DEPARTMENT OF EDUCATION
SCHOOLS DIVISION OF NEGROS ORIENTAL
REGION VII
Kagawasan Ave., Daro, Dumaguete City, Negros Oriental

ELECTRIC POTENTIAL

for GENERAL PHYSICS 2/ Grade 12/ Quarter 3/ Week 2

SELF-LEARNING KIT

NegOr_Q3_GenPhysics2_SLKWeek2_v2

FOREWORD

In our study on electric charges and fields, we just scratched the surface (or at least rubbed it) of electrical phenomena. Two terms commonly used to describe electricity are its energy and voltage, which we show in this chapter is directly related to the potential energy in a system.

We know, for example, that great amounts of electrical energy can be stored in batteries, are transmitted cross-country via currents through power lines, and may jump from clouds to explode the sap of trees. In a similar manner, at the molecular level, ions cross cell membranes and transfer information.

We also know about voltages associated with electricity. Batteries are typically a few volts, the outlets in your home frequently produce 120 volts, and power lines can be as high as hundreds of thousands of volts. But energy and voltage are not the same thing. A motorcycle battery, for example, is small and would not be very successful in replacing a much larger car battery, yet each has the same voltage. In this SLK, we examine the relationship between voltage and electrical energy, and begin to explore some of the many applications of electricity.

The energy released in a lightning strike is an excellent illustration of the vast quantities of energy that may be stored and released by an electric potential difference. In this chapter, we calculate just how much energy can be released in a lightning strike and how this varies with the height of the clouds from the ground.

Equipotential surfaces is also covered in this SLK where you can infer the direction and strength of electric field vector, nature of the electric field sources, and electrostatic potential surfaces given the equipotential lines. Various applications of electric fields, equipotential lines and electric potential are cited such as but not limited to the human heart, electron guns in CRT TV picture tubes and Van de Graaff generators.

OBJECTIVES

At the end of this module, you will be able to:

K: define electric potential energy;

S: calculate the electric field in the region given a mathematical function describing its potential in a region of space; and

A: recognize the importance of solving problems on electric potential energy and electric potentials in contexts such as, but not limited to, electron guns in CRT TV picture tubes and Van de Graaff generators.

LEARNING COMPETENCIES

Relate the electric potential function with work, potential energy, and electric field **(STEM_GP12EMIIIb-15).**

Determine the electric potential function at any point due to highly symmetric continuous-charge distributions (**STEM_GP12EMIIIb-17).**

Infer the direction and strength of electric field vector, nature of the electric field sources, and electrostatic potential surfaces given the equipotential lines **(STEM_GP12EMIIIc-18).**

Calculate the electric field in the region given a mathematical function describing its potential in a region of space **(STEM_GP12EMIIIc-20).**

Solve problems involving electric potential energy and electric potentials in contexts such as, but not limited to, electron guns in CRT TV picture tubes and Van de Graaff generators **(STEM_GP12EMIIIC-22).**

I. WHAT HAPPENED
PRE-TEST:

I. **True or False:** Write the word ***True*** if the statement is correct and ***False*** if otherwise. Write your answer on your notebook/Answer Sheet.

________ 1. Voltage is not the same as energy.

________ 2. Voltage is the common name for potential difference.

________ 3. The work done on is independent of the path taken, therefore, the electrostatic or Coulomb force is not conservative.

________ 4. Electron volt (eV) is the energy given to a fundamental charge accelerated through a potential difference of 1 V.

________ 5. Potential energy accounts for work done by an independent force.

II. Jumbled Words:

Directions: Identify the words being referred by the brief description below. Use the jumbled words as your clue to the words being described. Write your answers on your notebook/Answer Sheet.

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1. ____________________ is the electric potential energy per unit charge.

OTAPINLET DFICERFNEE

2. _________________ is defined to be the change in potential energy of a charge moved from A to B, divided by the charge.

VGOLTAE

3. _____________ is the energy per unit charge.

ETEONLCR VOTL

4. ____________ is the energy given to a fundamental charge accelerated through a potential difference of 1 V.

MCEALNHCIA EEYNGR

5. ___________ is the sum of the kinetic energy and potential energy of a system.

II. WHAT I NEED TO KNOW
DISCUSSION

Electric Potential Energy: Potential Difference

Observe Figure 1 below. When a free positive charge is accelerated by an electric field, it is given kinetic energy. The process is analogous to an object being accelerated by a gravitational field. It is as if the charge is going down an electrical hill where its electric potential energy is converted to kinetic energy. Let us explore the work done on a charge by the electric field in this process, so that we may develop a definition of electric potential energy.

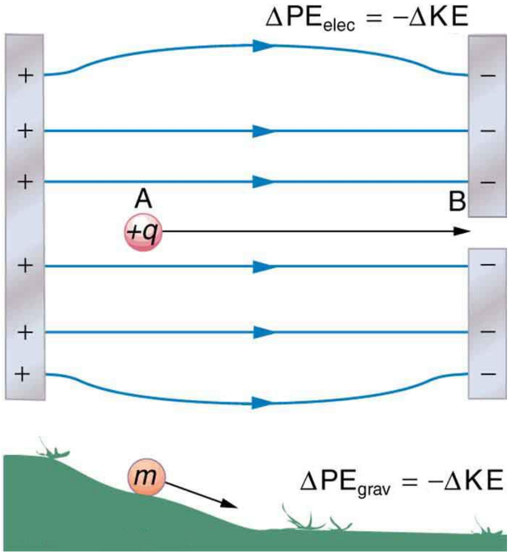


Figure 1. *A charge accelerated by an electric field is analogous to a mass going down a hill. In both cases potential energy is converted to another form. Work is done by a force, but since this force is conservative, we can write* $W = -\Delta PE$.

The work done on is independent of the path taken, therefore, the electrostatic or Coulomb force is conservative. This is exactly analogous to the gravitational force in the absence of dissipative forces such as friction. When a force is conservative, it is possible to define a potential energy associated with the force, and it is usually easier to deal with the potential energy (because it depends only on position) than to calculate the work directly.

We use the letters ***PE*** to denote electric potential energy, which has units of joules (J). The change in potential energy, $\boldsymbol{\Delta PE}$**,** is crucial, since the work done by a conservative force is the negative of the change in potential energy; that is, $\boldsymbol{W} = -\boldsymbol{\Delta PE}$. For example, work done to accelerate a positive charge from rest is positive and results from a loss in ***PE***, or a negative. There must be a minus sign in front of $\boldsymbol{\Delta PE}$ to make $\boldsymbol{W}$ positive. PE can be found at any point by taking one point as a reference and calculating the work needed to move a charge to the other point.

Potential Energy

$$\mathbf{W = -\Delta PE}$$

For example, work done to accelerate a positive charge from rest is positive and results from a loss in ***PE***, or a negative. There must be a minus sign in front of to make positive. ***PE*** can be found at any point by taking one point as a reference and calculating the work needed to move a charge to the other point.

Gravitational potential energy and electric potential energy are quite analogous. Potential energy accounts for work done by a conservative force and gives added insight regarding energy and energy transformation without the necessity of dealing with the force directly. It is much more common, for example, to use the concept of voltage (related to electric potential energy) than to deal with the Coulomb force directly.

Calculating the work directly is generally difficult, since $\boldsymbol{W = Fd\, cos\, \theta}$ and the direction of the magnitude $\boldsymbol{F}$ can be complex for multiple charges, for odd-shaped objects, and along arbitrary paths. But we do know that, since, $\boldsymbol{F = qE}$, the work and hence $\boldsymbol{\Delta PE}$**,** is proportional to the test charge $\boldsymbol{q}$**.**

To have a physical quantity that is independent of test charge, we define electric potential $\boldsymbol{V}$ (or simply potential, since electric is understood) to be the potential energy per unit charge:

$$\mathbf{V} = \frac{\mathbf{PE}}{\boldsymbol{q}} \qquad \textbf{Electric potential}$$

Since $\boldsymbol{PE}$ is proportional to $\boldsymbol{q}$, the dependence on cancels. Thus $\boldsymbol{V}$ does not depend on $\boldsymbol{q}$. The change in potential energy $\boldsymbol{\Delta PE}$ is crucial, and so we are concerned with the difference in potential or potential difference $\mathbf{\Delta V}$ between two points, where

$$\mathbf{\Delta V} = \mathbf{V_B} - \mathbf{V_A} = \frac{\mathbf{\Delta PE}}{\boldsymbol{q}}$$

or

$$\mathbf{\Delta V} = \frac{\mathbf{\Delta PE}}{\boldsymbol{q}} \qquad \textbf{Potential Difference}$$

The potential difference between points A and B, $\mathbf{V_B} - \mathbf{V_A}$, is thus defined to be the change in potential energy of a charge $\boldsymbol{q}$ moved from A to B, divided by the charge. Units of potential difference are joules per coulomb, given the name volt (V) after Alessandro Volta.

$$\mathbf{1V} = \mathbf{1}\,\frac{\mathbf{J}}{\mathbf{C}}$$

The familiar term **voltage** is the common name for **potential difference.** Keep in mind that whenever a voltage is quoted, it is understood to be the potential difference between two points. For example, every battery has two terminals, and its voltage is the potential difference between them. More fundamentally, the point you choose to be zero volts is arbitrary. This is analogous to the fact that gravitational potential energy has an arbitrary zero, such as sea level or perhaps a lecture hall floor.

In summary, the relationship between potential difference (or voltage) and electrical potential energy is given by

$$\mathbf{\Delta V} = \frac{\mathbf{\Delta PE}}{\boldsymbol{q}}$$

and

$$\Delta \mathbf{PE} = \boldsymbol{q}\Delta \mathbf{V}$$

The second equation is equivalent to the first.

Voltage is not the same as energy. Voltage is the energy per unit charge. Thus, a motorcycle battery and a car battery can both have the same voltage (more precisely, the same potential difference between battery terminals), yet one stores much more energy than the other since $\Delta \mathbf{PE} = \boldsymbol{q}\Delta \mathbf{V}.$ The car battery can move more charge than the motorcycle battery, although both are 12 V batteries.

Sample Problem 1: Calculating Energy

Suppose you have a 12.0 V motorcycle battery that can move 5000 C of charge, and a 12.0 V car battery that can move 60,000 C of charge. How much energy does each deliver? (Assume that the numerical value of each charge is accurate to three significant figures.)

Strategy:

To say we have a 12.0 V battery means that its terminals have a 12.0 V potential difference. When such a battery moves charge, it puts the charge through a potential difference of 12.0 V, and the charge is given a change in potential energy equal to

$$\Delta \mathbf{PE} = \boldsymbol{q}\Delta \mathbf{V}$$

So, to find the energy output, we multiply the charge moved by the potential difference.

Solution:

For the motorcycle battery, $\boldsymbol{q} = \mathbf{5000\ C}$ and $\Delta \mathbf{V} = \mathbf{12.0\ V}.$ The total energy delivered by the motorcycle battery is

$$\begin{aligned} \Delta \mathbf{PE_{cycle}} &= (\mathbf{5000\ C})(\mathbf{12.0\ V}) \\ &= (\mathbf{5000\ C})(\mathbf{12.0\ J/C}) \\ &= \mathbf{6.00 \times 10^4\ J} \end{aligned}$$

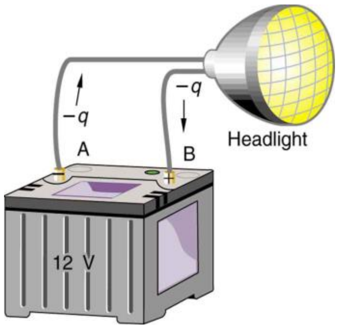
Similarly, for the car battery, $\boldsymbol{q} = \mathbf{60,000\ C}$ and

$$\begin{aligned} \Delta \mathbf{PE_{car}} &= (\mathbf{60,000\ C})(\mathbf{12.0\ V}) \\ &= (\mathbf{60,000\ C})(\mathbf{12.0\ C/J}) \\ &= \mathbf{7.20 \times 10^5\ J} \end{aligned}$$

Discussion on Sample Problem 1:

While voltage and energy are related, they are not the same thing. The voltages of the batteries are identical, but the energy supplied by each is quite different. Also note that as a battery is discharged, some of its energy is used internally and its terminal voltage drops, such as when headlights dim because of a low car battery. The energy supplied by the battery is still calculated as in this example, but not all the energy is available for external use.

Note that the energies calculated in the previous example are absolute values. The change in potential energy for the battery is negative, since it loses energy. These batteries, like many electrical systems, actually move negative charge—electrons in particular. The batteries repel electrons from their negative terminals (A) through whatever circuitry is involved and attract them to their positive terminals (B) as shown in Figure 2.



(Paul Peter Urone 2012)

Figure 2. *A battery moves negative charge from its negative terminal through a headlight to its positive terminal.*

The change in potential is $\mathbf{\Delta V = V_B - V_A = +12V}$ and the charge $\boldsymbol{q}$ is negative, so $\mathbf{\Delta PE} = \boldsymbol{q}\mathbf{\Delta V}$ is negative, meaning the potential energy of the battery has decreased when $\boldsymbol{q}$ has moved from point A to point B.

Sample Problem 2: How Many Electrons Move through a Headlight Each Second?

When a 12.0 V car battery runs a single 30.0 W headlight, how many electrons pass through it each second?

Strategy:

To find the number of electrons, we must first find the charge that moved in 1.00 s. The charge moved is related to voltage and energy through the equation $\mathbf{\Delta PE} = \boldsymbol{q}\mathbf{\Delta V}.$ A 30.0 W lamp uses 30.0 joules per second. Since the battery loses energy, we have $\mathbf{\Delta PE = -30.0\ J}$ and, since the electrons are going from the negative terminal to the positive, we see that $\mathbf{\Delta V = +12.0\ V}$.

Solution:

To find the charge $\boldsymbol{q}$ moved, we solve the equation $\mathbf{\Delta PE} = \boldsymbol{q}\mathbf{\Delta V}$:

$$\boldsymbol{q} = \frac{\mathbf{\Delta PE}}{\mathbf{\Delta V}}$$

Entering the values for $\mathbf{\Delta PE = -30.0\ J}$ and $\mathbf{\Delta V = +12V}$, we get

$$\boldsymbol{q} = \frac{\mathbf{-30.0\ J}}{\mathbf{+12.0\ V}} = \frac{\mathbf{-30.0\ J}}{\mathbf{+12.0\ J/C}} = \mathbf{-2.50\ C}$$

Note that voltage is equal to Joules per Coulombs or $\mathbf{V = J/C}$.

The number of electrons $\mathbf{n_e}$, is the total charge divided by the charge per electron. That is,

$$\mathbf{n_e} = \frac{\mathbf{-2.50\ C}}{\mathbf{-1.60\ \times 10^{-19}\ C}/e^{-}} = \mathbf{1.56 \times 10^{19}\ electrons}$$

Discussion on Sample Problem 2:

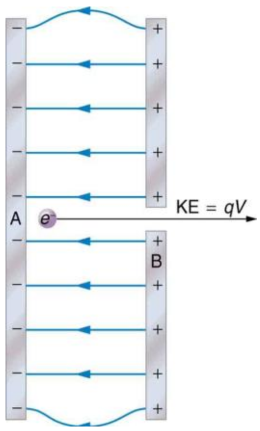
This is a very large number. It is no wonder that we do not ordinarily observe individual electrons with so many being present in ordinary systems. In fact, electricity had been in use for many decades before it was determined that the moving charges in many circumstances were negative. Positive charge moving in the opposite direction of negative charge often produces identical effects; this makes it difficult to determine which is moving or whether both are moving.

The Electron Volt

On the submicroscopic scale, it is more convenient to define an energy unit called the **electron volt (eV)**, which is the energy given to a fundamental charge accelerated through a potential difference of 1 V. In equation form,

$$\mathbf{1eV} = (\mathbf{1.60} \times \mathbf{10^{-19}C})(\mathbf{1V}) == (\mathbf{1.60} \times \mathbf{10^{-19}C})(\mathbf{1J/C})$$
$$= \mathbf{1.60} \times \mathbf{10^{-19}\ J}$$

It is useful to have an energy unit related to submicroscopic effects. Figure 3 shows a situation related to the definition of such an energy unit. An electron is accelerated between two charged metal plates as it might be in an old-model television tube or oscilloscope. The electron is given kinetic energy that is later converted to another form—light in the television tube, for example. (Note that downhill for the electron is uphill for a positive charge.) Since energy is related to voltage by $\mathbf{\Delta PE} = \ \boldsymbol{q}\mathbf{\Delta V}$, we can think of the joule as a coulomb-volt.



(Paul Peter Urone 2012)

Figure 3. *A typical electron gun accelerates electrons using a potential difference between two metal plates. The energy of the electron in electron volts is numerically the same as the voltage between the plates. For example, a 5000 V potential difference produces 5000 eV electrons.*

An electron accelerated through a potential difference of 1 V is given an energy of 1 eV. It follows that an electron accelerated through 50 V is given 50 eV. A potential difference of 100,000 V (100 kV) will give an electron an energy of 100,000 eV (100 keV), and so on. Similarly, an ion with a double positive charge accelerated through 100 V will be given 200 eV of energy. These simple relationships between accelerating voltage and particle charges make the electron volt a simple and convenient energy unit in such circumstances.

Connections: Energy Units

The electron volt (eV) is the most common energy unit for submicroscopic processes. This will be particularly noticeable in the chapters on modern physics. Energy is so important to so many subjects that there is a tendency to define a special energy unit for each major topic. There are, for example, calories for food energy, kilowatt-hours for electrical energy, and terms for natural gas energy.

Conservation of Energy

The total energy of a system is conserved if there is no net addition (or subtraction) of work or heat transfer. For conservative forces, such as the electrostatic force, conservation of energy states that mechanical energy is a constant. Mechanical energy is the sum of the kinetic energy and potential energy of a system; that is, $\mathbf{KE - PE = constant}$. A loss of PE of a charged particle becomes an increase in its KE. Here PE is the electric potential energy. Conservation of energy is stated in equation form as

$$\mathbf{KE - PE = constant}$$

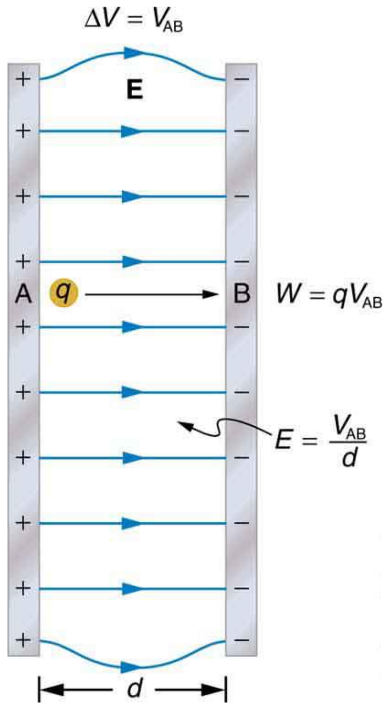
or

$$\mathbf{KE}_{\boldsymbol{i}} - \mathbf{PE}_{\boldsymbol{i}} = \mathbf{KE}_{\boldsymbol{f}} - \mathbf{PE}_{\boldsymbol{f}}$$

where **i** and **f** stand for initial and final conditions, respectively. As we have found many times before, considering energy can give us insights and facilitate problem solving.

Electric Potential in a Uniform Electric Field

Observe Figure 4 on the right side, the relationship between and for parallel conducting plates is $E = V/d$. (Note that $\Delta\mathbf{V} = \mathbf{V_{AB}}$ in magnitude. For a charge that is moved from plate A at higher potential to plate B at lower potential, a minus sign needs to be included.



(Paul Peter Urone 2012)

Figure 4

The work done by the electric field in Figure 4 to a positive charge $\boldsymbol{q}$ from A, the positive plate, higher potential, to B, the negative plate, lower potential, is

$$\mathbf{W} = -\Delta\mathbf{PE} = -\boldsymbol{q}\Delta\mathbf{V}$$

The potential difference between points A and B is

$$-\Delta\mathbf{V} = -(\mathbf{V_B} - \mathbf{V_A}) = \mathbf{V_A} - \mathbf{V_B} = \mathbf{V_{AB}}$$

Entering this into the expression for work yields

$$\mathbf{W} = \boldsymbol{q}\mathbf{V_{AB}}$$

Work is $\mathbf{W} = \mathbf{F}\boldsymbol{d}\cos\boldsymbol{\theta}$, here $\cos\boldsymbol{\theta} = \mathbf{1}$, since the path is parallel to the field, and so $\mathbf{W} = \mathbf{F}\boldsymbol{d}$. Since $\mathbf{F} = \boldsymbol{q}\mathbf{E}$, we see that $\mathbf{W} = \boldsymbol{q}\mathbf{E}\boldsymbol{d}$. Substituting this expression for work into the previous equation gives

$$\boldsymbol{q}\mathbf{E}\boldsymbol{d} = \boldsymbol{q}\mathbf{V_{AB}}$$

The charge $(\boldsymbol{q})$ cancels, and so the voltage between points A and B is seen to be

$$\left.\begin{aligned} \mathbf{V_{AB}} &= \mathbf{E}\boldsymbol{d} \\ \mathbf{E} &= \frac{\mathbf{V_{AB}}}{\boldsymbol{d}} \end{aligned}\right\} \textbf{(Uniform E – field only)}$$

where is the distance from A to B, or the distance between the plates in Figure 4. Note that the above equation implies the units for electric field are volts per meter. We already know the units for electric field are newtons per coulomb; thus the following relation among units is valid:

$$\mathbf{1\ N/C = 1\ V/m}$$

Sample Problem 3. What Is the Highest Voltage Possible between Two Plates?

Dry air will support a maximum electric field strength of about $\mathbf{3.0 \times 10^{6}\ N/m}$. Above that value, the field creates enough ionization in the air to make the air a conductor. This allows a discharge or spark that reduces the field. What, then, is the maximum voltage between two parallel conducting plates separated by 2.5 cm of dry air?

Strategy:

We are given the maximum electric field between the plates and the distance $\boldsymbol{d}$ between them. The equation $\mathbf{V_{AB} = E}\boldsymbol{d}$ can thus be used to calculate the maximum voltage.

Solution:

The potential difference or voltage between the plates is

$$\mathbf{V_{AB} = E}\boldsymbol{d}$$

Entering the given values for $\mathbf{E}$ and $\boldsymbol{d}$ gives

$$\mathbf{V_{AB} = (3.0 \times 10^{6}\ V/m)(0.025\ m) = 7.5 \times 10^{24}\ V}$$

or

$$\mathbf{V_{AB} = 75\ kV}$$

(The answer is quoted to only two digits since the maximum field strength is approximate.)

Discussion about Sample Problem 3:

One of the implications of this result is that it takes about 75 kV to make a spark jump across a 2.5 cm (1 in.) gap, or 150 kV for a 5 cm spark. This limits the voltages that can exist between conductors, perhaps on a power transmission line. A smaller voltage will cause a spark if there are points on the surface, since points create greater fields than smooth surfaces. Humid air breaks down at a lower field strength, meaning that a smaller voltage will make a spark jump through humid air. The largest voltages can be built up, say with static electricity, on dry days.

Sample Problem 4. Field and Force inside an Electron Gun:

(a) An electron gun has parallel plates separated by 4.00 cm and gives electrons 25.0 keV of energy. What is the electric field strength between the plates? (b) What force would this field exert on a piece of plastic with a $\mathbf{0.500}\ \boldsymbol{\mu}\mathbf{C}$ charge that gets between the plates?

Strategy:

Since the voltage and plate separation are given, the electric field strength can be calculated directly from the expression $\mathbf{E} = \frac{\mathbf{V_{AB}}}{d}$. Once the electric field strength is known, the force on a charge is found using $\mathbf{F} = q\mathbf{E}$. Since the electric field is in only one direction, we can write this equation in terms of the magnitudes, $\mathbf{F} = q\mathbf{E}$.

Solution for (a):

The expression for the magnitude of the electric field between two uniform metal plates is

$$\mathbf{E} = \frac{\mathbf{V_{AB}}}{d}$$

Since the electron is a single charge and is given 25.0 keV of energy, the potential difference must be 25.0 kV. Entering this value for $\mathbf{V_{AB}}$ and the plate separation of 0.0400 m, we obtain

$$\mathbf{E} = \frac{\mathbf{25.0\ kV}}{\mathbf{0.0400\ m}} = \mathbf{6.25 \times 10^5\ V/m}$$

Solution for (b):

The magnitude of the force on a charge in an electric field is obtained from the equation

$$\mathbf{F} = q\mathbf{E}$$

Substituting known values gives

$$\mathbf{F} = (\mathbf{0.500 \times 10^{-6}}\ C)(\mathbf{6.25 \times 10^5\ V/m}) = \mathbf{0.313\ N}$$

Discussion Sample Problem 4:

Note that the units are newtons, since $\mathbf{1\ V/m = 1\ N/C}$. The force on the charge is the same no matter where the charge is located between the plates. This is because the electric field is uniform between the plates.

In more general situations, regardless of whether the electric field is uniform, it points in the direction of decreasing potential, because the force on a positive charge is in the direction of $\mathbf{E}$ and also in the direction of lower potential $\mathbf{V}$. Furthermore, the magnitude of $\mathbf{E}$ equals the rate of decrease of $\mathbf{V}$ with distance. The faster $\mathbf{V}$ decreases over distance, the greater the electric field. In equation form, the general relationship between voltage and electric field is

$$\mathbf{E} = -\frac{\Delta\mathbf{V}}{\Delta\mathbf{s}}$$

where $\Delta \mathbf{s}$ is the distance over which the change in potential, $\Delta \mathbf{V}$, takes place. The minus sign tells us that $\mathbf{E}$ points in the direction of decreasing potential. The electric field is said to be the gradient (as in grade or slope) of the electric potential.

For continually changing potentials, $\Delta \mathbf{V}$ and $\Delta \mathbf{s}$ become infinitesimals and differential calculus must be employed to determine the electric field.

Electrical Potential Due to a Point Charge

Point charges, such as electrons, are among the fundamental building blocks of matter. Furthermore, spherical charge distributions (like on a metal sphere) create external electric fields exactly like a point charge. The electric potential due to a point charge is, thus, a case we need to consider. Using calculus to find the work needed to move a test charge $\boldsymbol{q}$ from a large distance away to a distance of $\boldsymbol{r}$ from a point charge $\mathbf{Q}$, and noting the connection between work and potential ($\mathbf{W} = -\boldsymbol{q}\Delta \mathbf{V}$), it can be shown that the electric potential of a point charge is

$$\boldsymbol{V} = \frac{\boldsymbol{kQ}}{\boldsymbol{r}} \quad (\boldsymbol{Point\ Charge})$$

where $\boldsymbol{k}$ is a constant equal to $\mathbf{9.0} \times \mathbf{10^9\ N \cdot m^2/C^2}$.

The potential at infinity is chosen to be zero. Thus $\boldsymbol{V}$ for a point charge decreases with distance, whereas $\mathbf{E}$ for a point charge decreases with distance squared:

$$\mathbf{E} = \frac{\boldsymbol{F}}{\boldsymbol{q}} = \frac{\boldsymbol{kQ}}{\boldsymbol{r^2}}$$

Recall that the electric potential $\boldsymbol{V}$ is a scalar and has no direction, whereas the electric field $\mathbf{E}$ is a vector. To find the voltage due to a combination of point charges, you add the individual voltages as numbers. To find the total electric field, you must add the individual fields as ***vectors***, taking magnitude and direction into account. This is consistent with the fact that $\boldsymbol{V}$ is closely associated with **energy, a scalar**, whereas $\mathbf{E}$ is closely associated with **force, a vector.**

Sample Problem 5. What Voltage Is Produced by a Small Charge on a Metal Sphere?

Charges in static electricity are typically in the nanocoulomb (nC) to microcoulomb (μC) range. What is the voltage 5.00 cm away from the center of a 1-cm diameter metal sphere that has a $-3.00\ nC$ static charge?

Strategy:

Charge on a metal sphere spreads out uniformly and produces a field like that of a point charge located at its center. Thus, we can find the voltage using the equation $\boldsymbol{V = \frac{kQ}{r}}$.

Solution:

Entering known values into the expression for the potential of a point charge, we obtain

$$\boldsymbol{V = \frac{kQ}{r}}$$

$$\boldsymbol{= (8.99 \times 10^{9} N \cdot m^{2}/C^{2})\left(\frac{-3.00 \times 10^{-9}\ C}{5.00 \times 10^{-2}\ m}\right)}$$

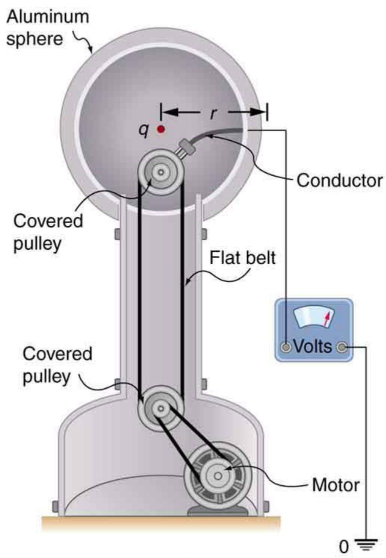
$$\boldsymbol{= -539\ \mathrm{V}}$$

Discussion about Sample Problem 5:

The negative value for voltage means a positive charge would be attracted from a larger distance, since the potential is lower (more negative) than at larger distances. Conversely, a negative charge would be repelled, as expected.

Sample Problem 6. What Is the Excess Charge on a Van de Graaff Generator?

A demonstration Van de Graaff generator has a 25.0 cm diameter metal sphere that produces a voltage of 100 kV near its surface. See Figure 5 on the next page. What excess charge resides on the sphere? (Assume that each numerical value here is shown with three significant figures.)



(Paul Peter Urone 2012)

Figure 5. *The voltage of this demonstration Van de Graaff generator is measured between the charged sphere and ground. Earth's potential is taken to be zero as a reference. The potential of the charged conducting sphere is the same as that of an equal point charge at its center.*

Strategy:

The potential on the surface will be the same as that of a point charge at the center of the sphere, 12.5 cm away. (The radius of the sphere is 12.5 cm.) We can thus determine the excess charge using the equation

$$\boldsymbol{V = \frac{kQ}{r}}$$

Solution:

Solving for $\boldsymbol{Q}$ and entering known values gives

$$\boldsymbol{Q = \frac{rV}{k}}$$

$$= \frac{\boldsymbol{(0.125\ m)(100 \times 10^3\ V)}}{\boldsymbol{8.99 \times 10^9 N \cdot m^2/C^2}}$$

$$= \boldsymbol{1.39 \times 10^{-6}\ C\ =\ 1.39 \mu C}$$

Discussion about Sample Problem 6:

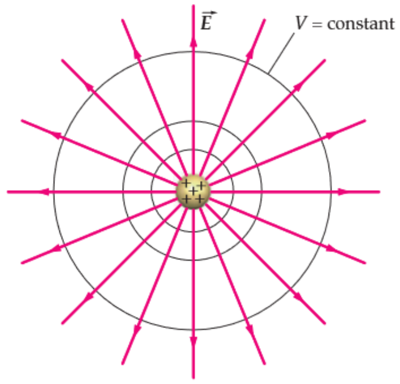
This is a relatively small charge, but it produces a rather large voltage. We have another indication here that it is difficult to store isolated charges.

The voltages in both examples could be measured with a meter that compares the measured potential with ground potential. Ground potential is often taken to be zero (instead of taking the potential at infinity to be zero). It is the potential difference between two points that is of importance, and very often there is a tacit assumption that some reference point, such as Earth or a very distant point, is at zero potential. This is analogous to taking sea level as $\boldsymbol{h = 0}$ when considering gravitational potential energy, $\mathbf{PE_g} = \boldsymbol{mgh}$.

Equipotential Surfaces

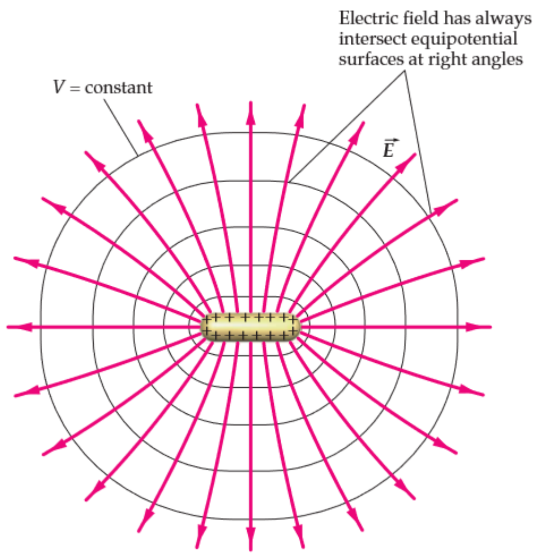
Because there is no electric field inside the material of a conductor that is in static equilibrium, the value of the potential is the same throughout the region occupied by the conducting material. That is, the conductor is a three-dimensional **equipotential region** and the surface of a conductor is an **equipotential surface**.

The potential V has the same value everywhere on an equipotential surface. If a test charge on an equipotential surface is given a small displacement $d\vec{l}$ parallel to the surface, $dV = -\vec{E}\cdot d\vec{l} = 0$. Because $\vec{E}\cdot d\vec{l}$ is zero for any $d\vec{l}$ parallel to the surface, $\vec{E}$ must either be zero or be perpendicular to any and every $d\vec{l}$ that is parallel to the surface. The only way $\vec{E}$ can be perpendicular to every $d\vec{l}$ parallel to the surface is for $\vec{E}$ to be normal to the surface. Therefore, we conclude that electric field lines are normal to any equipotential surfaces they intersect. **Figures 6 and 7** show equipotential surfaces near a spherical conductor and a nonspherical conductor. Note that anywhere a field line meets or penetrates an equipotential surface, shown in gray, the field line is normal to the equipotential surface. If we go from one equipotential surface to a neighboring equipotential surface by undergoing a displacement $d\vec{l}$ along a field line in the direction of the field, the potential changes by $dV = -\vec{E}\cdot d\vec{l} = Edl$. It follows that equipotential surfaces that have a fixed potential difference between them are more closely spaced where the electric field strength E is greater.



Adapted from https://openstaxcollege.org

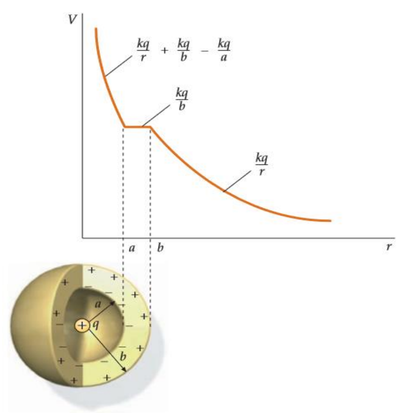
Figure 6. Equipotential surfaces and electric field lines outside a uniformly charged spherical conductor. The equipotential surfaces are spherical and the field lines are radial. The field lines are normal to the equipotential surfaces.



Adapted from https://openstaxcollege.org

Figure 7. Equipotential surfaces and electric field lines outside a nonspherical conductor.

Figure 8 on the right shows the electric potential as a function of the distance from the center of the cavity. Inside the conducting material, where $a \leq r \leq b$, the potential has the constant value $\frac{kq}{b}$. Outside the shell, the potential is the same as that of a point charge q at the center of the shell. Note that $V(r)$ is continuous everywhere. The electric field is discontinuous at the conductor surfaces, as reflected in the discontinuous slope of $V\ (r)$ at $r = a$ and $r = b$.



Adapted from https://openstaxcollege.org

Figure 8. The electric potential as a function of the distance from the center of the cavity.

Two conductors that are separated in space will typically not be at the same potential. The potential difference between such conductors depends on their geometrical shapes, their separation in space, and the net charge on each. When two conductors touch, the charge on the conductors redistributes itself so that electrostatic equilibrium is established and the electric field is zero inside both conductors. While touching, the two conductors can be considered to be a single conductor with a single potential. If we put a spherical charged conductor in contact with a second spherical conductor that is uncharged, charge will flow between them until both conductors are at the same potential. If the spherical conductors are identical, after touching they share the original charge equally. If the identical spherical conductors are now separated, each has half the original charge.

An important application of electric fields and equipotential lines involves the *heart*. The heart relies on electrical signals to maintain its rhythm. The movement of electrical signals causes the chambers of the heart to contract and relax. When a person has a heart attack, the movement of these electrical signals may be disturbed. An artificial pacemaker and a defibrillator can be used to initiate the rhythm of electrical signals. The equipotential lines around the heart, the thoracic region, and the axis of the heart are useful ways of monitoring the structure and functions of the heart. An electrocardiogram (ECG) measures the small electric signals being generated during the activity of the heart.

Sample Problems Involving Electric Potential Energy and Electric Potentials

Example 7: Van de Graaff

The metal sphere of a small Van de Graaff generator has a radius of 18 cm. When the electric field at the surface of the sphere reaches 3.0×10^6 V/m, the air breaks down, and the generator discharges. What is the maximum potential the sphere can have before breakdown occurs?

Note:

a. The excess charge on the sphere will be uniformly distributed over its surface.
b. The electric field and the electric potential outside the sphere is the same as if all the excess charge were concentrated as a point charge at the center of the sphere.

The electric field formula is

$$E = k\,\frac{Q}{r^2}$$

And the electric potential can be calculated using the formula

$$V_E = \frac{kQ}{r}$$

Therefore, through algebraic manipulation we are left with the equation

$$V_E = r \cdot E$$

Solving for electric potential, convert the *centimeter radius to meter first.*

$r = 18 \times 10^{-2}\ m$

$\boldsymbol{V_E = r \cdot E}$

$V_E = (18 \times 10^{-2}\ m)(3.0 \times 10^{6}\ V/m)$

$\boldsymbol{V_E = 5.4 \times 10^{5}\ V}$

Performance Task:

Directions: Read the given situation below and do what is asked. After which, submit your recorded video to your subject teacher.

You are a Physics instructor who always wants to make laboratory classes engaging and relevant. You decided to discuss how Van de Graaff generators operate as part of your lesson on electric potential. Come up with an audio-visual presentation on the topic. Your use of appropriate teaching methodologies and your ability to make the lesson relevant to your students are part of their criteria in assessing your discussion.

III. WHAT I HAVE LEARNED

EVALUATION/POST TEST

I. **TRUE OR FALSE**: Write the word ***True*** if the statement is correct and ***False*** if it is not. Write your answers in your notebook/Activity Sheet.

__________1. The conductor is a three-dimensional equipotential region and the surface of a conductor is an equipotential surface.

__________ 2. The potential V has the different value everywhere on an equipotential surface.

__________ 3. Electric field lines are normal to any equipotential surfaces they intersect.

__________ 4. Two conductors that are separated in space will typically be at the same potential.

__________ 5. An important application of electric fields and equipotential lines involves the contraction and relaxation of the human heart.

II. PROBLEM SOLVING:

Directions: Read and answer the given problems below. Show your solutions and write them in your notebook. (5 points each item)

1. What is the strength of the electric field between two parallel conducting plates separated by 1.00 cm and having a potential difference (voltage) between them of $1.50 \times 10^4\ V$?
   a. *Given:*
   b. *Formula:*
   c. *Solution*
   d. *Final Answer with unit:*

2. A 0.500 cm diameter plastic sphere, used in a static electricity demonstration, has a uniformly distributed 40.0 pC charge on its surface. What is the potential near its surface?
   a. *Given:*
   b. *Formula:*
   c. *Solution*
   d. *Final Answer with unit:*

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SYNOPSIS AND ABOUT THE AUTHOR

Electric potential is the amount of electric potential energy per unit charge. This is equivalent to the amount of work needed to move a charge from one reference point to another. It is mathematically described as:

$$V_E = \frac{kQ}{r} = \vec{E}$$

Electric field can also be computed given the potential. $E_x = -\frac{dV\,(x)}{dx}$ can be used if the potential V depends only on x, and there will be no change in V for displacements in the y or z direction; it follows that E_y and E_z equal zero.

Moreover, equipotential lines are places where the electric potential is constant. The term equipotential is also used as a noun, referring to an equipotential line or surface. The potential V has the same value everywhere on an equipotential surface. An important application of electric fields and equipotential lines involves the contraction and relaxation of the human heart.

ANSWER KEY

Pre–Test:

I. TRUE OR FALSE:
1. True
2. True
3. False
4. True
5. False

II. JUMBLED WORDS:
1. ELECTRIC POTENTIAL
2. POTENTIAL DIFFERENCE
3. VOLTAGE
4. ELECTRON VOLT
5. MECHANICAL ENERGY

Post–Test:

I. True or False:
1. True
2. False
3. True
4. False
5. True

II. Problem Solving:
1. $1.50 \times 10^6\ V/m$
2. $144\ V$

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