PHY1025 Notes
Charge, Current, Resistance, Voltage and Ohm's Law

Electric Charge (Q)

As we discussed in class, electric charge is a property of matter. While many sub-atomic particles carry charge, for the purposes of this class, the important charged particles are protons and electrons. There are two kinds of charge, which we call positive and negative charge. These names are historical, and we could just as well call them black and white charge, or male and female charge. The point is that there are two kinds of charge. Charges that are of the same type (negative and negative or positive and positive) repel each other. Charges that are different (negative and positive) attract each other. The S.I. unit for charge is the Coulomb, where 1 Coulomb is the charge on 6.25×10^{18} electrons or protons. This means that the charge on 1 electron or 1 proton is 1.6×10^{-19} Coulombs (where the protons have positive charge and the electrons have negative charge). Coulomb's Law tells us how strong the attractive or repulsive force is.

$$F_C = k\, Q_1\, Q_2 / r^2$$

where Q_1 and Q_2 are the charges in Coulombs, r is the distance between the charges (in meters), and k is the Coulomb constant, which is approximately 9×10^9 N m^2 / C^2. Since there is an r^2 in the denominator of this force equation, this is an inverse square law force, similar to the gravity force. Unlike the gravity force, the electric force is extremely strong, as shown by the size of the Coulomb constant compared to the Universal Gravitational constant (6.67×10^{-11} Nm^2 / kg^2).

Electric Current (I)

Most of the interesting and useful applications of electricity are due to the movement or flow of charge. The <u>flow</u> of electric charge is called <u>electric current</u>, and electric current is measured by the <u>rate of flow</u> of charge. So we have

$$I = \Delta Q / \Delta t$$

where the letter I represent the current. Because the rate of flow often fluctuates very rapidly, we sometimes distinguish between <u>average</u> and <u>instantaneous</u> current. The S.I. unit for current is the Ampere (Amp), where 1 Ampere = 1 Coulomb per second (1A = 1C/s). Electric current can refer to positive or negative charges flowing but, in most cases, we are talking about electrons moving in a conductor.

Current and Drift Speed

Bottom line here – Electrons don't go flowing unobstructed through a wire like water in a stream. They bounce off of atoms in the conductor constantly, and so the actual average speed of an electron in a wire (called the "drift speed") is actually very tiny (a fraction of a millimeter per second). So then, why does a light turn on immediately when you flick the switch, even though there may be many feet of wire between the switch and the light? Because the <u>electric field</u> travels at nearly the speed of light in a wire, so the electrons <u>already in the wire and the light bulb</u> start to move instantly. In class, we will use the analogy of water flow in a new hose vs. water flow in a hose that has already been used.

Resistance, Resistivity and Ohm's Law

Different materials present varying opposition to the flow of current. Some materials, called conductors (copper, silver) conduct electricity easier while some materials, called insulators (plastic, rubber), present much more opposition to the flow of current. A property of the material, called the resistivity (ρ), is a measure of how poor of a conductor it is, so a high resistivity material will allow less current to flow than a low resistivity material of the same size and shape. The resistivity of <u>most</u> materials increases with temperature so, as wires get hotter, they allow less electricity to flow. This makes sense when we remember that the temperature of a solid is a measure of the microscopic thermal kinetic energies of the molecules in the solid.

In addition to the resistivity of the material, the length (L) and thickness (cross-sectional area – A)) of a particular sample (like a certain piece of wire) also affect how much it opposes the flow of current. The combined effect of these three factors is called the <u>resistance</u> (R) of the particular sample and is measured in Ohms (Ω).

Mathematically, we have

$$R = \rho L / A$$

where ρ is is the resistivity of the material (measured in Ωm), L is the length (in meters), and A is the cross-sectional area measured in m^2.

So let's try a problem. What is the resistance (in Ω) of a copper electrical extension cord that is 30.5 m long, has a cross sectional area of $1.31 \times 10^{-6}\ m^2$, and is made of copper, which has a resistivity of $1.7 \times 10^{-8}\ \Omega m$? We simply plug the numbers into our formula to get:

$$R = (1.7 \times 10^{-8}\ \Omega m) \times (30.5\ m)/ (1.31 \times 10^{-6}\ m^2)$$
$$= 0.419\ \Omega$$
(about half an ohm).

Ohm's Law

This is almost like Newton's Second Law for electrical circuits. It's that important. Ohm's Law says that the current in a circuit depends on the voltage and the resistance of the circuit elements in a very simple way:

$$I = V / R$$

Yes, it's that simple. The current is directly proportional to the voltage and inversely proportional to the resistance. So if you connect that 0.419 Ω wire across the terminals of your 12 volt car battery, you will have a current in the wire of I = 12/0.419 = 28.6 Amps. As the wire warms up (wires warm up when current flows through them), the resistance will increase and the current will decrease if the voltage (potential difference) across the wire stays the same.

The filament of a 100 W light bulb has a resistance of about 144 Ω once it heats up (almost instantly). In the US, our standard voltage for mass power distribution is 120 volts. So the current in a 100W bulb is

$$I = V/R = 120V/144\ \Omega = 0.83 \text{ Amps}$$

While you are starting your car, the starter motor is connected to the 12 volt battery and draws somewhere around 500 amps of current (that's why the battery cables are so thick – they need to safely carry a large current). So the approximate resistance of your starter motor is

$$R = V/I = 12V / 500A = 0.024\ \Omega = 24m\ \Omega$$

That seems like a pretty small resistance until you see (as we will later) that electric motors basically consist of lots of coils of wires (along with some magnets – more on that later).

17.6 Electrical Energy and Power

In an electric circuit, the power delivered by the voltage source (the battery or wall outlet) is simple to calculate.

$$P = IV = V^2/R = I^2R$$

From this we can see that P,I,V and R are all interdependent so, if you know any two of those variables, you can figure out the other two using Ohm's Law and the Power equation.

Lets use this power equation to find the power of our starter motor and 100W bulb:

For the 100 W light bulb with R = 144 Ω, V = 120V, I = 0.83 Ω, we can do this:

$$P = I^2R = (0.83A)^2\ 144\ \Omega = 100W$$

or

$$P = V^2/R = (120V)^2/144\ \Omega = 100W$$

For the starter motor, we have V = 12V, R = 24m Ω and I = 500 A. So the power of the motor is

$$P = I^2R = (500A)^2\ (24m\ \Omega) = 6000W$$

or

$$P = V^2/R = (12V)^2\ /24m\ \Omega = 6000W$$

Remembering that 1 HP = 746 W, we can calculate the power of the starter motor to be about 8 HP.