Charge, Electricity and Magnetism

Skills to Develop

• Explain the following laws within the Ideal Gas Law

Charge

“Charge” is the technical term used to indicate that an object participates in electrical forces. This is to be distinguished from the common usage, in which the term is used indiscriminately for anything electrical. For example, although we speak colloquially of “charging” a battery, you may easily verify that a battery has no charge in the technical sense, e.g., it does not exert any electrical force on a piece of tape that has been prepared as described in section 5.1.

Two types of charge

We can easily collect reams of data on electrical forces between different substances that have been charged in different ways. We find for example that cat fur prepared by rubbing against rabbit fur will attract glass that has been rubbed on silk. How can we make any sense of all this information? A vast simplification is achieved by noting that there are really only two types of charge. Suppose we pick cat fur rubbed on rabbit fur as a representative of type A, and glass rubbed on silk for type B. We will now find that there is no “type C.” Any object electrified by any method is either A-like, attracting things A attracts and repelling those it repels, or B-like, displaying the same attractions and repulsions as B. The two types, A and B, always display opposite interactions. If A displays an attraction with some charged object, then B is guaranteed to undergo repulsion with it, and vice-versa.
The coulomb

Although there are only two types of charge, each type can come in different amounts. The metric unit of charge is the coulomb (rhymes with “drool on”), defined as follows:

One Coulomb (C) is the amount of charge such that a force of $9.0 \times 10^9$ N occurs between two pointlike objects with charges of 1 C separated by a distance of 1 m.

The notation for an amount of charge is $q$. The numerical factor in the definition is historical in origin, and is not worth memorizing. The definition is stated for pointlike, i.e., very small, objects, because otherwise different parts of them would be at different distances from each other.

A model of two types of charged particles

Experiments show that all the methods of rubbing or otherwise charging objects involve two objects, and both of them end up getting charged. If one object acquires a certain amount of one type of charge, then the other ends up with an equal amount of the other type. Various interpretations of this are possible, but the simplest is that the basic building blocks of matter come in two flavors, one with each type of charge. Rubbing objects together results in the transfer of some of these particles from one object to the other. In this model, an object that has not been electrically prepared may actually possesses a great deal of both types of charge, but the amounts are equal and they are distributed in the same way throughout it. Since type A repels anything that type B attracts, and vice versa, the object will make a total force of zero on any other object. The rest of this chapter fleshes out this model and discusses how these mysterious particles can be understood as being internal parts of atoms.

Use of positive and negative signs for charge

Because the two types of charge tend to cancel out each other's forces, it makes sense to label them using positive and negative signs, and to discuss the total charge of an object. It is entirely arbitrary which type of charge to call negative and which to call positive. Benjamin Franklin decided to describe the one we've been calling “A” as negative, but it really doesn't matter as long as everyone is consistent with everyone else. An object with a total charge of zero (equal amounts of both types) is referred to as electrically neutral.

induction

Figure c: The paper has zero total charge, but it does have charged particles in it that can move.

Criticize the following statement: “There are two types of charge, attractive and repulsive.”

Coulomb's law

A large body of experimental observations can be summarized as follows:
Coulomb's law: The magnitude of the force acting between pointlike charged objects at a center-to-center distance \( r \) is given by the equation

\[
equation
\]
where the constant \( k \) equals \( 9.0 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2 \). The force is attractive if the charges are of different signs, and repulsive if they have the same sign.

**Conservation of charge**

An even more fundamental reason for using positive and negative signs for electrical charge is that experiments show that with the signs defined this way, the total amount of charge is a conserved quantity. This is why we observe that rubbing initially uncharged substances together always has the result that one gains a certain amount of one type of charge, while the other acquires an equal amount of the other type. Conservation of charge seems natural in our model in which matter is made of positive and negative particles. If the charge on each particle is a fixed property of that type of particle, and if the particles themselves can be neither created nor destroyed, then conservation of charge is inevitable.

**Electrical forces involving neutral objects**

As shown in figure 5.2.3, an electrically charged object can attract objects that are uncharged. How is this possible? The key is that even though each piece of paper has a total charge of zero, it has at least some charged particles in it that have some freedom to move. Suppose that the tape is positively charged, 5.2.3. Mobile particles in the paper will respond to the tape's forces, causing one end of the paper to become negatively charged and the other to become positive. The attraction is between the paper and the tape is now stronger than the repulsion, because the negatively charged end is closer to the tape.

*Figure b*: A charged piece of tape attracts uncharged pieces of paper from a distance, and they leap up to it.

What would have happened if the tape was negatively charged?

**The atom, and subatomic particles**

I once had a student whose father had been an electrician. He told me that his father had never really believed that an electrical current in a wire could be carried by moving electrons, because the wire was solid, and it seemed to him that physical particles moving through it would eventually have drilled so many holes through it that it would have crumbled. It may sound as though I'm trying to make fun of the father, but actually he was behaving very much like the model of the skeptical scientist: he didn't want to make hypotheses that seemed more complicated than would be necessary in order to explain his observations. Physicists before about 1905 were in exactly the same situation. They knew all about electrical circuits, and had even invented radio, but knew absolutely nothing about subatomic particles. In other words, it hardly ever matters that electricity really is made of charged particles, and it hardly ever matters what those particles are. Nevertheless, it may avoid
some confusion to give a brief review of how an atom is put together:

**table**

The symbol $e$ in this table is an abbreviation for $1.60 \times 10^{-19}$ C. The physicist Robert Millikan discovered in 1911 that any material object (he used oil droplets) would have a charge that was a multiple of this number, and today we interpret that as being a consequence of the fact that matter is made of atoms, and atoms are made of particles whose charges are plus and minus this amount.

### Electric current

If the fundamental phenomenon is the motion of charged particles, then how can we define a useful numerical measurement of it? We might describe the flow of a river simply by the velocity of the water, but velocity will not be appropriate for electrical purposes because we need to take into account how much charge the moving particles have, and in any case there are no practical devices sold at Radio Shack that can tell us the velocity of charged particles. Experiments show that the intensity of various electrical effects is related to a different quantity: the number of coulombs of charge that pass by a certain point per second. By analogy with the flow of water, this quantity is called the electric current, $I$. Its units of coulombs/second are more conveniently abbreviated as amperes,

$[3] \quad 1 \text{ A} = 1 \text{ C/s}$. (In informal speech, one usually says “amps.”)

**ampere**

$e$ / André Marie Ampère (1775-1836).

The main subtlety involved in this definition is how to account for the two types of charge. The stream of water coming from a hose is made of atoms containing charged particles, but it produces none of the effects we associate with electric currents. For example, you do not get an electrical shock when you are sprayed by a hose. This type of experiment shows that the effect created by the motion of one type of charged particle can be canceled out by the motion of the opposite type of charge in the same direction. In water, every oxygen atom with a charge of $+8e$ is surrounded by eight electrons with charges of $-e$, and likewise for the hydrogen atoms.

We therefore refine our definition of current as follows:

### definition of electric current

When charged particles are exchanged between regions of space A and B, the electric current flowing from A to B is

$$I = \frac{\text{charge}}{\text{time}} = \frac{\text{coulombs}}{\text{second}}$$

where the transfer occurs over a period of time $t$.

In the garden hose example, your body picks up equal amounts of positive and negative charge, resulting in no change in your total charge, so the electrical current flowing into you is zero.
Example 1: Ions moving across a cell membrane

The figure below shows ions, labeled with their charges, moving in or out through the membranes of four cells. If the ions all cross the membranes during the same interval of time, how would the currents into the cells compare with each other?

- Cell A has positive current going into it because its charge is increased, i.e., has a positive change in its charge.
- Cell B has the same current as cell A, because by losing one unit of negative charge it also ends up increasing its own total charge by one unit.
- Cell C's total charge is reduced by three units, so it has a large negative current going into it.
- Cell D loses one unit of charge, so it has a small negative current into it.

It may seem strange to say that a negatively charged particle going one way creates a current going the other way, but this is quite ordinary. As we will see, currents flow through metal wires via the motion of electrons, which are negatively charged, so the direction of motion of the electrons in a circuit is always opposite to the direction of the current. Of course it would have been convenient of Benjamin Franklin had defined the positive and negative signs of charge the opposite way, since so many electrical devices are based on metal wires.

If a lightbulb has 1.0 A flowing through it, how many electrons will pass through the filament in 1.0 s?

- We are only calculating the number of electrons that flow, so we can ignore the positive and negative signs. Solving for (charge) = \( I t \) gives a charge of 1.0 C flowing in this time interval. The number of electrons is

That's a lot of electrons!

Contributors and Attributions

- Benjamin Crowell, Conceptual Physics