THE MECHANICAL UNIVERSE

High School Adaptation

QUAD VI

MAGNETISM AND BEYOND

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High School Adaptation

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

QUAD VI

MAGNETISM AND BEYOND

Magnetic Fields
Electromagnetic Induction
Alternating Current
The Michelson-Morley Experiment

An Annenberg/CPB Project

National Science Foundation

Materials Development Council

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The Mechanical Universe, from which these materials have been adapted, is funded by a grant from the Annenberg/CPB Project and is a production of the California Institute of Technology and the Southern California Consortium.

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This material is based upon work supported by the National Science Foundation under Grant No.SPE-8318420, MDR-8550178, MDR-8652023, and MDR-8751537. It was excerpted from the college television course, **The Mechanical Universe**, and re-edited specifically for use in the high school curriculum. **The Mechanical Universe** is funded by The Annenberg/CPB Project.

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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Lynn Strech, Artist
Judy Sullivan, Southern California Consortium, Design and typesetting

Finally, we offer special thanks to Mary Kohlerman of the National Science Foundation.

Materials Development Council
Irving, Texas
July 1989

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 VI

MAGNETIC FIELDS

HOW DO MAGNETS AND MAGNETIC FORCES BEHAVE? The video examines these questions and others. Properties of magnets are discussed and magnetic lines of flux described. The interaction between a magnetic field and magnetic lines of flux are described. The interaction between a magnetic field and a moving charge is also examined. The contributions of Gilbert, Oersted, and Ampere are woven into this video. Emphasis is given to the discovery of the earth's magnetism, the aurora, and the Van Allen belts.
Running time: 17:29

ELECTROMAGNETIC INDUCTION

HOW DOES A MAGNETIC FIELD PRODUCE AN ELECTRICAL CURRENT? In 1829 Oersted discovered an electric current produces a magnetic field. This discovery led Michael Faraday on a search to find a mechanism that would cause a magnetic field to produce an electrical current. This video focuses on Faraday's law that relates induced electric fields and changing magnetic flux. The computer graphics used to portray magnetic forces, fields, and current loops help students form a mental picture of these unseen physical occurrences.
Running Time: 9:11

ALTERNATING CURRENT

WHY TRANSMIT ELECTRIC POWER USING ALTERNATING RATHER THAN DIRECT CURRENT? This video introduces alternating current and develops the rationale of using it for electric power transmission. The development includes the history of the famous dispute between Thomas Edison, the proponent of direct current, and Nikola Tesla, the proponent of alternating current. The principles behind a transformer and the importance of such a device in the transport of electric power are also discussed.
Running time: 10:09

THE MICHELSON-MORLEY EXPERIMENT

HOW WAS THE AETHER SHOWN TO BE NONEXISTENT? The stationary aether--the medium through which light was thought to travel in space--was every bit as important to nineteenth century scientists as the stationary earth was to the Aristotelians before Copernicus. Discarding the aether theory was not small step. The video describes how two American scientists, Michelson and Morley, performed their experiment to detect the aether and the implications of their result.
Running time: 15:31

TEACHER'S GUIDE TO MAGNETIC FIELDS

CONTENT AND USE OF THE VIDEO - The video provides an excellent introduction to magnetism. Properties of magnets are discussed and magnetic lines of flux described. The interaction between a magnetic field and a moving charge is examined. The contributions of Elizabethan England's most famous scientist, William Gilbert, are woven into this video as are those of the Dane, Hans Christian Oersted, and the Frenchman, Andre Marie Ampere. Emphasis is given to the discovery of the earth's magnetism, the aurora, and the Van Allen belts.

The video assumes some knowledge of currents. The concept of forces on charges moving in a uniform magnetic field is developed. These ideas need to be amplified and extended, however, through the use of other materials to enable students to understand the equations used in determining magnetic fields and/or forces on electric currents.

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.

aurora--the northern and southern lights; a glow in the sky near the earth's magnetic poles that are produced by charged particles from the sun.

magnetic dipole--two magnetic poles, north and south, separated by a distance; a bar magnet is an example of a magnetic dipole.

magnetic field--an alteration of space surrounding a magnet or current that will exert a force on another magnet or on moving charges.

solar wind--a stream of charged particles, mostly protons and electrons ejected from the sun.

Van Allen belts--regions surrounding the earth in which charged particles mostly from the sun, are trapped by the earth's magnetic field.

magnetic flux--the total number of magnetic lines of force passing through a surface.

WHAT TO EMPHASIZE AND HOW TO DO IT - Anyone who has ever played with magnets is intrigued by their ability to exert force at a distance. The interest of the scientist leads to questions. How do magnets behave? What factors determine a magnet's force? The video examines these questions and others. In William Gilbert's pursuit of an understanding of magnetism can be found the beginnings of seventeenth century experimental science. He offered data and experiments to confirm observations; he organized his observations into connected phenomena; and he provided a starting point for scientists of the next century. Galileo, the master experimentalist of his age, held Gilbert's work in great esteem.

Objective 1: Describe the basic properties of magnets.

The video depicts the attractive force between unlike poles and the repulsive force between like poles. The formation of two smaller magnets is shown when a larger magnet is cut in half.

Prior to viewing the video, DEMONSTRATION #1 on the basic properties of magnets could be used to focus student attention. Discuss why magnets attract some objects and not others. Students could be presented with the challenge of determining which of two identical iron bars is magnetic, given no other materials than the bars themselves. If no solution is forthcoming, wait until after the video to readdress the problem. Students should then realize that, if the end of one bar picks up the other at the center, the first bar is a magnet.

DEMONSTRATION #2 on the nature of a magnet offers an opportunity to assess whether students can apply concepts addressed in the video. This demonstration provides a novel approach that can be extended to a lab.

In investigating the force between magnets, the video presents a mathematical description of the force between magnetic monopoles:

$$F_m = K_m \frac{p_1 p_2}{r^2} \hat{r} \ .$$

Be sure that students do not think of the poles as + and − charges. The interaction is not between electrostatic fields but, rather, between magnetic fields. Since no actual monopoles have been found, this equation is rarely used. However, it is introduced here to stress its similarity to Coulomb's law and the universal law of gravitation. The SUPPORTIVE BACKGROUND INFORMATION section gives further consideration to the mathematics of magnetism. The video does not explore the effect of heat on a magnet, nor is mention made of the domain theory.

Objective 2: Sketch the magnetic field patterns associated with

(a) bar magnets,
(b) the earth,
(c) straight current-carrying wires,
(d) parallel current-carrying wires.

Magnetic fields for all of the above are depicted in the video. It may be helpful to stop the video at each situation and allow students time to sketch the patterns. DEMONSTRATION #3 on magnetic fields will also help the students to visualize the various patterns. The fields for a single wire loop, solenoids, and toroids are also shown. You may wish to include these here.

Magnetic fields have numerous applications, some of which are discussed in the section on EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS.

Objective 3: Describe phenomena associated with the earth's magnetic field.

The video includes a discussion of the auroras and the Van Allen belts which result from the interaction of the solar wind and the earth's magnetic field. Since students are so fascinated by these phenomena, a replay of this section of the video may be desirable. The SUPPORTIVE BACKGROUND INFORMATION develops the magnetism of earth and sun more fully.

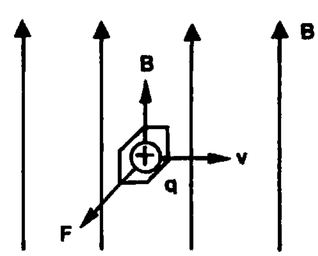
In discussing the earth's magnetic field, you may wish to introduce another phenomenon associated with induced magnetism: The steel in submarine hulls tends to become permanently magnetized by the earth's field as they lie in place during the long period of construction. Unless degaussed by having large electric currents flow through cables wrapped around them during their preparation for sea, the subs would announce their presence magnetically to a possible adversary. The sub's field must be neutralized in all three components: forward and aft, port to starboard, and top to bottom. Underwater electronic test equipment measures any residual magnetism prior to sending the sub to sea.

Students and most other people are often confused about the naming of the N and S poles on the earth. The idea that the earth's S magnetic pole could be located in Northern Canada seems illogical. The problem stems from a convention established by none other than Benjamin Franklin. He said that, if one looks at a compass, the end of the small freely-moving magnetic needle that points in a northerly direction is its N pole. Since unlike poles of a magnet attract, the N pole of a compass must point to the earth's S magnetic pole, which is in Northern Canada. By convention the earth's magnetic field external to the earth is said to be in a direction from a N pole to a S pole. This means that the magnetic field which affects all compass needles is in the direction northward from the Antarctic toward Northern Canada.

Objective 4: Describe the interaction between a magnetic field and a moving charge.

The fact that moving charged particles are deflected by a magnetic field is shown in the video. The force **F** exerted on a charge q moving at velocity **v** in a magnetic field **B** is given by $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$. **F** is perpendicular to both **v** and **B** as illustrated below. DEMONSTRATION #4 may be used to examine this concept more closely. The direction on the force is described by the right-hand-rule: To find the direction of the force F on a charge q moving with velocity v, place the fingers of your right hand in the direction of **v** then curl your fingers in the direction of the magnetic field **B**. Your thumb will be pointing in the direction of F. Be sure that your students are able to use the right-hand-rule to determine the direction of the force on a moving charge in a uniform magnetic field.

If your book uses the left-hand rule for electron flow and the motion of negative charges, point out that the right-hand rule is the analogous situation for conventional current flow and the motion of positive charges.



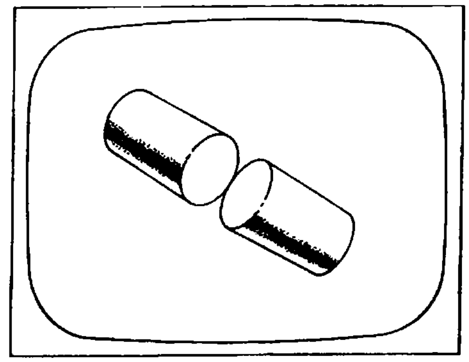
When a charged particle enters a magnetic field parallel to the field lines, it experiences no force and passes through undeflected. A charged particle which enters the field perpendicular to the field lines will experience a force that will move it in a circular path. Charged particles which enter at any other angle are moved in a helix (spiral). These motions account for the capture of charged particles in the earth's Van Allen belts, which is depicted in the video. Unlike electric fields, magnetic fields do not speed up charged particles, but only change their direction of motion.

The SUPPORTIVE BACKGROUND INFORMATION discusses the contribution of Oersted and Ampere to an understanding of magnetism and electricity.

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.

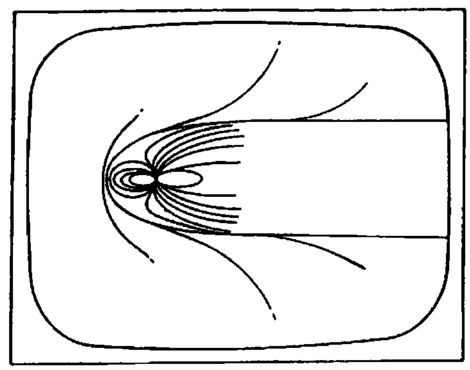
What happens when a bar magnet is cut in two between its poles?

Each one becomes a bar magnet, having its own N and S poles. No isolated magnetic monopoles have been observed.



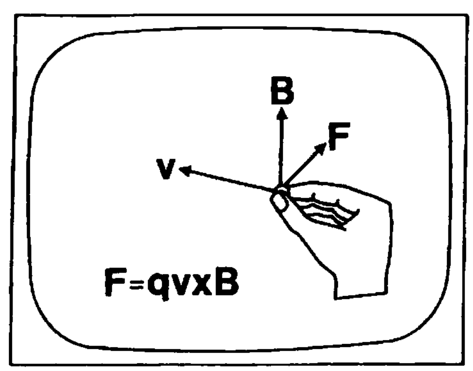
Is the earth's magnetic field in space like that of a simple dipole?

No. The solar wind compresses the earth's magnetic field in the direction toward the sun and stretches it out on the side away from the sun.



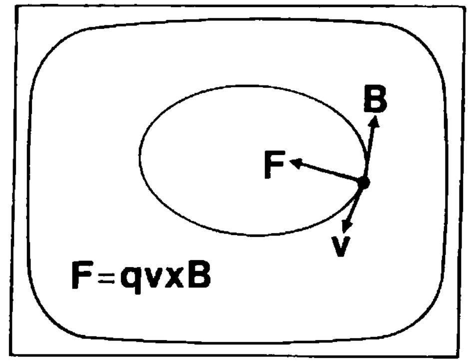
A charged particle will experience a force due to a magnetic field if two conditions are met. What are they?

Relative to the field, the charge must be in motion and this motion must be in a direction that has a component perpendicular to the magnetic field.

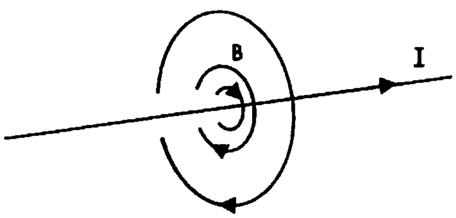


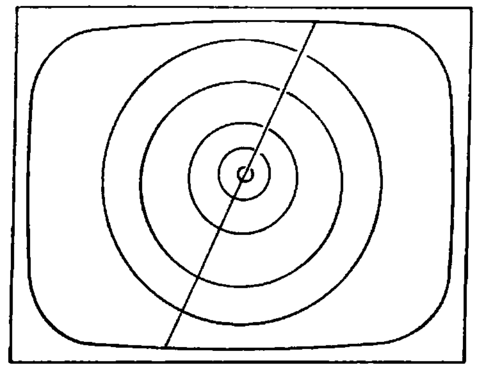
If a charged particle has an initial velocity perpendicular to a magnetic field, describe the path along which it will move.

It will move in a circular path.



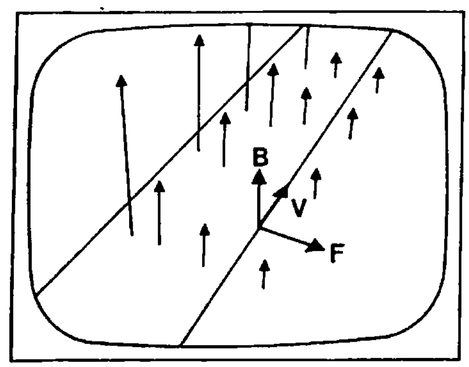
Sketch the magnetic lines of force about a long straight wire carrying a current.





What would be the direction of the force on two long straight parallel wires each carrying a current in opposite directions?

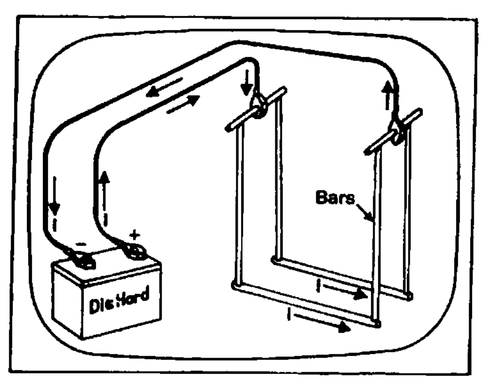
The wires would repel.



In the video notice that the wires to the battery move apart while the bars move together. Why does this happen?

Note to students: The video does not show the electrical connections for this apparatus. Ask your teacher to sketch it on the board if you have difficulty visualizing it.

The current in the wires are in opposite directions. Their magnetic fields result in forces which cause the wires to repel. The current in the bars are in the same direction and thus their magnetic fields result in forces which cause the bars to attract. (A detailed explanation is found in the SUPPORTIVE BACKGROUND INFORMATION section.)



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. **If the north pole of a compass needle points "north," what pole of the earth is actually in the Arctic region?**

   A magnetic south pole is in the Arctic region.

2. **During space shuttle operations, astronauts stay beneath the Van Allen belts. Why?**

   The belts trap radiation from the sun and stars; regions beneath the belts are much less dangerous. Cosmic rays and the solar wind, which contain high-speed charged particles, are deflected by the earth's magnetic field as they near the earth. Positive and negative particles curved in opposite directions at all places other than the vicinity of the magnetic poles. The earth is thus protected to some extent from this radiation which can damage living things. During the periods when the earth's magnetic field is changing direction, the earth undoubtedly experiences a marked increase in the radiation it receives from space. These periods may be related to the past periods of extinction of certain species.

3. **When a beam of charged particles enters a region of a uniform magnetic field with its velocity perpendicular to the field, its velocity changes but not its speed. Explain.**

   The force is always at right angles to the velocity vector. This means no work is done on the beam; hence, the direction of the velocity vector changes, but the speed does not.

4. **The following are additional topics of interest:**

   The study of transmission of nerve impulses is progressing as better detectors of moving charges and their magnetic fields are developed.

   Magnetic bubbles in chips to store information in binary form are being tested.

   Stronger permanent magnets are being developed from rare earth materials. Stronger magnets facilitate the study of hard to detect magnetic fields in the human body and elsewhere.

   Recent discoveries suggest that many animals, from pigeons to certain bacteria, contain chains of magnetic particles in their bodies. These living species utilize the earth's magnetic field for migration or food finding.

   The nuclei of hydrogen atoms (protons) generate magnetic fields as the positive charges spin. This is similar to the way charges moving in a wire generate a magnetic field. Magnetic nuclei have a north and south pole and ordinarily have no preferred orientation in space. These nuclei will tend to line up when placed in a magnetic field. Energy from a radio transmitter with the proper frequency can be used to turn them so they point the other way. The turning of the nuclei is called resonance, and the associated frequency is the resonance frequency. The frequency is equal to the magnetic field strength times a nuclear constant. With a 3,500 gauss magnetic field, the resonance frequency for protons in water is 15 MHz. As the nuclei decay or relax to their lined up state, radio signals are converted to graphs or pictures, depending on the receiving device.

Compounds containing hydrogen atoms can be analyzed by placing the material in a magnetic field and aligning the protons. Likewise human bodies can be analyzed because of the hydrogen atoms in them. Obviously the more protons contained in biological materials the stronger the signal received in the reading. Blood, cerebrospinal fluid, fat, muscle, brain white and grey matter contain different proton contents. Bone contains the least. This technique is known as nuclear magnetic resonance imaging. Newer applications, using phosphorus rather than protons, hold promise for studying metabolism.

Cyclotrons use magnetic fields to direct accelerated charged particles in a circular pattern.

Meters such as galvanometers, ammeters, and voltmeters use magnetic fields interacting with the magnetic field of a current-carrying wire to deflect the needles.

Magnetic fields can be used to separate sickle cells from normal red blood cells.

Magnetic recording technology uses magnetic fields to record information on magnetic tape. An electromagnet in the recording head magnetizes the magnetic medium in the direction of the field. Changing the direction of the field can store information by magnetizing different regions of the medium in opposite directions. A binary system can be used with the presence or absence of magnetic reversal.

The magnetic field of the earth can also affect an oscilloscope as its position is changed in the lab. Any display on the oscilloscope must be recentered if the oscilloscope is moved.

SUMMARY - This module introduces magnetism. The work of Gilbert, Oersted, and Ampere are highlighted. Also included are properties of magnets, the magnetic field, and the motion of charged particles in magnetic fields.

NOTE OF EXPLANATION REGARDING THE STUDENT'S GUIDE - The following two pages of the STUDENT'S GUIDE should be duplicated and distributed to the students for use in preparation for viewing the video.

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 MAGNETIC FIELDS

INTRODUCTION - The video introduces magnetic fields and magnetic materials. A description of magnetic fields based on the work of William Gilbert and Andre Marie Ampere is presented.

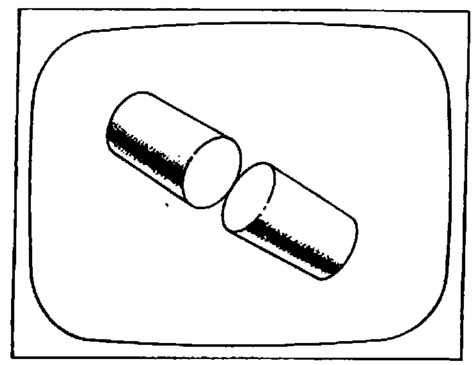
Terms Essential for Understanding the Video

aurora	solar wind
magnetic dipole	Van Allen belts
magnetic field	magnetic flux

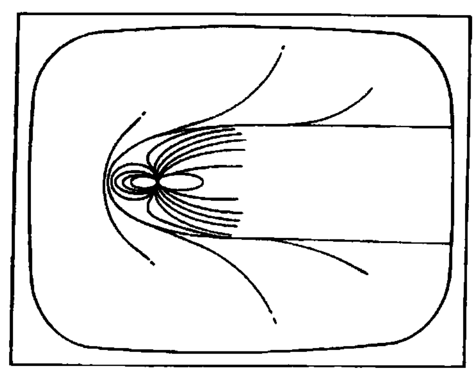
**** NOTE: Parts of the video, especially mathematical equations, may go by quickly on the screen. If you have questions, you should ask your teacher to replay these sections. ****

Points to Look for in the Video

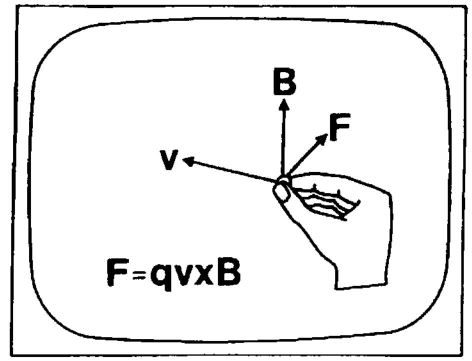
What happens when a bar magnet is cut in two between its poles?



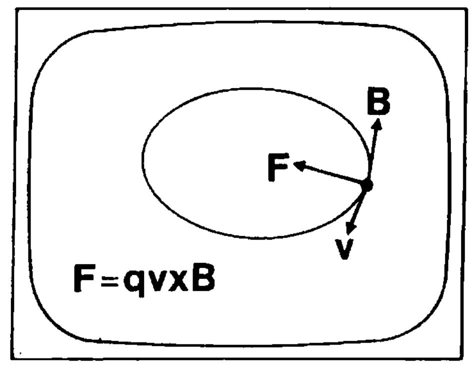
Is the earth's magnetic field in space like that of a simple dipole?



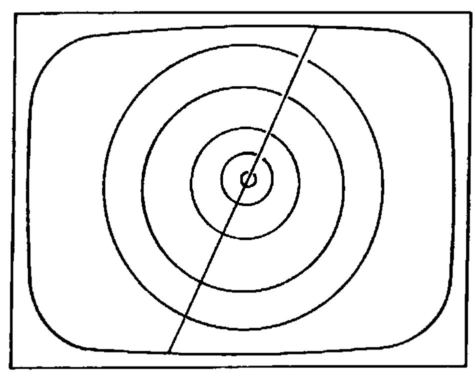
A charged particle will experience a force due to a magnetic field if two conditions are met. What are they?



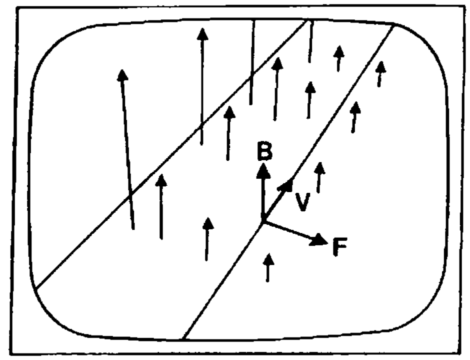
If a charged particle that has an initial velocity perpendicular to a magnetic field experiences a force, describe the path along which it will move.



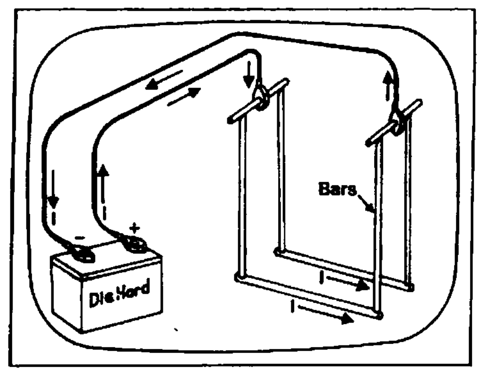
Sketch the magnetic lines of force about a long straight wire carrying a current.



What would be the direction of the force on two long straight parallel wires each carrying a current in opposite directions?



In the video notice that the wires to the battery move apart while the bars move together. Why does this happen?



The video does not show the electrical connections for this apparatus. Ask your teacher to sketch it on the board if you have difficulty visualizing it.

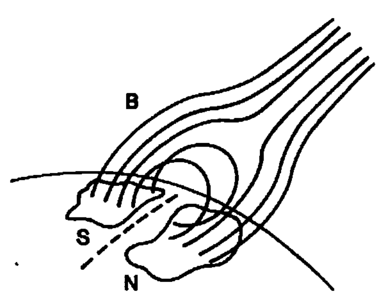
TEACHER RESOURCES

SUPPORTIVE BACKGROUND INFORMATION - The first recorded accounts of magnetism date from the ancient Greeks. The mineral magnetite or lodestone was found in Magnesia, a district of Asia Minor. In the thirteenth century, Peter Peregrinus, a Crusader also known as Pierre de Maricourt, investigated the properties of lodestones. He traced the magnetic field using a magnetized needle and a spherical lodestone. In addition to recognizing the presence of poles, he discovered the repulsion of like poles and the attraction of unlike poles. He discovered that each fragment of a broken magnet is in itself a small magnet. Using the information he had accumulated, he designed a compass with a pivoted needle and a graduated scale.

William Gilbert, an English scientist, was to become known as the "Father of Magnetism." A contemporary of Kepler and Galileo, Gilbert wrote a book about magnetism entitled *De Magnete*. It was published in the year 1600. That same year Gilbert, a prominent London physician, became "personal physician" to Queen Elizabeth, the First. When she died, she left Gilbert money so that he could continue to study magnetism.

Gilbert wrote about some of the fundamental properties of magnets. He discovered that you could heat a magnet and destroy its magnetism. By stroking a magnet in one direction with another magnet, Gilbert found that you can make a magnet stronger. He also found that an iron bar can be magnetized by keeping it strictly aligned in the earth's magnetic field for a long period of time. Perhaps one of Gilbert's most important discoveries was the fact that the earth itself behaves like a giant magnet. Subsequent studies have shown that most of the other planets are also magnetic.

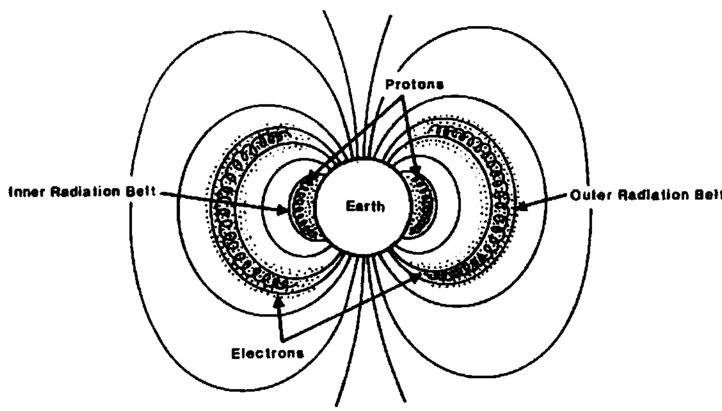
The earth's magnetic field has far reaching effects. Although we don't know exactly how the field is produced, several theories relate the earth's magnetism to the motion of the molten conducting materials within it and its rotation. The geographic and the magnetic poles do not coincide. The magnetic field seems to miss alignment with the earth's rotation by about eleven and a half degrees. Magnetic compasses must be adjusted to correct for this discrepancy. In addition, the magnetic field is constantly changing. It actually changes polarity every half million years or so. This is in contrast to the magnetic field of the sun which changes direction every eleven years. The cycle of sunspots offers evidence of the sun's shifting magnetic field.



Sunspots

Sunspots appear as dark regions on the sun which are the result of intense magnetic fields. The sunspots always occur in pairs, a north and south polarity together. The magnetic lines of force will go from one sunspot into another. It is as though a large tube of magnetic flux comes from below the surface and intersects with the surface of the sun. This tube of flux has a north and a south pole. Solar flares and solar winds are associated with sunspot activity.

The earth's magnetic field also produces some interesting effects, particularly in conjunction with solar winds. The solar wind is the stream of ionized gas particles produced by the sun. The motion of these ions through a magnetic field results in the ions experiencing a magnetic force. This force tends to make the solar wind spiral or curve in a helical path. These moving electric charges, when trapped in a non-uniform magnetic field, create the Van Allen radiation belt around the earth as well as the Aurora Borealis. Protons and electrons from the sun are trapped in the magnetic field of the earth. These trapped particles spiral along the field lines between the North and the South poles. In the polar regions, the particles sometimes penetrate the atmosphere, thereby exciting oxygen and nitrogen molecules. Light is then emitted as the molecules lose energy. In the northern hemisphere these lights are called the Aurora Borealis, and in the southern hemisphere they are called the Aurora Australis.



The earth's magnetic field is actually confined in the direction toward the sun to a distance of 40,000 kilometers. In the other direction it appears to have a tail similar to that of a comet. This tail of magnetic flux extends for millions of kilometers.

The earth's magnetic field protects us from ionized particles and cosmic rays coming from the sun. The earth's magnetic field diverts these from entering the atmosphere. Some scientists have suggested that Venus is a "dead" planet because it lacks this protecting field.

In 1820, Hans Christian Oersted discovered a connection between current-carrying wire and a compass needle. He also discovered that the magnetic field is perpendicular to the direction of the current. Andre Marie Ampere, a Frenchman, confirmed this finding and further discovered that a coil of wire carrying electric currents behaves like an iron magnet. Ampere developed the theory of electrodynamics which describes magnetism as a force between electric currents.

Ampere also examined the force between two current-carrying wires. He discovered that there is an attractive force between two parallel wires carrying current in the same direction and a repulsive force if currents are in opposite directions. Through experiments he showed that magnetic fields are produced by electric charge in motion and deduced a general force law. This force law, when applied to two wires, becomes the basis for the modern definition of the ampere. His law can also be applied to loops, solenoids, and toroids. The toroid is basically a solenoid bent into a doughnut-like shape.

The Mathematics of Magnetism

In an effort to relate magnetism to the various inverse square laws, an equation is presented in the video. This equation is not commonly found in high school texts:

$$F_m = K_m \frac{P_1 P_2}{r^2} \hat{r}, \text{ where}$$

F_m is the magnetic force in newtons.

K_m is the magnetic constant and equals $1.0 \times 10^{-7}\ \frac{N \cdot s^2}{C^2}$.

P_1 and P_2 are the pole strengths in C m/s.

r is the distance between the poles in meters.

The equation represents the force between two monopoles. Monopoles exist theoretically but have not actually been found. For this experiment, long thin magnetic needles were used in an attempt to isolate the poles. Quantitative determinations of this force were made independently in the eighteenth century in both England and France.

The magnetic field strength around a straight conductor carrying current is illustrated qualitatively. The video also depicts the concentric circles of the magnetic field around the conductor. Positive or conventional charge flow is used. Some textbooks use electron flow will have to visualize flow in the opposite direction. The equation used for the magnetic field strength near the current carrying conductor directs attention to the inverse nature of the field:

$$B \approx 1/r\ ,$$

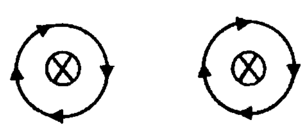
where B is the magnetic field strength or intensity in webers/m^2 or N • s/C • m and r is the distance from the conductor in meters.

Two straight current-carrying wires will experience forces due to the interaction of their magnetic fields. Two wires with current moving in the same direction will attract each other, while two wires with current flowing in opposite directions will repel each other.

Each of the wires produces a magnetic field that in turn influences the other wire. The direction of the magnetic field can be found by pointing the right thumb in the direction of the positive current and curling the fingers around the wire. The fingers will then curl in the direction of the magnetic field. In addition to using the method shown in the video, the repulsive and the attractive forces on the wires may be explained in terms of vector fields or by using an analogy of bar magnets.

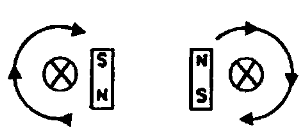
For a current in the *same* direction:

1.



The vectors will subtract or cancel each other between the wires.

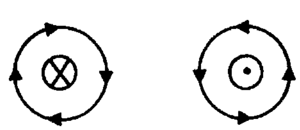
2.



Replacing the vectors with bar magnets shows that the poles line up to produce an attractive force. Thus the wires move toward each other.

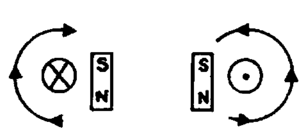
For a current in the *opposite* direction:

1.



The vectors will add and produce a larger field between the wires.

2.



Replacing the vectors with bar magnets shows like poles opposing like poles. Thus, a repulsive force occurs and the wires are pushed apart.

ADDITIONAL RESOURCES

Demonstration #1: Fundamental Properties of Magnets

Purpose: To describe the basic properties of magnets.

Materials: Two small magnets; magnetic and non-magnetic box of paper clips; drill bit; nails; aluminum; copper, zinc, gold or silver ring; U.S. coins, Canadian coins, and magnetic toys, if available.

Procedure and Notes:

1. Show that magnets attract and repel other magnets when held near them. Balance one magnet on the edge of a watch glass to reduce friction.
2. Demonstrate that a magnet will pick up a cardboard box if it is filled with paper clips, but will not attract such common metals as aluminum, copper, or zinc.
3. Attach a nail to a permanent magnet and then use the combination to pick up paperclips. With the paperclips still hanging from the nail, detach the nail from the magnet. Note what happens to the paperclips. Soft iron such as nails can be made into a temporary magnet, whereas steel can be made into a permanent magnet.
4. Stroke a piece of tool steel such as a drill bit with a permanent magnet. The stroking should be done lengthwise from top to bottom. Move the magnet away when returning it to the top of the drill bit. Use the drill bit to pick up paperclips.

Explanation: Magnetic forces exist between magnetic materials. Unlike magnetic poles attract, while like poles repel. The strength of attraction or repulsion between two magnets is a function of distance between them.

Demonstration #2: What is a Magnet?

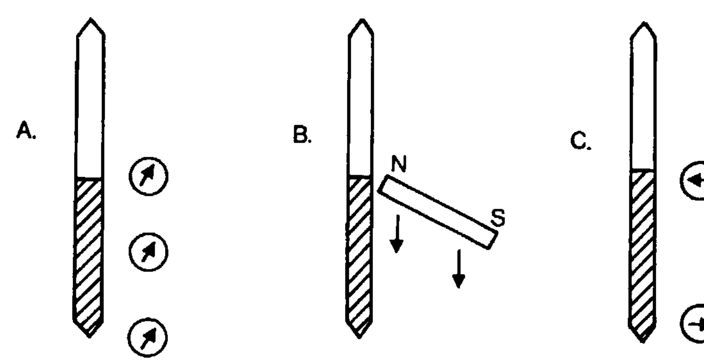
Purpose: To demonstrate that a magnet is composed of small magnetic areas that together combine to give the overall effect called a magnet.

Materials: A transparent plastic soda straw; iron filings; compass; small bar magnet.

Procedure and Notes:

1. Heat one end of a plastic straw with a match and quickly pinch it together, sealing it. Fill the straw with small iron filings and heat; seal the other end as well.
2. Hold the straw up and place the compass next to it, showing that there is no evidence of a magnetic field associated with it (See Figure 1).
3. Stroke the straw 6 - 10 times from top to bottom with the same end of a permanent bar magnet (See Figure 2). Then test it with the compass. A definite N and S pole can be detected on opposite ends of the straw. A permanent magnet has been formed (See Figure 3).
4. Turn the straw upside-down allowing the filings to rearrange themselves in the opposite end of the straw. Retest for magnetism with the compass. No N and S poles can be found.

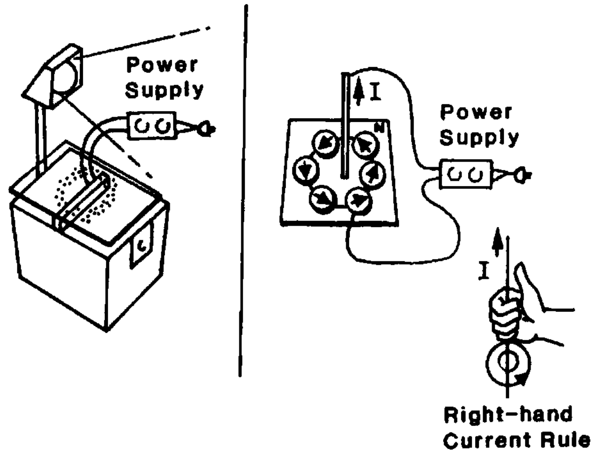
Explanation: Each individual iron filing is in fact a very small magnet. Thousands of these small magnets randomly arranged will produce no net magnetic field. When rearranged by the strong magnetic field of the bar magnet, the individual iron filings tend to become aligned to produce a stronger permanent magnet. Turning the straw upside-down causes random re-alignment, again producing no net magnetic field.



Demonstration #3: Magnetic Field Patterns

Purpose: To demonstrate magnetic field patterns surrounding various magnetic devices.

Materials: Power supply of 10 - 20 volts and 6 - 10 amperes; transparent plastic platform approximately 20 cm by 20 cm; overhead projector; heavy connection wire; 4 - 8 small compasses; iron filings; a permanent bar magnet.



Procedure and Notes:

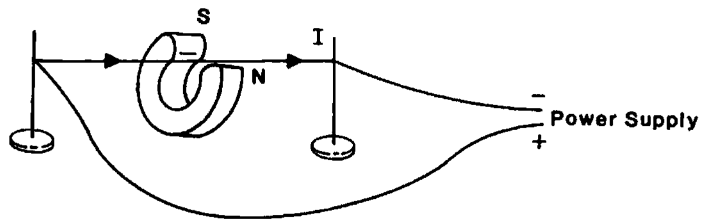
1. Raise the plastic platform several centimeters above the top of the overhead projector. Place iron filings on the platform and focus on the filings.
2. Show the field that results when a permanent bar magnet or a solenoid carrying a large current is placed below the platform.
3. The field around a single current-carrying wire can be demonstrated by running a heavy wire perpendicular to a heavy piece of paper or cardboard and surrounding the wire with a ring of compasses. Two to five amps of current are required to demonstrate the effect of the magnetic field on the compasses.

Explanation: According to the convention established by Benjamin Franklin, magnetic field lines leave the N pole of a bar magnet or solenoid and return to the S pole. Iron filings in a magnetic field behave as if they were small magnets themselves and align longitudinally along the field lines from the magnet. Since the N pole of a compass placed at any point lines up with the magnetic field, the compasses show circular patterns around the wire.

Demonstration #4: Moving Charges in a Magnetic Field

Purpose: To demonstrate the interaction between a current-carrying wire and an external magnetic field.

Materials: DC power supply of 20 - 40 volts and 6 - 10 amps; large magnetron magnet; power switch; two ring stands; 3 m hookup wire; 3 m ribbon of foil such as one found in a paper capacitor (optional).



Procedure:

1. Set up the equipment as shown above. The wire or foil ribbon, if available, must be held loosely between the faces of the poles so that upward and downward deflection can be seen easily.
2. Close the switch. Observe that the wire moves upward in accordance with the right-hand rule.
3. Change the wires connected to the power supply, thus changing the direction of current through the wire. Observe the results.
4. Rotate the magnet 180 degrees. Turn the circuit on again. Note the results.

Explanation: A force is produced on a current-carrying conductor when it interacts at right angles with a magnetic field. The direction of force is determined by the equation $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$, according to the right hand force rule. Reversing the direction of current or the direction of the magnetic field will change the direction, but not the magnitude, of the force produced.

EVALUATION QUESTIONS

1. **The ultimate source of all magnetism is**

   A. moving electric charge.
   B. nickel and iron atoms.
   C. ferromagnetics.
   D. loadstones.

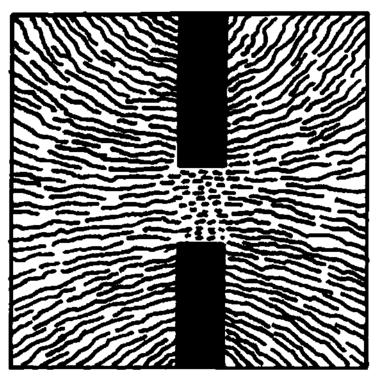
2. **A force could be produced on a moving electric charge**

   A. in a magnetic field.
   B. in an electric field.
   C. in both A and B.
   D. in neither A nor B.

3. **The Van Allen Belts**

   A. cause the aurora.
   B. protect the earth from charged particles.
   C. are the source of the solar winds.
   D. reverse polarity every 11 years.

4. **The figure shows the pattern of iron filings on a piece of paper on top of two bar magnets. Which of the following statements is *false*?**

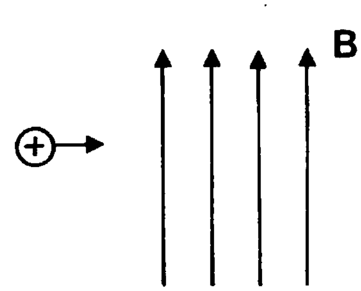


   A. Both the ends of the magnets could be north poles.
   B. Both the ends of the magnets could be south poles.
   C. The poles are opposite.
   D. The magnets are repelling each other.

5. **The probable cause of the earth's magnetic field is**

   A. huge magnetic lodestone deposits near the poles.
   B. the motion of molten conducting material inside the earth.
   C. moving charged particles ejected from the sun.
   D. a magnetic monopole at the center of the earth.

6. **If a positively charged sphere enters a region of magnetic field as shown, in which direction would it be deflected?**



   A. Out of the plane of the page.
   B. Into the plane of the page.
   C. Toward the top of the page.
   D. Toward the bottom of the page.

7. **When a large current is allowed to flow through two wires which are parallel and carrying current in the same direction, what is the motion of the cables with respect to each other?**

   A. They move together by magnetic attraction.
   B. They move apart by magnetic repulsion.
   C. They do not move at all due to canceling magnetic forces.
   D. They shorten due to magnetic contraction behavior.

8. **The north poles of two bar magnets are brought close together. The force between the two poles can be best described as**

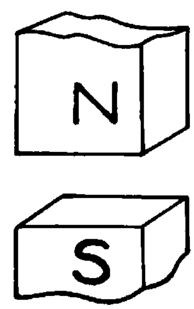
   A. attraction.
   B. repulsion.
   C. contraction.
   D. convulsion.

9. **Which phenomenon is associated with a magnetic field?**

   A. The aurora
   B. Van Allen belts
   C. A current in a wire
   D. All of the above

10. **In what direction is the magnetic field between the poles of the magnet shown in the figure?**

   A. Up (south to north)
   B. Down (north to south)
   C. Left to right
   D. Right to left



ESSAY QUESTIONS

11. **An electric charge always experiences a force when in an electric field, but not always when in a magnetic field. Explain.**

12. **Describe the magnetic field near a long straight current carrying wire.**

KEY

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

SUGGESTED ESSAY RESPONSES

11. An electric charge must have a component of its motion directed perpendicular to the magnetic field to experience a magnetic force, since the magnetic force is given by $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$.

12. The magnetic field forms closed circles about the wire. The direction of the field follows the right-hand rule. The field decreases with distance from the wire as the inverse of the distance and it depends directly on the magnitude of the current, i.e., $B \propto I/r$.

TEACHER'S GUIDE TO ELECTROMAGNETIC INDUCTION

CONTENT AND USE OF THE VIDEO - In its focus on electromagnetic induction, the video provides insights into Faraday's principle relating induced electric fields and changing magnetic flux. The graphics used to portray magnetic forces, fields, and loops help the student form a mental picture of these unseen physical occurrences. While laboratory studies offer students an opportunity to study the effects of these phenomena, the video offers a visualization of the phenomena themselves.

Computer animations demonstrate (1) charges moving in a magnetic field; (2) magnetic flux extending through the surface of a loop; and (3) changing magnetic flux producing an induced voltage. Because of the sophistication of these concepts, parts of the video may require several re-plays for students to achieve understanding. The concepts of electrostatic charge and fields, magnetism and magnetic fields, and electric circuits should be studied prior to viewing the video.

TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO - The following terms will facilitate an understanding of the concepts presented in the video. Although students may already be familiar with a few of the terms, a review will be helpful.

electric current--a flow of electric charge.

magnetic field--the alteration of space in the region around a magnetic material and moving charges that exerts force on other magnetic material and moving charges.

magnetic field lines--imaginary lines which form a pattern of closed loops representing the magnetic field. The tangent to the line at any point gives the direction of the magnetic field.

potential difference--the electric potential energy difference per unit charge between two points; it is often referred to as voltage.

conventional current--conventionally taken to mean that positive charge flows from a positive to negative direction; in metals where only electrons flow, this is called negative electron current.

magnetic force on a moving charge--force $\mathbf{F}$ experienced by a charge q moving in a magnetic field $\mathbf{B}$: $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$; the direction of $\mathbf{F}$ is given by the right hand rule.

flux--the quantity of something, such as field lines, passing through a unit area.

magnetic flux--the quantity of a magnetic field through any surface; mathematically, it is defined as the product of the perpendicular component of the magnetic field, $\mathbf{B}$, and the area, A, through which this flux passes.

induced emf or induced voltage--the generation of a voltage in a closed circuit by a changing magnetic flux through the circuit.

electromagnetic induction--a phenomenon wherein a changing magnetic flux induces an electric field and an induced emf (and, if a closed conducting loop is present, an induced current).

induced current--an electric current resulting from an induced emf.

Faraday's law of electromagnetic induction--the induced emf ε produced by a changing magnetic flux ϕ depends on the rate at which the magnetic flux changes: $\varepsilon = -\Delta\phi/\Delta t$.

Lenz's law--the induced emf and induced current produce a magnetic field that opposes the original change in flux.

WHAT TO EMPHASIZE AND HOW TO DO IT - Many of our modern technologies have been made possible because of Michael Faraday's brilliant meshing of electricity and magnetism into electromagnetism. The video focuses on this remarkable phenomenon of electromagnetic induction. Of particular importance is the development of the idea that the occurrence of electromagnetic induction requires that electric charges move relative to a magnetic field or that the magnetic flux must change.

Prior to viewing the video, it might be helpful to perform DEMONSTRATION #1 on Oersted's discovery that an electric current produces a magnetic field. By convention, magnetic field lines directed out of a page are denoted by "Θ" and those directed into a page are denoted by "x."

Objective 1: Explain the meaning of magnetic flux.

The quantity of field lines through some area is called the magnetic flux. Students often have a poor understanding of magnetic flux. It may be necessary to stop the video at this point and discuss the concept. A mathematical description of magnetic flux is provided in the SUPPORTIVE BACKGROUND INFORMATION. DEMONSTRATION #2 on changing flux offers students an opportunity to observe examples. These observations can clarify and reinforce the idea that magnetic flux is the quantity of field lines through some specified area.

Objective 2: Explain Faraday's law of electromagnetic induction.

The video shows Faraday working in his laboratory with a makeshift galvanometer and his consequent discovery of the principle of electromagnetic induction. DEMONSTRATION #3 on induced current uses a modern galvanometer to demonstrate the same concept. The SUPPORTIVE BACKGROUND INFORMATION is helpful in developing a mathematical interpretation. Students should be aware not only that a changing magnetic flux induces an electric field but also that the induced current depends on the rate at which the magnetic flux changes. The computer animation demonstrating Faraday's law may require several viewings to assure student understanding.

In discussing electromagnetic induction with your students, it might be helpful to introduce some applications of the concept. The section on EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS offers some examples.

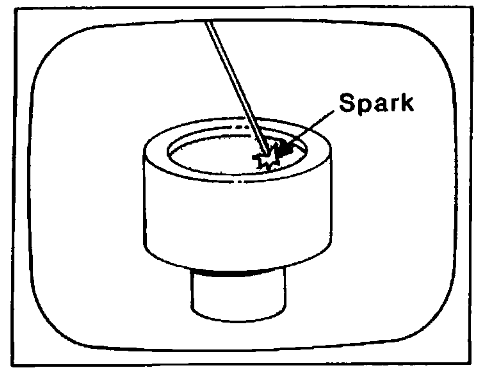
Objective 3: Explain Lenz's law.

The video follows the presentation of the concepts of magnetic flux and electromagnetic induction with a brief description of Lenz's law. Lenz's law summarizes the observation that an induced current always flows in a direction to create a magnetic field that opposes the change in the negative field that caused the induced current. For students to understand fully the relationships among these three concepts, it may be necessary to replay this section of the video several times. Lenz's law can also be illustrated through DEMONSTRATION #4.

POINTS TO LOOK FOR IN THE VIDEO - Several questions directly related to the video are posed in the Student's Guide. Here are some suggested responses to those questions.

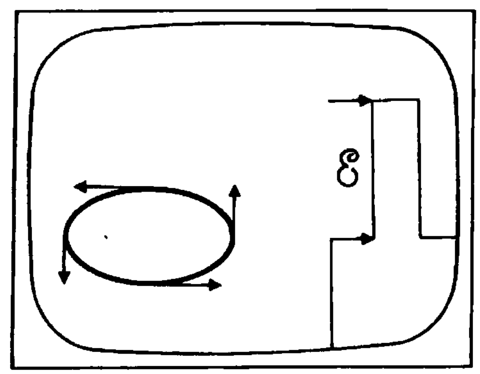
What "world's first" did Faraday invent?

Faraday invented the electric motor.



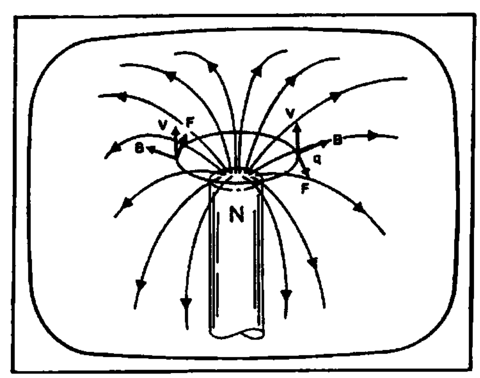
In an animated sequence illustrating a wire loop moving relative to the field of a bar magnet, charges are shown flowing. Does this represent conventional current or electron flow?

Conventional current is represented.



In the same sequence, a vector illustrates the force on charges in the wire. Does the vector represent the force on electrons or on positive charges?

The vector represents the force on electrons.



Contrary to what was previously thought, Faraday discovered the way to make closed loops of electric lines. How can this be done?

By changing magnetic flux Faraday was able to make closed loops of electric field lines.

Describe Lenz's law.

Lenz's law states that the induced electric field (or induced voltage or induced current) is established in such a way as to oppose the changing magnetic flux that induced it. This law represents the physical interpretation of the negative sign in Faraday's law, $\varepsilon = -\Delta\phi/\Delta t$.

EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS - To reinforce further the ideas contained in the video, you might discuss the following applications and questions with your students.

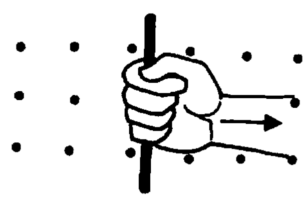
1. **The following examples are practical applications of electromagnetic induction:**

   Some proposed transportation systems use magnetic levitation. The levitation effect is coupled with the vehicle's forward motion. As it travels over a conducting surface, the vehicle-borne electromagnet induces currents in the conductor. According to Lenz's law these act in such a direction as to establish their own magnetic field which repels the electromagnet and thus lifts the moving vehicle.

   Some microphones work on the principle of electromagnetic induction. In a "ribbon" microphone, a thin metal ribbon is suspended between the poles of a magnet. The ribbon vibrates in response to sound waves. The voltage that is induced is proportional to the ribbon's velocity. The electrical signals are amplified then converted into sound.

   Tape player heads read recorded tapes when the tape passes the head. The tape which is magnetized along its length with the program material becomes a changing magnetic field as it passes the head of the player. A tiny emf is induced in a coil located in the head. This electrical signal is converted to sound in the player.

2. **A straight line of insulated wire is moved to the right in a region where there is a uniform magnetic field as shown. Describe what happens.**



   Positive charges experience a force qvB downward, causing a current to flow. (Of course, electrons actually flow upward in the wire.) Since the wire is open, the top accumulates a net negative charge and the bottom is left with a net positive charge. The resulting field balances the force due to the magnetic field, and no more current flows.

3. **Your car travels east to west, cutting across the earth's magnetic field lines, at 80 km/hr. On its roof is mounted a long straight wire. How long should the wire be if you want to develop a voltage between the ends of the wire equaling the car's 12 V battery? (Take the earth's magnetic field strength to be 5×10^{-5} T.)**

   The force on positive charges in the wire is $F = qvB$. The work done pushing charges along the length of wire, L, is $W = FL = qvBL$.

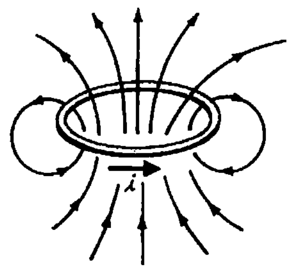
   The voltage developed is

$$V = W/q = qvBL/q = vBL.$$

   So,

$$L = V/(vB) = \frac{12\ V}{\dfrac{80 \times 10^3\ m}{3600\ S}\ (5 \times 10^{-5} T)} \approx 10^4\ m.$$

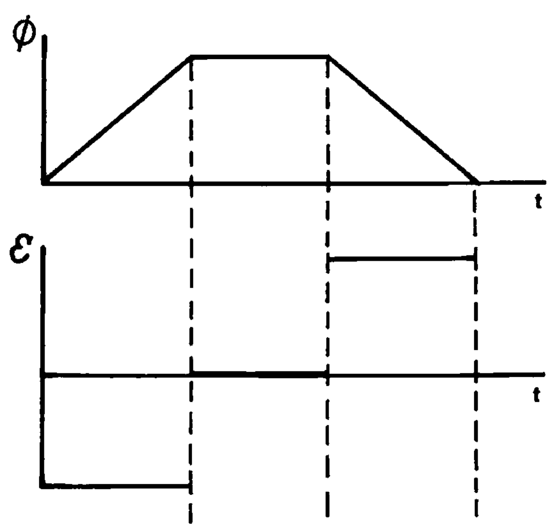
4. **A circular loop of wire has a current. Draw in some representative magnetic field lines.**



5. **When you push a magnet toward a loop of wire, current is induced in the wire. How would this current change if the loop had been cooled down in dry ice?**

The induced emf is the same. Since the resistance is lower at the lower temperature, the current increases in accordance with Ohm's law, I = V/R.

6. **Given a graph of the magnetic flux ϕ_m versus time, make a graph of induced voltage, ε, versus time.**



The induced emf ε is represented by the negative of the slope of the flux graph, $\varepsilon = -\Delta\phi/\Delta t$.

SUMMARY - Oersted's discovery of the link between electricity and magnetism generated new avenues of thought and experimentation within the scientific community. These studies revealed the amazing phenomenon of electromagnetic induction.

Faraday's investigations suggested that, if an electric current is produced, a type of change occurs in some aspect of the arrangement of the magnetic field and loops of wire. The concept of magnetic flux enabled him to describe this "change": a changing magnetic flux induces an emf in a closed conducting loop.

A listener to a lecture on electromagnetic induction given by Faraday questioned the usefulness of the phenomenon. He replied, "Of what use is a newborn baby?" Today we recognize electromagnetic induction as the foundation of electric power generation so necessary in our modern world.

NOTE OF EXPLANATION REGARDING THE STUDENT'S GUIDE - The following two pages of the STUDENT'S GUIDE should be duplicated and distributed to the students for use in preparation for viewing the video.

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 ELECTROMAGNETIC INDUCTION

INTRODUCTION - The video presents Faraday's principle of electromagnetic induction which relates induced electric fields and changing magnetic flux. The scientific significance of his discovery is evidenced in the technologies dependent upon electromagnetism.

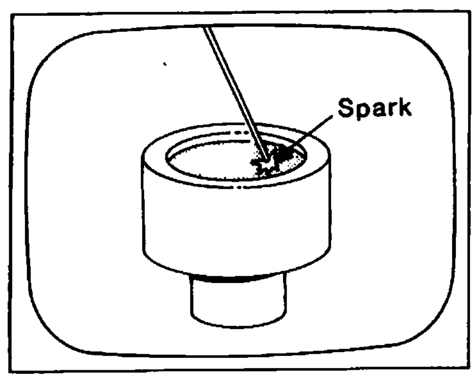
Terms Essential for Understanding the Video

electric current
magnetic field
magnetic field lines
potential difference
conventional current
magnetic force on a moving charge
flux
magnetic flux
induced emf or induced voltage
electromagnetic induction
induced current
Faraday's law of electromagnetic induction
Lenz's law

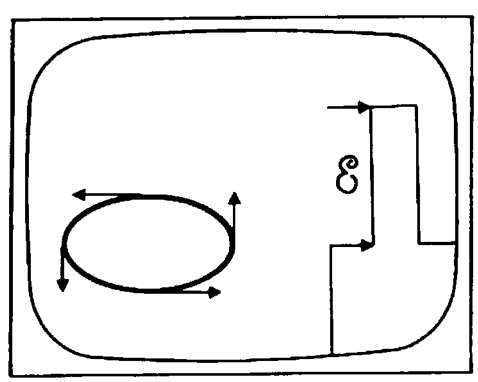
**** NOTE: Parts of the video, especially mathematical equations, may go by quickly on the screen. If you have questions, you should ask your teacher to replay these sections. ****

Points to Look for in the Video

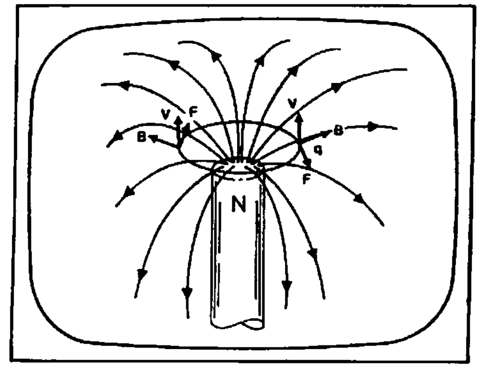
What "world's first" did Faraday invent?



In an animated sequence illustrating a wire loop moving relative to the field of a bar magnet, charges are shown flowing. Does this represent conventional current or electron flow?



In the same sequence, a vector illustrates the force on charges in the wire. Does the vector represent the force on electrons or on positive charges?



Contrary to what was previously thought, Faraday discovered the way to make closed loops of electric lines. How can this be done?

Describe Lenz's law.

TEACHER RESOURCES

SUPPORTIVE BACKGROUND INFORMATION - In 1820 Oersted discovered that an electric current produces a magnetic field. This discovery led Michael Faraday on a twelve-year search to find a mechanism that would cause a magnetic field to produce an electrical current. This search for induced currents plunged Faraday into exhaustive studies of electromagnetic induction. Faraday's name became associated with electromagnetic induction even though the American Joseph Henry was the first man knowingly to observe the phenomenon. Henry's discovery was not immediately recognized since most of the world's important scientific work was going on in Europe.

Utilizing his discovery of electromagnetic induction, Faraday invented the first motor and thereby showed how an electric current could produce physical work. From this invention evolved the many practical machines in today's society. Thus, Faraday's momentous discovery altered civilization through new technologies.

Faraday showed that currents are induced in a circuit when any of the following conditions prevail:

1. A magnet in motion is brought near the circuit.
2. The circuit is moved in the presence of a magnet or another current-carrying circuit.
3. The current flow in a neighboring circuit is established or interrupted.

Faraday's magnetic needle surrounded by a coil of wire was simply a crude version of a galvanometer. Suppose a loop of wire is attached to a sensitive galvanometer. If the north pole of a magnet is moved toward the loop, the galvanometer deflects in the positive direction, indicating that there is a current. And if the magnet is withdrawn, the galvanometer again deflects, but this time in the opposite direction, indicating that the induced current flows in the opposite direction. These observations confirm Faraday's realization that relative motion is the key. With a fixed magnet and a fixed loop, there is no induced current. But as long as the magnet moves toward the loop, or vice versa, current is induced.

The following illustration relates the magnetic force on a moving charge to the induced emf. Consider pulling a loop of wire out of a region of uniform magnetic field at a constant speed, as shown in Figure 1.

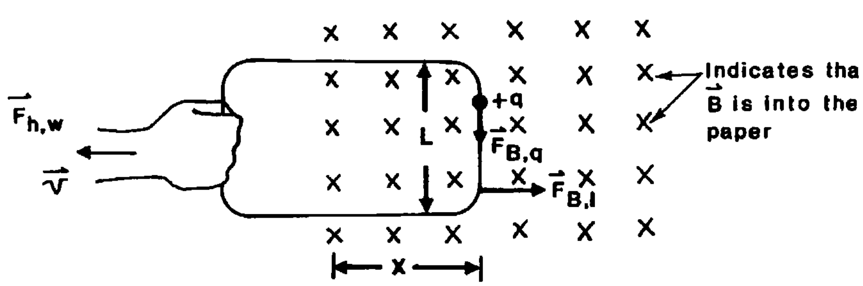


Figure 1

A positive charge in the vertical section of the wire in the field experiences a downward force, Fq = qvB. This causes a clockwise current. The work done by the hand pulling on the wire is

$$W_{h,w} = F_{h,w}\,(\text{distance}),$$
$$W_{h,w} = F_{h,w}\,v\Delta t.$$

As predicted by Newton's third law, the hand experiences a force opposing the pull:

$$F_{h,w} = -F_{B,I} = -ILB$$

This is the force experienced by the vertical section of the wire in the magnetic field where I represents current, L is the length of the vertical section of the wire, and B is the magnetic field strength. Therefore, by substitution,

$$W_{h,w} = -I\,L\,B\,v\,\Delta t.$$

But since

$$I = q/\Delta t,$$

then

$$W_{h,w} = -(q/\Delta t)\,L\,B\,v\,\Delta t,$$

so that the work done by the hand on each unit of charge in the wire is

$$W_{h,w}/q = -L\,B\,v,$$

or

$$\varepsilon = -L\,B\,v.$$

The quantity on the left is called the induced voltage, or electromotive force*, or emf, and is measured in volts. The magnetic flux through the loop is

$$\phi = \mathbf{B} \cdot \mathbf{A} = B\,L\,x,$$

where x denotes the position of the loop in the field. The rate of change of flux is

$$\Delta\phi/\Delta t = B\,L\,\Delta x/\Delta t = B\,L\,v.$$

Therefore, the induced voltage, ε, may be expressed

$$\varepsilon = -\Delta\phi/\Delta t.$$

This last equation, called Faraday's Law, relates the induced emf in the loop to the changing magnetic flux.

As long as the magnetic flux is changing, the emf is not zero. In the study of electrostatic fields, however, we find that the voltage around a closed loop must be zero. This apparent contradiction is easily explained. We are now dealing with an electric field that is not created by point charges but by a changing magnetic field. No distribution of electric charges, no matter how complicated, can create closed loops of electric field lines. However, a magnetic field that is changing in time at a fixed point in space can accomplish this.

*This name is unfortunate. It resulted from a lack of complete understanding of the phenomenon when it was discovered. The "electromotive force" is not a force at all, but the electrical energy per unit positive charge gained in the transfer of charge by non-electrostatic forces (i.e., a voltage).

If the loop is moved near a permanent magnet (or vice versa), the magnetic field that it experiences is not uniform. Indeed, the magnetic field is stronger near the magnet and weaker away from the magnet. Faraday's lines can help visualize what is happening (see Figure 2). As the loop moves toward the magnet (or vice versa), some lines are left behind, but new ones enter the loop. The important point is that the total number of lines changes. That is how Faraday visualized the process: The magnetic flux through the loop changes as the loop moves, and the changing magnetic flux through the loop induces a current in the loop.

Faraday noticed that the direction of the current flow depended upon the way in which the magnetic flux was changing. If the flux decreases, the current flows one way; and if the flux increases, the current flows the opposite way. If we move a loop of wire toward a magnet (flux is increasing), we can feel a force resisting the motion. That force on the loop is created by current flowing in the loop. The induced current creates a magnetic field which is in the opposite direction to the change of the magnetic field that is producing the current. This observation, known as Lenz's law, may be stated: *The induced current always flows to create a magnetic field that opposes the change in the external flux.* This result is reminiscent of mechanical stability. The situation is illustrated in Figure 2. It can be worked out using the right-hand rule shown in Figure 3.

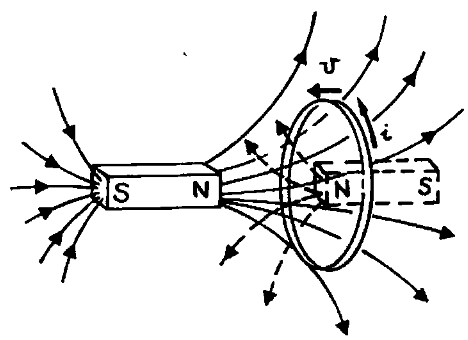


Figure 2

The magnetic flux through the loop changes as long as the loop and magnet are moving relative to one another. The imaginary magnet illustrates Lenz's law.

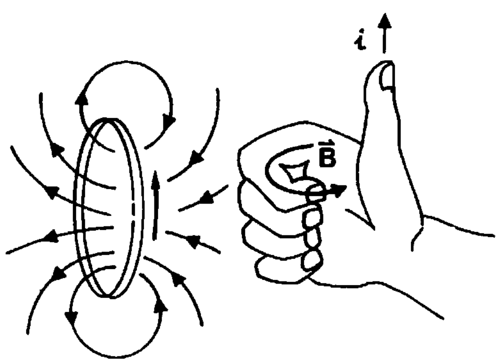


Figure 3

Right-Hand Current Rule: Grasp the loop with your right hand so that your thumb points (tangentially) in the direction of the induced current. Your fingers will curl around the loop in the direction of the resulting magnetic field.

Thus far we have discussed only a single loop of wire in a changing magnetic field and have described the resulting emf as

$$\varepsilon = -\Delta\phi/\Delta t.$$

A coil consists of loops of wire that are, in a sense, connected in series. Therefore, the induced voltage across the coil is simply the sum of voltages in the individual loops. A coil of N turns has N times the induced emf of the individual turns. Therefore,

$$\varepsilon = -N\Delta\phi/\Delta t.$$

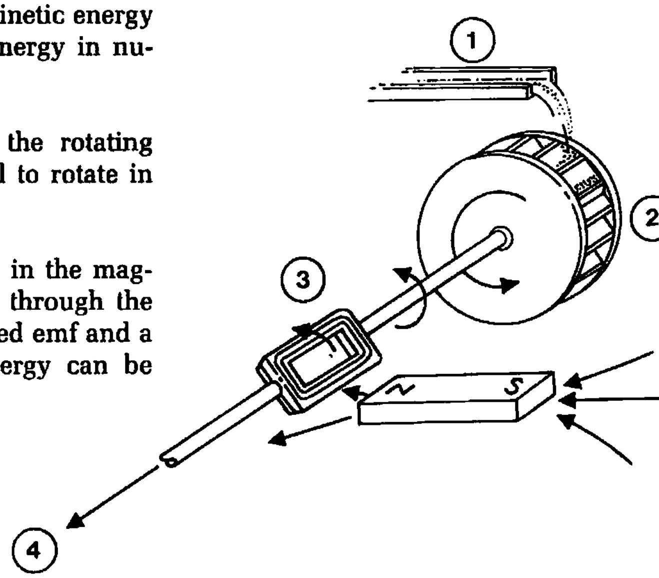
The fact that voltage can be altered by changing the number of turns in the coil provides the basis for effective use of electric power. Huge multiple-turn coils rotate in magnetic fields to generate the electricity that society has become so dependent upon.

Since the most important use of Faraday's law is the operation of electric generators, the following offers a brief diagramatic explanation of the ac generator and the transformation of energy processes involved:

1. **Initial energy source**: (in this case kinetic energy of moving water; could be steam energy in nuclear power plant, etc.)

2. **Mechanical Energy**: in this case the rotating water wheel which allows for a coil to rotate in the field of a magnet.

3. **Electrical Energy**: The coil rotating in the magnetic field causes the magnetic flux through the coil to change, resulting in an induced emf and a resultant current. The electrical energy can be transported to use as desired.



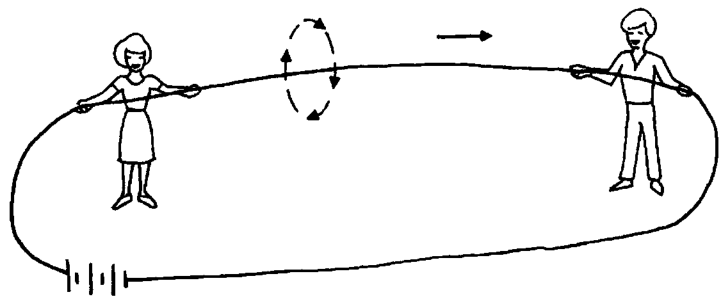
ADDITIONAL RESOURCES

Demonstration #1: Oersted's Discovery

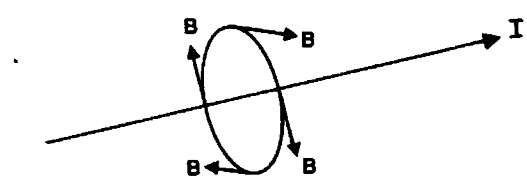
Purpose: To see how magnetic fields arise out of moving charges or current.

Materials: 2 m or 3 m section of wire; dc power supply capable of about 5 A; large demonstration compass needle.

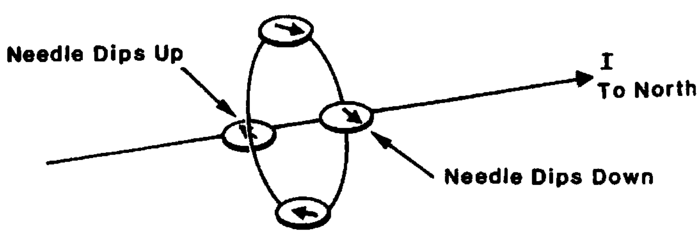
Procedure and Notes: Arrange the wire in the air along a N - S line. It may be suspended on ring-stand clamps or held by two students. Hold the compass at various locations around the wire (top, bottom, sides) and initiate the current. Observe the deflection of the compass needle.



Explanation: Conventional current flowing through a wire produces a magnetic field with field lines forming circles centered on the wire.



The strength of the field lines diminishes with increasing radius. If a strong enough current is used (greater than 5 A), the needle should point in the direction of the magnetic field as shown on the top and bottom of the wire.



When located at the sides, the compass needle will point north but may dip up or down in response to the field at the side locations. As soon as the current is stopped, the compass needle points north in all locations.

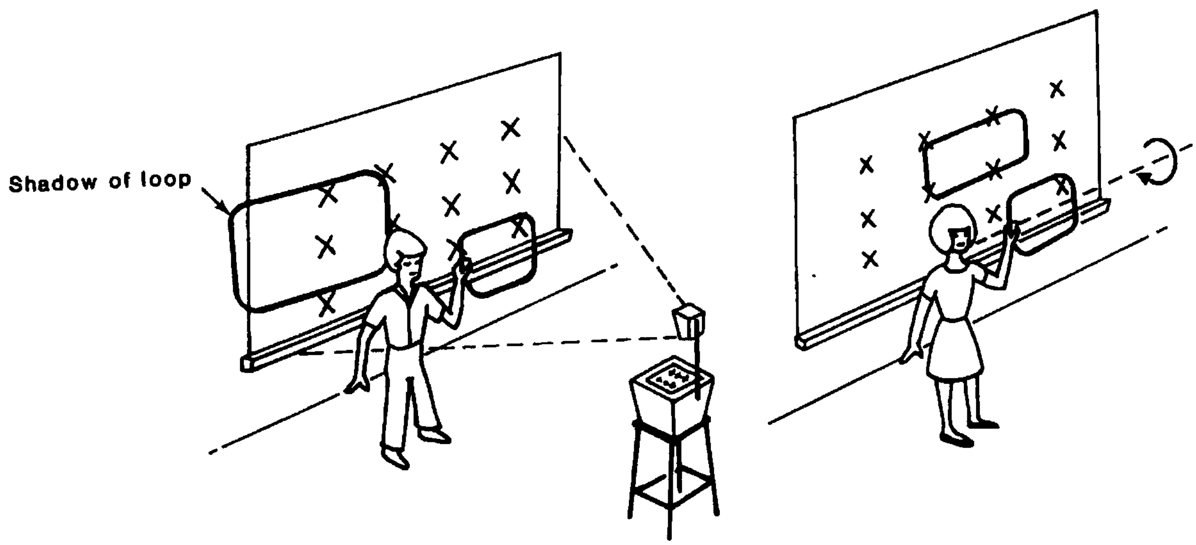
Demonstration #2: Changing Flux

Purpose: To observe examples of changing flux.

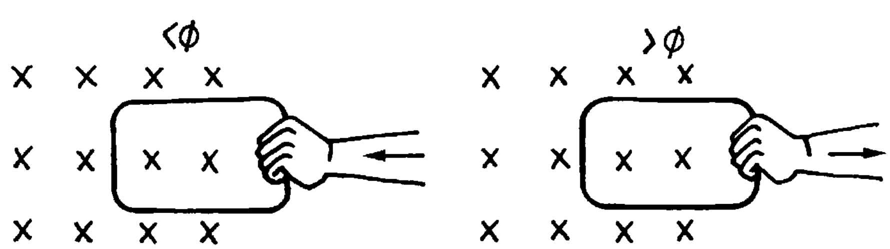
Materials: Overhead projector; acetate overlay showing a magnetic field into or out of the plane of the blackboard; rectangular loop of stiff wire.

Procedure and Notes:

1. Project the acetate overlay of a B field on the chalkboard which is indicated by uniformly spread X's. Hold the loop in the beam of light so its shadow is cast on the board, partly in the X'ed region, partly out of it. Move the loop left or right to show a decrease and increase in flux, respectively, when part of the loop's area is out of the X'ed region. If the loop's area is totally within the region, which is assumed to be uniform, there should be no change in flux.
2. Rotate the loop about an axis as shown below and observe the changing flux.



Explanation: As the loop is pulled to the left, the flux is decreasing, since flux equals **B** • **A** and A decreases. As the loop is pushed to the right, the flux is increasing, since A increases. As the loop is rotated, the projection of the area changes on the board causing the flux to vary. If the loop is turned at a constant rate, this demonstration can lead to a discussion of an ac generator.

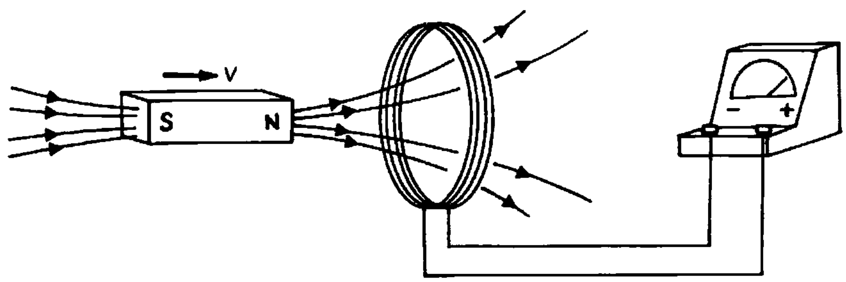


Demonstration #3: Induced Current

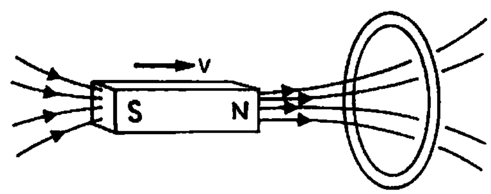
Purpose: To induce current in a wire.

Materials: Loop of wire; galvanometer (large demonstration type desirable); *strong* bar or horseshoe magnet; (optional solenoid).

Procedure and Notes: Connect the loop of wire to the galvanometer and thrust the magnet in and out of the loop. Alternatively, hold the magnet still and move the wire. Observe the deflection of the galvanometer. If the magnet is too weak to affect noticeably the needle of the galvanometer, use a solenoid or multiple loops for a more pronounced effect.



Explanation: Moving the magnet (or wire) causes a change in flux, increasing or decreasing as the function of the motion. If the magnet if pushed to the right, the flux through the wire increases.



If pushed left, the flux decreases. The galvanometer needle moves in one direction and then the other to indicate a current.

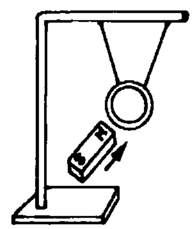
Demonstration #4: Lenz's Law

Purpose: To demonstrate Lenz's law.

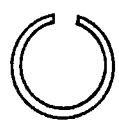
Materials: Metal ring; cut metal ring; strong bar magnet; ring stand; string.

Procedure and Notes:

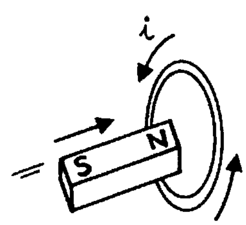
1. Suspend the metal ring like a pendulum. Move the bar magnet toward and then away from the ring. Observe the motion of the ring.



2. Repeat the procedure with a cut ring.



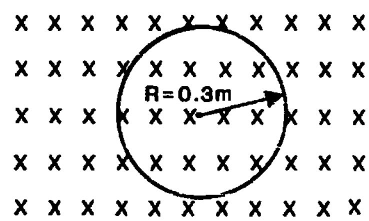
Explanation: When the magnet is moved toward the ring, it induces current in the ring. In accordance with Lenz's law, the current is set up in such a direction as to oppose the increasing flux, i.e., counter-clockwise. This current establishes its own magnetic field which repels it from the magnet.



When the magnet moves away, the reverse effect occurs. With the cut ring the circuit is open, so there is no current.

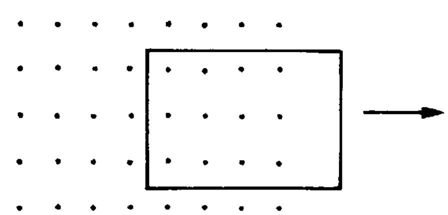
EVALUATION QUESTIONS

1. A circular loop of wire of 0.3 m radius, is situated in a region of uniform magnetic field of intensity 1 tesla as shown. What is the flux through the loop?



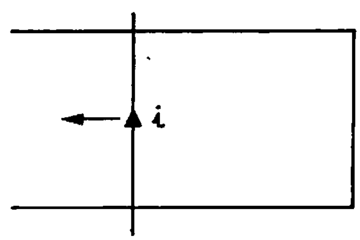
   A. 2π units
   B. 0.3π units
   C. 0.09π units
   D. 1π unit

2. A loop of wire is removed from a region containing a uniform magnetic field, as shown. What is the direction of the induced current, if any?



   A. Clockwise
   B. Counter-clockwise
   C. There is no induced current
   D. The direction cannot be determined on the basis of the given information

3. A wire circuit immersed in a uniform magnetic field contains a movable section. If the section is moved toward the left, a current is induced. What is the direction of the magnetic field?



   A. Out of the page
   B. Into the page
   C. Up toward the top of the page
   D. Down toward the bottom of the page

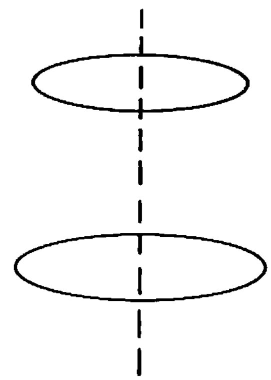
4. Which of the following statements about Lenz's law is correct?

   A. It is an exception to the law of conservation of energy.
   B. It is a consequence of conservation of charge.
   C. The induced electric field starts and stops on charges.
   D. The direction of an induced current opposes the cause that produced it.

5. A rectangular loop of wire is immersed in an external magnetic field that is becoming stronger as time goes on. Which of the following statements about flux through the loop is correct?

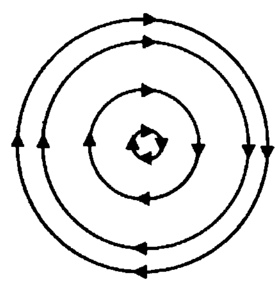
   A. The flux is constant.
   B. The flux is zero.
   C. The flux is increasing.
   D. The flux is decreasing.

6. Two conducting loops are arranged as shown with their centers on the same vertical axis. If the lower loop has an increasing current in a counter-clockwise direction, which of the following statements is true about the induced current, if any, in the upper loop?



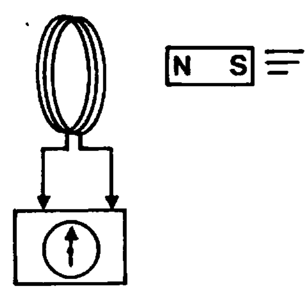
A. It is clockwise.
B. It is counter-clockwise.
C. There is no induced current.
D. It is steady.

7. The adjoining diagram could represent what type of field lines?



A. Either a magnetic or an electric field
B. Neither a magnetic nor an electric field
C. Only a magnetic field due to a straight wire
D. Only electric fields due to a point charge

8. A bar magnet is shoved into a coil of wire and remains inside motionless. During this process, a sensitive galvanometer, which measures charge flow, will

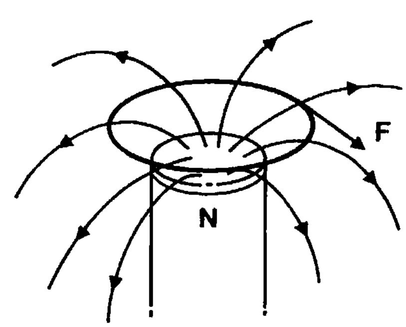


A. deflect only while the magnet is moving.
B. not deflect at all.
C. deflect and remain deflected as long as the magnet remains inside.
D. have an oscillating deflection until the magnet is removed.

9. Which of the following could never produce a current in a closed loop of wire?

A. Moving the loop into the field of a magnet.
B. Keeping the loop stationary while bringing the magnet closer to it.
C. Turning off the flow of current in a neighboring wire.
D. Simultaneously moving both the loop and a magnet, with the same velocity in the same direction.

10. A loop of wire is moving upward in the field of a bar magnet. The vector F in the diagram indicates



A. the force acting on an electron.
B. the electromotive force.
C. a centripetal force.
D. the direction of the magnetic field.

ESSAY QUESTIONS

11. **Are the electric field lines induced by a changing magnetic flux in any way different from electric field lines due to charges? Explain.**

12. **State and discuss the significance of Faraday's law of electromagnetic induction.**

KEY

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

SUGGESTED ESSAY RESPONSES

11. Yes. Changing magnetic fluxes cause closed loops of electric field lines. Electric field lines associated with charges start and stop on charges.

12. Faraday's law says that a changing magnetic flux will give rise to an electric field. Faraday's law is the basis of electric power generation, responsible for lighting, heating, air conditioning, as well as power for industry.

TEACHER'S GUIDE TO ALTERNATING CURRENT

CONTENT AND USE OF THE VIDEO - The video develops the rationale for transmitting electric power using alternating rather than direct current. The development includes the history of the famous dispute between Thomas Edison, the proponent of direct current, and Nikola Tesla, the proponent of alternating current. The difference between direct and alternating current is described briefly. A simple introduction to the transformer is provided through computer animation and is followed by a discussion of the importance of the transformer in the transport of electric power.

The video should be used after the study of Faraday's law of electromagnetic induction. Although the video does not discuss the concept of induced electromagnetic force, this idea is considered briefly in the SUPPORTIVE BACKGROUND INFORMATION.

TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO - Although the students may have previously encountered the following terms, it is important to review them prior to showing the video:

alternating current (ac)--electric current which periodically reverses in its direction of flow from the generator or power supply; an individual electric charge in an ac circuit usually undergoes simple harmonic motion.

direct current (dc)--electric current in which the electric charges in the circuit have a slow drift always in the same direction; although the individual charges slowly drift through the conductor, the electrical effects of potential difference and current propagate very rapidly.

power--the rate of transfer of energy; electrical power can be evaluated using the equations $P = VI = I^2R = V^2/R$, where P is the power, V is the potential difference, I the current, and R the resistance.

resistance--in a conductor the resistance is the slope of the voltage versus current graph. The video emphasizes another aspect of resistance, i.e., that electrical resistance is directly proportional to length of conductor.

transformer--an electrical device formed by two coils of wire that are connected by an iron core; in an ac circuit a transformer makes it possible either to raise or lower the voltage of the power transmitted to the second coil.

WHAT TO EMPHASIZE AND HOW TO DO IT - The industrial revolution of the latter part of the nineteenth century dramatically changed the face of the world. Michael Faraday's discovery of electromagnetic induction laid the groundwork for the conversion of mechanical energy into electrical energy. But the technology that put electrical energy into practical use was invented by a native-born American, Thomas Edison, and an immigrant to America, Nikola Tesla. In discussing the struggle between the ideas of these two giants, the video presents the physics of alternating currents, the type of current that eventually made Tesla's vision of transporting electric power more practical than Edison's method.

Objective 1: Distinguish between alternating current and direct current.

The video utilizes computer animated circuit diagrams to depict alternating current and direct current while the narrator describes each one. To insure that students understand the distinction between alternating current and a current that flows steadily in one direction, you might want to stop the video for discussion at the point where the two circuit diagrams are presented simultaneously on the screen. DEMONSTRATION #1, on alternating versus direct current, helps students to visualize the motion of charges in the two types of currents.

Objective 2: Describe the essence of the dispute between Edison and Tesla.

For many years, Tesla and Edison engaged in a dispute about electric currents. Edison advocated direct current as the safest and most effective type of electricity to power the nation. To point out the danger of alternating current to the public, Edison conducted gruesome experiments on animals. Tesla's reputation suffered greatly from his battle with Edison. Nonetheless, students may be interested to know that Edison's accusations were erroneous. Alternating current is no more dangerous than direct current. Essentially, the electric power (I^2R) dissipated by the cells of the body causes injury, not the direction of the current flow.

Both the video and the background information cite the accomplishments of Edison that endeared him to the public. These include the incandescent bulb, the phonograph, and the motion picture camera.

Objective 3: Discuss the basic relationships of electric power, current and voltage.

Since power is equal to current times voltage, the same power can be transmitted at high current and low voltage or low current and high voltage. This relationship is presented briefly in the video, and students are asked to apply the relationships in solving several problems in the STUDENT'S GUIDE. Both DEMONSTRATION #4, on power, current, and voltage, and DEMONSTRATION #2, on heating in wires of different resistance, can be used to emphasize and reinforce the relationships. A commonplace example to cite is an electrical space heater which is a resistor and which converts electrical energy to heat energy at the rate I^2R. Students often confuse power with energy, so the difference between the two should be carefully pointed out. Also, students frequently believe that a larger resistor *always* dissipates more power. It must be stressed that, when different resistors are placed across the *same* potential difference, the smaller resistor will dissipate more power.

Objective 4: Explain the problem of transmitting electric power over great distances.

Power cables offer resistance to the flow of current and thereby cause heating. The video describes the impact of heating on the electrical energy transmitted and how such transmission can be accomplished most effectively. Students may have difficulty understanding the equation, so the meaning of each term should be carefully discussed. The SUPPORTIVE BACKGROUND INFORMATION develops these same equations.

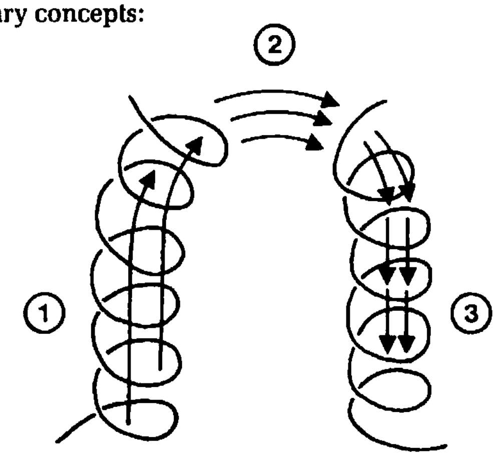
DEMONSTRATION #2 visually illustrates that a greater resistance of wire leads to greater heating loss in a series circuit. The demonstration offers reinforcement of the concepts presented in the video.

Objective 5: How does the transformer give Tesla's alternating current an advantage over Edison's direct current?

Stepping up and stepping down voltage is difficult to achieve with direct current. However, the transformer makes this transformation relatively easy in an alternating current circuit with very little power loss. The video uses computer animation to describe how the transformer works in stepping up the voltage for energy efficient long-range transmission.

If students have difficulty understanding the nature of the transformer a diagram could be used to help them in the development of three primary concepts:

1. A current creates a magnetic field in the primary coil (*Ampere's law*). Changing the current changes the magnetic field.
2. An iron core directs the magnetic field produced by the primary coil through the secondary coil.
3. The changing magnetic field in the secondary coil induces an emf (*Faraday's Law*). The size of the emf is governed by the number of loops in the primary and secondary coils.



Both DEMONSTRATION #3 and DEMONSTRATION #5 illustrate characteristics of transformers. DEMONSTRATION #5 should also help to correct the following common misconceptions about transformers:

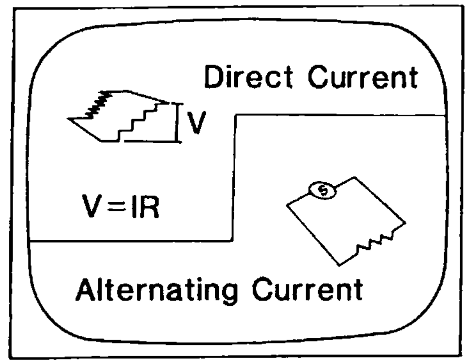
(a) Transformers are just amplifiers. Point out that in a transformer the power output is approximately equal to the power input. However, in an amplifier the power output can be appreciably greater than the power input due to added power supplied to the amplifier.
(b) Transformers give you something for nothing. Point out that a transformer must have a source of power.
(c) Step-down transformers are no different from voltage dividers. Point out that a voltage divider, as its name indicates, only taps off part of the power input into it; the remaining part is dissipated as heat energy.

At this time it would be helpful to discuss with students several observable applications of transformers. Point out the large transformers in the power distribution network which can be seen in neighborhood sub-stations as well as on power poles before the electric lines come into homes. Also make students aware of the smaller scale transformers in electronic devices, e.g., the transformers for electric trains and radios.

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 video frames.

Explain the difference between direct current (dc) and alternating current (ac).

Direct current is that current in which the electric charges in the circuit have a slow drift always in the same direction. Although the charges move slowly, the electrical effects of the applied potential difference will propagate very rapidly. Alternating current is current that periodically changes in its direction.



Who fought the "war of currents" and for what reason was it fought?

The "war of currents" was the name used to describe the dispute between Edison and Tesla as to whether electrical distribution systems should be based on ac or on dc. The battle reached far beyond the domain of scientific theory; many other interests were involved.

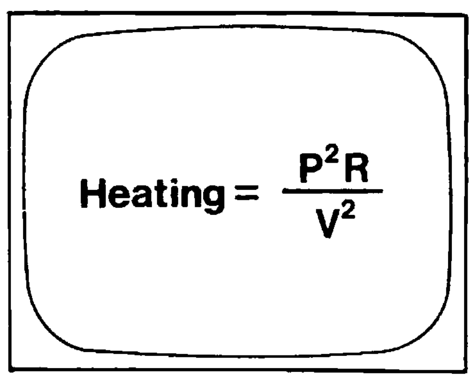
It is suggested that you stop the video at the point where the equations appear superimposed over the control room of the generating station. Give the students time to solve the problems.

How much power will be lost to heat in a long distance power distribution system if the lines have a total resistance of 10^2 ohms and if 10^6 watts of power is to be delivered at a potential difference of 10^5 volts?

Rework the previous problem with the potential difference equal to only 10^3 volts.

The problem can be solved by using the following relationships:

$$P_G = IV_G \text{ and } P_R = I^2R.$$



Solving for I from the first relation and substituting into the second, we get

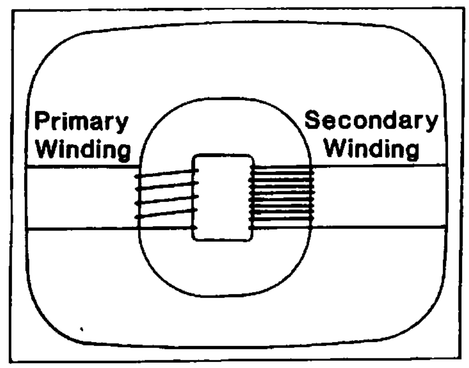
$$P_R = \frac{P_G^{\,2}R}{V_G^{\,2}} \; .$$

Substituting values we have $P_R = (10^6)^2(10^2)/(10^5)^2 = 10^4$ *watts for the higher voltage,*

and, $P_R = (10^6)^2(10^2)/(10^2)^2 = 10^{10}$ *watts for the lower voltage.*

The lower voltage results in an enormous energy waste.

How does the power in the secondary winding of a transformer compare to the power in the primary winding?



The power in the secondary winding will be equal to, or less than the power in the primary winding.

Why do transformers require ac?

To induce a potential difference across the secondary winding in the transformer, it is necessary for a changing magnetic flux to be guided through the coil by the iron core. A changing magnetic flux can be initiated in the core only by a changing or alternating current through the primary winding.

EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS - One of the most important concepts developed in this module is the basic idea behind the operation and application of the transformer. Particular attention is given to the application of the transformer to the problem of large scale electric power distribution, but it might be well to point out a few of the other applications of the transformer.

1. **Assorted Electronic Devices**

   Almost all TV sets, video recorders, stereo sound systems, electronic computers, etc., operate on voltages which are different from the line voltage. When you plug these devices into the wall, the first circuit element encountered by the incoming ac is a transformer which steps the voltage up or down before it is applied to other circuit elements. As well as the "power transformer," which powers the majority of the circuits in your TV, a special "fly back" transformer is connected to the output of the "horizontal oscillator" circuit to produce the very high voltage necessary to power the picture tube.

2. **Toys and battery chargers**

   Toys such as electric trains and slot cars use step down transformers to reduce the line voltage to a safe level. Devices which charge rechargable batteries must first step the voltage down with a transformer and then use a device called a rectifier to convert the ac to the dc necessary to charge the battery.

3. **Camera strobe units**

   To store enough energy to flash a high energy camera strobe, a high voltage potential difference must be used to charge a storage capacitor. To accomplish this with batteries, the batteries are connected to an oscillator circuit which turns the dc to ac. This low voltage ac is then applied to a step up transformer, the output of which is passed through a rectifier which changes the high voltage ac back to dc. Finally, this high dc voltage can now charge the capacitor to a much higher energy than the battery could have reached alone.

4. **Automobile ignition system**

   The coil in an automobile ignition system is actually an "auto transformer." This name has nothing to do with the fact that it is used in an "automobile"; rather it means it is a special type of transformer which operates on self inductance. The low voltage dc from the battery is interrupted by the "breaker points" which produce a rapidly changing current pulse in the primary winding of the auto transformer. This induces a high voltage pulse in the secondary winding which is directed through the distributor rotor to the proper spark plug.

SUMMARY - This module addresses the important question of why electrical energy distribution systems are based on alternating current (ac) rather than on direct current (dc). The question is set within the historical context of the dispute between Thomas Edison and Nikola Tesla. An understanding of that dispute and its resolution necessitates a study of the difference between alternating and direct current, the relationships of power, current, and voltage to heat loss in electrical cables, and the function of the transformer.

NOTE OF EXPLANATION REGARDING THE STUDENT'S GUIDE - The following two pages of the STUDENT'S GUIDE should be duplicated and distributed to the students for use in preparation for viewing the video.

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.

STUDENTS GUIDE TO ALTERNATING CURRENTS

INTRODUCTION - This video develops the physical reasons for transmitting electric power using alternating current rather than direct current. The development includes the historical dispute between Thomas Edison, the proponent of direct current, and Nikola Tesla, the proponent of alternating current. The operation of a transformer is also presented.

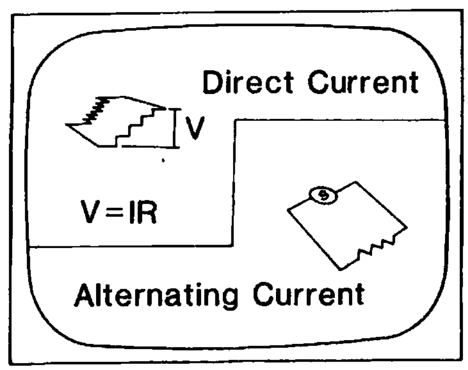
Terms Essential for Understanding the Video

alternating current (ac)
direct current (dc)
power
resistance
transformer

**** 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. ****

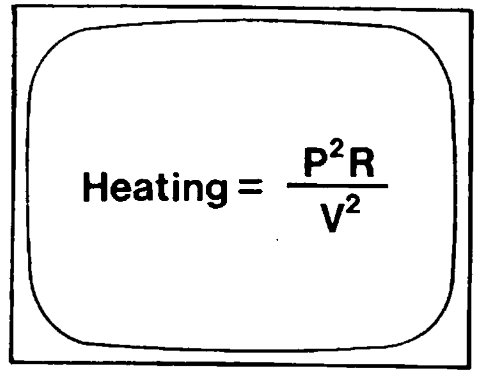
Points to Look for in the Video

Explain the difference between direct current (dc) and alternating current (ac).



Who fought the "war of currents" and for what reason was it fought?

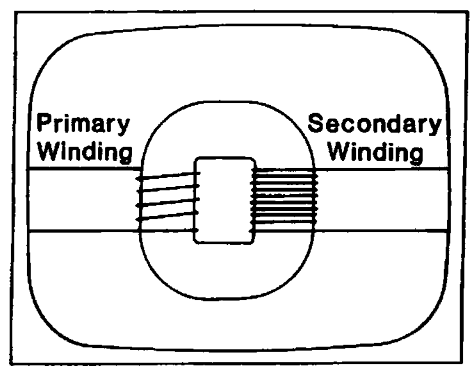
How much power will be lost to heat in a long distance power distribution system if the lines have a total resistance of 10^2 ohms and if 10^6 watts of power is to be delivered at a potential difference of 10^5 volts?



Rework the previous problem with the potential difference equal to only 10^2 volts.

(You might ask your teacher to stop the video when the appropriate equations appear for working this problem.)

How does the power in the secondary winding of a transformer compare with the power in the primary winding?



Why do transformers require ac?

TEACHER RESOURCES

SUPPORTIVE BACKGROUND INFORMATION - The growth of the electric industry has resulted from an increasing public demand for products that use electrical energy. In the United States, one of the first commercially successful of these products was the electric light bulb. Although Thomas Edison developed an incandescent light bulb suitable for use in the home, he did not invent the light bulb, nor did he advance any new scientific principles to explain its operation. However, he did develop a system for local distribution of electric power. His direct current systems made the light bulb practical and opened the way for mass consumption of electrical energy.

Edison established a laboratory that was a prototype for modern industrial research. He invented by design. When he saw a human need, such as street lighting, he would invent something to fill this need. His approach to every task was careful and methodical, and he did nothing haphazardly. He held over 1,000 important patents, and among his inventions were many devices that became commonplace in everyday life, including the the phonograph and the motion picture camera.

Nikola Tesla, another great inventor of the same era, was born in Serbia (now part of Yugoslavia). Although his original occupational intentions were directed towards the clergy, he developed a taste for mathematics and science that soon distracted him from that work. In 1884 he arrived in the United States with 4 cents in his pocket, a book of poetry, knowledge of a dozen languages, and a desire to work for Edison.

Although Tesla initially worked for Edison, there soon developed a difference of opinion between these two giants on the best method of power distribution. Tesla was determined to make alternating current the world standard. Since Edison was already committed to direct current, the working relationship did not prosper. Edison's direct current systems for the generation and distribution of electricity were small in scale. They depended on local sources of power which could economically supply users who were less than 1/2 mile from the generating plant. Alternating current systems were initially handicapped by the lack of an efficient alternating current motor. Nonetheless, Tesla foresaw that newly evolving devices would overcome these difficulties.

George Westinghouse was one of the few men who had faith in Tesla's ideas. Several patents describing Tesla's inventions were granted in 1888 and bought by Westinghouse. The first attempts to put them into practice were met with tremendous opposition. By 1895, however, 100,000 horsepower of electrical energy was generated at Niagara Falls, an output equaling that of all other generating stations in the United States. A significant part of that energy was transmitted and converted to mechanical energy by Tesla's inventions. Within a year some of this energy was transmitted 20 miles to Buffalo to light its streets and homes. The electric revolution was well on its way as old systems were scrapped and replaced by those of Tesla's design.

Alternating current was preferred to direct current because it minimized electrical energy transformation to heat energy. The electric generator produces power which must be transmitted through wires that have a resistance. Since electrical resistance is directly proportional to the length of wire, longer transmission lines result in larger resistance. Power is equal to the product of applied voltage and current or $P = VI$. The rate of energy transformation can be seen by considering the units:

$$P = \text{volts} \cdot \text{amps} = \frac{\text{Joules}}{\text{second}} = \text{watt}\,.$$

The electrical power made available by a generating station is transmitted to the line and then to the consumer. The same power output can be delivered at a smaller current if the voltage can be made larger. When current I flows in a transmission line of resistance R, the electric power transformed to heat is given by the relationship:

$$Rate\ of\ Heating = P_R = IV_R = I^2R\,.$$

Ohm's law provides the connection between the potential drop across the resistor V_R and the current I, $V_R = IR$. Because of the power loss in the transmission lines, the power available to consumers is

$$P_{OUTPUT} = P_{GENERATOR} - P_R\,.$$

It is important to distinguish between the power of the generator (P_g) and the power loss due to heating in the transmission lines (P_R). Transmission lines have a fixed length and diameter and thus a fixed resistance. To minimize the power loss to heating, the electric current should be as small as possible. Since $P_G = IV_G$, $I = P_G/V_G$. Using $PR = I^2R$ it then follows that

$$P_R = \frac{P_G^{\,2}}{V_G^{\,2}}\,R\,.$$

For a given power output of the generator and resistance of a transmission line, increasing the output voltage decreases the energy lost to heating.

In modern electric power grids, energy is routinely transmitted over thousands of kilometers at hundreds of thousands of volts. However, the consumer wants the power at a low, safe voltage (now accepted to be about 115 V or 230 V). The key to a practical electric power grid is the ability to transform electrical energy to high voltage for transport over long distances and then step it down to low voltage for consumer use. Using transformers, this task is easily achieved with alternating currents. There was no direct current equivalent until recently. Using more recent technology, it is now possible to transmit direct current at very high voltage over long distances. Such transmission is becoming economically more attractive and is presently being used to a small extent. More information can be found in a *Scientific American* article entitled "High Voltage Power Transmissions" by L.O. Barthold and H.G. Pfeiffer in the May 1964 issue.

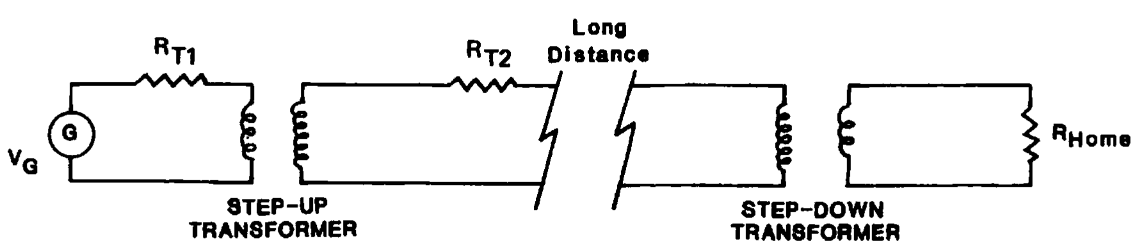


Figure 1
Schematic wiring from generating plant to home.

Figure 1 shows a simplified form of the distribution system for electricity from generating plant to home. R_{T1} and R_{T2} represent the resistance in the transmission lines; V_G is the potential difference across the terminals of the generator. Transformers are the key elements in modifying the size of current and voltage.

Two coils of wire arranged around a common iron core form a transformer.

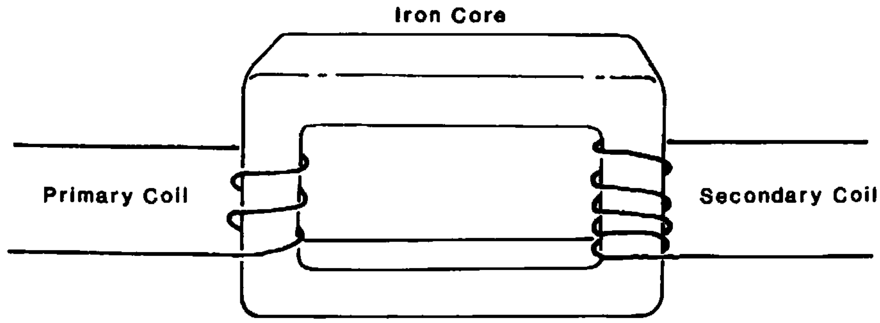


Figure 2
Transformer

An alternating current is applied to one coil of wire (the primary coil) which creates an alternating magnetic field. The iron core directs this changing magnetic field through a second coil of wire (the secondary coil). It is assumed that there is no energy loss in the transfer from primary to secondary i.e., all the power delivered by the primary coil is transferred to the secondary coil. However, there are energy losses in a transformer. Energy is dissipated as heat in the coils and in the iron core. The heating in the core is normally minimized by using a laminated core consisting of many layers of thin steel strips. The laminations minimize eddy currents.

In the primary coil there is an alternating current that causes an induced emf which, ignoring coil resistance, must equal the potential drop. According to Faraday's law, the induced emf, ε_p, equals the rate of change of flux and, hence,

$$\varepsilon_p = -\frac{\Delta\phi_p}{\Delta t} .$$

The iron core has the effect of guiding all the changing flux in the primary coil through the secondary coil. Again employing Faraday's law,

$$\frac{-\Delta\phi_s}{\Delta t} = \varepsilon_s$$

or

$$V_s = \frac{\Delta\phi_s}{\Delta t}$$

where V_s is the output voltage of the secondary. If ϕ is the flux through each turn of wire, then $\phi_p = N_p\phi$ and $\phi_s = N_s\phi$. N_p is the number of turns of wire in the primary coil while N_s is the number of turns of wire in the secondary coil. Since

$$\varepsilon_p = -\frac{\Delta\phi_p}{\Delta t} = -N_p\frac{\Delta\phi}{\Delta t} ,$$

$$\frac{\varepsilon_p}{N_p} = -\frac{\Delta\phi}{\Delta t} .$$

Similarly,

$$\frac{\varepsilon_s}{N_s} = -\frac{\Delta\phi}{\Delta t} .$$

Thus it can be seen that

$$\frac{\varepsilon_p}{N_p} = \frac{\varepsilon_s}{N_s} ,$$

or,

$$\varepsilon_s = \varepsilon_p \frac{N_s}{N_p} .$$

If the resistance of the primary and secondary is ignored, the relationship can be expressed as

$$V_s = V_p \frac{N_s}{N_p} .$$

The induced emf in the secondary coil is related to the induced emf in the primary by the ratio of number of turns of wire in the secondary to the primary. For example, if the primary coil has 10 turns and the secondary coil has 500 turns, the voltage in the secondary coil will be nearly 50 times greater than that in the primary coil. Such a transformer is a step-up transformer and is typically found at electric generating stations.

When electric power is transmitted over long distances, the potential difference created by the generator is stepped up to a very high value (typically from 30,000 to 220,000 volts or even higher values). At substations, the power passes through step-down transformers reducing it to approximately 4,000 volts. Another step-down transformer further reduces the voltage to 115 or 230 volts for use in homes. These systems are used successfully because transformers can transfer power from the primary to the secondary with an efficiency between 90% and 99%.

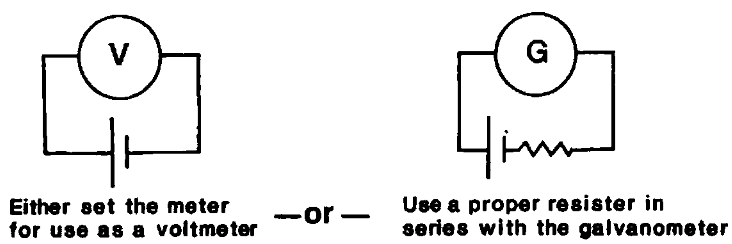
ADDITIONAL RESOURCES

Demonstration #1: Alternating vs. Direct Current

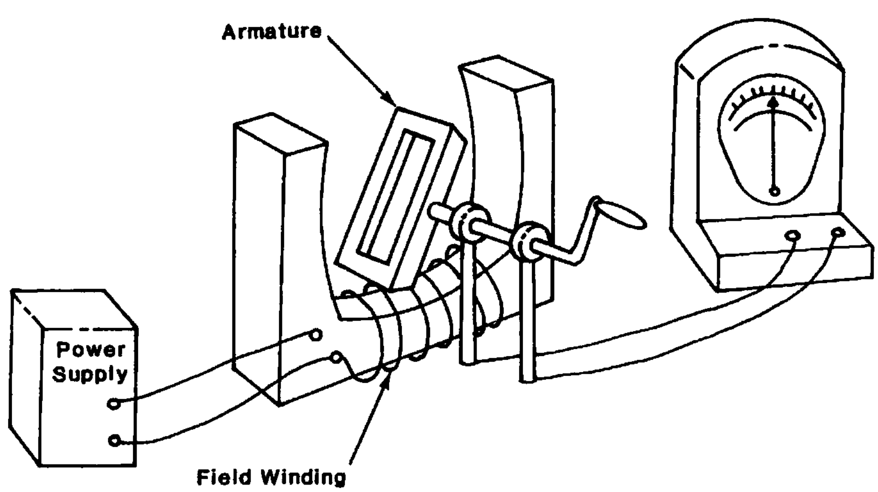
Purpose: To show how voltage varies with time in alternating and direct current and to help students visualize the motion of charges in these two different types of current.

Materials: A galvanometer with a zero at center scale (preferably a demonstration type); a dry cell; a demonstration motor generator (such as Welch #2408 "Dynamo Electric Machine", Miller-Cowan design); and a low voltage power supply or, lacking the motor generator, a large coil of low resistance wire and a bar magnet.

Procedure and Notes: CAUTION: Do not attach a dry cell directly across a galvanometer. Either convert the galvanometer to a voltmeter, using the provided series resistance or place a proper resistor in series with the dry cell (try about 3K). A 1.5V dry cell can damage a galvanometer if connected without a series resistance.



1. Connect the dry cell across the voltmeter (properly protected galvanometer) and note that it gives a constant reading. Reverse the leads and show how it gives the same value with the opposite sign.

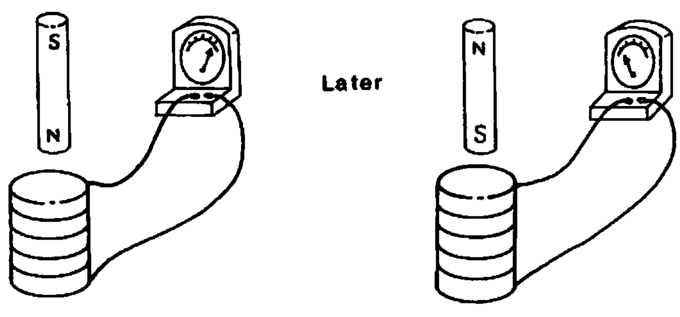


2. Connect the armature of the demonstration generator directly to the galvanometer through the brushes attached to the slip rings. Attach the low voltage power supply to the field winding and carefully increase the current to several amps. (Note: The galvanometer will probably deflect while you are changing the current. Proceed with caution so as not to damage the galvanometer. This will be discussed in DEMONSTRATION #3.) Slowly rotate the armature and notice that the reading on the galvanometer will swing from + to − and back again. Rotating more rapidly will at first increase the amplitude of swing but, if rotated too rapidly, the inertia of the galvanometer movement will act to give a lower reading. Don't be fooled. Current is still passing through the galvanometer, but the meter is not quick enough to register the current. Strive to rotate at a frequency which gives a large deflection so that the students will be able to correlate the movement of the armature with the reading on the meter.
3. If you do not have a demonstration motor generator, connect a large coil of low resistance wire directly to the galvanometer. Thrust a bar magnet into the coil, withdraw it, reverse its polarity, and thrust it into the coil again. With quickness and coordination you should be able to make the galvanometer swing back and forth in a fairly smooth fashion.

Explanation:

The dry cell causes the charges in the wire to flow only in one direction or--"direct current." You can help to make this clear to your students by letting your hand represent a charge and moving it slowly in one direction as an illustration of "dc."

As the armature rotates in the external magnetic field, the force on the charges (through magnetic induction) is constantly changing in magnitude and direction. This causes the charges to move back and forth in the wire, thus producing an "alternating current." As before, let your hand represent a charge and move it back and forth to represent the motion of the charges in "ac."



Demonstration #2: Heating in Wires of Different Resistance

Purpose:

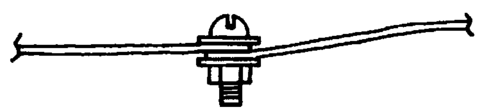
To demonstrate that more heating will take place in a high resistance wire than in a low resistance wire when the two are wired in series, and to show that the opposite is true when the two are wired in parallel.

Materials:

A low voltage--high current variable power supply; large diameter and small diameter nichrome wire; heavy copper wire (large diameter extension cord wire works well); several small brass machine screws; washers and nuts.

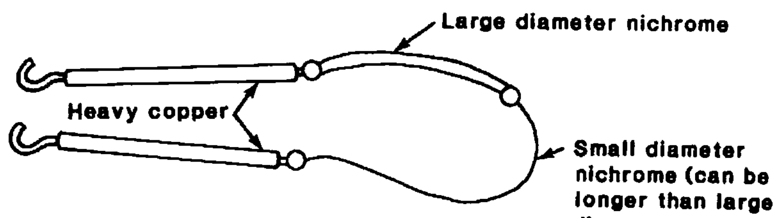
Procedure and Notes:

1. Since the wires will be heating to a fairly high temperature, soldering, or even twisting, wires together will not be a satisfactory method of making a connection. One simple method for joining two or more wires together is to use two washers, a small machine screw, and a nut as illustrated. Brass works better than steel.



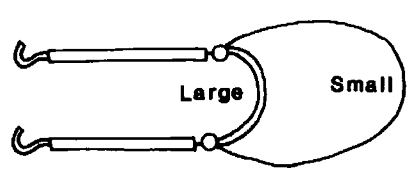
Machine screw wire connector

2. As illustrated, make a series connection of the large diameter nichrome wire and small diameter nichrome wire using the large copper wire to establish a return to the power supply.



Series Configuration

3. Also you can make a parallel connection as illustrated. (The parallel demonstration is *not* necessary, however, for the development of this module.)



Parallel Configuration

Note: It will be necessary for you to experiment to discover how long a piece of nichrome is required with your power supply to produce a red hot glow.

Place the series configuration across your power supply, darken the room, and turn up the power until the small diameter wire begins to glow. Don't heat beyond the "red hot" temperature since the wire could melt.

To clear up the common misconception that the high resistance wire *always* dissipates the greater heat, repeat this demonstration with the parallel configuration. In this case the large diameter will glow first.

Explanation:

Your students should know that the smaller diameter (and perhaps longer piece of) nichrome wire has a large resistance. In the series configuration, the fact that the small diameter wire glows and the large diameter wire does not indicates that the smaller one is at a higher temperature. It dissipates more heat.

While the parallel demonstration is not necessary in the development of this module, it can help to identify a common misconception about resistance and heating. To help resolve this misconception, remind the students that, in a resistive circuit:

Rate of Heating $= I^2R,$ (1)

however, $I = V/R,$

therefore, Rate of Heating $= V^2/R.$ (2)

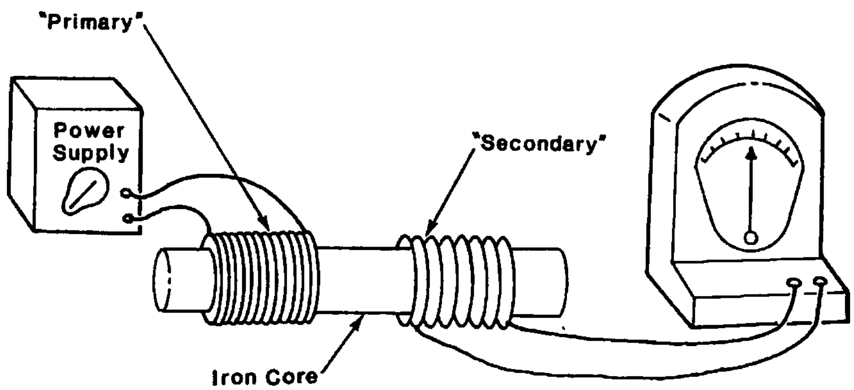
Equation (1) explains the series case where the current is the same throughout. Equation (2) must be used in the parallel case because here the voltage across each resistor is the same. Consequently, in a parallel circuit, the smaller resistor will dissipate the greater amount of heat.

Demonstration #3: Transformers Require Changing Currents

Purpose: To show that the current in the primary winding of a transformer must change with time for a current to be induced in the secondary. ac not dc, is required to make a transformer work.

Materials: A low voltage, high current variable dc power supply; two coils of wire which can be "linked" with an iron core; a demonstration galvanometer with zero at center; assorted leads.

Procedure and Notes: With the power off, attach the power supply to one of the coils. Link this primary coil to the secondary coil with the iron core. Then attach the secondary coil to the galvanometer.



CAUTION: Do not turn on the power supply unless the adjustment knob is at its lowest setting. Too rapid a change in the current in the primary coil could cause damage to the galvanometer. Do *not* use alternating current!

With the knob at its lowest setting, turn on the power. Slowly increase the voltage and the galvanometer will deflect. However, if you hold the current at a constant setting, the galvanometer will return to zero. Increase and decrease the current while noting that the galvanometer will deflect *only* when the current is changing. Make sure you have returned the power supply to its lowest setting before you turn off the current.

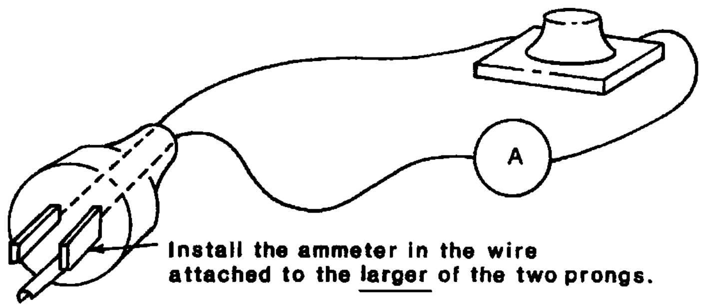
Explanation: Current is induced in the secondary only when the magnetic flux through it *changes*, and this will occur only if the current in the primary is changing. A constant current, or dc, cannot be used in a transformer.

Demonstration #4: Power, Current, and Voltage

Purpose: To show how current, voltage, and power are related in a simple electric circuit.

Materials: Several different wattage light bulbs; ac current meter; ac voltmeter (not essential); modified light socket, plug, and wire.

Procedure and Notes: Prepare the light socket, connection wire, and plug as illustrated.



CAUTION: In certain parts of this circuit, line voltage will be exposed. For additional safety, use a three wire plug and insert the ac ammeter in the "power company ground" side of the wire. Even with this precaution, the *exposed wires should be regarded with respect.*

Place a particular wattage bulb in the socket and with the ac ammeter in series with the circuit, plug it in. Either measure the voltage across the bulb with the ac voltmeter or assume it to be the standard 115 volts. Measure the current and observe that the product of the current and the voltage nearly equals the power rating of the bulb.

Explanation: The only dissipative element in the circuit is the bulb. Since $P = IV$, all the power input to the circuit will be dissipated by the bulb. The ratings given on standard bulbs are reasonably accurate.

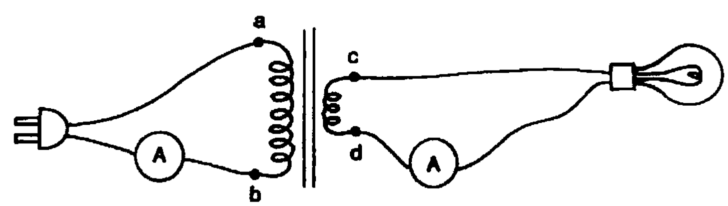
Demonstration #5: Electric Power and Transformers.

Purpose: To show that, although a transformer can change voltage and current, the electric power is almost the same in the primary coil as in the secondary coil.

Materials: A 115V - 12V step down transformer (The type used in a "Tensor" high intensity lamp will work nicely. Check at Radio Shack, your local electronic parts store, or sacrifice a high intensity lamp for this demonstration!); an ac ammeter (two would be better); an ac voltmeter (A multimeter set to ac will work fine).

Procedure and Notes: Note: As with DEMONSTRATION #4 you will be using exposed line voltages. Exercise the proper caution.

Wire the ammeter(s) in series with the primary and secondary of the transformer and put a 12 volt bulb across the secondary as illustrated.



Plug the circuit into a wall outlet and carefully measure the input voltage V_i across points ab and the output voltage V_0 across points cd. Observe that the product of the input current and voltage should be slightly larger than the product of the output current and voltage.

Explanation: Power is the product of current and voltage. Since a transformer is a fairly efficient device, the power on the output almost equals the power on the input. The slight difference can be accounted for by the heating of the transformer.

EVALUATION QUESTIONS

1. **Which of the following is true *only* for alternating current?**

   A. It is defined as charge per time.
   B. It can be transported over *large* distances.
   C. It can be used effectively with transformers.
   D. It is more dangerous at high voltages.

2. **The conflicting ideas of Edison and Tesla lead to a monumental debate known as the "war of the currents." Which of the following was *not* a factor in this debate?**

   A. A difference of opinion on how light bulbs operate.
   B. Personal jealousies and prejudices.
   C. A consideration of safety.
   D. Large amounts of money.

3. **An electric light bulb of resistance R is to be used in a standard lamp socket at ordinary line voltage. What should be the resistance of another bulb which is to be used in this same socket at the same voltage if the new bulb is to use twice the power?**

   A. 4R
   B. 2R
   C. R/2
   D. R/4

4. **A major problem in linking a source of power to a distant city is the heat loss in the long distance power transmission lines. Which of the following changes in the long distance power lines will minimize this loss?**

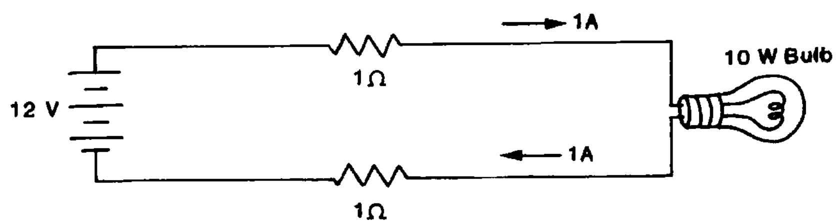
   A. Increasing the voltage and the current in the transmission lines.
   B. Increasing the current and the resistance of the transmission lines.
   C. Increasing the voltage with the same line resistance.
   D. Lowering the input voltage with a transformer.

5. **The *main* reason transformers are used in *long* distance power distribution systems is:**

   A. They use direct current rather than alternating current.
   B. They can change voltage and current with little loss in power.
   C. They are a safe and efficient method of transforming energy.
   D. They change the direction of the current so magnetic induction can take place.

Use the following information for Questions 6 - 8:

A young scientist is designing a lighting system in which the battery will be in one location and the light will be some distance away. Each of the two long wires that go from the battery to the light has a resistance of 1 ohm. He wants to use a bulb of exactly 10 watts at the other end. He first tries to use a 12 volt battery as his source of potential difference as shown below:



6. **If he knows the current in this circuit is one amp, what must be the resistance of the 10 watt bulb?**

   A. 1 ohm
   B. 1.2 ohm
   C. 6 ohm
   D. 10 ohm

7. **How much power is wasted as heat in the connection lines?**

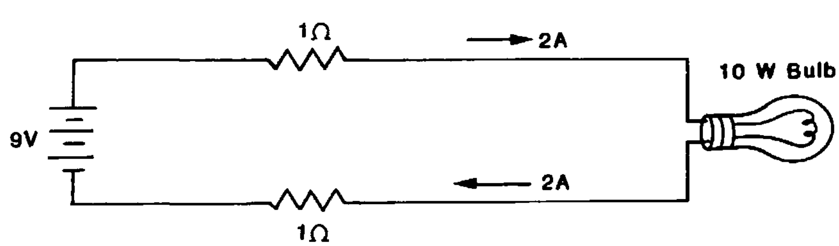
   A. 1.2 watts
   B. 2 watts
   C. 4 watts
   D. 12 watts

8. **What is the total power supplied by the battery?**

   A. 10 watts
   B. 12 watts
   C. 14 watts
   D. 144 watts

Use the following additional information for Questions 9 - 10:

Now he wishes to see the effect of using a 9 volt battery rather than the 12 volt battery. Again he wants the bulb to be a 10 watt bulb so he must select one with a different resistance. This time he reasons correctly that the current in the wires will be 2 amps.



9. What must be the resistance of the 10 watt bulb in this lower voltage system?

   A. 1 ohm
   B. 2.5 ohm
   C. 4.5 ohm
   D. 5 ohm

10. How much power is wasted in the connecting lines?

   A. 8 watts
   B. 10 watts
   C. 18 watts
   D. 28 watts

ESSAY QUESTIONS

11. Discuss why it is more economical to transmit electric power using ac rather than dc.

12. Discuss why a transformer will *not* operate if steady dc is furnished to the primary coil.

KEY

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

SUGGESTED ESSAY RESPONSES

11. Since less energy will be lost due to heating in the transmission lines if the current is reduced, the power must be transmitted at as high a voltage as possible. However, high voltages would be dangerous in most ordinary consumer situations. Therefore, some method of stepping the voltage up and down efficiently must be used. Transformers are the most efficient and economical method of accomplishing the stepping up and down of voltages, but they require ac for their operation. Direct current cannot be efficiently stepped up and down.

12. Transformers operate by electromagnetic induction and a changing magnetic flux is required. The alternating current, supplied to the primary winding provides this changing magnetic flux to the secondary winding. Steady dc would not produce the necessary changing magnetic flux.

TEACHER'S GUIDE TO THE MICHELSON-MORLEY EXPERIMENT

CONTENT AND USE OF THE VIDEO - The stationary aether was every bit as important to nineteenth century scientists as the stationary earth was to the Aristoteleans before Copernicus. Discarding the aether theory was no small step. The video describes how two American scientists, Michelson and Morley, performed their experiment to detect the aether. The results and implications are also discussed. Students should be exposed to a study of optics before seeing the video, since an understanding of the phenomenon of light interference is assumed. Ideally, the video should precede a unit on relativity.

TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO - The video introduces terms associated with the Michelson-Morley experiment which might be helpful for students to discuss prior to viewing. All terms are defined according to their use within the context of the module.

aether (luminiferous aether)--the supposed medium allowing the propagation of light waves from sun to earth.

Einsteinian relativity--the special theory of relativity led to the assertion that mass and energy are equivalent. It is based on two postulates: (1) absolute motion cannot be determined, and (2) the speed of light is the same to all observers. The theory of relativity was later extended to include gravitation and related phenomena and it is called the general theory of relativity. The special theory of relativity holds only for inertial frames of reference, while the general theory of relativity holds for all frames of reference.

Galilean relativity--if Newton's laws hold in any one laboratory, then they will hold equally well in any other laboratory (or reference frame) moving at constant velocity with respect to the first.

constructive interference--the superposition of two or more waves such that the combined displacements are a maximum.

destructive interference--the superposition of two or more waves such that the combined displacements are a minimum.

interferometer--an instrument that utilizes the interference of light for precise determinations of wavelength, indices of refraction, or very small linear displacements.

inertial frame--a reference frame in which Newton's Laws hold true.

WHAT TO EMPHASIZE AND HOW TO DO IT - The Michelson-Morley experiment is perhaps the most important experiment in the history of physics. It was designed to detect the motion of the earth through the luminiferous aether, which was the medium that was supposed to carry light from the sun to the earth. The video presents both a description of how the experiment was performed and its implications for the history of science.

Objective 1: Identify the properties of the aether.

The video emphasizes the properties of the hypothetical aether and points out its importance in scientific history. The aether was thought to be the medium that allowed the transmission of light waves. It was considered to be either a fluid or a solid of low density which pervaded the entire universe. The material was considered colorless, tasteless, and odorless.

DEMONSTRATION #1 on waves and springs will contribute to a discussion of the supposed aether. Students commonly confuse "organic ether" with the luminiferous aether. Organic ether is used to anesthetize insects and the like.

Objective 2: Describe the operation of a Michelson interferometer.

The operation and theory of the interferometer are detailed in the video. A review of constructive and destructive interference would facilitate this study. Initially students may have difficulty following the theory. If so, replay the video using the still frame to view the graphics of the interferometer. The beam paths are evident and easily traced for students. DEMONSTRATION #2 on a simple interferometer and DEMONSTRATION #3 on the Michelson interferometer provide reinforcement for the video. The SUPPORTIVE BACKGROUND INFORMATION offers extensive coverage of the topic.

Objective 3: Explain the purpose of the Michelson-Morley experiment.

Michelson and Morley set out to detect the hypothetical aether by observing the effects of the earth's motion through it. Michelson, who was already known for accurate work in optics, invented the interferometer for this purpose. With it, extremely precise measurements of length and time could be achieved.

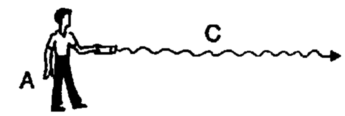
Objective 4: Explain the Fitzgerald contraction.

Michelson and Morley did not succeed in measuring a difference in time for light to travel the two different paths of their interferometer. G. F. Fitzgerald suggested that this might happen if the light path in the direction of the earth's motion would shrink. He even predicted by how much. Point out to students that this part of the video shows the path length contracting.

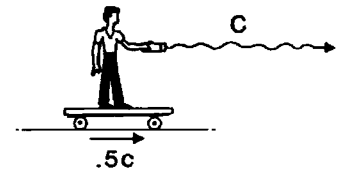
Objective 5: List the implications of the Michelson-Morley experiment.

The Michelson-Morley experiment made a profound impression on the scientific world. The results helped to confirm the Einstein Theory of Relativity and disproved the existence of the aether. The latter part of the video clearly points out the troubling results of the experiment which presented a dilemma. Be sure that students understand the nature of this dilemma. You might want to illustrate the nature of the dilemma as follows:

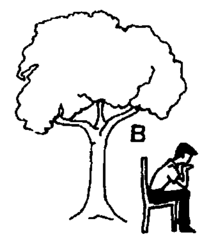
1. Observer A sees a beam of light travel at C.



2. Observer A moves at 0.5c with respect to Observer B.



Galilean relativity (DEMONSTRATION #4) implies that Observer B should see the light travel at c + 0.5c = 1.5c.



The dilemma is that all observers must see the beam travel at c, which is contrary to Galilean relativity as applied to light.

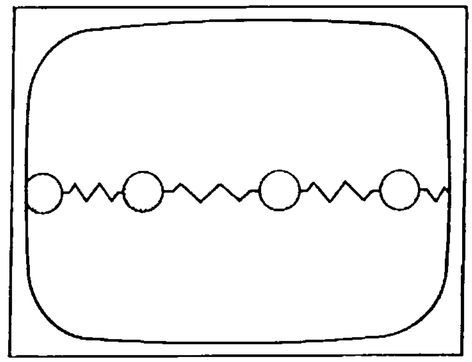
The Fitzgerald contraction was offered as a partial solution to the dilemma. Poincaré suggested that a new kind of dynamics would be necessary. Eventually, Lorentz and Einstein offered theories that helped explain the results of the experiment. Special relativity is the theory that finally resolved the dilemma.

After studying relativity, students may have the misconception that light always travels at the same speed. This is *not* true. Light does travel at different speeds in different materials. The special theory of relativity is based on the idea that observers in any frame of reference would measure the same value for the speed of light in a vacuum.

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.

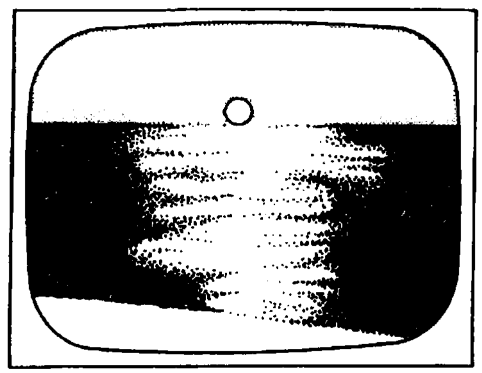
Why did people in the 1800's need an aether to explain how light moved from the sun to the earth?

From the work of Huygens, Young, and Maxwell light was apparently a wave. Since that was the case, it was argued that light needed a medium in which to propagate. This argument prevailed because all waves known at that time required a medium for transmission.



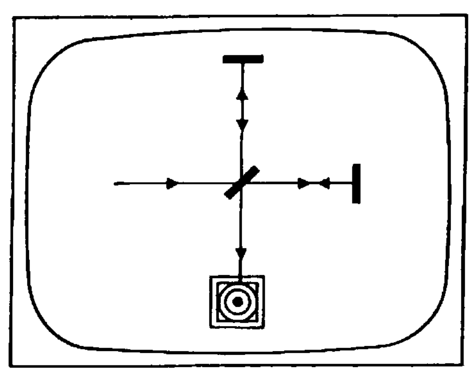
What were two properties of the hypothetical aether?

The aether was stiff but yet provided no resistance to the motion of the planets. It was colorless, tasteless, and odorless.



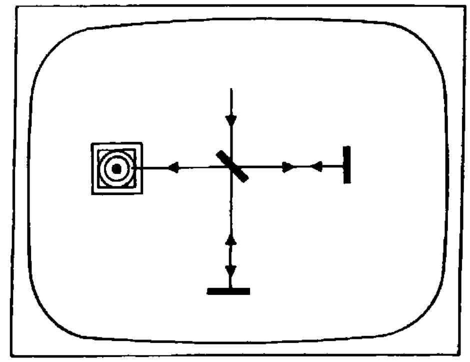
If the aether existed, in an Michelson interferometer which beam would arrive earlier, the one parallel to the flow of the aether or the one perpendicular to the flow of the aether? Why?

The beam perpendicular to the flow of the aether will arrive first since it covers the shorter distance. This is not obvious, but the small difference expected is illustrated in the video.



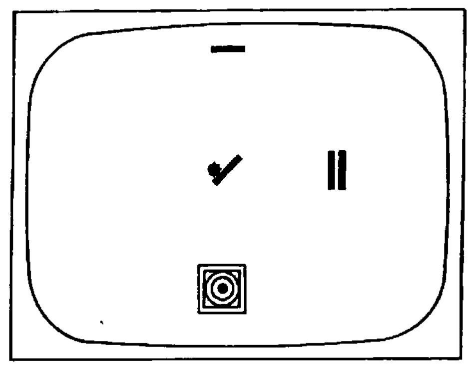
If the aether concept were correct, what should have happened to the interference fringes?

A shift in the fringes would have been apparent.



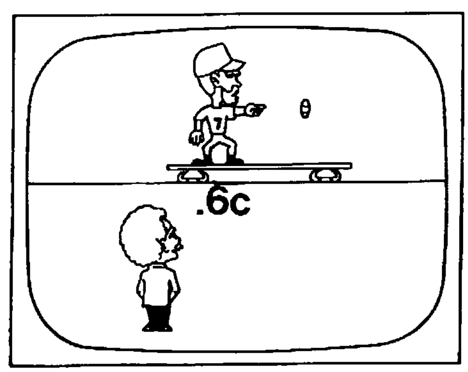
What explanation did Fitzgerald and Lorentz suggest to make the mathematics agree with the experimental results.

They suggested that the path length in the direction parallel to the aether flow would shorten.



The video clearly shows the Lorentz "fast ball" deformed. Why? Since the ball deforms in the direction it is going, must it also deform in the vertical direction?

Objects traveling close to the speed of light will contract in the direction of motion.



SUMMARY - Michelson and Morley set out to detect the aether. The method they used involved an interferometer. The interferometer divided a beam of light into two beams. One beam took a round trip path perpendicular to the motion of the earth about the sun, and the other took a round trip path parallel to the motion of the earth. The motion of the earth through the aether should have been evident in the interference fringes caused by the two light beams recombining out of phase. If the earth were moving through the aether, the two beams would arrive with one delayed and an appropriate pattern would result. Since the fringe pattern did not change, the existence of the aether was not confirmed. The unanticipated outcome prompted conjectures from Fitzgerald, Poincaré, and Lorentz to reconcile theory with experiment. The results contributed to the later confirmation of Einstein's theory of relativity.

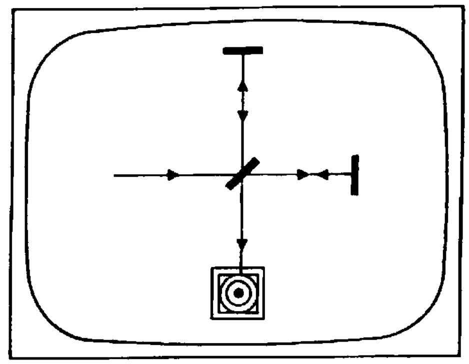
NOTE OF EXPLANATION REGARDING THE STUDENT'S GUIDE - The following two pages of the STUDENT'S GUIDE should be duplicated and distributed to the students for use in preparation for viewing the video.

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.

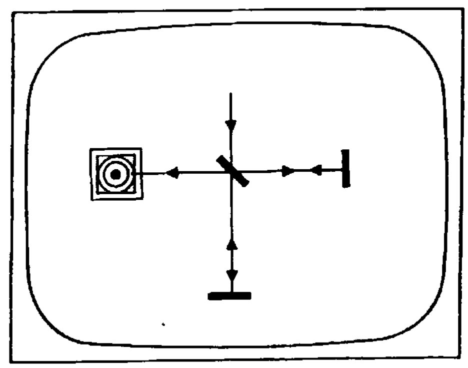
The students should be informed that the INTRODUCTION, TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO, and POINTS TO LOOK FOR IN THE VIDEO should be read and discussed *prior* to viewing the VIDEO. These should also be rediscussed following the viewing.

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.

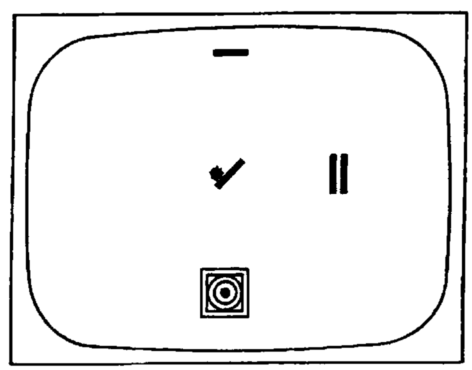
If the aether existed, in a Michelson interferometer, which beam would arrive earlier, the one parallel to the flow of the aether or the one perpendicular to the flow of the aether? Why?



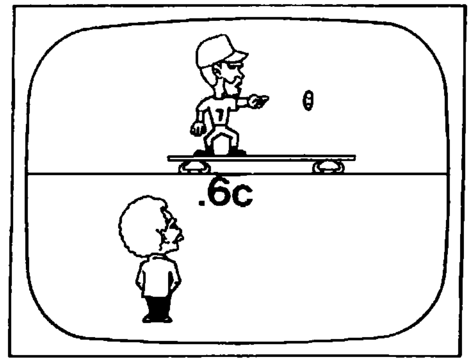
If the aether concept were correct, what should happened to the interference fringes?



What explanation did Fitzgerald and Lorentz suggest to make the mathematics agree with the experimental results?



The video clearly shows the Lorentz "fast ball" deformed. Why? Since the ball deforms in the direction it is going, must it also deform in the vertical direction?



TEACHER RESOURCES

SUPPORTIVE BACKGROUND INFORMATION - Light waves will interfere constructively at a point where the difference in the distance the two waves travel is an integer multiple of one wavelength, and they will interfere destructively at any point where this difference is an odd multiple of half a wavelength. The two types of interference should produce alternate bright and dark fringes on the screen. This effect was actually observed in Thomas Young's experiments in the early 1800's. Because the particle theory of light could not account for the observed interference patterns, Young's work and related experiments were eventually taken as conclusive evidence that light is, indeed, a wave.

Once the wave nature of light was accepted, the next task was to determine what was actually waving. Because sound waves or water waves can only propagate in a medium, it seemed reasonable to assume that light would also require some kind of transmitting medium. To nineteenth century physicists familiar with the mechanical workings of nature, that medium was the *luminiferous aether.*

The notion of an aether can be traced back to ancient Greek philosophers, including Aristotle, who believed it to be the medium through which the planets and other heavenly bodies moved. In the seventeenth and eighteenth centuries, the aether was imagined as an invisible fluid of very low density. This fluid could penetrate all matter and fill all space. It was even thought to be associated with the "effluvium" (something that "flows out") that was imagined to explain magnetic and electric forces.

Light waves must be transverse to explain polarization, and transverse waves propagate only through a *solid* medium. Although transverse waves can exist at the surface of fluids, they cannot be propagated through them. Therefore nineteenth-century physicists assumed that the aether must be a solid. The speed of propagation of a wave increases with the stiffness of the medium, and decreases with its density. Since the speed of propagation of light is very high compared to that of other kinds of waves, such as sound, the aether was imagined a very stiff solid with a very low density. Yet, it seemed absurd to say that a stiff, solid aether fills all space. Since the planets move without slowing down, they apparently encounter no resistance as they move around in a space which transmits light freely.

Without aether, the wave theory seemed improbable. But the aether itself had absurd properties. Until early in this century, the problem remained unsolved. Only after Einstein developed his special theory of relativity did a solution to the problem emerge.

The Michelson-Morley Experiment

During the nineteenth century, various attempts were made to detect the motion of the earth through the aether. Among them was the most significant failure in the history of physics: the Michelson-Morley experiment. Albert A. Michelson became interested in experiments probing the nature of light when he was a physics instructor at the U.S. Naval Academy. Michelson's forte was careful, precise optical measurements. In 1873 he devised an ingenious experiment that yielded the most accurate value at that time for the speed of light. He undertook such a measurement after reading a letter from the great James Clerk Maxwell to David Peck Todd, a colleague of Michelson's at the Nautical Almanac Office. Michelson was intrigued by Maxwell's statement that no terrestrial method for measuring the speed of light could detect the earth's motion through the aether because the effect would depend on the square of the ratio of the earth's velocity to that of light--an effect too small to be observed.

Maxwell presented a very simple argument. Imagine that the earth is moving at some speed v through the aether. If a beam of light travels at speed c in the rest frame of the aether, then an earth-bound observer, moving through the aether at speed v, should measure c + v for the speed of light when the light is traveling against the motion of the earth. Similarly, the observer should measure c − v for the speed of a beam of light moving in the same direction as the earth. By comparing the speed of light in the forward and backward directions with respect to the speed of the earth, one should be able to measure the speed v of the earth through the aether.

The speed of the earth through the aether was taken to be its speed about the sun: 3×10^4 m/s, or 10^{-4} times the speed of light. The difference in the two speeds c + v and c − v is 2v, which is extremely small compared to c. As we will show later, the difference in time for light to travel a certain distance down and back depends on $(v/c)^2$, which is even smaller and very difficult to detect by experiment. The challenge of devising an optical instrument sufficiently sensitive to detect the earth's motion led Michelson to study the interference of light.

In 1880, Michelson was granted a leave to study optical techniques in Europe, and he immediately began working on an apparatus to detect the motion of the earth through the aether. In the laboratory of Hermann von Helmholz at the University of Berlin, Michelson invented a new instrument of unprecedented sensitivity which has come to be known as the Michelson interferometer.

A diagram representing the principle of a Michelson interferometer is shown in Figure 1. A beam of light is directed at a plate of partially silvered glass that partly transmits and partly reflects light. The silvered surface splits the beam into two components that travel in perpendicular directions as shown. The transmitted beam travels a distance L to a mirror M_1 and is reflected back along the same path to the silvered glass plate. Similarly, the reflected portion of the beam travels an equal distance L, reflects from mirror M_2, and returns along its original path to the glass plate. At the glass plate both beams recombine as two superposed beams.

If both beams travel the same distance and arrive in phase with one another, they produce a bright fringe from the constructive interference. On the other hand, if the two waves travel different distances and arrive out of phase, destructive interference will result. Consequently a series of bright and dark fringes is seen, similar to those shown in Figure 2.

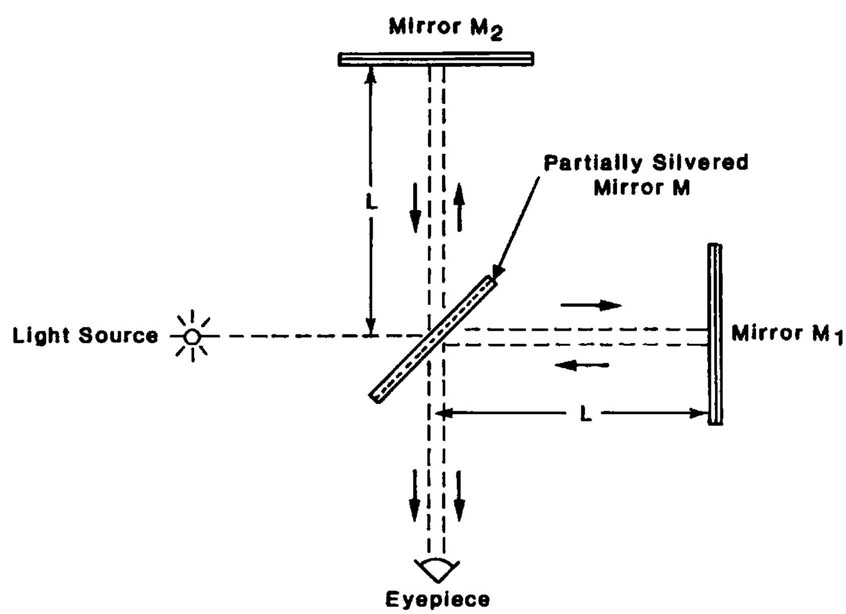


Figure 1

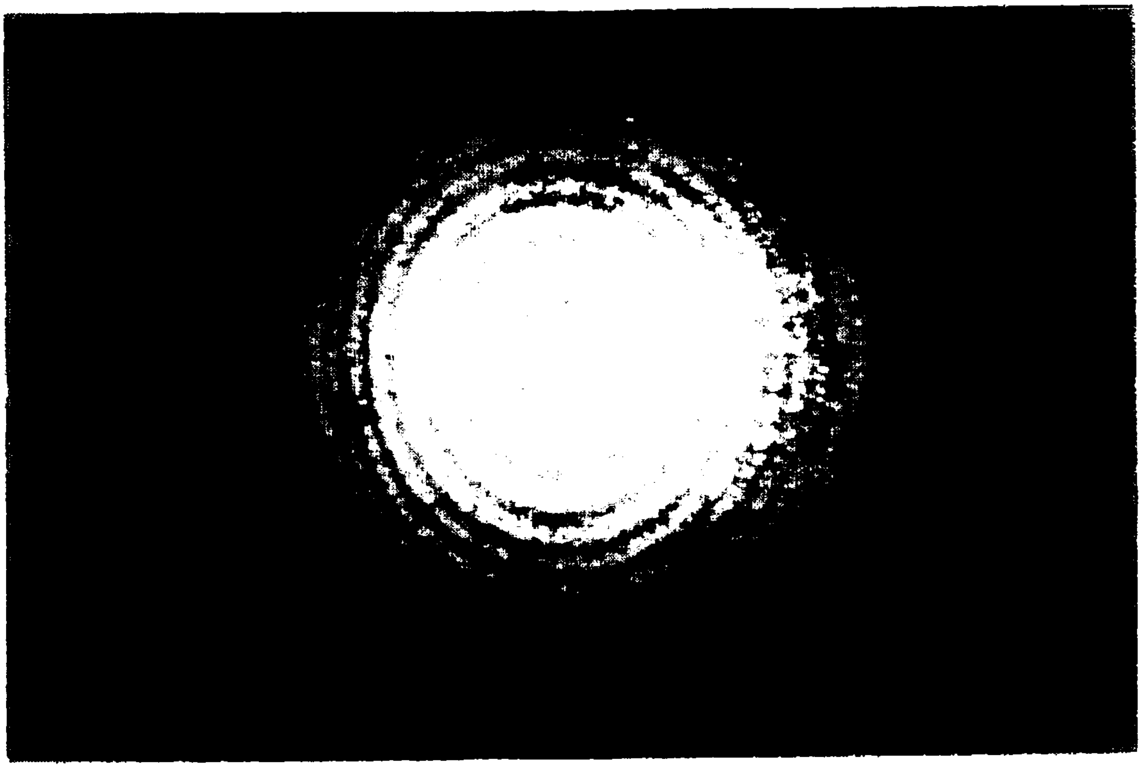


Figure 2

Now imagine the whole laboratory moving relative to the aether at speed v in the direction of mirror M_1. From the viewpoint of the laboratory frame, an aether wind is blowing past the apparatus. It is easy to calculate the effect of this aether wind on the travel times for light along the arm of the interferometer parallel to and perpendicular to the wind. If the times are different, the beams will have traveled different distances and the difference between distances will show up as either constructive or destructive interference fringes in the telescope.

When light travels against the wind, as shown in Figure 3, its speed is $c - v$, and when it travels downwind, its speed is $c + v$. The time T required for one round trip is the sum of time out and time back. In each case the time required is simply the distance L divided by the speed for that portion of the trip. Therefore, the total time is

$$T = \frac{L}{c - v} + \frac{L}{c + v} .$$

Adding the fractions we obtain

$$T = \frac{2Lc}{c^2 - V^2} = \frac{2L/c}{1 - v^2/c^2} . \quad (1)$$

The numerator of this last expression is the time it would have taken if everything were at rest and there were no relative motion to worry about--the total distance $2L$ divided by c, the speed of light. The denominator represents the correction factor due to the aether wind.

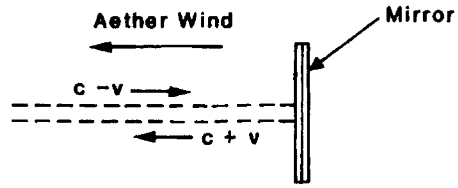


Figure 3

To calculate the time it takes light to make the journey up and down perpendicular to the aether wind, it is most useful to describe the process as it would be seen by an observer at rest in the aether. Such an observer would see the interferometer flying by and would be interested in how long light takes to leave the beam splitter and return. As the light travels up and down toward the mirror, as shown in Figure 4, the earth moves a distance vt through the aether. The light doesn't return to the same place because the mirror is moving.

The distance the light beam travels can be found from the Pythagorean theorem and is equal to $2(vt/2)^2 + L^2$. The speed of light in the aether rest frame is simply c, so the time it takes the light beam to travel down and back is the distance divided by c:

$$t = \frac{2\,(vt/2)^2 + L^2}{c} \,.$$

To determine t we square both sides,

$$t^2 = (4/c^2)\,[(vt/2)^2 + L^2] = v^2t^2/c^2 + 4L^2/c^2,$$

then solve for t^2, and take the positive square root to get

$$t = \frac{2L/c}{\sqrt{1 - v^2/c^2}} \,. \tag{2}$$

Comparing Eq. (2) with Eq. (1) we see that the travel times differ by a factor $\sqrt{1 - v^2/c^2}$, and, therefore, the light beams travel different distances. The actual difference is equal to

$$T - t = \frac{2L/c}{1 - v^2/c^2} - \frac{2L/c}{\sqrt{1 - v^2/c^2}} = \frac{2L/c}{1 - v^2/c^2}\left[1 - \sqrt{1 - \frac{v^2}{c^2}}\,.\right]$$

Multiplying and dividing the expression in parentheses by $1 + \sqrt{1 - v^2/c^2}$, we can rewrite it as

$$T - t = \frac{2L/c}{(1 - v^2/c^2)}\;\frac{v^2/c^2}{(1 + \sqrt{1 - v^2/c^2})} \,.$$

Now v/c is a small number (on the order of 10^{-4}), and its square $(v/c)^2$ is even smaller (on the order of 10^{-8}). Therefore, we can disregard the terms v^2/c^2 in the denominator and obtain the approximation

$$T - t = \frac{2L}{c}\;\frac{v^2/c^2}{2} = L\,\frac{v^2}{c^3} \,.$$

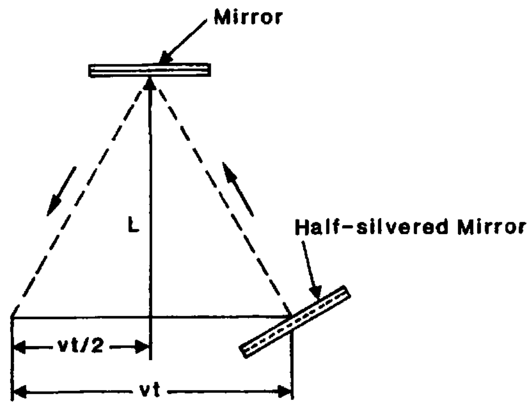


Figure 4

Since the lengths of the arms in the Michelson interferometer were 11 meters, the time difference between the arrival of the two beams is

$$T - t = \frac{11 \text{ meters } 3\,(3 \times 10^{4}\text{m/s})^{2}}{(3 \times 10^{8}\text{ m/s})^{3}} = 4 \times 10^{-16}\text{ s.}$$

The light source that Michelson used had a wavelength of 5.7×10^{-7} m. Its period, therefore, is 19×10^{-16} s. Michelson should have expected a phase delay between the two beams of phase shift given by

$$\text{phase shift} = \frac{T - t}{\text{period}} = 0.2.$$

Michelson then rotated his interferometer through an angle of 90°. Since the beam that had been trailing was now leading, the total phase shift should have been 0.2 + 0.2 = 0.4. A shift that severe would move the reference point from a region of constructive interference to a region of destructive interference. This obvious shift should have been detectable, yet none was observed. The Michelson-Morley experiment has been repeated many times, but the expected shift has never been observed. The null result of the Michelson-Morley experiment gave rise to some new ideas about the meaning of length, space, and time.

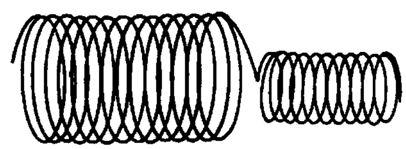
Demonstration #1: Waves on Springs

Purpose: To demonstrate how the speed of waves is affected by the stiffness of the springs and density of the material of which they are composed.

Materials: Slinky spring; snake spring about 3 cm in diameter.

Procedure and Notes:

1. With the snake spring resting on the floor and pulled to about 1½ to 2 times its original length, produce some transverse waves on the spring. Have the students observe the resulting velocity.
2. Stretch the spring to 3 or 4 times its original length and compare these speeds with earlier speeds.
3. Carefully tie the snake spring and slinky spring together. Stretch the springs by pulling on the free ends. Be careful not to over stretch the slinky.



4. Shake some waves into the slinky and watch as they travel into the snake spring. Next shake some waves into the snake spring. Have students compare the velocity in the two springs.

Explanation: In parts one and two the students should notice a significant increase of the wave velocity in the spring with a greater tension. The waves may take about the same time to travel the length of the spring. Because, however, the second spring has a greater length, the velocity in the second case will be larger. The comparison illustrates the greater the tension of a material, the faster the waves will propagate through it. Parts three and four examine how density affects the speed of waves in materials. The springs must be tied together so that they will have the same tension. Since the waves will travel much faster in the slinky than in the snake spring, the slinky can be assumed to be considerably less dense This is surprising to most students, who expect that waves would travel much faster in the snake spring. The two factors of the medium which affect the speed of waves are tension and density. The greater the tension or stiffness of a medium, the faster the waves will travel. The greater the density of a material, the slower the waves will travel.

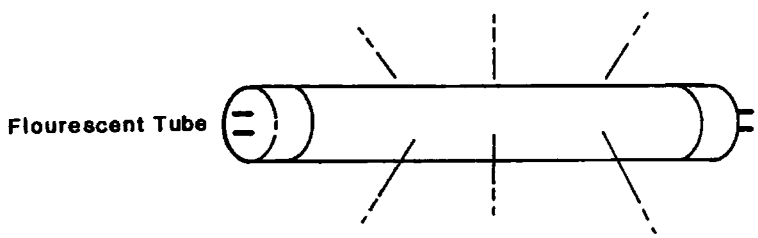
Demonstration #2: Simple Interferometer

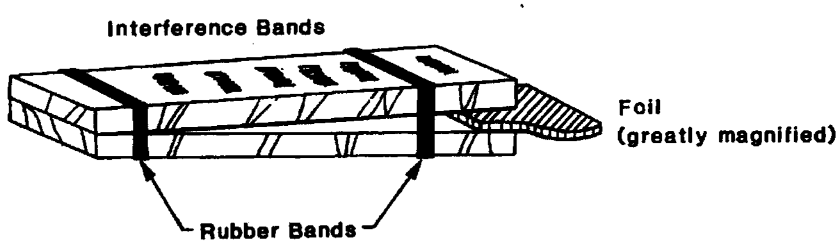
Purpose: To demonstrate a simple interferometer and show how it can be used to measure very small distances.

Materials: Two clean 6 mm (¼ inch) glass plates about 50 mm by 100 mm; monochromatic light source such as an uncoated fluorescent tube; rubber bands; and some thin foil.

Procedure and Notes:

1. Review the concept of interference.
2. Wrap a couple of rubber bands tightly around each end of the two glass plates. Slip a thin piece of foil between the plates at the one end. The rubber bands will hold one end of the glass plates close together while the foil will slightly separate the other ends. The net result will be a very long thin wedge of air between the plates.





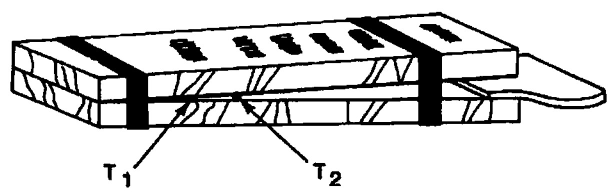
3. Illuminate the plates with monochromatic light. Although the demonstration theoretically should work with any monochromatic light source, it seems to work best with a broad diffused light source such as an uncoated fluorescent tube.
4. Count the number of bright lines or fringes which cross the glass plates.
5. Determine the thickness of the foil in wavelengths of light.
6. Determine the thickness of the air wedge in meters by multiplying the number of wavelengths by ½.

Explanation:

Interference occurs when different light beams meet. If the beams arrive out of phase, they produce destructive interference. The light beams can have different phases because of different phases of the sources or because they have traveled different distances. This experiment relies on different path lengths to produce phase changes. A path length difference of one whole wavelength represents a phase change of 360°. Therefore, the distance from one bright band to another represents a path length difference of one wavelength or a change in thickness between the plates of 1/2 wavelength. Remember that the light must travel down and back. The number of bands, therefore, can be used as a measure of the thickness of the foil since the bands represent the number of half wavelengths that would be equal to the thickness of the foil:

$$T = n\lambda/2 .$$

Note: *PSSC* has a detailed discussion of the phase changes that take place at each reflecting surface.



T_1 = first thickness, T_2 = second thickness

$$T_2 - T_1 = \lambda/2$$

Demonstration #3: Michelson Interferometer

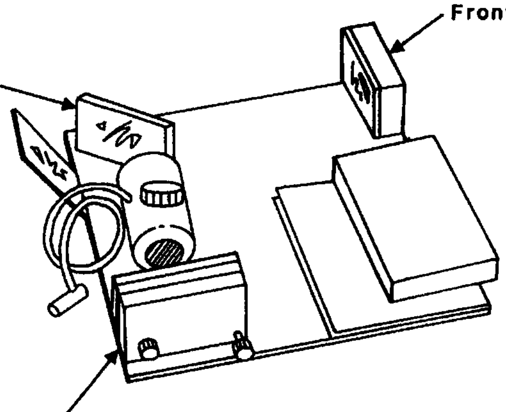
Purpose: To demonstrate a Michelson interferometer and its operation.

Materials: Michelson interferometer; monochromatic light source.

Procedure and Notes:

1. Show the apparatus to the students and point out the important features of the Michelson apparatus, including the following:
   a. Partially silvered mirror which acts as a beam splitter to separate the light into two beams.
   b. The two perpendicular beam paths.
   c. The front surface mirrors used to reflect the beams back along their original paths.

   It is important that students understand the general operation of the Michelson apparatus if they are to understand the experiment. The students are often interested in the partially silvered mirror, commonly called a one way mirror. CAUTION: The Michelson apparatus is easily knocked out of alignment, especially when being observed by several students.



2. Set up the apparatus and securely attach to the table top by clamps or tape.
3. Have students observe the fringes. If using a mercury light source, this observation will have to be done individually. If using a laser, the pattern can be projected on a wall in a very dark room using a beam spreader. Gently blowing across one path will make the fringes flutter.
4. The interference pattern set up in the apparatus does not have to be circular as shown in the video. As long as the fringes are adjusted so they are generally vertical, the movement of the fringes can be observed.

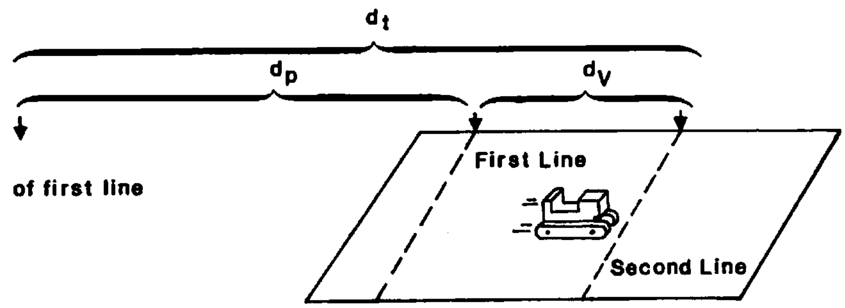
Demonstration #4: Relative Velocities

Purpose: To demonstrate the additive nature of velocities in Galilean relativity.

Materials: Battery operated vehicle with a constant velocity; large sheet of paper about 50 cm by 200 cm; small objects for use as position markers; timing device.

Procedure and Notes:

1. Mark two lines across the sheet of paper about 100 cm apart.
2. Put the paper on the floor and set a position marker next to the first line.
3. Set the vehicle at the first line. As it moves forward, pull the paper in the same direction with a constant velocity. Time how long it takes for the vehicle to move from the first line to the second line.
4. When the vehicle reaches the second line, stop and set position markers next to the first and second lines on the floor.



5. Calculate the following velocities:

   Velocity of vehicle on paper is $V_v = \frac{d_v}{t}$.

   Velocity of paper on floor is $V_P = \frac{d_p}{t}$.

   Velocity of vehicle relative to floor is $V_T = d_t/t$.

6. Compare the velocity of the vehicle relative to the floor to the sum of the other two velocities.

$$V_T = V_V + V_P$$

7. Repeat the entire experiment with the vehicle starting at the second line and heading towards the first line. Pull the paper in its original direction of motion with a speed greater than that of the vehicle. Calculate the velocities, and then the sum of the other two velocities.

$$V_T = V_V + V_P$$

8. Repeat the entire experiment with the vehicle again going backwards. This time pull the paper with a speed less than that of the vehicle. Calculate the three velocities and again compare.

$$V_T = V_V + V_P$$

Explanation:

This is a good demonstration to show the vector addition of velocities. If it was done earlier in the year, it provides a good review. If it was not done earlier, it provides a good example of the addition of velocities in Galilean relativity.

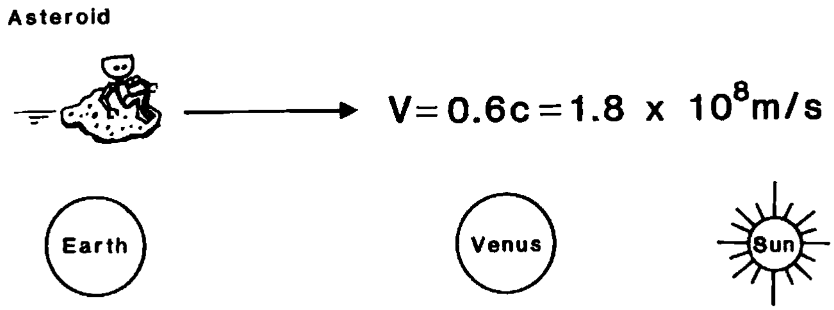
The velocity of the vehicle on the paper, V_V , is equal to the distance along the paper that the vehicle moves divided by the time it takes. Similarly, the velocity of the paper across the floor, V_P , is equal to the displacement across the floor divided by the time. Finally, the velocity of the vehicle with respect to the floor, V_T , is equal to the total displacement of the vehicle along the floor divided by the time.

In step six of the procedure, both V_V and V_P would be positive and should add up to a positive V_T. In step seven of the procedure, V_P would be positive, but V_V would be negative. Since V_P is larger in magnitude, the total velocity, V_T, will still be a positive value. In step eight of the procedure, V_P is again positive, and V_V is again negative. This time, however, V_V has the larger magnitude. Consequently, V_T is negative.

Note: This same general procedure can also be used to investigate perpendicular velocities.

EVALUATION QUESTIONS

Questions 1 - 5 refer to the following situation:



As viewed from the earth, an asteroid with a humanoid on board is moving toward the sun. The velocity of the asteroid is 1.8×10^8 m/s relative to the earth. The humanoid measures his asteroid to be perfectly spherical with a diameter of 900 km.

1. **As measured by an observer on earth, which of the following could be the length of the asteroid in the direction of motion?**

   A. 0 km
   B. 720 km
   C. 900 km
   D. 1,125 km

2. **As measured by an observer on earth, which of the following could be the width of the asteroid, that is, the dimension of the asteroid *perpendicular to the direction of motion*?**

   A. 0 km
   B. 720 km
   C. 900 km
   D. 1,125 km

3. **As measured by an observer on earth, the shape of the asteroid would most nearly resemble**

   A. a football pointing perpendicular to the motion.
   B. a football pointing parallel to the motion.
   C. a baseball.
   D. a pencil pointing forward.

4. **Assume that Venus and the sun are *not* moving relative to the earth and as viewed by an observer on earth, the distance between earth and Venus is 1.8×10^{10} meters. What is the length of time it would take the asteroid to go from earth to Venus?**

   A. 10 s
   B. 100 s
   C. 900 s
   D. 1000 s

5. **As viewed by an observer on the asteroid, the speed at which Venus is passing by him is**

   A. 0.60 c.
   B. 0.80 c.
   C. 0.99 c.
   D. 1.00 c.

6. **Which of the following is *not* a property of the hypothetical aether?**

   A. It propagated transverse waves.
   B. It was impenetrable.
   C. It was at rest with respect to the "fixed" stars.
   D. It allowed the planets to move freely through it.

7. **Michelson and Morley intended to repeat their experiment at intervals of 3 months because:**

   A. it would not be necessary to rotate the interferometer.
   B. they wanted to check the effect of temperature variations on their experiments.
   C. different orientations in the earth's orbit might make a difference in the measurements.
   D. only at 3-month intervals was the hypothetical aether dragged along at the same speed as the earth.

8. **It was assumed that there existed an aether that transmitted light waves because**

   A. transmitted waves need a medium on which to travel.
   B. transmitted sound waves travel only through solids.
   C. the surface of the sun is gaseous.
   D. light waves travel through the medium of air on earth.

9. **A boy swims downstream in a river flowing at 3 m/s. The boy swims at 5 m/s in still water. If the boy swims 40 meters downstream and then returns to the same spot by swimming upstream, what is the total time that it will take?**

   A. 17 s
   B. 20 s
   C. 25 s
   D. 40 s

10. **The results of the Michelson-Morley experiment can be used to support**

   A. the fact that the earth is moving around the sun.
   B. the existence of an aether.
   C. Einstein's theory of relativity.
   D. the particle theory of light.

ESSAY QUESTIONS

1. **Discuss the result of the Michelson-Morley experiment in relation to its impact on theories of light.**

2. **Discuss why track and field records are sometimes not allowed for the 100 meter dash on a windy day but are allowed for the 10,000 meter run.**

Key

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

SUGGESTED ESSAY RESPONSES

1. The result of the Michelson-Morley experiment, indicated that the effects of the aether were undetectable and, therefore, the aether was non-existent. This indicated that light did not need a medium in order to propagate and that the speed of light was c to all observers.

2. The 100 meter dash can be run solely in one of the directions of the wind. Since the 10,000 meter run is run around an oval it involves all orientations of the wind. The effect of the wind blowing against the runner almost offsets the effect of running with the wind.