THE MECHANICAL UNIVERSE

High School Adaptation

QUAD V

ELECTRICITY

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High School Adaptation

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

QUAD V
ELECTRICITY

Electric Fields and Forces
Potential Difference and Capacitance
Equipotentials and Fields
Simple DC Circuits

An Annenberg/CPB Project

National Science Foundation

Materials Development Council

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FOREWORD

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

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

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

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

INTRODUCING

THE MECHANICAL UNIVERSE

High School Adaptation

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

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

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

PREFACE

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

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

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

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

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

ACKNOWLEDGEMENTS

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

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

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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 1987

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 V

ELECTRIC FIELDS AND FORCES

HOW DOES THE ELECTRIC FORCE ACT? Coulomb suggested that the electric force, like gravity, is a force acting at a distance obeying an inverse square law. The idea of a force being transmitted without bodies in contact with one another was difficult for most eighteenth and nineteenth century scientists to accept, despite the fact that the same idea was inherent in Newton's visualization of gravitational forces acting through empty space. In the mid-nineteenth century, Michael Faraday helped resolve this dilemma by introducing the concept of an electric field. His powerful insight provided a qualitative description of the behavior of electric forces which has since been mathematically interpreted.
Running time: 15:10

EQUIPOTENTIALS AND FIELDS

WHAT IS THE DIFFERENCE BETWEEN ELECTRIC POTENTIAL AND ELECTRIC FIELD? This video explore the relationships between electric potentials and electric fields. Contour lines of a landscape are mapped as an analogy for mapping the contours of electric potentials in an electric field. Electrical discharges are also discussed along with the relationships among energy, voltage. and charge.
Running Time: 11:14

POTENTIAL DIFFERENCE AND CAPACITANCE

HOW CAN ELECTRIC CHARGE BE STORED? Benjamin Franklin performed many experiments in electricity and as a result formulated a theory of electric charge. In his theory he recognized that electric charge is not created, but is simply transferred from one body to another – a fundamental principle known today as conservation of electric charge. A triumph of Franklin's theory was that it could describe how a device used to store electric charge, the capacitor, works. In this video Franklin's experiments in electricity are correlated with an understanding of modern capacitors and how they work.
Running time: 15:11

SIMPLE DC CIRCUITS

WHAT IS ELECTRIC CURRENT AND HOW DOES IT BEHAVE? Electric current, resistance and their effects in series and parallel circuits are the topics of this video. The video uses the analogy of water flow to correlate ideas between water flow and electric current. Ohm's law is explored to illustrate the relationship among current, voltage, and resistance.
Running time: 14:04

TEACHER'S GUIDE TO ELECTRIC FIELDS AND FORCES

CONTENT AND USE OF THE VIDEO - This video focuses on the nature of the forces experienced by charges placed in the vicinity of other charges and, thereby, develops understanding of the electric field. The term electric field refers to an electrostatic field. Using the model Michael Faraday devised, a visualization of electric fields is presented. The material should follow a study of electrostatics and of Coulomb's law. The video does not include a detailed treatment of flux, nor is Gauss' law addressed.

The video uses a color code that assigns red to positive charge and blue to negative charge. The appearance of the 3-D patterns on the screen gives the illusion of the lines of force crossing. It is important to point out that these lines do not really intersect.

TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO - Prior to viewing the video, there are a few terms describing electric field characteristics which might be helpful for students to discuss briefly.

Coulomb's law--a mathematical description of the relationship between the magnitudes of two charges, the distances between their centers, and the strength of the force exerted by one charge on the other at this distance. The electric force between two charges at rest is directly proportional to the product of the magnitudes of the charges and inversely proportional to the square of the distance between them. In symbols: $F_e = K_e q_1 q_2 / r^2$ where F_e is the magnitude of the force, q_1 and q_2 are the magnitudes of the two charges, r is the distance between the centers of the charges, and $K_e = 9 \times 10^9$ Nm^2/C^2. Figure 1(a) illustrates the direction of the force between unlike charges, which is attractive, and Figure 1(b) illustrates the direction of the force between two like charges, which is repulsive.

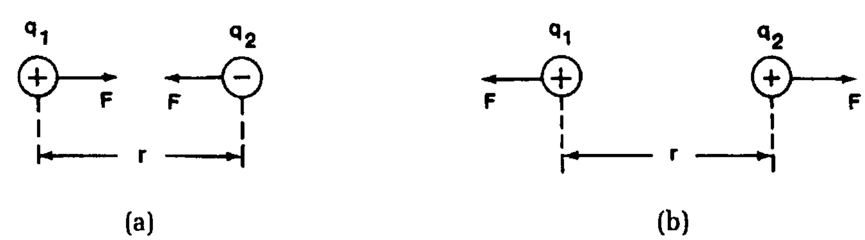
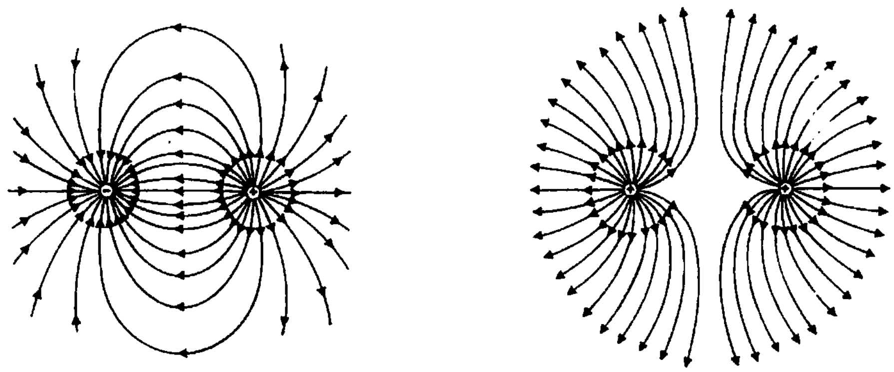


Figure 1

electric field--the alteration of the properties of space around a charged body that will affect a test charge with a force, F. The closer the test charge is to the body, the greater the force. The direction of the net electric field is defined to be in the direction of the force acting on a positive test charge. The strength of the force acting on the test charge at each point in space is the magnitude of the test charge times the electric field strength. Figure 2(a) illustrates the electric field in the region of a pair of unlike charges and Figure 2(b) illustrates the electric field in the region of a pair of like charges.



(a) (b)

Figure 2

test charge--a charge used to investigate an electric field. By convention, the test charge is positive and assumed to be so small in both size and magnitude that it does not disturb the field being investigated.

lines of force--imaginary lines used in visualizing fields such as electric fields. The lines emanate from positive charges and terminate on negative charges. The density of the lines in a region indicates the strength of the field there.

inverse square law--a mathematical relationship stating that a physical quantity has an inverse square dependence on the distance of the observation point from the physical source.

electrical conductor--a material such as a metal that has mobile electrons that are free to move through the whole volume of the material.

electrostatic equilibrium--a state in which all electric charges in a system experience no net electric force.

electroscope--a simple instrument used qualitatively to obtain information about charges and charge distribution.

WHAT TO EMPHASIZE AND HOW TO TO IT - Coulomb's inverse square law suggested that the electric force, like gravity, is a force acting at a distance. The idea of force being transmitted without bodies being in contact with one another was difficult for most eighteenth and nineteenth century scientists to accept, despite the fact that the same idea was inherent in Newton's visualization of gravitational forces acting through empty space. In the mid-nineteenth century, Michael Faraday helped resolve this dilemma by introducing the concept of an electric field. His powerful insight provided a qualitative description of the behavior of electric forces which has since been mathematically interpreted.

Objective 1: Draw lines of force for simple charge configurations.

The idea of lines of force is a difficult concept for most students to comprehend. They need help in visualizing how charges invisibly alter the properties of space such that, when other charges are in their vicinity, they experience attractive or repulsive forces. You might remind students about gravitational fields--the alteration of the properties of space around matter such that, when other masses are in its vicinity, they experience attractive (gravitational) forces.

The video provides graphic representations of the lines of force between like charges and unlike charges as well as more complex arrangements of charges. It is important to use the still frame and replay options on the video recorder in order to allow students adequate time to examine these patterns of forces. Remind your students that *lines of force do not actually exist*, although Michael Faraday and the scientists of his time believed them to be real physical entities. Lines of force are aids used in visualizing various fields such as magnetic, gravitational, and electric fields. In the case of this video, the lines of force represent electric fields. DEMONSTRATION #1 on lines of force could be used at this time to support the discussion, or it could be performed and discussed prior to showing the video. DEMONSTRATION #2 on electric field line patterns is also helpful here. In discussing these patterns, you should emphasize that, even if a test charge is not present to experience a force due to a charge system, the lines can still be imagined to exist. These lines depict the electric field of the array of charges. Students often assume that Coulomb's Law, $F_e = K_e q_1 q_2 / r^2$ is valid for all charge systems. Emphasize that Coulomb's law is only valid for point charges and spherical charge distributions.

Objective 2: Explain the inverse square law as it relates to electric forces and fields.

Once students understand that lines of force represent the electric field around charged bodies, the next step is to describe the direction and strength of the electric fields surrounding simple charged systems. You may want to pause the video at particular frames to explain to students that the test charge experiences a force in the direction tangent to the line of force it encounters. Also show them that the force on the test charge is stronger where the density of the lines of force is greater. Density is always greater closer to a charge, as indicated in Figure 3.

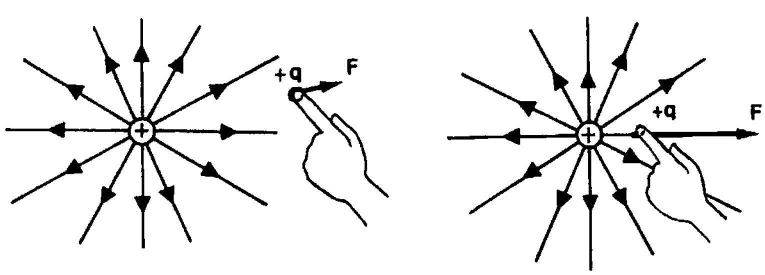


Figure 3

The inverse square law provides a mathematical description of how the force between electric charges varies with their distance from one another: $F \propto 1/r^2$. The force becomes stronger when charges are closer together and weaker when they are farther apart. You might want to replay the section of the video that describes the inverse square law in terms of light flowing out from the sun. DEMONSTRATION #3 on the inverse square law is appropriate at this point. Be sure to point out that the demonstration offers only an analogy to the inverse square nature of electric forces and the fields surrounding point charges.

Objective 3: Calculate the electric field for point charges.

The video does not explicitly calculate the electric field for point charges. It does, however, provide the equation for doing so:

$$\mathbf{E} = \mathbf{F}/q_0 = \sum_i K_e q_i / r_i^2 \, \hat{\mathbf{r}}_i .$$

The electric field, being the force per unit charge, is measured in units of newton per coulomb (N/C). You might stop the video at this point and perform several calculations for simple charge systems. It may be necessary to review the unit vector and the summation symbol. The SUPPORTIVE BACKGROUND INFORMATION may prove helpful at this time.

Objective 4: Explain why the electric field inside a conductor is zero.

It may be necessary to replay the section of the video that explains why the electric field inside any conductor becomes equal to zero when electrostatic equilibrium is established. Make sure students understand that if a conductor is placed in an electric field, its mobile electrons will experience forces causing them to flow until they are at equilibrium. They pile up at the surface, repelling the motion of further electrons, thus leaving the interior free of any net field. Any test charge placed in the interior should therefore experience no net force.

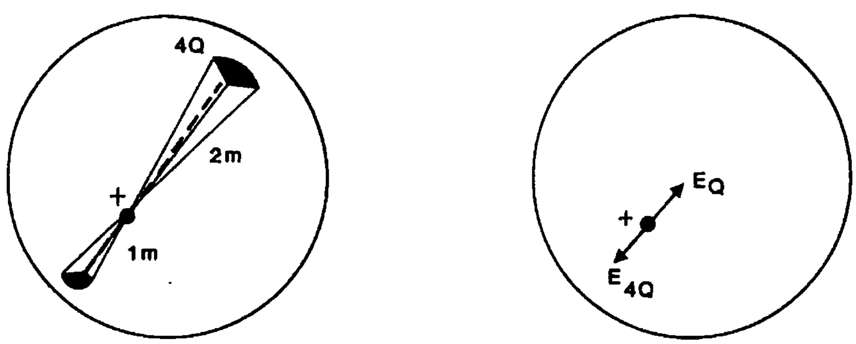


Figure 4

This is true even if there is a net charge on the conductor. To illustrate how a charged conductor can have zero field inside, a uniformly charged spherical conductor is used in Figure 4 for purposes of symmetry. A test charge is placed one meter from the bottom section of charge Q and two meters from the top section of charge $4Q$. The charge is $4Q$ on the top and Q on the bottom section because the area (and therefore the amount of charge) on the top section is 4 times the area (amount of charge) on the bottom patch. The field due to the section of charge $4Q$ is $K_eQ/1^2$.

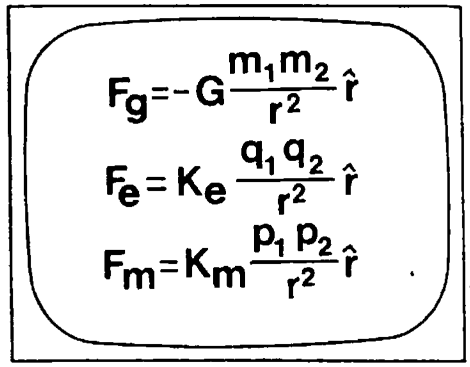
$$K_e 4Q/2^2 = K_e Q/1^2.$$

Since the fields are equal but oppositely directed, they cancel. You can extend this reasoning to cover the entire area of the sphere with the result that no field exists within the conductor. (The PSSC film "Coulomb's Law" develops this argument beautifully.)

Explain to your students that, although this result was obtained for a spherical conductor, it is true in general for any other closed, solid, or hollow conductor, whether it is charged or not, and whether it is in an external field or not. The last question in the section on EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS leads into a discussion of *how* charges distribute themselves on the surface of a conductor under electrostatic conditions. The charges distribute themselves in such a way that the interior field is zero. This distribution of charge is the basis of the Faraday cage mentioned in the video. DEMONSTRATION #4 on shielding by a Faraday cage reiterates the video presentation and can be used as reinforcement of the concept.

POINTS TO LOOK FOR IN THE VIDEO - Below is a reproduction of a portion of the STUDENT'S GUIDE, including some suggested responses to the questions posed.

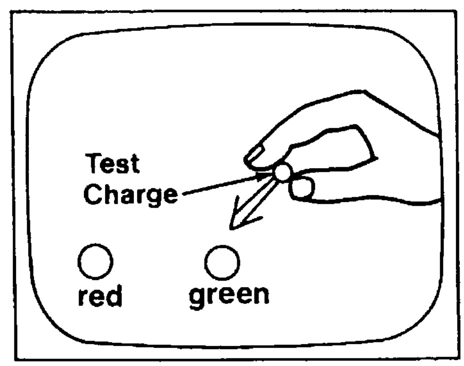
What are the similarities and differences in the force equations shown?



All equations have an r^2 term in the denominator, making them all inverse square laws. The equations all represent "action-at-a-distance" forces rather than contact forces. Furthermore, while gravitational forces are always attractive (indicated by the minus sign), electrostatic and magnetic forces can be either attractive or repulsive. (Note: The form of the magnetic force equation that appears in the video is not traditional in high school texts but nonetheless illustrates the inverse square nature of the force.)

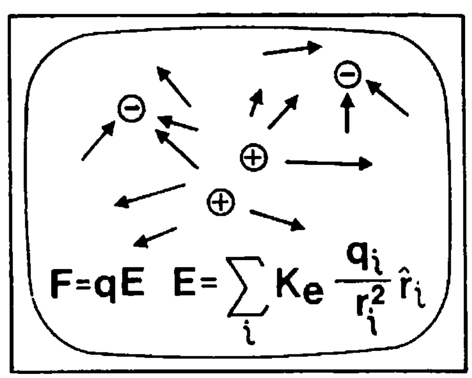
Faraday envisioned "lines of force" which establish an electric field in the space surrounding a charge. His lines of force reached out from positive charges and ended on negative charges. (Note: Even though the video gives the illusion that the lines of force cross, they really do not intersect. The illusion stems from projecting a three-dimensional diagram onto a two-dimensional television screen.)

What does the arrow in this frame from the video illustrate? What is the sign of the green charge?



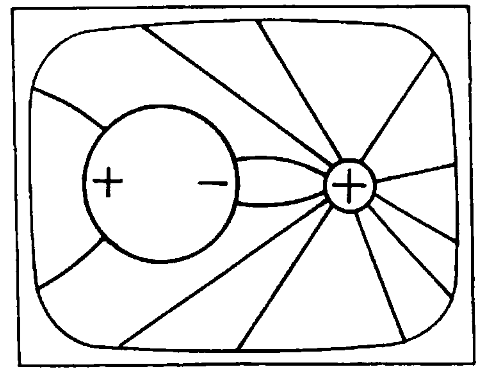
The arrow represents the force on a test charge that is held by the hand. Since the test charge is positive and the force on it is toward the larger sphere, the larger sphere is negatively charged.

In your own words describe the meaning of these two equations.



An electric field can be examined either in terms of the force acting on a test charge or in terms of the distance from a source charge. The SUPPORTIVE BACKGROUND INFORMATION develops explanations and mathematical derivations of both.

If the larger sphere is an uncharged conductor, what happens to it in the presence of the smaller positively charged sphere?

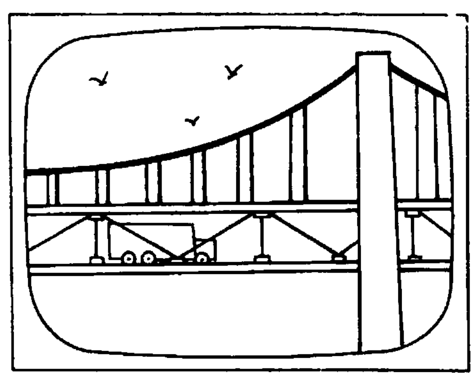


The nearby positive charge induces a charge separation on the sphere. Since the charges are free to move on the conducting sphere, negative charges that are attracted to the smaller positive sphere migrate to the side near it. Because the larger sphere was originally neutral, an equal amount of positive charge remain on the side away from the positive charge.

Is there an electric field inside the sphere?

No. Because the sphere is a closed conductor, the charges on it move until there is no net force on them. This reshifting of charges cancels out the electric field inside the conductor from the smaller sphere.

Why is the *lower* level of the bridge like a Faraday cage, whereas the upper level is not?



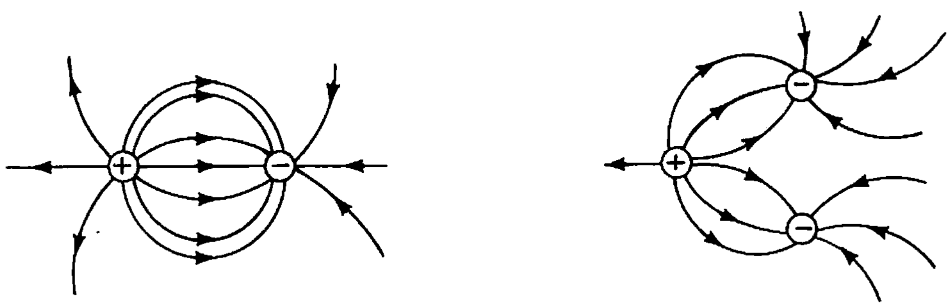
Steel girders enclose the lower level, forming a nearly closed conductor. The top is not enclosed by girders so it does not form a closed conductor.

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

1. **Early scientists initiated the intuitive view of a force being a push or a pull. How can electric charges exert such pushes and pulls without coming in contact with each other? In fact, how does one charge "know" that another is around?**

   The question of pushes and pulls without actual contact centers on the idea of "action at a distance", a concept that bothered even Isaac Newton in his description of universal gravitation. Michael Faraday first proposed the notion that a charge alters the space around itself and creates a force field.

2. **After viewing the three-dimensional patterns of lines of force presented in the video, try sketching below some patterns yourself in two dimensions.**



3. **Why can a metal box of any sort, even a flimsy, screen-covered cage, keep out an electric field?**

   An electric field passing through a conductor forces the electrons to flow until there is no longer any force on them. This means the electric field inside any conductor becomes equal to zero when electrostatic equilibrium is established. There is no net charge inside, but there can be charge on the surface. No matter what is outside, the charge on the surface makes the field inside equal to zero. Since only the charge at the surface matters, even a flimsy screen-covered cage can keep out an electric field.

4. **Why is car radio reception poor inside a tunnel or the interior of even a steel bridge structure?**

   Radio waves are disturbances in the electromagnetic field. These disturbances terminate, however, at the surface of any conductor because at that location the free electrons present in the conductor maintain electrostatic equilibrium by arranging themselves on the surface. As shown in the video, a steel bridge can form an effective "Faraday Cage." (Note: Students may cite cases when this does not hold true. These occur because of the peculiarity of radio wave wavelengths and the nature of the structural material.)

5. **What is the difference between the electric charge on an object and the associated electric field?**

   An electric field does not deal with the body itself, but the region surrounding it. It describes the alteration of the space in the region surrounding the body and results in an electric force detected by a test charge entering the region. In other words, the charge is the "thing" that causes the field. An analogy might be the difference between a rose and the pleasant fragrance which surrounds it.

6. **Why do electric lines of force never cross?**

   The electric field E *has a unique direction at any point in space. If two lines crossed, two directions would be indicated for* E *at the point of intersection and the electric field would not be unique at that point.*

7. **How do charges distribute themselves on the surface of a spherical conductor under electrostatic conditions?**

   The charge is distributed uniformly on the surface of a spherical conductor. The easiest way to "explain" this is to appeal to symmetry, but symmetry is more of a feeling than an explanation. One way to think about the distribution of charge might be to assume that it is not uniform and then to "prove" that condition impossible. If the charge were not uniformly distributed, the forces of repulsion would be greater in the high concentration area. Since the electrons are free to move, they would tend to get as far as possible from one another. Only when the charge is uniformly distributed would electrostatic equilibrium be achieved. (Note: On arbitrarily shaped conductors the charge will not necessarily be distributed uniformly but in complicated ways that depend on the shape of the conductor.)

SUMMARY - An electric field exists as a consequence of a charge or group of charges. An electric force on a charged object is caused by the electric field existing in the region. Electric fields are represented by lines of force which originate on positive charges and terminate on negative charges. Similar to the gravitational force, the magnitude of the electric force caused by interacting charges obeys the inverse square law. Michael Faraday developed a model for an electric field using lines of force to describe the configuration, the direction, and the relative strength of the field. He identified the following characteristics of lines of force:

(1) Lines of force indicate the direction of the electric field.
(2) The electric field is stronger in regions where the lines of force are closer together.
(3) Electric field lines start on positive charges and end on negative charges.

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 ELECTRIC FORCES AND FIELDS

INTRODUCTION - This video focuses on the nature of forces experienced by charges placed in the vicinity of other charges and develops the concept of the electric field.

Terms Essential for Understanding the Video

Coulomb's law
electric field
test charge
lines of force
inverse square law
electrical conductor
electrostatic equilibrium
electroscope

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

Points to Look for in the Video

Scientists use mathematical equations to express quantitatively the relationships they observe. Note in the video how the formulas for the forces of gravity, electrostatics and magnetism are similar enough to suggest a single underlying principle. Have your teacher stop the video at this point so you may answer the following question:

What are the similarities and differences in the force equations shown?

$$F_g = -G\frac{m_1 m_2}{r^2}\hat{r}$$

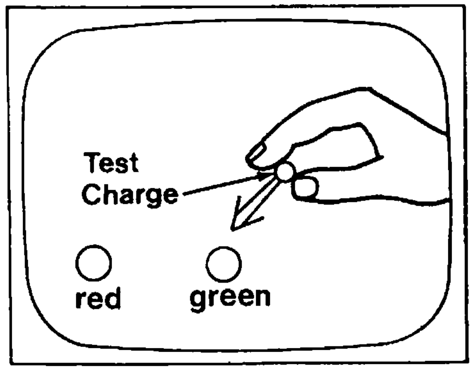
$$F_e = K_e\frac{q_1 q_2}{r^2}\hat{r}$$

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

Faraday envisioned "lines of force" which establish an electric field in the space surrounding a charge. His lines of force reached out from positive charges and ended on negative charges.

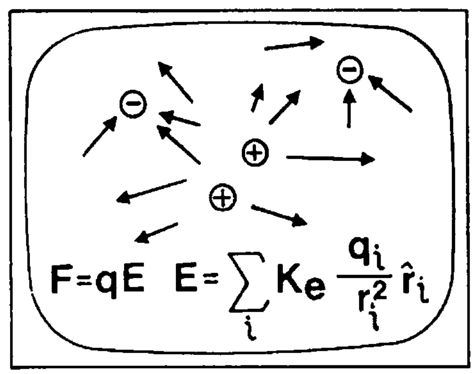
(Note: Even though the video gives the illusion that the lines of force cross, they really do not intersect. The illusion is because a three dimensional diagram is projected in two dimensions.)

What does the arrow in this frame from the video illustrate? What is the sign of the green charge?



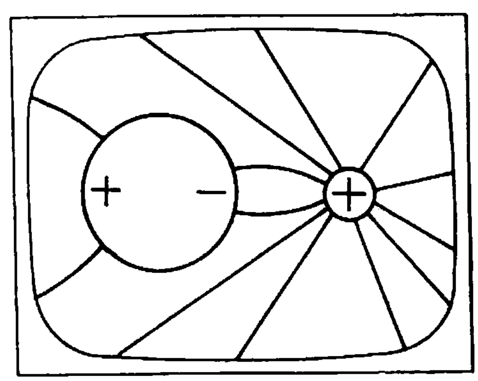
Ask your teacher to stop the video when the electric field equation is defined mathematically. You might ask you teacher to work several problems using the electric field equation.

In your own words describe the meaning of these two equations.

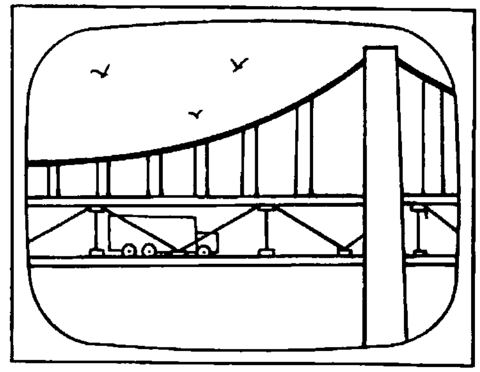


If the larger sphere is an uncharged conductor, what happens to it in the presence of the smaller positively charged sphere?

Is there an electric field inside the sphere?



Why is the *lower* level of the bridge like a Faraday cage whereas the *upper* level is not?



TEACHER RESOURCES

SUPPORTIVE BACKGROUND INFORMATION - An historical look into the eighteenth and mid-nineteenth centuries allows us to glimpse the beginning of James Clerk Maxwell's electromagnetic wave theory. Coulomb (1738 - 1806) had provided direct experimental evidence that the inverse square law held true for electric charges and the fields surrounding them. Priestley had proposed this even earlier when he predicted that electrical forces should behave in a way similar to gravitational force. However, it took the experimental genius of Michael Faraday (1791 - 1867) to introduce the concept of the electric field and, thereby, to provide a qualitative description of the behavior of electric forces.

Faraday was basically self-taught with little formal education. Nonetheless he became a remarkable chemist before turning his abilities as an experimentalist to physics. Although Faraday understood little mathematics, this did not inhibit his powerful insight which yielded qualitative descriptions of the electrical field and electric forces. Scientists like Gauss and Maxwell would eventually give a mathematical explanation of Faraday's experimental description of the electric field.

After observing how iron filings arrange themselves around a bar magnet, Faraday called the curved paths of the filings lines of force. He visualized a similar pattern of lines around positively and negatively charged bodies. Just as the lines appeared to originate on one pole of the magnet and terminate on the other, so he imagined that the lines of force of an electrical field would originate on a positive charge and end on a negative charge.

Are Faraday's lines of force real? Faraday believed that physical lines of force actually existed everywhere in space; today we no longer believe that this is true. However, Faraday's visualization of lines of force offers a model for understanding the electric field and has provided the foundation for a quantitative explanation of the phenomenon.

To define the electric field in mathematical terms, imagine a single point charge q in space. When this is the only charge present, there is no force acting on it. But let's imagine a small positive charge q_0, called a test charge, placed at a distance r from q. Now both q and q_0 experience the Coulomb force

$$F = K_e \frac{q q_0}{r^2} \hat{\mathbf{r}}.$$

Regrouping the equation yields

$$F = q_0 \left[\frac{K_e q}{r^2} \hat{\mathbf{r}} . \right]$$

The quantity in the brackets does not depend on the magnitude of the test charge, but only on its distance from q. The test charge detects the force, but the quantity in brackets exists whether or not q_0 is there to detect it. That quantity is denoted by E and is called the electric field generated by an isolated point charge q.

$$E = K_e \frac{q}{r^2} \hat{\mathbf{r}}.$$

The magnitude of E is called the electric field strength or intensity. It is measured in newtons/coulomb (N/C). Therefore, if we know the electric field at some point in space, the force acting on any charge q_0 placed in the field is simply equal to

$$F = q_0 E.$$

In this way we have defined the force on a test charge, not by the effect of another distant charge, but by the effect of the electric field at that location. The direction of E is the same as F. This field concept resolved the dilemma of action-at-a-distance forces, which were difficult for eighteenth and nineteenth century scientists to accept. Even Newton was bothered by the notion that the earth experienced a force due to the sun even though the two were separated by millions of kilometers.

Since the electric field strength is inversely proportional to the square of the distance between the charge producing the field and the other test charge, it represents an inverse square law. Inverse-square laws in physics include:

$F_g = -G \frac{m_1 m_2}{r^2}\ \hat{r}$	$F_e = K_e \frac{q_1 q_2}{r^2}\ \hat{r}$	$Fm = K_m \frac{p_1 p_2}{r^2}\ \hat{r}$	$I = \frac{L}{4\pi r^2}$
Law of Universal Gravitation	Coulomb's Law	Magnetic Force	Luminous Intensity

Why is each of these equations associated with a factor of $1/r^2$? Consider Faraday's lines of force emanating from a point charge in space radially in all directions as illustrated in Figure 5.

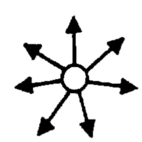


Figure 5

Faraday's model specifies that the electric force is stronger where the lines are closer together and weaker where the lines are farther apart. Let's surround the charge with a series of concentric spherical shells and see what happens to the separation of the lines of force. Only two dimensions are shown for simplicity in Figure 6.

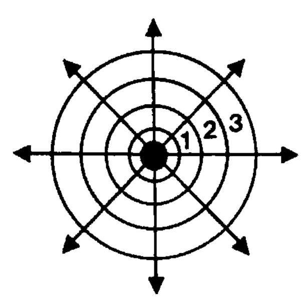


Figure 6

Notice how, as we go farther out from the charge producing the field, the force lines become spaced farther apart. This indicates a weaker electric field at the surface of sphere #3 than at the surface of sphere #1. But how is this decrease in field intensity related to the inverse-square law?

Let's use a single spherical shell of radius R and "detect" the number of lines that pierce the shell in a "patch" of area A (Figure 7).

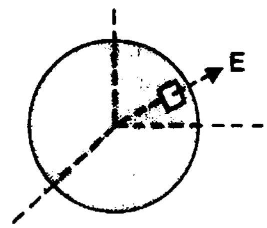


Figure 7

Let's say that the number of lines piercing the shell within the patch is n. The electric field intensity can be expressed as

$$\text{intensity} = \frac{\text{number of lines}}{\text{surface area of patch}},$$

$$\text{intensity} = \frac{n}{A}.$$

If the detection sphere is enlarged to a radius of $2R$ the area is enlarged by 2^2 or 4 because it depends on the square of the radius. The intensity then becomes

$$\text{intensity} = \frac{n}{4A} = \frac{1}{4}\left[\frac{n}{A}\right].$$

When the sphere's radius is doubled, its surface area is quadrupled and the intensity over the surface is diminished by a factor of four. Likewise, if the original detection sphere's radius is tripled, its surface area is multiplied by nine, and the field intensity on its surface would be one-ninth that of the original sphere. Hence, if the distance from the charge to the sphere (or test charge) is r, the field intensity is affected by a factor of $1/r^2$.

Some students may be unfamiliar with the "Σ" summation notation shown in the video. "Σ" can be read as "the summation of ... " and indicates the total of a number of identically-derived quantities. For example,

$$\sum_{i=1}^{n} E_i = E_1 + E_2 + E_3 + \ldots + E_n$$

represents the sum of n quantities, each represented by E_i. Thus, from the video, the total electrical force on a test charge q_0 is equal to the sum of all the Coulomb forces resulting from each of the charges present in the electric field, represented by

$$F = K_e \frac{q_0 q_i}{r_i^2} \hat{r} .$$

This equation can be written without Σ notation by using subscripts in the following manner:

$$F = K_e \frac{q_0 q_1}{r_1^2} \hat{r}_1 + K_e \frac{q_0 q_2}{r_2^2} \hat{r}_2 + K_e \frac{q_0 q_3}{r_3^2} \hat{r}_3 + \ldots$$

By factoring and regrouping we have

$$F = q_0 \left[K_e \frac{q_1}{r_1^2} \hat{r}_1 + K_e \frac{q_2}{r_2^2} \hat{r}_2 + \ldots \right]$$

But from the result $E = K_e \frac{q}{r^2} \hat{r}$ we obtain

$$F = q_0 (E_1 + E_2 + E_3 + \ldots),$$

or

$$F = q_0 \sum_i E_i .$$

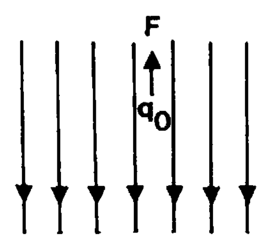
where $\sum_i E_i$ represents a vector sum, that is, adding vectors in the traditional fashion.

EXAMPLE 1: A small sphere having a charge of -1.5×10^{-8} C is placed in a uniform (constant) electric field given by $E = 7.2 \times 10^5$ N/C. Determine the electric force experienced by the small sphere.

SOLUTION: $F_e = q_0 E$,

$F_e = (-1.5 \times 10^{-8}\ \text{C})(7.2 \times 10^5\ \text{N/C})$,

$F_e = -1.1 \times 10^{-2}$ N.

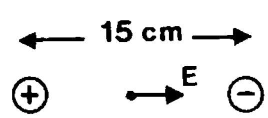


The negative sign indicates the force is opposite to the direction of the electric field.

EXAMPLE 2: Two equal and opposite charges of magnitude 2.0×10^{-7} C are 15 cm apart. What is the magnitude and direction of the electric field at a point midway between the charges?

SOLUTION: If only the positive charge q_1 were present, the electric field detected by a positive test charge q at a point 7.5 cm away, would have magnitude

$$E_1 = \frac{(9.0 \times 10^9\ \text{Nm/C}^2)(2.0 \times 10^{-7}\ \text{C})}{(7.5 \times 10^{-2}\ \text{m})2},$$

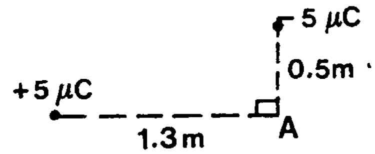


$E_1 = 3.2 \times 10^5$ N/C,

and be directed away from q_1. If only the negative charge q_2 were present, the electric field detected by a positive test charge q_0 at a point 7.5 cm away would have the same magnitude and be directed toward q_2. Since the directions and magnitudes are the same, the electric field detected midway between the charges would be $E = 2(3.2 \times 10^5 \text{ N/C}) = 6.4 \times 10^5$ N/C toward the negative charge.

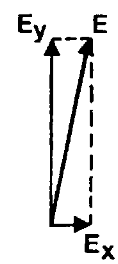
EXAMPLE 3: Determine the magnitude of the electric field vector at Point A for the charges shown.

SOLUTION: The horizontal component is due to the field created by the +5 charge:



$$E_x = \frac{(9.0 \times 10^9 \text{ Nm}^2/\text{C}^2)(5.0 \times 10^{-6}\text{C})}{(1.3 \text{ m})^2},$$

$E_x = 2.7 \times 10^4$ N/C, directed to the right (repulsion).



The vertical component is due to the field created by the −5 C charge:

$$Ey = \frac{(9.0 \times 10^9 \text{ Nm}^2/\text{C}^2)(-5.0 \times 10^{-6} \text{ C})}{(0.5 \text{ m})^2}$$

$Ey = -1.8 \times 10^5$ N/C, directed upward (attraction).

The magnitude of the resultant electric field is

$$E = \sqrt{E_x^2 + E_y^2},$$

$$E = 1.8 \times 10^5 \text{ N/C}.$$

Notice that the electric field's magnitude is determined principally by the charge 0.5 m away; the charge of equal magnitude 1.3 m away has very little effect. This illustrates the rapid decrease in field intensity due to the inverse square law.

A practical application of electric fields is the Cottrell or electrostatic precipitator which reduces industrial air pollution by removing particulate matter from flue gases. The basic principle is illustrated in the figure below. The positively charged plates are called discharge plates while the negatively charged plates are called collection plates. As a result of a large electric field between the plates, electrical discharges occur near the pointed projections on the positive plates (see Figure 8).

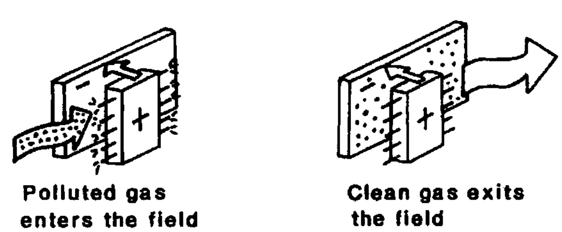


Figure 8

The particles in the gas are positively ionized by these discharges and move toward the negative collection plates as a result of the electric field. The particulate matter accumulates, falls to the bottom of the chamber, and is removed. Electrostatic precipitators are capable of removing more than 90% of the particulate matter from flue gases.

Copying machines that use the Xerox process also make use of electric fields in much the same manner. A special dark powder is charged and then ultimately accumulated on a paper which has been oppositely charged in the outline of the original pattern.

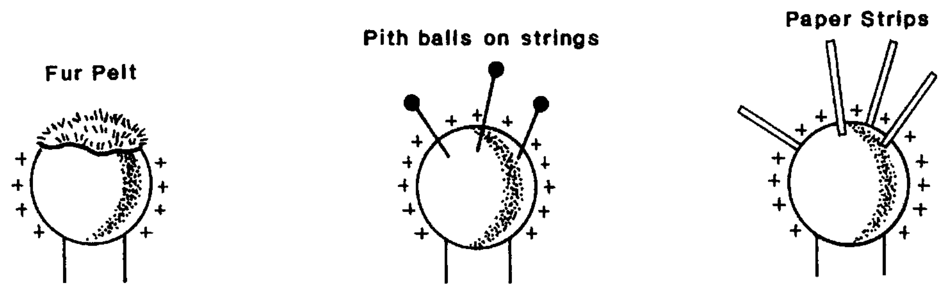
ADDITIONAL RESOURCES

Demonstration #1: Lines of Force

Purpose: To demonstrate the nature of the lines of force around a charged metal sphere.

Materials: Van de Graaff generator; cat fur; pithballs on strings; paper strips (such as a pom pom)

Procedure and Notes: Place the cat fur pelt on the surface of the Van de Graaff generator ball. Turn it on and observe. This can be repeated with other materials such as pithballs on strings, paper strips, etc.



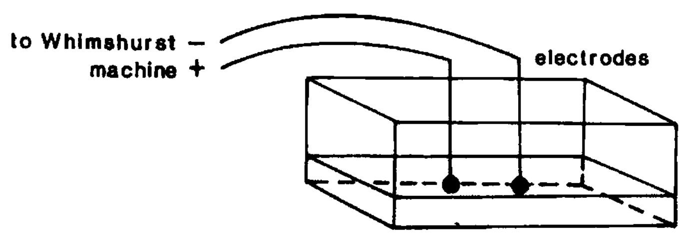
Explanation: The fur, pithballs, paper strips, etc., stand on end, perpendicular to the surface of the conductor and essentially line up along the field lines.

Demonstration #2: Electric Field Line Patterns

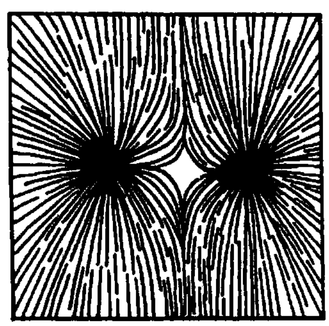
Purpose: To visualize electric field line patterns for some simple configurations of charge.

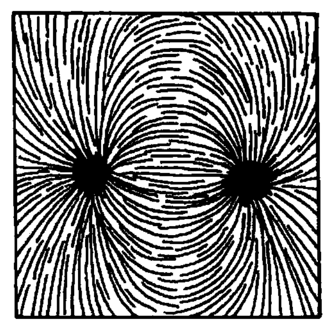
Materials: Transparent plastic box; mineral oil; tiny rayon fibers (velveteens) or grass seeds, metal pieces shaped as circles, lines, etc., to be used as electrodes; Wimshurst machine; connecting wires; overhead projector.

Procedure and Notes: Fill the plastic box about 5 mm deep with mineral oil that has rayon fibers or grass seed suspended in it. Immerse various electrodes in the oil and produce an electric field by connecting them to a Wimshurst machine. Place the transparent box on the overhead projector and observe the patterns on the screen. (Note: Stir the suspension of fibers or seeds well prior to establishing the field.)



Explanation: The rayon fibers will align parallel with the electric field lines similar to the way iron filings behave in a magnetic field. Typical patterns might be as follows:



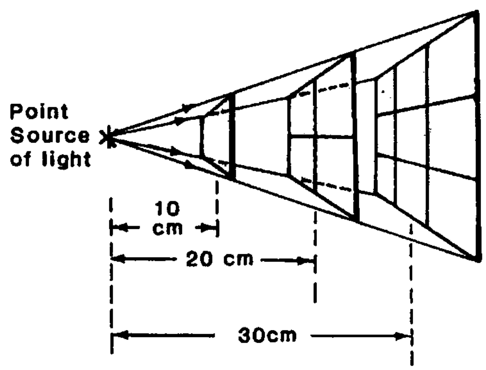


Demonstration #3: Inverse Square Law

Purpose: To demonstrate the nature of an inverse square law.

Materials: Small, intense light source; white cardboard screens, 10 cm × 10 cm, 20 cm × 20 cm, 30 cm × 30 cm; light meter (optional). Note: do not use a light source with a parabolic reflector!

Procedure and Notes: Set the light source 10 cm from the 10 cm × 10 cm screen. Observe the illumination of the screen. Set the 20 cm × 20 cm screen at 20 cm and observe the illumination. Repeat with largest screen at 30 cm distance. Notice the less intense illumination on the larger screen. If you have a light meter, make readings at both locations.



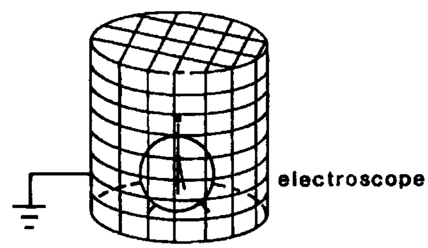
Explanation: Light intensity from a point source diminishes as the inverse square of the distance: $I \propto 1/r^2$. The 20 cm × 20 cm screen has the same amount of light impinging upon it as the 10 cm × 10 cm screen, but it is spread out over four times the area. Thus the intensity is reduced by a factor of four. If a light meter is used, the reading at 20 cm should be 1/4 the reading at 10 cm.

Demonstration #4: Shielding by a Faraday Cage

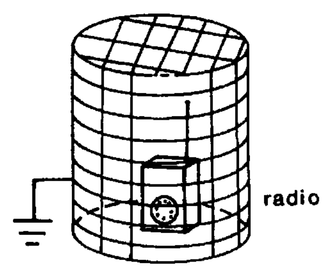
Purpose: To demonstrate the shielding effect of a "Faraday cage."

Materials: Screen cage or enclosure; electroscope; charging rods and fur or silk: small radio.

Procedure and Notes: Place the screen cage over an electroscope and ground the cage. Try to cause the electroscope leaves to diverge by bringing a charged rod nearby.



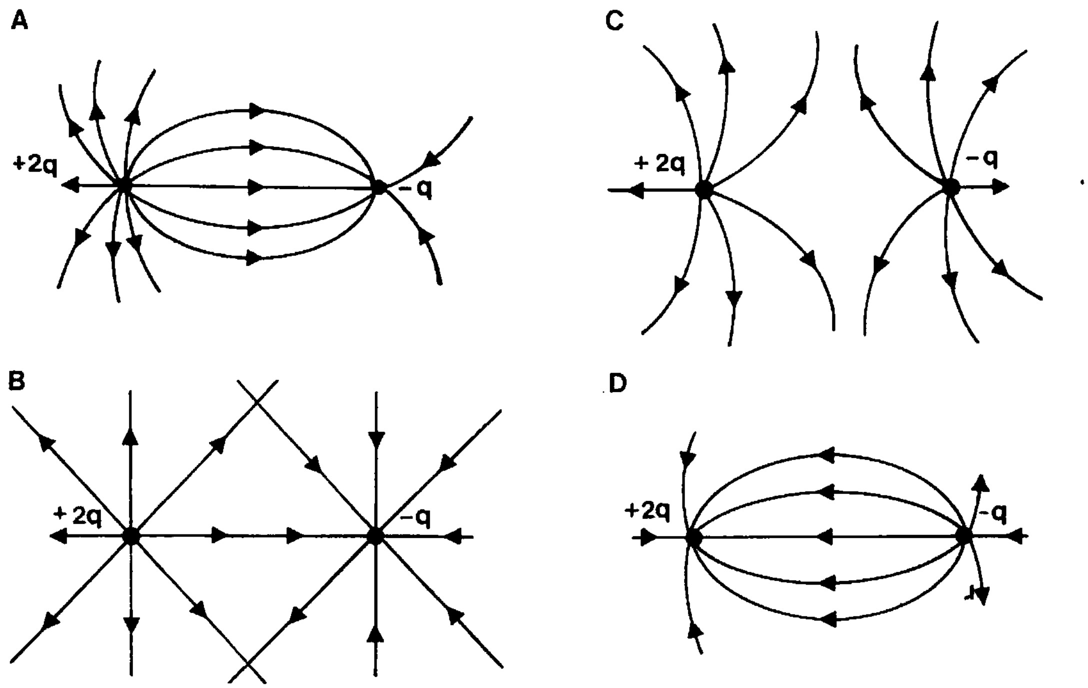
Then place the cage over a small radio which is playing.



Explanation: Any closed conducting container can shield an electric field. Even a flimsy screen cage will work. Since radio waves are a kind of disturbance in an electric field, they are also shielded.

EVALUATION QUESTIONS

1. Which of the following diagrams best represents a two dimensional lines of force pattern for the charges shown?



2. Suppose a positive test charge was brought to a distance of 10 cm from the center of a small, hollow, charged copper ball. How would the force change if the test charge were moved to 20 cm?

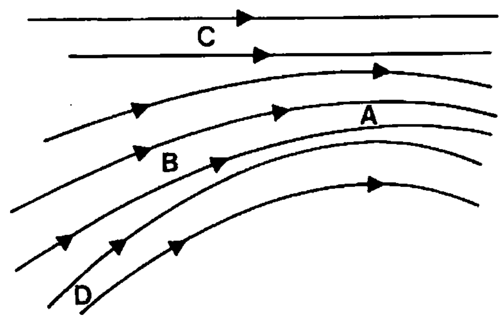
   A. 4 times the force.
   B. 2 times the force.
   C. 1/4 times the force.
   D. 1/2 times the force.

3. Using the same copper ball described in Question 2, what is the force if the test charge is placed at the center of the hollow ball as compared to its original 10 cm distant location?

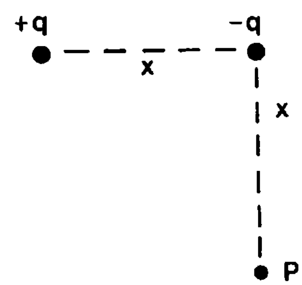
   A. The same as at 10 cm.
   B. 2 times the force.
   C. zero.
   D. 1/2 times the force.

4. The diagram illustrates a region of electric field. At which location would a test charge experience the greatest force?

A B C D



5. Which of the following shows the direction of the electric field at Point P?



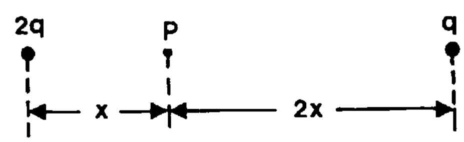
6. For the charge arrangement shown, what is the strength of the electric field at Point P?

A. $\frac{K_e q}{x^2}$

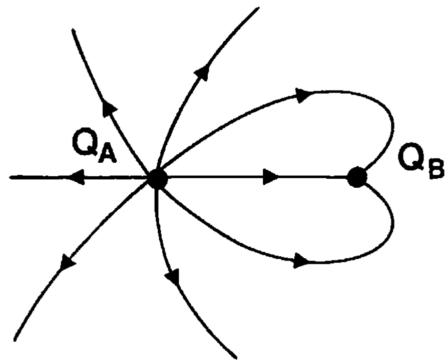
B. $\frac{3K_e q}{x^2}$

C. $\frac{7K_e q}{4x^2}$

D. $\frac{9K_e q}{4x^2}$



Questions 7 and 8 refer to the following diagram:



7. **How do the charges compare?**

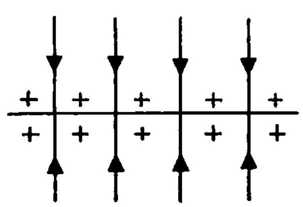
   A. Q_A is greater than Q_B.
   B. Q_B is greater than Q_A.
   C. Q_A equals Q_B.
   D. Q_A equals Q_B equals 0.

8. **How do the signs of the charges compare?**

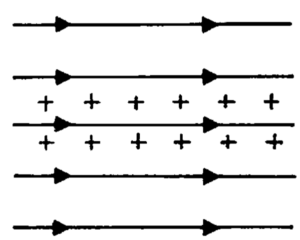
   A. Both are negative.
   B. Both are positive.
   C. Q_A is negative and Q_B is positive.
   D. Q_A is positive and Q_B is negative.

9. **Which of the following most accurately shows the electric field near a flat, positively charged metal plate?**

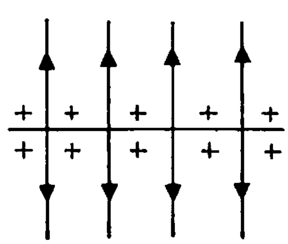
A.



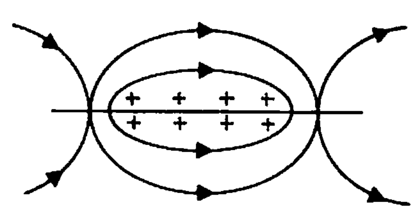
C.



B.



D.



10. A small charged plastic ball is lying on a desk. An oppositely charged plastic pen is held close to the ball. No effect is noticed. The probable reason for this is that

A. the pen has a negative charge.
B. the ball acts as an insulator.
C. the ball does not intersect field lines.
D. the electric force on the ball is less than the gravitational force on it.

ESSAY QUESTIONS

11. What is an electric field? How is it similar to a gravitational field and how is it different?

12. Given a charged copper ring, what is the value of the electric field at the center of the ring? Explain.

KEY

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

SUGGESTED ESSAY RESPONSES

11. Both represent an alteration of the properties of space around the source of the field. Both obey an inverse square relationship, but the gravitational field is always attractive, whereas the electric field can be attractive or repulsive.

12. Due to symmetry the center of the ring is the same distance from any part of the ring. Therefore the magnitude of the electric field contributions due to two diametrically opposed parts of the ring are equal. However, the electric field is a vector quantity and the fields of these contributions are in opposite directions. Consequently the resultant field is zero at the center of the ring.

TEACHER'S GUIDE TO POTENTIAL DIFFERENCE AND CAPACITANCE

CONTENT AND USE OF THE VIDEO - The video presents an historical perspective on the theory of electricity through a study of Benjamin Franklin's experiments with lightning and Leyden jars. These experiments are correlated with an understanding of modern capacitors and the mathematics illustrating how they work. The concept of potential difference is developed by relating mechanical work to electrical phenomena.

The video should be shown after students have completed the study of electrostatics, Coulomb's law, and electric fields. The characteristics of capacitors are explored, but those of dielectrics are not.

TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO - You may wish to discuss the following terms briefly before viewing the video.

work--the product of a force component in the direction of motion and the object's displacement; $W = \mathbf{F} \cdot \mathbf{d}$.

potential energy--stored energy that a body possesses due to its position with respect to a position at which the potential energy is defined to be zero.

electric potential difference--the change in electric potential energy of a charge, or the work done against the electric field as a positively charged body moves between two points, divided by the charge of the body; $\Delta V = \Delta U/q = W/q$.

capacitor--a device used to store electric charge consisting of two conducting surfaces separated by an insulator or vacuum.

capacitance--the ratio of the amount of charge q that can be placed on a capacitor to the potential difference V used in establishing that charge: $C = q/V$, where C is the capacitance. Capacitance is measured in units of coulombs per volt, known as a farad, 1 F = 1 C/V.

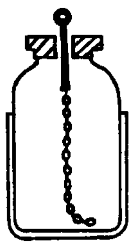
Leyden jar--type of capacitor, usually a glass jar which has its inner and outer surfaces coated part of the way up the side with a conducting material.

electric field--a condition produced by a charged object in the region surrounding it, which then exerts an electric force on any other charged object in that region; $\mathbf{E} = \mathbf{F}/q$.

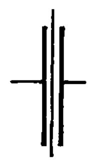
WHAT TO EMPHASIZE AND HOW TO DO IT - Benjamin Franklin performed many experiments but was not content merely to record his observations. He also sought to explain the phenomena he observed and, consequently, was the first to publish a theory of electric charge. In his theory he recognized that electric charge is not created, but is simply transferred from one body to another. This fundamental principle is known today as conservation of electric charge. One of the earliest triumphs of Franklin's theory was its ability to explain the Leyden jar, the forerunner of today's parallel-plate capacitor.

Objective 1: Describe how a capacitor stores electric charge.

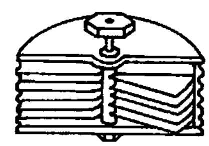
The small amount of charge from assorted electrostatic generators is not always a useful form of electricity. A method of storing that charge is necessary to allow for its utilization. One such device is a capacitor. A typical capacitor consists of two parallel plates separated by a small distance. The area of the plates is large compared to the distance between them. The plates may be rolled into a cylinder as in the case of a paper capacitor. Several illustrations of capacitors are given below.



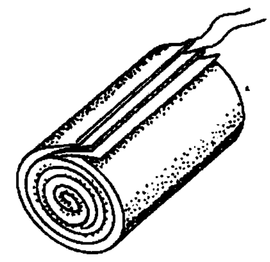
Leyden Jar



Parallel Plate Capacitor



Variable Capacitor (radio tuner)



Paper Capacitor

One plate of a capacitor is connected to the source of electrons, such as the negative terminal of a battery. The second plate is connected to the positive terminal of a battery. Electrons will accumulate on one plate. This creates an electric field which then repels the electrons on the other plate causing them to flow to the positive terminal of the battery. The process continues until the potential difference across the capacitor is equal to the potential difference of the battery.

When a capacitor discharges under ordinary conditions the charge *never* flows across the space or material between the plates. The electrons flow from the negative side of the capacitor through the circuit to the other plate of the capacitor until it is fully discharged.

The Leyden jar was the first capacitor. It consists of an insulator (glass jar) with conducting material on the inside and the outside. Metal foil is commonly used as the conducting material. The inner conductor is connected to a charging device and the outer conductor is grounded. If the inner conductor is positive, the outer conductor attracts electrons from the ground. If the inner conductor is negative, it repels electrons from the outer conductor to the ground. The electric forces between the charges hold them on the conductors until some easy path is made available for them to recombine. Thus, to store charge in a Leyden jar means that charges equal in magnitude but opposite in sign are stored on the inner and outer conductor respectively. A charged Leyden jar and a discharged Leyden jar have the same net charge, i.e., zero.

Prior to viewing the video, you may wish to perform DEMONSTRATION #1, the construction of a Leyden jar. DEMONSTRATION #3 on storing electric charge or DEMONSTRATION #2 on a dissectable Leyden jar can be used to reinforce the concepts presented in the video. Examples of radio tuners and paper capacitors might be passed around for observation.

Objective 2: Name the parts of a capacitor and describe how varying the geometry of the plates changes the capacitance.

The video describes the fundamental components of a capacitor as large electrically charged plates separated by air or glass. A constant electric field is formed between the parallel plates. Increasing the area of the plates increases the capacitance; decreasing the separation of the plates also increases the capacitance. The SUPPORTIVE BACKGROUND INFORMATION provides additional information concerning the dielectric and the dielectric constant.

It would be helpful for students to observe various capacitors. They should note that capacitors having the same capacitance and voltage rating may be different in size because of different dielectrics, dielectric thickness, and plate area. The SUPPORTIVE BACKGROUND INFORMATION provides instructions for constructing a "home made" capacitor. Students can vary its capacitance by changing its parameters. You might ask students to notice how the amount of effective plate surface (alignment) varies as a radio tuner is turned.

Objective 3: Recognize that work is done when a charge is moved within an electric field in a direction which is not perpendicular to the field lines.

If a charge q is placed in a uniform electric field E, it will experience a force F such that $F = qE$. When this charge is moved against the electric field, an external force must act on the charge. As the charge moves through a displacement **d**, work W is done to change the electric potential energy ΔU:

$$W = \mathbf{F} \cdot \mathbf{d} = \Delta U.$$

DEMONSTRATION #4 may be used to demonstrate that work is done when a charged object is moved parallel to an electric field.

Objective 4: Define electrical potential difference.

In an electric field, charged particles experience forces acting on them. If the particles are moved through some distance parallel to the electric field, work is done ($W = \mathbf{F} \cdot \mathbf{d}$). Work also denotes a change in electric potential energy, $W = \Delta U$. The quantity of work or change in electric potential energy per charge, W/q or $\Delta U/q$, is called electric potential difference, ΔV, which is commonly written simply as V. Potential differences are measured in units of joules per coulomb known as volts (1 V = 1 J/C).

Work must be done to place charge on the plates of a capacitor. Therefore, charged capacitors exhibit voltages across their plates, measured by work per charge in volts. The ratio of the charge to the electric potential difference, q/V, is called the capacitance, C. Capacitance is measured in units of coulombs per volt known as farads (1 F = 1 C/V).

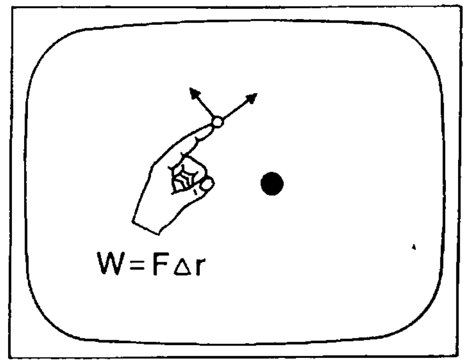
The video presents the mathematical derivation of electric potential difference. Since the video moves quickly, it may be helpful to students if you replay this section.

DEMONSTRATION #5 on capacitance and electric potential difference is designed to show that the voltage across a capacitor increases as charges are added to the plates. Performing this demonstration after the video will provide an opportunity to reinforce the concepts and clarify any misunderstanding.

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.

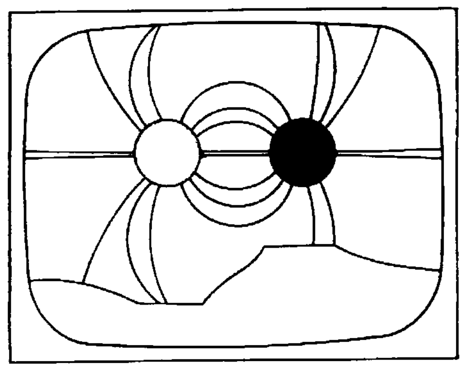
Describe the work done on the charge as it is moved in the frame from the video.

Positive work is done if the motion has a component opposite to the electric force, negative work if it has a component along the force, and no work at all if the motion is perpendicular to the electric force.



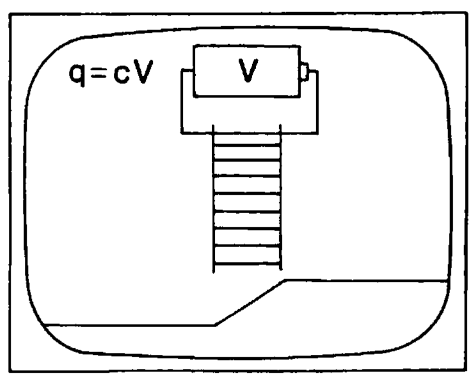
What does the graph of electric potential energy versus distance show about the dependence on the position of the test charge?

As the test charge is moved closer to the other charge, the electrical potential energy is increased.

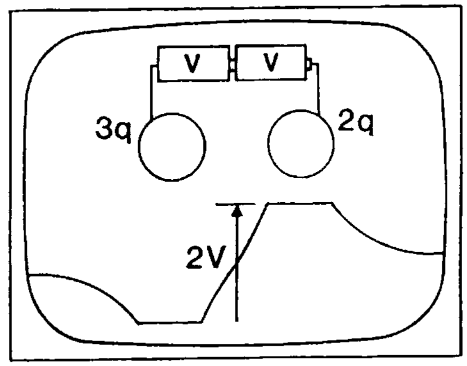


What does the potential difference between two pieces of metal depend upon?

The potential difference depends upon the following: (1) net charge on each piece of metal, (2) the physical characteristics of the capacitor, such as size and relative separation of the pieces of metal, and (3) the type of medium separating the pieces.



On the graph of potential as a function of distance, what do the flat portions represent?



The flat portions represent regions of constant potential, such as the interiors of conductors. The surface of a conductor is an equipotential surface.

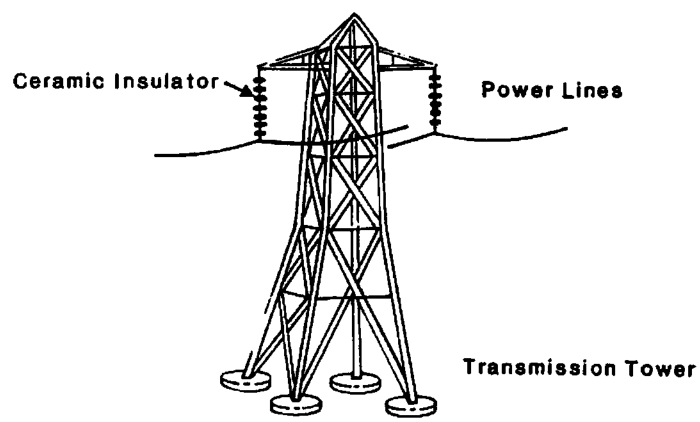
EVERYDAY CONNECTIONS AND OTHER THINGS TO DISCUSS - To reinforce further the ideas contained in the video, you might pose the following questions to your students.

1. **Why is it necessary to exert a force and do work to separate a sock from a sweater just taken out of a clothes dryer?**

   "Static cling" results when opposite charges develop on the sock and sweater. Work is needed to separate oppositely charged objects since a force must be exerted to overcome the electric attractive force holding them to each other.

2. **How can ceramic insulators on transmission towers act as capacitors?**

   Large insulators can act as capacitors since they have charges on opposite ends with a good dielectric between them. They are usually constructed with sharp "fins," as illustrated below, to promote electrostatic discharge to the air and thereby avoid capacitive effects in the power distribution system. In other words, they prevent excessive charge from building up on either side of the insulator.



3. **What is capacitance?**

   When a battery is connected across two pieces of metal, it forces charge to flow from one to the other until the potential difference between them is equal to the voltage of the battery. That creates an electric field between them. For a given capacitor, the charge transferred is proportional to the voltage applied. The constant of proportionality, C, is called the capacitance. Therefore, capacitance C is the ratio between the charge q placed on a capacitor and the potential difference V across the plates of that capacitor: $C = q/V$.

4. **How is the amount of charge stored on a capacitor related to: (a) the potential difference of the source? (b) the area of the plates? (c) the separation of the plates?**

   (a) *The charge is directly proportional to the potential of the source,* $Q \propto V$. *The higher the voltage, the greater the charge.*

   (b) *The charge is directly proportional to the area of the plates if the potential difference remains constant,* $Q \propto A$.

   (c) *The charge is inversely proportional to the separation of the plates if the potential remains constant,* $Q \propto 1/d$. *The closer the plates, the greater the charge.*

5. **Name some devices that use capacitors.**

   Automobile ignition systems, radio tuning circuits, road construction flashers, power supplies, strobe lights, and electronic flash camera are just a few examples of devices using capacitors.

6. **Why do tank trucks carrying flammable liquids use tires that conduct electricity**

   As the tires rub along the road and air flows over the surface, charge can be accumulated. If a difference of electrical potential occurs, the stored charge will produce a spark when discharged. This spark is sufficient to ignite vapors of the flammable liquid. Years ago chains were used to carry off the charge. Now tires that are conductors prevent the accumulation of charge.

SUMMARY - This video deals with static electric charges. It describes the use of the Leyden jar and the force between electric charges (Coulomb's law). The video also develops the idea that moving a charge in an electric field usually results in work being done. Finally the video explores charging a capacitor and the variables that affect the amount of charge a capacitor holds.

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 POTENTIAL DIFFERENCE AND CAPACITANCE

INTRODUCTION - The video presents a historical perspective on the theory of electricity through a study of Benjamin Franklin's experiments in electricity. The ideas of potential difference, potential energy, and capacitance are introduced and discussed.

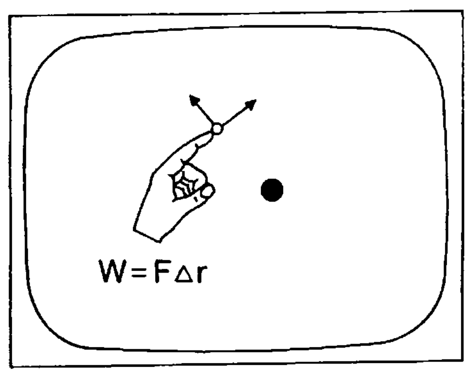
Terms Essential for Understanding the Video

work
potential energy
electric potential difference
capacitor
capacitance
electric field
Leyden jar

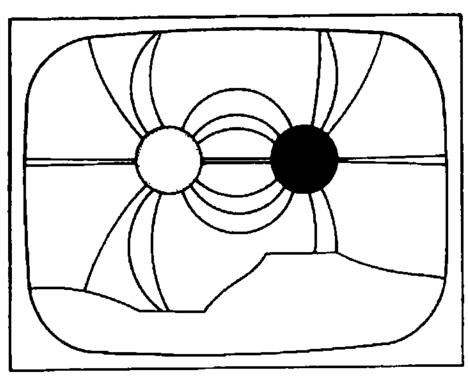
**** Note: Parts of the video, especially mathematical equations may go by quickly on the screen. If you have questions, you should ask your teacher to replay these sections. ****

Points to Look for in the Video

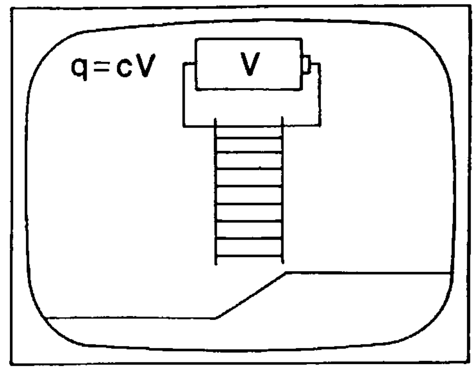
Describe the work done on the charge as it is moved in the frame from the video.



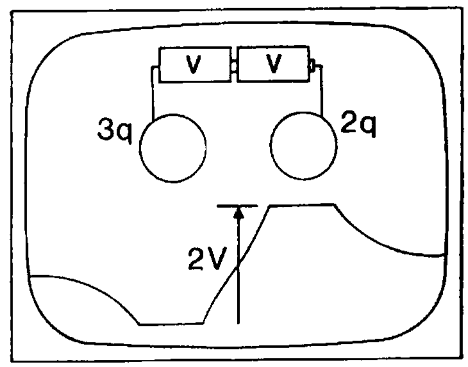
What does the graph of electric potential energy versus distance show about the dependence on the position of the test charge?



What does the potential difference between two pieces of metal depend upon?



On the graph of potential as a function of distance, what do the flat portions represent?



TEACHER RESOURCES

SUPPORTIVE BACKGROUND INFORMATION - The capacitor, an electrostatic device that stores rather than produces electric charge, was discovered accidentally in 1745 by a German cathedral dean, E.J. von Kleist, while attempting to construct a portable sparking machine. Von Kleist never realized the importance of his discovery. A few months later, Professor Pieter van Musschenbroek of the University of Leyden independently pursued experiments culminating in a similar discovery. He accidentally received a surprisingly powerful blow and later reported his distressing experience to the Paris Academy. The discovery of the capacitor, which came to be known as the "Leyden jar", turned out to be one of the most important of the 18th century.

In its basic form, a Leyden jar consists of an outer conductor separated by a glass jar from an inner conductor. Metal foil is often used to coat the inner and outer surfaces of the jar. The inner conductor is connected to a charging device, whereas the outer conductor is grounded. If the inner conductor is positively charged, for example, it attracts negative charges from ground to the outer conductor. The electric forces between the charges hold them there until some path is made available for them to recombine. In this way the Leyden jar stores electric charge. When we speak of the charge stored in a Leyden jar, we mean that charges equal in magnitude, but opposite in sign, are stored on the inner and outer conductor respectively.

The study of science or natural philosophy in colonial America was promoted by Benjamin Franklin in the early 1740's and eventually resulted in the establishment of the American Philosophical Society, which still exists today. In a letter to a friend, Peter Collinson, in 1747 he wrote about his experiments with electricity, "I never before was engaged in any study that so totally engrossed my attention and my time as this has lately done."

Although Franklin performed many experiments, he was not content to record merely his observations. A person of great insight and intelligence, he also sought to explain the phenomena he observed.

One of Franklin's triumphs was the formulation of a theory that could explain how the Leyden jar works. The positive and negative charges on the jar are always balanced, and the jar merely maintains a separation of charge. A charged Leyden jar contains the same net charge as one that is not charged, i.e., zero.

Franklin also realized that the shape of the Leyden jar is not critical. Any device consisting of two conductors insulated from each other will exhibit the same characteristics.

In a sense, Franklin's cleverest invention was the lightning rod. He realized that lightning rods should have sharp points at the ends. At a sharp point, the electric field is large; therefore, a point is the preferred configuration for a lightning rod. The large electric field serves two purposes. It could draw off charge from the vicinity, preventing a strike, and it could become a primary strike point, protecting a structure.

Electrostatics involves the study of electric forces, charges, and electric fields. Like charges repel each other while unlike charges attract each other. In order to move two like charges closer, an external force is needed. Thus work is done against the repelling electric force. Conversely, in order to separate two unlike charges, work must be done against the attractive force. A change in potential energy due to a change of position occurs. This change in the potential energy is equal to the work done

$$W = \Delta U,$$

where W is the work done and ΔU is the change in potential energy.

The intensity of an electric field is measured by the electric force on a unit charge, $E = F/q$. The electric field and the electric force are vectors.

In defining electric potential, we assume a reference point where the electric potential, as well as the electric potential energy, will be equal to zero. The electrical potential V of a charge q at some point is equal to its electrical potential energy U at this point divided by the amount of charge q:

$$V = U/q.$$

As with energy, we are usually interested in the difference of potential between any two points. Since the change in potential energy equals the work done on the charge,

$$\Delta V = W/q,$$

the unit of electric potential or potential difference is a joule/coulomb or a volt. Sometimes potential difference is called voltage.

The charge on the plates of a parallel plate capacitor creates a uniform electric field between the plates. The electric field intensity is $E = V/d$ where E is the electric field intensity in volts, V is the electric potential difference in volts, and d is the distance between the plates in meters.

A measure of a system's ability to store charge is called its capacitance. In a system with two parallel plates, separated by an insulator, we find that the greater the electric potential difference placed across the system, the more charge it will store. Experimentation also shows that the amount of charge stored on either plate is directly proportional to the electric potential difference. The ratio of the charge stored on either plate q to the electric potential difference V used to store the charge is known as capacitance C.

$$C = \frac{q}{V},$$

where C is the capacitance in farads, q is the charge in coulombs, and V is the electric potential difference in volts.

This important relationship defines capacitance. The unit of capacitance is the farad. Since a capacitance of one farad is inconveniently large, we usually find ordinary circuit components rated in millionths of farads or microfarads (μF).

Capacitance varies directly with the area of the plates and inversely with the distance between them. Putting capacitors in series is analogous to increasing the distance between the plates of a capacitor. The quantity of charge is the same on each plate and, hence, the total capacitance of the combination decreases. The total capacitance of a series combination is given by

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2}.$$

Putting capacitors in parallel essentially increases the area of the plates available to store charge, thereby increasing the amount of charge that can be stored and the total capacitance. The total capacitance of a parallel combination is given by

$$C_T = C_1 + C_2.$$

The video lesson does not address the effect of using different insulating materials in a capacitor. The insulating material is commonly referred to as the dielectric. Each material has a different dielectric constant, K, which compares its electric properties to those of a vacuum. $K = C/C_0$, where C_0 is the capacitance using a vacuum and C is the value using the material in question. A short table of K values is given with the directions for building a homemade capacitor in the ADDITIONAL RESOURCES section.

The dielectric serves several purposes:

(a) Dielectrics break down less easily than air, thus allowing the use of higher voltages.

(b) Dielectrics allow the plates to be moved closer without fear of their touching.

(c) The dielectric material increases the capacitance by a factor K.

Each capacitor has a maximum voltage rating which reflects the capability of the dielectric to prevent "puncture" by the stored charges. Directions for building a homemade capacitor are provided in the TEACHER RESOURCE section.

ADDITIONAL RESOURCES

Demonstration #1: Construction of a Leyden Jar

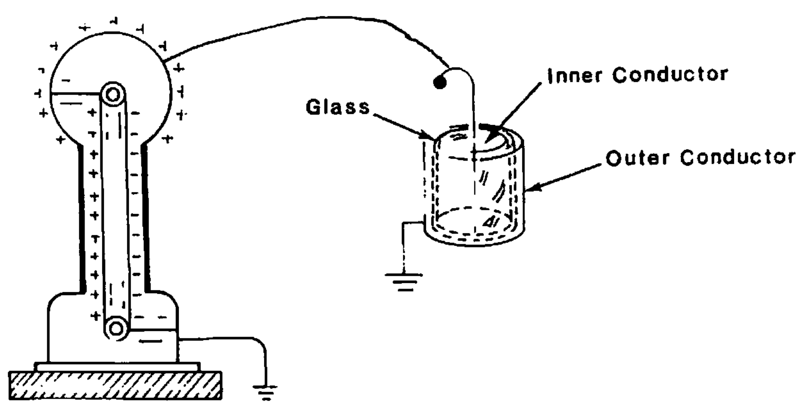
Purpose: To show how to construct a demonstration Leyden jar and how it is used.

Materials: Aluminum foil, lab beaker (600 mL to 1 L), top for the beaker made of stiff cardboard or wood, bolt, length of metal chain, a charging ball 1 - 2 cm in diameter, discharging wire with insulated handle, and a Wimshurst or Van de Graaff generator.

Procedure and Notes:

1. Line the inside and outside of the beaker with foil. Avoid creating sharp points wherever possible.
2. Assemble ball, bolt, and chain so as to contact the inner foil lining when the top is in place.
3. Charge the Leyden jar with a Wimshurst or Van de Graaff electrostatic generator.
4. To discharge the Leyden jar safely use a discharge wire connected to ground and touch the inner conductor of the jar several times.

CAUTION: THIS DEVICE CONTAINS CHARGE AT A VERY HIGH VOLTAGE.



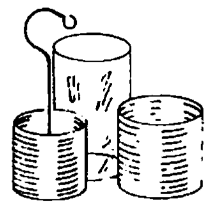
Explanation:

1. Contact with an electrostatic generator will cause charge to be shared between it and the charging ball. Grounding the outer foil will permit it to assume an equal but opposite charge to the charge on the inner foil.
2. Once charged, the Leyden jar can hold its charge for hours. Providing a conducting pathway will allow the charges to flow so as to discharge the device.

Demonstration #2: A Dissectable Capacitor

Purpose: To show where a capacitor stores electric charge.

Materials: Wimshurst or Van de Graaff electrostatic generator, dissectable capacitor, discharging wire.



Procedure and Notes:

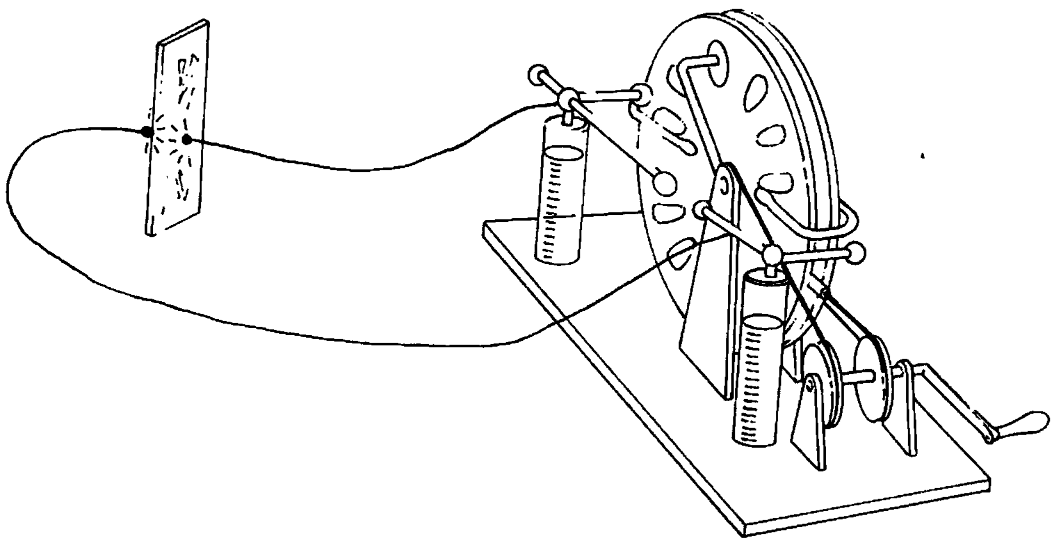
1. Assemble the capacitor and charge it with an electrostatic generator.
2. Withdraw the inner foil carefully with the discharging wire. Extract the glass from the outer foil. The two plates can be handled separately without hazard.
3. Touch the inner and outer foils together. A small spark results.
4. Reassemble the capacitor and discharge it with the discharge wire. A large discharge is seen and heard despite the previous contact between the foils.

Explanation: The charge on a charge capacitor is found mostly on the dielectric, in this case, the glass plate, not on the plates. This is evidenced by the larger spark obtained by discharging the capacitor when the glass is between the plates than discharging when the glass has been removed.

Demonstration #3: Storing Electric Charge

Purpose: To show how a capacitor stores electric charge.

Materials: Wimshurst or Van de Graaff electrostatic generator, insulated wire, sheet of heavy plastic or glass about 15 cm 3 20 cm in area.



Procedure and Notes:

1. Check your school's liability insurance.
2. Hold the sheet of plastic or glass approximately 1 cm from the exposed ends of the wires connected to the + and - terminals of the generator.
3. Run the generator allowing the discharge to flow over the exposed faces of the sheet.
4. Stop the generator and remove the sheet. Have a volunteer touch the faces of the sheet on opposite sides with one finger from each hand. A sizable discharge will be felt by the volunteer. CAUTION: **The larger the area touched, the greater the discharge.**

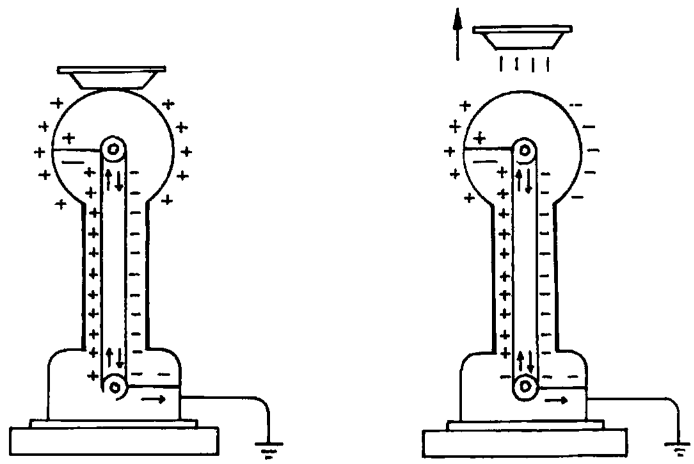
Explanation: During the charging process, a surplus of electrons on one side and a deficiency of electrons on the other were produced. These charges were placed on an insulated surface and could NOT move. They were "STATIC." Touching with your fingers allows some of these charges to flow through your body with shocking results.

Demonstration #4: Work in an Electric Field

Purpose: To show that work must be done to move a charged object parallel to an electric field.

Materials: A Van de Graaff electrostatic generator, 4 - 6 small aluminum pans (pot-pie size or frozen pie plate).

Procedure and Notes: Set the stack of pie pans on top of the generator and turn it on.



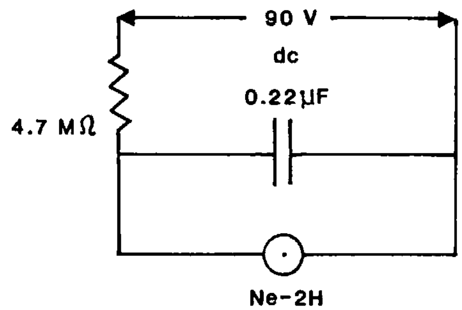
Explanation: The charged pans are in an area of an electrical field surrounding the dome. The resulting repulsive force on the pans causes them to rise one at a time while they are in the area of the electric field. As the pans lift, an increase in their gravitational potential energy occurs. This increase in gravitational potential energy is evidence that work has been done on the pans.

Demonstration #5: Capacitance and Electric Potential Difference

Purpose: To show that adding electric charge to a capacitor produces an increased electrical potential across the capacitor.

Materials: 90 V dc source, 4.7 MΩ resistor (Yel Viol Grn) 1/4 W, 0.22 μF capacitor (150 volt rating or higher), Ne-2H Neon bulb, insulated wires to connect components.

Procedure and Notes: Connect the components according to the diagram below. The neon bulb will flash at regular intervals related to the resistance and the capacitance used.



Explanation: A small current (flow of charge) passes through the resistor to charge the capacitor. As the capacitor charges, the potential difference across its plates increases according to the relationship

$$V = Q/C.$$

When this electrical potential difference reaches about 70 volts, the Ne-2H bulb conducts, producing a blink of light, discharges the capacitor, and the cycle repeats.

A large resistance or capacitance will slow down the rate of blinking; a lower resistance or capacitance will increase the rate. If 90 V dc is not available, a diode in series with the resistor will permit the circuit to be used with 120 V ac.

Activity: Building a Homemade Capacitor

Directions:

Parallel sheet capacitors consist of two parallel sheets of aluminum foil separated by a thin sheet of plastic. To get a large area in a convenient package, the sheets are usually a few centimeters wide but several meters long. The resulting sandwich is then covered by another sheet of plastic and rolled into a compact cylinder. Plastic garbage bags are a good source of the necessary plastic sheets.

For this capacitor, the capacitance can be found using the following equation:

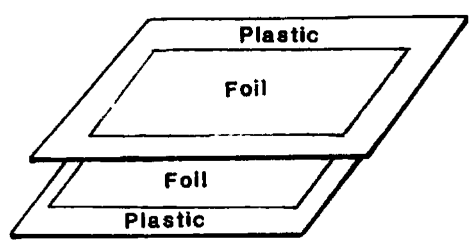
$$C = K\varepsilon_0 A/d.$$

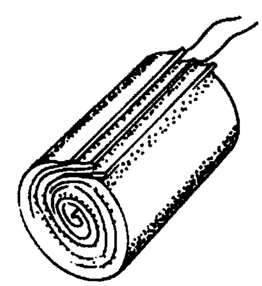
C = capacitance in farads (coulombs/volt),
K = dielectric constant which varies for each insulating material

K value	Material
1.0000	vacuum
1.0006	air
2.2	paraffin
2.8 - 4.5	plastic
3.0 - 7.0	paper
7.0	mica

$\varepsilon_0 = 8.85 \times 10^{-12}$ C/V, m,
A is the area in m^2 of each of the identical foil sheets,
d is the thickness of insulating sheet in meters.

One farad is a large capacitance. Most capacitors in common use have capacities measured in $\mu F = 10^{-6}$ F (microfarads) or $pF = 10^{-12}$ F (picofarads).





Changing the area or thickness of the dielectric, or changing the dielectric material itself will affect the capacitance of the device. In general:

Capacitance $\propto$ area,
Capacitance $\propto$ 1/dielectric thickness,
Capacitance $\propto$ K (nature of dielectric).

EVALUATION QUESTIONS

1. In an electric field the electric potential energy or work done per charge, (w/q), is equal to the

   A. magnitude of the electric field.
   B. potential difference.
   C. capacitance.
   D. rate of charging.

2. Using a constant source of potential, a capacitor is charged. A second capacitor with identical plates, but twice the separation, is charged using the same source of potential. If the charge on the first capacitor is q, the charge on the second will be

   A. 1/4 q.
   B. 1/2 q.
   C. 2 q.
   D. 4 q.

3. A parallel plate capacitor will hold no more charge after a source of potential difference has been placed across it for a period of time. A similar capacitor, having twice the area, is attached to an identical source of potential. If the charge on the first capacitor was q, the charge on the second will be

   A. 1/4 q.
   B. 1/2 q.
   C. 2 q.
   D. 4 q.

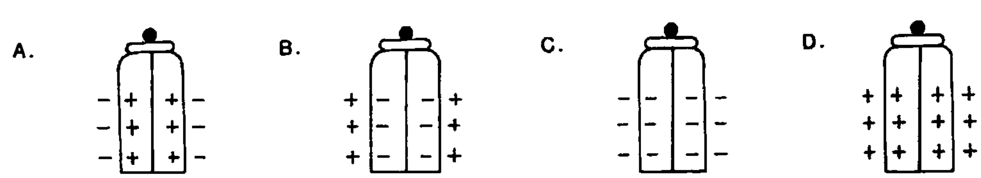
4. If you use 20 joules of work to move a 4-coulomb charge within an electric field, the charge would move through a potential difference of

   A. 4 V.
   B. 5 V.
   C. 20 V.
   D. 80 V.

5. During a lightning storm the clouds and the earth must have opposite charges in order that a bolt arc between the two. This system is most like

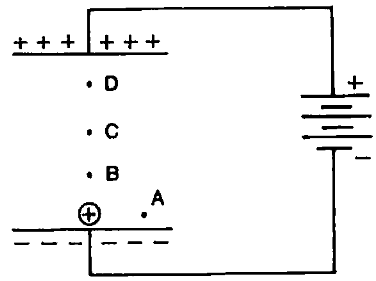
   A. a resistor.
   B. an electroscope.
   C. a Faraday cage.
   D. a capacitor.

6. A negatively charged rod is brought in contact with the ball of a neutral Leyden jar that has its outer coating connected by a wire to the ground. Which of the following diagrams represents the Leyden jar after it has been charged?



7. **The greatest amount of work would be required to move the positive test charge (+) from its present position to**

   A. Point A.
   B. Point B.
   C. Point C.
   D. Point D.



Use the following information to answer Questions 8 - 10.

Imagine that the front wall of the classroom is charged positively and the back wall charged negatively. A small positively charged helium balloon is brought into the middle of the room and it is held halfway between the floor and the ceiling. Assume the electrical forces can and do affect the balloon.

8. **If the balloon is released, how would it move in the room?**

   A. It would move toward the front of the room.
   B. It would move toward the back of the room.
   C. It would experience balanced forces and not move at all.
   D. It would move if pushed by hand but stop when released.

9. **Where in the room would the electric field strength be greatest?**

   A. Near the front of the room.
   B. Near the back of the room.
   C. In the middle of the room.
   D. It is about the same anywhere in the room.

10. **Where in the room would the balloon experience the greatest net force?**

    A. Nearer the front wall.
    B. Nearer the back wall.
    C. In the middle of the room.
    D. It is about the same anywhere in the room.

ESSAY QUESTIONS

11. **Describe how the plates of a charged capacitor create an electric potential difference between them.**

12. **Describe how and why the capacitance changes when there is a doubling of the area of the plates of a parallel-plate capacitor that is connected to a battery.**

KEY

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

SUGGESTED ESSAY RESPONSES

11. The potential difference between the plates of a charged capacitor is due to the electric field that exists between the plates. That electric field is created by the charges on the plates, and to move a charge from one plate to the other requires work against that electric field. The work done per unit charge moved defines the electric potential difference.

12. If the area of a capacitor's plates is doubled, the amount of charge that can be stored on the plates is also doubled. Since the capacitor is connected to a battery, the potential difference remains constant. Thus the capacitance, being the ratio of the charge to the potential difference, also doubles.

TEACHER'S GUIDE TO EQUIPOTENTIALS AND FIELDS

CONTENT AND USE OF THE VIDEO - Since the video explores the relationships between electric potentials and electric fields, a study of both concepts should precede a showing of the video. The contour lines of a landscape are mapped as an analogy for mapping the contours of electric potentials in an electric field. The electric fields for several charge arrangements are then examined.

The video also considers the cause of electrical discharges by observing the electron-molecule collisions in the air surrounding a Van de Graaff generator. In answering the question of how much energy an electric device such as a Van de Graaff can deliver, the video includes a discussion of the mathematical relationships among energy, voltage, and charge.

TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO - Since the following terms are introduced in the video, it should be helpful to discuss them with students prior to viewing the video.

work--the product of the component of the force in the direction of motion and the object's displacement; $W = \mathbf{F} \cdot \mathbf{d}$.

charge--a fundamental quantity that is responsible for electric forces.

test charge--a charge used to investigate an electric field. By convention, the test charge is positive and assumed to be so small in both size and magnitude that it does not disturb the field being investigated.

electric field--the alteration of the properties of space around a charged body that will affect a test charge q with a force $\mathbf{F}$; the electric field at a point in space is defined to be the force divided by the magnitude of the test charge, i.e., $\mathbf{E} = \mathbf{F}/q$.

electric potential energy--energy possessed by an electric charge by virtue of its position in an electric field. Equal to the work done to move the charge into that position at constant speed.

electron volt--a unit of electric potential energy; one electron volt (eV) equals 1.6×10^{-19} joules.

electric potential difference--equal to the work W done to move a unit test charge q at constant speed from one point to another in an electric field divided by the magnitude of the charge: $\Delta V = W/q$.

electric potential (at a point)--the work per unit charge required to move a test charge from infinity to the point in question.

equipotential surface--a surface on which the electric potential is constant; equipotential surfaces are everywhere perpendicular to electric fields. This is equivalent to equielevations on a contour map. Conductors under electrostatic conditions are equipotential surfaces.

WHAT TO EMPHASIZE AND HOW TO DO IT - The video assumes that students have already studied various electrical concepts such as charges, forces, fields, and potential and, consequently, have developed insights into the nature of electricity and its effects. A further exploration of the relations between these concepts, in particular the relation between fields and potentials, constitutes the focus of this module. The analogy of topographic mapping is used to help students understand how these concepts fit together.

Objective 1: When given a charge distribution, draw equipotential surfaces.

The collection of all connected points in space at which the electric potential V has the same value determines an equipotential surface. DEMONSTRATION #1 on plotting equipotentials can be used to illustrate equipotential surfaces around simple charge configurations, Equipotential surfaces also have the property that they are perpendicular to electric field lines of force. You might illustrate this for the case of a point charge in which the electric field lines are radial and the equipotential surfaces form spheres centered on the charge.

Objective 2: When given equipotential surfaces, draw the electric field lines.

Students have the misconception that electric fields and electric potential are the same. To correct this misconception point out that an electric field represents the force per unit charge, whereas electric potential represents the negative of the work done per unit charge in moving it. The electric field is greatest where the equipotential contours are the "steepest." The electric field measures the change in potential ΔV with change in distance Δr and so is given by $E = -\Delta V/\Delta r$. The direction of the electric field is found from the direction of greatest increase in the potential, i.e., the steepest ascent of equipotentials. Unit analysis might be used to help correct the misconception.

DEMONSTRATION #2 on plotting electric field lines might be used to relate field lines and equipotential surfaces. Be sure to emphasize that electric field lines are everywhere perpendicular to equipotential surfaces.

Objective 3: When given electric field lines, draw equipotential surfaces.

Remind students that electric field lines are perpendicular to equipotential surfaces. DEMONSTRATION #2 might be used to reinforce this concept.

Objective 4: Describe the condition for an electric discharge to occur.

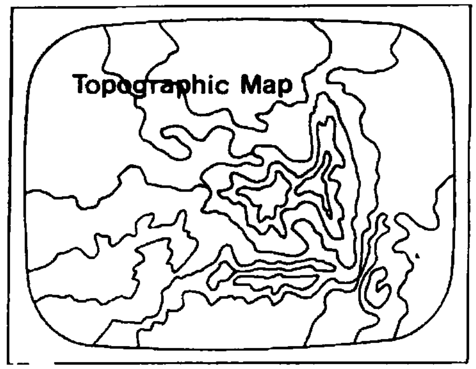
In the vicinity of the Wimshurst machine air molecules are in constant motion. Although most of the molecules are neutral, there are a few stray electrons. Imagine an electron attracted to a positive electrode of a Wimshurst machine. Because the electron "feels" a force, it accelerates and gains energy. The chances are good that the electron, as it accelerates toward the positive electrode, will collide with another air molecule and ionize that molecule. If the electron is able to gain an energy of tens of electron volts before the collision, it is quite capable of knocking an electron off the molecule. Consequently, another electron is created and both of them are accelerated and collide with other air molecules, which become ionized, and so on. The whole process cascades, creating an avalanche of electrons that momentarily turns the air into a conductor. For a brief instant a vast number of positive ions are separated from their electrons. These electrons are free to move around and conduct electricity by moving to the positive electrode of the Wimshurst machine. The light given off is emitted by the ionized air molecules as electrons recombine with them. That's the spark. The air is momentarily a charged gas, known as a plasma, that releases the potential of the Wimshurst machine. If a steady discharge takes place and results in a visible glow or halo, the discharge is known as *corona discharge.*

Objective 5: Describe the relationships among energy, potential, and charge.

The amount of energy a charge has depends on the size of the charge and the potential difference it moves through, $U = q\Delta V$. Students may have the misconception that high voltage is always dangerous; that is, that high voltage means high energy. Use the relationships among energy, potential, and charge to point out that a small amount of charge can have little energy even if the potential is very large, as in the case of a Van de Graaff generator. Likewise, a large amount of charge going through a small potential difference, as in a battery, can have a large amount of energy. Students will find DEMONSTRATION #5 of interest because it shows that high voltage is not necessarily dangerous, whereas relatively low voltage can be dangerous. DEMONSTRATION #6 illustrates how the movement of a charge within an electric field can change its potential.

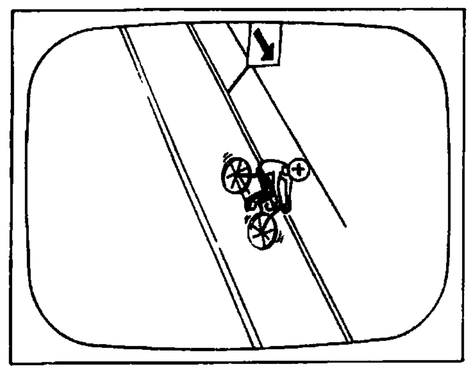
POINTS TO LOOK FOR IN THE VIDEO - Several questions are posed in the STUDENT'S GUIDE. Here are those questions along with suggested responses and selected frames from the video.

What is the significance of the contour lines on a topographic map? The separation of lines of equal electric potential identifies what aspect of the region that surrounds those charges?



On a topographic map, the closer together the contour lines are, the steeper the slope. Similarly, in the case of electricity, the closer together the equipotentials are, the larger the electric field is.

As you move a test charge in the space surrounding several charged objects, a particular direction will take you from one equipotential to the next in the least distance. What is the significance of moving along this direction?

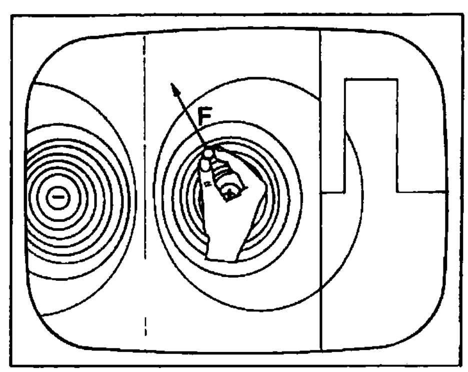


Moving in a direction which takes you from one equipotential to the next in the least distance is like going down a hill in the steepest possible direction. Moving in such a direction in an electric field means you are moving along a field line.

The change in potential with distance can be related to the electric field with the following expression:

$$E = -\Delta V/\Delta r$$

Discuss the connection between the electric field and changes in electric potential.

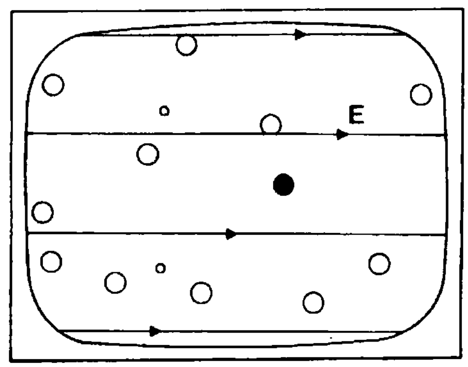


As you move from a high potential to a low potential, you are moving in the direction of the field. That is, if the potential decreases, you are moving with the field.

Is work done in moving a charge along an equipotential line?

Work is the product of the component of the force in the direction of the charges motion and the distance moved. When a charge is moved along an equipotential line, there is no force component in the direction of motion and hence no work is done.

List two conditions that can assist an electric spark to form. (Hint: Consider the kinetic energy of the ionizing electron.)



Free electrons must be given enough energy by the electric field between collisions to ionize the air molecules. The conditions are:

1. *The average spacing between collisions must be great enough (i.e., the molecular density must be small enough);*

2. *The intensity of the electric field must be large enough. Thus, for a given voltage between conductors, there will be a range of gas pressures, or at atmospheric pressure there is a certain voltage at which sparks will jump.*

Why is a battery vastly more useful than a Van De Graaff generator or a Leyden jar?

The battery is more useful because it can store so much more energy. Its potential difference is less but the amount of charge it can, store is much greater.

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. **Comment upon the hazards associated with coming in contact with:**

   (a) a Van de Graaff generator.

   It will hurt, but you will live. Here we have a large potential but only a small charge.

   (b) a car battery.

   A car battery offers a large amount of charge but only a small potential to push it. Here the hazard is quite small unless something has happened to lower your skin resistance such as a break in your skin. (At this time you could discuss how your skin resistance keeps the current flow through your body at such a low level that you are safe when your hands are across a battery.

   (c) a broken high voltage line which has fallen on the hood of your car.

   Here you are in real trouble! The potential is high enough to overcome your skin resistance and there is more than enough charge to finish you off!

2. **Would you expect the molecular density to be high or low inside a fluorescent tube compared to the molecular density of air at atmospheric pressure? (Note: This question is designed to stimulate thought prior to DEMONSTRATION #4: Fluorescent tube and Van De Graaff.)**

   The molecular density inside the tube is less than the air. This can be verified by breaking a fluorescent tube and noticing that it implodes, but that is a very dangerous demonstration and should not be performed.

3. **The following applications utilize the concepts of equipotentials and electric fields.**

   (a) The spark plug:

   A small amount of energy is required to initiate the chemical reaction of the fuel and air in an automobile engine. The high voltage from the ignition coil is placed across the small gap in the spark plug, this, in turn, creates an intense electric field between this gap which initiates the discharge process as discussed in the video.

   (b) Fluorescent light:

   Again, ionization is made possible by the electric field between the ends of the tube. (This is discussed in more detail in Explanation 2 of DEMONSTRATION #4.)

(c) **Wires in electric circuits:**

The function of a wire in an electric circuit can be understood by considering the concept of an equipotential surface. Since a potential difference is placed across the wire, an electric field appears in the wire. However, the free electrons in the wire will immediately start to flow in response to the force of the field; hence an electric current will be established. As long as an external source of potential difference is applied across the ends of the wire, current will flow through the wire as the charges "try" to return all parts of the wire to the same potential.

(d) **Lightning rod:**

When a charged cloud passes over a tall building, the field between the building and the cloud may become so intense that the air between them can be ionized allowing charge to pass between them. The resulting energy release could damage the building. If, on the other hand, a sharp point attached through a wire to the ground were protruding above the top of the building, the very intense electric field in the vicinity of the point could constantly ionize the air above it and release the energy in a controlled fashion long before an explosive energy release could occur. The sharp point plays a second role in that, if a discharge does take place, it will most likely occur at the site of the most intense field, i.e., at the point of the rod. The wire connected to the rod then directs the discharge safely to ground. (For more details, see DEMONSTRATION #3.)

SUMMARY - The video develops the concept that a connection exists between electric potentials and electric fields. Electric field lines are always perpendicular to equipotential surfaces. When these surfaces are closer together, the electric field is stronger.

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 EQUIPOTENTIALS AND FIELDS

INTRODUCTION - The video discusses the relationship between electric potential and electric fields. The contour lines on a topographic map are used as analogous illustrations of the contours of electric potentials in an electric field. The cause of electrical discharge is also examined.

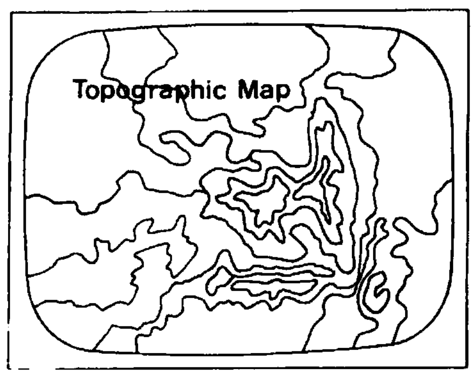
Terms Essential for Understanding the Video

work
charge
test charge
electric field
electric potential energy
electron volt
electric potential difference
electric potential
equipotential surface

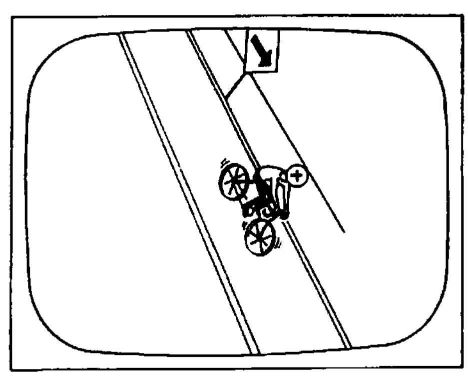
**** NOTE: Parts of the video, especially mathematical equations, may go by quickly on the screen. If you have questions, you should ask your teacher to replay these sections. ****

Points to Look For in the Video

What is the significance of the contour lines on a topographic map? The separation of lines of equal electric potential identifies what aspect of the region that surrounds those charges?



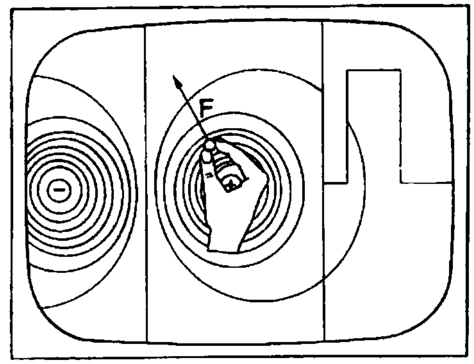
As you move a test charge in the space surrounding several charged objects, a particular direction will take you from one equipotential to the next in the least distance. What is the significance of moving along this direction?



The change in potential with distance can be related to the electric field with the following expression:

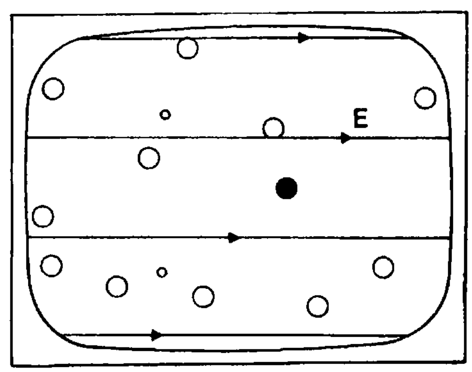
$$E = -\Delta V/\Delta r.$$

Discuss the connection between the electric field and changes in electric potential.



Is work done in moving a charge along an equipotential line?

List *two* conditions that can assist an electric spark to form. (Hint: Consider kinetic energy of the ionizing electron.)



Why is a battery vastly more useful than a Van De Graaff generator or a Leyden jar?

TEACHER RESOURCES

SUPPORTIVE BACKGROUND INFORMATION

- The electric force between two point charges is given by Coulomb's law.

$$F = K_e \frac{q_1 q_2}{r^2} \hat{r} .$$

This force can be either attractive or repulsive depending on whether the signs of the electric charges (q_1 and q_2) are the same or different. A more frequent consideration, however, is the force exerted by a large number of electric charges such as on the surface of a conductor or in a dielectric. In these situations it is necessary to sum over all the electric charges on the given surface, a problem requiring more sophisticated mathematics than is usually present in high school physics.

The concept of an electric field is introduced to describe the alteration of space around an electrically charged body. The field is defined by the force F that it can exert on a small positive test charge q. The test charge is so small that it does not affect the field created by the charged body. By measuring the force, the electric field can be deduced at each point in space. The electric field is defined as the electric force divided by the magnitude of the test charge:

$$E = F/q .$$

Since force is a vector quantity, the electric field is also a vector quantity; however, through the concept of work, it is related to the scalar quantities electric potential energy and electric potential.

To understand electric potential and electric potential energy, it is first necessary to understand the concept of work. Work is the product of displacement and the force in the direction of that displacement. The total work in moving from a starting point A to some point B is the area under the force-displacement graph where it is understood that the force is in the direction of the displacement:

$$W = \text{area under force-displacement graph,}$$

$$W = \sum_i F \cdot \Delta d_i .$$

If the force is constant and is in the direction of the displacement, then

$$W = Fd .$$

In keeping with the constraint that a constant force is acting in the direction of the displacement, the work done by an outside agent in moving a charge q against the electric field can be expressed as

$$W = -qEd ,$$

where

$$F = qE .$$

The force required to move q *against* the electric field must be applied by an outside agent. Figure 1 illustrates this situation. The negative sign indicates that the applied force is opposite in direction to the electric field so that the charge does not accelerate as it is being moved. The work done in moving a charge *against* the electric field from Point A to Point B is defined to be the *change in electric potential energy.*

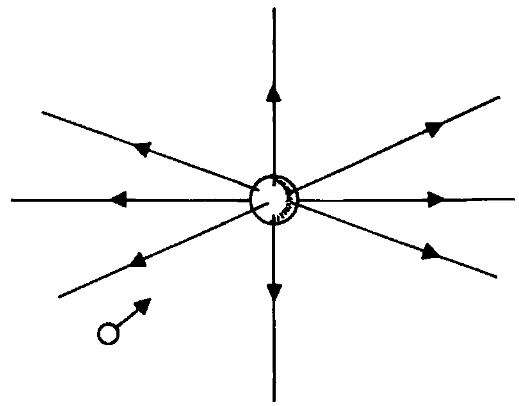


Figure 1

Substituting for the work, we obtain

$$\Delta U_e \equiv W = -qE\Delta d\,.$$

Removing the constraint of a constant force, ΔV_e may be written as

$$\Delta U_e = -q\sum_i \mathbf{E}\cdot\Delta \mathbf{d}_i\,.$$

This equation is analogous to the general definition of gravitational potential energy found in most physics textbooks.

To define the electric potential at a point in space, it is necessary to choose an *arbitrary* point of reference. The choice most frequently made is that $V_\infty = 0$ at $r = \infty$. Adopting this choice, it can be shown that, for a point charge q_2 in the vicinity of another charge q_1, the potential energy of the system is

$$U_p = K_e \frac{q_1 q_2}{r}\,,$$

where r represents the distance between q_2 and q_1.

Just as the electric field is defined as the electric force per unit charge so, too, the ratio of electric potential energy to a unit charge is defined as the electric potential:

$$V \equiv U/q\,.$$

Electric potential is a scalar quantity, measured in volts, equal to a joule per coulomb. The electric field and electric potential due to a point charge are given by, respectively,

$$\mathbf{E} = K_e \frac{q}{r^2}\,\hat{\mathbf{r}}\,,$$

$$V = K_e \frac{q}{r}\,.$$

A point charge is merely *one* specific example of this relationship. Other charge distributions produce different equations to describe the electric potential and the electric field.

The electric potential describes the electric potential energy per unit charge. The region around any charged distribution may be described by equipotential surfaces. *These are imaginary surfaces in space.* Their visualization provides a model for picturing energy changes as a charge is moved in the neighborhood of charged body. The difference from "surface" to "surface" provides information about the difference in energy for a unit charge moving between these surfaces.

From the equation $V \equiv U/q$ follows an important general relationship. The energy of a charge q in an electric potential V is given by

$$U_e = qV .$$

A small change in electric potential energy is given by

$$\Delta U_e = q\Delta V .$$

Examples of Electric Potential Configuration

(1) For a point charge q, the equipotential surfaces are a series of concentric spheres. Figure 2 shows a diagram of such concentric spheres.

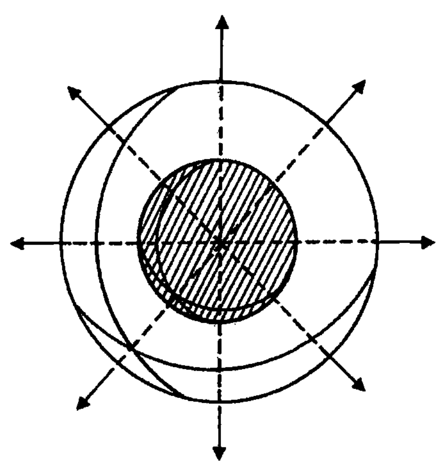


Figure 2.
Equipotential surfaces are concentric spheres around a point charge. The electric field lines are radially outward (solid lines).

(2) For two parallel plates that are very large compared to their separation the equipotential surfaces are planes parallel to the actual plates. Figure 3 diagrams this situation. Equipotential surfaces around other charge distributions are more complicated in shape. The video provides a display around a dipole, which is a positive and a negative charge separated by a small distance.

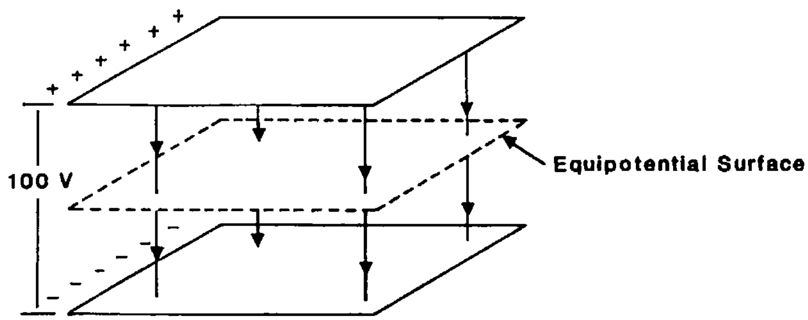


Figure 3.
Equipotential surface between parallel charge plates. The electric field lines (solid lines) are uniform and point from the positively charged plate to the negatively charged plates (All planes are assumed to be infinite in extent.)

Comments on Equipotential Surfaces

A diagram of equipotentials is analogous to a topographic map. On a topographic map each line, or contour, represents a line of constant elevation. Similarly, each contour of equipotential represents a region at exactly the same electric potential. The work required to move anywhere along an equipotential surface is zero for $\Delta V = 0$ and thus $\Delta U_e = 0$.

On a topographic map the difference in the contour lines gives the difference in elevations, and the ratio of the difference in elevation to the separation of lines gives a measure of the steepness. In an analogous manner, the ratio of the difference in electric potential to the separation of these contours gives a measure of steepness which is called the electric field, i.e., the force per unit electric charge. Electric field lines are shown (solid lines) in both Figure 2 and Figure 3.

The relationship between potential difference and electric field can be derived easily for the specific case of a parallel plate capacitor like that shown in Figure 3. Consider two points on equipotential surfaces between the plates that are separated by a distance Δr. The difference in electric potential between these surfaces is given by

$$\Delta U_e = -qE\Delta r\,.$$

Remembering *the definition of electric potential difference,*

$$\Delta V = \Delta U_e/q\,,$$

we have

$$\Delta V = \Delta U_e/q = -E\Delta r\,.$$

Solving for the electric field magnitude, we obtain

$$E = -\Delta V/\Delta r\,.$$

In other words, the electric field is the potential difference divided by the distance, Δr, between the equipotential surfaces. The negative sign indicates that the electric field is directed toward points of progressively lower electric potential. The distance Δr must be the minimum separation between the equipotentials. The electric field is measured in units of newtons/coulomb or volts/meter, which are equivalent units.

Equipotential surfaces cannot touch or intersect. Consider the implication if two such surfaces did intersect. The interaction would imply that a point on the intersection line simultaneously has two different potential energies--an impossible situation!

Electric field lines are perpendicular to equipotentials. If they were not, there would be a component of the electric field along the equipotential surface, $\Delta V = -E_{//}\, \Delta r$, where $E_{//}$ is the component parallel to the surface. But, equipotential surface means $\Delta V = 0$. Hence, $E_{//} = 0$ and E must be entirely perpendicular to the equipotentials.

Equipotential surfaces are closed surfaces, whereas electrostatic field lines must begin and must end on charged bodies.

The concept of electric potential associates a number--a scalar--with each point in space surrounding a charge distribution. On the other hand, the electric field associates a vector with every point in space.

The electric field can be mapped with electric lines of force. If a conductor of some arbitrary shape has a stationary electric charge on it, all of the net charge must reside on the outer conductor surface. If this were not so, there would exist electric forces *inside* the conductor which would cause the motion of charges in the conductor. Since the conductor is assumed to be under *electrostatic* equilibrium, the charges must be at rest. Therefore, the conductor must represent an equipotential region and the lines of force leaving it must be perpendicular to the surface. Since the electric field is zero inside a conductor, the electric potential at all points within a conductor in electrostatic equilibrium is constant, i.e., equal to the electric potential on the surface.

A Van de Graaff and a Wimshurst machine are common laboratory devices capable of generating very high potentials which are then discharged by a spark. What causes the spark? It is not caused by the high potentials of the machines setting up very intense electric fields which rip apart the molecules in the air. Rather, there are previously existing electrons in the vicinity of the high voltage dome. One of these electrons will experience a force, accelerate, and gain both speed and kinetic energy. Stated slightly differently, the electrons will fall through a potential difference between molecules, thus gaining kinetic energy. The spacing between molecules in a gas is large compared with atomic and molecular distances. Therefore, an electron moving between gas molecules will be able to gain considerable energy before colliding with a molecule. If this electron gains an energy of tens of electron volts, it is capable of knocking an electron off the molecule. Consequently, chances are good that the collision of an electron with an air molecule will ionize the molecule. When this happens, another electron will be released to join the original electron. Now both electrons will fall through a potential difference while gaining kinetic energy. These electrons, in turn collide with other air molecules, ionize them to producing more free electrons, and on and on. This cascading process creates an avalanche of electrons and positive ions which turn the air into a conductor. For a brief instant, a large number of positive ions are separated from their electrons and now the ions and electrons are free to move and to conduct electricity. Light is emitted by the air molecules as electrons recombine with the positive ions. That's the spark.

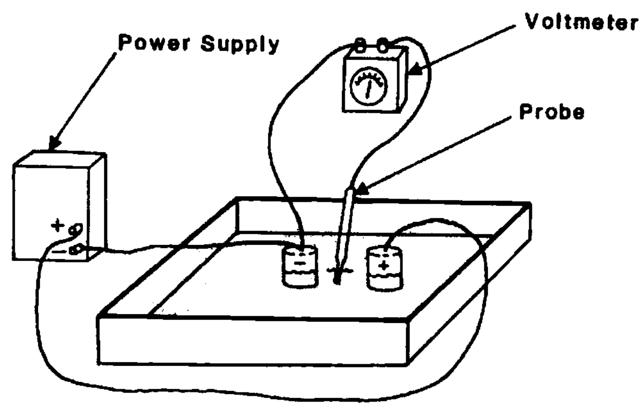
ADDITIONAL RESOURCES

Demonstration #1: Plotting Equipotentials

Purpose: To show the general shape of equipotentials around a simple charge configuration.

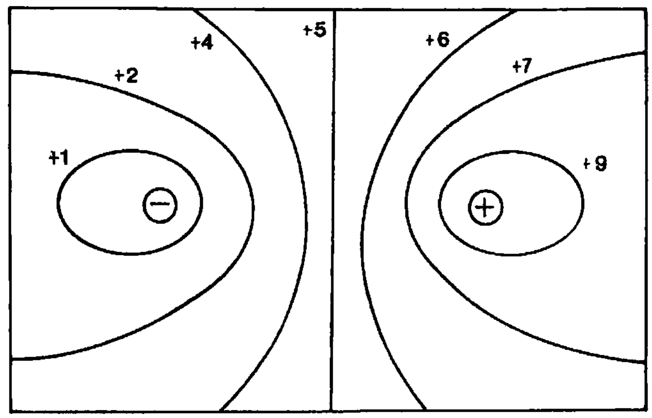
Materials: A ripple tank which can be used with an overhead projector to project objects in the tank on to a chalk board. (If your ripple tank has a conducting outer edge, steps must be taken to insulate the inside so that salt water will not make electrical contact with the edge. Using transparent plastic wrap inside the tank or spraying the inside edge with acrylic spray will usually work.) Low voltage power supply (10 or more volts); voltmeter (the higher the resistance of the voltmeter the better--a VTVM is excellent); metal electrodes (two 200 gram masses will do nicely); a conducting solution of salt and water; and a metal cylindrical ring and assorted electrical leads.

Procedure and Notes: Fill the ripple tank with salt water and arrange it so that images can be projected on the chalk board.



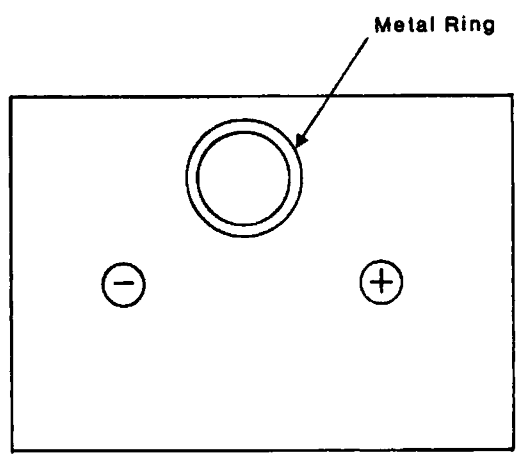
Connect the power supply to the electrodes as illustrated and adjust the potential to approximately 10 volts. Attach one lead of the voltmeter to one of the electrodes and let the other lead of the voltmeter be the "probe" that will be used to plot the equipotentials. As a preliminary check, place the probe on the "+" electrode and note the full scale reading. Then move the probe into the salt water very near the "+" electrode. You should note only a small change in the reading in the voltmeter. If a large change is observed, this means either the water is not sufficiently conductive or you should use a voltmeter with a higher internal resistance. Now move the probe between the electrodes and you should observe a fairly linear change in voltage with distance from the "−" electrode. You are now ready to plot equipotentials.

1. Place the probe fairly near the "−" electrode; note the voltage and then move the probe around in a way that keeps the same reading on the voltmeter. Make sure you can move all the way around the electrode.



Have a student plot the position of the probe on the chalk board for assorted points as you move along the equipotentials.

2. Now move the probe near the "+" electrode and find a higher potential (e.g., 9 volts) that allows you to move around the "−" electrode. Again plot the equipotentials.
3. Repeat for several different potentials. Although not all values will allow you to completely circle the electrode, the incomplete equipotential "surface" can be plotted.
4. Now place a large metal ring in the tank between the electrodes. You will notice that the potential will change as you move the probe in the region outside of the ring but that it will remain the same when the probe is moved around in the region inside of the metal ring. Hence a conductor placed in an electric field will have the same potential everywhere.



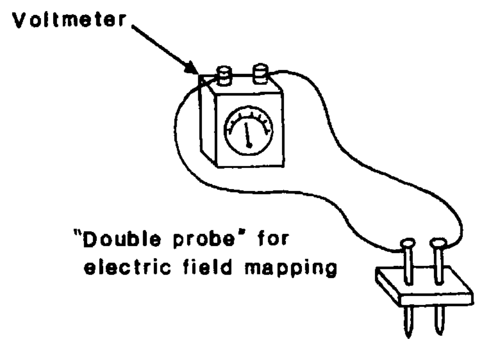
Explanation: This demonstration should help students to understand the illustrations given in the video.

Note: This experiment is *not* an electrostatic experiment. As electric current passes through the salt water, an IR drop is established and you are using the voltmeter to measure this IR drop. As you move the probe, keeping the readings on the voltmeter constant, you will be moving along regions of constant IR drop. Therefore, you will be identifying lines of constant potential difference. In this electric current situation, lines of constant potential difference correspond to equipotentials in the region surrounding the charges in an electrostatic situation.

Demonstration #2: Plotting Electric Field Lines

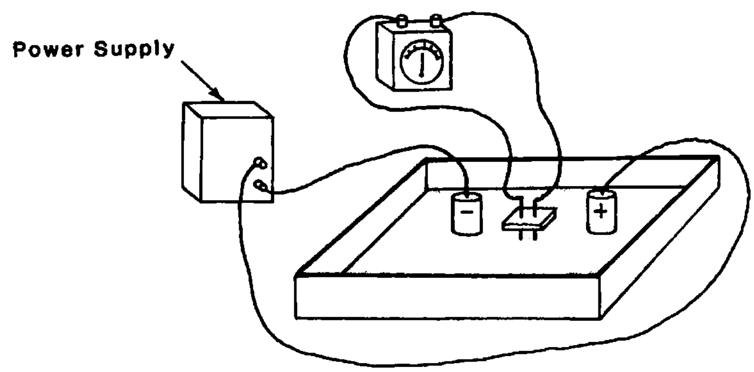
Purpose: To show the electric field around a simple charge configuration and to relate these electric field lines to the equipotential lines in the previous demonstration.

Materials: This demonstration uses the same equipment as DEMONSTRATION #1 on plotting equipotentials except that the probe will now be two contacts held a fixed distance apart. This can be accomplished with nails through a small piece of wood or plastic (clear plastic will give a better view). A separation between the nails of about 3 cm usually works well.



Procedure and Notes: Wire the apparatus exactly as in DEMONSTRATION #1 except that this time the voltmeter will not be attached to the "−" electrode, instead it will be across the double probe as illustrated on the next page. Place the double probe in the salt water somewhere between the electrodes. Notice that, when you rotate the double probe, there will be a particular orientation which will give a maximum reading on the voltmeter. In this position the line between the two probes will indicate the direction of the electric field. If you start near the negative electrode, rotate the double probe until you find the maximum reading. Then move it so that the first nail is now in the position of the second nail and again rotate to find the maximum reading. This process will map out the electric field between the two electrodes. Repeating this procedure with the map in another position will result in plotting out another field line. After you have plotted several field lines, compare these results with those of DEMONSTRATION #1 and notice that the equipotentials are always perpendicular to the electric field lines.

This illustration shows how the apparatus is to be connected to map out the electric field lines in the region between the two electrodes. Rotating the double probe to give a maximum voltage reading will indicate the direction of the electric field.



The illustrations show the results of mapping two different field lines.

Path when the mapping is started on the the straight line joining the two charges.

Path when the mapping is started at some other place.

Explanation:

When you move along an equipotential with a test charge, you will do no work. In an external electric field this would be possible only if the charge were moved perpendicular to the field. By the same token, if you move in a direction of maximum potential difference, you will be moving along a electric field line and you do work. Rotating the double probe until the voltage across it is maximum results in finding the maximum potential change and, consequently, the direction of the electric field.

Demonstration #3: Electric Discharge From Points.

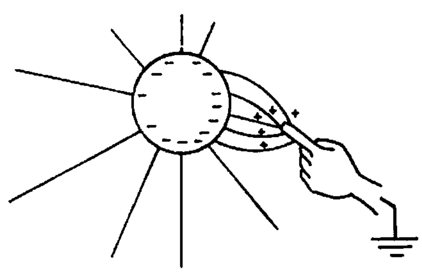
Purpose: To show that a smooth surface with a large radius of curvature can be charged to a much higher potential than the same surface with a point protruding from it.

Materials: Van de Graaff generator, straight pin, small piece of tape.

Procedure and Notes:

1. With the Van de Graaff running, carefully demonstrate to students how close you must move your finger or a grounding sphere before the spark will fly. Repeat several times to establish the separation between the Van de Graaff and object at which the discharge will take place.
2. With the Van de Graaff off, push the pin through the tape and tape the head of the pin to the Van de Graaff sphere. Turn on the Van de Graaff and again approach it with your finger or grounding sphere and note the separation at which sparks first fly. The separation will be much less than in (1).
3. To help understand what is happening, hold your hand over the pin point and you will notice a wind coming from it. This "corona wind" is due to ions rapidly moving in the vicinity of the intense electric field near the point.

Explanation: The entire conducting sphere of the Van de Graaff is at the same potential. As your finger approaches, the opposite charge will be induced in it from the ground. thereby creating an intense field in the region between your finger and the Van de Graaff. As you get nearer and nearer, the electric field becomes more and more intense until finally the free electrons in the field acquire enough energy to ionize the air molecules. Thus they move between the Van de Graaff and the finger and thus initiate the spark.



When the pin is placed on the top of the Van de Graaff, the very small area of the tip of the pin results in a very high concentration of charge at the point. Consequently, the electric field at the tip of the pin will be much more intense than on the rest of the sphere. This intense electric field will be able to ionize the air in its immediate vicinity and will cause charge to leak off the Van de Graaff and, thereby, not allow it to rise to as high a potential as before. Your finger must be much closer in order for the field between it and the Van de Graaff to become sufficiently intense to ionize the air between them.

The illustration from the video shows how the electric field between air molecules gives enough energy to a free electron to ionize these molecules.

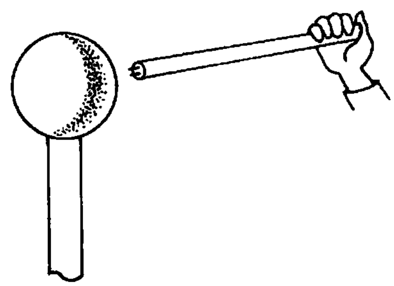
Demonstration #4: Fluorescent Tube and Van de Graaff

Purpose: To show that ionization of a gas will take place more easily if the pressure of the gas is reduced.

Materials: Van de Graaff generator and fluorescent tube (a tube from a desk lamp is probably best).

Procedure and Notes:

1. With the Van de Graaff running, establish the distance a spark will jump through air to ground (see DEMONSTRATION #3).
2. Place your thumb on the electrical pins protruding from one end of a fluorescent tube and bring the other end near the running Van de Graaff until the tube glows. When the "spark" flies this time, the distance between the Van de Graaff and ground (your thumb) is much greater than in the case of air alone.



Explanation: The air is at atmospheric pressure and the average distance between molecules is relatively small. The free electrons in the air accelerate only a small distance before they crash into air molecules. Therefore, they may not have enough energy to ionize it. Only by moving your finger very close to the Van de Graaff will the field be sufficiently intense to give enough energy to the free electrons that their movement ionizes the air molecules.

Since the mercury vapor in the fluorescent tube is at a much lower pressure, the mercury atoms will be farther apart. As a free electron is accelerated by the electric field between atoms, it moves a greater distance before it makes a collision. Therefore, it can gain sufficient energy to ionize the mercury atoms even in a weaker field. Even though the distance between the Van de Graaff and the grounded hand at the other end of the fluorescent tube is much greater than in the case of air alone, the weaker electric field can still cause a "spark" to fly.

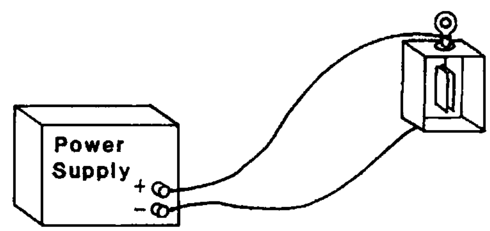
Demonstration #5: Static vs. Current Sources of Potential Difference

Purpose: To show that a high voltage does not always mean danger and that a relatively low voltage can be dangerous. Also, to establish that an electroscope is really a voltage measuring device rather than a charge measuring device.

Materials: A power supply which can produce a few hundred volts; a voltmeter; an electroscope (Since the observed effect on the electroscope will be very small, a method of projecting an image of the leaves of the electroscope is recommended.); a rubber rod and animal fur; assorted electrical leads.

Procedure and Notes:

1. Attach the power supply to the voltmeter and adjust to the highest possible voltage. *Discuss* with the class that the voltage of this power supply is high enough to be able to give you a powerful shock. (It should not be necessary for you to demonstrate this fact.) With the power off, and after allowing sufficient time for the capacitors in the power supply to bleed off, attach the leads of the power supply to the electroscope as illustrated. Be sure to attached one side to the case of the electroscope and the other side to a point near the knob.



Assuming you *have* been using the electroscope for other electrostatic demonstrations, your students will probably expect a large separation of the leaves when you turn on the power. The barely perceptible separation of the leaves should be a surprise to all.

2. Disconnect the power supply and again charge the electroscope. This time use the rubber rod and animal fur. What does the resulting large deflection suggest?
3. If your power supply has a sufficiently high voltage, you should be able to wire it as previously done and show that the deflection on the electroscope is fairly proportional to the *voltage* placed across it.

Explanation: Electric potential is energy per unit charge. The large power supply can deliver lots of charge to an external circuit *but*, relative to the rubber rod, the energy per charge is small. The rubber rod has a relatively small amount of excess charge on it, but the the amount of work done *per charge* in charging the rod is large. Consequently, a very high potential difference is produced.

Neither charge nor voltage alone determines the ability of a "power supply" to do damage or to cause injury. Since the power supply can deliver so much more charge, even at a much lower voltage, the result will be a much larger amount of energy than can be delivered by the rubber rod.

The reason that an electroscope gives a measure of voltage and not of charge can be explained by considering that the electroscope has a fixed value of capacitance. The potential difference placed across this fixed capacitance will cause a given amount of charge to flow into the electroscope until the potential of the electroscope equals the potential of the device to which it is attached. Even a device which contains an enormous amount of charge will not be able to "force" this charge on to the electroscope. As the electroscope charges, its potential will rise until the potential of the electroscope equals the potential of the charging device. Since the capacitance of the electroscope is so very small, only a very small amount of charge is required to cause it to deflect. The *potential* difference placed across it will be the limiting factor. *not* the amount of charge in the charging device.

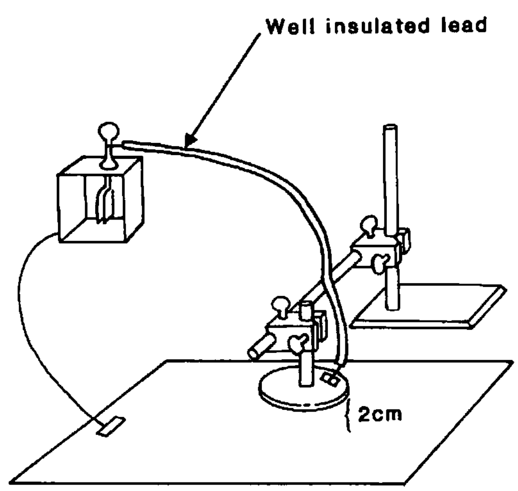
Demonstration #6: How Work on a Charge Increases Potential

Purpose: To show that moving a charge in the direction of an electric field will increase its potential, but moving a charge perpendicular to the field will not change its potential.

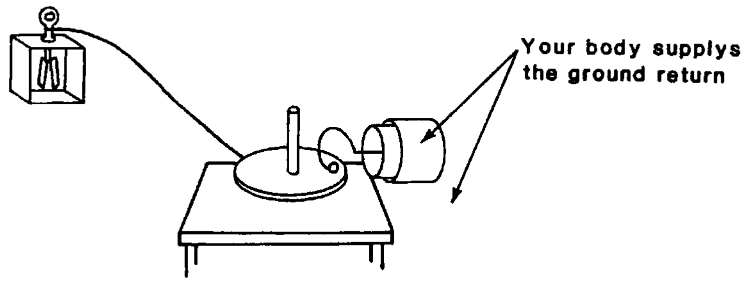
Materials: Large metal plate (or perhaps a sheet of aluminum foil taped to a table top); small metal plate on an insulating support (A circular metal plate from an electrophorous and its insulating handle works well.); source of very high potential (Van de Graaff or Wimshurst machine); electroscope; assorted ring stands and clamps; and electrical leads with very good insulation.

Procedure and Notes: This experiment will work only on days when the humidity is low. If you observe an unexplained leakage of charge, you will have to postpone the demonstration.

1. Support the insulated plate about 2 cm above the large plate. Arrange the supports so that the insulated plate can easily be moved up and down as well as in a direction parallel to the large plate.



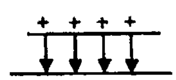
2. Tape the stripped end of a well insulated lead to the insulated disk and attach the other end to the electroscope. Attach the case of the electroscope to the large metal plate.
3. Carefully charge the insulated plate, taking care not to overcharge the electroscope. This can be accomplished by transferring charge from a Van de Graaff with a smaller sphere on an insulated stand. Touch the large plate with one hand as you touch the transfer sphere to the insulated plate. You can also use a Leyden jar as illustrated below. Do not overcharge the Leyden jar.



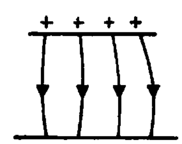
4. Once it is established that the system will hold charge, carefully lift the insulated plate a small distance. The leaves of the electroscope will separate more. When the insulated plate is lowered, the leaves will return to their original position. Carefully move the insulated plate sideways without changing the separation between it and the lower plate. As long as the plate does not get too near the edge, the leaves of the electroscope will remain unchanged.

Explanation:

Electric potential is work or energy per charge. The electroscope is actually a voltage or potential measuring device. As you pull the charged metal plate away from the large plate that was oppositely charged by induction, you are doing work on the charges in the electric field between them. This work increases the potential of the charge which is registered on the electroscope. When the insulated plate is moved so that its separation from the large plate does not change, no work is done. Consequently, the potential does not change. In other words, when the charge is moved along an equipotential surface, no work is done.



When first charged

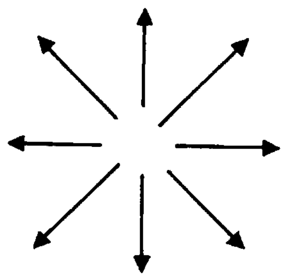


After separation of plates

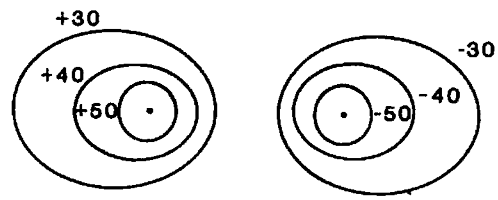
EVALUATION QUESTIONS

1. Which of the configurations below best displays equipotential lines around two point charges, one positive and one negative?

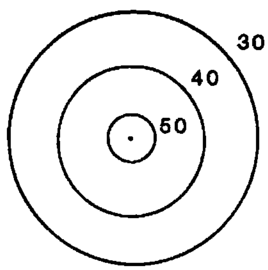
A.



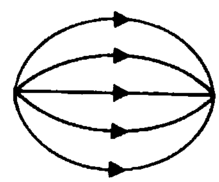
C.



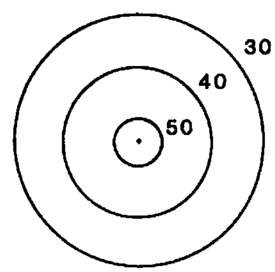
B.



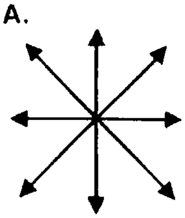
D.



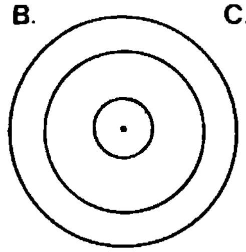
2. The illustration shown to the right represents the equipotentials around a charge distribution. Which diagram best represents the electric field lines for these equipotentials?



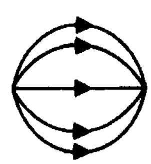
A.



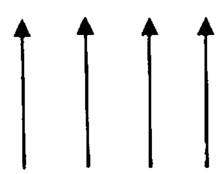
B.



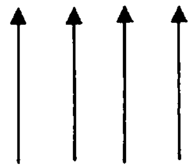
C.

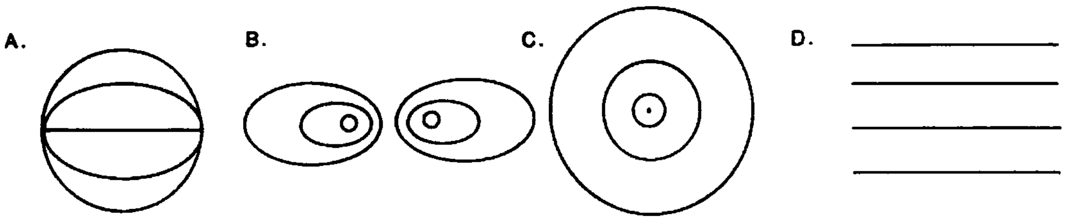


D.



3. **The illustration shown represents electric field lines. Which diagram below represents the equipotentials for these electric field lines?**





4. **A student is experimenting with a Van de Graaff electrostatic generator. He finds it easier to make a spark if he points his finger at the sphere than if he approaches it with a flat hand. This is because**

   A. the field is more intense at the pointed finger.
   B. the flat hand is along an equipotential.
   C. the field is more intense at the flat hand.
   D. the hand with the pointed finger has less resistance.

5. **The Van de Graaff is capable of producing a large electric potential because**

   A. the field lines are so close together that they can easily ionize the air.
   B. the sphere at the top is a very good conductor.
   C. the spherical shape of the dome prevents discharges.
   D. a large amount of charge is transferred to the sphere from the ground by the rotating belt.

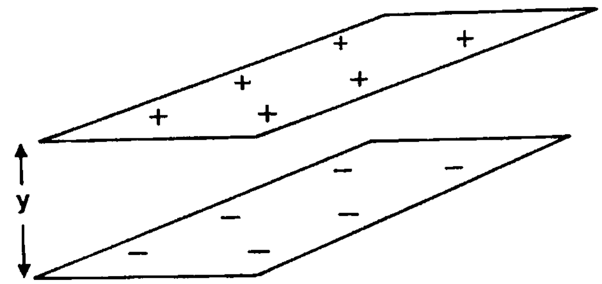
6. **A Wimshurst machine can produce more energetic sparks than a Van de Graaff machine because**

   A. Leyden jars are connected to Wimshurst machines.
   B. the Van de Graaff sphere is not as well insulated from the ground.
   C. the brushes of the Wimshurst are smaller than the brushes of the Van de Graaff.
   D. the sphere of a typical Van de Graaff is charged negatively.

7. **A spark is able to jump from a charged Van de Graaff sphere to ground because**

   A. the electrons on the sphere have such a high potential.
   B. the high potential of the Van de Graaff is higher than the ionization potential of air molecules.
   C. the field between the sphere and the ground gives free electrons enough energy to ionize air molecules.
   D. the pressure of the air is high enough to begin the discharge.

8. Consider two insulated parallel plates as shown in the diagram. Positive charge is placed on the top plate and an equal amount of negative charge is placed on the bottom plate.



When the distance y is increased by Δy, the electric potential energy of the system increases because

A. external work done in separating the plates increases the electric potential difference.
B. more charge is induced on the top plate as it moves.
C. a decrease occurs in the electric potential between the plates.
D. a change occurs in both the charge on the plates and the separation of the plates.

9. If we consider only a region near the center between the two parallel plates, equipotential surfaces will be

A. a series of planes perpendicular to the plates.
B. a series of planes parallel to the two plates.
C. a series of lines perpendicular to the two plates.
D. a series of concentric circles around the two plates.

10. Why can a 12-V battery start an automobile when a Van de Graaff at 20,000 volts cannot?

A. The battery provides greater voltage than a Van de Graaff.
B. The battery provides greater potential difference than a Van de Graaff.
C. The battery provides more resistance than a Van de Graaff.
D. The battery store more potential energy than a Van de Graaff.

ESSAY QUESTIONS

11. Briefly discuss the sequence of events that describe an electric discharge.

12. Compare and contrast the electric potential with electric field lines.

KEY

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

SUGGESTED ESSAY RESPONSES

11. (a) Free electrons colliding with molecules cause ionization of gas molecules.
    (b) Cascading of collisions causes air to become a conductor.
    (c) Electric discharge occurs through plasma.

12. (a) A surface of constant electric potential--called an equipotential surface--is one of constant electric potential energy for any given charge. They are similar to contour lines on a topographic map.
    (b) Electric field lines are everywhere perpendicular to equipotential surfaces--they indicate the force exerted on a unit positive charge.

TEACHER'S GUIDE TO SIMPLE DC CIRCUITS

CONTENT AND USE OF THE VIDEO - The video introduces series and parallel circuits and the concepts of resistance and power. Although it could be used a number of places in a study of electricity, it would be most effective following a presentation on fields and potential difference.

The video illustrates the effects of connecting resistors into series or parallel circuits. Electron flow in a typical conductor, resistance, and power dissipation are also discussed.

TERMS ESSENTIAL FOR UNDERSTANDING THE VIDEO - Prior to viewing the video, it might be helpful to discuss the following terms briefly with students:

circuit--a closed conducting path around which charge or matter can flow.

current--the flow of electric charge or matter from one place to another.

ampere--the standard electrical unit of current which is described as a coulomb of charge flowing past a given point in one second. One ampere equals one coulomb per second, 1 A = 1 C/s.

resistance--a constant of proportionality (R) between potential difference and current; $V \propto I$ ... $V = RI$. This relationship is called Ohm's law. Any device which obeys this relationship is known as an ohmic resistor. The unit of resistance is called the ohm with a symbol Ω. 1 ohm = 1 volt/ampere. The resistance of a wire depends on its length, cross-sectional area, and resistivity.

resistor--a circuit element having resistance; the symbol for resistor is: 

resistivity--a material's tendency to inhibit the flow of charge. This tendency to resist is characteristic of all materials but to varying degrees; it usually depends on the temperature of the material. Viscosity is the analogous quantity for a fluid's tendency to inhibit the flow of matter.

power--the time rate of transfer of energy from one place or form into another; in an electric circuit, it is the rate at which electrical energy is transferred.

watt--the unit of power equivalent to joule/second, volt-amp, or ohm-amp^2.

WHAT TO EMPHASIZE AND HOW TO DO IT - The topic of electric circuits often presents difficulties for students. Consequently, it is essential that the theory presented in the video be coupled to demonstrations and applications. Students need an opportunity to explore series and parallel circuits, and to manipulate the placement of resistors within the circuits.

Objective 1: Recognize that an electric circuit is a closed path for the flow of electric charges.

When electric charges flow, the charges must move in a closed circuit. The word circuit derives from the same root as circle. Electric charges usually flow from a source through wires to one or more electrical devices, then back through wires, and finally back to the source. A common misconception among students is that electricity only has to get to an appliance through a wire to be useful, analogous to water getting to a lawn through a hose. It is important to stress that charges must flow back to the source in order to complete the circuit, unlike water from a faucet.

Many students wrongly hold a model of sequential charge flow. This model treats electric charges as starting out from one end of the battery, moving through the first element attached to the battery, then moving through the second element, and so on back to the other end of the battery. In actuality a net flow of charge occurs almost instantaneously. One of the items in the STUDENT'S GUIDE addresses this misconception.

DEMONSTRATION #1 on a simple electric circuit can be used to help clarify the concept of an electric circuit. Although rather simple, the demonstration emphasizes that the current leaving one terminal of the battery must be equivalent to the current received at the other terminal. Students can fail to understand the closed nature of a circuit unless it is specifically pointed out.

Objective 2: Use Ohm's law to determine the current in a circuit when the resistance is given.

The video clearly illustrates that a voltage will cause a current to flow in a circuit. This current, I, is proportional to the voltage, $V \propto I$. The constant of proportionality in the equation, $V = IR$, is called resistance. It is helpful to stop the video at this point and point out to your students that voltage is represented by vertical height in the animation. An analogy between a gain (climbing) and loss (descending) in gravitational potential energy can be drawn to gains and losses in electrical potential energy. To remember Ohm's law, students can remember the ungramatical mnemonic "I are".

DEMONSTRATION #3 provides a mechanical model of conduction and can be used to show students the qualitative relationship between voltage and current. After the students understand this relationship, it can be reinforced by using actual measurements from a simple circuit or sample problems which involve calculations of current or voltage.

Objective 3: Recognize the factors that determine the resistance of a conductor.

The video illustrates the difference between electrons moving in electrostatic equilibrium and electrons moving in an electric field. Electrons in electrostatic equilibrium are not acted on by a net force. When a battery is connected, an electric field is produced and equilibrium is destroyed. If a perfect crystalline metal at absolute zero temperature could exist, the mobile electrons would accelerate continuously in the electric field. However, all metals contain imperfections. Electrons release kinetic energy as heat in their many collisions with these impurities. The resistance to flow is determined by the length, cross-sectional area, type of material, and temperature of the conductor. Each of these affects the overall number and violence of the collisions.

DEMONSTRATION #3 illustrates the effect of the length of a conductor (a nail board) on charge flow by lengthening it. This demonstration can also serve to introduce discussion of the effects of resistivity (type of material) and the cross-sectional area on charge flow. Resistivity corresponds to the number of nails on the given board. Ask your students how a change in the number of nails would affect a flow of marbles. The width of the board corresponds to area. Ask your students if more marbles could roll down the board in a given time if it were wider.

Discuss with your students the similarities between water flow and electron flow and how these similarities influence hydraulic engineers in the design and operation of aqueducts.

Objective #4: Describe the characteristics of resistors connected in series or parallel.

The video compares resistors in series with those in parallel. Resistors in series increase the length of the resistive material. This tends to raise the total number of internal collisions and thus the total resistance. The total resistance of a series arrangement is given by the formula, $R_T = R_1 + R_2 + R_3 + \ldots$ Resistors in parallel increase the cross-sectional area of the resistive material and tend to lower the resistance to current flow. The total resistance of a parallel arrangement is given by the formula $1/R_T = 1/R_1 + 1/R_2 + 1/R_3 + \ldots$

The video presents an excellent comparison of the flow of water through hydraulic systems to the flow of electric current in series and parallel circuits. Replaying the video after discussing the analogy may help student understanding.

DEMONSTRATION #2 uses lights to illustrate the changes in electric current in series and in parallel circuits. Similar experiments can be found in most high school lab books. It is important that students explore the differences in the two types of circuits by actually handling equipment.

Objective 5: Describe the relationship of the rate of heating of a resistor, or the power consumed, to current and voltage.

The video presents power as the rate at which electrical energy is transformed to thermal energy. Power can be calculated using the formulae, $P = VI$, $P = I^2R$, or $P = V^2/R$.

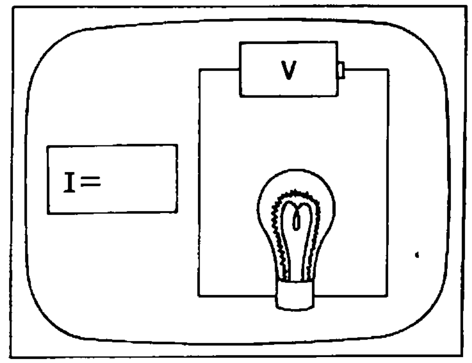
Following the video, DEMONSTRATION #4 on electrical power in series and parallel circuits can reinforce the concept of power. A laboratory activity on electrical power will also enhance student understanding (e.g., the *PSSC* lab on "Efficiency of a Motor").

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.

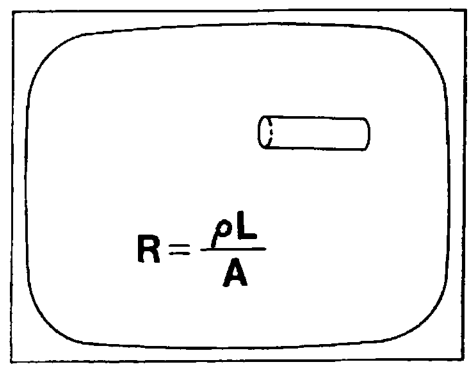
What is electric current? How quickly is current established throughout a circuit when the switch is closed?

Electric current is the rate of flow of electric charge. Students frequently have the misconception that electrons travel through wires at the speed of light. Actually an average drift velocity of a few millimeters per second is established by the electrons. To facilitate student understanding, use the analogy of a pipe jammed with marbles. If you push one marble in an end, one will pop out the other end almost instantaneously. It is not the same marble, and it did not move through the pipe quickly.



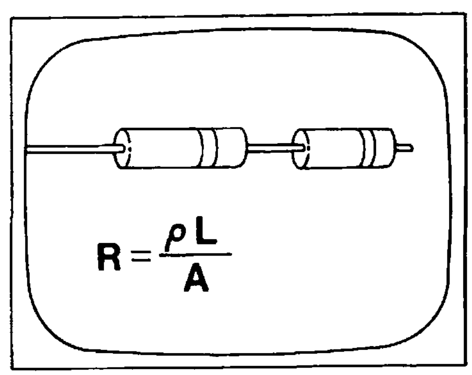
What factors influence the resistance to a flow of current? How does this compare with resistance to water flow in a hydraulic system?

Resistance to a flow of current is proportional to the length of the resistor, inversely proportional to its area, and proportional to its resistivity, or its tendency to inhibit the flow of electrons. All materials have this tendency to resist, but to varying degrees. On level land the rate at which water flows through a pipe depends on the length and diameter of the pipe, the viscosity and density of water, and the pressure applied.

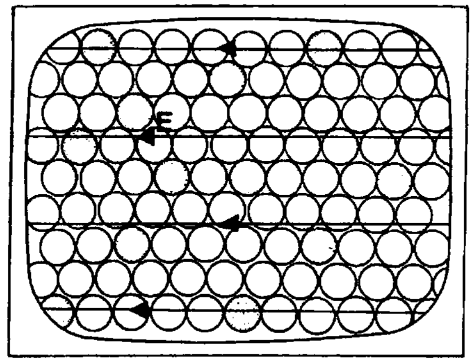


How do resistors in series differ from resistors in parallel?

Resistors in series are added to a circuit one after another and have the same effect as making one longer resistor. Resistors in parallel are added to a circuit side by side, thereby increasing the area through which the current can flow. Two resistors in parallel have a lower resistance than either one alone. Current is everywhere the same in a series circuit but may vary at different points in a parallel circuit because it divides at branches, although the total current must remain the same.

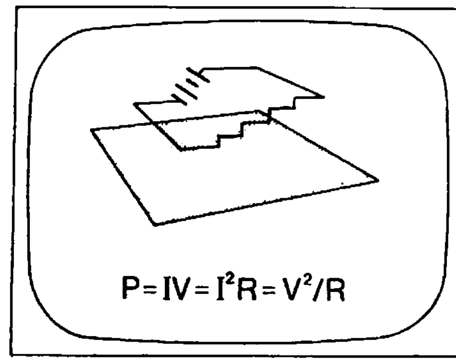


In a conductor, what resists the flow of electricity?



Inside a metal, electrons constantly move in all directions. This kind of movement produces no net flow in one end and out the other. Under these conditions, the conductor is in electrostatic equilibrium. If a battery makes a current flow, equilibrium is destroyed and an electric field is produced inside the conductor. Inside a perfect crystalline metal, the mobile electrons would continuously accelerate. In the real world, crystals have defects and impurities and their atoms vibrate with thermal energy. Electrons, accelerated by the force of the electric field, bounce off the imperfections. All that bouncing, stopping, and starting produces the resistance that prevents the electron flow from building up speed.

What is electrical power and how can you measure it?



Power is the rate at which energy is transformed from one form into another. Power consumed is equal to the current times the potential difference. Power is measured in watts where one watt is one amp times one volt. Power plants operate in megawatts (millions of watts).

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

1. **Why won't your car start if one of the terminals falls off the battery?**

   If the terminal has fallen off the car battery, the charge necessary to start the car cannot flow. The circuit essentially has been broken.

2. **Which of these situations will cause your stereo amplifier to work harder to deliver more energy to two speakers? (1) Connect two speakers in series to the output jack. (2) Connect two speakers in parallel to the output jack.**

   The second choice will make the amplifier work harder. Since the speakers are in parallel, the resistance of the circuit is low and thus more current can flow.

3. **A bulb burns out in a set of Christmas tree lights, yet the remaining lights stay lit. Are the lights wired in series or in parallel?**

   The lights are wired in parallel. When one bulb burns out, closed circuits remain for the other bulbs that are connected in parallel; therefore, the remaining bulbs stay lit. If the lights had been wired in series and one bulb burned out, all the bulbs would go off because the closed circuit would have been broken by that one bulb.

4. **Is your home wired in series or parallel?**

   A home wired in series would be impractical. The potential difference across the elements of a series circuit adds to the total potential difference. More than a few appliances wired in series would drop the potential along the line and eventually the potential difference (voltage) would be too low to run an appliance. Turning the bathroom light out could turn off the kitchen light and the rest of the house as well.

5. **Why can we use the same unit, watt, for mechanical power as well as electrical power?**

   Power is the rate at which energy is transformed; it makes no difference if the transfer is from mechanical energy to heat energy or electrical energy to heat energy.

SUMMARY - Electrons in a typical metal move about randomly in electrostatic equilibrium. If an electric field is applied to an ideal metal, the electrons accelerate in one direction. However, metals contain impurities. The electrons collide with these impurities and liberate energy in the form of heat. Instead of accelerating, the electrons reach a terminal velocity in one direction. Connecting a conductor across a potential difference produces an electric field in the material and thereby causes charges to flow. The flow of charge is called a current.

All materials present a resistance to the flow of charge to varying degrees. The resistance depends on the length, cross-sectional area, type of material, and temperature of the material.

Resistors in series increase the length of the conductor and thus increase its resistance. Resistors in parallel increase the cross-sectional area of the conductor and thus reduce the total resistance of the circuit.

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 SIMPLE DC CIRCUITS

INTRODUCTION - The video introduces series and parallel circuits and the ideas of resistance and power. In addition it illustrates the effects of connecting resistors into series or parallel circuits.

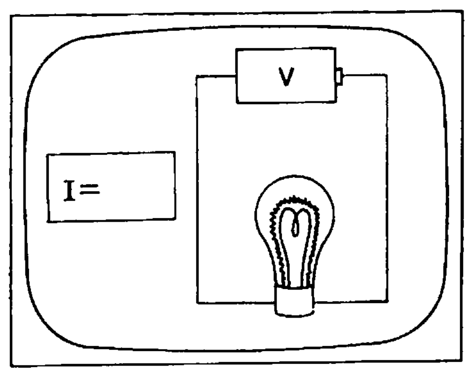
Terms Essential for Understanding the Video

circuit	resistor
current	resistivity
ampere	power
resistance	watt

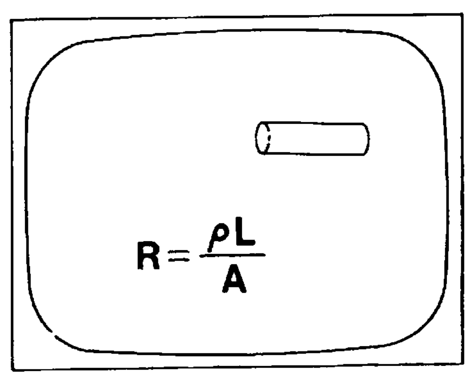
**** NOTE: Parts of the video, especially mathematical equations, may go by quickly on the screen. If you have questions, you should ask your teacher to replay these sections. The graphics of the figure below can be somewhat confusing if viewed incorrectly.****

Points to Look for in the Video

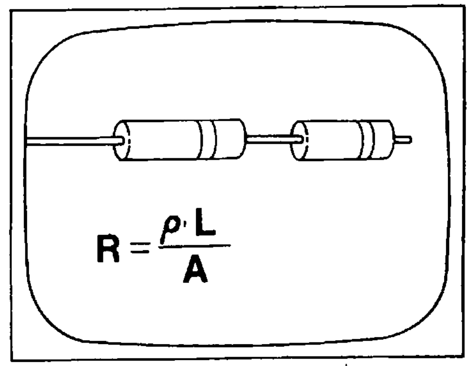
What is electric current? How quickly is current established throughout a circuit when the switch is closed?



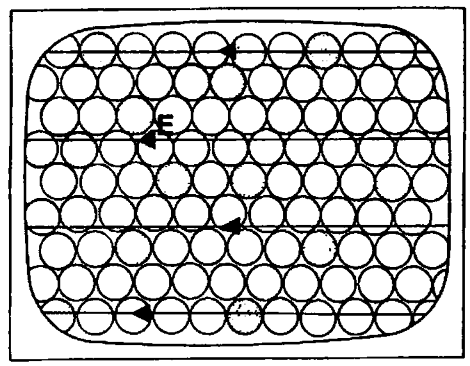
What factors influence the resistance to a flow of current? How does this compare with resistance to water flow in a hydraulic system?



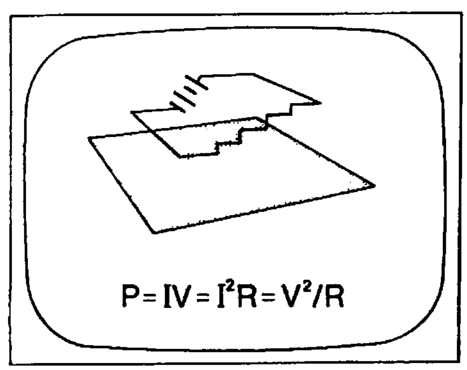
How do resistors in series differ from resistors in parallel? Which is this?



In a conductor, what resists the flow of electricity?



What is power, and how can you measure it?



TEACHER RESOURCES

SUPPORTIVE BACKGROUND INFORMATION

Water and Electrical Circuits

The video devotes considerable attention to a comparison of electrical circuits with water circuits. When water circuits are in a gravitational field, the analogy works well. Gravitational fields are defined as the force per mass ($g = F/m$), while electrical fields are force per charge ($E = F/q$). The uniform gravitational field near the surface of the earth corresponds to the electrical field inside a resistor or wire. The direction of the force on a positive charge defines the direction of the electric field vector.

Current is the amount of material that passes by a point in a certain amount of time. Water current is expressed as mass per time ($I = \Delta m/\Delta t$), and electrical current is measured in charge per time ($I = \Delta q/\Delta t$). In the SI system of units, the electrical current would be measured in coulombs per second, or amperes.

Potential difference describes how much the potential energy changes if a unit test object is moved from one point to another in a force field. The object does not have to move for the potential difference to exist. The potential difference is created by the source that is producing the force field and not by the test object. Gravitational potential difference is the change in gravitational potential energy per test mass ($V_g = U_g/m$). At the surface of the earth there is a gravitational potential difference of about 9.8 joules/kilogram for every one meter increase in elevation. Electrical potential difference is the change in electrical potential energy per unit positive charge ($V = U/q$). In many books electrical potential difference is defined as the work done against the electric field per charge ($V = W/q$). The units of electrical potential difference are joules per coulomb, or volts. In the comparison between gravitational and electrical potential difference, the height of an object in a gravitational field corresponds to the voltage.

In a water circuit, gravitational resistance is the ratio of gravitational potential difference to water current ($R_g = V_g/I_g$). Correspondingly, electrical resistance is the ratio of electrical potential difference to electrical current ($R = V/I$). The unit of electrical resistance is called the ohm. Both kinds of resistances depend on the length, cross sectional area, and internal make up of the conductor.

Although students usually have little difficulty with the concepts of current or resistance, the concept of potential difference generally causes a great deal of trouble. To help develop the analogy between water and electrical circuits in the video, positive potentials are represented by higher elevations which indicate a higher gravitational potential for a water circuit.

Current Direction

The direction of current flow can be confusing to students. Consistent with his fluid theory of electricity, Benjamin Franklin defined the flow of current from a positive object which had an excess of electric fluid to a negative object which had a deficiency of the electric fluid. Since Franklin was so influential in the early development of electrical concepts, his definition became the conventional way of describing electrical current.

Later it was discovered, however, that in metals and in vacuum tubes only negative electrons move. Consequently, classroom discussion is frequently focused on electron currents. However, there are circumstances where both positive and negative charges seem to flow as in the case of electrolytes and semiconductors. Here negative current flow seems to lose its conceptual advantage.

Another difficulty with negative current is that it flows against the direction of the electric field. Although electrical current can be defined using either positive or negative currents, most high school texts emphasize negative current. All major college texts now use conventional positive current flow.

Resistivity

The resistance of a material depends upon three things: the length of the material, its cross sectional area, and a property of the material known as resistivity. Materials vary in their resistivity. Copper has a low resistivity, while glass has a high resistivity. Resistivity indicates how much resistance a material has for a given length and cross sectional area at a specific temperature. It is generally denoted by the Greek letter ρ, as represented in the equation $R = \rho L/A$. Generally, the units of resistivity are ohm meters. In conductors resistivity increases with an increase in temperature. However, in semiconductors, the resistivity can decrease with an increase in temperature.

Meters and Circuits

Ammeters and voltmeters are used to measure current and potential difference in electric circuits. Whenever something is measured, it is disturbed to some extent. The meters themselves use electrical energy and, therefore, need to be designed to affect the circuit as little as possible. Since ammeters are used to measure current, they need to be connected in series within a circuit. To produce as small a change as possible in the current, ammeters are built to have a very low resistance. Thus they add only a small amount to the total resistance. The very low resistance of ammeters means that they are easy to damage if hooked up improperly. If an ammeter is connected in parallel, large currents could flow through the meter because of its low resistance. These large currents can "peg" the meter with such force that the needle can be permanently bent or the coils inside the meter can be burned out.

Since a voltmeter measures the potential difference between two points, it must be connected in parallel across the two points in the circuit. To draw as little current as possible, voltmeters must have a large resistance. If voltmeters are improperly connected in series, the current in the circuit will be greatly reduced due to the large resistance of the meter. Although improperly connecting an ammeter can destroy the meter, improperly connecting a voltmeter will only give incorrect readings.

ADDITIONAL RESOURCES

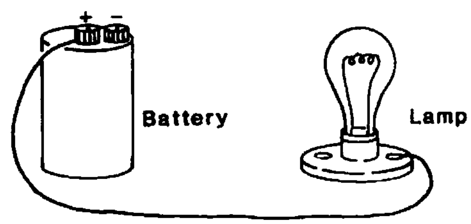
Demonstration #1: A Simple Electric Circuit

Purpose: To demonstrate what is needed to produce a simple electric circuit.

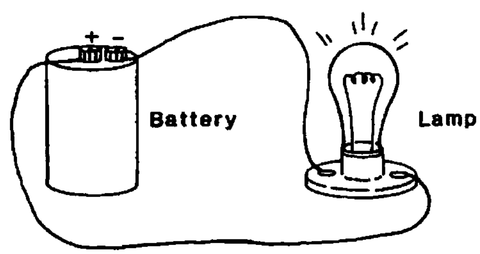
Materials: 1.5 to 6 volt battery; lightbulb and socket; at least two pieces of hookup wire.

Procedure and Notes:

1. Attached a piece of hookup wire to the battery and show that the bulb will not light if the wire is attached to either terminal of the light bulb or either terminal of the battery.



2. Attach two pieces of hookup wire to the battery, one to each terminal. Show that the bulb lights only when one wire is attached to one terminal of the bulb and the other wire to the second terminal of the bulb. Point out that in an electric circuit there must be a path from the source to the appliance, through the appliance, and back to the source. It often helps to point out that the word circuit has the same root as the word circle.



Explanation: Because charge is conserved, current must flow equally in all points of the circuit. The source receives as much current at one terminal as leaves from the other.

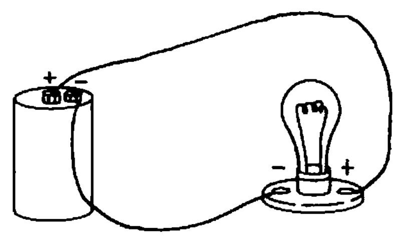
Demonstration #2: Lights in Series and Parallel

Purpose: To illustrate the effects of series and parallel circuits on an electric current.

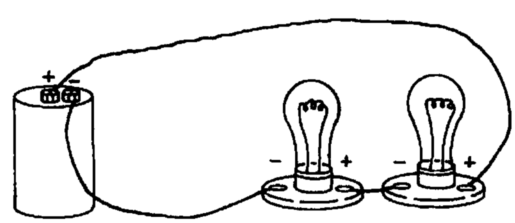
Materials: A fresh 1.5 to 6 volt battery; three bulbs and sockets; at least six pieces of hook-up wire.

Procedure and Notes: Series Circuit

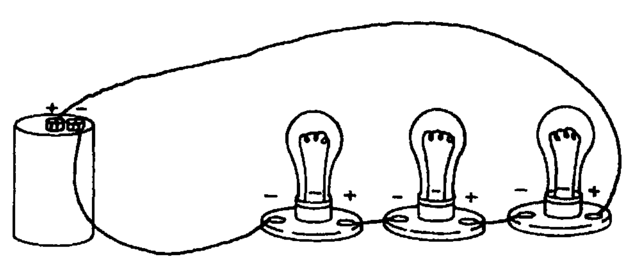
1. Connect one light in series with battery. Ask the students to observe the brightness. Remember that brightness will be proportional to current through the bulb.



2. Connect two lights in series with the battery. Ask the students to observe the brightness of each bulb and to note any change in brightness.



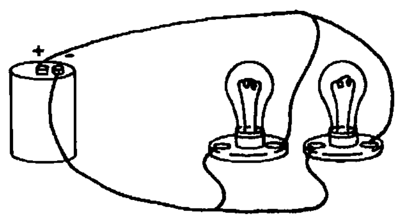
3. Connect three lights in series with the battery. Ask the students to observe again the brightness and to note any change in the brightness of each lamp.



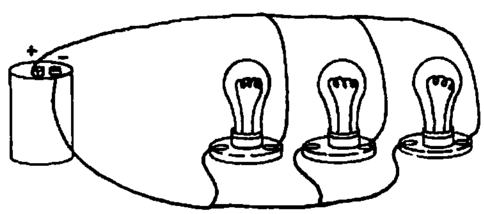
4. Remove any light from its socket. The students should note that all the lights go out.

Parallel Circuit

1. Connect two lights in parallel with the battery. Ask the students to observe the brightness of each bulb.



2. Unscrew either light from its socket. Students should note that the other light still remains on.
3. Connect a third lamp in parallel. Ask the students to compare the brightness of each of the three bulbs to the brightness of the previous two. They should note that they are about the same.



4. Disconnect any bulb, and ask students to note that the others remain on.

Explanation:

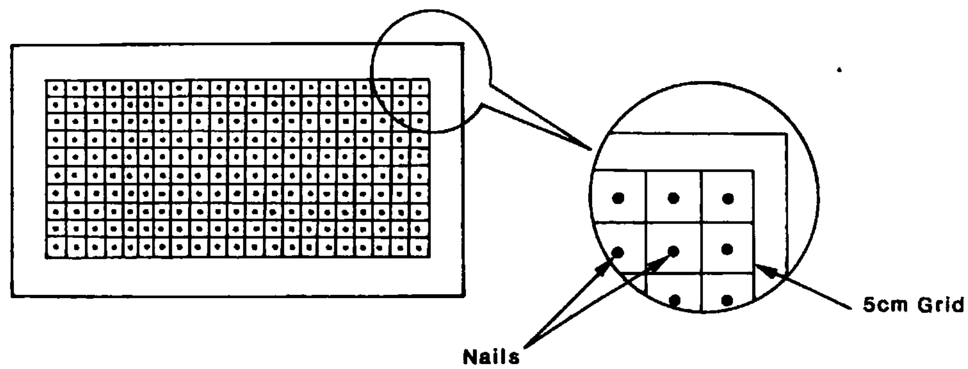
The bulbs in series decrease in brightness with each added light. Adding a lamp increases the resistance of the circuit and decreases the current flowing through all of them. When one bulb is disconnected, the circuit is broken and all charge flow stops.

Parallel lamps do not share the same current, but have the same voltage. Since brightness is proportional to the voltage, the brightness does not appreciably drop with each added bulb. Disconnecting one lamp from the circuit does not cause the other bulbs to go out because the circuit is not broken for the other lamps.

Demonstration #3: A Mechanical Model of Conduction

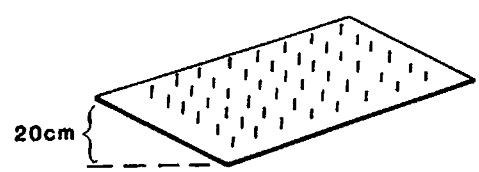
Purpose: To present a mechanical analogy to conduction and the corresponding concepts of voltage, current, and Ohm's law.

Materials: Marbles and a nail board. The nail board is a piece of plywood twice as long as it is wide (about 1 m × 0.5 m) with a 5 cm square grid marked on its surface. Nails are driven in the board at the corners and center of each square.

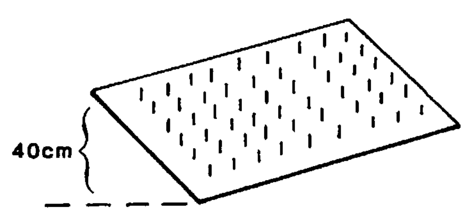


Procedures and Notes: This demonstration is not quantitative in nature but does help relate some of the more abstract concepts of electrical current to more familiar mechanical concepts.

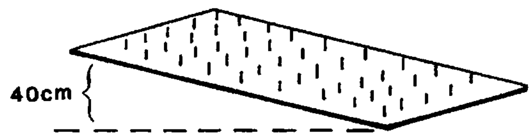
1. Set the nail board at an incline so that one long side is raised about 20 cm. The height of the incline corresponds to voltage.



2. Drop marbles representing electric charge down the incline so that, as one marble rolls off the incline, another is started at the top. The frequency with which marbles roll down the incline corresponds to current.
3. If the height of the incline ("voltage") is doubled, the rate at which marbles roll down the incline is increased.



4. Turn the board lengthwise without changing the height, thus simulating an increase in resistance. The frequency at which the marbles roll down the board decreases.



Explanation:

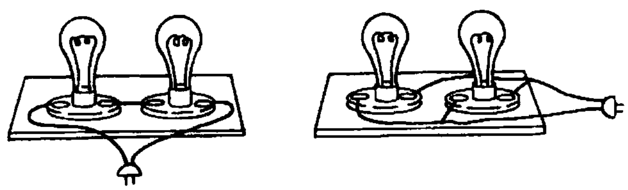
1. The height of the incline represents a very good analogy to voltage. Voltage is the electrical potential difference between two points. In a gravitational field, gravitational potential difference is equal to gh where h is the difference in height between two points.
2. Electric current is the number of electric charges flowing past a point in a certain unit of time ($I = \Delta q/\Delta t$). Since charge is represented by the marbles in this demonstration, the number of marbles rolling down the board in a given time corresponds to the current.
3. Increasing the height corresponds to an increase in voltage.
4. The nail board represents the resistance of a material. Increasing the length of the nail board represents an increase in resistance.

Demonstration #4: Electrical Power in Series and Parallel Circuits

Purpose: To reinforce the concepts of electrical power.

Materials: Four lamp sockets; hook up wire; two 60 watt bulbs; two 150 watt bulbs; and two 20 cm × 40 cm pieces of plywood.

Before class, set up both a series and a parallel circuit, one on each board. Make sure all exposed connections are well insulated for safety. Commercial circuit boards are available; however, they often contain exposed parts which are electrically hot and thus require extreme care.



Procedure and Notes:

1. Put two 60 watt bulbs in the parallel circuit. Then replace them with the 150 watt bulbs. Finally, replace one of the 150 watt bulbs with a 60 watt bulb. Have students note the brightness of the bulbs each time.
2. Ask students which of the bulbs has the greatest resistance.
3. Calculate on the chalkboard the resistance of both bulbs.
4. Put a 60 watt bulb and a 150 watt bulb in the series circuit and ask students to predict which will glow more brightly when plugged in.

Explanation:

1. The potential difference is 120 volts in all cases because of the parallel circuit. The 60 watt bulbs will be equally bright in both situations as will the 150 watt bulbs.
2. Since power = voltage × current and the voltage is constant, the 150 watt bulb must have the largest current and, therefore, the smallest resistance.
3. Using $P = V^2/R$, the resistance of the light bulbs should be:

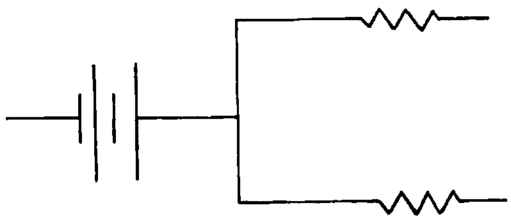
   60 watts: $R = V^2/P = (120\text{V})^2/60\text{ W} = 240$ ohms,
   150 watts: $R = V^2/P = (120\text{V})^2/150\text{ W} = 96$ ohms.

4. Students are often surprised that the lower wattage bulb glows more brightly when the bulbs are in series. Since $P = I^2R$, and the current must be the same in both bulbs, the bulb with the greatest resistance (the 60 watt bulb) will glow brighter.

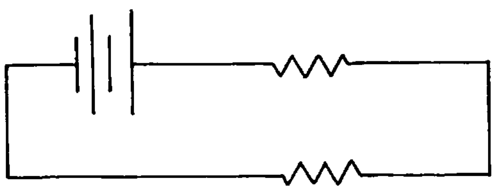
EVALUATION QUESTIONS

1. Which of the following arrangements would *not* produce a constant electric current?

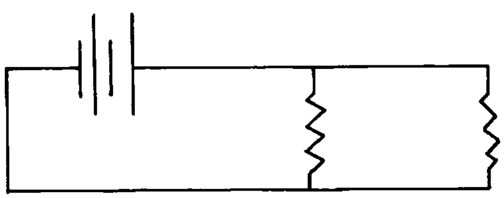
A.



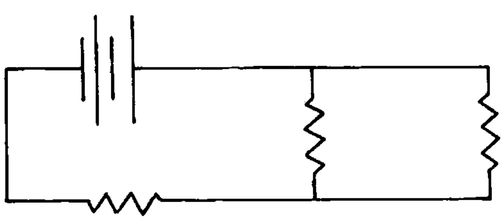
B.



C.



D.



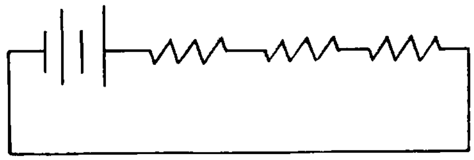
2. If you increase only the voltage in a series circuit,

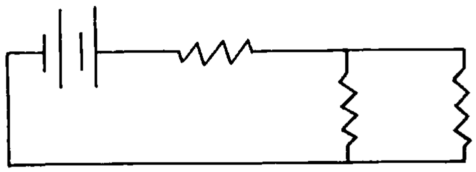
   A. the resistance will increase.
   B. the resistance will decrease.
   C. the current will increase.
   D. the current will decrease.

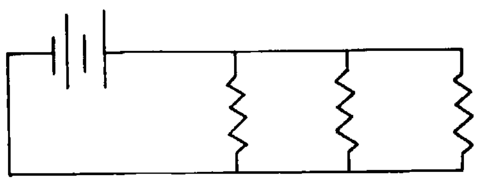
3. To double the resistance of a piece of copper wire you could

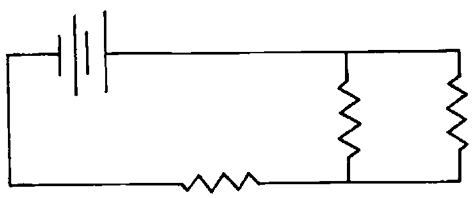
   A. double its length.
   B. double its area.
   C. decrease the temperature.
   D. double the voltage across it.

4. Which arrangement of a battery and three identical resistors will produce the largest value of current?

A. 

B. 

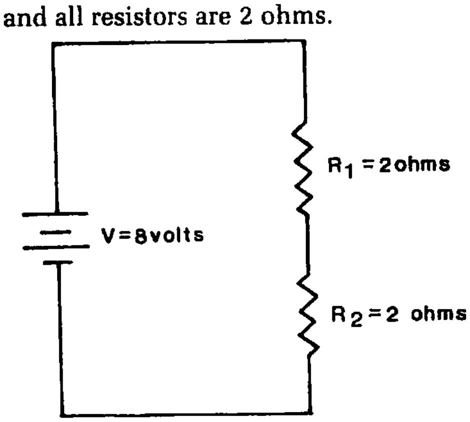
C. 

D. 

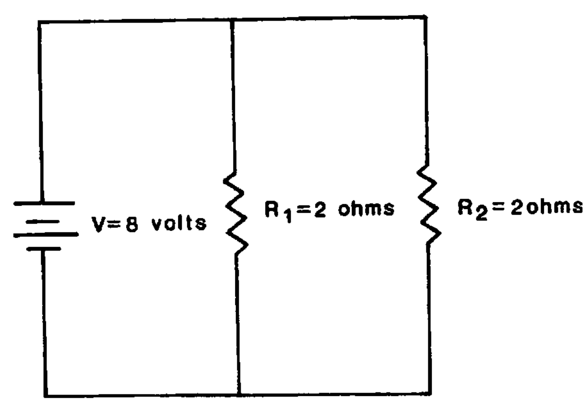
5. What is the current in a common 100 watt light bulb when connected across a potential difference of 120 volts?

A. 12,000 amperes
B. 12 amperes
C. 1.2 amperes
D. 0.83 amperes

Use the following two diagrams to answer Questions 6 - 10. The voltage source in each diagram is 8 volts and all resistors are 2 ohms.



Circuit 1



Circuit 2

6. Electrical charge flows in Circuit 1 because

A. $R1 + R2$ is less than the voltage.
B. the resistors are in series.
C. the resistors are in parallel.
D. a closed path exists.

7. What is the current in Circuit 1 when charge is flowing?

A. 8 amperes
B. 4 amperes
C. 2 amperes
D. 0.5 amperes

8. Resistors 1 and 2 could be replaced without changing the current from the battery in Circuit 2 by

A. one resistor with twice the cross-sectional area of one of the resistors shown.
B. one resistor with one-half the cross-sectional area of one of the resistors shown.
C. one resistor twice as long as one of the resistors shown.
D. one resistor twice as long and with one-half the cross-sectional area of one of the resistors shown.

9. Circuit 2 carries more current than Circuit 1 because

A. the power in 2 is less than in 1.
B. the potential difference in 1 is greater than in 2.
C. the total resistance in 2 is greater than in 1.
D. the total resistance in 2 is less than in 1.

10. What is the electrical power developed in Circuit 1?

A. 2 watts
B. 8 watts
C. 16 watts
D. 32 watts

ESSAY QUESTIONS

11. Discuss the ways that water currents are similar to electric currents.

12. Explain why is it necessary to have a completed circuit for current to flow.

KEY

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

SUGGESTED ESSAY RESPONSES

11. Both currents are usually caused by a change in potential, i.e., gravitational and electrical. Current flow in both cases depends on the length, cross-sectional area, and material properties of the fluid or the conductor.

12. If a complete charge path is not established, then a constant electric field cannot exist in the conductor. The field causes the charges to move in one direction. If they can't flow out of the circuit, they accumulate until they create a field that exactly opposes the imposed field, and electrostatic equilibrium with no current flow results.