General Physics - E&M (PHY 1308) Lecture Notes

Lecture 002: Electric Charge and Coulomb's Law (Wolfson 20.1-20.2)

SteveSekula, 26 August 2010 (created 19 August 2010)

no tags

Main Goals of this Lecture

- Define basic concepts in electricity: charge, units of charge, and force
- Define the mathematical relationship between charge and force exerted by one charge on another (Coulomb's Law)

Electric Charge

- What is "electric charge"?
  - fundamentally, nobody really knows the answer to that yet
  - don't lose heart! Fundamentally, nobody really know what "mass" is either - however, we are familiar with mass because we spend our lives pushing things around.
  - we understand "electric charge" in the same way that we understand "mass" - through observations of the natural world, careful measurement, and the use of the language of mathematics to express observations, develop frameworks to describe the world and make predictions about the outcomes of experiments

- Here are some things we DO know about electric charge
  - It comes in two varieties - positive and negative
    - Benjamin Franklin - yes, one of the Founders of the United States - is credited with devising this naming scheme
    - this naming scheme is VERY useful, because it connects directly to an observation: the total charge in any system is

THE ALGEBRAIC SUM OF THE INDIVIDUAL CHARGES IN THE SYSTEM. For instance,

$$q_{total} = q_1 + q_2 + q_3 + ... = \sum_{i=1}^{N} q_i$$

- It is a property that is "carried" by particles like electrons and protons

Class discussion: What are electrons and what are protons? What other particles make up matter?

- Total electric charge in a defined system (e.g. an enclosed region) is CONSERVED - that is, no matter what happens to the system the total charge cannot change. Charged particles may be created, or they may be annihilated, in various physical processes, but those processes cannot change the total electric charge.

Quantities of Charge

All electrons carry the same charge. All protons carry the same charge. The proton's charge has exactly the same MAGNITUDE as, but the opposite sign of, the electron's charge.

Given that the electron and proton are so different in many other ways (e.g. mass, radius, etc.) this is a remarkable fact.

The magnitude of the electron or proton charge is the **elementary charge**, e. Electrons have charge $-e$, and protons have charge $+e$. Electric charge is *quantized* - that is, there is a smallest unit below which you can no longer subdivide a system of electric charge. Charge only comes in discrete amounts.

Class discussion: Have you taken Chemistry (either in high school or college)? If so, who was it that discovered that electric charge has a "smallest unit", and therefore is quantized? ANSWER: The American physicist R. A. Milliken, who performed a delicate and difficult experiment balancing the falling of oil drops in a gravitational field with an electric force. This is the so-called "Millikan Oil Drop Experiment."

Optional class discussion: Is the electron charge the smallest unit of charge? ANSWER: No. It turns out the proton is made from even tinier subatomic particles, called quarks. Quarks can carry either 1/3e or 2/3e magnitude electric charges. If we had discovered quarks before electrons and protons, we would call the electron charge 3e instead of just e

Algebraic Exercise: What is the total charge of a system that consists of 3 electrons and 2 protons? ANSWER: $(3 \cdot -e) + (2 \cdot +e) = -1 \cdot e = -e$

And what is e? The Standard International (SI) unit of electric charge is the *Coulomb*, named after Charles-Augustin de Coulomb and denoted by a capital letter *C*. It is convention to define:

$$1C = 6.25 \times 10^{18} \text{ elementary charges}$$

Making the elementary charge:

$$1e = 1.60 \times 10^{-19} C$$

Exploring Charge

See the supplementary slides for Lecture 002 for movies and images that illustrate electric charge:

- The charged balloon demonstration and simulation

- The charged plastic comb water-deflection demo
- The beam tree as an example of charge and aesthetics
- Arc flash injury simulation using a dummy
- Fluffy carpet and the danger of touching grounded metal objects

Electric Force

As some of these demonstrations indicate, electric charge is able to exert a force. We tend not to notice this force most of the time because the electrons and protons in our bodies, and in the work around us, are largely paired up and thus electrically neutral (zero electric charge) on a human scale.

As the balloon demonstration and the funny video of the electric shock from the carpet illustrate, electric charge and force go hand-in-hand. Many observations and measurements of the relationship between:

- The magnitude of the charges involved
- the distance between the charges (it's direction AND magnitude)
- the sign of the charges
- the force exerted between charges

have been carefully studied. The result is mathematical statement that has been upheld by thousands upon thousands of repeated experiments carried out over hundreds of years - a LAW. This law is known as "Coulomb's Law":

$$\vec{F_{12}} = \frac{k \cdot q_1 \cdot q_2}{r^2} \hat{r}$$

where $\vec{F_{12}}$ is the force VECTOR (magnitude and direction) that charge 1 exerts on charge 2. k is a constant, determined from repeated experimentation, whose value is:

$$k = 9.0 \times 10^9 \mathrm{N} \cdot \mathrm{m}^2/\mathrm{C}^2$$

Let's draw a picture of this and illustrate the pieces of this formula. It combines two key areas of mathematics: standard algebra and vector algebra. The picture will help us to parse the meaning of this formula, considering two cases: a pair of like-signed charged, and a pair of opposite-signed charges.

When solving a problem it's good to develop a strategy for attacking thinks step-by-step with Coulomb's Law.

Strategies for dealing with problems involving the force between two particles

Remember: Coulomb's Law reminds us that force is a VECTOR, and thus Coulomb's Law provides us both with the MAGNITUDE and the DIRECTION of the force exerted by charge 1 on charge 2

1. Interpret the problem to determine what you need to figure out: First, make sure that you're dealing with the electric force alone, and that no other forces also need to be considered. Identify the charge or charges on which you want to calculate the force. Next, identify the charge or charges producing the force - the SOURCE charges. In the above example, we implicitly chose charge 1 and the source and wanted to know the force it exerted on charge 2.
2. Develop a set of information for attacking the problem: Begin with a DRAWING that shows the charges. If you're given coordinates for the charges, place the charges on coordinates; if not, define a suitable coordinate system that makes the problem easier. Determine the unit vectors in Coulomb's Law ($\hat{r}$). If two charges lie along the same coordinate axis, then the unit vector will be one of $\hat{\imath}$, $\hat{\jmath}$, $\hat{k}$. When the charges don't lie simply on a single coordinate axis, find the unit vector by writing the vector $\vec{r}_{12}$ and determining the unit vector $\hat{r}$ as follows:

   $$\hat{r} \equiv \frac{\vec{r}_{12}}{|\vec{r}_{12}|}.$$

   Please note that for simplicity, we will in the future write

   $$|\vec{r}_{12}| = r_{12}.$$

3. Evaluate the electric force: Apply Coulomb's Law, using the pieces you assembled during the Interpretation phase of the problem

1. Assess the outcome: Think about your answer to see if it makes sense. Check the little things: does you force point in the direction you expect, based on the charges involved? Compare to an order-of-magnitude estimate of the answer: ignoring the specific values of the numbers involved and multiple just by the appropriate powers of ten, does your answer get within a factor of about 10 of your fully computed answer?

First In-Class Quiz