Essentials of Electricity 2:
Circuits

A **circuit** is a path through which electrical energy flows. Electrons are attracted down a wire towards a source of positive charge. In order for a circuit to work, the path must form an uninterrupted loop, i.e., the circuit must be **closed**. If there is a gap in the circuit, the circuit is **open** and no electricity will flow. We can measure how much energy flows through a circuit in terms of the amount of charge (**q**) that flows past a point in a fixed amount of time (t). This is the **current (I)**, and it is measured in **amperes (A)** or **amps**. The equation for current is shown below:

$$I = q/t$$

The direction in which current flows is defined as the direction in which a *positive* charge would move through the circuit.

COMPONENTS OF AN ELECTRICAL CIRCUIT

A **battery** is a source of electrical energy. It has two **terminals**, which are places to connect to the battery. Current flows from the positive terminal through the circuit to the negative terminal.

A **resistor** or **load** on a circuit is anything that draws out some of the energy in the circuit because the current has a harder time flowing through it. Appliances are resistors (they use the energy to do things) but the wire itself is also a resistor, since it turns some of the energy into heat. **Resistance (R)** is a measure of how easily current flows through something. Resistance can be calculated in terms of voltage and current using **Ohm's Law**:

$$R = \frac{V}{I}$$

The units of resistance are **ohms (Ω)**. Note that current is not a constant; it changes with the arrangement of wires and loads in a circuit. A battery will always have a consistent voltage, and a load will have a consistent resistance. These two things will determine the amount of current in any part of a circuit.

Each battery and each resistor in a circuit has a potential difference across it. A resistor in a circuit is a **potential drop**, meaning the potential difference across the resistor is a negative number. A battery that is powering a circuit is a **potential rise**, meaning the potential difference across the battery is a positive number. If there's only one battery, it must be the power source, so it must be a potential rise. But be careful! It is important to pay attention to the direction of battery symbols in circuit diagram if there's more than one battery. If a battery is installed backwards in a circuit, it serves as a resistor and becomes a potential drop!

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If two resistors are wired so that you can follow the wiring directly through them, then they are said to be **in series** with each other. When a section of a circuit is wired in series, the current throughout the section is constant. The energy has to follow the wire path, and since there are no branches, all the energy passes through each resistor in the section. Since each resistor is a potential drop, the voltage and resistance in a series subcircuit are both cumulative.

If the wiring splits (at a point called a **junction**) and each branch of the circuit goes through a different resistor, then those resistors are said to be in **parallel**. In a section of a circuit that is wired in parallel, the current can take different routes. **The total amount of current going into a junction must equal the total amount of current coming out of the junction.** The voltage along each branch of wire in a parallel circuit is the same. (This will be explained later in this handout.) The overall resistance, or **equivalent resistance (R_{eq})**, of a parallel subcircuit is harder to calculate. The formulas for current, voltage, and resistance for parallel and series circuits are shown in the table below:

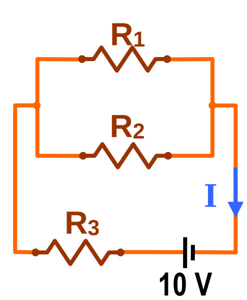
	current	voltage	resistance
In series:	all equal	$V = V_1 + V_2 + V_3 + \ldots$	$R_{eq} = R_1 + R_2 + R_3 + \ldots$
In parallel:	$I = I_1 + I_2 + \ldots$	all equal	$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$

Many circuits have parts that are in series and parts that are in parallel. Such a circuit is called a **compound circuit**. The secret to finding currents, voltages and resistances within a compound circuit is finding the equivalent resistance for each section and “collapsing” the circuit properly. To find the equivalent resistance for a compound circuit:

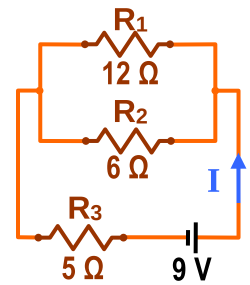
1) If there are any subcircuits in series, add the resistances together to get one equivalent resistance.
2) For a parallel subcircuit (which should have only one resistor per branch after step #1), combine the resistances together as per the equation above.
3) Alternate between steps #1 and #2 until you’ve covered the whole circuit.

Kirchhoff’s Laws are then used to “solve” a circuit. One law has already been mentioned before: current in must equal current out at any junction. The other law says that **for any loop the current takes through the circuit, the total of all potential rises and drops is zero.** This explains why we know that different branches in a parallel subcircuit have the same voltage.

Consider this small circuit. If we start from any point on the circuit, such as the battery, and trace any loop through the circuit back to the battery, the overall potential difference must be zero. The 10-volt battery is the only potential rise. That means all the potential drops in any loop around the circuit must total −10 V. The possible loops include either R_1 and R_3, or R_2 and R_3. The potential drop across R_1 would have to be 10 minus the potential drop across R_3, and the same can be said for R_2. This means the potential drop for either branch has to be the same.



Here is a simple example of a circuit problem. Using the diagram to the right, we are asked to find the voltage across each resistor and the current in each wire.



There is a parallel subcircuit at the top of the diagram. The equivalent resistance for the subcircuit is $\frac{1}{R_{eq}} = \frac{1}{12} + \frac{1}{6} = \frac{3}{12} = \frac{1}{4}$. $\therefore$ $R_{eq} = 4\ \Omega$.

The entire subcircuit behaves like a single 4-ohm resistor. That resistor would be in series with the 5-ohm resistor. The total equivalent resistance of the circuit is 4 Ω + 5 Ω = 9 Ω.

According to Ohm's Law, the total current for the circuit is 9 V ÷ 9 Ω = 1 A. This will be true everywhere on the wire that contains the battery. This means that the voltage across R_3 is 5 Ω × 1 A = 5 V.

As we go around the circuit starting at the battery, we have a potential rise of +9 V (the battery itself), some unknown potential drop in the parallel subcircuit and lastly a potential drop of −5 V at R_3. That means that both branches of the parallel subcircuit must be a potential drop of −4 V (so that the total of all potential rises and drops is zero). It's the only way Kirchhoff's Law of loops can be followed. R_1 then has a current of 4 V ÷ 12 Ω = 0.33 A and R_2 has a current of 4 V ÷ 6 Ω = 0.67 A. Notice that the load with less resistance has the higher current running through it. The electrical energy literally takes the path of least resistance.

POWER

When we use electrical energy, we are usually converting it into some other form: kinetic energy, sound, heat, etc. The rate at which the energy conversion takes place is called **power (P)**. Power is measured in **watts (W)**. Some electrical devices, like light bulbs, have a power rating, but the rating only applies when the device is connected to a given voltage and not in series with other resistors. Under other conditions the power of a device must be recalculated. The formula for power is:

$$P = VI$$

You can use Ohm's Law to express power in terms of either voltage or current and resistance.

CAPACITORS

Electrical energy can be stored up in a device called a **capacitor**. An example of a capacitor is a camera flash bulb: it stores up energy to release in one burst, and it recharges again afterwards. A capacitor usually consists of two separated plates of opposite charges. The charge differential between the plates creates potential difference as charge accumulates on the plates. **Capacitance (C)** is the ratio of charge to voltage across the plates, and it's measured in **farads (F)**:

$$C = \frac{q}{V}$$