# Phys 100: The Physical World
# Chapters 24 & 25

Aaron Wirthwein

Department of Physics and Astronomy
University of Southern California

# The Universe is Electric!

Electricity is all around us. Atoms, molecules, and chemical reactions all exist because of electricity. We have electric lights, electric scooters, electric cars. Your nervous system runs on electricity. You could not feel without it. Your heart could not beat without it. You could not see without it. In fact, visible light is an electromagnetic phenomenon like radio waves.

We begin our study of electricity by examining the nature of electric charges and the forces between them. We will introduce the concept of the electric field as a convenient way to describe interactions, and later we will learn that the field is every bit as "real" as the charges that make it!

# Electric Charge

One fundamental property of electric charge is its existence in the two varieties that were historically named *positive* and *negative*. The observed fact is that all charged particles can be divided into two classes; all members of one class repel each other while attracting members of the other class.

Two positive charges or two negative charges repel each other.
A positive charge and a negative charge attract each other.

Charge is a scalar quantity that can be measured in terms of the force between charges a certain distance apart. Two important aspects of charge are its *quantization* and *conservation*.

# Conceptual Question 1

Three objects are brought close to each other, two at a time. When objects A and B are brought together, they repel. When objects B and C are brought together, they also repel. Which of the following are true? Select all that apply.

(a) Objects A and C possess charges of the same sign.

(b) Objects A and C possess charges of opposite sign.

(c) All three objects possess charges of the same sign.

(d) One object is neutral.

(e) Additional experiments must be performed to determine the signs of the charges.

# The Structure of Matter

The structure of atoms can be described in terms of three particles: the negatively charged electron, the positively charged proton, and the uncharged neutron. The number of protons or electrons in a neutral atom of an element is called the atomic number of the element. If one or more electrons are removed from an atom, what remains is called a positive ion. A negative ion is an atom that has gained one or more electrons. This gain or loss of electrons is called ionization.

In most cases, negatively charged (and highly mobile) electrons are added or removed, and a positively (negatively) charged object is one that has lost (gained) electrons. When we speak of the charge of an object, we always mean its net charge.

# Quantization of Charge

Every observable amount of electric charge is an integer multiple of a basic unit called the fundamental charge equal to the absolute value of charge carried by the electron or proton. In other words $Q_{\mathrm{net}} = \pm Ne$ where $N$ is an integer (0, 1, 2, ...) and $e$ is the fundamental charge. The SI unit of charge is the Coulomb (C) and the fundamental charge is about $1.6 \times 10^{-19}$ C.

It is a remarkable fact that the proton and the electron have the same magnitude of charge to within 1 part in $10^{20}$. As far as we know, they have the same absolute value of charge.

When we deal with macroscopic charged objects, we will usually ignore the quantization because the value of $N$ is enormous–so big we might as well pretend the charge is spread continuously throughout the object.

# Conservation of Charge

The total charge in an isolated system is a constant and equals the algebraic sum of the positive and negative charges present.

In any charging process, charge is never created or destroyed; it is merely transferred from one object to another, usually in the form of mobile electrons which carry negative charge. Additionally, charge is conserved locally, meaning we can't conserve charge by destroying it in one place and making it reappear in another distant location simultaneously–the charge has to physically move from one place to another.

When a glass rod is rubbed with silk, the silk acquires a negative charge and the glass rod acquires a positive charge. In fact, Benjamin Franklin defined a positive charge as the charge acquired by a glass rod when rubbed with silk, and this convention has persisted ever since.

# Conceptual Question 2

When you brush your hair and scrape electrons from your hair, the charge of your hair becomes

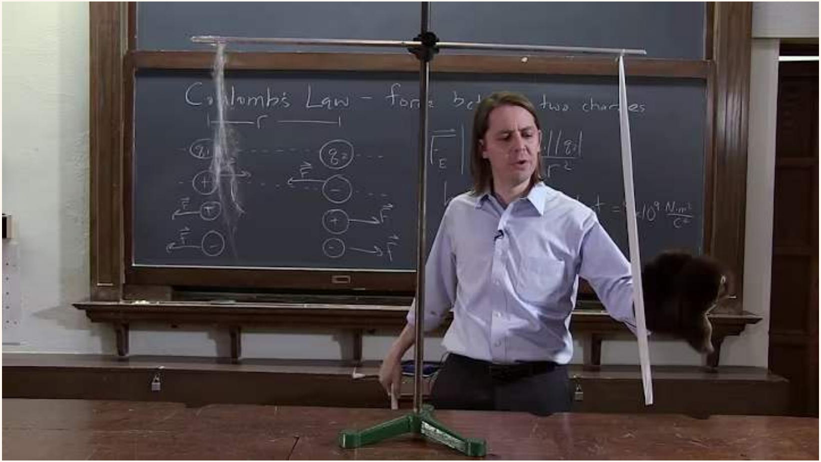
(a) positive

(b) negative

(c) both A and B

(d) neither A nor B

# Electrostatic Attraction and Repulsion



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# Conductors and Insulators

The motion of charges is called electrical conduction. Electrical conductors have free electrons that are not bound to particular atoms. Electrons in insulators are bound to atoms and cannot move freely through the material.

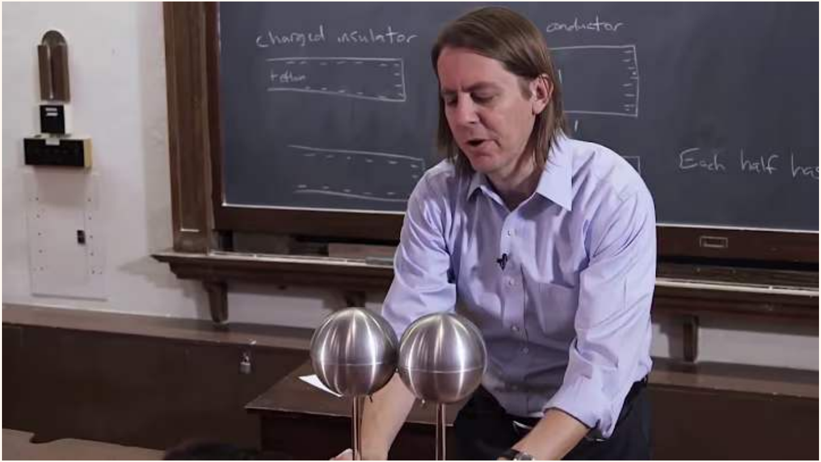
Most metals are good conductors, while most nonmetals are insulators. Within a solid metal such as copper, one or more outer electrons in each atom become detached and move freely throughout the material. Some materials called *semiconductors* are intermediate in their properties between good conductors and good insulators.

# Charging by Induction

Charging by induction involves bringing a charged object close to a neutral conductor. This causes electrons in the conductor to move, creating regions of positive and negative charge. When the charged object is removed, the neutral conductor retains a temporary charge called an induced charge that is opposite to the charged object.

Induction requires no contact with the object inducing the charge. A process similar to induction in conductors takes place in insulators. Electrical forces cause a slight shift of charge within the molecules of the neutral insulator, an effect called polarization.

# Charging by Induction

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# Conceptual Question 3

Three objects are brought close to one another, two at a time. When objects A and B are brought together, they attract. When objects B and C are brought together, they repel. Which of the following are necessarily true? Select all that apply.

(A) Objects A and C possess charges of the same sign.

(B) Objects A and C possess charges of opposite sign.

(C) All three objects possess charges of the same sign.

(D) One object is neutral.

(E) Additional experiments must be performed to determine information about the charges on the objects.

# Conceptual Question 4

A thin stream of water bends toward a positively charged rod as the electrons in the stream are attracted toward the rod. When a negatively charged rod is placed near the stream, it will

(a) bend in the same direction.
(b) bend in the opposite direction.
(c) not bend at all.

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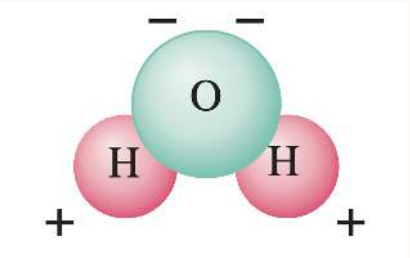
# Polar Molecules

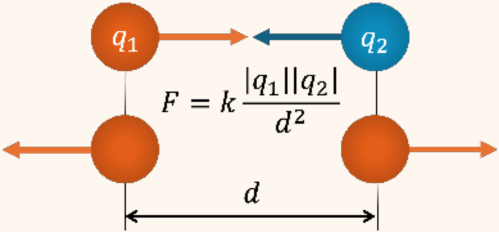
Polar molecules have an uneven distribution of electrical charge, resulting in one end being slightly positive and the other slightly negative. Water ($H_2O$) is a good example. Electrons are pulled toward the oxygen, so the oxygen end is negative and the hydrogen end is positive, giving water its polar character.



# Coulomb's Law

Charles Coulomb measured the magnitudes of the electric forces between charged objects using a torsion balance, which he invented in 1784 and was later used by Cavendish to study the much weaker gravitational interaction.

Coulomb's law states that two stationary charges repel or attract one another with a force along the line joining them that is proportional to the product of the magnitude of the charges and inversely proportional to the square of the distance between them.



# Strength of the Electric Force

Consider a pair 1-kg particles separated by 1 meter that each carrying +$1$ C of total charge. The electric force would be found experimentally to have the value $9 \times 10^9$ N. The Coulomb constant is therefore $k = 9 \times 10^9\ \mathrm{N} \cdot \mathrm{m}^2/\mathrm{C}^2$.

Compare this to the strength of the gravitational force between them. Recall that $G = 6.7 \times 10^{-11}\ \mathrm{N} \cdot \mathrm{m}^2/\mathrm{kg}^2$, so the force would be $6.7 \times 10^{-11}$ N. For this reason, we typically say the electric force is much stronger than the gravitational force, but it depends on the context. Most macroscopic objects are neutrally charged since they have roughly equal numbers of positive and negative charges. At the microscopic level, the properties of atoms and molecules are overwhelmingly dictated by electric forces, and polarization effects are especially important since many atoms and molecules themselves are neutrally charged.

# Conceptual Question 5

If the distance between two charged particles is doubled then, according to Coulomb's law, the new electrostatic force compared with the original electrostatic force will be

(a) half as strong.

(b) one-quarter as strong.

(c) twice as strong.

(d) four times as strong.

# Conceptual Exercise 6

Two oppositely charged particles, an alpha particle with 2 positive charges and a less-massive electron with a single negative charge are attracted to each other.

1. Compared to the force that the alpha particle exerts on the electron, the electron exerts a force on the alpha particle that is

   (A) greater. (B) the same. (C) less.

2. The particle with the greatest acceleration is the

   (A) alpha particle. (B) electron. (C) same for each.

3. As the particles get closer, each experiences an **increase** in

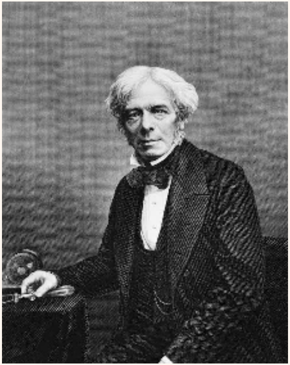
   (A) force. (B) speed. (C) acceleration. (D) all of the above.

   (E) none of the above.

# Michael Faraday (1791–1867)

British scientist who made ground-breaking contributions to physics and chemistry, despite having little formal education. He is best known for developing the concept of a field.

He proposed that electric forces are not transmitted instantaneously over a distance, but rather through fields that fill the intervening space. This idea reinforced the principle of locality, where objects influence each other through their immediate surroundings.



# Electric Field

Electric fields are created by charges (called source charges) and influence other charges (called test charges). Formally, the electric field of a source charge is the force exerted on a test charge at some location divided by the value of the test charge. In this way, we obtain a quantity that is a property of space that depends only on the source charge.

The electric field strength at a point in space located a distance $d$ away from an object with total charge $Q$ is given by

$$\text{electric field strength} = \frac{\text{electric force of } Q \text{ on } q}{\text{test charge } q}$$

$$E = \frac{kQ}{d^2}$$

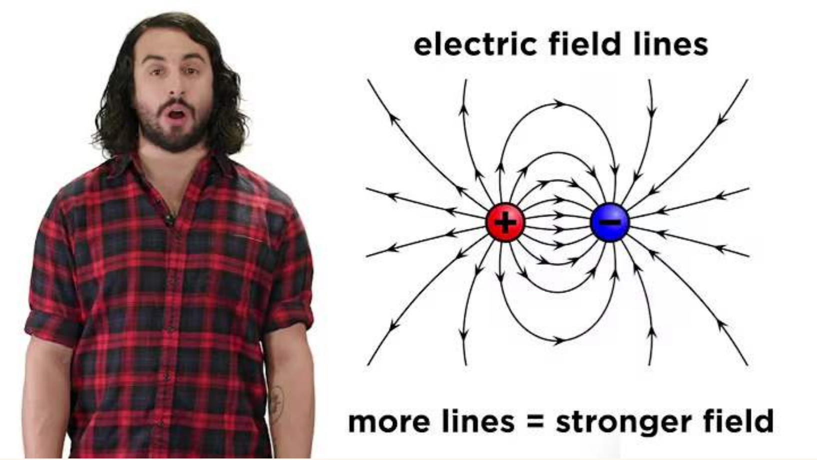
# Properties of Electric Fields

The electric field

1. fills the space surrounding charges.
2. is a vector; it has both magnitude and direction.
3. has a magnitude which diminishes as the inverse-square of the distance from the particle creating the field.
4. points away from (+) charges and towards (−) charges.
5. has units of force per charge (e.g., newtons per coulomb)

Additionally, the force felt by a charged particle in an electric field is in the direction of the field for a positive charge, and opposite the field direction for a negative charge.

# Electric Charges and Fields

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# Visualizing Electric Fields

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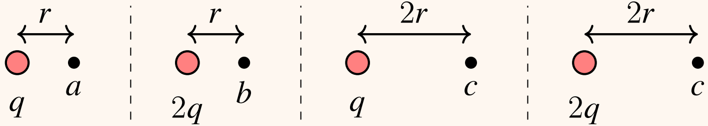
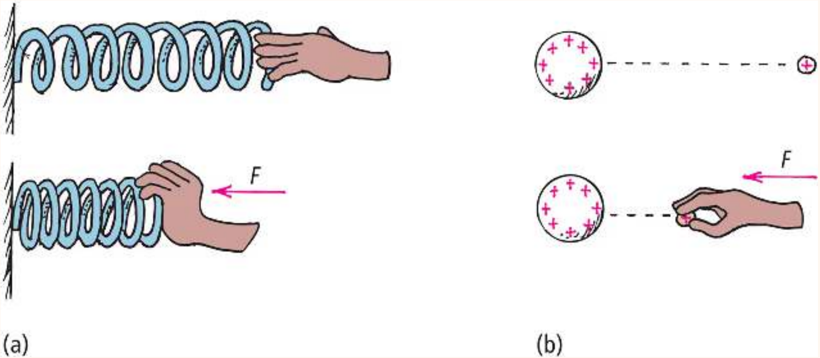
# Conceptual Question 7

Rank in order, from largest to smallest, the electric field strengths $E_a$, $E_b$, $E_c$, and $E_d$ at points $a$, $b$, $c$, and $d$. Each point experiences the electric field of only one point charge (the points are very far away from each other, hence the dashed lines).



# Electric Potential Energy

Work is required to push a charged particle against an electric field. Electric potential energy is the energy possessed by a charged particle due to its location in an electric field.



# Conceptual Question 8

A point charge is interacting with an electrostatic field. Which of the following statements are true? Select all that apply.

(a) The system loses potential energy as a positive charge moves in the direction of the field.

(b) The system gains potential energy as a negative charge moves in the direction of the field.

(c) The system loses potential energy as a positive charge moves in the direction opposite to the field.

(d) The system loses potential energy as a negative charge moves in a direction opposite to the field.

# Voltage and Electric Potential

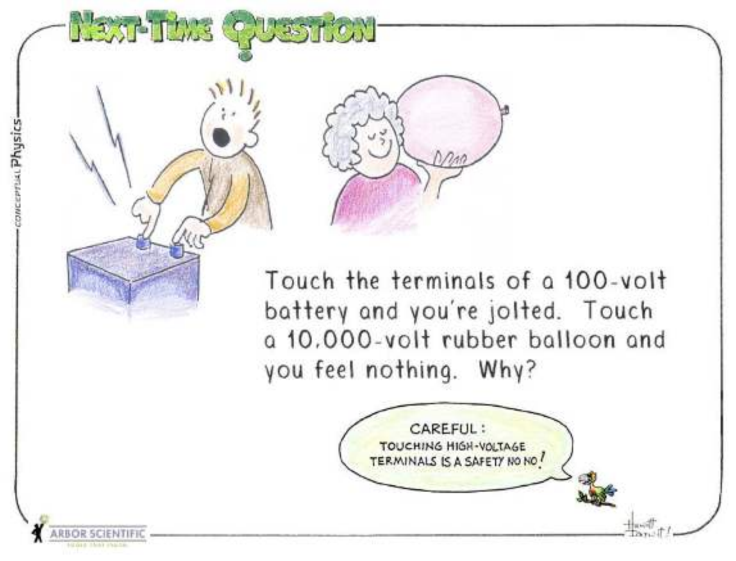
Voltage is work done per unit charge against an electric field. Electric potential is the electric potential energy per unit charge. Electric potential is *potentially* confusing because it's only one word away from a different but related concept.

$$\text{electric potential} = \frac{\text{electric PE}}{\text{amount of charge}} = \frac{\text{electric force} \times \text{distance}}{\text{amount of charge}}$$

For our purposes, voltage and electric potential are basically the same thing. They are both measured in volts (V) where one volt is one joule per coulomb. Electric potential, a scalar quantity, is another property of the space surrounding source charges.

$$1 \text{ volt} = \frac{1 \text{ joule}}{1 \text{ coulomb}}$$

# Conceptual Question 9

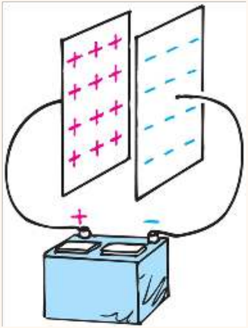


# Electrical Energy Storage

Electrical energy can be stored in a common device called a capacitor.

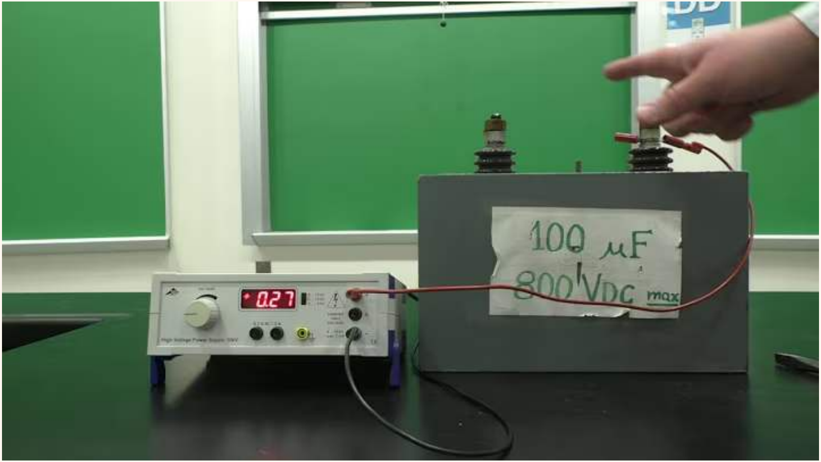
The simplest capacitor is a pair of conducting plates separated by a small distance, but not touching each other.

A battery can be used to charge the capacitor by transferring electron from one plate to the other.




The energy stored in a capacitor ultimately comes from the work done by the battery to charge it. The charging process is complete when the potential difference between the plates equals the potential difference between the battery terminals.

# Shorting a Capacitor

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# Exploding Wire


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# Shorting a Battery

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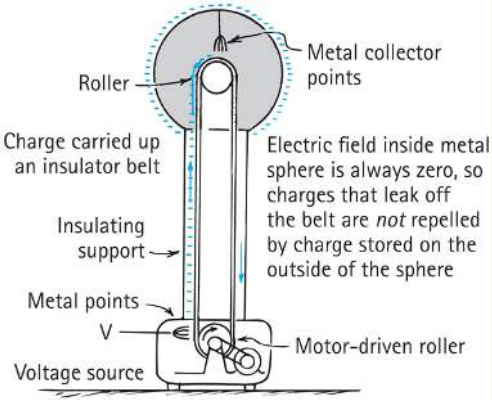
# Van de Graaff Generator

Common laboratory device for producing high voltages and creating static electricity. A demonstration Van de Graaff generator might store a charge of 1 microcoulomb at a potential of 100,000 volts, resulting in a potential energy of 100 joules (still a dangerous amount if discharged rapidly).



# Demo: Van de Graaff Generator

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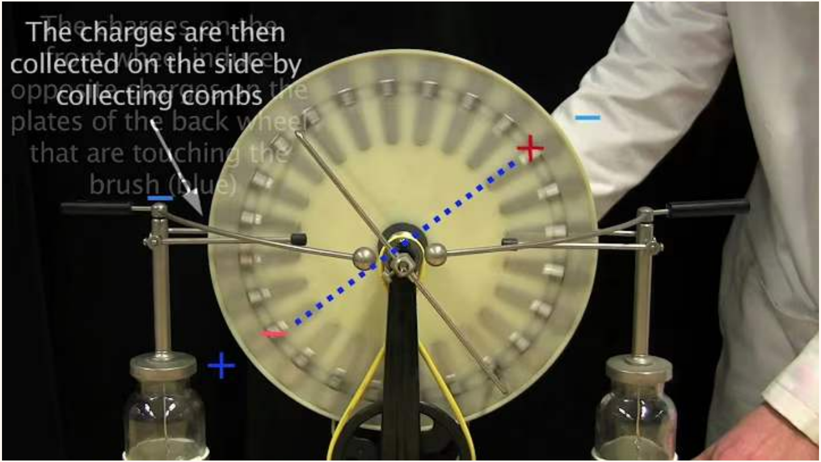


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