Electricity and Magnetism

Second lecture

Conductors, Insulators and Coulomb's law

Dr. Mohammed Hashim Abbas

first stage

Department of medical physics

Al-Mustaqbal University-College

2021- 2022

Outline

1. Conductors and Insulators
2. Induced Charge
3. Charging an object
4. Coulomb's Law
5. References

2.1 Conductors and Insulators

We can classify materials generally according to the ability of charge to move through them (What is the classification of materials according to the ability of charge moving through them or according to the conductivity?)

2.1.1 *Conductors* are materials through which charge can move rather freely; examples include metals (such as copper in common lamp wire), the human body, and tap water.

- Free electrons are not bound to the atoms.
- These electrons can move relatively freely through the material.
- Examples of good conductors include copper, aluminum and silver.
- When a good conductor is charged in a small region, the charge readily distributes itself over the entire surface of the material.

2.1.2 Insulators: Electrical insulators are materials in which all of the electrons are bound to atoms.

- These electrons cannot move relatively freely through the material.
- Examples of good insulators include glass, rubber and wood.
- When a good insulator is charged in a small region, the charge is unable to move to other regions of the material.

2.1.3 Semiconductors: The electrical properties of semiconductors are somewhere between those of insulators and conductors.

- Examples of semiconductor materials include silicon and germanium.
- Semiconductors are commonly used in making electronic chips.

- The electrical properties of semiconductors can be changed by the addition of controlled amounts of certain atoms to the material.

The properties of **conductors** and **insulators** are due to the structure and electrical nature of atoms. Atoms consist of **positively** charged protons, **negatively** charged electrons, and electrically neutral neutrons. The protons and neutrons are packed tightly together in a central nucleus. The charge of a single electron and that of a single proton have the same magnitude but are opposite in sign. Hence, an electrically neutral atom contains equal numbers of electrons and protons. **Electrons** are held near the nucleus because they have the electrical sign opposite that of the protons in the nucleus and thus are attracted to the nucleus. Were this not true, there would be no atoms and thus no you.

- Most metals are good conductors, while most nonmetals are insulators. Within a solid metal such as copper, In an insulator there are no, or very few, free electrons, and electric charge cannot move freely through the material. Some materials called semiconductors are intermediate in their properties between good conductors and good insulators.

2.2 Induced Charge

The experiment of Figure 1 demonstrates the mobility of charge in a conductor. A negatively charged plastic rod will attract either end of an isolated neutral copper rod. What happens is that many of the conduction electrons in the closer end of the copper rod are repelled by the negative charge on the plastic rod. Some of the conduction electrons move to the far end of the copper rod, leaving the near end depleted in electrons and thus with an unbalanced positive charge. This positive charge is attracted to the negative charge in the plastic rod. Although the copper rod is still neutral, it is said to have an *induced charge*, which means that some of its positive and negative charges have been separated due to the presence of a nearby charge.

Similarly, if a positively charged glass rod is brought near one end of a neutral copper rod, induced charge is again set up in the neutral copper rod but now the near end gains conduction electrons, becomes negatively charged, and is attracted to the glass rod, while the far end is positively charged.

Note that only conduction electrons, with their negative charges, can move; positive ions are fixed in place. Thus, an object becomes positively charged only through the *removal of negative charges*.

What are the steps for charging an object by induction?

1. Negative rod brought near neutral object.

2. Electrons in rod repel electrons to opposite end of object, causing one end to become positive.

3. If object is grounded (connected to ground), electrons from negative end of object travel into the ground.

4. Now object has more protons than electrons so it becomes positive.

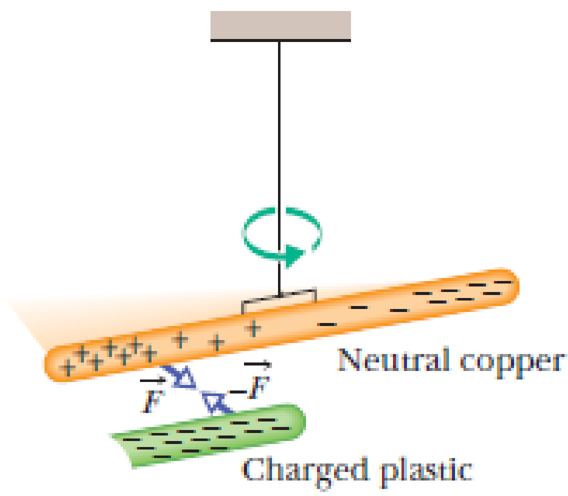

Figure 1: A neutral copper rod is electrically isolated. Either end of the copper rod will be attracted by a charged rod.

2.3 Charging an object

There are Main methods of charging an object:

2.3.1 Charging by Friction (Rubbing)

When two neutral materials are rubbed together, they may become charged. Electrons are transferred by rubbing from one material that becomes negatively charged to the other material becomes positively charged. Rubbing does not create charge but only transfers it from one body to another.

2.3.2 Charging by Contact

One material is already charged the other material is either neutral or charged. "Electrons are transferred from a negatively charged object to either a neutral or positively charged object by contact."

2.3.3 Charging by Induction

The movement of electrons within a substance caused by a nearby charged object, without direct contact between the substance and the object.

2.4 Coulomb's Law

Now we come to the equation for Coulomb's law, but first a caution. This equation works for only charged particles. If two charged particles are brought near each other, they each exert an **electrostatic force** on the other. The direction of the force vectors depends on the signs of the charges. If the particles have the same sign of charge, they repel each other. That means that the force vector on each is directly away from the other particle (Figure 2 a and b). If we release the particles, they accelerate away from each other. If, instead, the particles have opposite signs of charge, they attract each other.

That means that the force vector on each is directly toward the other particle (Figure 2 c). If we release the particles, they accelerate toward each other.

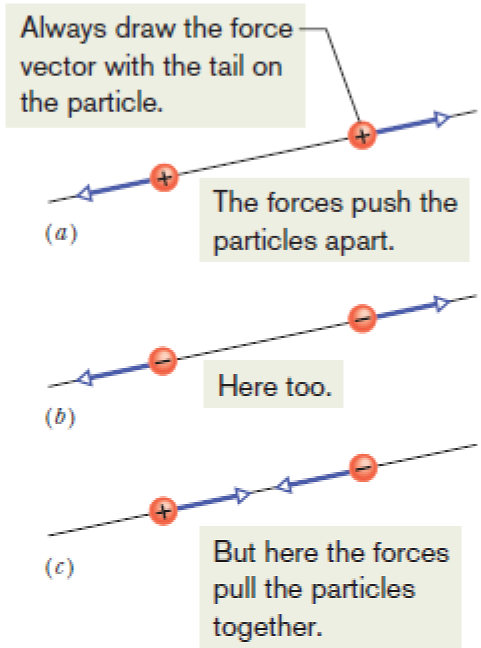

Figure 2: Two charged particles repel each other if they have the same sign of charge, either (*a*) both positive or (*b*) both negative. (*c*) They attract each other if they have opposite signs of charge.

Coulomb's law after Charles-Augustin de Coulomb, whose experiments in 1785 led him to it. Let's write the equation in vector form and in terms of the particles shown in Figure 3, where particle 1 has charge q_1 and particle 2 has charge q_2.

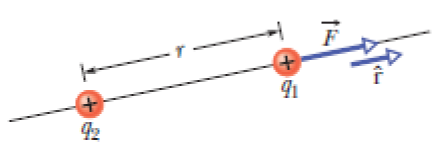

Figure 3: The electrostatic force on particle 1 can be described in terms of a unit vector along an axis through the two particles, radially away from particle 2.

Let's write the force acting on particle 1 in terms of a unit vector $\hat{r}$ has a magnitude of exactly 1 and no unit that points along a radial axis extending through the two particles, radially away from particle 2. we write the electrostatic force as:

$$\vec{F} = k\frac{q_1 q_2}{r^2}\hat{\mathbf{r}} \quad \text{(Coulomb's law)},$$

where r is the separation between the particles and k is a positive constant called the electrostatic constant or the Coulomb constant.

Unit. The SI unit of charge is the **coulomb**. For practical reasons having to do with the accuracy of measurements, the coulomb unit is derived from the SI unit *ampere* for electric current i. Let's just note that current i is the rate dq/dt at which charge moves past a point or through a region:

$$i = \frac{dq}{dt} \quad \text{(electric current)}.$$

Rearranging above and replacing the symbols with their units (coulombs C, amperes A, and seconds s) we see that:

$$1\text{ C} = (1\text{ A})(1\text{ s}).$$

Force Magnitude. The electrostatic constant k is often written as $1/4\pi\varepsilon_0$ and The quantity ε_0, called the permittivity constant. Then the magnitude of the electrostatic force in Coulomb's law becomes:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_2|}{r^2} \quad \text{(Coulomb's law)}.$$

$$k = \frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2.$$

$$\varepsilon_0 = 8.85 \times 10^{-12}\ \text{C}^2/\text{N}\cdot\text{m}^2.$$

Multiple Forces. Suppose we have n charged particles near particle 1, then the net force on particle 1 is given by the vector sum:

$$\vec{F}_{1,\text{net}} = \vec{F}_{12} + \vec{F}_{13} + \vec{F}_{14} + \vec{F}_{15} + \cdots + \vec{F}_{1n},$$

In which, for example, $\vec{F}_{14}$ is the force on particle 1 due to the presence of particle 4.

Examples:

1. Figure 4 *a* shows two positively charged particles fixed in place on an *x* axis. The charges are $q_1 = 1.60\times10^{-19}$ C and $q_2=3.2\times10^{-19}$ C, and the particle separation is R=0.02 m. **What are the magnitude and direction of the electrostatic force $\vec{F}_{12}$ on particle 1 from particle 2?**

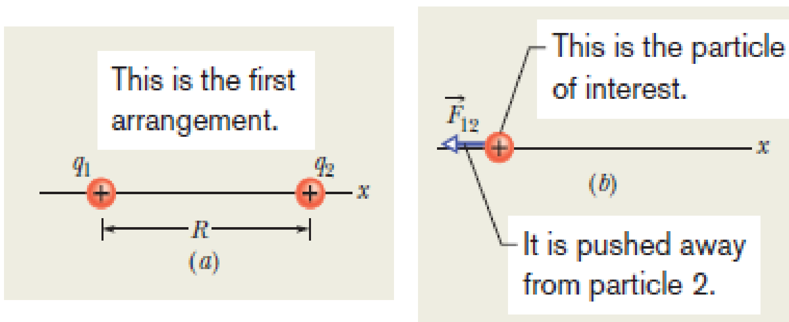

Figure 4: (*a*) Two charged particles of charges q_1 and q_2 are fixed in place on an *x* axis. (*b*), showing the electrostatic force on particle 1from particle 2.

Solution:

Because both particles are positively charged, particle 1 is repelled by particle 2. Thus, the direction of force $\vec{F}_{12}$ on particle 1 is *away from* particle 2, in the negative direction of the *x* axis, as indicated in Figure 4 *b*.

$$
\begin{aligned}
F_{12} &= \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_2|}{R^2} \\
&= (8.99\times10^{9}\ \mathrm{N\cdot m^2/C^2}) \\
&\quad \times \frac{(1.60\times10^{-19}\ \mathrm{C})(3.20\times10^{-19}\ \mathrm{C})}{(0.0200\ \mathrm{m})^2} \\
&= 1.15\times10^{-24}\ \mathrm{N}.
\end{aligned}
$$

Thus, force $\vec{F}_{12}$ has the following magnitude and direction (relative to the negative direction of the x axis):

$$1.15 \times 10^{-24}\ \text{N} \quad \text{and} \quad 180^{\circ}.$$

We can also write in unit-vector notation as:

$$\vec{F}_{12} = -(1.15 \times 10^{-24}\ \text{N})\hat{\text{i}}.$$

2. Figure 5 *c:* is identical to Figure 4 *a* except that particle 3 now lies on the x axis between particles 1 and 2. Particle 3 has charge $q_3 = -3.2 \times 10^{-19}$ C and is at a distance $\frac{3}{4}R$ from particle 1.**What is the net electrostatic force $\vec{F}_{1,net}$ on particle 1 due to particles 2 and 3?**

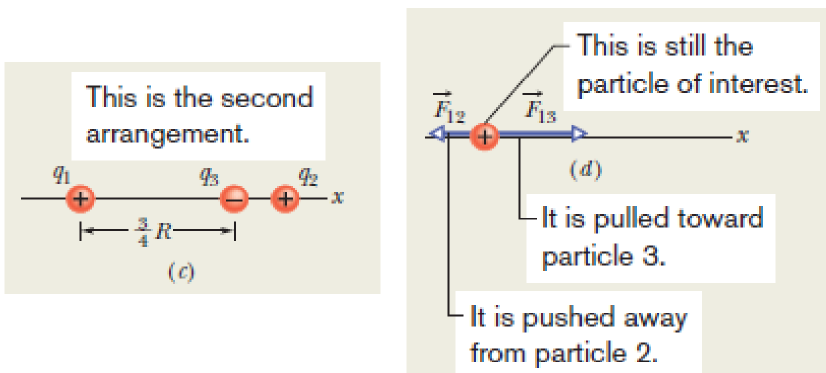

Figure 5: (*a*) Three charged particles of charges q_1, q_2 and q_3 are fixed in place on an x axis. (*b*), showing the electrostatic force on particle 1from particle 2 and 3.

The presence of particle 3 does not alter the electrostatic force on particle 1 from particle 2. Thus, force $\vec{F}_{1,2}$still acts on particle 1. Similarly, the force $\vec{F}_{1,3}$ that acts on particle 1 due to particle 3 is not affected by the presence of particle 2. Because particles 1and 3 have charge of opposite signs, particle 1 is attracted to particle 3. Thus, force v is directed toward particle 3, as indicated in of Figure 5 d.

Solution:

To find the magnitude of $\vec{F}_{1,3}$

$$F_{13} = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_3|}{(\frac{3}{4}R)^2}$$
$$= (8.99 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)$$
$$\times \frac{(1.60 \times 10^{-19}\ \text{C})(3.20 \times 10^{-19}\ \text{C})}{(\frac{3}{4})^2(0.0200\ \text{m})^2}$$
$$= 2.05 \times 10^{-24}\ \text{N}.$$

We can also write $\vec{F}_{1,3}$ in unit-vector notation:

$$\vec{F}_{13} = (2.05 \times 10^{-24}\ \text{N})\hat{\text{i}}.$$

$$\vec{F}_{1,\text{net}} = \vec{F}_{12} + \vec{F}_{13}$$
$$= -(1.15 \times 10^{-24}\ \text{N})\hat{\text{i}} + (2.05 \times 10^{-24}\ \text{N})\hat{\text{i}}$$
$$= (9.00 \times 10^{-25}\ \text{N})\hat{\text{i}}. \qquad \text{(Answer)}$$

Thus, $\vec{F}_{1,net}$ has the following magnitude and direction (relative to the positive direction of the *x* axis):

$$9.00 \times 10^{-25}\ \text{N} \quad \text{and} \quad 0^{\circ}.$$

2.5 References

Walker, Jearl, Robert Resnick, and David Halliday. Halliday and resnick fundamentals of physics. Wiley, 2014.