

Unit 7 Parent Guide: Electricity & Magnetism

Part I: Electrostatics

Coulomb's Law: All matter is made of atoms that contain charged particles (protons & electrons). Some of the electrons in atoms are not fixed on the atom but can be pulled away, creating an imbalance in the overall charge. Charged particles exert force on one another. The force is given by the following equation, known as Coulomb's Law or simply electric force equation:

$$F_e = \frac{kq_1q_2}{r^2}$$

where F_e is the electrostatic force, k is the Coulomb's constant, q_1 and q_2 are the charges of the two particles, and r is the separation distance between the particles. The value of the Coulomb's constant is $9.0 \times 10^9 \text{ N m}^2/\text{C}^2$. The electric force equation has the same form as the equation for the gravitational force, described in Unit 2:

$$F_g = \frac{Gm_1m_2}{r^2}$$

These two equations have similar structure and dependencies, but are significant on much different scales. For example, a proton and electron in a hydrogen atom are attracted by a gravitational force due to their masses, and an electric force due to their charges. The gravitational force between the proton and electron can be calculated from known quantities. It turns out that the electric force is greater than the gravitational force by a factor of over 10^{39} . That's over 1,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000 times greater. While both forces depend on the inverse square of separation distance, clearly the electric force dominates in the size range of atoms. Atoms are not held together by gravity.

Charge Transfer: Electrically neutral atoms can gain or lose electrons to become charged. When one charged object transfers some of its charge to another object, we call this charge transfer.

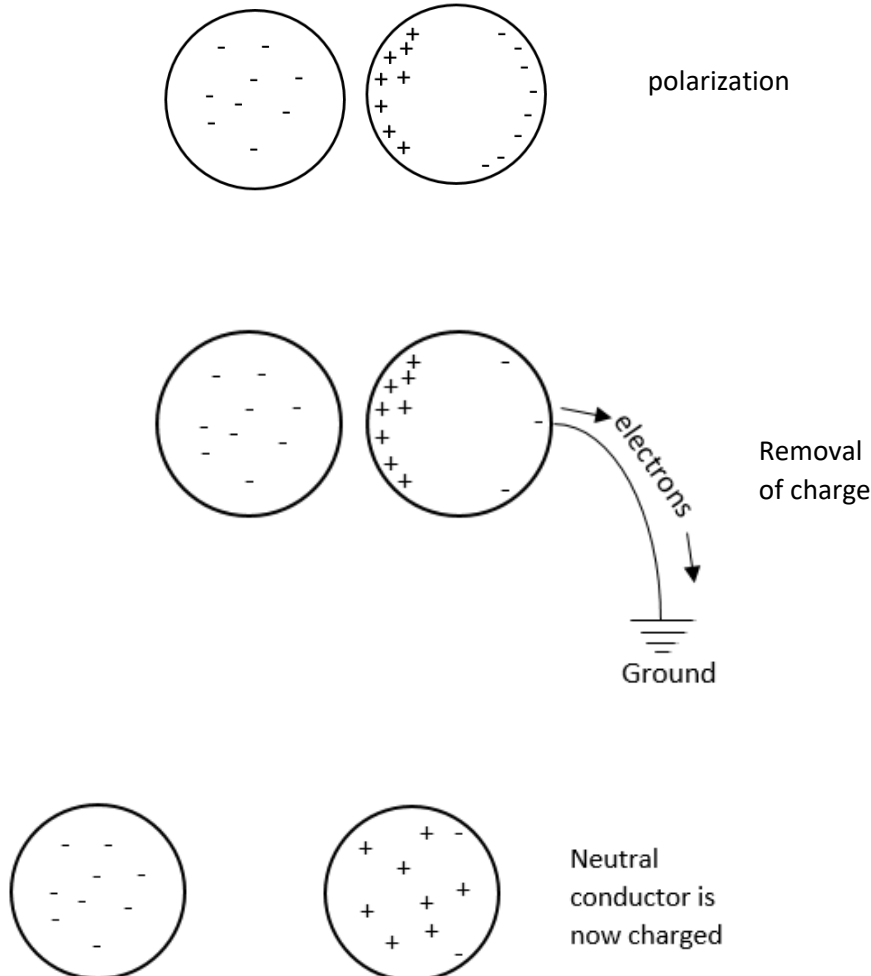
Conduction: When a charged object comes in contact with a neutral object and transfers some of its charge, this is called conduction. If a negatively charged sphere touches a neutral sphere, electrons from the charged sphere will move toward the neutral sphere, giving it a negative charge. A positively charged sphere will pull electrons from a neutral sphere so the neutral sphere becomes positively charged. Charges will transfer until there is no longer a potential difference between the spheres.

Charging by Friction: Electrons in insulators are tightly held by the atoms. However, different types of materials hold to electrons with varying degrees of attraction. A highly insulating material like rubber holds tighter to electrons than rabbit fur. If a rubber balloon is rubbed with rabbit fur, the rubber will pull electrons away from the fur, because the rubber has a greater attraction for the electrons. This process is called charging by friction. The fur will become positively charged because it has lost electrons, and the balloon will become negatively charged because it has gained electrons.

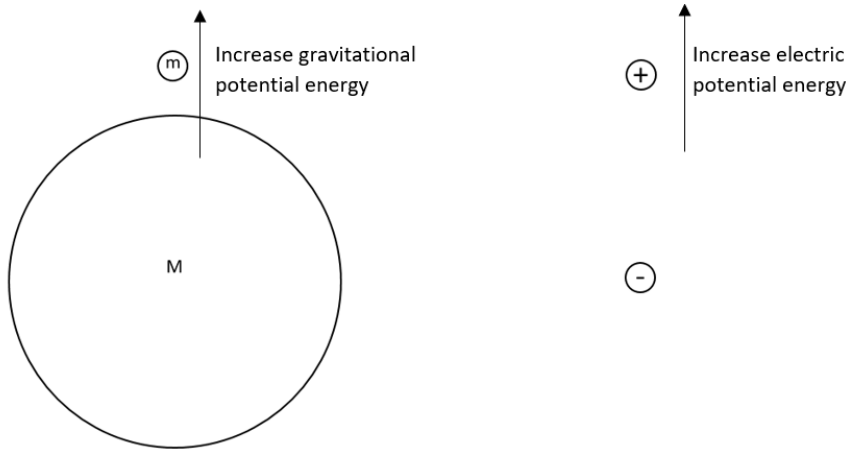
Charging by Induction: When a charged object is brought near, but not in contact with a neutral conductor, electrons in the neutral conductor will migrate to one side. This process is said to be

polarized because the charges have separated to opposite sides. This polarization is temporary but the charge can be made permanent by removing electrons from the opposite side of the neutral conductor.

This process is shown below for a negatively charged object transferring charge by induction to a neutral conductor without the two being in contact.

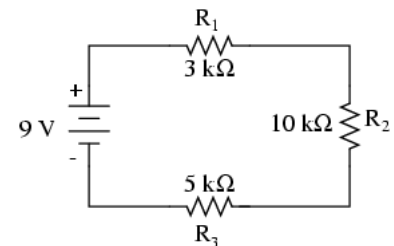


Electric Potential Energy: If multiple charged particles exert force on one another, then they represent a system whose energy depends on the position of the objects (see Unit 3, Potential Energy). When a positive and negative charge are near one another, they attract each other in a manner analogous to a massive object in a gravitational field. As the small mass m is separated from the large mass, the potential energy of the system increases. Similarly, if the positive charge is separated from the negative charge, the electric potential energy of the system increases. When you push the positive charge upward, you work against the force of attraction between the charges, doing work on the system and thus increasing the electric potential energy. If you were to move the positive charge closer to the negative charge, you would be pushing in the same direction as the electric force of attraction, so the electric potential energy would decrease. If the electric force were repulsive, the electric potential energy would increase if you pushed the charges closer together.



Part II: Electric Circuits

Circuit Diagrams: In a simple circuit such as a flashlight, a battery, wire, switch and bulb are connected together. The battery provides electric potential energy for the circuit and the bulb transforms that potential energy into light. A circuit is a path for electric current to flow through. Electric current is the rate of flow of electric charge. Although for most circuits, the current carrying particles are electrons, we designate the direction of electric current to be from positive to negative. In the circuit below are 2 batteries totaling 9V. The symbol for a battery is a long line for the positive terminal, and a short line for the negative terminal. The current in this circuit will move clockwise around the circuit. There is a complete path from positive to negative, so we say that the circuit is closed. The zig-zag symbols are resistors. A resistor is a circuit element that reduces the current and electric potential energy. This arrangement of resistors is called series, because the three resistors lie along the same path. Incandescent light bulbs are fundamentally a kind of resistor.



Voltage: Voltage is defined as electric potential energy per unit charge. The batteries in this circuit raise the electric potential by 9 volts. The resistors in total reduce the voltage of the circuit by 9 volts. Along any loop traced from + to – of the battery, the potential difference must be zero. This is a consequence of the conservation of energy. A voltmeter is a device that measures the potential difference of a circuit element such as a battery, bulb, or resistor. Voltmeters must be attached across the circuit element in parallel.

Ohm's Law: Voltage, current and resistance are related by Ohm's Law:

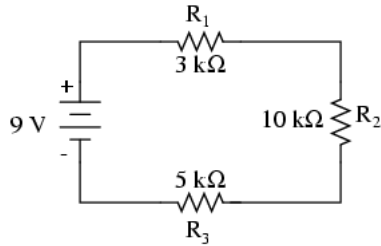
$$I = \frac{V}{R}$$

where I is current in Amperes, V is voltage (or potential difference) in Volts, and R is resistance in ohms. The current is inversely related to resistance. Even very high resistance allows some small amount of current to flow. Ohm's law is useful in analyzing a single part of a circuit, a branch or pathway containing multiple circuit elements, or even the entire circuit.

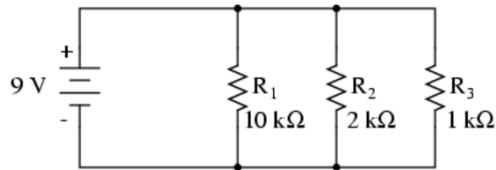
Direct & Alternating Current: A circuit containing a battery has current that only flows from + to – , which is called direct current. When a circuit contains a voltage source such as a common outlet, the

current in the circuit alternates in direction. The voltage source produced by the electrical power generation industry in the U.S. is commonly 110-1120 V of alternating current with a frequency of 60 Hz.

Series Circuits: When multiple circuit elements are connected so that there is only a single path for the current to flow, it is series circuit. Because there is only one path, the current is the same along each part of the path. One behavior of a series circuit is that if there is a break in one part of the path, the current along every other part of the path will stop.



Series Circuit



Parallel Circuit

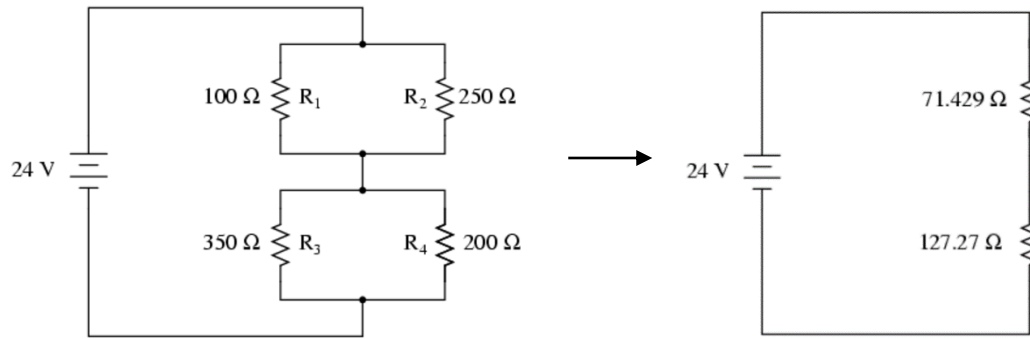
Parallel Circuits: In a parallel circuit, current flows along multiple paths. When there is a branch point, the current divides so that the current through each path adds up to the amount of current before the branch. If there is a break in the circuit along the path containing R₁, the other paths are unaffected.

Equivalent Resistance: In the series circuit, the three resistors each have an amount of resistance, but we can combine them together to get the *equivalent resistance*, R_{eq} . For a series path, R_{eq} is the sum of the resistors along the path. For the parallel circuit, we find the R_{eq} a different way, using the following formula:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

The current would be found by using Ohm's Law. It is worth noting that in a parallel circuit, the total amount of resistance is actually less than that of any of the individual resistors. Increasing the number of paths actually increases the amount of current. So a battery used in a parallel circuit with several bulbs will "die" faster than the same bulbs arranged in series. Note: Batteries don't die. They also do not "run out of charge". If you measure a "dying" battery, you will notice that the measured voltage will drop near the end of its useable life. Batteries do not contain charge. They store potential energy that is converted to other forms of energy such as light, heat, or mechanical energy. The charged particles are present in a circuit even when there is no battery. The battery provides the energy to "push" the charges around the circuit. Instead of measuring the amount of energy the batteries contain, we use the potential, which is the energy per unit charge.

Combination Circuits: Some circuits like the one shown below, are a mixture of series and parallel. In this circuit, R₁ and R₂ are arranged parallel, and so are R₃ and R₄. But instead of 4 parallel resistors, we have two sets of parallel resistors and those sets are arranged in series. First we combine each set of parallel resistors, then we will have an equivalent circuit, like the one drawn on the right.

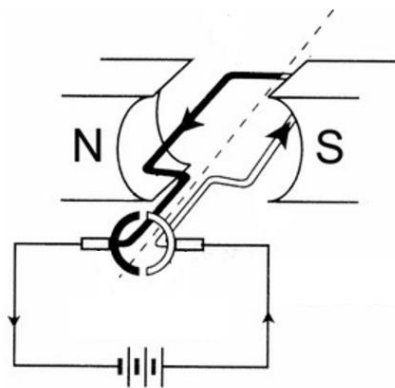


By inspecting the arrangement of these 4 resistors, we can simplify them to an equivalent circuit that is easier to analyze. The circuit on the right has two resistors in series whose values can be added together to get a total of 198.7 Ω .

Part III: Electromagnetism

It has been known since the 1800s that electricity and magnetism are actually distinct manifestations of the same phenomenon, called electromagnetism. Hans Christian Oersted showed that an electric current in a wire creates a magnetic field near the wire. Michael Faraday showed that a changing magnetic field can cause electric current in a coil of wire, a phenomenon known as electromagnetic induction. This phenomenon is the principle behind the operation of motors and generators.

Motors: Electric motors use electromagnetism to convert electrical energy into mechanical energy.



This diagram shows a square loop of wire between the poles of a permanent magnet. The loop is connected to a battery so that current flows through the loop. The loop is attached by a special connector that allows the loop to rotate. The current in the loop induces a magnetic field through the loop. The loop is now a small electromagnet that gets pushed by the permanent magnet and rotates. So the electrical energy has been transformed into the energy of a moving loop of wire. The motor can do useful work such as rotate a fan or a wheel.

Generators: Electric generators use electromagnetism to convert mechanical energy into electrical energy. This diagram shows a very similar setup as the motor, except that instead of a battery there is a light bulb. If the square loop is rotated by an external force, the permanent magnet's field through the loop changes. When the magnetic field through a loop changes, a current is induced in the loop. The

wire loop is connected to a light bulb which lights up because current flows through it. So the movement of the loop creates electric energy.

