PHYS:1200 LECTURE 25 — ELECTRICITY AND MAGNETISM (3)

This lecture is devoted entirely to the very practical topic of electric circuits. This discussion will include concepts that everyone should be aware of, and will hopefully remove some of the mystery and fear of surrounding electricity. The basic concept that will be presented is the relationship between three important circuit parameters: voltage, current, and resistance, or **Ohm's Law**. We will also discuss the fact that the flow of current in wires always involves the generation of heat – wires carrying current get hot, which can be a dangerous situation leading to fires, as shown in the photo on the right. The more devices that are plugged into a circuit, the more current that is drawn. The heat produced by currents is proportional to the square of the current. Appliances like hair dryers and curling/straightening irons draw a substantial current and should be used on separate circuits.

25-1. Current, Voltage and Resistance.—Electric current is the flow of electric charge. If an amount of charge q passes a given point in a wire in time t, the current is

Electric current	$I = \dfrac{q}{t},$	[1]

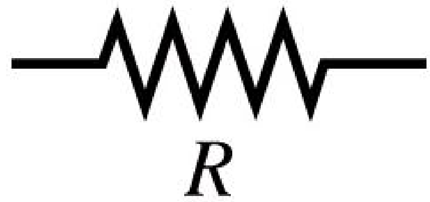
measured in C/s. **One C/s is defined as 1 ampere or amp (A)**.

Example 25-1: A total charge of 25 C passes through a wire every 5 seconds. What is the current in this wire?

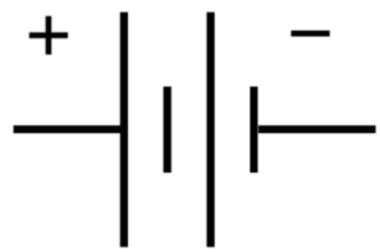
Solution- $I = \dfrac{q}{t} = \dfrac{25\ C}{5\ s} = 5\ C/s = 5\ A.$

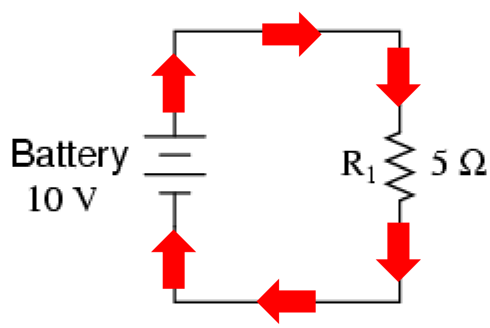
Example 25-2: A conductor carries a current of 10 A. How much charge passes through this conductor in one minute?

Solution- Solve equation [1] for $q \to q = It = 10\,C/s \times 60\ s = 600\ C.$



The electric current in a wire (conductor) is due to the **directed motion** of the free electrons in a particular direction. As the electrons move, they make frequent collisions with the ions, so their path is not straight but a zig-zag like motion as shown in **slide 19**. The degree to which the electron's motion is impeded by collisions is characterized by a parameter called **electrical resistance**, denoted by R, and measured in the unit Ohms (Ω). The resistance of the wires and other devices that may be part of an electric circuit is represented by the symbol shown on the right. To maintain a directed motion of the electrons, a **source of electric potential or voltage** must be applied across the ends of the wire. This potential difference or voltage is provided by a **battery**. A battery is represented in a circuit by the symbol shown below on the right.





A simple circuit containing a battery and resistor is shown above on the right side. The direction of the current is indicated by the arrows. The direction of electric current is defined as the direction away from the positive terminal of the battery, **which is the direction that positive charges would move**. Remember that it is only the electrons which move in a wire and they move in the opposite direction. This may be confusing, but just remember that current is always taken to flow from the positive to the negative of the battery. (This confusion is due to the fact that Benjamin Franklin arbitrarily defined the electron charge to be the negative charge.) The resistor in the circuit may represent any device such as a light bulb or a door bell. All the elements in a circuit that carry the same current (in the same path) are lumped together in one resistor for convenience.

25-2. Ohm's Law.—The current (I), voltage (V) and resistance (R) are related by a simple formula known as **Ohm's Law:**

OHM'S LAW $$I = \frac{V}{R},$$ [2]

where, V is the potential difference or voltage, R is the resistance, and I is the current. In formula [2], V is in volts, R in Ohms (Ω), and I is in amps (A).

Example 25-3: What current flows in the circuit shown at the top of this page?

Solution: $I = \frac{V}{R} = \frac{10\ V}{5\ \Omega} = 2\ A.$

Ohm's law is a relationship among three parameters. If two are known, the other one can be computed. If I and R are known, then $V = IR.$ If I and V are known, then $R = \frac{V}{I}.$ Thus the three forms of Ohm's law are:

FORMS OF OHM'S LAW $$V = IR, \quad I = \frac{V}{R}, \quad R = \frac{V}{I}.$$ [3]

25-3. Electric Power.—Electrical work must be done to push current through a circuit. This results in the conversion of electrical energy into other forms of energy- heat in a toaster, light in a light bulb, and mechanical energy in turning a motor. The amount of work done per unit time is called **power** (P):

POWER $$P = \frac{W}{t}.$$ [4]

Power is measured in Joules (J) per second, and 1 J/s = 1 Watt (W). **The Watt is the basic unit of power**. You will recognize this unit from everyday usage. Light bulbs and hair dryers, for example, are specified in Watts. A 60 W light bulb uses 60 J of electrical energy each second. A hair dryer might be listed as 1200 W, or 2000 W. Electric power is given by the product of current and voltage

ELECTRICAL POWER $$P = IV,$$ [5]

so that the product of 1 A and 1 V = 1 W.

Power dissipated as heat in a resistor.—When we talk about “resistors” we are just referring to any element in an electric circuit. All conductors have a certain amount of resistance depending on their geometry and the material that they are made from. A copper wire has an electrical resistance that depends on its diameter and length. When current flows in a conductor, the electrons make many collisions with the ions. The ions cannot move around in the conductor, but they can vibrate. When an electron hits an ion, it can make the ion vibrate, and the vibrational motion of the ions appears in the conductor as heat energy. This process is used in an electric stove. Current passing through the heating element produces heat – the element gets red hot, and the heat is used to cook food. Electric clothes dryers use this heat to dry clothing. Energy must be continuously supplied to a circuit to maintain the current, since the current produces heat which dissipates the energy. **The amount of electrical energy converted into heat per second in a resistor is called the power loss in the resistor,** and is given by the product of current and voltage according to equation [5]. We can combine equation [5] with Ohm’s law to get other useful forms of the power loss in a resistor:

$$V = IR\ (Ohm) \rightarrow P = IV = I\left(IR\right) = I^2R,$$

$$\text{or using } I = \frac{V}{R}\ (Ohm) \rightarrow P = IV = \left(\frac{V}{R}\right)V = \frac{V^2}{R},$$ so that:

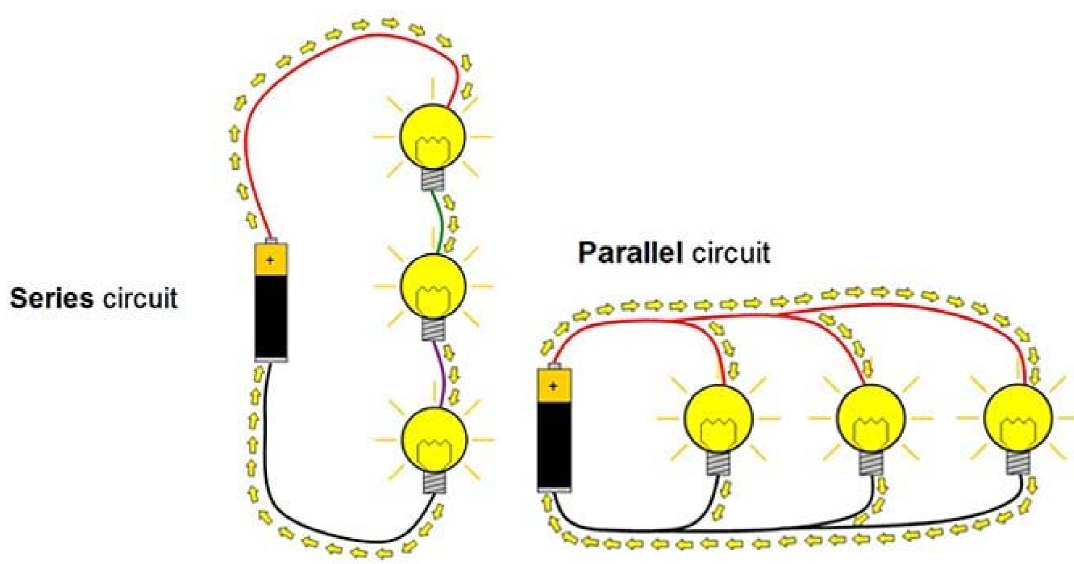
RATE OF HEAT PRODUCTION IN A RESISTOR: $P = IV = I^2R = \dfrac{V^2}{R}.$ [6]

Example 25-4: A 50 W appliance operates on a 100 V power source. (a) How much current will it draw? (b) What is the resistance of this appliance?

Solution- (a) $P = IV \rightarrow I = \dfrac{P}{V} = \dfrac{50\ W}{100\ V} = 0.5\,A.$ (b) $R = \dfrac{V}{I} = \dfrac{100\ V}{0.5\ A} = 200\ \Omega.$

Because of the heat loss associated with electric currents, caution must be exercised when using extension cords and power strips. The amount of resistance that a wire has depends on its length – longer wires have higher resistance. If a very long extension cord is used to power a device that draws a large current, the extension cord can get very hot. One needs to be careful also with power strips since each element that is plugged into it adds to the total current that must be drawn from the outlet. The wire used in a power cord must be of larger diameter than any of the individual elements that are being powered. The resistance of a wire is inversely proportional to the cross sectional area of the wire which is proportional to the square of the wire diameter. In high current applications, wires of large diameter should be used to make the resistance as small as possible, to minimize the amount of heat produced.

25-4. Series and Parallel Circuits.—Suppose we have three identical light bulbs and a battery. Two ways in which the light bulbs can be connected to the battery are shown below.



The circuit on the left is called a **series circuit**, and the circuit on the right is called a **parallel circuit**. The arrows show the current flow.

- A series circuit has only one path for the current; a parallel circuit has multiple paths.
- In a series circuit, the same current passes through each element; i.e., every electron that passes through one bulb also passes through the other bulbs. In a parallel circuit, different currents (electrons) pass through each element (if the resistances of the lights are the same, the amount of current is the same).

- In the parallel circuit, each element has a voltage across it equal to the voltage of the battery. In the series circuit, the battery voltage is divided between the individual elements. If the battery is 1.5 V and the bulbs are identical, each bulb in the series circuit has 0.5 V across it.
- In the series circuit, if one bulb is removed, there is no current through any of the other bulbs. Removing a bulb removes the current path for the entire circuit and they all go out. In the parallel circuit, if a bulb is removed, the other bulbs remain lighted because there is a current path. [If a string of lights on a Christmas tree are connected in series, if one goes out, they all go out.]
- If the bulbs are identical (have the same resistance), the bulbs in the series circuit will have a smaller current through them compared to the bulbs in the parallel circuit. → the bulbs in the parallel circuit will be brighter. In the series circuit, the total resistance is 3R, where R is the resistance of one bulb. In the parallel circuit, the total resistance is R/3. The current through each bulb in the parallel circuit is 3 times the current through each bulb in the series circuit.
- The battery in the parallel circuit will be drained more quickly than the battery in the series circuit because the current is larger in the parallel circuit. The lights will be on for a longer period of time in the series circuit, but of course they will not be as bright as those in the parallel circuit while the batteries are at their maximum voltage.

Batteries can also be connected in series or in parallel as shown in the diagram below. The top diagram is the parallel configuration and the bottom diagram is the series configuration. Each individual battery is 1.5 V. In the series configuration, the connections are

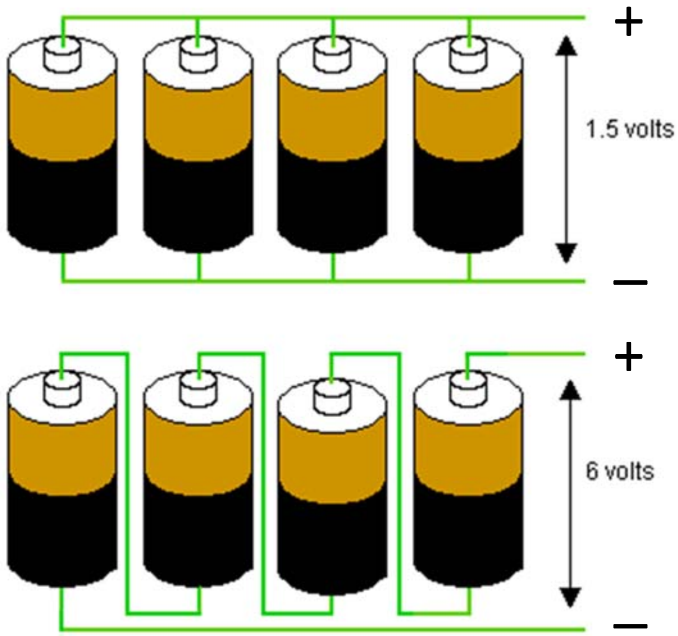
$$+ \rightarrow - + \rightarrow - + \rightarrow - + \rightarrow -.$$

The load is then connected to the negative of the first battery and positive of the last battery. A series connection of batteries is used to produce a larger voltage than that of one battery alone.

In this case, he total voltage is 4 x 1.5 V = 6 V. Most flashlights have 2, 1.5 V connected in series

Batteries in parallel

Batteries in series



to provide a voltage source of 3.0 V to the bulb. In the parallel configuration all the positive terminals of the batteries are connected together and all the negative terminals are connected together. The load is then connected across the positive to negative sides and sees only 1.5 V. The purpose of the parallel configuration is not to produce more voltage, but to increase the capacity to provide either more current to a load, or for a longer duration. Putting batteries in parallel is the same as using a larger battery (not in voltage but in capacity). For example, a 9 V battery is just a package of 6, 1.5 V batteries.