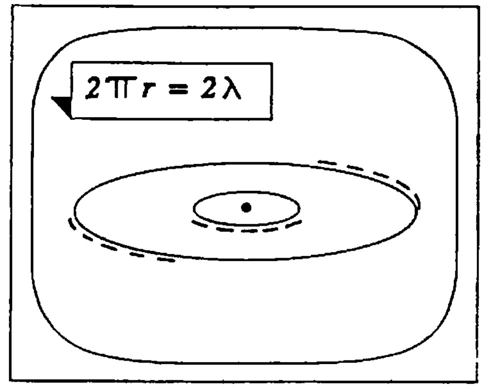
Why isn't the effect noticed when a glass plate is inserted between the zinc plate and the UV light?

Ordinary glass blocks UV light but allows visible light to pass through it. Photons of visible light do not have sufficient energy to eject electrons from zinc.



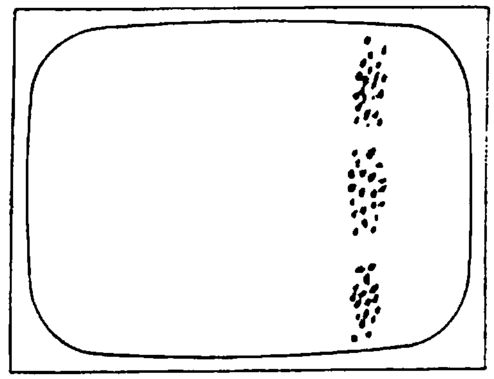
In the de Broglie model of the atom, if electrons are viewed as waves circling the nucleus, why do they have to exist in orbits that increase a whole wavelength at a time?

Each orbit consists of electron waves that interfere constructively and reinforce themselves on the orbit, setting up an integral number of wavelengths in an orbit.



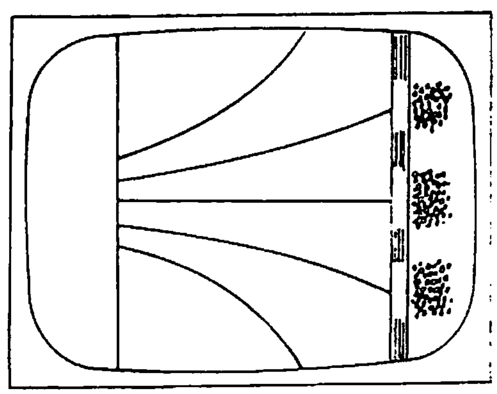
Waves produce an interference pattern. How can the pattern be explained in terms of particles of light (photons)?

There is a higher probability that more photons land in some places than in others.



To what do the white light spots correspond where the wave pattern hits the screen?

They correspond to the bright areas on the screen, areas of constructive wave interference (antinodes).



IV. **HEISENBERG'S UNCERTAINTY PRINCIPLE:** The Heisenberg Uncertainty Principle reflects the wave-particle duality of light and matter: The more we know about matter as a particle (well-defined position), the less we know about its momentum (wavelength), and vice versa.

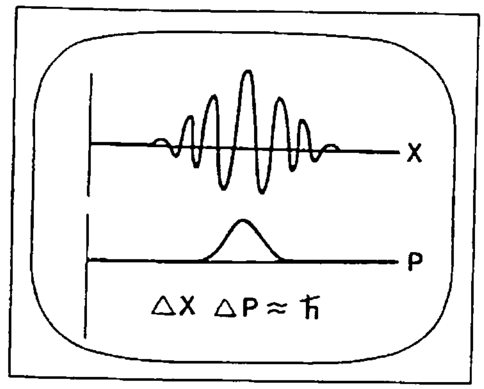
Terms for Heisenberg's Uncertainty Principle:

uncertainty principle
wave-particle duality

How can a particle's location be made more definite?

Its location can be made more definite by adding waves of different wavelengths.

[NOTE TO THE TEACHER: Not only do we add different wavelengths, but also different amplitudes. The vertical axes of these graphs represent amplitude.]



As the position of the wave becomes more definite, what happens to the momentum?

It becomes less definite.

Match each of the following scientists to his contribution.

1. Planck *(C)*
2. Einstein *(B)*
3. de Broglie *(E)*
4. Schrödinger *(D)*
5. Heisenberg *(A)*

A. Uncertainty Principle
B. photoelectric effect
C. quanta
D. electron cloud model
E. matter waves

TEACHER'S GUIDE TO STUDENT EXERCISES AND ACTIVITIES –

These are take-home questions and activities for students with suggested responses. Copies of the questions *without* the responses appear following the STUDENT GUIDE.

I. THERMAL RADIATION

1. **As the cells in a flashlight get weaker, the filament appears redder. Why?**

   Weaker battery → smaller current → less energy → lower filament temperature → lower frequency.

2. **The surface temperatures of Vega, our Sun, and Barnard's star are 10,000 K, 6,000 K, and 3,000 K respectively. Which of these appears blue in color; red in color; yellow in color? Why?**

Vega	*blue*
Sun	*yellow*
Barnard's star	*red*

II. PHOTOELECTRIC EFFECT

1. **As a mechanical analog of the photoelectric effect, consider a ball at rest in a depression. If a sufficient amount of energy, E, is given to the ball of mass, m, by the push of the hand, it will roll up the hill and escape with velocity v. Write an equation of energy conservation for this situation and explain each term in the equation by analogy to Einstein's photoelectric effect equation.**

   $E = mgh + \frac{1}{2} mv^2$

   E analogous to photon energy

   mgh analogous to work function

   $\frac{1}{2} mv^2$ analogous to kinetic energy of photon

2. **The following is a table of the work function for various metals:**

Cesium	**3.0×10^{-19} J**
Potassium	**3.5×10^{-19} J**
Sodium	**3.7×10^{-19} J**
Calcium	**4.3×10^{-19} J**
Zinc	**6.1×10^{-19} J**
Platinum	**8.5×10^{-19} J**

   a. **If green light will cause the photoelectric effect to occur in sodium metal, for which other metals listed will it definitely also eject photoelectrons?**

      Potassium and Cesium.

   b. **What would be the effect of doubling the intensity of the light used?**

      More photoelectrons, each having the same energy as before.

c. **What would be the effect of changing the color of the light used, for example, from green to blue or ultraviolet?**

As the frequency increases, so will the kinetic energy of the photoelectrons.

3. **Name some devices that utilize the photoelectric effect.**

Light meters, solar calculators, cameras, movie projectors (sound system).

III. de BROGLIE MATTER WAVES

1. **Why does one not observe wave-like behavior for common objects like baseballs in flight or automobiles in motion?**

The wavelength of a particle is inversely related to its momentum. Only particles of very small mass have wavelengths that are observable.

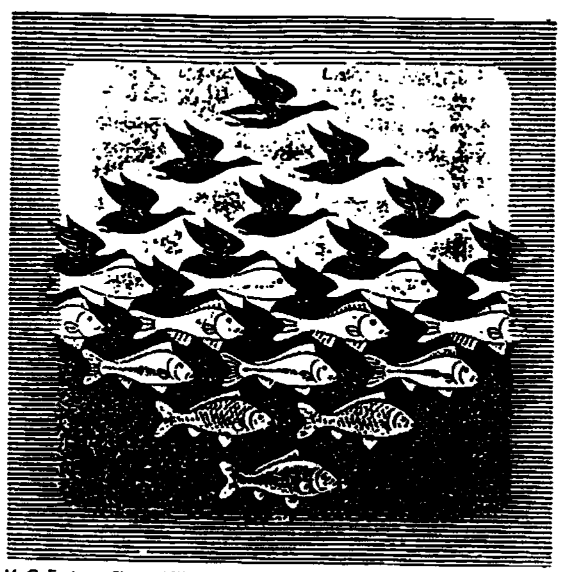
2. **How did de Broglie explain the stability of the hydrogen atom?**

Only an integral number of wavelengths fit on a given orbit's circumference, producing a standing wave. The energy is trapped in the standing wave pattern.

3. **Experimental evidence for de Broglie's concept of matter waves was provided by Davisson and Germer. Research this experiment and report on what it involved.**

They scattered electrons from metallic crystals and observed diffractional patterns similar to those produced by light.

4. **Particles and waves represent different views of the same phenomenon. Comment on the dual nature of the Escher drawing below:**



M. C. Escher—Sky and Water II, 1938. Collection Haags Gemeentemuseum—The Hague, 1981. © BEELDRECHT, Amsterdam/V.A.G.A., New York.

At the top it is really fowl, but at the bottom it is fish. Each is needed to describe the drawing.

IV. HEISENBERG'S UNCERTAINTY PRINCIPLE

1. **State Heisenberg's Uncertainty Principle in your own words.**

   Responses will vary.

2. **A moving electron is in a shoebox-size container. The ends of the container are slowly pushed together.**

   a. **What is the uncertainty of the electron's position before the ends are pushed together?**

      The length of the box.

   b. **What happens to the position uncertainty as the ends are pushed together?**

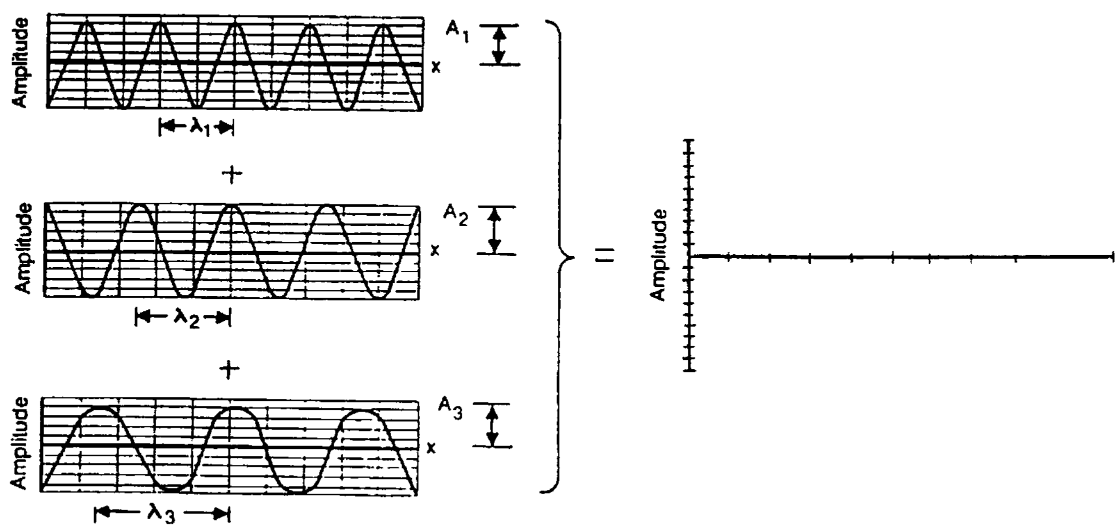
      The position uncertainty is less.

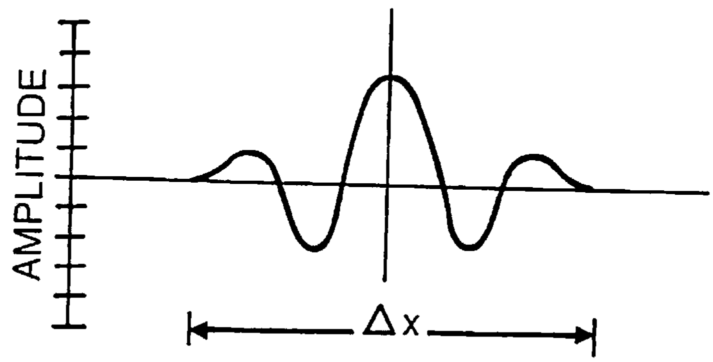
   c. **What does pushing the ends together do to the uncertainty of the electron's momentum? Why?**

      The uncertainty of the momentum is increased.

      $$\Delta p \approx \frac{\hbar}{\Delta x}$$

3. a. **Add the amplitude of the following waves of slightly different frequency to observe that these waves of infinite position uncertainty become more localized.**





b. **If the width, Δx, of your resulting localized wave is 2.2×10^{-12} m, what is the uncertainty in the momentum, Δp?**

$$\Delta p \approx \frac{\hbar}{\Delta x} = 3 \times 10^{-22} \text{ kg m/s}$$

EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS –

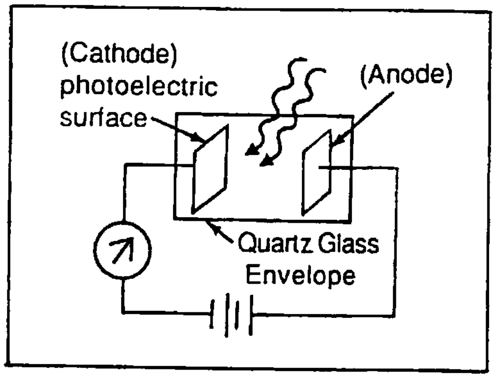
To reinforce further the concepts presented in the video, you might pose the following questions to your students for discussion.

1. **How can one estimate the surface temperatures of stars?**

   The surface temperatures of stars can be estimated by observing their spectra because the color of any glowing body is related to its temperature. A red star is relatively cool compared to a blue-white star, because it lacks enough energy to produce photons of higher frequency, $E = hf$. *Our sun with a surface temperature of about 6,000 K glows yellow.*

2. **How does a photocell operate?**

   The photocell makes use of the photoelectric effect. A potential difference is placed across two metal surfaces. When light shines on the cathode, the emitted photoelectrons are attracted to the anode, producing a current. This current could then power a photographic light meter. The current could also trigger another device, such as a warning buzzer in an entry alarm or smoke detector. Sound in a movie projector is produced by a beam of light passing through the sound track on the film and onto the photo cell.



3. **How are matter waves used to magnify objects in an electron microscope?**

   We can "view" objects only if the wavelength used to illuminate the object is smaller than the object. To "view" an object smaller than the wavelength of any visible light calls for a wave having a length smaller than visible light. In an electron microscope, electrons are accelerated to high velocities so that they have short wavelengths. The microscope is ideal in taking "pictures" of very small objects. A light microscope can resolve a separation of 10^{-7} *m, but an electron microscope can resolve separations one thousand times smaller. Because an electron microscope is operated with higher energy, this can result in damage to the specimen. Live materials are not usually observed with it.*

4. **Why will a luke-warm cup of coffee never simultaneously produce an ice cube and heat up the remaining liquid? Why is the arrow of time in our universe only forward, i.e., why do we live in an irreversible universe?**

   Both questions have the same answer: the effects are results of the uncertainty principle. Quantum uncertainty makes it impossible to define any set of conditions precisely for a system. To have a reversible event, every atom's precisely determined position would have to stay the same while its precisely determined momentum would be reversed. But precise position and precise momentum cannot be known simultaneously. Thus, it is not possible to reverse the direction of every atom in a system.

5. **How may quantum theory provide for a new species of semiconductor devices which will probably replace today's transistor?**

   The new semiconductor devices will be so small that the dimensions approach the electron's wavelength, approximately 2×10^{-10} *m. In this realm, quantum mechanics, in particular the* *uncertainty principle, governs the electron's behavior. New design and fabrication techniques will be required.*

SUMMARY – The wave model of light could not explain the fact that at relatively cooler temperatures a glowing body does not radiate the higher frequencies of light. Nor could it explain the emission of photoelectrons. To describe accurately these observations, electromagnetic radiation must be considered to be particle-like, having a discrete amount of energy. If a photon has sufficient energy, greater than the work function, it will free an electron from the surface of a material. Conversely, particles can demonstrate wave-like characteristics. Thus particles exhibit both particle and wave characteristics and waves exhibit both wave and particle characteristics. This is wave-particle duality. According to Heisenberg's Uncertainty Principle, the more we know about a particle's location, the more uncertain we are about its momentum. Through these ideas we think of matter waves as probability waves. In this way we can view the electron of an atom as a cloud which indicates the probability of the electron being in that location.

NOTE OF EXPLANATION REGARDING THE STUDENT'S GUIDE –

The following four pages of the STUDENT'S GUIDE should be duplicated and distributed to the students for use in preparation for viewing the video. The same may be done with the additional four pages of STUDENT EXERCISES AND ACTIVITIES.

In general, the STUDENT'S GUIDE lists topics, terms, and questions, and the TEACHER'S GUIDE provides definitions, discussion, and answers to the questions. It is very important to have the students receive an appropriate "preparatory set" for viewing the VIDEO and also, following the showing of the VIDEO, to have a systematic discussion, analysis, and summarization of the objectives of the module.

The students should be informed that the INTRODUCTION, TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO, and POINTS TO LOOK FOR IN THE VIDEO should be read and discussed *prior* to viewing the VIDEO. These should also be rediscussed following the viewing.

Answers to the questions listed in the STUDENT'S GUIDE have been included under POINTS TO LOOK FOR IN THE VIDEO in the TEACHER'S GUIDE. The questions which follow this section of the TEACHER'S GUIDE and deal with EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS as well as the SUMMARY should be discussed as a part of the activities that *follow* the viewing(s) of the VIDEO and give closure to the lesson.

STUDENT'S GUIDE TO WAVE-PARTICLE DUALITY

INTRODUCTION – This video examines duality in nature. A complete description of certain phenomena may include more than one model. Light may be considered a wave for much of its behavior, but under certain conditions it must be considered particle-like. Strangely enough, matter, which we think of as being particulate, also exhibits wave-like behavior.

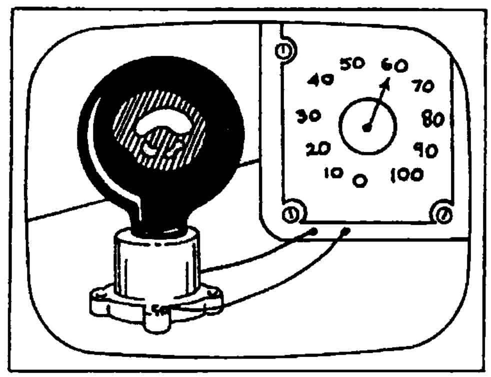
****NOTE: Parts of the video, especially mathematical equations, may go by quickly on the screen. If you have questions, you should ask your teacher to replay those sections.****

Points to Look For in the Video

As you are watching the video be aware of the contributions of the following scientists: Planck, Einstein, de Broglie, Schrödinger, and Heisenberg.

I. **THERMAL RADIATION:** All physical objects radiate energy; hot bodies such as an incandescent bulb can radiate enough visible light to glow.

Upon what physical quantity does the color of any glowing body depend?



II. **PHOTOELECTRIC EFFECT:** Certain frequencies of light cause electrons to be emitted from certain metal surfaces. Ultraviolet light for instance, ejects electrons from zinc metal. Einstein was able to explain this phenomenon, using Planck's equation.

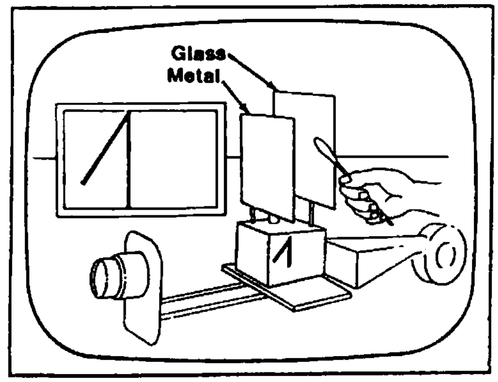
Terms for Photoelectric Effect:

quantum
photon
photoelectric effect
work function

In Planck's equation $E = hf$, what does each symbol represent?

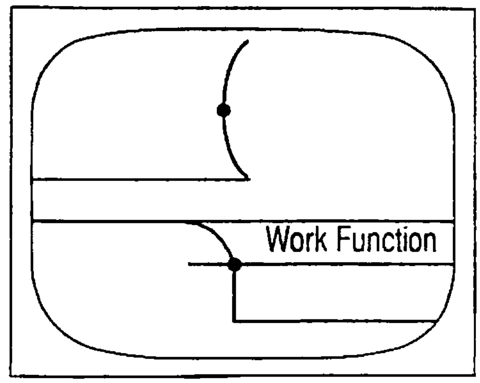
An ultraviolet light discharges a negatively charged electroscope. The effect is known as ___________.

Why isn't the effect noticed when a glass plate is inserted between the zinc plate and the UV light?

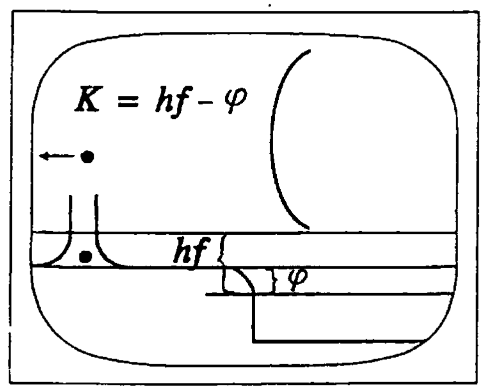


What does the work function usually denoted by φ represent?

[NOTE TO THE STUDENT: When this diagram appears, your teacher will pause the video. The upper half of the screen shows an electron trying to escape from the surface of the metal. The bottom half is a graph. The vertical axis represents the electric potential energy of the electron. As you watch the video, notice that the electron slides along the bottom line and slips up the edge to the bottom of the work function line. This represents the most energetic electrons, the ones that will escape from the surface if photons strike the surface with energy equal to or greater than the work function.]



If an electron absorbs a photon of ultraviolet light with energy hf greater than φ, what will happen to the electron?

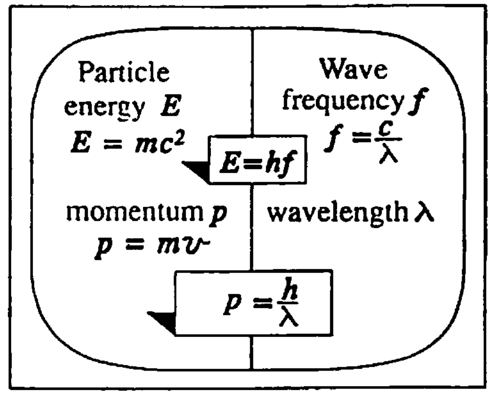


III. **de BROGLIE MATTER WAVES:** French physicist Louis de Broglie questioned, "If light exhibits dual wave-particle behavior, why can't any particle of matter, such as an electron, exhibit a wave nature?"

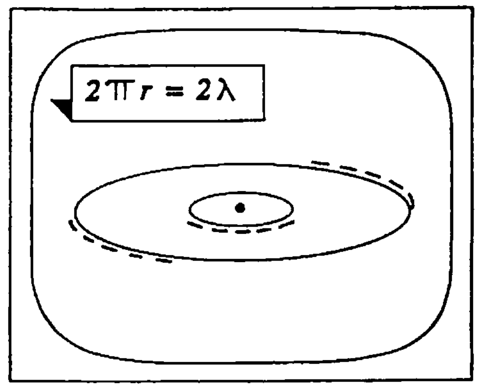
Terms for de Broglie Matter Waves:

matter waves
wave-particle duality

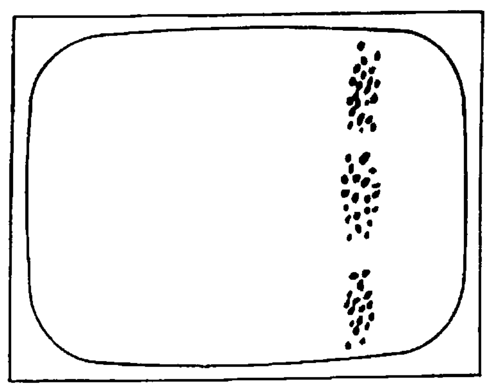
de Broglie thought that a particle moving at less than the speed of light could have wave properties. How did he relate a particle's momentum to its wavelength?



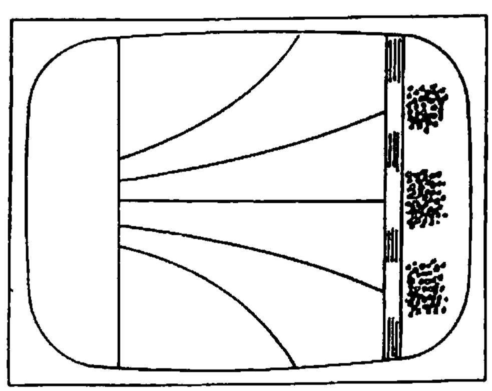
In the de Broglie model of the atom, if electrons are viewed as waves circling the nucleus, why do they have to exist in orbits that increase a whole wavelength at a time?



Waves produce an interference pattern. How can the pattern be explained in terms of particles of light (photons)?



To what do the white light spots correspond where the wave pattern hits the screen?



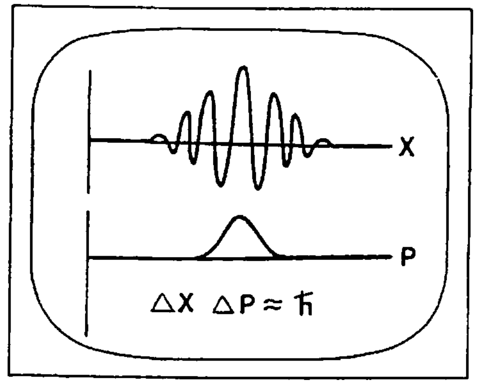
IV. **HEISENBERG'S UNCERTAINTY PRINCIPLE:** The Heisenberg Uncertainty Principle reflects the wave-particle duality of light and matter: The more we know about matter as a particle (well-defined position), the less we know about its momentum (wavelength), and vice versa.

Terms for Heisenberg's Uncertainty Principle:

uncertainty principle
wave-particle duality

How can a particle's location be made more definite?

As the position of the wave becomes more definite, what happens to the momentum?



Match each of the following scientists to his contribution.

1.	Planck	A.	Uncertainty Principle
2.	Einstein	B.	photoelectric effect
3.	de Broglie	C.	quanta
4.	Schrödinger	D.	electron cloud model
5.	Heisenberg	E.	matter waves

STUDENT EXERCISES AND ACTIVITIES

I. THERMAL RADIATION

1. As the cells in a flashlight get weaker, the filament appears redder. Why?

2. The surface temperatures of Vega, our Sun, and Barnard's star are 10,000 K, 6,000 K, and 3,000 K respectively. Which of these appears blue in color; red in color; yellow in color? Why?

II. PHOTOELECTRIC EFFECT

1. As a mechanical analog of the photoelectric effect, consider a ball at rest in a depression. If a sufficient amount of energy, E, is given to the ball of mass, m, by the push of the hand, it will roll up the hill and escape with velocity v. Write an equation of energy conservation for this situation and explain each term in the equation by analogy to Einstein's photoelectric effect equation.

2. The following is a table of the work function for various metals:

Cesium	3.0×10^{-19} J
Potassium	3.5×10^{-19} J
Sodium	3.7×10^{-19} J
Calcium	4.3×10^{-19} J
Zinc	6.1×10^{-19} J
Platinum	8.5×10^{-19} J

   a. If green light will cause the photoelectric effect to occur in sodium metal, for which other metals listed will it definitely also eject photoelectrons?

   b. What would be the effect of doubling the intensity of the light used?

   c. What would be the effect of changing the color of the light used, for example, from green to blue or ultraviolet?

3. Name some devices that utilize the photoelectric effect.

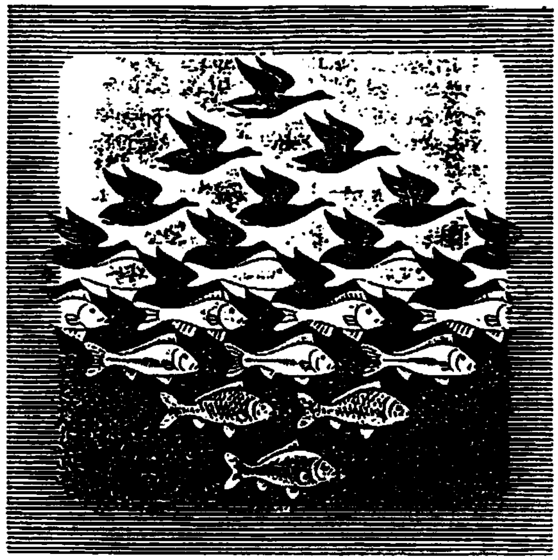
III. DE BROGLIE MATTER WAVES

1. Why does one not observe wave-like behavior for common objects like baseballs in flight or automobiles in motion?

2. How did de Broglie explain the stability of the hydrogen atom?

3. Experimental evidence for de Broglie's concept of matter waves was provided by Davisson and Germer. Research this experiment and report on what it involved.

4. Particles and waves represent different views of the same phenomenon. Comment on the dual nature of the Escher drawing below:



M. C. Escher—Sky and Water II, 1938. Collection Haags Gemeentemuseum—The Hague, 1981. © BEELDRECHT, Amsterdam/V.A.G.A., New York.

IV. HEISENBERG'S UNCERTAINTY PRINCIPLE

1. **State Heisenberg's Uncertainty Principle in your own words.**

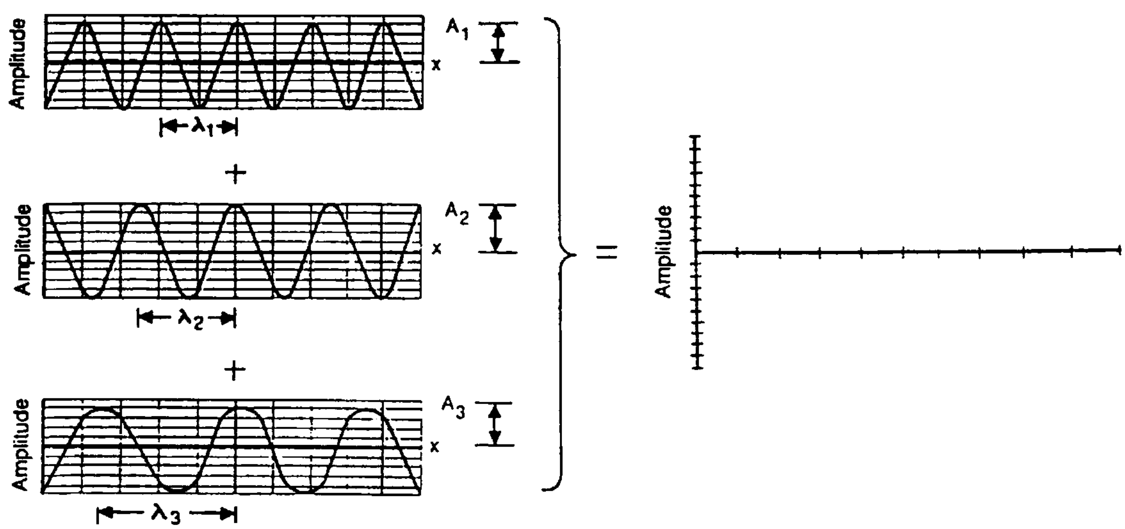
2. **A moving electron is in a shoebox-size container. The ends of the container are slowly pushed together.**

   a. **What is the uncertainty of the electron's position before the ends are pushed together?**

   b. **What happens to the position uncertainty as the ends are pushed together?**

   c. **What does pushing the ends together do to the uncertainty of the electron's momentum? Why?**

3. a. Add the amplitude of the following waves of slightly different frequency to observe that these waves of infinite position uncertainty become more localized.



b. If the width, Δx, of your resulting localized wave is 2.2×10^{-12} m, what is the uncertainty in the momentum, Δp?

TEACHER RESOURCES

SUPPORTIVE BACKGROUND INFORMATION – At the turn of the twentieth century two observed phenomena spelled trouble in classical physics: radiation from glowing substances (blackbody radiation) and the photoelectric effect. All physical objects radiate energy; hot bodies such as an incandescent bulb can radiate enough visible light to glow, but they also emit electromagnetic radiation at all wavelengths. Experiments showed that the hotter the temperature of the glowing body, the shorter the wavelength for which the emitted radiation is greatest, as indicated by the graph of Figure 1.

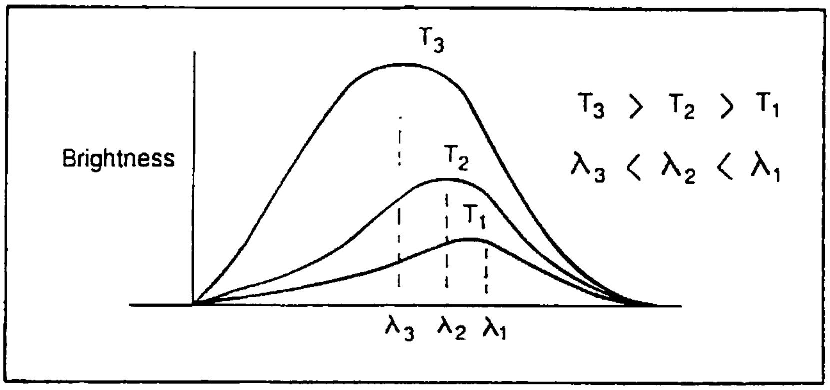


Figure 1

But the reason eluded physicists until Max Planck formulated an explanation based on the assumption that a hot body does not emit energy of a given wavelength in arbitrary amounts but, rather, in fixed amounts or quanta at that wavelength. He related the energy of the quanta to the frequency of the oscillators (vibrating electrons) associated with the quanta in the following way:

$$\text{Energy} \propto \text{frequency}$$

or

$$E = hf,$$

The constant of proportionality, h, has a value of 6.626×10^{-34} J s and is known as Planck's constant.

The significance of Planck's relation was not fully realized by Planck. Rather, it was Albert Einstein who, in 1905[1], utilized Planck's relation in providing an explanation for the other troublesome phenomena, discovered in the late 1800's – the photoelectric effect.[2]

It had been known for some years that certain types of light cause electrons to be emitted from certain metal surfaces. Ultraviolet light, for instance, ejects electrons from zinc metal. The problem with all this is that classical physics cannot fully explain the phenomenon. Maxwell's wave theory of light

1 This was the same year he explained Brownian motion and revealed his theory of special relativity.

2 It was his explanation of the photoelectric effect, not relativity, for which Einstein received the 1921 Nobel Prize.

predicts that the incoming wave's energy would take time to build up sufficiently to rip the electron out of the atom and that any frequency of light could accomplish this task, given enough time. But the photoelectrons are ejected almost instantaneously and only with a definite minimum (threshold) frequency or higher frequency of incident light. Einstein attributed the quantum properties to electromagnetic waves incident on the metal plate. He viewed light as a stream of particles called *photons*. One photon is absorbed by each photoelectron ejected by the metal. According to Planck's equation, $E = hf$, ultraviolet radiation, which has higher frequency than visible light, has more energy; in fact, it has sufficient energy to expel electrons from zinc. When radiation of a given frequency f falls on a metal, it gives up energy in bundles of hf. If hf is greater than the energy φ binding the electrons to the metal (work function), then electrons can be emitted, with the surplus energy in the form of kinetic energy K, according to the relation

$$K = hf - \varphi .$$

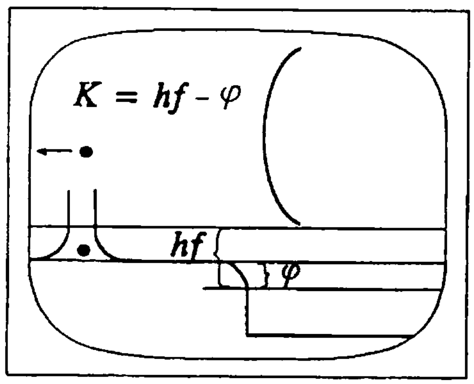


Figure 2

In 1924, French physicist Louis de Broglie (de Broy) combined the energy associated with a photon, $E = hf$, with Einstein's equation $E = mc^2$:

$$mc^2 = hf$$

since

$$f = c/\lambda$$

$$mc^2 = hc/\lambda$$

$$mc = h/\lambda .$$

de Broglie questioned: if light exhibits this dual wave-particle behavior, why then can't any particle of matter, such as an electron, exhibit a wave nature? In other words, why can't electrons exhibit diffraction and interference for example?

In a bold leap of imagination he argued that if a particle of mass m moving with speed v has a wave structure, then by analogy

$$mv = h/\lambda$$

$$p = h/\lambda$$

or

$$\lambda = h/p .$$

Although he gave no physical description of the wave structure of a moving particle, de Broglie referred to the wave as a "matter wave."

de Broglie applied these ideas to the problem of the structure of the hydrogen atom. He conceived the idea that the electron appears as a stationary wave when in orbit, with the wave wrapped around in a circle rather than being along a straight line, as illustrated in Figure 3.

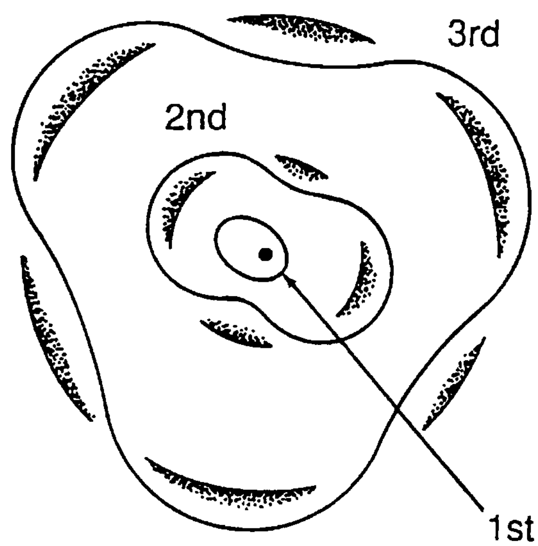
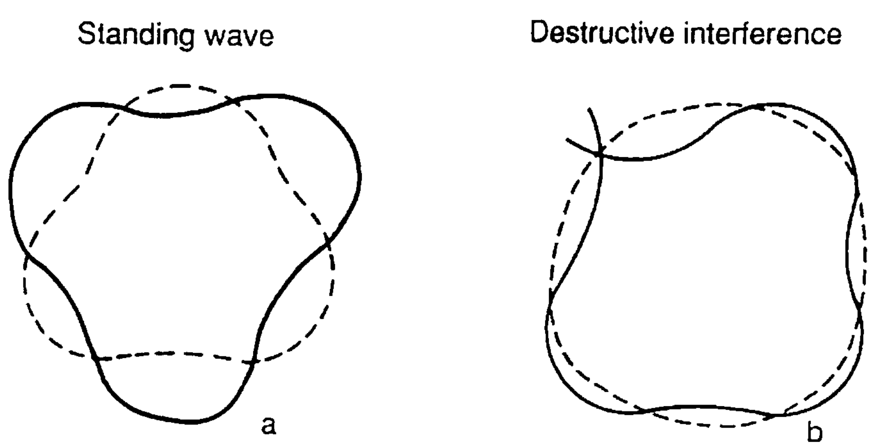


Figure 3

This condition could explain why atoms exist, i.e., why the accelerating electrons do not continuously radiate away energy and spiral down into the nucleus, collapsing the atom. The energy is trapped in the stationary wave.

A stationary wave must contain a whole number of wavelengths fit evenly into the circumference of the orbits; otherwise destructive interference would occur, collapsing the atom as illustrated in Figures 4a and 4b.



Figures 4a and 4b

This condition requires

$$2\pi r_n = n\lambda, \qquad n = 1, 2, 3, \dots$$

But de Broglie's equation $\lambda = h/p$ transforms this to

$$mvr_n = nh/2\pi = n\hbar,$$
$$L_n = n\hbar.$$

Thus L_n, the angular momentum of the electron, is quantized and constant for a given orbit. This result was in agreement with Bohr's model of the atom and the fundamental principle of the conservation of angular momentum.

Experimental evidence for de Broglie's concept of matter waves was soon provided by two Americans, Davisson and Germer. They scattered electrons from metallic crystals and observed diffraction patterns similar to those produced by light.

Within a few years after de Broglie published his model of the atom, Austrian physicist Erwin Schrödinger formulated an abstract mathematical wave equation that incorporated de Broglie's concept of matter waves. Other investigations of the same ideas by Werner Heisenberg, Max Born, and Paul Jordan, combined with Schrödinger's work, resulted in a much broader theory called quantum mechanics. In quantum mechanics, the question of what exactly is waving in matter waves is answered as interfering waves of probability. For the hydrogen atom it provided a new quantum mechanical model in which the orbiting electron occupies a position that is not specified precisely. Only its probable position is known.

A wave with a definite wavelength is spread out infinitely in space. In other words, its location is completely indefinite.

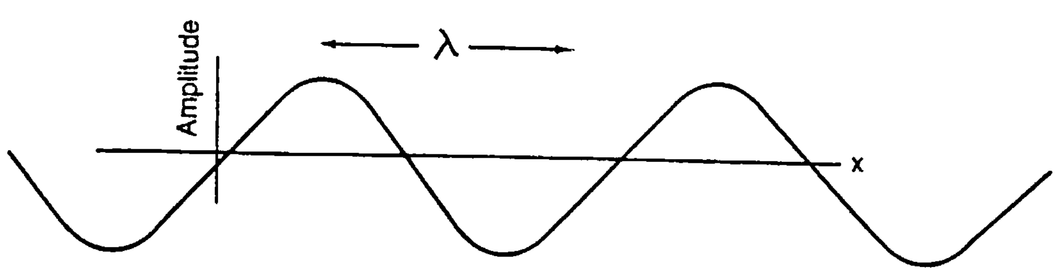


Figure 5

But this wave represents a particle; its wavelength corresponds to a definite momentum given by $p = h/\lambda$.

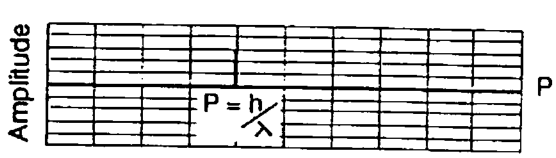


Figure 6

The particle can be localized by adding waves of slightly different wavelengths and amplitudes such as in the following example. Recall that any wave form may be shown as the superposition (sum) of up to an infinite number of sines and cosines. As a crude approximation to infinity, we will sum just three waves to localize the particle.

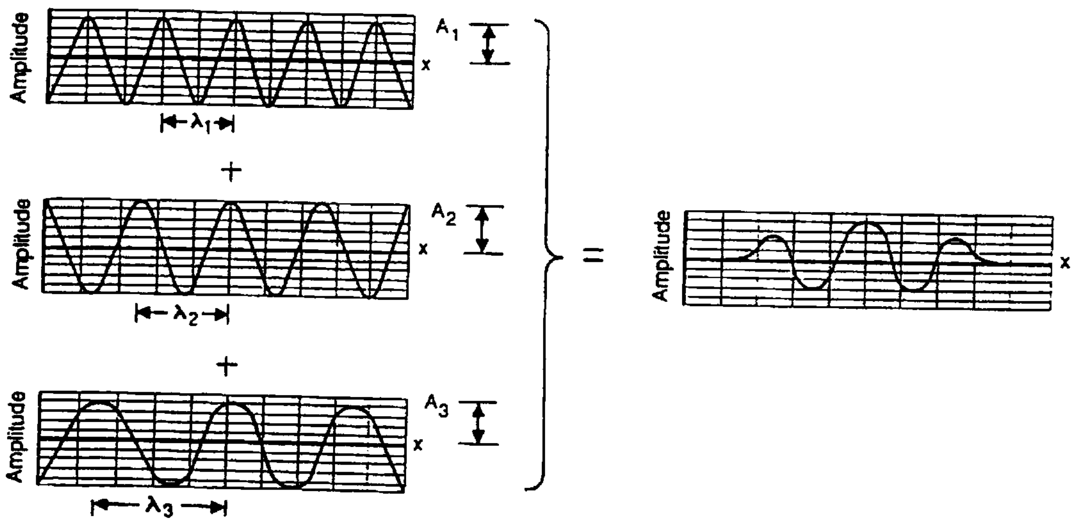


Figure 7

But, since $p = h/\lambda$, each wavelength means a new momentum. The three momenta shown below in Figure 8 correspond to the waves in Figure 7 above.

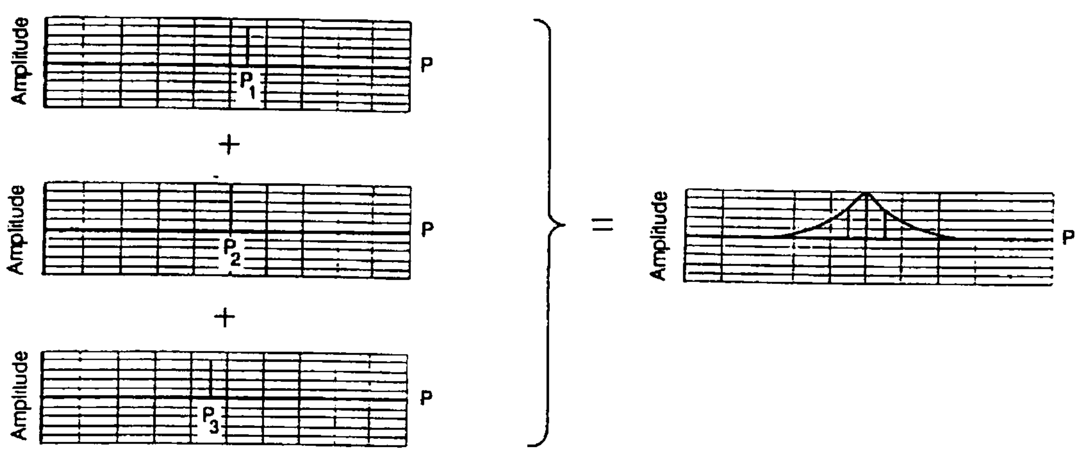


Figure 8

The momentum of the particle becomes less definite. Thus, as we localize the particle (i.e., making its position more definite by adding more wavelengths), Δx is reduced as shown in Figure 9.

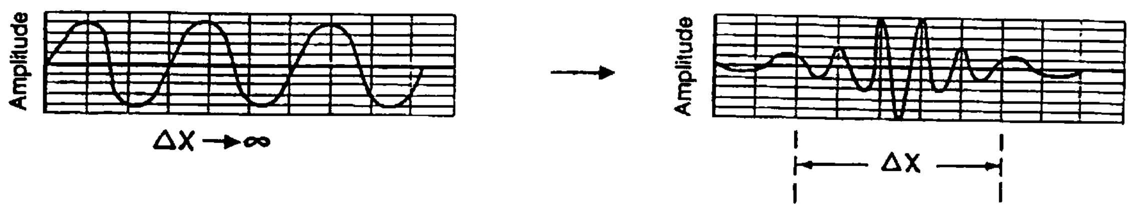


Figure 9

Consequently Δp is increased, as shown in Figure 10,

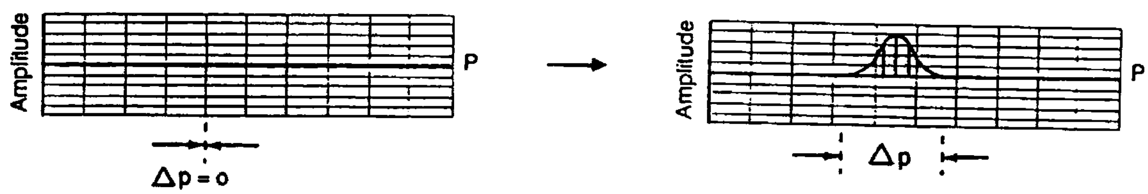


Figure 10

leading to $(\Delta x)(\Delta p) \geq \hbar$, which is called the Heisenberg Uncertainty Principle. It asserts a quantifiable uncertainty inherent in nature. Increasing precision in specifying location x implies increasing uncertainty in knowledge of momentum p, and conversely.

The Heisenberg Uncertainty Principle reflects the wave-particle duality of light and matter: The more we know about matter as a particle (well-defined position), the less we know about its momentum (wavelength), and vice versa.

A commonly accepted physical interpretation of the Heisenberg Uncertainty Principle is that it imposes some kind of upper limits to precision of measurements, or lower limits to their imprecision. In particular it states that it is not possible to obtain exact knowledge of the position and momentum of a particle simultaneously. If p is known precisely (see Figure 10 where $\Delta p = 0$), then x is completely unknown, as illustrated in Figure 9, where $\Delta x \rightarrow \infty$.

By applying the uncertainty principle to an electron and a proton having the same speed, we see via $(\Delta x)(\Delta p) \approx \hbar$ or $m(\Delta v)(\Delta x) \approx \hbar$ that, since the mass of an electron is much smaller than that of a proton, Δx for the electron is much larger than Δx for the proton. Consequently, the electron must occupy a relatively large region of space, whereas a proton occupies comparatively a much smaller region. Carried over to the hydrogen atom, this implies that the proton is surrounded by a cloud representing possible positions of the electron.

ADDITIONAL RESOURCES

Demonstration #1: Incandescent Bulb

Purpose:

To demonstrate that greater energy is needed to produce radiation of higher frequencies. To demonstrate that higher frequencies occur when the source has higher temperature.

Materials:

Showcase bulb (unfrosted bulb 40 W - 150 W long line filament), variable 120 V power supply, diffraction grating (optional).

Procedure and Notes:

Connect the bulb to the variable source. Slowly increase the voltage. Students should see a very dull red glow. If they are using a diffraction grating, they should see red-orange only.

Increase the voltage. As more thermal energy is transferred to the filament, there will be sufficient energy to produce photons of higher frequency; i.e., yellow → green → blue. Ask a student to put his/her hand near the bulb as you increase the voltage. An increase in temperature should be noticeable.

Explanation:

At low voltage the current is small and provides only a small amount of heat to the filament, resulting in a relatively low temperature. The frequency of the light produced is directly related to the energy, $E = hf$. So at low energy the low frequency and longer wavelengths will be produced. As the energy is increased more energetic photons will be produced at a higher temperature.

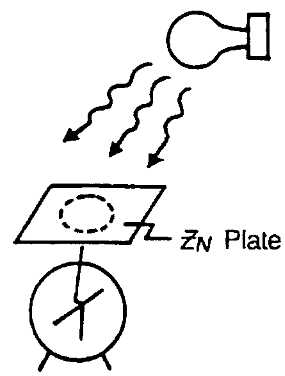
(If students are not using a grating, the combination of different wavelengths produces white light.)

The student will then see the higher frequency colors and feel the higher temperature. If we think of the light as being a "gas" of photons, we recall that the average kinetic energy of a gas is proportional to the absolute temperature, $E_{ave} \propto T$. But for light, $E_{ave} = hf_{ave}$. Therefore, f_{ave} is proportional to T; higher frequencies occur when the source has higher temperatures.

Demonstration #2: The Photoelectric Effect

Purpose: To demonstrate the emission of photoelectrons from a metal surface.

Materials: Electroscope (gold leaf, PSSC type or other), cat fur, rubber rod or PVC pipe, zinc plate, incandescent bulbs 40 W and 150 W, a UV source, colored light filters, glass plate, steel wool.



Procedure and Notes:

1. Clean the zinc strip surface with steel wool. Place a zinc strip in contact with the electroscope.

2. Charge the electroscope negatively by direct contact with a negatively-charged rubber or plastic rod. Use the cat fur to produce a negative charge on the rod. (Alternatively, charge it negatively by induction using a positively-charged glass rod.)

3. Expose the charged zinc plate to UV light with and without the glass plate interposed.

4. Repeat using other frequencies of light. Try different colored filters in front of the 40 W incandescent bulb.

5. Repeat using the 150 W incandescent bulb.

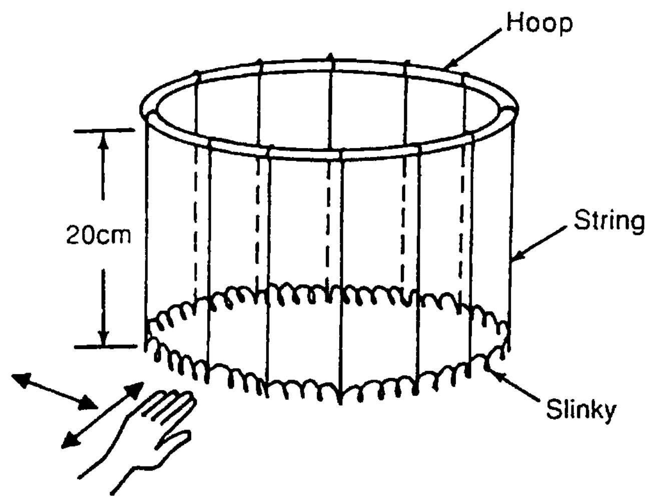
Explanation: The suggested light sources, other than UV, do not contain photons energetic enough to eject electrons. The light must have a certain minimum frequency, and visible light does not. The intensity does not matter below the threshold frequency. Above the threshold frequency, as in UV light, a greater intensity will eject more electrons, causing the electroscope to discharge faster. The energy of the photoelectrons is not changed, however, by changing the intensity of the light.

Demonstration #3: Circular Standing Waves

Purpose: To show standing waves on the circumference of a circle. To demonstrate how a whole number of wavelengths could fit on a circular orbit.

Materials: Slinky, hula hoop, string.

Procedure and Notes: Make a permanent apparatus by suspending the Slinky by pieces of string at a number of locations on the hula hoop.



Move the Slinky in and out transversely or longitudinally, at a given point with a certain frequency. Notice that once the driving force ceases, the amplitude dies out very quickly.

Try other frequencies until a standing wave is produced. Note the whole number of wavelengths and how little energy input is needed to sustain the wave.

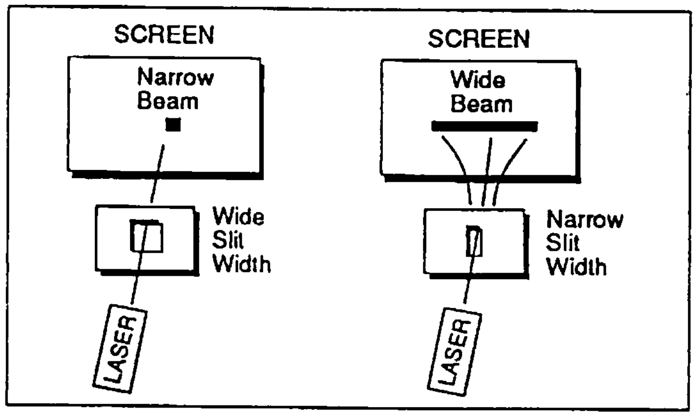
Remind students that standing waves could exist only on the orbits because non-standing waves would interfere destructively, causing the electron to lose energy and spiral into the nucleus.

Explanation: This is a demonstration of the de Broglie model of the atom where the vibrating Slinky corresponds to the electron matter wave circling the nucleus in an orbit. It interferes constructively to produce a circular standing wave. Note to the students that this model (de Broglie's) is not really "correct." It was an improvement to Bohr's model and led to the development of the electron cloud model of Schrödinger and others.

Demonstration #4: Particle or Wave

Purpose: To demonstrate that the uncertainty principle and particle definition of light lead to the same result as a wave definition for light passing through a slit.

Materials: Monochromatic light source (laser, or projector with colored filter), variable width slit, or cornell type slit film.



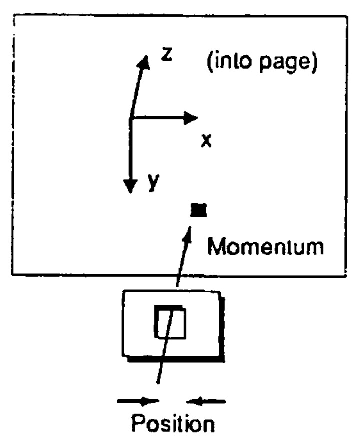
Procedure and Notes: Project a laser beam, or other monochromatic light source, through a variable width slit. Gradually decrease the slit width. As the slit narrows, the beam projected beyond it will broaden.

Explanation: Wave:

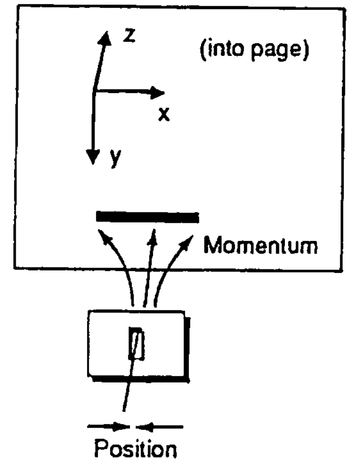
A wave explanation would involve diffraction (bending) of light.

Particle:

A particle explanation involves the uncertainty principle. For a wide slit, the position of a single photon in the x direction is quite uncertain; therefore, the momentum is more certain in that direction (being nearly zero) and has components primarily in the z direction.



As the slit width is decreased, the position in the *x* direction is known more precisely. The uncertainty principle dictates that this must be accompanied by a wide range of possible momenta in the *x* direction, as evidenced by the widening beam.



Activity #1: **Matter Waves**

Purpose: To compare the wavelength of a moving baseball to that of a moving electron.

Procedure and Notes: Calculations similar to the following will place the wavelengths of ordinary objects in proper perspective. You may wish to use student estimated values for the ordinary objects.

Baseball:

Let us assume a baseball has a mass of 0.20 kg and is thrown at 90 mph by a major league pitcher. (90 mph $\approx$ 44 m/s)

$$\lambda = h/mv = \frac{6.6 \times 10^{-34}\ \mathrm{J\ s}}{(0.20\ \mathrm{kg})(44\ \mathrm{m/s})} = 7.5 \times 10^{-35}\ \mathrm{m}$$

This wavelength is much smaller than the diameter of a nucleus of an atom and too short to be detected.

Electron:

Let us assume the electron has been caused to move at 3.3×10^{6} m/s. It has a mass of 9.1×10^{-31} kg.

$$\lambda = h/mv = \frac{6.6 \times 10^{-34}\ \mathrm{J\ s}}{(9.1 \times 10^{-31}\mathrm{kg})(3.3 \times 10^{6}\mathrm{m/s})}$$

$$\lambda = 2.2 \times 10^{-10}\ \mathrm{m}.$$

The wavelength of blue light is about 4.5×10^{-7} m. The wavelength of the electron is about two-thousandths of the wavelength of blue light. Using the spacing between atoms in a crystal as slits, wavelengths of this size are readily detected by laboratory scientists.

Explanation: Doing these calculations will help students understand that every "particle" has a wave associated with it, but only when the momentum is very small do these effects become noticeable.

Activity #2: Using the Uncertainty Principle

Purpose: To estimate the uncertainty in the position of a moving baseball and that of a moving electron.

Procedure and Notes: Make a comparison calculation of two objects' uncertainty in position. Students will see that for ordinary objects it is a negligible factor.

Baseball:

Assume the baseball has a mass of 0.20 kg and moves at 44 m/s. Also assume the uncertainty in determining the momentum is about 5%.

$p = mv\,(0.20 \text{ kg})(44 \text{ m/s}) = 8.8 \text{ kg m/s},$

$\Delta p = 5\%\, p = (0.05)(8.8 \text{ kg m/s}) = 0.44 \text{ kg m/s},$

$\Delta x\, \Delta p \approx \hbar,$

$$\Delta x \approx \hbar/\Delta p = \frac{(6.6 \times 10^{-34} \text{ J s})/(2\pi)}{0.44 \text{ kg m/s}} \approx 2.4 \times 10^{-34} \text{ m}.$$

This length is much smaller than the diameter of a nucleus.

Electron:

The electron has a mass of 9.1×10^{-31} kg and is moving at 3.3×10^{6} m/s. As with the baseball, assume the uncertainty in determining the momentum to be about 5%.

$p = mv = 9.1 \times 10^{-31} \text{ kg}\,(3.3 \times 10^{6} \text{ m/s}) = 3.0 \times 10^{-24} \text{ kg m/s},$

$\Delta p = 5\%\, p = (0.05)(3.0 \times 10^{-24} \text{ kg m/s}) = 1.5 \times 10^{-25} \text{ kg m/s},$

$\Delta x\, \Delta p \approx \hbar,$

$$\Delta x \approx \hbar/\Delta p = \frac{6.6 \times 10^{-34} \text{ J s}/(2\pi)}{1.5 \times 10^{-25} \text{ kg m/s}} = 7 \times 10^{-10} \text{ m}.$$

This is about the diameter of an atom.

Explanation: This calculation once again compares the baseball and electron. This time Heisenberg's Uncertainty Principle is used to show the uncertainty in locating positions. For the baseball the uncertainty is too small to be of consequence. It is immeasurable. We can precisely locate the baseball. For the electron, the uncertainty is measurable, though small. Its location within the atom is not precise.

EVALUATION QUESTIONS

1. **Stars vary in color. Which color indicates the hottest surface temperature of a star?**

   A. Red
   B. Orange
   C. Yellow
   D. Blue

2. **Which of the following objects, all moving at the same speed, would have a de Broglie wavelength associated with them that would be larger than that of a proton travelling at the same speed?**

   A. an electron
   B. a neutron
   C. a bacteria
   D. a baseball

3. **When green light shines upon a given metal, it emits photoelectrons. Which of the following will also produce photoelectric emission, using this same metal?**

   A. Low intensity blue light
   B. Low intensity red light
   C. High intensity red light
   D. High intensity yellow light

4. **Ultraviolet light shines upon a sheet of zinc metal, and photoelectrons are emitted. If the intensity of the light is increased,**

   A. the electrons will have less energy.
   B. the electrons will have more energy.
   C. more electrons will be emitted.
   D. fewer electrons will be emitted.

5. **Consider the following frequencies of electromagnetic radiation. Which photon has the greatest energy?**

   A. 6.6×10^{-34} Hz
   B. 6.6×10^{-4} Hz
   C. 6.6×10^{4} Hz
   D. 6.6×10^{18} Hz

6. **Compared to a photon of blue light, a photon of red light has**

   A. more energy.
   B. less energy.
   C. shorter wavelength.
   D. the same wavelength.

7. An electron is confined to a box of sides L and it has a definite speed. If the walls of the box were to move inward so that the box shrinks, the electron

A. would speed up.
B. would slow down.
C. would move with the same speed.
D. would exhibit none of the above.

8. The idea of packets or quanta of energy originated with

A. Louis de Broglie.
B. Max Planck.
C. Werner Heisenberg.
D. Erwin Schrödinger.

9. A matter wave

A. applies only to "massless" particles.
B. applies only to a photon.
C. has a wavelength inversely related to its momentum.
D. has a wavelength directly related to its momentum.

10. Which of the following does *not* demonstrate the wave nature of matter?

A. The cloud model of the atom
B. The two slit interference pattern
C. An electron in motion in a conducting wire
D. Electron diffraction

ESSAY QUESTIONS

11. What determines (a) the amount of kinetic energy photoelectrons will have and (b) the number of photoelectrons emitted from a metal?

12. Explain how a double slit interference pattern of light occurs in terms of (a) light waves and (b) particles of light (photons).

KEY

1. D
2. A
3. A
4. C
5. D
6. B
7. A
8. B
9. C
10. C

SUGGESTED ESSAY RESPONSES

11. (a) The total energy available is equal to the energy of the photon, $E = hf$. To produce the emission of a photoelectron, the electron must be given enough energy to escape. This is called the work function. The kinetic energy of the photoelectron is the energy of the photon minus the amount needed to free the electron from the surface.

    (b) The effect of increasing the intensity is to produce more photoelectrons, each having the same kinetic energy as before, thus increasing the intensity.

12. (a) Light waves from both slits interfere constructively and destructively, producing a pattern of light and dark areas on the screen.

    (b) As photons pass through the slits, there is a higher probability that more photons land in some places than in others, producing the pattern of light and dark areas on the screen.

TEACHER'S GUIDE TO MODELS OF THE ATOM

CONTENT AND USE OF THE MODULE – This module traces the development of the changing model of the atom from the time of Dalton to the electron cloud model. An effort is made to show that scientific models are based on observations, and they are revised and evolve as new data are received. This module is designed to be used with materials involving atomic physics or modern physics and can best be utilized following the viewing of the module on *Wave-Particle Duality.* It is also appropriate for use in chemistry class.

SECTIONS WHICH FOLLOW

TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO – Since the following terms are introduced in the video, students would benefit from a discussion of them prior to viewing the video.

model – analogy or representation based on observations and measurements and developed to guide understanding of something.

spectrum – the range of electromagnetic radiation. When discussing a single element, it is often used to represent those specific frequencies that are emitted by individual atoms of that element.

Dalton model – the simple model of the atom proposed by John Dalton about 1800 to explain chemical compounds. According to this model atoms are small particles which combine in certain ways.

electron – the lightest particle of an atom. It was discovered by Sir J.J. Thomson in 1897 and has a negative charge and a mass of 9.1×10^{-31} kg or about $1/1837$ the mass of hydrogen.

plum pudding model – the first model of the atom to include smaller parts. This model was devised about 1900 by Sir J.J. Thomson after his discovery of the electron. Electrons, like raisins, were spread uniformly throughout a positive pudding (no nucleus).

nucleus – the heavy dense positive center of the atom, first discovered by Sir Ernest Rutherford. The nucleus contains nearly the entire mass of the atom but has a diameter about 100,000 times smaller than the atom. Protons and neutrons are in the nucleus.

alpha particle – particle given off by the nucleus of a heavy atom during radioactive decay. Alpha particles have a double positive charge and a mass equal to about 4 times the mass of hydrogen. An alpha particle is a helium nucleus.

Planck's constant – (h) the constant which relates the energy of light to its frequency and defines the size of energy quanta. It is equal to 6.626×10^{-34} J s.

Bohr model – the model of the atom which is based on the idea that the electron can occupy certain special orbits around the nucleus. As the electron moves between orbits, it either loses or gains energy in specific amounts. It was suggested by Niels Bohr in 1913.

radiation – electromagnetic waves or light energy emitted as electrons move from a higher energy orbit to a lower energy orbit.

energy state – the energy of an atom with an electron in a particular orbit about its nucleus.

quantum – a discrete or definite amount; in this video, a packet or discrete amount of energy.

quantum jumps – changes in the orbit of electrons which involve definite steps or units of energy.

de Broglie wave – The concept first expressed by Louis de Broglie that the electron can be thought of as a standing wave in orbit around the nucleus. The wave is wrapped around in a circle rather than along a straight line. The fact that the orbit must close on itself in a smooth way is a physical condition that forces the frequencies, wavelengths, energies, and angular momenta to be quantized.

Heisenberg Uncertainty Principle – the principle first proposed by Werner Heisenberg in 1927 stating that there is a limit to how precisely the position and momentum of an object can be measured. More specifically, the uncertainty in the position of an object times the uncertainty in its momentum will always be equal to or greater than Planck's constant divided by 2π. ($\Delta x \Delta p \geq h/2\pi$)

electron cloud model – also called the quantum mechanical model. It is the current model of the atom which suggests that, since the exact position of the electron cannot be found and therefore only its probability at any particular position can be calculated, electrons form a "cloud" about the nucleus. This model was first initiated by Erwin Schrödinger and Werner Heisenberg and implies that the properties of electrons in atoms can be given by a set of four "quantum" numbers, (n, l, m, s).

WHAT TO EMPHASIZE AND HOW TO DO IT – Atoms are so much smaller than the wavelength of visible light that it will never be possible by known methods to see them through any kind of optical microscope. Therefore it is not possible to observe directly the structure of the atom. However, it is possible to make indirect observations and propose models of what might be happening. This module outlines the model-building process that scientists have undergone to try to gain an understanding of the atom. Models have changed from the simple model of Dalton to the modern electron cloud model.

Objective 1: Trace the progress in the development of the atomic model.

The concept of the atom is fundamental to our modern understanding of science. Before showing the video, it would be appropriate to perform DEMONSTRATION #2, Black Box, to demonstrate how models are inferred from available data. It is important to outline the basic concepts of the atom as they have been developed. It would be important to point out not only the basic features of each model but also what new discoveries led to the development of that model.

Dalton		Thomson		Rutherford and Bohr		de Broglie Heisenberg and Schrödinger
spheres	→	plum pudding	→	planetary	→	electron cloud
(chemical properties)		(discovery of electron)		(discovery of nucleus)		(wave-particle duality)

The SUPPORTIVE BACKGROUND INFORMATION provides an overview of the development of atomic models.

Objective 2: Explain why the scattering of alpha particles led to the concept of a nucleus in each atom.

In 1911, when Rutherford bombarded a thin gold foil about 500 atoms thick with alpha particles, he expected the alpha particles to go nearly straight through. When he observed that some of the heavy positively-charged alpha particles bounced nearly straight back, Rutherford drew several conclusions. In order for the alpha particles to have been repelled, there must have been something positively-charged and much more massive than an alpha particle inside the atom. Also, since very few of the alpha particles were repelled, this massive positively-charged object must have been very small.

DEMONSTRATION #5, Alpha Particle Scattering Analog, may enable the students to visualize better the difference between Thomson's plum pudding model and Rutherford's nuclear model.

Objective 3: Describe how the spectra of atoms imply discrete energy levels.

Each element has its own characteristic set of spectral lines. According to Planck's theory, each line has associated with it a definite energy. This implies that within the atom there must be something which has specific amounts of energy. In the Bohr model of the atom these specific amounts of energy are radiated when an electron jumps from an outer orbit to an inner orbit. These same energies, or certain wavelengths of light, can be absorbed and cause an electron to move from an inner orbit to an outer one. The teacher may wish to show DEMONSTRATION #3, Flame Tests, which shows the unique colors produced by each individual element or

DEMONSTRATION #4, Spectral Lines and Their Energies, which actually measures and calculates the energy associated with specific spectral lines.

Objective 4: Understand the departure of the Bohr model from classical physics.

Negatively-charged electrons moving in circles are accelerated, and, according to classical physics, accelerated electrons should radiate energy. Thus electrons in atoms should constantly lose energy and eventually fall into the nucleus. Bohr suggested that electrons in special orbits, which could be determined with the help of Planck's constant, would not radiate energy. Energy would only be emitted when electrons moved from outer orbits of higher energy to inner orbits of lower energy.

Objective 5: Compare the electron cloud model of the atom with the Bohr model.

The Bohr model has electrons moving in certain special orbits; however, the electron cloud or quantum theory model states that it is not possible to determine the exact location of electrons. Within the atom, only the probability that the electron exists at any specific point can be calculated. Interestingly enough, both theories give the same results for simple atoms. The quantum theory model, however, is more accurate for complicated atoms. This is a very difficult concept and it might prove helpful to show DEMONSTRATION #6, Paper Loop Electron Wave Model. This demonstration illustrates the point that electrons seem to have wave properties as well as particle properties, and a proper description of electrons needs to take both into account.

See the chart on page 5 for planning suggestions. If this module is used to teach single topics it is still important that the video be shown more than once to emphasize the logical, scientific, and historical flow of the concepts of *Models of the Atom*.

SUGGESTED ORGANIZATION FOR PRESENTATION OF INDIVIDUAL TOPICS

MODELS OF THE ATOM

TOPIC	19TH CENTURY MODELS	PARTS OF THE ATOM	BOHR'S HYPOTHESIS	ELECTRON-CLOUD MODEL
TERMS	model spectrum Dalton model	electron plum pudding model nucleus alpha particle Planck's constant	Bohr model radiation energy state quantum quantum jump de Broglie waves	Heisenberg Uncertainty Principle electron cloud model
OBJECTIVES	1	2	3 4	5
POINTS TO LOOK FOR (STUDENT GUIDE)	Frame # 1 2	Frame # 3 4 5 6	Frame # 7 8	Frame # 9 10
EVERYDAY CONNECTIONS	1 2 3	4 5	7 8	9
ADDITIONAL RESOURCES	Demonstration 1 Demonstration 2 Demonstration 3	Demonstration 4 Demonstration 5	Demonstration 6	
EVALUATION QUESTIONS	1 2	3 5 6 11	4 7 8 11 12	9 10 11

POINTS TO LOOK FOR IN THE VIDEO – Several questions are posed in the STUDENT'S GUIDE. Here are those questions along with suggested responses and selected frames from the video.

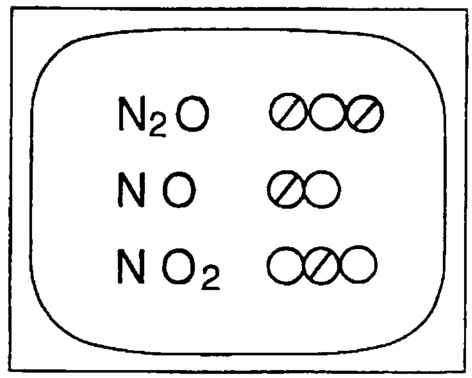
I. **19TH CENTURY MODELS:** Modern models of the atom began to be developed during the 19th century to explain chemical properties. Additional information about the atom was obtained through the use of spectroscopes.

Terms for 19th Century Models:

model
spectrum
Dalton model

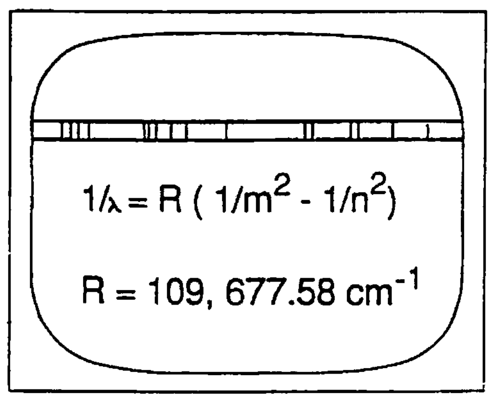
According to Dalton's law of simple and multiple proportions, what must be true of the substances involved in order to combine in definite ratios?

If Dalton's law is followed, then the substances must have ultimate parts or atoms in order to form simple ratios and multiples thereof. (DEMONSTRATION #1, Law of Multiple Proportions, might be used to clarify this.)



Different elements have different spectra. Why does this fact provide a clue to the inner nature of the atom?

The unique spectrum of each element must be explained on the basis of a structure inside the atom. Each color of light has its own special frequency. To produce a spectrum, something within the atom must vibrate at the frequency of the emitted light. Note: n denotes an outer orbit and m denotes an inner orbit.



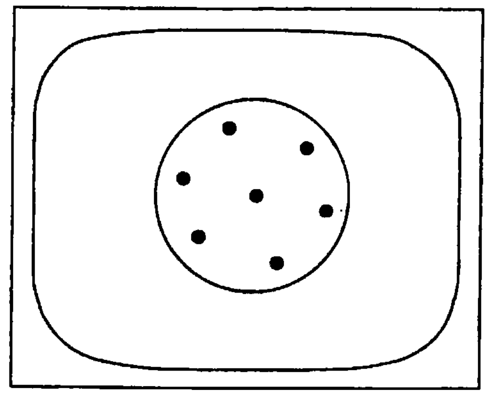
II. **PARTS OF THE ATOM:** Near the turn of the century the atom was found to have a number of parts. Sir J.J. Thomson discovered electrons in 1897. Thomson proposed the first model of the atom, the plum pudding model. About 1910, Rutherford bombarded gold foil with alpha particles from radioactive materials and discovered that atoms had a nucleus. Rutherford proposed the planetary model of the atom. Also, about the turn of the century, Planck determined that matter emits light in discrete quantities.

Terms for Parts of the Atom:

electron
plum pudding model
nucleus
alpha particle
Planck's constant

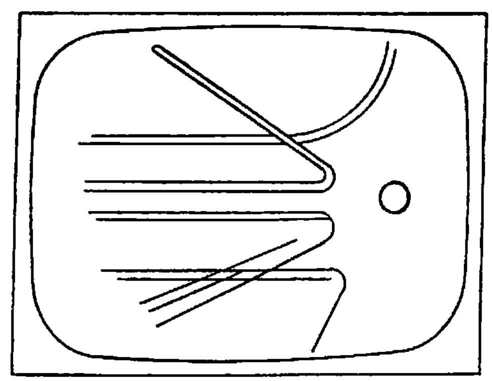
In Professor J.J. Thomson's plum pudding model, each atom consists of a large sphere of positive electric charge with just enough negative electrons inside to make it neutral. What would produce the spectral lines in Thomson's model?

The vibrating electrons produce the spectral lines.



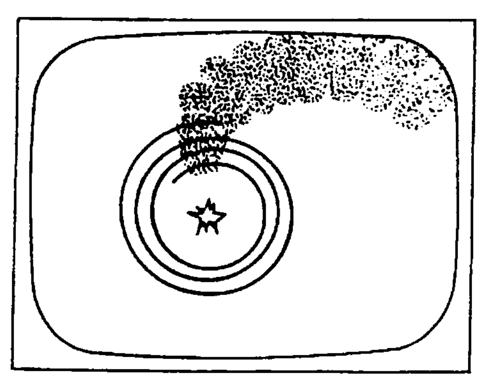
Rather than cutting through the foil like a knife through butter, some of the alpha particles bounced back. What are the paths that you might predict for the alpha particles in the Rutherford model of the atom?

1. *Straight through if an alpha particle does not come close to a nucleus.*
2. *Recoil due to a direct hit since the positively-charged alpha particles and nuclei would repel each other.*
3. *Hyperbolic paths due to the Coulombic force exerted on the alpha particles by the nucleus.*



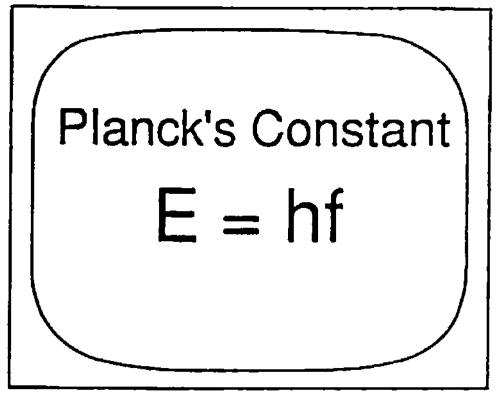
What was the paradox created by the planetary model of the atom?

According to classical theory, an accelerating electron should radiate energy in the form of electromagnetic waves. Since in the planetary atom the electron would be going in a circle, it should radiate energy constantly since anything moving in a circle is accelerating towards the center.



Max Planck held that matter emitted or absorbed energy only in discrete amounts of radiation, which involved a quantity we now call h. What is h?

"h" is called Planck's constant and is the proportionality constant that relates energy and frequency ($E = hf$). It is equal to 6.626×10^{-34} J s.



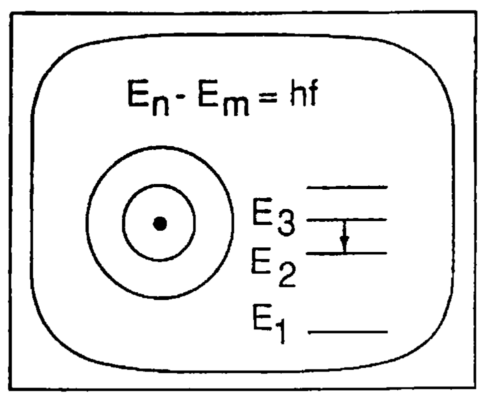
III. BOHR'S HYPOTHESIS: In 1913 Niels Bohr proposed that, when electrons were in certain specific orbits, they would not radiate energy, but when they moved from an outer to an inner orbit, they would give off light. If the atom absorbed energy, the electron could be moved from an inner orbit to an outer orbit. Later de Broglie proposed that electrons had wave properties and these wave properties could be responsible for Bohr's special orbits.

Terms for Bohr's Hypothesis:

Bohr model
radiation
energy state
quantum
quantum jump
de Broglie waves

Bohr assumed that the electron can exist in certain orbits defined by Planck's constant without radiating energy. Radiation at the frequency given by Planck's formula is emitted or absorbed when electrons move from one orbit to another. How do the changes involved for absorption and emission differ?

When an atom absorbs energy, the electron moves to an outer orbit with higher energy. For emission of energy, the electron moves to an inner orbit with lower energy.



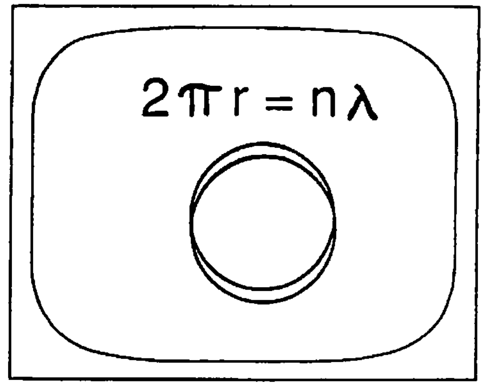
IV. **ELECTRON CLOUD:** Schrödinger expanded on the ideas of wave particles and produced a mathematical model which gives a probability for the location of the electrons. Thus, rather than give a definite orbit to the electron, we can picture a cloud of most probable location. This is easily understood by applying Heisenberg's Uncertainty Principle, which states that the uncertainty in position times the uncertainty in momentum of an electron is equal to or greater than $\hbar$ ($\Delta x \, \Delta p \geq \hbar$).

Terms for Electron Cloud:

Heisenberg Uncertainty Principle
electron cloud model

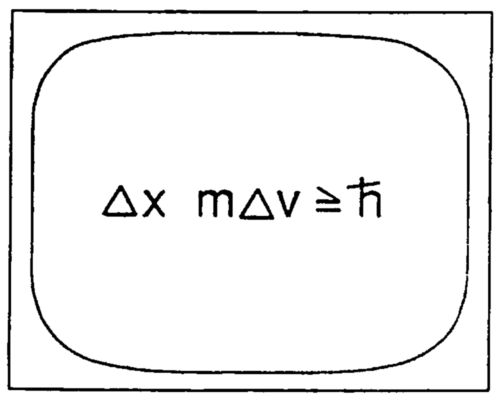
According to de Broglie, electrons are waves that can exist only in orbits where they interfere constructively. The hydrogen atom has only one electron. How is it possible for a single electron to form a standing wave?

A standing wave is formed when the circumference of the orbit of an electron is a whole number of wavelengths. Only orbits with angular momentum $L = nh/2\pi$ *and that allow whole numbers of wavelengths of the electrons exist due to interference.*

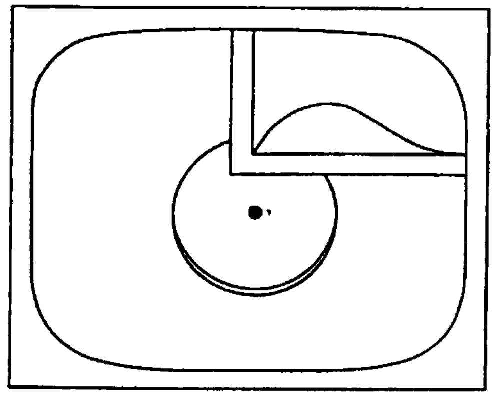


The Heisenberg Uncertainty Principle: "An electron has a relatively small mass and must, therefore, occupy a relatively large region of space. Conversely, the proton has such a large relative mass that it needs to occupy virtually no space at all." What does the above statement mean?

Heisenberg's Uncertainty Principle asserts that there is an uncertainty inherent in nature and that this uncertainty can be quantified. Normally this principle is stated in terms of momentum: $(\Delta x)(\Delta mv) \geq h/2\pi$ *or* $\hbar$. *Increasing the precision of specifying the location will decrease the precision of measuring its momentum and vice versa. For further clarification, see the module on Wave-Particle Duality.*



The radius of the maximum probability of finding the electron is precisely equal to the radius of the first orbit of Niels Bohr's model of the hydrogen atom. What then is the essential nature of this new quantum mechanics, and how is it different from the Bohr model?



In the quantum mechanical picture of the atom, electrons are not revolving about the nucleus in specific orbits. Instead the electrons exhibit a wave nature and consequently we only know the probability of finding an electron in any one position. Measurements of the position would indicate a cluster of points in space corresponding to the probable locations. We think of the electron as having its charge spread out into a cloud. The shape of the cloud should correspond to that of the clusters. Probability refers to a mathematical method of predicting the outcome of a series of events. The graph is technically that of the probability of finding the electron in a region about the nucleus.

TEACHER'S GUIDE TO STUDENT EXERCISES AND ACTIVITIES –

These are take-home questions and activities for students with suggested responses. Copies of the questions *without* the responses appear following the STUDENT GUIDE.

I. **19TH CENTURY MODELS:** About 1800 John Dalton used numerical data from the chemical combinations of elements to prove the necessity of atoms.

1. **When molecules of water are decomposed by electrolysis, two gases are produced. The volume of one of the gasses is twice that of the other. Explain this in terms of Dalton's models of the atoms and molecules.**

   Water molecules are composed of two atoms of hydrogen combined with one atom of oxygen. When separated they form new diatomic molecules of H_2 and O_2 but always in the ratio 2 H_2 to 1 O_2 by volume.

About 1860 James Clerk Maxwell used spectral data to propose that atoms might have parts.

2. **What does the term spectrum mean?**

   Spectrum is a range or spread of wavelengths or frequencies.

II. **PARTS OF THE ATOM:** About 1895 J. J. Thomson discovered the electron and proposed the "plum pudding" model.

1. **According to Thomson's model, how are spectral lines produced?**

   Thomson's model held that vibrating electrons, the raisins in the plum pudding, produced the spectral lines.

About 1900, after a study of light, Max Planck proposed that energy was radiated in discrete quantities or quanta according to the equation $E = hf$.

2. **Light quanta (photons) with what color (frequency) have just enough energy for you to see them when they strike the retina of your eye?**

   The color red. $E = hf$. Red light has the lowest detectable frequency.

3. **List the colors of the visible spectrum having the least through the most energy that your eye can detect.**

   Red, Orange, Yellow, Green, Blue, Indigo, Violet (the acronym ROY G BIV is useful here).

About 1910 Ernest Rutherford bombarded gold foil with alpha particles and discovered the nucleus. He was the first to propose a nuclear or planetary model.

4. **What properties of gold made it an excellent target material?**

   Gold has a large nuclear charge, is massive, and can be made into extremely thin foil. The charge aids in alpha particle repulsion, its mass avoids target recoil, and its thinness avoids overlapping nuclei.

5. **If gold were not used, what would be your second choice for a target?**

   Good choices might be platinum, silver, or lead.

III. **BOHR'S HYPOTHESIS:** About 1913 Niels Bohr combined Planck's idea of discrete energies and Rutherford's idea of a planetary model to propose a nuclear model with electrons occupying only certain special orbits of definite energy.

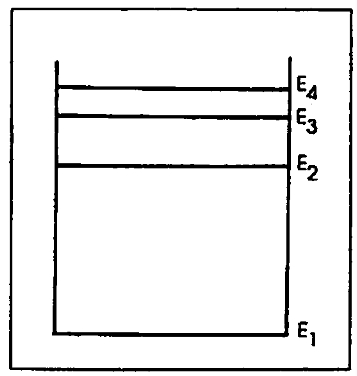
1. **From a physiological point of view, why should you avoid directly viewing ultraviolet light?**

   Ultraviolet photons have frequencies and energies high enough to damage the retina in the eye.

2. **The primary source of light in a fluorescent tube is a very high energy ultraviolet photon produced by excited mercury vapor. How can we see virtually all the spectral colors reflected from objects illuminated by fluorescent light?**

   The ultraviolet photons strike phosphors coating the inside of the tube. Electrons in the phosphors absorb the energy and are excited to high energy states (orbits). Instead of returning directly to the ground state (lowest energy level) electrons drop to intermediate levels producing a wide range of photons in the visual frequency range. (Ultraviolet photons cannot penetrate ordinary window glass, so they cannot get out of the fluorescent tube. Tanning lamps must use special quartz glass tubes to allow the ultraviolet to escape.

3. **Using the diagram at the right, show with arrows the six different quantum jumps or transitions that an electron might make moving from energy level 4 to energy level 1 resulting in spectral lines.**



About 1924 Louis de Broglie proposed that electrons have wave characteristics. The standing waves produced must fit into the circumference of Bohr's circular orbits.

4. **Make a wave on a strip of paper and use it to show that circular orbits must contain whole numbers of wavelengths. Try a combination using half a wavelength also.**

IV. ELECTRON CLOUD MODEL: The electron cloud or quantum mechanical model of the atom was developed using the ideas of many scientists. Erwin Schrödinger developed de Broglie's ideas into a mathematical theory involving a wave equation. The wave mechanics gave a general method of solving for the quantization values for a specific condition. Werner Heisenberg proposed the famous Uncertainty Principle $\Delta x \cdot \Delta mv \geq h/2\pi$. The Heisenberg Uncertainty Principle states mathematically the idea that it is impossible to measure exactly both the position and the momentum of a particle simultaneously. When one is measured more accurately, we introduce more uncertainty in the other measurement. In this video, when dealing with an atom, the velocity of the proton and the electron may be considered essentially equal. Thus, we can use mass and position in the equation $\Delta x \Delta p \leq \hbar$ or $\Delta x \, \Delta m \, v = \hbar$.

1. **Imagine that you are playing ping pong (or air hockey). Now turn on a strobe light and play again. Is the position of the ball (or puck) more certain or less certain? If it is convenient, set up a mini ping pong game using a lab table. If you have an air hockey table, you might set this up.**

With only a strobe light on, the position of the ball (or puck) is more uncertain because it moves appreciably between flashes of the strobe.

2. **Visualize your classroom on a warm spring day. The window is open. A bee flies in.**

   (a) What change(s) occur(s) in the classroom?
   (b) Which is easier to catch or locate – a student or a bee?
   (c) Which is more massive?
   (d) Which occupies a large area in its movements?
   (e) What analogy could we form in relating this classroom situation to the movement of a proton and that of an electron in an atom?

   (a) Attention is shifted toward the bee.
   (b) A student is easier to catch or locate because its momentum is nearly zero.
   (c) A student.
   (d) The bee.
   (e) The bee is analogous to the electron in an atom. Being less massive, it moves around more and has greater uncertainty in position.

3. **Picture a football team on a playing field. The front line is relatively massive. They tend to stay in a relatively small area of the field. The backfield tends to be composed of less massive players who move over a larger area of the playing field. How is this analogous to the Heisenberg Uncertainty Principle where the more massive particle (proton) occupies a smaller region of space and the less massive particle (electron) can be found in a larger region of space. (NOTE: We are assuming the same velocities so that mass is used to represent momentum.)**

   By $m\Delta v\,\Delta x \approx \hbar$, objects with more mass have smaller Δx, which means they are more localized. In this analogy, the front line of football players who have more mass are localized like the nucleus in an atom. The lighter backfield players, like electrons, move about much more.

EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS –

To reinforce further the concepts presented in the video, you might pose the following questions to your students.

1. **What is a model?**

   A model is a visual and mental picture that helps us to understand better a real system that cannot be seen as a whole such as an atom. It addresses the known and predictable properties of a real system.

2. **Give some examples of atomic models that you recall from previous studies. Draw a picture of each model (that is, put your mental picture in visual form).**

   Thomson's plum pudding model, Bohr's planetary model and quantum mechanical or electron cloud model are possible examples.

3. **How and why might a model be changed, modified, or discarded?**

   Models may be modified as new data are applied. For example, Thomson's model was modified by Rutherford, who added his data to the knowledge of the atom. Rutherford's model of the atom was modified by Bohr. Models that do not fit new data may have to be modified or totally discarded. For example, Thomson's plum pudding model did not explain the experimental data of Rutherford. Models may be retained if they consistently explain or agree with data. For example, the concept of a positive and negative charge has been retained throughout all models.

4. **How are an alpha particle and a nucleus of an atom similar?**

   An alpha particle is a helium nucleus (2 protons + 2 neutrons). Thus an alpha particle has a positive charge, as does every nucleus.

5. **Why can't the reversal of the path of an alpha particle be due to a collision with an electron?**

   Striking an electron would not reverse an alpha particle for two reasons: (1) the mass of an electron is so small compared to the mass of the alpha particle (would a billiard ball bounce back in a collision with a stationary marble?), and (2) the charges are opposite and an attraction would result.

6. **Spectra of atoms have been studied since the mid 1800's. How have spectra influenced the choice of atomic models?**

   The presence of the spectral lines along with Rydberg's equation and Planck's equation suggested the presence of energy levels. Bohr used these data in developing his model.

7. **What does the term quantum mean?**

   A quantum means a discrete amount of something is involved. For example, people come in a discrete unit called a person. In this video, the discrete amounts are units of energy which are called quanta. Light quanta are called photons.

8. **What are some characteristics of waves?**

   Characteristics of waves include frequency, wavelength, energy, and amplitude.

9. What are some applications of atomic models?

Changes in the model of the atom have given us insights into observed phenomena such as spectra and radiation. Understanding these models and the principles they represent enabled the development of devices used in research as well as our everyday life. Likewise, they have aided us in our understanding of the Periodic Table and chemical bonding.

The detection of waves depends on their frequencies. Semiconductor diodes detect radio waves which have low frequencies. Human eyes detect light waves at intermediate frequencies. Photographic emulsions can detect x-rays which have high frequencies. Crystals can be ground to specific size and shape to detect a certain radio frequency. Smaller crystals vibrate at high frequencies while larger crystals vibrate at lower frequencies.

Accelerating electric charges radiate energy in the form of electromagnetic waves. Since charges in atoms are accelerating, all matter emits electromagnetic waves. Only certain of these waves will produce spectral lines that we can see. The others will require a special receiver.

Modern instruments such as lasers are practical results of increased understanding of atoms. Electrons moving from a higher energy level to a lower energy level release energy in the form of light. Technological advances, such as infrared spectrometers and scanners using nuclear magnetic resonance (MRI), are also possible due to increased understanding of atomic and nuclear models.

As our understanding of the relationship of energy and momentum increases, we realize that it becomes more difficult to locate electrons. If we use light to locate one, we add energy and thus change its momentum and its position. Associating electrons with probability waves has enabled us to free ourselves from the constraints of classical mechanics. Probability theories tell us that something has a possibility of occurring. The probability may be low, but the possibility is there. Such possibilities have led to modern theories of semiconductors. Materials can be thought of as potential energy wells. Classical mechanics states that an electron lacking a finite amount of energy cannot leave the well. Wave mechanics allows for the possibility that the electron can be found outside the well even without the correct amount of energy. Tunneling is also possible with the wave mechanical model: Using probability waves, a particle or wave can penetrate, or tunnel through, barriers which would be insurmountable in classical physics.

In addition, assuming a wave model implies that all concepts involved with waves will apply here. Such concepts would include Doppler shifts and superposition, including both constructive and destructive interference as well as diffraction and reflection.

SUMMARY – Most people are fascinated by puzzles of some type. Scientists find the puzzles in nature particularly enjoyable. Developments in spectra and spectroscopes provided parts of a puzzle, and models of the atom were evolved to fit with these parts. As new information or parts were found, the model has been changed to accommodate them.

Dalton used numerical data to prove the necessity of an atom. J. J. Thomson modified this picture by proving that atoms are composed of smaller parts and that the properties of atoms can be explained in terms of their atomic structure. Experiments with alpha particles enabled Rutherford to modify Thomson's model to that of a planetary model with a nucleus concentrated at the center. Bohr used emission spectra data and Planck's quantized energy to improve Rutherford's nuclear model by stating that only certain selected electron orbits are allowable. de Broglie amplified the picture further with his concept of circular standing waves. The Bohr orbits must correspond to those orbits accommodating whole numbers of Louis de Broglie wavelengths. Heisenberg then raised the question of limits for measuring the location and momentum of a particle. This then led to the quantum mechanical or electron cloud model by Schrödinger and others. This model uses electron probability clouds that describe the probable location of an electron. Since models are always subject to change as new data are discovered, our present models are probably not the final word but will be modified as new discoveries occur in the future.

NOTE OF EXPLANATION REGARDING THE STUDENT'S GUIDE –

The following four pages of the STUDENT'S GUIDE should be duplicated and distributed to the students for use in preparation for viewing the video. The same may be done with four pages of STUDENT EXERCISES AND ACTIVITIES.

In general, the STUDENT'S GUIDE lists topics, terms, and questions, and the TEACHER'S GUIDE provides definitions, discussion, and answers to the questions. It is very important to have the students receive an appropriate "preparatory set" for viewing the VIDEO and also, following the showing of the VIDEO, to have a systematic discussion, analysis, and summarization of the objectives of the module.

The students should be informed that the INTRODUCTION, TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO, and POINTS TO LOOK FOR IN THE VIDEO should be read and discussed *prior* to viewing the VIDEO. These should also be rediscussed following the viewing.

Answers to the questions listed in the STUDENT'S GUIDE have been included under POINTS TO LOOK FOR IN THE VIDEO in the TEACHER'S GUIDE. The questions which follow this section of the TEACHER'S GUIDE and deal with EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS as well as the SUMMARY should be discussed as a part of the activities that *follow* the viewing(s) of the VIDEO and give closure to the lesson.

STUDENT'S GUIDE TO MODELS OF THE ATOM

INTRODUCTION – The video traces the development of the changing model of the atom from the time of Dalton to the "electron cloud" model. An effort is made to show that scientific models are based on observations, then revised, and thus they evolve as new data are received.

****NOTE: Parts of the video, especially mathematical equations, may go by quickly on the screen. If you have questions, you should ask your teacher to replay these sections.****

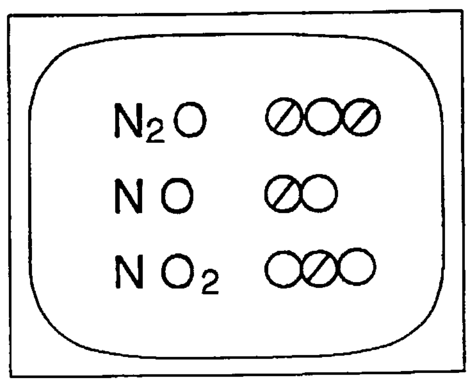
Points to Look for in the Video

I. **19TH CENTURY MODELS:** Modern models of the atom began to be developed during the 19th century to explain chemical properties. Additional information about the atom was obtained through the use of spectroscopes.

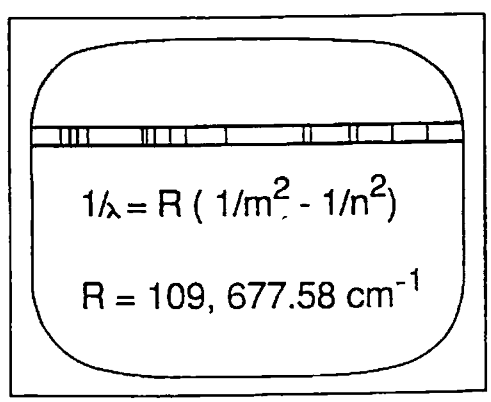
Terms for 19th Century Models:

model
spectrum
Dalton model

According to Dalton's law of simple and multiple proportions, what must be true of the substances involved in order to combine in definite ratios?



Different elements have different spectra. Why does this fact provide a clue to the inner nature of the atom?

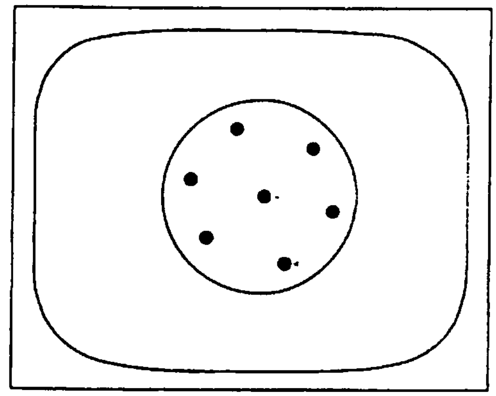


II. **PARTS OF THE ATOM:** Near the turn of the century the atom was found to have a number of parts. Sir J.J. Thomson discovered electrons in 1897. Thomson proposed the first model of the atom, the plum pudding model. About 1910, Rutherford bombarded gold foil with alpha particles from radioactive materials and discovered that atoms had a nucleus. Rutherford proposed the planetary model of the atom. Also, about the turn of the century, Planck determined that matter emits light in discrete quantities.

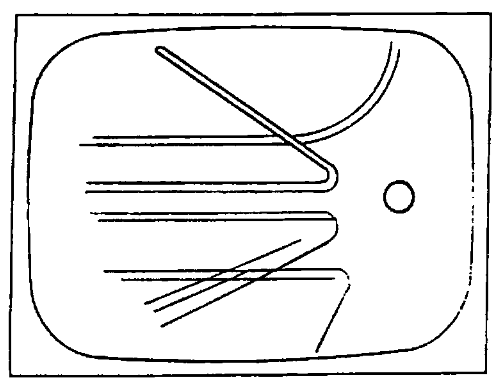
Terms for Parts of the Atom:

electron
plum pudding model
nucleus
alpha particle
Planck's constant

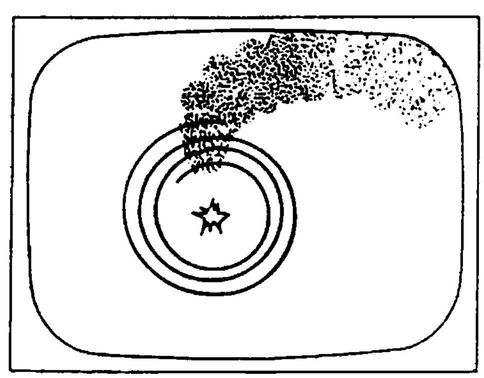
In Professor J.J. Thomson's plum pudding model, each atom consists of a large sphere of positive electric charge with just enough negative electrons inside to make it neutral. What would produce the spectral lines in Thomson's model?



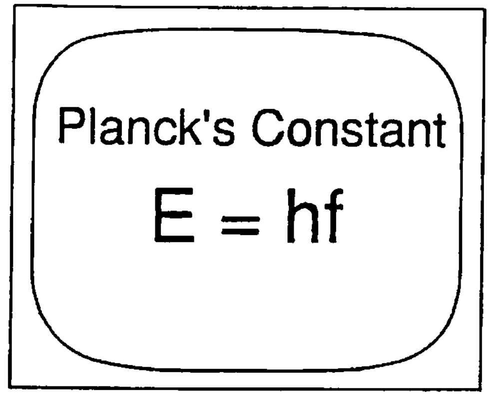
Rather than cutting through the foil like a knife through butter, some of the alpha particles bounced back. What are the paths that you might predict for the alpha particles in the Rutherford model of the atom?



What was the paradox created by the planetary model of the atom?



Max Planck held that matter emitted or absorbed energy only in discrete amounts of radiation, which involved a quantity we now call *h*. What is *h*?

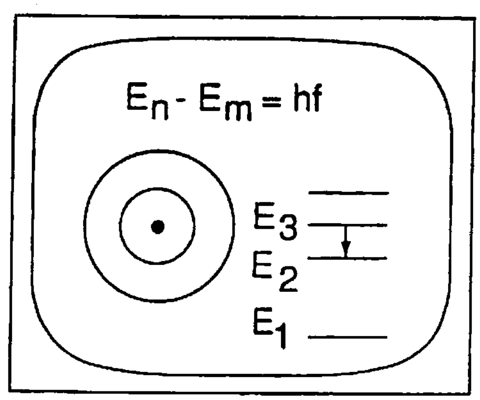


III. **BOHR'S HYPOTHESIS:** In 1913 Niels Bohr proposed that, when electrons were in certain specific orbits, they would not radiate energy, but when they moved from an outer to an inner orbit they would give off light. If the atom absorbed energy, the electron could be moved from an inner orbit to an outer orbit. Later de Broglie proposed that electrons had wave properties and these wave properties could be responsible for Bohr's special orbits.

Terms for Bohr's Hypothesis:

Bohr model
radiation
energy state
quantum
quantum jump
de Broglie waves

Bohr assumed that the electron can exist in certain orbits defined by Planck's constant without radiating energy. Radiation at the frequency given by Planck's formula is emitted or absorbed when electrons move from one orbit to another. How do the changes involved for absorption and emission differ?

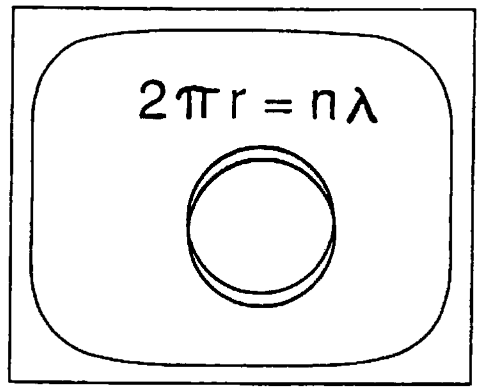


IV. ELECTRON CLOUD: Schrödinger expanded on the ideas of wave particles and produced a mathematical model which gives a probability for the location of the electrons. Thus, rather than give a definite orbit to the electron, we can picture a cloud of most probable location. This is easily understood by applying Heisenberg's Uncertainty Principle, which states that the uncertainty in position times the uncertainty in momentum of an electron is equal to or greater than $\hbar$ ($\Delta x \Delta p \geq \hbar$).

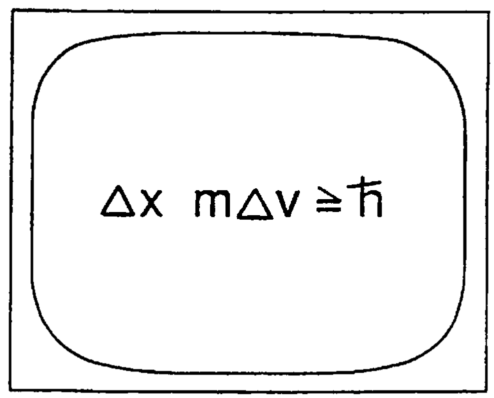
Terms for Electron Cloud:

Heisenberg Uncertainty Principle
electron cloud model

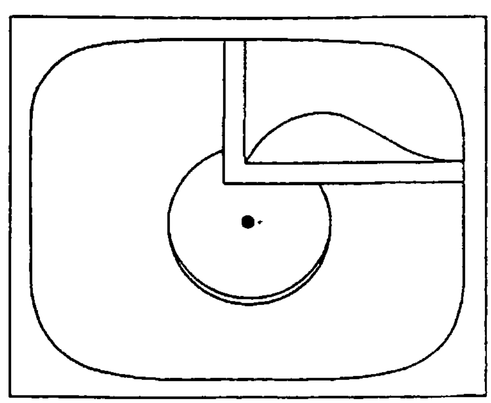
According to de Broglie, electrons are waves that can exist only in orbits where they interfere constructively. The hydrogen atom has only one electron. How is it possible for a single electron to form a standing wave?



The Heisenberg Uncertainty Principle: "An electron has a relatively small mass and must, therefore, occupy a relatively large region of space. Conversely, the proton has such a large relative mass that it needs to occupy virtually no space at all." What does the above statement mean?



The radius of the maximum probability of finding the electron is precisely equal to the radius of the first orbit of Niels Bohr's model of the hydrogen atom. What then is the essential nature of this new quantum mechanics, and how is it different from the Bohr model?



STUDENT EXERCISES AND ACTIVITIES – These are take-home questions and activities for students.

I. 19TH CENTURY MODELS: About 1800 John Dalton used numerical data from the chemical combinations of elements to prove the necessity of atoms.

1. **When molecules of water are decomposed by electrolysis, two gases are produced. The volume of one of the gasses is twice that of the other. Explain this in terms of Dalton's models of the atoms and molecules.**

About 1860 James Clerk Maxwell used spectral data to propose that atoms might have parts.

2. **What does the term spectrum mean?**

II. PARTS OF THE ATOM: About 1895 J. J. Thomson discovered the electron and proposed the "plum pudding" model.

1. **How would Thomson's model produce spectral lines?**

About 1900, after a study of light, Max Planck proposed that energy was radiated in discrete quantities or quanta according to the equation $E = hf$.

2. **Light quanta (photons) with what color (frequency) have just enough energy for you to see them when they strike the retina of your eye?**

3. **List the colors of the visible spectrum having the least through the most energy that your eye can detect.**

About 1910 Ernest Rutherford bombarded gold foil with alpha particles and discovered the nucleus. He was the first to propose a nuclear or planetary model.

4. **What properties of gold made it an excellent target material?**

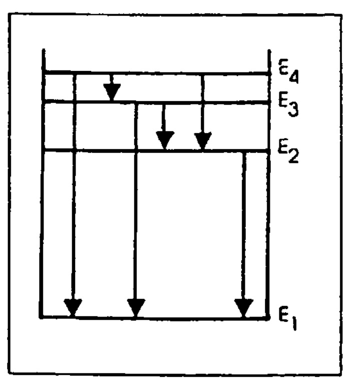
5. **If gold were not used, what would be your second choice for a target?**

III. BOHR'S HYPOTHESIS: About 1913 Niels Bohr combined Planck's idea of discrete energies and Rutherford's idea of a planetary model to propose a nuclear model with electrons occupying only certain special orbits of definite energy.

1. **From a physiological point of view, why should you avoid directly viewing ultraviolet light?**

2. **The primary source of light in a fluorescent tube is a very high-energy ultraviolet photon produced by excited mercury vapor. How can we see virtually all the spectral colors reflected from objects illuminated by fluorescent light?**

3. **Using the diagram at the right, show with arrows the six different quantum jumps or transitions that an electron might make moving from energy level 4 to energy level 1 resulting in spectral lines.**



About 1924 Louis de Broglie proposed that electrons have wave characteristics. The standing waves produced must fit into the circumference of Bohr's circular orbits.

4. **Make a wave out of paper and use it to show that circular orbits must contain whole numbers of wavelengths. Try a combination using half a wavelength also.**

IV. ELECTRON CLOUD MODEL: The electron cloud or quantum mechanical model of the atom was developed using the ideas of many scientists. Erwin Schrödinger developed de Broglie's ideas into a mathematical theory involving a wave equation. The wave mechanics gave a general method of solving for the quantization values for a specific condition. Werner Heisenberg proposed the famous uncertainty principle $\Delta x \cdot \Delta mv \geq h/2\pi$. The Heisenberg Uncertainty Principle states mathematically the idea that it is impossible to measure exactly both the position and the momentum of a particle simultaneously. When one is measured more accurately, we introduce more uncertainty in the other measurement. In this video, when dealing with an atom, the velocity of the proton and the electron may be considered essentially equal. Thus, we can use mass and position in the equation $\Delta x \Delta p \leq \hbar$ or $\Delta x \; \Delta m \; \Delta v = \hbar$.

1. **Imagine that you are playing ping pong (or air hockey). Now turn on a strobe light and play again. Is the position of the ball (or puck) more certain or less certain? If it is convenient, set up a mini ping pong game using a lab table. If you have an air hockey table, you might set this up.**

2. **Visualize your classroom on a warm spring day. The window is open. A bee flies in.**

   (a) What change(s) occur(s) in the classroom?

   (b) Which is easier to catch or locate – a student or a bee?

   (c) Which is more massive?

   (d) Which occupies a large area in its movements?

   (e) What analogy could we form in relating this classroom situation to the movement of a proton and that of an electron in an atom?

3. **Picture a football team on a playing field. The front line is relatively massive. They tend to stay in a relatively small area of the field. The backfield tends to be composed of less massive players who move over a larger area of the playing field. How is this analogous to the Heisenberg Uncertainty Principle where the more massive particle (proton) occupies a smaller region of space and the less massive particle (electron) can be found in a larger region of space? (Note we are assuming the same velocities so that mass is used to represent momentum.)**

TEACHER RESOURCES

SUPPORTIVE BACKGROUND INFORMATION – A model is a visual and mental picture that enables us to understand something that we cannot actually see as a whole. A model is based on our interpretation of facts. A model is retained, modified, or discarded as new data are received.

The concept of atomic or granular structure of matter was formulated by Indian philosophers as early as 1200 B.C. The idea was further expounded in the fifth century B.C. by the Greek philosopher Leucippus and his distinguished pupil Democritus, who proposed that matter consisted of eternal, impenetrably hard atoms that moved inertially in a vacuum. Their views were immortalized in verse by Lucretius, the famous Roman poet of the first century B.C., in what has been described as "the greatest philosophical poem of all times," *De Rerum Natura* (On the Nature of Things). Although much of the qualitative nature of the early atomic theory has survived to modern times, the theory was based on pure philosophical speculation rather than controlled quantitative measurements. Twenty-two centuries were to elapse before these speculations could be substantiated by experimental evidence.

Credit for the quantitative form of atomic theory is generally ascribed to the English chemist and physicist John Dalton, whose work in the period 1803-10 culminated in his treatise A New System of Chemical Philosophy. A number of experiments on chemical reactions had been performed prior to Dalton's work by the French chemists Antoine-Laurent Lavoisier in 1775 and Joseph Louis Proust in 1780. Dalton's atomic theory provided a simple explanation of the results of these experiments, and the theory was further verified by subsequent experiments in chemistry and physics.

Sometimes a certain amount of substance A will combine with an amount of substance B to form substance C, but the same amount of substance A will combine with a different amount of B to form a different substance D. Dalton found that when this happens one of the amounts of B required must be a rational multiple of the other (a rational number being the ratio of two integers). For example, 16 g of oxygen can combine with 14 g of nitrogen to form 30 g of nitric oxide, but 16 g of oxygen can also combine with twice as much nitrogen (28 g) to form 44 g of nitrous oxide. Also, 16 g of oxygen can combine with 7 g of nitrogen to form 23 g of nitrogen dioxide. This illustrates the *law of simple and multiple proportions.*

						Ratio of Nitrogens
16 g	Oxygen +	7 g	Nitrogen =	23 g	Nitrogen Dioxide	1
16 g	Oxygen +	14 g	Nitrogen =	30 g	Nitric Oxide	2
16 g	Oxygen +	28 g	Nitrogen =	44 g	Nitrous Oxide	4

Another clue to the structure of the atom came from the study of light and electromagnetic waves. Every electromagnetic wave has associated with it a wavelength λ and a frequency f related by the equation

$$\lambda f = c,$$

where c is the speed of light. The fundamental properties of electromagnetic waves are basically the same at all frequencies, but different methods are needed for detecting these waves depending on their frequencies.

The spectroscope was invented in 1859 by Kirchhoff. The spectroscope detects electromagnetic waves by analyzing the wavelength of light. If materials in the gaseous or vapor state are excited by heat or an electric spark, the atoms of the material will emit light of definite wavelengths. This light is called emission spectra. Spectra are characteristic of elements and can be used for identification. A study of the sun's spectra has enabled the identification of elements present in the sun. The spectra of these elements are absorption spectra and are called Fraunhofer lines after the Bavarian optician who first studied them.

In 1885, a Swiss high school teacher named Johann Balmer developed an empirical formula that fit some of the lines for hydrogen spectra. The wavelength shown is measured in angstrom units (10^{-10} m).

$$\lambda = 3645.6\, n^2/(n^2-4) \quad (n = 3,4,5,...)$$

A Swedish spectroscopist, Johannes R. Rydberg, later generalized this formula to include all of the hydrogen spectral lines.

$$1/\lambda = R(1/m^2 - 1/n^2) \quad (m = 1,2,3 \;\; n = m+1, m+2...)$$

where R is the Rydberg constant and has the value $R = 109{,}677.58\ \text{cm}^{-1}$.

Neither Balmer nor Rydberg proposed a physical mechanism to explain why these formulas predicted wavelengths so accurately.

The modern views of atomic structure were built largely from a series of discoveries made at the very end of the nineteenth century. They included Roentgen's discovery of X-rays in 1895, Becquerel's discovery of radioactivity in 1896, and J. J. Thomson's discovery in 1897 that the electron was a common constituent of many kinds of matter. Incidentally, the name *electron* for the unit of electrical charge was suggested by G. Johnstone Stoney in 1874. Thomson wanted to use the name *corpuscle*, but his wish did not prevail.

J. J. Thomson visualized the atom as a "plum pudding." The pudding was the positive component, while the raisins represented the electrons. The negative charge of the electrons was exactly enough to cancel out the positive charge and produce a neutral atom.

In Thomson's original model, the positively-charged component had no mass, as the entire mass of the atom was due to the mass of the electron. Thomson had measured the electron to be about 1⁄1000 of the mass of a hydrogen atom (modern value is 1⁄1837). A hydrogen atom would need nearly 1000 electrons, while a uranium atom needed nearly a quarter million. Thomson was able to show that such large numbers of electrons would arrange themselves into special patterns involving many concentric layers or shells. Using his model, Thomson was the first person to try to explain the chemical behavior of the atoms as due to their internal structure. He also explained the unique spectrum of each element as the vibration and interaction of its electrons.

The nuclear model proposed in 1911 by Ernest Rutherford of the University of Manchester superseded the earlier model of J. J. Thomson. Thomson's model was not consistent with results of experiments performed by Rutherford and his colleagues Hans Geiger and Ernest Marsden, who studied the scattering of energetic alpha particles from radioactive elements passing through thin foils of heavy metals such as gold.

If Thomson's model of the atom were correct, firing alpha particles into gold foil would be somewhat like firing bullets into a bag of marshmallows. One would not expect the bullets to deviate very much from their path.

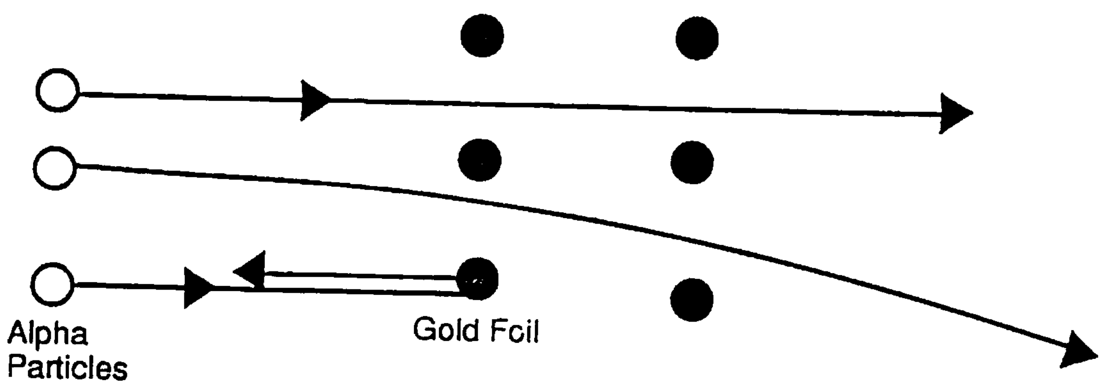
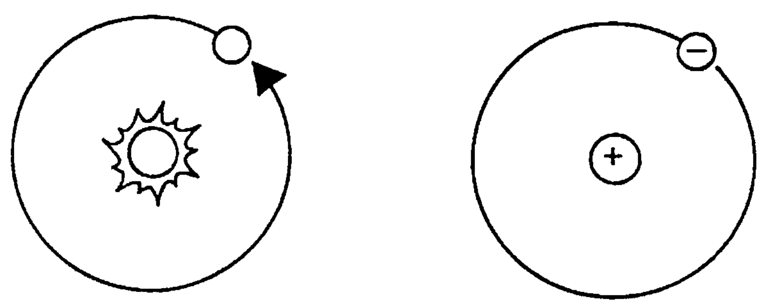


Figure 2.

Although most alpha particles went straight through, unexpectedly, some were scattered backward.

These experiments led Rutherford to formulate the nuclear model of the atom with electrons moving around a massive nucleus. This is sometimes called the *planetary model* because it suggests that the electrons move around the nucleus like planets orbiting the sun. This model has great appeal, but it is not entirely consistent with classical physics. To understand some of the difficulties this model implies, we consider the simplest type of atom, the hydrogen atom, and assume that its single electron moves with constant speed v in a circular orbit.



Solar System

$$F = \text{Gravity} = -\frac{GMm}{R^2}$$

Hydrogen Atom

$$F = \text{Electricity} = \frac{KQq}{R^2}$$

Figure 3. Planetary model of a hydrogen atom with one electron moving at a constant speed in a circular orbit around the nucleus.

We know from study of uniform circular motion that the electron must undergo centripetal acceleration. A problem occurs, however, because, as James Clarke Maxwell had found, accelerating charges emit electromagnetic energy.

If an orbiting electron in a hydrogen atom loses energy as it accelerates, the radius of the orbit must decrease. In other words, a constantly radiating electron should spiral into the nucleus, thereby destroying the planetary nature of the model. Moreover, as the electron spirals in, its frequency of rotation would vary continuously, and this implies that the atom should emit electromagnetic waves with continuously varying frequencies.

An atomic model that replaced Rutherford's model was introduced by Niels Bohr. In 1913, Bohr learned about the Rydberg formula during a casual conversation with a friend. The existence of integers in Rydberg's formula was consistent with the fact that the emission of hydrogen lines was somehow quantized. Bohr was also aware of the new quantum concepts that had been introduced by Planck in 1900 and extended by Einstein in 1905.

Planck had proposed that hot bodies emit energies in fixed amounts, or quanta, at a particular frequency, $E = hf$. Einstein extended the concept to light itself saying that light comes in definite packets of energy. Einstein then used this concept to explain the photoelectric effect.

First, Bohr assumed that the classical electromagnetic theory did not necessarily apply to atomic phenomena. Specifically, he asserted that the orbiting electron in the planetary model of the hydrogen atom does not *normally* radiate energy while being accelerated. He needed this information to explain why the planetary model could survive. Radiation does occur, but only in special circumstances. Bohr postulated that not all orbital radii are possible. In fact, only certain discrete values of radii, $r_1, r_2, r_3 ...$, with corresponding energies in those orbits $E_1, E_2, E_3 ...$ are possible. He referred to these stable orbits as *stationary states* because electrons in these orbits do not radiate. He also suggested that an electron could change from one stable orbit of radius r_n to another of larger radius r_m by acquiring sufficient energy $E_m - E_n$, or, it could at a later time fall back from the larger orbit to the smaller and, in so doing, emit the same amount of energy $E_m - E_n$. He also asserted that this energy would be radiated as a photon or light quantum whose frequency f would satisfy the relation

$$E_m - E_n = hf\,,$$

where h is Planck's constant. This assumption is one form of energy conservation, but it deviates from the classical theory that requires the frequency of radiation to be the same as that of the vibrating charged particle.

Bohr's model provided a mechanism for spectral emission. Because the allowable energy levels were discrete, the corresponding spectral lines would also be discrete.

The ultimate test of any theory is whether or not it agrees with data obtained through experimentation. The Bohr model of the atom certainly had striking success in predicting and explaining the physical basis for Rydberg's formula which gives the spectral lines of atomic hydrogen.

In order for his model to work Bohr had to assume that his stationary states had orbits in which the angular momentum of the electron was quantized. Bohr was not able to explain why this should be true. In 1924 Louis de Broglie suggested that electrons may have wave characteristics. He had conceived the idea that the electron appears as a standing wave in the stationary states of the atom. The orbits would have to be whole wavelengths long such that $mvr = nh/2\pi$ or $mvC = nh$ $(C = 2\pi r)$, which determined the wavelengths that are allowed.

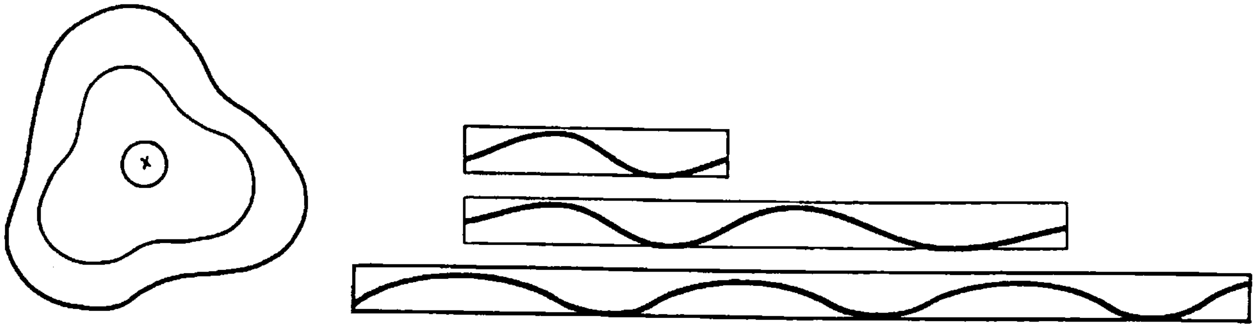


Figure 4. The de Broglie model of the hydrogen atom showing (a) some of the possible orbits and (b) the unrolled orbits as standing waves.

One of the theoretical questions that arose from the de Broglie electron-wave idea was to determine the actual nature of the wave and to find how the mass and charge of the electron were distributed along the wave. The search for solutions to these problems gave birth to one of the most productive periods in theoretical physics and it led to the discovery of new aspects of nature now referred to as quantum phenomena. The mathematical laws governing these phenomena are known as *quantum mechanics*, and the new atomic model that came out of this theory is called the quantum mechanical model or the electron cloud model.

The birth of quantum mechanics came from two independent streams of thought. One stream was Louis de Broglie's concept of matter waves which was further extended by Erwin Schrödinger. This stream expressed particle mechanics in wavelike equations.

The other stream of thought was a treatment of the radiative properties of an atom in late 1925 by Werner Heisenberg, Max Born, and P. Jordan, who used the mathematics of matrices together with ideas from mathematical probability to develop what came to be known as matrix mechanics. It was soon realized that the two streams were simply different mathematical approaches to the same physical ideas. In a famous paper published in 1926, Born established the fundamental basis for applying wave mechanics to collision problems and introduced a probability interpretation that to this date has not been superseded.

The complete quantum mechanical view of the atom as we presently understand it involves not one but four quantum numbers for each electron in an atom. At present the quantum mechanical model offers the most complete explanation of the behavior of all electrons in all elements that we have. It will be subject to change, however, if new data are discovered.

Quantum Number	Symbol	Explanation
1st Principle Quantum No.	n	Determines the energy state of the electron (k, l, m, n, etc. in the Bohr model).
2nd Orbital Quantum No.	l	Determines the magnitude of the orbital angular momentum.
3rd Orbital Quantum No.	m	Specifies the directions of the angular momentum.
4th Electron Spin Quantum No.	s	Represents the intrinsic angular momentum of the spinning electron.

ADDITIONAL RESOURCES

Demonstration #1: Law of Multiple Proportions

Purpose: To demonstrate how quantitative information can lead to the idea of a basic unit.

Materials: Triple beam balance; 4 pennies and 4 nickels; envelopes

Procedure and Notes:

1. In this experiment pennies will represent "A" atoms and nickels will represent "B" atoms.
2. Into an envelope put one penny and one nickel. Mark on the envelope "AB."
3. Into another envelope put one penny and two nickels. Mark on the envelope "AB_2."
4. Into the third envelope put two pennies and one nickel, then mark on the envelope "A_2B."
5. Have a student measure the mass of the envelopes and put those data, as well as the information from the front of the envelopes, on the board. Ask students what they might be able to conclude about the envelopes and what they contain.

Explanation: This simple experiment is similar to Dalton's puzzle over how the chemical elements combine, and it demonstrates why he developed the atomic model to explain chemical reactions. From the data and information given, students should be able to calculate the mass of both "A" and "B" atoms (even the mass of the envelopes). Dalton was able to arrive at relative weights for several common atoms.

Demonstration #2: Black Box

Purpose: To see how much information can be found out indirectly.

Materials: Triple beam balance; 3 boxes; some suitable materials to put in boxes such as flashlight batteries, wadded-up paper, pieces of iron, a magnet, etc.

Procedure and Notes: Place an item in each of the three boxes. Allow students to handle each box and to give his or her observation.

Explanation: Working with indirect evidence to predict what is inside the box is very much like the problems faced by scientists when trying to determine what is inside an atom. Since atoms are much smaller than the shortest of visible light it will never be possible to "see" inside an atom. Therefore scientists must make use of many forms of indirect evidence to understand what is actually happening inside the atom.

Demonstration #3: Flame Tests

Purpose: To demonstrate that each element has its own characteristic color.

Materials: Various metal salts such as NaCl, $CuCl_2$, LiCl, $CaCl_2$, SrCl, KCl: distilled water; burner; wood splints

Procedure and Notes:

1. Make separate solutions of each of the compounds.
2. Dip a wood splint into one of the solutions for a moment.
3. Place saturated wood splint into flame of burner and note color of flame.
4. Repeat above procedure with new wood splints and each of the remaining solutions.

Explanation: Each element produces its own characteristic spectrum of light. Our eyes take all of these characteristic colors and combine them to produce an "average" characteristic color. When the light is viewed through a spectroscope, the individual spectral lines can be seen. Starting about the mid 1800's, the spectroscope became an important analytical tool for identifying elements. Scientists can pass starlight through a spectroscope and identify what elements are present in distant stars.

Note: Wood splints of the kind used in chemistry are much better than the traditional wire loops used for flame testing. They hold more solution so the colored flame lasts longer, and since they are used once and thrown away, there is no cleaning or contamination problem.

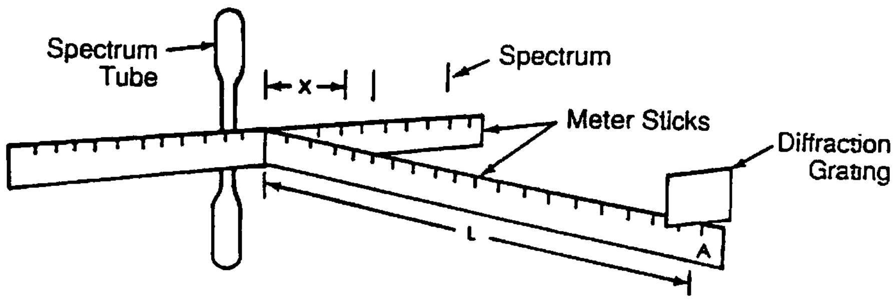
Demonstration #4: Spectral Lines and Their Energies

Purpose: To demonstrate a relationship between spectral lines, their frequencies, and their energies.

Materials: Diffraction grating with known spacings; hydrogen spectrum tube and suitable power supply; two meter sticks.

Procedure and Notes:

1. Set up equipment as shown in the diagram; then dim the lights.



2. Turn on the spectrum tube power supply carefully.

3. Have a student look through the diffraction grating (point A) along one of the meter sticks directly at the spectrum tube. The length along this meter stick will represent "*L*."

4. Have the student determine how far left or right two or three of the hydrogen spectrum lines appear. The distance from the center out to the lines will represent "*x*."

5. Have students calculate the wavelengths of the light by using the formula $\lambda/d = x/L$ where "*d*" is the distance between grooves on the diffraction grating and "*x*" and "*L*" are measured data.

6. After calculating the wavelength, have students determine the frequencies of the lines of light using $c = f\lambda$.

7. Finally have students calculate the energies involved by using Planck's formula $E = hf$.

Explanation: By knowing the wavelength of the spectral lines emitted from an atom, it is possible to determine the corresponding frequencies. Once the frequencies are known, the energies of photons that produce the spectral lines can be calculated. Finally, by applying the law of conservation, the loss in energy of the electrons can be determined by knowing the gain in energy of the light that departs. Compare this explanation to the ripple tank experiment. How would you produce a "water" spectrum?

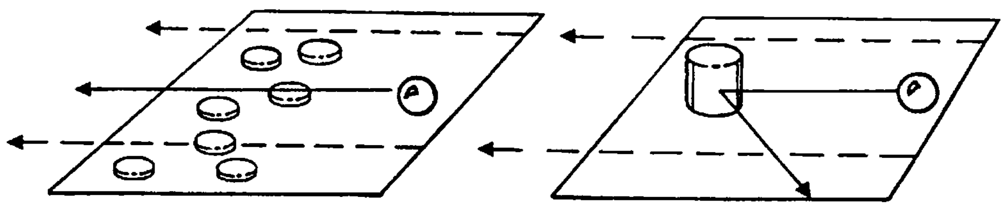
Demonstration #5: Alpha Particle Scattering Analog

Purpose: To demonstrate some of the important concepts of Rutherford's alpha particle scattering.

Materials: Several pennies; a few marbles; one or two large masses (500 g or 1000 g).

Procedure and Notes:

1. Scatter several of the pennies on a large sheet of paper as shown below.
2. Roll marbles across the paper at a medium rate of speed and notice how the path of each marble is affected by collisions with the pennies.
3. Replace the pennies with one or two large masses and again roll the marbles across the paper, again paying particular attention to the paths of the marbles.



Explanation: Because the mass of the pennies is small compared to the mass of the marbles, there are only small deviations in the paths of the marbles. This is similar to what was expected when Rutherford bombarded gold atoms with alpha particles. At the time, the atom was thought to be similar to Thomson's plum pudding model. This consisted of a positively charged area in space within which was imbedded the small negatively charged electrons. Since alpha particles were thousands of times heavier than the electrons, it was expected that they should pass through the gold atoms with little deviation. When the experiment was actually done, most of the alpha particles did pass nearly straight through. However, some of the alpha particles were deflected almost straight back. This implied that there was something massive enough inside the atom to deflect alpha particles. It also suggested that this massive object was rather small since most alpha particles were not affected. Although not shown by this simple demonstration, Rutherford's experiment also implied that the massive object inside the atom was positively charged since the positively charged alpha particles were being repelled by Coulomb forces and not actually bouncing off as in this demonstration.

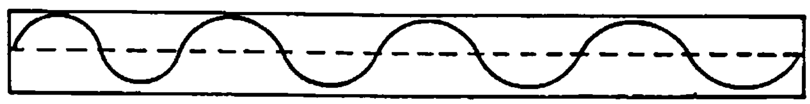
Demonstration #6: Paper Loop Electron Wave Model

Purpose: To demonstrate how the concept of de Broglie electron waves can help explain the concept of definite orbits in the hydrogen atom.

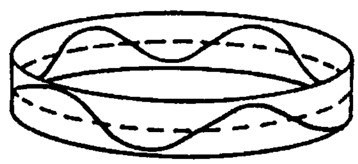
Materials: A long strip of paper about four inches wide; magic marker.

Procedure and Notes:

1. On the long strip of paper, draw a dotted line down the center then a sine wave about four or five wavelengths long as shown below.



2. Roll the strip of paper into circles with circumferences of one wave length, then two, three etc. Show that the only time the waves are in phase is when the circumference equals a whole number of wavelengths.



Explanation: Bohr found that he was able to explain the atom by assuming that the angular momentum of the electrons was quantized; that is, $mvr = nh/2\pi$. He gave no reason, however, why this should be true. When de Broglie proposed that electrons should have both wave and particle properties, the reason for the quantization became clearer. According to de Broglie, electrons should have a wavelength equal to Planck's constant divided by its momentum ($\lambda = h/mv$) where v was determined for the atom by Newton's laws and energy of electron.

Also, if electrons were going to remain in any one particular orbit, they would have to set up standing waves so that the electrons would not end up "eating their own tails." Thus the circumference of the orbit would have to be an integral number of wavelengths. ($2\pi r = n\lambda$). Combining these two equations would give exactly the same results as those proposed by Bohr.

EVALUATION QUESTIONS

1. **To help in our understanding of the atom during the last 200 years we have developed several models. Which of the following lists the models in their correct chronological order?**

   A. plum pudding, Dalton, electron cloud, Bohr
   B. Bohr, plum pudding, Dalton, electron cloud
   C. electron cloud, Bohr, plum pudding, Dalton
   D. Dalton, plum pudding, Bohr, electron cloud

2. **During the last 200 years, scientists have constructed several models of the atom, each building on its predecessors. Any new model of the atom will start by considering atoms**

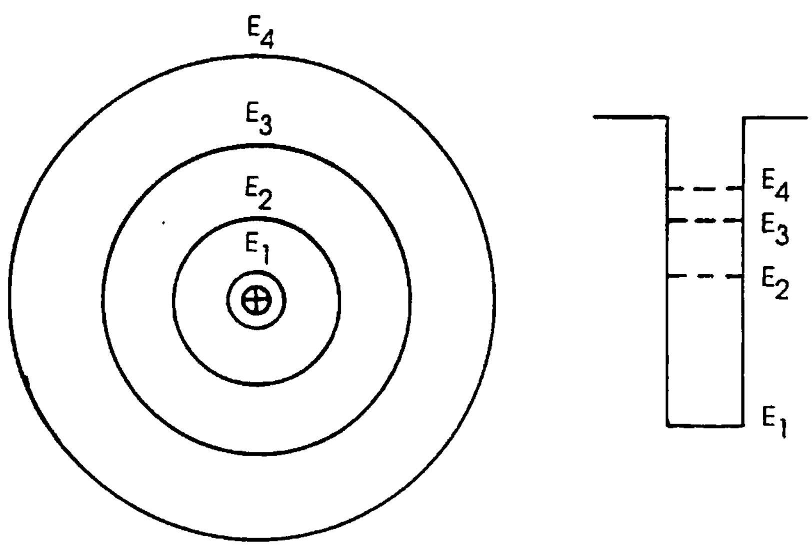
   A. to have negative-charged nuclei probably surrounded by electrons.
   B. to have positive-charged nuclei surrounded by an electron cloud.
   C. to have nuclei surrounded by electrons in well-defined orbits.
   D. to be non-interacting spheres.

3. **Two different colors or frequencies of light are emitted by two different hydrogen atoms. According to the Bohr model, it can be concluded that the atom that gave off light with the higher frequency**

   A. had the electron that started in the innermost orbit.
   B. had the electron that started in the outermost orbit.
   C. had the electron that gained the most energy.
   D. had the electron that lost the most energy.

4. **If electrons start in the third orbit and eventually end in the first orbit as represented in the diagram below, how many possible spectral lines could be formed?**

   A. two
   B. three
   C. six
   D. nine



5. **One of the most important conclusions reached from Rutherford's experiment of bombarding gold atoms with alpha particles was that**

   A. atoms are mostly empty space.
   B. the positive charge in an atom is spread evenly throughout.
   C. the electron's charge is equal but opposite to the charge on a proton.
   D. the nucleus is composed of neutrons and protons.

6. **For the information given in the box below, which of the conclusions are probably justified?**

   > **If a student randomly fires one hundred bullets at a bale of hay and twenty-six of them bounce back, the student can reasonably conclude that**
   >
   > **1. There is an object inside the bale.**
   > **2. The object is about one-fourth the size of the bale.**
   > **3. The object is less dense than hay.**

   A. 1 only
   B. 1 and 2
   C. 1 and 3
   D. 1, 2, and 3

7. **According to the Bohr model, emission of radiation from a hydrogen atom occurs when an electron moves**

   A. from an orbit to the nucleus.
   B. from an inner orbit to an outer orbit.
   C. from an outer orbit to an inner orbit.
   D. More than one of the above is correct.

8. **According to the Bohr model, electrons can orbit about the nucleus of a hydrogen atom without radiating energy if the orbit has**

   A. any energy and any radius.
   B. a definite radius but any energy.
   C. a definite energy but any radius.
   D. a definite radius and a definite energy.

9. **Scientists have replaced the Bohr model of the atom with the electron cloud model because**

   A. it is simpler and easier to work with.
   B. electron microscopes have enabled us to see atoms.
   C. it is more mathematical and can be used with computers.
   D. it is more accurate and fits more of the data available.

10. **Which of the following statements about the quantum theory or electron cloud model of the atom is *least* correct?**

    A. The electron actually forms a small cloud around the nucleus of the atom.
    B. The actual location of an electron cannot be determined, only its probability of existence at any particular location.
    C. The value given for the most probable radius of the hydrogen atom is the same as that given by the Bohr model.
    D. The model predicts the behavior of electrons in atoms other than hydrogen.

ESSAY QUESTIONS

11. **Identify at least two 20th century contributions to the current model of the atom and the experimental evidence on which they are based.**

12. **Classical theories in physics state that accelerating electrons will radiate energy. Using the Bohr model of the atom, explain why atoms emit specific lines rather than continuous spectra.**

KEY

1. D
2. B
3. D
4. B
5. A
6. B
7. C
8. D
9. D
10. A

SUGGESTED ESSAY RESPONSES

11. The student might include any of the following in the answer:

    J. J. Thomson's plum pudding model based on the discovery of the electron. (Although this is 1897, its close enough to be allowed.)

    Rutherford's planetary or nuclear model based on the alpha particle back scattering experiment.

    Bohr's model based on Planck's quantization of energy and the observation of spectral lines.

    Quantum mechanical model or electron cloud model based on de Broglie's matter waves and the Heisenberg Uncertainty Principle and the Schrödinger equation.

    Experimental evidence might also include the failure of Bohr's model in explaining more complex atoms.

12. Bohr assumed that the electron will not radiate energy if it stays in a specific orbit. There was more than one allowable orbit. The electron must gain energy to move to higher orbits. When the electron falls back to a lower energy state, the energy is emitted in the form of radiation during the move. Since the energy is related to frequency by $E = hf$, color of a specific frequency will be emitted.

TEACHER'S GUIDE TO SPECIAL RELATIVITY*

CONTENT AND USE OF THE MODULE – The video introduces Einstein's two postulates of special relativity. It uses these postulates to explain four concepts: simultaneity, time dilation, length contraction, and relativistic mass. Space-time diagrams are developed to enhance the presentation of each of these concepts.

These concepts are unfamiliar to most students. Frequent pauses in the video for classroom discussion are strongly suggested.

See the table on page 5 for planning suggestions. If the module is used to teach single topics it is still important that the video be shown in parts and also in its entirety to emphasize the logical, scientific, and historical flow of the concepts of special relativity.

SECTIONS WHICH FOLLOW

TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO – The following terms are used in the video. It would be helpful to discuss them with students prior to use of the video.

postulate – a statement that is assumed to be true without proof.

frame of reference – a set of coordinate axes and clocks used to describe the position and time of events and motions of objects.

* Special thanks to Professor Wolfgang Rindler of the University of Texas and Professor Carl Rotter of West Virginia University for their invaluable contributions to this module.

inertial frame of reference – a frame of reference whose spatial axes are moving without rotation at constant velocity. Einstein postulated that the laws of physics are equally valid in any inertial frame of reference.

event – an occurrence at one point of space and time, such as the flash of a flashbulb, the collision of two protons, or the triggering of a detector.

simultaneity – the set of events at different points in space that occur at the same time relative to an inertial frame.

length contraction – the shrinking of an object along the direction of motion when moving at relativistic speeds, i.e., at more than about 1/7 the speed of light (at which speed the shrinkage is one percent).

time dilation – the effect that a clock moving at relativistic speeds relative to an observer ticks more slowly than a clock at rest.

mass increase – the effect that the mass of an object is greater when moving at relativistic speeds relative to an observer than when it is at rest.

conservation of momentum – a statement representing the fact that the sum total of momenta of all parts of a system remains constant if no outside forces act on the system.

special relativity – the theory based on Einstein's postulates: (1) All the laws of physics are the same in all inertial frames of reference; (2) The speed of light in free space is the same to any uniformly moving observer.

general relativity – the generalization of special relativity from flat to curved space-time; the curvature represents gravity, so general relativity is the modern theory of gravity (discussed in *Curved Space and Black Holes* module).

space-time diagram – a graphical representation of events in space and time. Each frame of reference has its own "time axis" and "space axis."

time coordinate line – a line in a space-time diagram along which only time varies and which represents the history of a point fixed in the frame of reference. "Time axis" is the time coordinate line through the space origin. Any time coordinate line is parallel to the "time axis."

space coordinate line – a line in a two-dimensional space-time diagram along which only one of the space coordinates (e.g., x) varies while time stays constant. "Space axis" is the space coordinate line which goes through the time origin. Any space coordinate line is parallel to the "space axis."

relativistic speed – any speed great enough to show relativistic effects, while for all practical purposes when v is greater than $0.1\,c$. ($v = 3 \times 10^7$ m/s)

gamma factor (γ) – the relativistic increment/decrement factor for length, mass, and time. Its value is $1/\sqrt{1 - v^2/c^2}$, where v is the velocity of the object and c is the velocity of light (3×10^8 m/s).

microsecond (μs) – 1×10^{-6} s.

muon – an elementary radioactive particle created when cosmic rays crash into the upper atmosphere. It has a half-life of 1.5 microseconds.

WHAT TO EMPHASIZE AND HOW TO DO IT – This video could be used to initiate a study of special relativity. This study typically occurs at the end of the school year. The video, however, could well be used after a study of mechanics and the *Michelson-Morley Experiment* module. Students who understand kinematics, dynamics, and conservation of momentum have sufficient background to benefit from the video. Students should have been exposed to electromagnetic induction, however, in order to understand DEMONSTRATION #2 on relative speed. DEMONSTRATION #1 on the moving magnet serves as an introduction and should be done before viewing the video.

It is essential that the concept of relativity be presented in such a way that students understand it as a *measurement system* rather than as a descriptive system.

Objective 1: State Einstein's Special Relativity Postulates. Distinguish between the postulates and their consequences.

Einstein's postulates are stated at the beginning of the video. They are:

(1) All the laws of physics are the same in all inertial frames of reference.

(2) The speed of light in free space is the same to any uniformly moving observer regardless of his/her velocity.

DEMONSTRATION #1, Moving Magnet vs. Moving Loop, illustrates Postulate #1 and should be done before viewing the video. DEMONSTRATION #4, Conceptual Demonstration of Relativistic Length, Mass, and Time Effects, can be used at the appropriate stops in the video.

Many students have the preconception that one of Einstein's postulates can be stated: "Nothing travels faster than the speed of light." In Einstein's development, this is not a postulate but, rather, a consequence of the Postulates and is addressed in the video when time dilation is derived. Students might believe that Einstein's predicted effects are not "real" but just apparent. Nothing could be further from the truth. Students need clarification on the role of relativity as the more accurate method of measurement—particularly as technology permits movement and speed in ways not possible before in history—while still understanding that, except for measurement, the laws of Newton still apply. It is important that students understand that in measurement, as objects approach the speed of light relative to an observer, lengths do shorten, clocks do slow down, and mass does increase.

Objective 2: Use Einstein's postulates to describe the new concept of simultaneity. Compare simultaneity in Galilean Relativity and Einsteinian Relativity.

Students usually believe, as did Newton and all scientists prior to Einstein, that "now" is the same for everyone. The video uses fixed and moving frames of reference to observe the same pulse of light. The order in which events occur is not the same to both observers. What one observer calls simultaneous events is not simultaneous to the other. The video uses a space-time diagram to explain how two observers (Albert and Henry) can perceive the same events at different times. The argument depends upon a rigid adherence to the second postulate which states that the speed of light is the same to all uniformly moving observers.

It is important to point out to students that the space-time diagram for Galilean Relativity does not have tilted space coordinate lines for either observer. On the other hand, in relativity, Henry's space coordinate lines are tilted to make them pass through events that are simultaneous to Henry. (See also the SUPPORTIVE BACKGROUND INFORMATION.)

Objective 3: Discuss time-dilation with the aid of space-time diagrams. Relate time measurements on a stationary and moving clock.

It is difficult for students to accept that time is not absolute, that all good clocks do not "tick tock" at the same rate. The video points out how time can be measured differently for different observers. It uses space-time diagrams and the Pythagorean theorem to show this. Many features of the diagrams are packed into these segments. You may wish to stop the video often to discuss and review the axes, labels, diagrams, interpretations, and consequences of these scenes. Be sure to emphasize the reasons for Henry's tilted "space and time axes." (See SUPPORTIVE BACKGROUND INFORMATION.)

The quantity gamma (γ) is developed in the video. One of the scenes shows a graph representing the value of γ as a function of velocity. (See SUPPORTIVE BACKGROUND INFORMATION.)

Time dilation is often used in science fiction stories. You may want to use this opportunity to examine how appropriately authors have used this concept.

DEMONSTRATION #3, Basketball Light Clock Model, will help students understand the clock discussion. The ball represents a photon bouncing between too mirrors. You may wish to stop the video and perform the demonstration during this segment. DEMONSTRATION #2, Relative Speed of a Ball vs. the Relative Speed of Light, illustrates the differences between the behavior of light and all other physical objects.

A real-life example of time-dilation is presented in the muon segment of the video.

Objective 4: Explain length contraction with the aid of space-time diagrams. Relate the lengths of a stationary and moving meter stick.

The video demonstrates how an observer can view another object contracting in length by using space-time diagrams and Einstein's postulates. Students often have the preconception that the length of an object should be an absolute thing. The measurement of length does indeed contract in the direction of the motion by the factor γ. (See STUDENT GUIDE SUPPLEMENT.) The video does a good job of showing the length contraction (note the contraction of the measurement of moving people, trains, cars, balls, etc.). Many students may also have the misconception that, since the object contracts, the mass decreases. This is not true. In fact the measurement of mass increases with velocity.

A real-life example of length contraction is presented in the muon segment of the video.

Objective 5: Discuss the relativity of mass and momentum.

Students often have the misconception that, since length is contracted, the object's volume is contracted and thus its mass must decrease (mass = density × volume). Point out that the mass is actually increasing even though the length is contracting.

Momentum conservation, an important ingredient of Newton's mechanics, is the main axiom on which relativistic mechanics is built. It has by now been validated for all kinds of particles at all speeds.

Relativistic mass considerations are critical in modern accelerators in which particles travel close to the speed of light, and mass increases by factors of 1000 are not uncommon.

SUGGESTED ORGANIZATION FOR PRESENTATION OF INDIVIDUAL TOPICS

SPECIAL RELATIVITY

TOPIC	POSTULATES	SIMULTANEITY	SPACE-TIME DIAGRAMS	TIME DILATION
TERMS	postulate frame of reference inertial frame of reference relativistic speed special relativity general relativity	event simultaneity	space-time diagram time coordinate line space coordinate line	time dilation gamma factor
OBJECTIVES	1	2	3	3
POINTS TO LOOK FOR (STUDENT GUIDE)	Frame # 1	Frame # 2	Frame # 2 3	Frame # 4 5
CONCLUSION	4	3		
ADDITIONAL RESOURCES	Demonstration 1	Demonstration 2		Demonstration 3 Demonstration 4
EVALUATION QUESTIONS	1 2 8	3 12	3 4 12	7 11

TOPIC	LENGTH CONTRACTION	CONFIRMING EVIDENCE	MASS INCREASE
TERMS	length contraction	microsecond muon	mass increase conservation of momentum
OBJECTIVES	4	3 4	5
POINTS TO LOOK FOR (STUDENT GUIDE)	Frame # 6	Frame #	Frame # 6
CONCLUSION	1	1	2
ADDITIONAL RESOURCES	Demonstration 4		Demonstration 4 Demonstration 5
EVALUATION QUESTIONS	5 6 11	9	10 11

TEACHER'S GUIDE TO STUDENT EXERCISES AND ACTIVITIES –

Several questions are posed in the STUDENT'S GUIDE. Here are those questions along with suggested responses and selected frames from the video.

I. POSTULATES

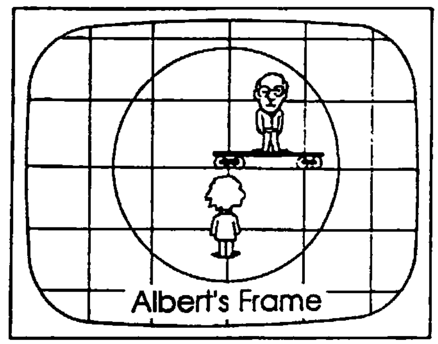
Terms for Postulates:

frame of reference
inertial frame of reference
special relativity
general relativity
relativistic speed
postulate

The rest frame of the television set is always the rest frame of the viewer.

Some people say that you can't go faster than the speed of light. Is this one of Einstein's postulates or a consequence of a postulate?

This is a result of the postulates and also an experimental fact.



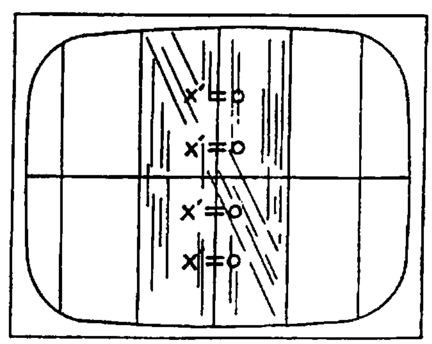
Who is moving? Who is at rest?

Henry is moving. Albert is at rest. Note that the light sphere is in the frame of reference of the video viewer in all cases. Whatever is at rest on the screen is at rest in this frame of reference. Labels remind student whose frame is at rest.

II. SIMULTANEITY AND SPACE TIME DIAGRAMS

Terms for Simultaneity and Space Time Diagrams:

event
simultaneous events
space-time diagram
time coordinate line
space coordinate line



What does the vertical axis stand for?

Time for Galileo. It is Galileo's history in space and time.

What does the slanted axis stand for?

Time for Albert. It is Albert's history in space and time.

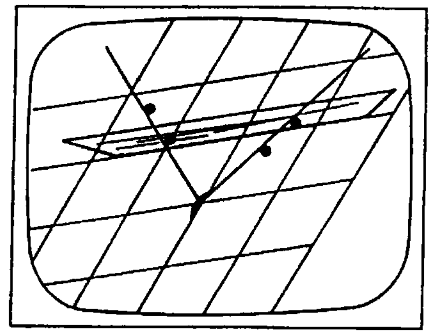
What does the horizontal axis stand for?

Galileo's and Albert's position axis. Their X coordinates at any time t are related by $x = x' + vt$.

Why does Galileo see Einstein's path tilted backward?

Galileo believes he is at rest while Einstein is moving away from him in the backward direction.

In this diagram, why are Henry's time and space axes both tilted?



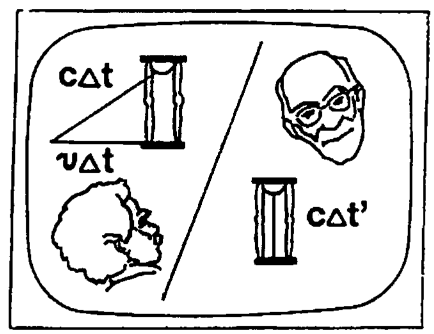
Albert sees Henry moving away from him and so the time axis is tilted with respect to Albert. The speed of light is the same to both Albert and Henry. The space time axis must tilt for Henry according to Albert so that Henry's two events occur simultaneously in Henry's frame of reference: they occur at different times according to Albert.

III. TIME DILATION

Terms for Time Dilation:

time dilation
gamma factor
muon

Why is Albert's time interval labeled Δt and Henry's $\Delta t'$?

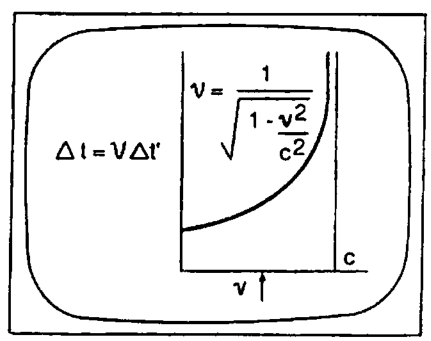


The diagram is drawn from Albert's frame of reference. $\Delta t'$ signifies the time measured by Henry in the moving frame of reference. Note that the clock that is being observed by both is on the moving frame. Henry sees the clock at rest. Albert sees the same clock moving.

Would it make a difference if a stopwatch rather than a light clock were used to measure Δt and $\Delta t'$?

The effect will be the same for all clocks, even biological clocks, because time itself is dilated.

What would γ be if v were equal to $2c$?



Velocities greater than the speed of light lead to imaginary solutions! $\gamma = 1/\sqrt{1-4} = 1/\sqrt{-3}$. *Note that v can be positive (motion to right) or negative (motion to left), but magnitude of velocity cannot be greater than c. Thus "nothing can move faster than the speed of light."*

IV. LENGTH CONTRACTION

Term for Length Contraction

length contraction

Which shaded band represents Henry's meter stick?

The slanted band.

Along what axis would Albert measure the lengths of the meter stick? Whose is shorter?

Along Albert's space axis. Henry's is shorter.

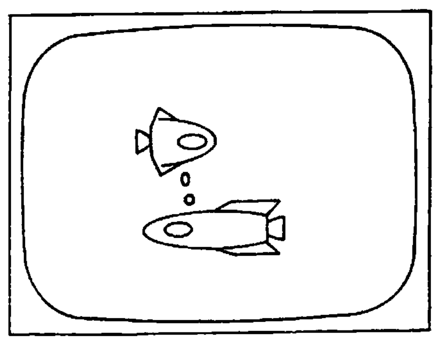
Along what axis would Henry measure the lengths of the meter stick? Whose is shorter?

Along Henry's space axis. Albert's is shorter.

V. MASS INCREASE

Terms for Mass Increase:

mass increase
conservation of momentum



Why is Henry's billiard ball flattened as measured by Albert?

It is length-contracted in Albert's frame of reference.

Is the mass of Henry's billiard ball less than that of Albert's, as determined by Albert?

No, Albert determined the mass of Henry's billiard ball to be greater, so that momentum is conserved in the collision.

SUMMARY – The video develops four concepts of Einstein's two postulates of special relativity: simultaneity, time dilation, length contraction, and relativistic mass are discussed with the aid of space-time diagrams.

NOTE OF EXPLANATION REGARDING THE STUDENT'S GUIDE AND SUPPLEMENT

– The following four pages of the STUDENT'S GUIDE should be duplicated and distributed to the students for use in preparation for viewing the video. The STUDENT GUIDE SUPPLEMENT may be duplicated and distributed to the students for study of the terms, background materials (not available in many texts) and a source of questions and exercises for study in class and at home.

In general, the STUDENT'S GUIDE lists topics, terms, and questions, and the TEACHER'S GUIDE provides definitions, discussion, and answers to the questions. It is very important to have the students receive appropriate preparation for viewing the VIDEO and also, following the showing of the VIDEO, to have a systematic discussion, analysis, and summarization of each of the objectives of the module.

The students should be informed that the INTRODUCTION, TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO, and POINTS TO LOOK FOR IN THE VIDEO should be read and discussed prior to viewing the VIDEO. These should also be rediscussed following the viewing or at appropriate discussion breaks in the video.

Answers to the questions listed in the STUDENT'S GUIDE have been included under POINTS TO LOOK FOR IN THE VIDEO in the TEACHER'S GUIDE. The questions which follow this section of the TEACHER'S GUIDE and deal with EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS as well as the SUMMARY should be discussed as a part of the activities that follow the viewing(s) of the VIDEO and give closure to the lesson.

The space-time diagram for *Special Relativity* on the next page may be used to make an overhead transparency for classroom discussion or duplicated for student exercises.

A note on the scales:

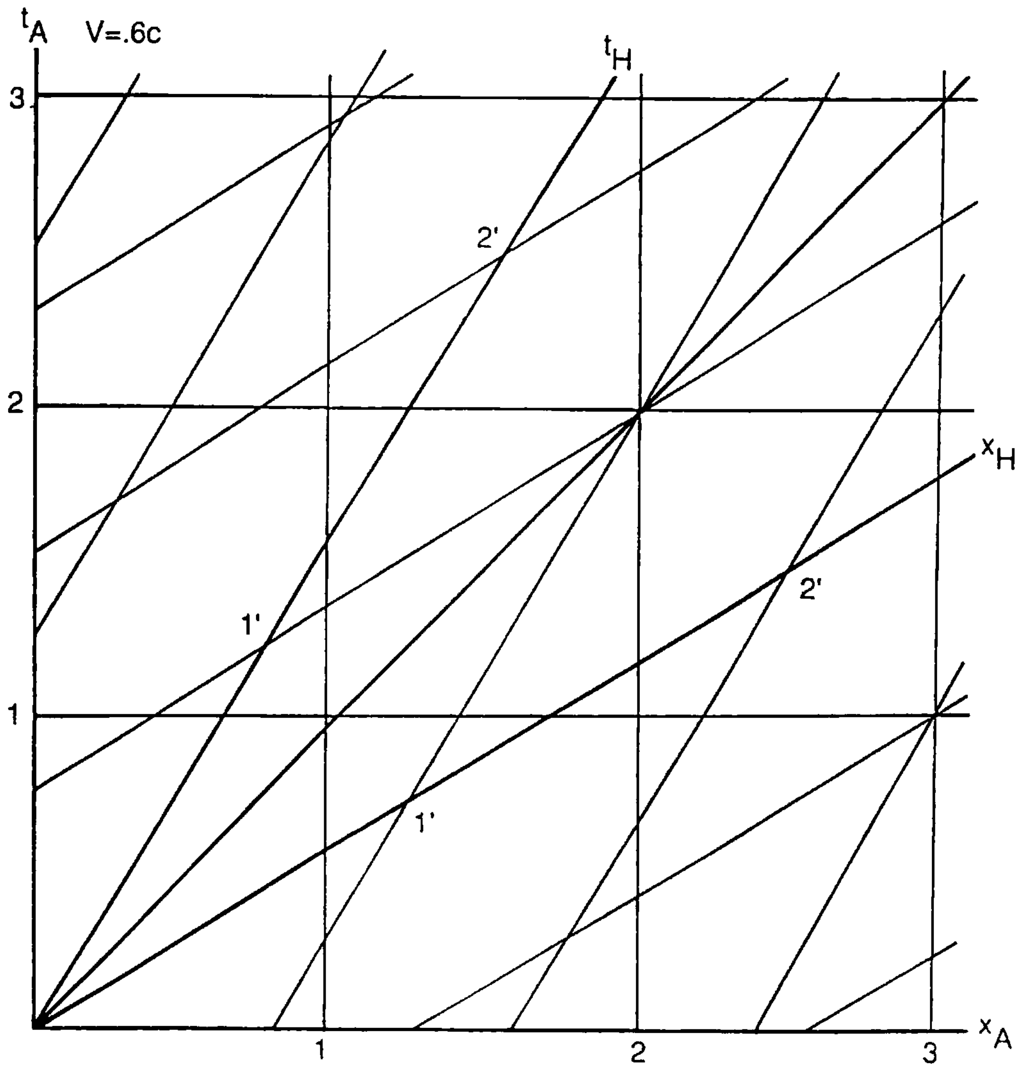
The space and time axes for Henry are shown for Henry moving to the right at velocity of 0.6 c relative to Albert.

For $v = 0.6\,c$

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} = \frac{1}{\sqrt{1 - 0.36}} = 1.25$$

Thus, Albert (on his time-axis) would measure the unit of Henry's time to be 1.25. A horizontal space coordinate line on Albert's grid at 1.25 would intersect Henry's time axis at the point marked 1', which established the scale for Henry's axis.

Space-Time Diagram



STUDENT'S GUIDE TO SPECIAL RELATIVITY

INTRODUCTION – The video introduces the exciting topic of special relativity. It presents Einstein's postulates and some of their consequences.

****NOTE: Parts of the video, especially mathematical equations, may go by quickly on the screen. If you have questions, you should ask your teacher to replay these sections.****

Points to Look For in the Video

The rest frame of the television set is always the rest frame of the observer in question.

I. POSTULATES

Terms for Postulates:

frame of reference
inertial frame of reference
special relativity
general relativity
relativistic speed
postulate

Some people say that you can't go faster than the speed of light. Is this one of Einstein's postulates or a consequence of a postulate?

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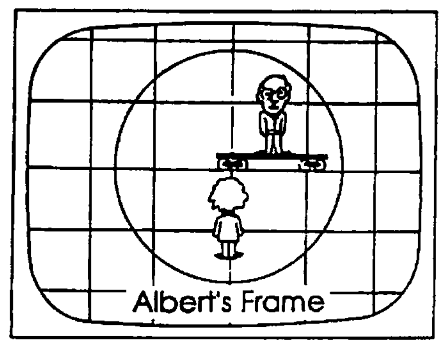


II. SIMULTANEITY AND SPACE-TIME DIAGRAMS

Terms for Simultaneity and Space-Time Diagrams:

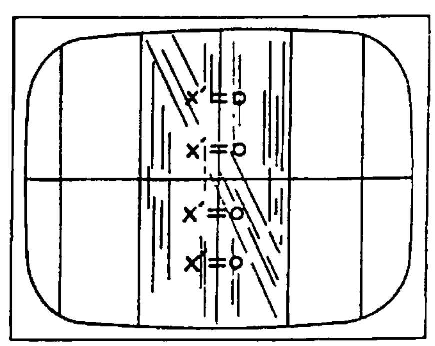
event
simultaneous events
space-time diagram
time coordinate line
space coordinate line

What does the vertical axis stand for?

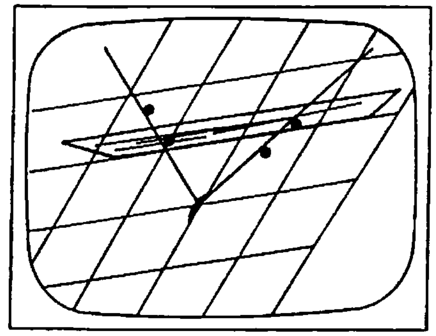
What does the slanted axis stand for?

What does the horizontal axis stand for?

Why does Galileo see Einstein's path tilted backward?



In this diagram, why are Henry's time and space axes both tilted?



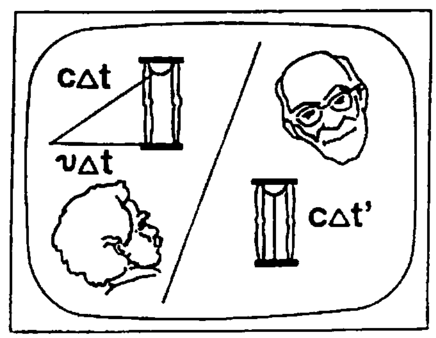
III. TIME DILATION

Terms for Time Dilation:

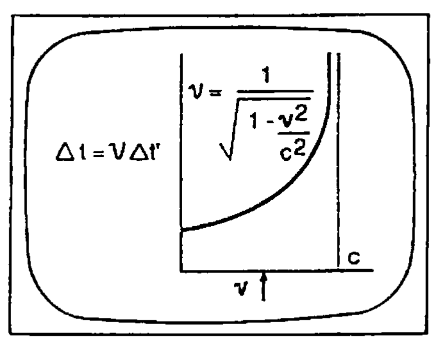
time dilation
gamma factor
muon

Why is Albert's time interval labeled Δt and Henry's $\Delta t'$?

Would it make a difference if a stopwatch rather than a light clock were used to measure Δt and $\Delta t'$?



What would γ be if v were equal to $2c$?



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Terms for Mass Increase:

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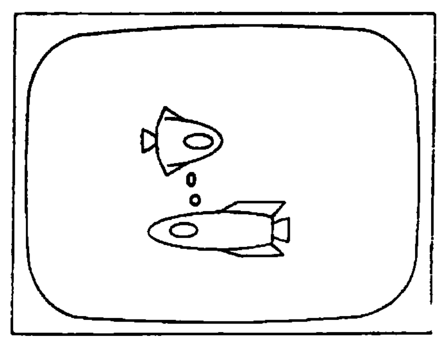


TEACHER'S GUIDE TO THE STUDENT GUIDE SUPPLEMENT – The following material is designed for class discussion and home study.

I. POSTULATES

A. TERMS TO KNOW

postulate – a statement that is assumed to be true without proof.

frame of reference – a set of coordinate axes and clocks used to describe the position and time of events and motions of objects.

inertial frame of reference – a frame of reference whose spatial axes are moving without rotation at constant velocity. Einstein postulated that the laws of physics are equally valid in any inertial frame of reference.

relativistic speed – any speed great enough to show relativistic effects, while for all practical purposes when v is greater than $0.1c$. At $v = \frac{1}{7}\,c$. the effects of time dilation, length contraction, and mass increase are all about 1%.

special relativity – the theory based on Einstein's postulates: (1) All the laws of physics are the same in all inertial frames of reference; (2) The speed of light in free space is the same to any uniformly moving observer.

general relativity – the generalization of special relativity from flat to curved space-time; the curvature represents gravity, so general relativity is the modern theory of gravity.

B. BACKGROUND INFORMATION

When Einstein worked out the theory of special relativity, he built it upon two postulates. The first postulate asserts that all laws of physics (even those that haven't been discovered yet) are the same when applied in all frames of reference moving at constant velocity. The second postulate asserts that the speed of light will be the same for all observers. These postulates are assumptions. Their validity will depend on the validity of the consequences derived from their application. All of the effects we will study, such as time dilation and space contraction, are logical consequences of these two postulates.

It is often said that the theory of relativity insists that nothing can go faster than the speed of light. We will see that this is, indeed, true. However, it should be understood that this is a consequence of the two postulates; hence, the "you can't go faster than the speed of light" statement is a consequence of the theory, not an assumption or postulate.

C. QUESTIONS AND EXERCISES

1. **Write some postulates that you used in your geometry course and list some of the consequences (theorems) that could be proved on the basis of these postulates.**

   A sample answer might include the postulate that the parallel lines don't intersect. A consequence could be the equality of interior angles formed when a line intersects two parallel lines.

2. **Name some postulates that the founding fathers used in setting up the government of the United States.**

   (1) Equality of humans, (2) basic freedoms, (3) God-given rights.

3. **What are some basic postulates that are made by many people in their decisions concerning:**

   (a) gun control?
   (b) use of nuclear energy?

   (a) Possessing guns encourages violence, for example.
   (b) Nuclear fission is unsafe, for example.

4. **Why is Einstein's theory called special relativity?**

   Einstein's theory applies to the "special" cases of non-accelerated frames of reference.

5. **Give an example of a non-inertial frame of reference.**

   The rotating Earth is a non-inertial frame.

6. **Give examples of objects in real life that travel at relativistic speeds.**

   Electrons at the Stanford Linear Accelerator and cosmic rays are examples.

II. SIMULTANEITY

A. TERMS TO KNOW

event – an occurrence at one point of space and time, such as the flash of a flashbulb, the collision of two protons, or the triggering of a detector.

simultaneity – the set of events at different points in space that occur at the same time relative to an inertial frame.

B. BACKGROUND INFORMATION

A surprising consequence of the theory of relativity is that events which take place at the same time according to one observer do not necessarily take place at the same time for all observers. Albert and Henry will attempt to synchronize bells and buzzers by using an expanding sphere of light. Since Albert and Henry are moving relative to each other and since the speed of light is the same from all frames of reference, they will disagree as to the meaning of "at the same time."

C. QUESTIONS AND EXERCISES

1. **Albert is at rest relative to us as Henry moves by at constant speed. At the instant they are nearest to one another (they have the same "x" coordinate) a light sphere is initiated centered on their position. Discuss the sequence of sounds we will hear as the light sphere arrives and triggers Henry's buzzers and Albert's bells.**

   We first hear a buzz as the sphere strikes the "back" of Henry's train car, we then hear two dings at once as the light sphere reaches Albert's bells, and finally we hear a buzz as the light sphere strikes the front of Henry's moving train car.

2. **Now we are moving along with Henry, hence, he seems to be at rest and Albert seems to be moving. Discuss the sequence of sounds we will hear.**

   We first hear a ding, then two buzzes at the same time, and finally a second ding.

3. **Which of the bells or buzzers really were sounded at the same time?**

   Neither or both were sounded at the same time depending on the frame of reference. The notion that two events can take place at the same time must be revised as we begin to consider the ideas of Albert Einstein. Once we accept the postulates of relativity, we find we must drop ideas like "simultaneous" and "absolute time."

III. SPACE-TIME DIAGRAMS

A. TERMS TO KNOW

space-time diagram – a graphical representation of events in space and time. Each frame of reference has its own "time axis" and "space axis."

time coordinate line – a line in a space-time diagram along which only time varies and which represents the history of a point fixed in the frame of reference. "Time axis" is the time coordinate line through the space origin. Any time coordinate line is parallel to the "time axis."

space coordinate line – a line in a two-dimensional space-time diagram along which only one of the space coordinates (e.g., x) varies while time stays constant. "Space axis" is the space coordinate line which goes through the time origin. Any space coordinate line is parallel to the "space axis."

B. BACKGROUND INFORMATION

One of the tools that is central to the video is the space-time diagram. Probably the best way to learn how it works is to view the video several times and the space-time diagrams will start to make more and more sense. However, a few specific things to watch for may make the understanding easier:

1. **Unlike traditional kinematics graphs, time is plotted vertically and space horizontally.**
2. **The initial graphics of Henry and Albert are two space-dimensional (x,y) and in the plane of the TV screen. When the 3-D space-time diagram is first created, this two-dimensional image is made horizontal and is then allowed to move in the upward direction which now represents time. It is as though we had taken hundreds of successive snapshots of the original video and stacked them up on a table in sequence, the earliest at the bottom, the latest at the top. If we look at this stack in the y direction (the "up" direction of the original video) we no longer see motion in the y direction; the result is a *two-dimensional* space-time diagram as viewed by Albert. If we stack full three-dimensional snapshots in a time direction (this is a little hard to imagine) we get the full *four-dimensional* space-time diagram.**

Two different Space-Time Diagrams are used in the video to see the difference between Galilean Relativity and Einsteinian Relativity. Galileo did not assume that the speed of light is the same to all observers, an assumption that Einstein made as the basis of the Special Theory of Relativity

GALILEAN RELATIVITY

In *Galilean relativity*, only the time axis of Galileo is tilted relative to the time axis of Albert. They share the same space axis. Recall that any space line (line parallel to the space axis) contains events which occur at the same (simultaneous) time. Thus events that are simultaneous for Galileo are also simultaneous for Albert. Time line (parallel to an observer's time axis) represents events which take place at the same place at different times. Since Galileo's time axis is tilted from Albert's, their time lines are different.

C. **QUESTIONS AND EXERCISES FOR GALILEAN RELATIVITY** (Einstein and Galileo Galilei are pictured in the video).

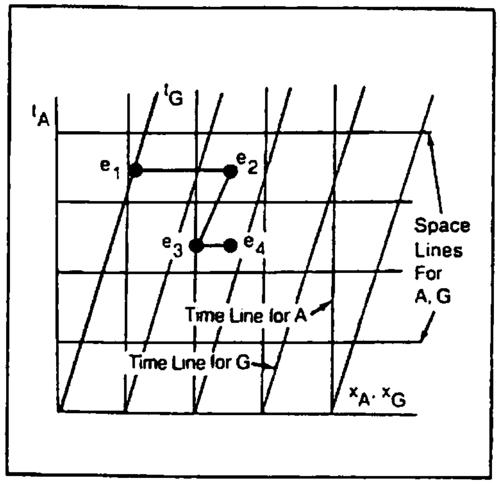
1. **Which events on the space-time diagram**

   a. **are simultaneous as viewed by**

      (1) Albert________
      (2) Galileo________

   b. **occurred at the same locations in space as viewed by**

      (1) Albert________
      (2) Galileo________



1. a. (1) $(e_3,e_4),(e_1,e_2)$ Simultaneity
(2) $(e_3,e_4),(e_1,e_2)$ is same for both.

b. (1) e_2,e_4
(2) e_2,e_3

2. **In what order did events occur for**

   a. **Albert________**
   b. **Galileo________**

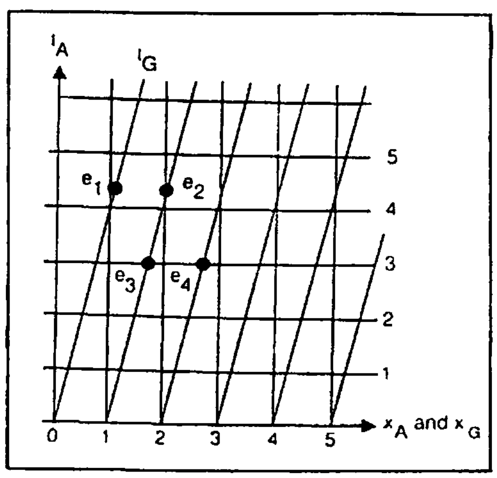
2. a. $(e_3,e_4),(e_1,e_2)$. Order is same
b. $(e_3,e_4),(e_1,e_2)$. for both.

3. **Draw a Galilean (pre-Einstein) space-time diagram relative to Galileo at rest. (Albert will be moving to the left). Draw the corresponding time and space coordinate lines.**

   Plot the events on this diagram which correspond to the data in part A.

4. **In the Galilean space-time diagram shown for Albert and Galileo:**

   a. **Which events are simultaneous for Albert? for Galileo?**
   b. **Which events, if any, occur at the same position for Albert? for Galileo?**



c. **How would the space-time diagram be different if drawn from Galileo's reference frame?**

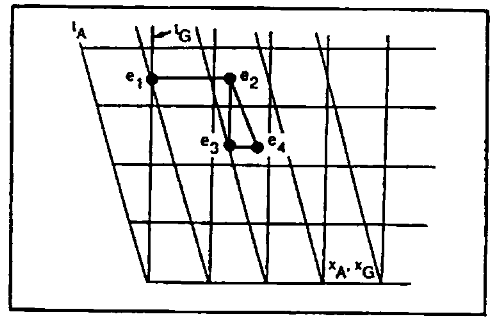
d. **In what order did the events occur for Albert? for Galileo?**

a. *(e_1,e_2) and (e_3,e_4). Order is same for both.*

b. *For Albert, none. For Galileo, e_2,e_3.*

c. *See drawing below.*

d. *$(e_3,e_4)(e_1,e_2)$. Order is same for both.*



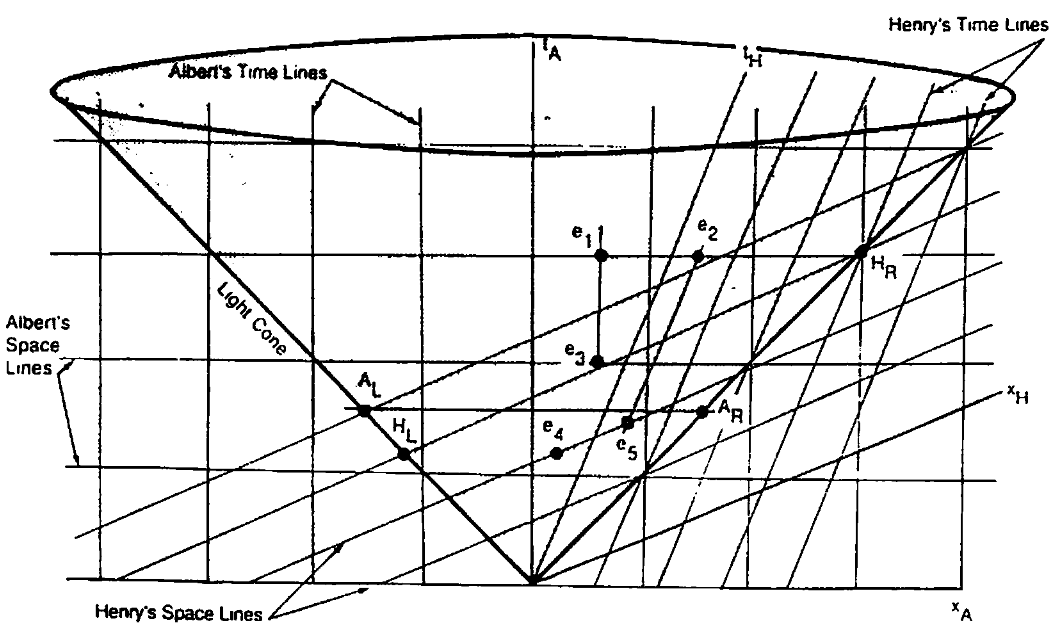
SPECIAL RELATIVITY

In *special relativity* the speed of light is the same for all observers. Relative motion of observers now tilts the time axis (as in Galilean relativity) *and* the space axis. Thus, events that are simultaneous (on same space coordinate line) in one frame are not simultaneous in the other frame. Note that the light cone bisects the space-time axes for each observer. This is because in such diagrams one always measures distance in light units (light years, light seconds, etc.) so that $c = 1$.

Shown on the diagram below are the light signals which triggered Albert's (A_L,A_R) and Henry's (H_L,H_R) detectors.

Since A_LA_R lie along Albert's space line, they are simultaneous events for Albert. They lie on different space lines for Henry, thus A_R is triggered before A_L for Henry. Since H_L and H_R lie along Henry's space line, they are simultaneous events for Henry. They lie on different space lines for Albert, thus H_L is triggered before H_R for Albert.

Other $(e_1 - e_5)$ events are shown for the exercises below:



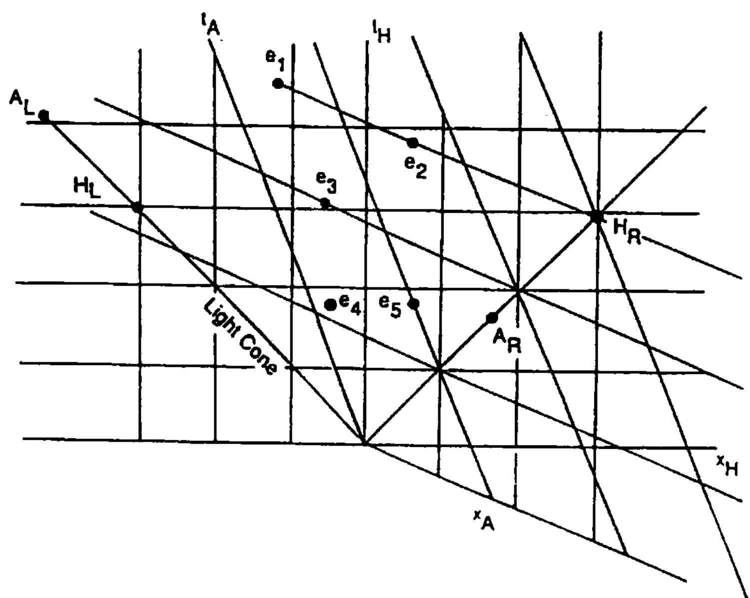
In order for all of these ideas to make sense, you should probably go back and view the video again, confirming for yourself that

(1) the time axis of the person at rest relative to the students is vertical;
(2) the two-dimensional TV world is rotated to make time perpendicular to it;
(3) in Galilean relativity, the x-axis is always horizontal;
(4) with Henry and Albert, Henry's x-axis is slanted to make it parallel to his points of simultaneous time;
(5) the expanding light sphere forms a circle in the plane perpendicular to the time axis;
(6) this expanding circle along the time axis generates the cone in the space-time diagram.

C. **QUESTIONS AND EXERCISES FOR SPECIAL RELATIVITY** (Albert Einstein and Henry Lorentz are shown in the video)

1. **Draw the space-time diagram of the events in the previous example as Henry would draw it, i.e., with Henry's time axis vertical.**

   ANSWER A.



Note that the time axes have been rotated counterclockwise and the space axes have been rotated clockwise and that the light cone again bisects each pair.

2. **Which events in the example above**

   a. **occur simultaneously according to**

      (1) Albert______________
      (2) Henry______________

   b. **occur at the same location in space according to**

      (1) Albert_____________
      (2) Henry______________

c. **occur in sequence order for**

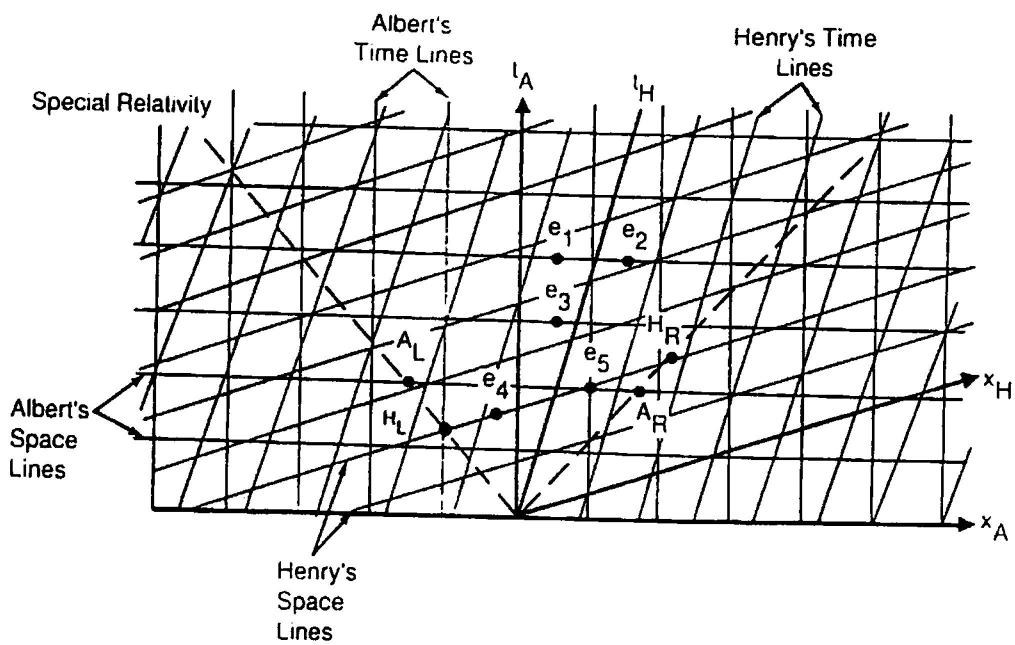
(1) **Albert**_____________
(2) **Henry**_____________

a. (1) e_1,e_2
(2) e_4,e_5

b. (1) e_1,e_3
(2) $(e_2,e_5),(e_3,e_4)$

c. (1) $e_4,\ e_5,\ e_3,\ (e_1,e_2)$
(2) $(e_4,e_5),\ e_3,\ e_2,\ e_1$

3. **Given the space-time diagram with events labeled**



a. **Which events are simultaneous for Albert? for Henry?**

b. **Which events, if any, occur at the same position for Albert? for Henry?**

c. **In what order did the events occur for Albert? for Henry?**

d. **Sketch a "ruler" two units long in Henry's reference frame. How does Albert perceive its length?**

a. $(e_1,e_2),(e_5,A_R)$ *for Albert;* (e_4,e_5,H^{R}) *for Henry.*

b. (e_1,e_3) *for Albert;* (e_2,e_5) *for Henry.*

c. $e_4,(A_L,e_5,A_R),\ H_R,e^3,(e_1,e_2)$ *for Albert;*
$A_R,(e_4,e_5,H_R),\ A_L,e_3,e_2,e_1$ *for Henry.*

IV. TIME DILATION

A. TERMS TO KNOW

time dilation – the effect that a clock moving at relativistic speeds relative to an observer ticks more slowly than a clock at rest.

gamma factor (γ) – the relativistic increment/decrement factor for length, mass, and time. Its value is $1/\sqrt{1 - v^2/c^2}$, where v is the velocity of the object and c is the velocity of light (3×10^8 m/s).

B. BACKGROUND

Derivation of Time Dilation

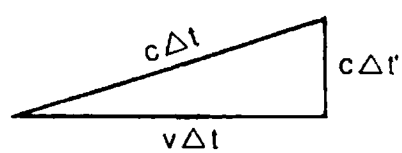
In the video Albert is watching Henry's moving clock.

distance = velocity × time

$c\Delta t$ = the distance Henry's light pulse traveled in one upward movement as viewed by Albert. Notice it is *unprimed.*

$v\Delta t$ = the distance the moving cart traveled in one upward movement of Henry's light pulse as viewed by Albert. Notice it is *unprimed.*

$c\Delta t'$ = the distance Henry's light pulse traveled in one upward movement as viewed by Henry in his rest frame. Notice it is *primed.*



According to the Pythagorean theorem, $a^2 + b^2 = c^2$

$$(v\Delta t)^2 + (c\Delta t')^2 = (c\Delta t)^2$$

$$(c\Delta t)^2 = (c\Delta t)^2 - (v\Delta t)^2 \qquad \text{(Rearrange terms)}$$

$$(c\Delta t')^2 = (c^2 - v^2)\,\Delta t^2 \qquad \text{(Group terms)}$$

$$\frac{(c\Delta t')^2}{c^2} = \frac{(c^2 - v^2)}{c^2}\,\Delta t^2 \qquad \text{(Divide both sides by } c^2\text{)}$$

$$\Delta t'^2 = (1 - v^2/c^2)\,\Delta t^2$$

$\Delta t' = \sqrt{1 - v^2/c^2}\ \Delta t$ (Take square root of both sides)

$\Delta t' / \sqrt{1 - v^2/c^2} = \Delta t$

$\gamma \Delta t' = \Delta t$

$(\gamma = 1/\sqrt{1 - v^2/c^2})$

Light Clocks vs. Everyday Clocks:

Henry spends his entire time on the moving car, i.e., in an inertial frame. *As in every inertial frame*, his aging processes, the light clock, the lifetime of stationary masses, etc., *all* keep time with a standard atomic clock. Therefore *all* these processes slow down, in Albert's view, by the same factor as the photon clock.

Relativity is Real:

The various predictions of special relativity have been amply verified by experiment – and especially the relativistic mass increase, sometimes by γ-factors of more than 1,000, is an every day occurrence in elementary particle collision experiments. The video shows how time dilation was verified. It is difficult to make macroscopic bodies move at relativistic speeds, and for this reason length contraction has not been, and probably never will be, directly observed. Nevertheless no one doubts the reality of this phenomena.

C. QUESTIONS AND EXERCISES

1. **Many science-fiction stories are based on the concept that, if humans are moving near the speed of light, their biological clock (their heart beat) slows down and consequently their aging process is reduced. What are some of those stories?**

   Star Trek – The Movie
   Superman – The Movie
   Planet of the Apes
   Forever Wars . . . etc.

   Although science fiction stories sometimes predict that time slows at high speeds, Einstein's postulates do not predict that time can be reversed.

2. **You observe a space alien traveling by the earth at 0.7c (7/10 the speed of light). How much time expires on the alien's chronometer during 1 hour of your time?**

   $\gamma \Delta t' = \Delta t$

   $1/\sqrt{1 - v^2/c^2}\ \Delta t' = \Delta t$

   $1/\sqrt{1 - (0.7c)^2/c^2}\ \Delta t' = 1\ hr$

   $1/\sqrt{1 - 0.49}\ \Delta t' = 1\ hr$

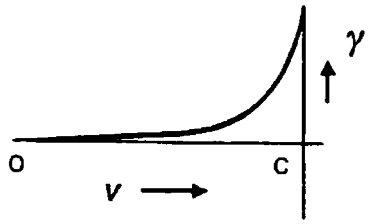
   $1/\sqrt{0.51}\ \Delta t = 1\ hr$

   $1/0.72\ \Delta t' = 1\ hr$

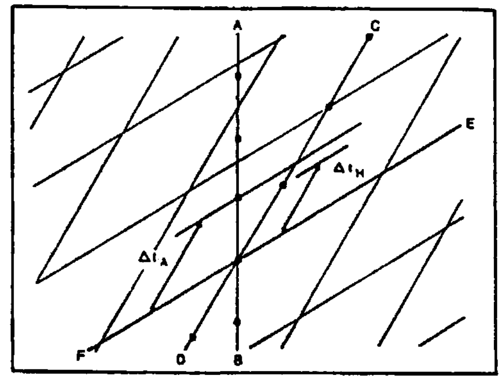
   $\Delta t' = 0.72\ hr$

3. **Three space ships, A, B, and C, are traveling at the respective speeds of 0.5c, 0.7c, and 0.9c, in the earth's frame of reference. In which ship will the clocks appear in the rest frame to run slowest? Is the difference between the time as indicated by the clocks A and B the same as the difference in time between the clocks B and C? Why?**

   As observed in the rest frame, the clocks on ship C will run slowest. The differences between clocks on A & B will not equal the difference between clocks on B and C. The relativistic *increment factor, γ, does not change linearly. Equal change in speed does not produce equal change in γ.*



4. **Referring to the frame to the right taken from the video:**



   a. **Describe the axis AB, CD, and EF.**
   b. **What do the dots on each axis represent?**
   c. **Who is making the measurement?**
   d. **Which clock is running slower?**

   a. AB is Albert's time axis, CD is Henry's time axis, and EF is Henry's space axis.
   b. Events of equal space location.
   c. Albert
   d. Henry's

V. LENGTH CONTRACTION

A. TERMS TO KNOW

length contraction – the shrinking of an object along the direction of motion when moving at relativistic speeds, i.e., at more than about 1/7 the speed of light (at which speed the shrinkage is one percent).

B. BACKGROUND

Derivation of Length Contraction from Time Dilation.

Consider a ruler whose rest length is l. A clock travels past the ruler and parallel to it with speed v. In the rest frame of the clock the length of the ruler is measured to be l' and the clock registers time $\Delta t'$ for the ruler to move by. Thus, in the rest frame of the clock the speed of the ruler is $v = l'/\Delta t'$. In the rest frame of the ruler, the moving clock travels the length of the ruler, l, in time Δt. Hence, the speed of the clock in the rest frame of the ruler is $v = l/\Delta t$. Since the relative velocity between the clock and the ruler must be the same, we get

$$l'/\Delta t' = l/\Delta t .$$

By time dilation, $\Delta t' = \Delta t/\gamma$ so that

$$l'/\Delta t/\gamma = l/\Delta t ,$$

$$l' = l/\gamma = l\sqrt{1 - v^2/c^2} .$$

Note that the length contraction occurs only in the direction of travel. The ruler will not become thicker or thinner.

C. QUESTIONS AND EXERCISES

1. **Consider the ruler described in the derivation above. If the rest length is 1 meter and it is traveling at 0.5*c*, what will be its length as viewed from the rest frame? How will the rest thickness of the ruler compare to the moving thickness as viewed from the rest frame?**

$$l' = l\sqrt{1-v^2/c^2}$$

$$l' = 1m\sqrt{1-(0.5\ c)^2/c^2}$$

$$l' = 1m\sqrt{0.75}$$

$$l' = 0.86\ m$$

The thickness will be the same since the ruler is not moving in the direction of thickness.

2. **From the frame of reference of the moving ruler in question (1), what will be the length of a similar ruler in the other frame of reference?**

The ruler will be 0.86 m long since someone in the moving frame will judge the other frame to be moving at 0.5c and themselves at rest.

3. **View the segment on length contraction again. Compare the height of Henry before and after length contraction. You can do this by holding a sheet of paper to the television screen and placing marks on the papers edge at Henry's feet and head. Use the marks to compare Henry's height before and after length contraction. How do the heights compare? Why? Try the heights and lengths of other illustrations like Albert, the clock, the train. Explain your results.**

The heights of Henry will be the same since the direction of motion is perpendicular to his height. It is an illusion that Henry appears taller after the length contraction. Similar results will be found when measuring other illustrations.

VI. CONFIRMING EVIDENCE

A. TERMS TO KNOW

microsecond (μs) – 1×10^{-6} s.

muon – an elementary radioactive particle created when cosmic rays crash into the upper atmosphere. It has a half-life of 1.5 microseconds in its rest frame.

B. BACKGROUND

Evidence of time dilation is that atomic clocks have been placed in airplanes and flown for a period of time. The moving clock did indeed run slower than a similar clock at rest on the earth.

High energy accelerators can move atomic particles to speeds near the speed of light. The equipment must be designed in order that relativistic effects of space and time be taken into consideration.

The verification of time dilation is taken from a film sponsored by the Physical Science Study Committee for use in the Advanced Topics segment of their curriculum. Elaboration that could add to the appreciation of this section might include the following:

1. Muons are radioactive particles created by cosmic rays smashing into the upper atmosphere. They decay randomly into a positron (e^+) and an antineutrino ($\bar{\nu}$). A decay is recorded as a blip of light on the oscilloscope screen.

2. Each horizontal division on the oscilloscope screen represents one microsecond of time (1×10^{-6} s).

3. Only muons with speed of $0.995c$ are stopped in the detector and allowed to "sit around" until they decay. Muons with less speed are stopped in the iron above the detector. Muons with greater speed pass through the detector to Mount Washington below.

   speed of light (c) = 9.83×10^8 ft/s

   $v = 0.995c \times (9.83 \times 10^8 \text{ ft/s})/c = 9.78 \times 10^8$ ft/s

4. If a muon with this speed moves for one microsecond, it traverses a distance $d = vt = 9.78 \times 10^8$ ft/s $\times 1 \times 10^{-6}$ s = 978 ft.

5. Mount Washington is roughly 6300 ft high. The scientists counted 568 muons on the top of the mountain. Based on the average life span of a muon in the rest frame, the scientists calculated that 27 should reach the bottom of the mountain. Twenty-seven of the 568 would survive the 6.4 microseconds required to traverse the 6300 feet. (6300 ft/(978ft/μs) = 6.4 μs.)

C. QUESTIONS AND EXERCISES

When they took the equipment to sea level, 412 muons were counted in a one-hour period. Clearly, moving clocks do not keep time at the same rate as stationary clocks, or distances are not the same in a fixed or moving frame. Thus we can analyze the results from either frame.

1. Earth Frame

Distance (height of mountain) = 6300 ft
Muon traveling at $v = 0.995c$

$\gamma = 1/\sqrt{1 - v^2/c^2} = 1/\sqrt{1-(.995\,c)^2/c^2} = 10$

Time for half the muons (½ of 568 = 284) to decay = $10 \times 1.5\,\mu s = 15\,\mu s$.

Distance covered in 15 μs before half of muons (284) decayed = $vt = 9.78 \times 10^8$ ft/s $\times 15 \times 10^{-6}$ s = 14670 ft.

No wonder 412 of the muons survived to sea level, since the mountain is only 6300 feet high.

2. Muon Frame

Time (one half life) = 1.5 μs.
earth coming up at 0.995 c

$\gamma = 1/\sqrt{1 - v^2/c^2} = 1/\sqrt{1-(.995c)^2/c^2} = 10$

Distance contraction: L/γ = 6300 ft/10 = 630 ft. Note: This is the height of the mountain as the mountain goes by the muon that is at rest.

Distance covered in 1.5 μs before half of muons decayed = 9.78×10^8 ft/s $\times 1.5 \times 10^{-6}$ s = 1467 ft.

Most of the muons (412) would be hit by the moving earth.

3. Half-Life

The concept of half-life implies that on the average, half of the muons will decay in 1.5 microseconds (1.5×10^{-6} s). Complete the chart of number of muons at various times to determine why approximately 27 were expected to remain after 6.4 microseconds.

Number of muons 568 at time = 0
Number of muons 284 at time = 1.5 microseconds
Number of muons 142 at time = 3.0 microseconds
Number of muons 71 at time = 4.5 microseconds
Number of muons 36 at time = 6.0 microseconds
Number of muons 18 at time = 7.5 microseconds

VII. MASS INCREASE

A. TERMS TO KNOW

mass increase – the effect that the mass of an object is greater when moving at relativistic speeds relative to an observer than when it is at rest.

conservation of momentum – a statement representing the fact that the sum total of momenta of all parts of a system remains constant if no outside forces act on the system.

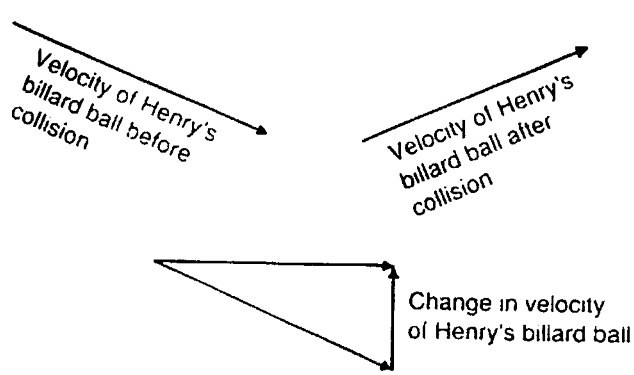
B. BACKGROUND

The understanding of this section of the video depends heavily on your use of the conservation of momentum. The scene is first viewed by an outside observer with both Henry and Albert moving at the same speed. The mass of the two billiard balls must be the same for momentum to be conserved. Momentum must also be conserved when viewed from Albert's frame. The mass of Henry's billiard ball must be increased in comparison with Albert's for Albert's observed effect to be measured. Note in the video that even though the volume of the moving ball is smaller, its mass increases.

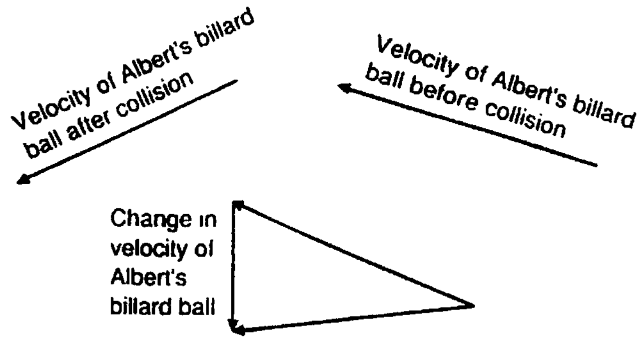
C. QUESTIONS AND EXERCISES

1. **Albert and Henry are both moving as seen by an outside observer. Complete the vector diagram by determining the change in velocity of each billiard ball.**

(a)



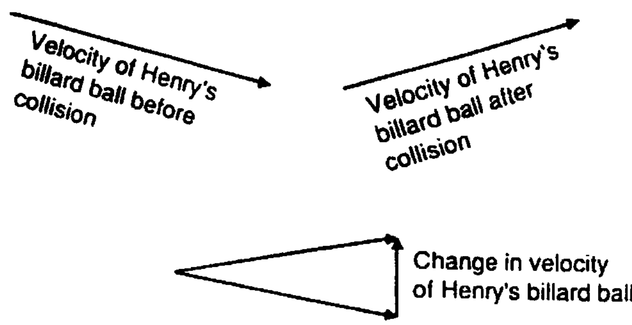
(b)



The change in velocity vectors of the two are equal and opposite. Conservation of momentum would dictate that the masses must be equal.

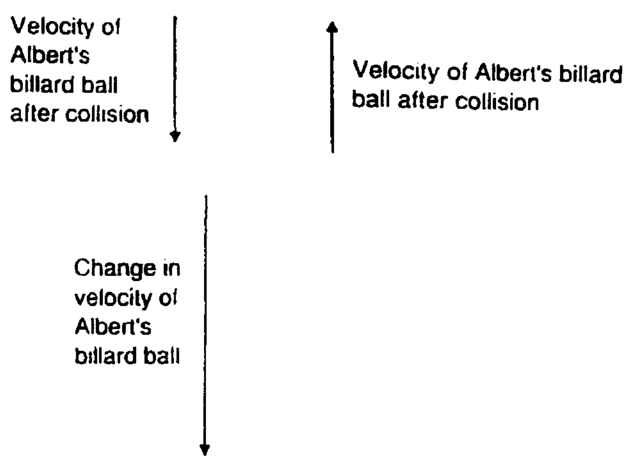
2. **Albert is at rest and Henry's space ship is moving. Complete the vector diagram by determining the change in velocity of each billiard ball.**

(a)



The change in the velocity vector of Albert's billiard ball is much greater than that of Henry's. Conservation of momentum dictates that the mass of Henry's billiard ball must be larger.

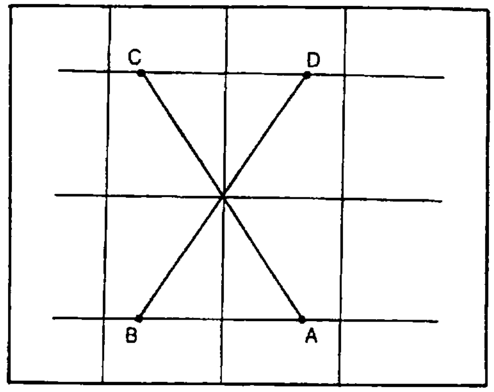
(b)



3. a. **Identify and label what took place at each label in this frame taken from the space billiards section of the film.**

   b. **Draw a labeled momentum vector diagram corresponding to labels.**

   c. **Show from your vectors in b that momentum was conserved in the collision.**



VIII. CONCLUSION

The following problem is given as an illustration of the consequences of Einstein's postulates to length contraction, mass increase, and simultaneity.

1. **Length Contraction**

   Billy is a 50 kilogram pole vaulter for a winning track team. Billy has a problem. He doesn't want his new 5-meter pole to get wet out in the rain, but his father won't let him keep it in the garage. This is mainly because the garage is only 3 meters long. The coach has a solution. If Billy could only run into the garage at $v = 0.8c$, the pole would be shortened to 3 meters. The coach knew that when Billy stopped it would go back up to 5 meters again, but he figured he could close the garage door in time, and he hoped the pole would bend rather than break once it got in. Besides, the advantages of having somebody on the team who could run that fast far outweighed the possible broken pole. Perform the calculation to show this length contraction.

$$L' = \sqrt{1 - v^2/c^2} \times L \qquad L' = 5\text{ m}$$

$$L' = \sqrt{1 - (0.8c)^2/c^2} \times 5\text{ m}$$

$$L' = \sqrt{1 - 0.64c^2/c^2} \times 5\text{ m}$$

$$L' = \sqrt{0.36} \times 5\text{ m} \qquad L' = 0.6 \times 5\text{ m} = 3\text{ m}$$

2. **Mass Increase**

   After a bit of training, Billy's speed finally got up to 0.8c. His mass increased as measured by other observers at rest. Perform the calculation to show his increase in mass. Suppose his rest mass is 50 kg.

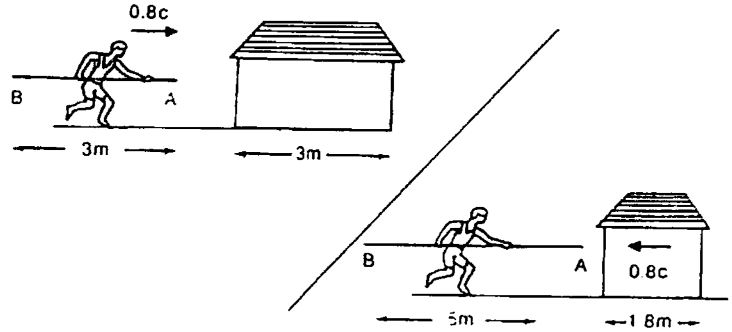
$$m' = \frac{m}{\sqrt{1 - v^2/c^2}}$$

$$m' = \frac{50\text{ kg}}{\sqrt{1 - (0.8c)^2/c^2}}$$

$$m' = \frac{50\text{ kg}}{\sqrt{1 - 0.64}}$$

$$m' = \frac{50\text{ kg}}{\sqrt{0.36}}$$

$$m' = 83.3\text{ kg}$$



The big day came, Billy's speed got up to 0.8c, he got the pole in the garage, and the coach closed the door. Afterwards Billy looked rather stunned. When asked why, he said, "Here I was carrying this 5-meter pole looking at a garage that was only 1.8 meters long! It was worse than before!" The coach recalculated and decided Billy's statement of a 5-meter pole and a 1.8-meter garage was true and his original plan was okay, too. Billy got the pole in the garage. We shall presently see why.

3. **Simultaneity**

Simultaneity is relative to the observer. Two events that are simultaneous in one reference frame may not be simultaneous in another reference frame.

a. **In the garage frame of reference, where is Point B when Point A hits the back wall of the garage?**

In the garage frame of reference (that is, the garage is at rest and the pole vaulter is moving at 0.8c), Point B goes in the door when Point A hits the wall.

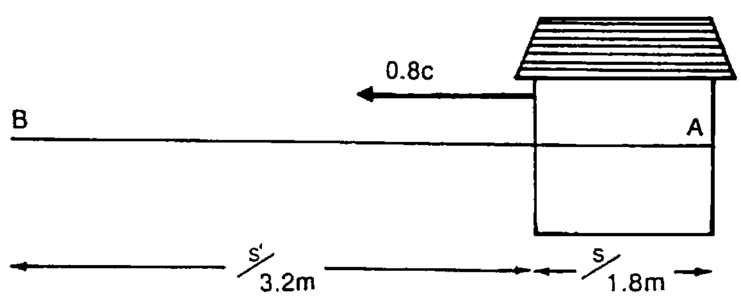
b. **In the pole vaulter's frame of reference, where is Point B when Point A is in first contact with the back wall of the garage?**

In the pole vaulter's frame of reference (that is, the pole vaulter is at rest and the garage is moving at 0.8c), Point A hits the wall first, while Point B is outside the garage.

4. **Postulates**

Remember that Einstein states as one of his postulates that there is no preferred reference frame, so only relative motion matters. If the pole vaulter is in motion and the garage is at rest and the pole fits in the garage so the door can be closed, the same must be true if the garage is in motion and the pole vaulter is at rest.

a. **Perform the necessary calculation to show that, with the garage moving and the pole vaulter at rest, the pole will get into the garage.**



Let's analyze the figure above. At t_0 in the pole vaulter frame, Point A is hit by a very fast moving garage wall. However, an observer at Point B on the pole has no knowledge of this at t_0. He can't see or feel the collision (event) until a later time, $t_0 + \Delta t$, where Δt is the time it takes for a light wave or a shock wave along the pole to reach him. No information travels faster than the speed of light (c) so:

$$\Delta t = l/c = 5.0\ m/c$$

$$v = 0.8 \times c$$

b. How far can Point B travel in that time? (or more appropriately asked, "How far does the garage door travel in that time?")

The distance the garage door can travel before Point B feels or sees the shock of collision is

$d = v\Delta t = 0.8 \times 5\ m = 4\ m$

Since the garage door is 1.8 meters in front of the back wall where the collision took place, the pole could make it into the garage in this frame of reference, and then some.

STUDENT GUIDE SUPPLEMENT – The following material is designed for class discussion and home study. It is to be duplicated and distributed.

I. POSTULATES

A. TERMS TO KNOW

postulate – a statement that is assumed to be true without proof.

frame of reference – a set of coordinate axes and clocks used to describe the position and time of events and motions of objects.

inertial frame of reference – a frame of reference whose spatial axes are moving without rotation at constant velocity. Einstein postulated that the laws of physics are equally valid in any inertial frame of reference.

relativistic speed – any speed great enough to show relativistic effects, while for all practical purposes when v is greater than $0.1c$. At $v = \frac{1}{7}$ c. the effects of time dilation, length contraction, and mass increase are all about 1%.

special relativity – the theory based on Einstein's postulates: (1) All the laws of physics are the same in all inertial frames of reference; (2) The speed of light in free space is the same to any uniformly moving observer.

general relativity – the generalization of special relativity from flat to curved space-time; the curvature represents gravity, so general relativity is the modern theory of gravity.

B. BACKGROUND INFORMATION

When Einstein worked out the theory of special relativity, he built it upon two postulates. The first postulate asserts that all laws of physics (even those that haven't been discovered yet) are the same when applied in all frames of reference moving at constant velocity. The second postulate asserts that the speed of light will be the same for all observers. These postulates are assumptions. Their validity will depend on the validity of the consequences derived from their application. All of the effects we will study, such as time dilation and space contraction, are logical consequences of these two postulates.

It is often said that the theory of relativity insists that nothing can go faster than the speed of light. We will see that this is, indeed, true. However, it should be understood that this is a consequence of the two postulates; hence, the "you can't go faster than the speed of light" statement is a consequence of the theory, not an assumption or postulate.

C. QUESTIONS AND EXERCISES

1. **Write some postulates that you used in your geometry course and list some of the consequences (theorems) that could be proved on the basis of these postulates.**
2. **Name some postulates that the founding fathers used in setting up the government of the United States.**
3. **What are some basic postulates that are made by many people in their decisions concerning:**

   (a) gun control?
   (b) use of nuclear energy?

4. **Why is Einstein's theory called special relativity?**
5. **Give an example of a non-inertial frame of reference.**

6. **Give examples of objects in real life that travel at relativistic speeds.**

II. SIMULTANEITY

A. TERMS TO KNOW

event – an occurrence at one point of space and time, such as the flash of a flashbulb, the collision of two protons, or the triggering of a detector.

simultaneity – the set of events at different points in space that occur at the same time relative to an inertial frame.

B. BACKGROUND INFORMATION

A surprising consequence of the theory of relativity is that events which take place at the same time according to one observer do not necessarily take place at the same time for all observers. Albert and Henry will attempt to synchronize bells and buzzers by using an expanding sphere of light. Since Albert and Henry are moving relative to each other and since the speed of light is the same from all frames of reference, they will disagree as to the meaning of "at the same time."

C. QUESTIONS AND EXERCISES

1. **Albert is at rest relative to us as Henry moves by at constant speed. At the instant they are nearest to one another (they have the same "x" coordinate) a light sphere is initiated centered on their position. Discuss the sequence of sounds we will hear as the light sphere arrives and triggers Henry's buzzers and Albert's bells.**
2. **Now we are moving along with Henry, hence, he seems to be at rest and Albert seems to be moving. Discuss the sequence of sounds we will hear.**
3. **Which of the bells or buzzers really were sounded at the same time?**

III. SPACE-TIME DIAGRAMS

A. TERMS TO KNOW

space-time diagram – a graphical representation of events in space and time. Each frame of reference has its own "time axis" and "space axis."

time coordinate line – a line in a space-time diagram along which only time varies and which represents the history of a point fixed in the frame of reference. "Time axis" is the time coordinate line through the space origin. Any time coordinate line is parallel to the "time axis."

space coordinate line – a line in a two-dimensional space-time diagram along which only one of the space coordinates (e.g., x) varies while time stays constant. "Space axis" is the space coordinate line which goes through the time origin. Any space coordinate line is parallel to the "space axis."

B. BACKGROUND INFORMATION

One of the tools that is central to the video is the space-time diagram. Probably the best way to learn how it works is to view the video several times and the space-time diagrams will start to make more and more sense. However, a few specific things to watch for may make the understanding easier:

1. **Unlike traditional kinematics graphs, time is plotted vertically and space horizontally.**

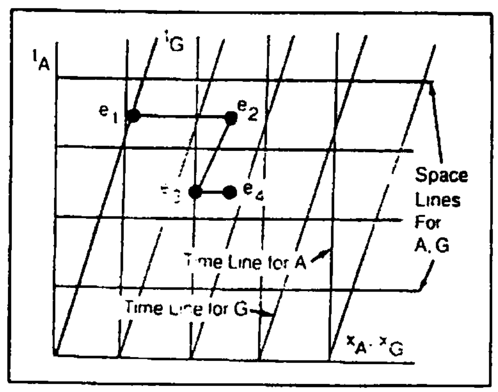
2. **The initial graphics of Henry and Albert are two space-dimensional (*x,y*) and in the plane of the TV screen. When the 3-D space-time diagram is first created, this two-dimensional image is made horizontal and is then allowed to move in the upward direction which now represents time. It is as though we had taken hundreds of successive snapshots of the original video and stacked them up on a table in sequence, the earliest at the bottom, the latest at the top. If we look at this stack in the *y* direction (the "up" direction of the original video) we no longer see motion in the *y* direction; the result is a *two-dimensional* space-time diagram as viewed by Albert. If we stack full three-dimensional snapshots in a time direction (this is a little hard to imagine) we get the full *four-dimensional* space-time diagram.**

Two different Space-Time Diagrams are used in the video to see the difference between Galilean Relativity and Einsteinian Relativity. Galileo did not assume that the speed of light is the same to all observers, an assumption that Einstein made as the basis of the Special Theory of Relativity.

GALILEAN RELATIVITY

In *Galilean relativity*, only the time axis of Galileo is tilted relative to the time axis of Albert. They share the same space axis. Recall that any space line (line parallel to the space axis) contains events which occur at the same (simultaneous) time. Thus events that are simultaneous for Galileo are also simultaneous for Albert. Time line (parallel to an observer's time axis) represents events which take place at the same place at different times. Since Galileo's time axis is tilted from Albert's, their time lines are different.

C. QUESTIONS AND EXERCISES FOR GALILEAN RELATIVITY (Einstein and Galileo Galilei are pictured in the video).



1. **Which events on the space-time diagram**

   a. **are simultaneous as viewed by**

      (1) Albert________
      (2) Galileo________

   b. **occurred at the same locations in space as viewed by**

      (1) Albert________
      (2) Galileo________

2. **In what order did events occur for**

   a. Albert________
   b. Galileo________

3. **Draw a Galilean (pre-Einstein) space-time diagram relative to Galileo at rest. (Albert will be moving to the left). Draw the corresponding time and space coordinate lines.**

Plot the events on this diagram which correspond to the data in part A.

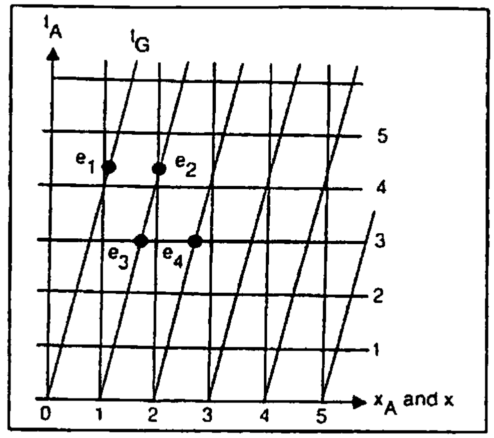
4. **In the Galilean space-time diagram shown for Albert and Galileo:**

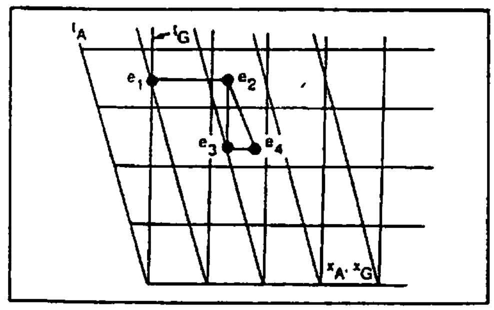
    a. **Which events are simultaneous for Albert? for Galileo?**

    b. **Which events, if any, occur at the same position for Albert? for Galileo?**

    c. **How would the space-time diagram be different if drawn from Galileo's reference frame?**

    d. **In what order did the events occur for Albert? for Galileo?**





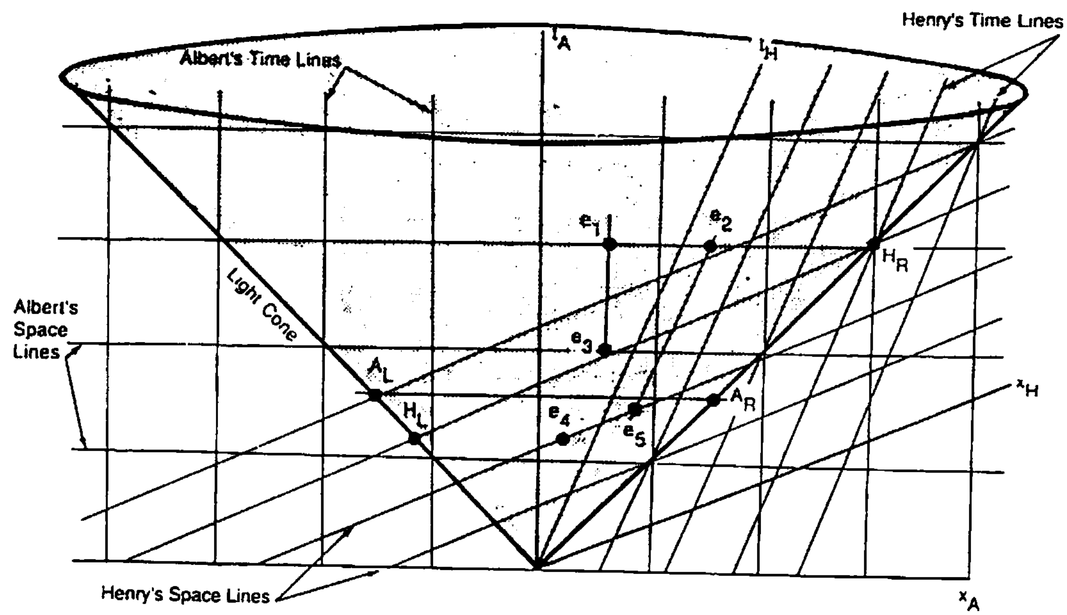
SPECIAL RELATIVITY

In *special relativity* the speed of light is the same for all observers. Relative motion of observers now tilts the time axis (as in Galilean relativity) and the space axis. Thus, events that are simultaneous (on same space coordinate line) in one frame are not simultaneous in the other frame. Note that the light cone bisects the space-time axes for each observer. This is because in such diagrams one always measures distance in light units (light years, light seconds, etc.) so that $c = 1$.

Shown on the diagram below are the light signals which triggered Albert's (A_L,A_R) and Henry's (H_L,H_R) detectors.

Since A_LA_R lie along Albert's space line, they are simultaneous events for Albert. They lie on different space lines for Henry, thus A_R is triggered before A_L for Henry. Since H_L and H_R lie along Henry's space line, they are simultaneous events for Henry. They lie on different space lines for Albert, thus H_L is triggered before H_R for Albert.

Other (e_1 - e_5) events are shown for the exercises below:

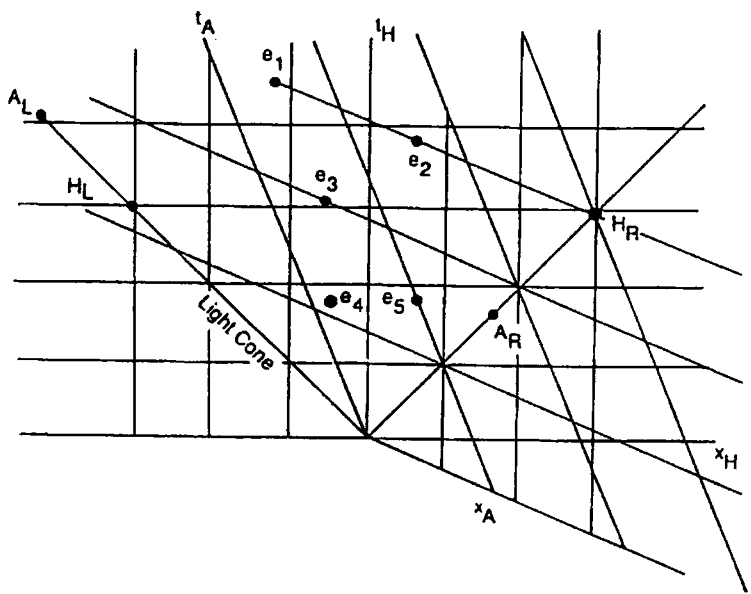


In order for all of these ideas to make sense, you should probably go back and view the video again, confirming for yourself that

(1) the time axis of the person at rest relative to the students is vertical;
(2) the two-dimensional TV world is rotated to make time perpendicular to it;
(3) in Galilean relativity, the x-axis is always horizontal;
(4) with Henry and Albert, Henry's x-axis is slanted to make it parallel to his points of simultaneous time;
(5) the expanding light sphere forms a circle in the plane perpendicular to the time axis;
(6) this expanding circle along the time axis generates the cone in the space-time diagram.

C. **QUESTIONS AND EXERCISES FOR SPECIAL RELATIVITY** (Albert Einstein and Henry Lorentz are shown in the video)

1. **Draw the space-time diagram of the events in the previous example as Henry would draw it, i.e., with Henry's time axis vertical.**



Note that the time axes have been rotated counterclockwise and the space axes have been rotated clockwise and that the light cone again bisects each pair.

2. **Which events in the example above**

   a. **occur simultaneously according to**

      (1) Albert______________
      (2) Henry______________

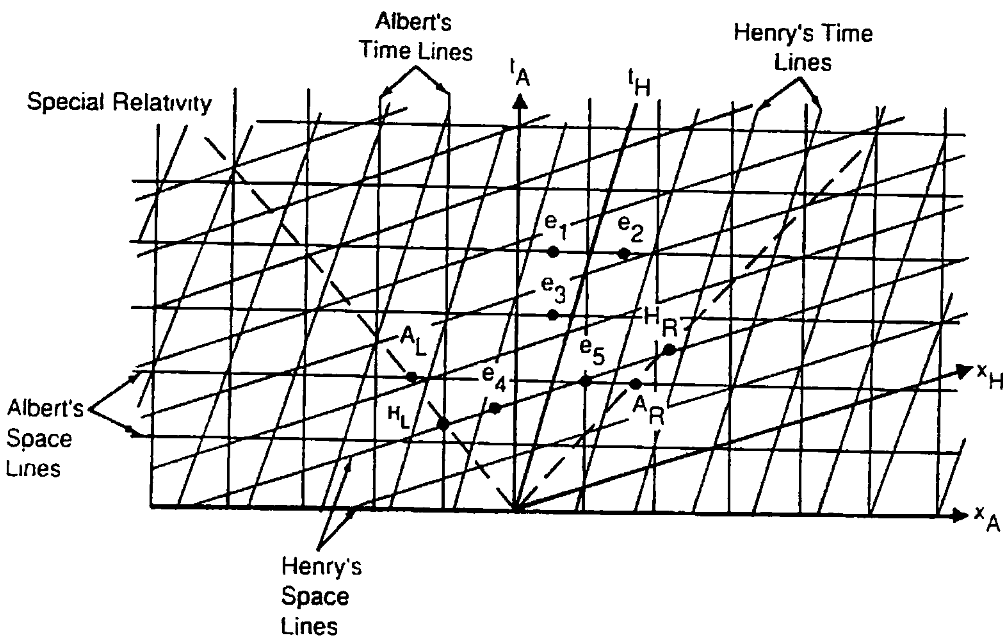
   b. **occur at the same location in space according to**

      (1) Albert______________
      (2) Henry______________

   c. **occur in sequence order for**

      (1) Albert______________
      (2) Henry______________

3. **Given the space-time diagram with events labeled**



a. **Which events are simultaneous for Albert? for Henry?**

b. **Which events, if any, occur at the same position for Albert? for Henry?**

c. **In what order did the events occur for Albert? for Henry?**

d. **Sketch a "ruler" two units long in Henry's reference frame? How does Albert perceive its length?**

IV. TIME DILATION

A. TERMS TO KNOW

time dilation – the effect that a clock moving at relativistic speeds relative to an observer ticks more slowly than a clock at rest.

gamma factor (γ) – the relativistic increment/decrement factor for length, mass, and time. Its value is $1/\sqrt{1 - v^2/c^2}$, where v is the velocity of the object and c is the velocity of light (3×10^8 m/s).

B. BACKGROUND

Derivation of Time Dilation

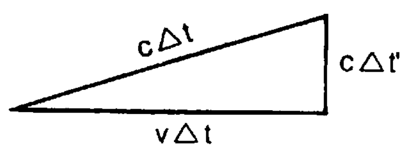
In the video Albert is watching Henry's moving clock.

distance = velocity × time

$c\Delta t$ = the distance Henry's light pulse traveled in one upward movement as viewed by Albert. Notice it is *unprimed.*

$v\Delta t$ = the distance the moving cart traveled in one upward movement of Henry's light pulse as viewed by Albert. Notice it is *unprimed.*

$c\Delta t$ = the distance Henry's light pulse traveled in one upward movement as viewed by Henry in his rest frame. Notice it is *primed.*



According to the Pythagorean theorem, $a^2 + b^2 = c^2$

$$(v\Delta t)^2 + (c\Delta t')^2 = (c\Delta t)^2$$

$$(c\Delta t')^2 = (c\Delta t)^2 - (v\Delta t)^2 \qquad \text{(Rearrange terms)}$$

$$(c\Delta t')^2 = (c^2 - v^2)\,\Delta t^2 \qquad \text{(Group terms)}$$

$$\frac{(c\Delta t')^2}{c^2} = \frac{(c^2 - v^2)\,\Delta t^2}{c^2} \qquad \text{(Divide both sides by } c^2\text{)}$$

$$\Delta t'^2 = (1 - v^2/c^2)\,\Delta t^2$$

$$\Delta t' = \sqrt{1 - v^2/c^2}\;\Delta t \qquad \text{(Take square root of both sides)}$$

$$\Delta t'/\sqrt{1 - v^2/c^2} = \Delta t$$

$$\gamma\Delta t' = \Delta t$$

$$(\gamma = 1/\sqrt{1 - v^2/c^2})$$

Light Clocks vs. Everyday Clocks:

Henry spends his entire time on the moving car, i.e., in an inertial frame. *As in every inertial frame*, his aging processes, the light clock, the lifetime of stationary masses, etc., *all* keep time with a standard atomic clock. Therefore *all* these processes slow down, in Albert's view, by the same factor as the photon clock.

Relativity is Real:

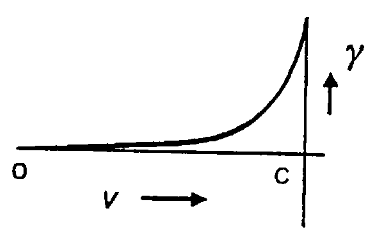
The various predictions of special relativity have been amply verified by experiment – and especially the relativistic mass increase, sometimes by γ-factors of more than 1,000, is an every day occurrence in elementary particle collision experiments. The video shows how time dilation was verified. It is difficult to make macroscopic bodies move at relativistic speeds, and for this reason length contraction has not been, and probably never will be, directly observed. Nevertheless no one doubts the reality of this phenomena.

C. QUESTIONS AND EXERCISES

1. **Many science-fiction stories are based on the concept that, if humans are moving near the speed of light, their biological clock (their heart beat) slows down and consequently their aging process is reduced. What are some of those stories?**

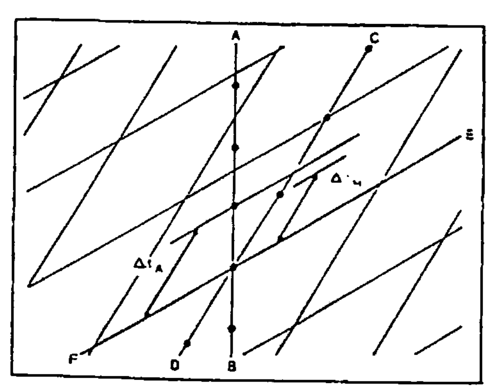
2. **You observe a space alien traveling by the earth at $0.7c$ (7/10 the speed of light). How much time expires on the alien's chronometer during 1 hour of your time?**

3. **Three space ships, A, B, and C, are traveling at the respective speeds of $0.5c$, $0.7c$, and $0.9c$, in the earth's frame of reference. In which ship will the clocks appear in the rest frame to run slowest? Is the difference between the time as indicated by the clocks A and B the same as the difference in time between the clocks B and C? Why?**



4. **Referring to the frame to the right taken from the video:**

   a. **Describe the axis AB, CD, and EF.**
   b. **What do the dots on each axis represent?**
   c. **Who is making the measurement?**
   d. **Which clock is running slower?**



V. LENGTH CONTRACTION

A. TERMS TO KNOW

length contraction – the shrinking of an object along the direction of motion when moving at relativistic speeds, i.e., at more than about 1⁄7 the speed of light (at which speed the shrinkage is one percent).

B. BACKGROUND

Derivation of Length Contraction from Time Dilation:

Consider a ruler whose rest length is l. A clock travels past the ruler and parallel to it with speed v. In the rest frame of the clock the length of the ruler is measured to be l' and the clock registers time $\Delta t'$ for the ruler to move by. Thus, in the rest frame of the clock the speed of the ruler is $v = l'/\Delta t$. In the rest frame of the ruler, the moving clock travels the length of the ruler, l, in time Δt. Hence, the speed of the clock in the rest frame of the ruler is $v = l/\Delta t$. Since the relative velocity between the clock and the ruler must be the same, we get

$$l'/\Delta t' = l/\Delta t\,.$$

By time dilation, $\Delta t' = \Delta t/\gamma$ so that

$$l'/\Delta t/\gamma = l/\Delta t\,,$$

$$l' = l/\gamma = l\sqrt{1 - v^2/c^2}\,.$$

Note that the length contraction occurs only in the direction of travel. The ruler will not become thicker or skinnier.

C. QUESTIONS AND EXERCISES

1. **Consider the ruler described in the derivation above. If the rest length is 1 meter and it is traveling at 0.5c, what will be its length as viewed from the rest frame? How will the rest thickness of the ruler compare to the moving thickness as viewed from the rest frame?**

2. **From the frame of reference of the moving ruler in question (1), what will be the length of a similar ruler in the other frame of reference?**

3. **View the segment on length contraction again. Compare the height of Henry before and after length contraction. You can do this by holding a sheet of paper to the television screen and placing marks on the papers edge at Henry's feet and head. Use the marks to compare Henry's height before and after length contraction. How do the heights compare? Why? Try the heights and lengths of other illustrations like Albert, the clock, the train. Explain your results.**

VI. CONFIRMING EVIDENCE

A. TERMS TO KNOW

microsecond (μs) – 1×10^{-6} s.

muon – an elementary radioactive particle created when cosmic rays crash into the upper atmosphere. It has a half-life of 1.5 microseconds in its rest frame.

B. BACKGROUND

Evidence of time dilation is that atomic clocks have been placed in airplanes and flown for a period of time. The moving clock did indeed run slower than a similar clock at rest on the earth.

High energy accelerators can move atomic particles to speeds near the speed of light. The equipment must be designed in order that relativistic effects of space and time be taken into consideration.

The verification of time dilation is taken from a film sponsored by the Physical Science Study Committee for use in the Advanced Topics segment of their curriculum. Elaboration that could add to the appreciation of this section might include the following:

1. Muons are radioactive particles created by cosmic rays smashing into the upper atmosphere. They decay randomly into a positron (e^+) and an antineutrino ($\bar{\nu}$). A decay is recorded as a blip of light on the oscilloscope screen.

2. Each horizontal division on the oscilloscope screen represents one microsecond of time (1×10^{-6} s).

3. Only muons with speed of $0.995c$ are stopped in the detector and allowed to "sit around" until they decay. Muons with less speed are stopped in the iron above the detector. Muons with greater speed pass through the detector to Mount Washington below.

   speed of light (c) = 9.83×10^8 ft/s

   $v = 0.995c \times (9.83 \times 10^8 \text{ ft/s})/c = 9.78 \times 10^8$ ft/s

4. If a muon with this speed moves for one microsecond, it traverses a distance $d = vt = 9.78 \times 10^8 \text{ ft/s} \times 1 \times 10^{-6} \text{ s} = 978$ ft.

5. Mount Washington is roughly 6300 ft high. The scientists counted 568 muons on the top of the mountain. Based on the average life span of a muon in the rest frame, the scientists calculated that 27 should reach the bottom of the mountain. Twenty-seven of the 568 would survive the 6.4 microseconds required to traverse the 6300 feet. (6300 ft/(978ft/μs) = 6.4 μs.)

C. QUESTIONS AND EXERCISES

When they took the equipment to sea level, 412 muons were counted in a one-hour period. Clearly, moving clocks do not keep time at the same rate as stationary clocks, or distances are not the same in a fixed or moving frame. Thus we can analyze the results from either frame.

1. Earth Frame

Distance (height of mountain) = 6300 ft
Muon traveling at $v = 0.995c$

$\gamma = 1/\sqrt{1-v^2/c^2} = 1/\sqrt{1-(0.995\,c)^2/c^2} = 10$

Time for half the muons (½ of 568 = 284) to decay = $10 \times 1.5\,\mu s = 15\,\mu s$.

Distance covered in 15 μs before half of muons (284) decayed = $vt = 9.78 \times 10^8 \text{ ft/s} \times 15 \times 10^{-6}\text{s} = 14670$ ft.

No wonder 412 of the muons survived to sea level, since the mountain is only 6300 feet high.

2. **Muon Frame**

Time (one half-life) = 1.5 μs.
earth coming up at 0.995 c

$\gamma = 1/\sqrt{1-v^2/c^2} = 1/\sqrt{1-(0.995c)^2/c^2} = 10$

Distance contraction: L/γ = 6300 ft/10 = 630 ft. Note: This is the height of the mountain as the mountain goes by the muon that is at rest.

Distance covered in 1.5 μs before half of muons decayed = 9.78×10^8 ft/s $\times 1.5 \times 10^{-6}$ s = 1467 ft.

Most of the muons (412) would be hit by the moving earth.

3. **Half-Life**

The concept of half-life implies that on the average, half of the muons will decay in 1.5 microseconds (1.5×10^{-6} s). Complete the chart to determine why approximately 27 were expected to remain after 6.4 microseconds.

Number of muons _____ at time = 0
Number of muons _____ at time = 1.5 microseconds
Number of muons _____ at time = 3.0 microseconds
Number of muons _____ at time = 4.5 microseconds
Number of muons _____ at time = 6.0 microseconds
Number of muons _____ at time = 7.5 microseconds

VII. MASS INCREASE

A. TERMS TO KNOW

mass increase – the effect that the mass of an object is greater when moving at relativistic speeds relative to an observer than when it is at rest.

conservation of momentum – a statement representing the fact that the sum total of momenta of all parts of a system remains constant if no outside forces act on the system.

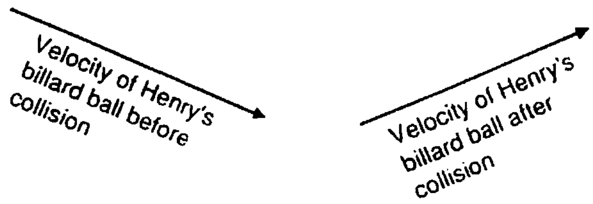
B. BACKGROUND

The understanding of this section of the video depends heavily on your use of the conservation of momentum. The scene is first viewed by an outside observer with both Henry and Albert moving at the same speed. The mass of the two billiard balls must be the same for momentum to be conserved. Momentum must also be conserved when viewed from Albert's frame. The mass of Henry's billiard ball must be increased in comparison with Albert's for Albert's observed effect to be measured. Note in the video that even though the volume of the moving ball is smaller, its mass increases.

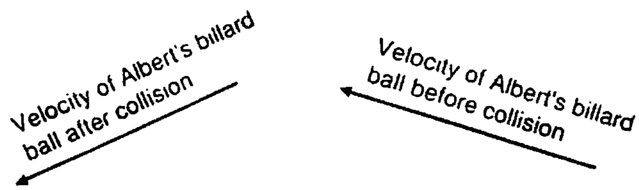
C. QUESTIONS AND EXERCISES

1. **Albert and Henry are both moving as seen by an outside observer. Complete the vector diagram by determining the change in velocity of each billiard ball.**

(a)

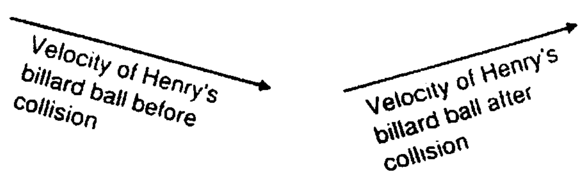


(b)

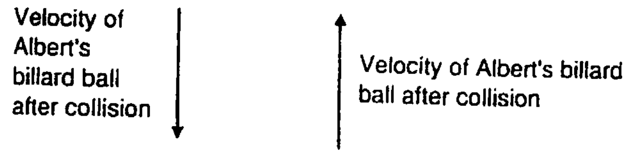


2. **Albert is at rest and Henry's space ship is moving. Complete the vector diagram by determining the change in velocity of each billiard ball.**

(a)



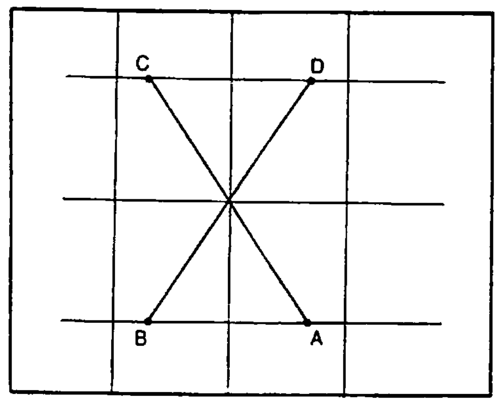
(b)



3. a. **Identify and label what took place at each label in this frame taken from the space billiards section of the film.**

   b. **Draw a labeled momentum vector diagram corresponding to labels.**

   c. **Show from your vectors in b that momentum was conserved in the collision.**



VIII. CONCLUSION

The following problem is given as an illustration of the consequences of Einstein's postulates to length contraction, mass increase, and simultaneity.

1. **Length Contraction**

   Billy is a 50 kilogram pole vaulter for a winning track team. Billy has a problem. He doesn't want his new 5-meter pole to get wet out in the rain, but his father won't let him keep it in the garage. This is mainly because the garage is only 3 meters long. The coach has a solution. If Billy could only run into the garage at $v = 0.8c$, the pole would be shortened to 3 meters. The coach knew that when Billy stopped it would go back up to 5 meters again, but he figured he could close the garage door in time, and he hoped the pole would bend rather than break once it got in. Besides, the advantages of having somebody on the team who could run that fast far outweighed the possible broken pole. Perform the calculation to show this length contraction.

$$L' = \sqrt{1 - v^2/c^2} \times L \qquad L' = 5\text{ m}$$

$$L' = \sqrt{1 - (0.8c)^2/c^2} \times 5\text{ m}$$

$$L' = \sqrt{1 - 0.64c^2/c^2} \times 5\text{ m}$$

$$L' = \sqrt{0.36} \times 5\text{ m} \qquad L' = 0.6 \times 5\text{ m} = 3\text{ m}$$

2. **Mass Increase**

After a bit of training, Billy's speed finally got up to 0.8c. His mass increased as measured by other observers at rest. Perform the calculation to show his increase in mass. Suppose his rest mass is 50 kg.

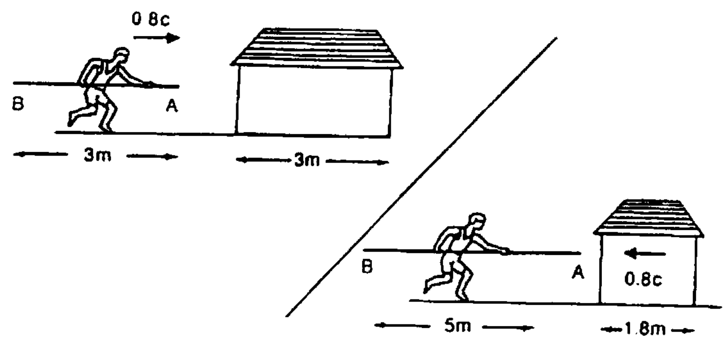
$$m' = \frac{m}{\sqrt{1 - v^2/c^2}}$$

$$m' = \frac{50\text{ kg}}{\sqrt{1 - (0.8c)^2/c^2}}$$

$$m' = \frac{50\text{ kg}}{\sqrt{1 - 0.64}}$$

$$m' = \frac{50\text{ kg}}{\sqrt{0.36}}$$

$$m' = 83.3\text{ kg}$$



The big day came, Billy's speed got up to 0.8c, he got the pole in the garage, and the coach closed the door. Afterwards Billy looked rather stunned. When asked why, he said, "Here I was carrying this 5-meter pole looking at a garage that was only 1.8 meters long! It was worse than before!" The coach recalculated and decided Billy's statement of a 5-meter pole and a 1.8-meter garage was true and his original plan was okay, too. Billy got the pole in the garage. We shall presently see why.

3. **Simultaneity**

Simultaneity is relative to the observer. Two events that are simultaneous in one reference frame may not be simultaneous in another reference frame.

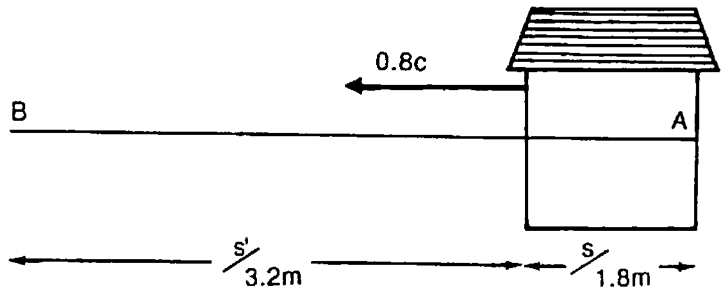
a. **In the garage frame of reference, where is Point B when Point A hits the back wall of the garage?**

b. **In the pole vaulter's frame of reference, where is Point B when Point A is in first contact with the back wall of the garage?**

4. **Postulates**

Remember that Einstein states as one of his postulates that there is no preferred reference frame, so only relative motion matters. If the pole vaulter is in motion and the garage is at rest and the pole fits in the garage so the door can be closed, the same must be true if the garage is in motion and the pole vaulter is at rest.

a. **Perform the necessary calculation to show that, with the garage moving and the pole vaulter at rest, the pole will get into the garage.**



Let's analyze the figure above. At t_0 in the pole vaulter frame, Point A is hit by a very fast moving garage wall. However, an observer at Point B on the pole has no knowledge of this at t_0. He can't see or feel the collision (event) until a later time, $t_0 + \Delta t$, where Δt is the time it takes for a light wave or a shock wave along the pole to reach him. No information travels faster than the speed of light (c) so:

$\Delta t = l/c = 5.0\ m/c$

$v = 0.8 \times c$

b. **How far can Point B travel in that time? (or more appropriately asked, "How far does the garage door travel in that time?")**

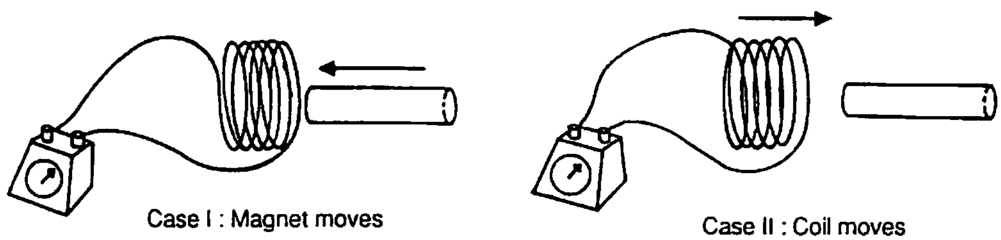
ADDITIONAL RESOURCES

Demonstration #1: Moving Magnet vs. Moving Loop

Purpose: To show how two separate laws of classical physics are required to explain two variations of a simple experiment and then to suggest how Einstein's theory of relativity treats the same experiments. (This demonstration can be used only after the students have been introduced to electromagnetism.)

Materials: A coil of wire, a demonstration galvanometer, and a bar magnet.

Procedure and Notes: Connect the coil of wire to the galvanometer as illustrated.



The coil of wire should have enough turns to produce a sizeable deflection when the bar magnet is passed through it. Approximately the same deflection, hence the same emf, should be produced in either of the following two cases:

1. The coil is held still and the magnet is moved through it.

2. The magnet is held still and the coil is passed over it.

Explanation: The important point of this demonstration is that, while it appears to be the same experiment, two separate explanations were required prior to Einstein's theory.

Case 1: Since the charges in the wire do *not* move, the induced emf can only be explained by a changing magnetic flux, *viz.* by using Faraday's law.

Case 2: The charges *are* moving relative to the magnet; hence, we can say the emf is produced by forces on these moving charges. In other words, the Lorentz force law $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$ is used to calculate the force which produces the emf.

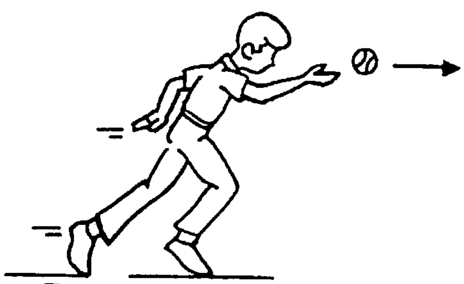
Suppose Henry performs experiment 1 on his car, and suppose v is numerically equal to the velocity of this car in Albert's frame. Experiment II is simply the view of this experiment from Albert's frame, who must see the galvanometer indicate the same current. By the relativity postulate, if *Henry* performed experiment 2 on his car, he also must therefore get the same answer. We see that according to the relativity postulate only the *relative* uniform motions in our experiment count.

Demonstration #2: Relative Speed of a Ball vs. the Relative Speed of Light

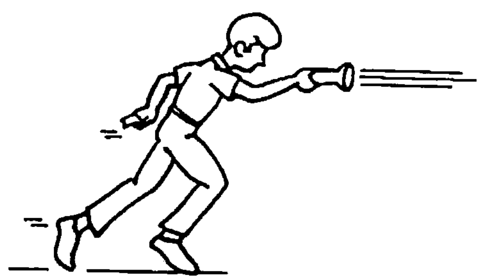
Purpose: To stress that the speed of light is the same from all frames of reference.

Materials: A flashlight and a ball.

Procedure and Notes: First stand still and toss a ball in a horizontal direction. Repeat tossing the ball in a horizontal direction, only this time while you are walking along.



Toss a ball
while moving along.



Shine a flashlight
while moving along.

Discuss the velocity of the ball relative to the class in these two instances. Now turn on a flashlight while standing still. Repeat, only this time turn on the flashlight while you are walking along. Discuss the motion of the light beam both relative to you and relative to the class.

Explanation: With the ball you can assert that the sum of your velocity relative to the class and the ball's velocity relative to you will equal the ball's velocity relative to the class.

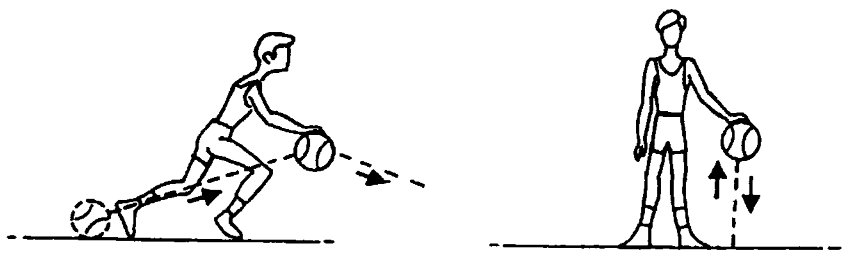
Emphasize that in *all* situations the speed of light relative to any observer is the same. Even if you could move at near the speed of light, you would still see the light beam moving away from you at the speed of light. The class *also* would see the light beam moving at the speed of light. Emphasize also that if you could walk faster and faster and could throw the ball faster and faster, ultimately its speed relative to the class would *not* just be the sum of your speed and its speed relative to you, e.g., if each were $\frac{3}{4}$ c, it would be $(\frac{3}{4}c + \frac{3}{4}c)/[1 + (\frac{3}{4})^2] = 0.96\,c$.

Emphasize the apparent contradiction in the comparison of the ball and the light. Discuss the measurements that need to be made by each observer (distance and time) to determine velocity.

Demonstration #3: Basketball Light Clock Model

Purpose: To provide a concrete example of the light clock concept.

Materials: Two basket balls and two agile and coordinated students.



Procedure and Notes: The two students are to practice bouncing the basketball from the same height so that the time of bouncing is fairly synchronized. Now one of the students will walk while bouncing the ball, still from the same height while the other student continues to bounce the ball while standing still. The moving ball "should" take longer to bounce if the height of bouncing is the same. The purpose here is to have the class see that since the ball moves a greater distance it should take a longer time. *However*, problems related to projectile motion and the horizontal component of the basketball's motion will introduce problems with this analogy.

Now discuss what would happen in this experiment if for some reason the basketball always had to move at the same speed. Hopefully the students will come to realize that with this peculiar constraint the moving student would surely require a longer time to dribble the ball. The second postulate of special relativity places such a peculiar constraint on light hence the moving light clock always will run slower to an observer when compared to an identical light clock which is stationary in his/her frame of reference.

Demonstration #4: A Conceptual Demonstration of Relativistic Length, Mass, and Time Effects

Purpose: To test student conceptions of relativistic effects. This demonstration could be used both before and after showing the video.

Materials: A meter stick and two other sticks, one obviously longer than one meter and the other obviously shorter. A kilogram mass and two other masses, one obviously larger and one obviously smaller. If convenient, a device which produces a second time interval and two others, one longer than a second time interval and one shorter. The devices could be metronomes, pendula of different lengths, or perhaps some sort of electronic clocks.

Procedure and Notes: The general idea behind this demonstration is to have students answer questions about length, mass, and time as viewed from different frames of reference. It will be the teacher's job to specify clearly who is the observer in each situation. It will be the class' job to select which ruler, mass, or clock represents correctly what the specified observer will "see."

Example #1: The teacher walks across the room holding the meter stick. The question is: "Which of the three sticks will represent what the class will observe if I am moving near the speed of light?" If this is done as a pre video exercise, the students will probably assert that they will see the same meter stick. After the video we hope they will select the shorter stick.

Example #2: Again the teacher moves across the room pretending to carry a meter stick in his/her hand. The question is: "I am still carrying a meter stick. Which of the three sticks correctly represents what I will now see as I move along?" The correct answer is the real meter stick and this might be the answer given before the video but maybe not after the video has been seen. It must be stressed that, if there is no relative motion between observer and the meterstick, no change will be observed.

Example #3: Again the teacher walks across the room, only this time a member of the class holds the true meterstick. The teacher asks: "Which stick represents what I would see if I were moving near the speed of light and I looked at you?" The correct answer is the short stick.

These exercises should help the student to learn that, when there is no relative motion, no change is observed. If there is relative motion, the observed change is always in the same direction. In the case of length, the meterstick in motion will always appear shorter.

The above examples can be extended to mass and time. In all cases the observer will report that mass, length, or time will be unchanged if it does not move relative to him/her. The same observer will report that length is contracted, time intervals are dilated, and masses will increase if the objects are moving relative to him/her.

Also walk with a meter stick held at *right* angles to the direction of motion, and point out it represents a meter to *both* observers.

Demonstration #5: Momentum Conservation in Simple Collisions

Purpose:

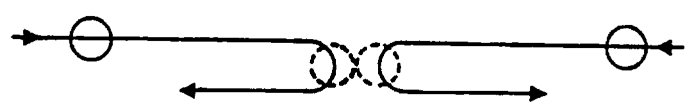
To review simple two-dimensional collisions in order to help students understand the relativistic mass increase in the "space billiards" game.

Materials:

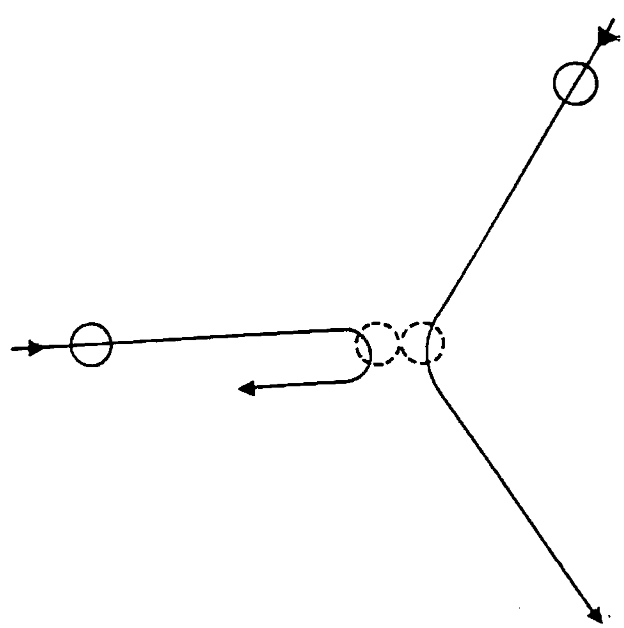
Two balls of the same mass and a third ball of about the same volume but of a different mass. Two tennis balls and a pool ball will work. Larger balls (a bowling ball and two soccer balls) might be easier to see and to manipulate.

Procedure and Notes:

This demonstration is probably best performed on the floor in a place where all students can view the action from above. First perform the following with two *equal* mass balls.



Practice several times rolling the balls at one another with the same speed in opposite direction and after the collision they should return with equal and opposite velocities.



Now roll one ball in at a much larger velocity but with a component in the direction of the original collision equal to the previous situation. Try to arrange collisions such that the high velocity ball is deflected symmetrically by the ball which was fired up in the straight line case (see illustration).

This will probably require some practice before a symmetric collision will be obtained in which the high velocity ball will be deflected with equal angles and the low velocity ball will be returned in the same line at about the same speed.

Next perform the same two collisions using balls of unequal mass. If the ball of larger mass is given the high velocity in case II the situation is analogous to the "space billiard" game in the video.

Explanation:

Although a review of collisions at an angle may not be required, this demonstration should help students to focus on the concepts involved in the "space billiards" game. Here we are using a different mass ball to illustrate what happens at velocities near the speed of light. In order to explain actual experiments with colliding particles moving near the speed of light, the conservation of mv necessitates that m be increased in order to account for the momentum transferred at the measured velocity. Einstein postulated that the laws of physics must be true in all inertial frames and since more momentum is transferred than could be accounted for by the higher velocity above, mass must also increase. Einstein predicted that the mass increases and such increase has been repeatedly observed in high velocity experiments.

EVALUATION QUESTIONS

1. **Einstein's *postulate* that concerns the *speed of light* is that**

    A. rulers and clocks cannot be used to measure the speed of light.
    B. nothing can travel faster than the speed of light.
    C. all uniformly moving observers measure the same speed of light.
    D. the speed of light is defined as 3×10^8 m/s.

2. **Several possible *consequences* of Einstein's special theory of relativity are suggested below:**

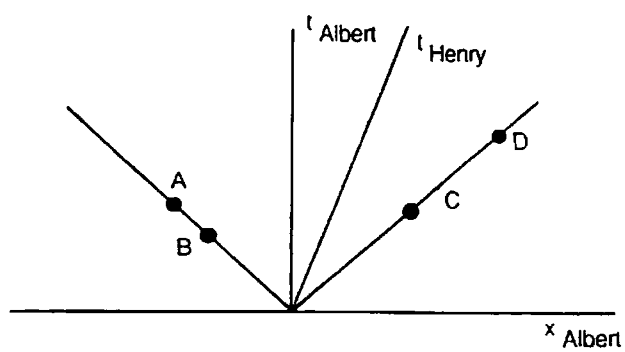
    I. The laws of physics are the same in all inertial frames of reference.
    II. It is impossible to tell if you are moving uniformly.
    III. It is impossible to go faster than the speed of light.
    IV. The speed of light in free space is the same to any observer regardless of his/her motion.

    Which of the above are consequences (not postulates) of the special theory of relativity?

    A. I and II
    B. I and III
    C. II and III
    D. III and IV

Refer to the diagram for Questions 3-4.

A, B, C, and D are events marked on a space-time diagram.



3. **Which events occur simultaneously for Albert?**

    A. A and D
    B. B and D
    C. Both A and B, and C and D
    D. A and C

4. Consider the diagram to be drawn to scale. How does Henry's speed compare to the speed of light?

A. Henry is at rest.
B. Slower
C. Same
D. Faster

5. If a meter stick moves to your right at a constant velocity of 0.8 c, what would you measure its length to be?

A. 0.4 m
B. 0.6 m
C. 0.8 m
D. 1.0 m

6. The meter stick is now oriented vertically but still continues to move to the right at a velocity of 0.8c. What length would you now measure the meter stick to be?

A. 0.6 m
B. 0.8 m
C. 1.0 m
D. 1.4 m

7. Albert views Henry moving by at constant velocity. Henry has a light clock and also a stop watch which were synchronized when at rest. As Albert views these two moving clocks, which of these statements would be true according to Albert?

A. The light clock runs slow compared to the stop watch.
B. The stop watch runs slow compared to the light clock.
C. The two are still synchronized but run fast.
D. The two are still synchronized but run slow.

8. Albert is on the earth and measures the speed of light from the sun as 3×10^8 m/s. He then gets in a space ship and speeds *toward* the sun at 1×10^8 m/s. He will measure the speed of light as

A. 2×10^8 m/s.
B. 3×10^8 m/s.
C. 4×10^8 m/s.
D. None of the above

9. 568 muons were counted by a detector on the top of Mount Washington in a one hour period of time. Assuming moving muons keep time at the same rate as stationary muons, then 27 should survive until sea level. The fact that 412 muons were detected by the same equipment at sea level reveals that

A. the stationary clock measures time differently at different altitudes.
B. the moving clocks keep time at the same rate as stationary clocks.
C. that moving clocks run slower.
D. that moving clocks run faster.

10. In the game of space billiards with Albert at rest, Henry's space ball changes vertical velocity less than Albert's. Albert believes in the conservation of momentum, so he believes for momentum to be conserved,

A. the collision must be elastic.
B. the mass of Henry's space ball must be less than his.
C. the mass of Henry's space ball must be equal to his.
D. the mass of Henry's space ball must be greater than his.

ESSAY QUESTIONS

11. Assume you live in a Einsteinian universe with the speed of light being only 60 km/hr. First you see a bicyclist at rest and later you see the same cyclist moving at 55 km/hr. Describe quantities that would change and those that would not.

12. How can two observers ascribe a different time ordering to two events, i.e., event A is *before* event B for Albert, but *after* event B for Henry?

KEY

1. C
2. C
3. D
4. B
5. B
6. C
7. D
8. B
9. C
10. D

SUGGESTED ESSAY RESPONSES

11. At low velocity (less than about 5 km/hr) everything would appear normal (that is, as the world exists at relative rest). When the bicyclist was moving at 55 km/hr, he/she and the bike would be contracted in the direction of motion. The perceived mass would also be greater. For example, if the bicyclist collided with a parked car, the car would suffer significant damage since the bike and rider have increased in mass. Even though there is contraction in the direction of motion, there would not be contraction in other dimensions. Height, for example, would not change. The watch on the cyclist's wrist would run slow. These are all observations.

12. Draw and label a Space-Time Diagram for two observers moving at 0.6c relative to each other. Carefully label the axes. Denote two events that would be simultaneous in one frame and two that would be simultaneous in the other frames