ELECTRIC CURRENT

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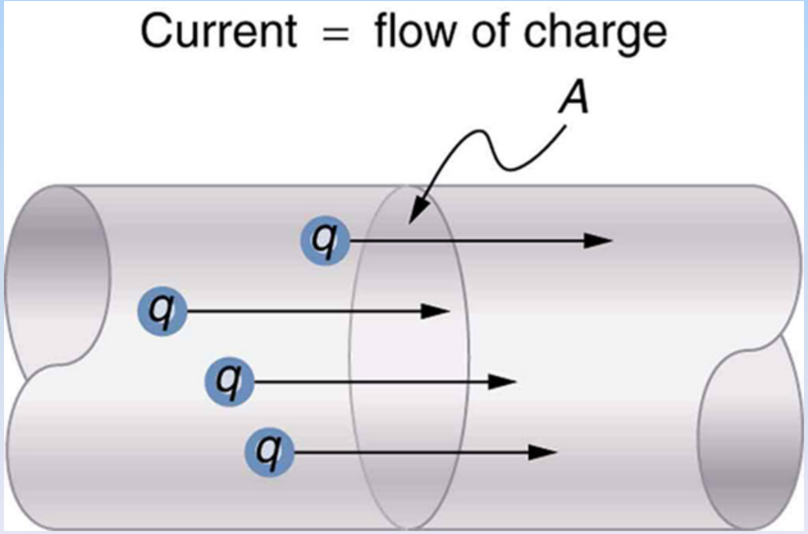
Main topics

- ✓ What is electric current?
- ✓ Ohm's laws
- ✓ Joule effect
- ✓ Electric circuits

Electric current

Electric current is a flow of electric charge through a conductor.



Conductors and insulators

Conductors are materials through which charge can move rather freely, such as metals, the human body, tap water and ionic solutions.

Non-conductors - also called **insulators** - are materials through which charge cannot move freely; examples include rubber, plastic, glass, and chemically pure water.

Charge carriers

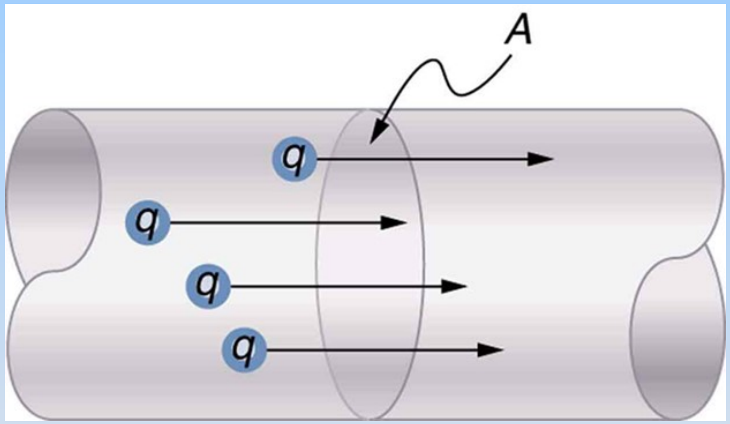
In a **metal conductor**, such as a copper wire, electric current is due to the motion of conduction electrons.

In **ionic solutions**, such as salt water, the current consists of a flow of positive ions in one direction together with a flow of negative ions in the opposite direction.

Moving charges, whether positive or negative, are referred to as **charge carriers**.

Current intensity

Suppose that an amount of charge ΔQ passes through a cross section A of a conductor in a time interval Δt.



Then the **electric current intensity *I*** through that section is equal to the amount of charge divided by the time interval:

$$I = \frac{\Delta Q}{\Delta t} \, .$$

Current intensity is often referred to simply as **current**.

The ampere

The SI unit of current, the **ampere** (**A**), is named after the French physicist André-Marie Ampère (1775–1836) and is defined as 1 coulomb per second:

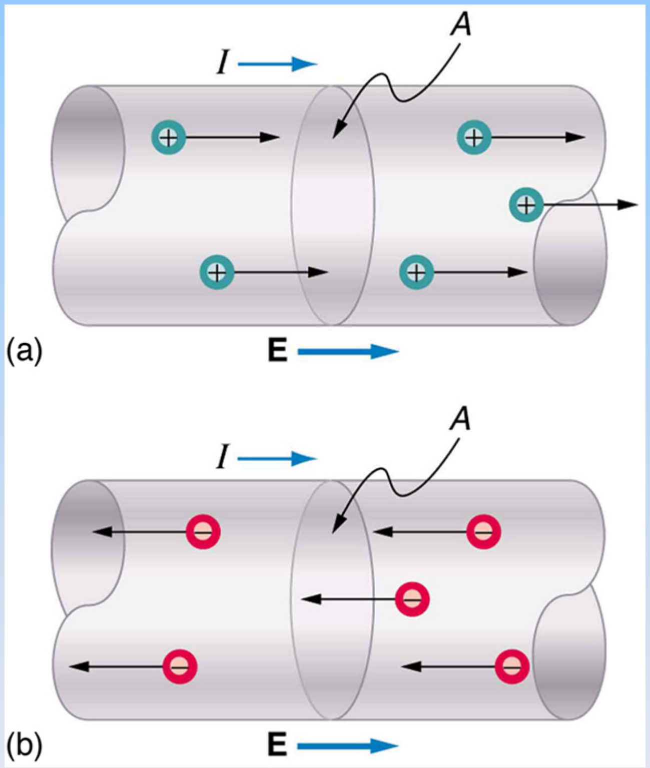
$$1\text{A} = 1\frac{\text{C}}{\text{s}}.$$

One ampere of current is equivalent to one coulomb of charge passing through a cross sectional area of a conductor in a time interval of 1 s.

Current direction

When charge flows through a conductor, the charge carriers can be positive, negative, or both.

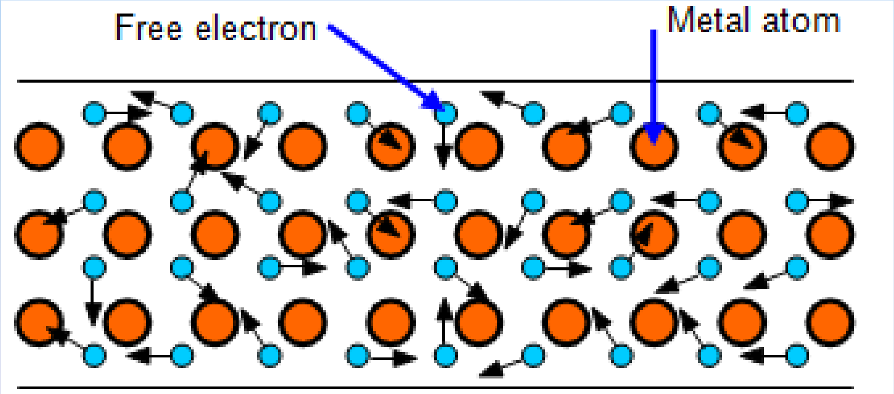
For historical reasons, the **direction** of electric current is by convention the direction in which a **positive** charge would move.



Random motion

Consider a metal conductor, in which the charge carriers are conduction electrons.

If the potential difference ΔV across the conductor is zero, so there is no electric field inside the conductor, the conduction electrons move randomly in all directions like gas molecules, at speeds of the order of 10^6 m/s.

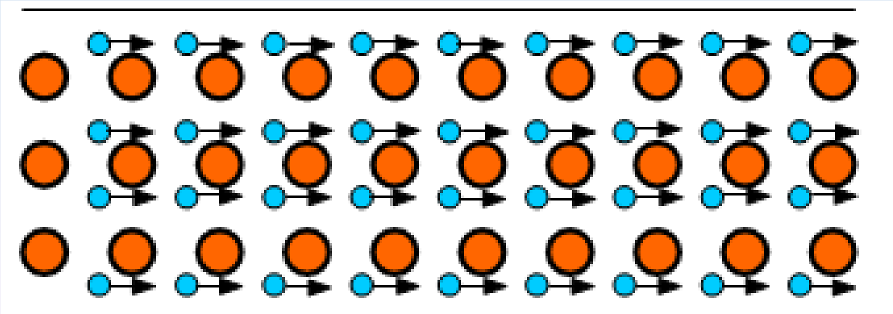


Consequently, there is no net flow of charge in any particular direction, thus no electric current.

Drift velocity

When a potential difference (a **voltage**) is applied between the ends of the conductor (for example, with a battery), an electric field is set up in the conductor, exerting an electric force on the conduction electrons in the direction opposite that of the applied electric field.

As a result, these electrons tend to drift in that direction, thus producing a current.



Drift speed vs random-motion speed

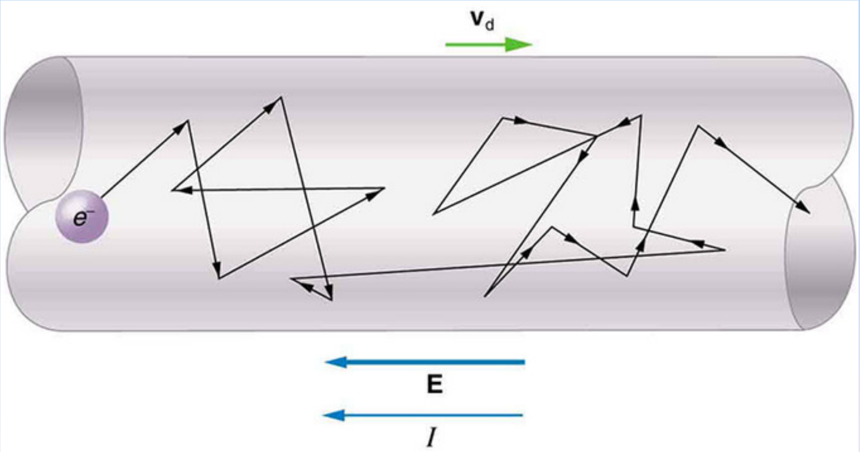
In reality, the electrons don't simply move in straight lines along the conductor.

Instead, they undergo repeated collisions with the ions of the metal, and the result is a complicated zigzag motion with only a small average drift speed along the wire.

The drift speed is tiny compared with the speeds in the random motion:

drift speed ~ 10^{-4} m/s

r-m speeds ~ 10^{6} m/s



Microscopic model of current

If the charge carriers move with a drift speed v_d, the displacement they experience in a time interval Δt is

$$\Delta x = v_d \Delta t.$$

So the charge carriers passing through the section A in Δt are all those contained in the cylinder shown in the figure, let's say N, and the amount of charge passing is

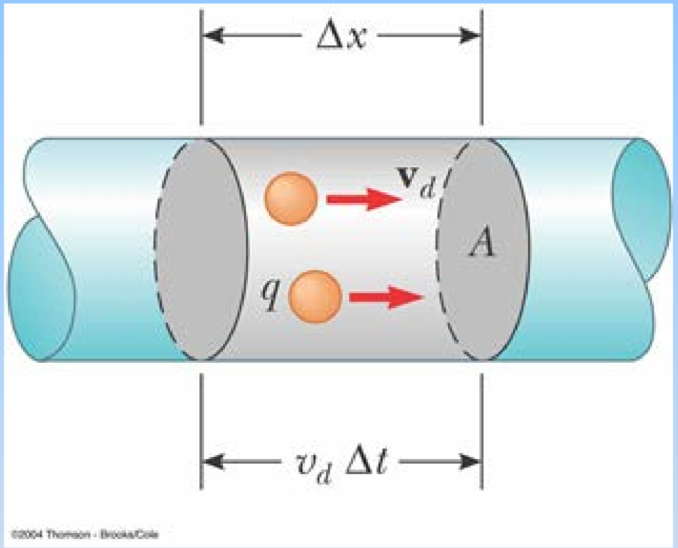
$$\Delta Q = Nq,$$

where q is the charge on each carrier.

On the other hand,

$$N = nV_{cyl},$$

where n is the number of charge carriers per unit volume and V_{cyl} is the cylinder's volume.



As a result:

$$\Delta Q = Nq = nV_{cyl}q =$$

$$= n(A\Delta x)q = n(Av_d\Delta t)q$$

$$I = \frac{\Delta Q}{\Delta t} = nAv_d q$$

Ohm's first law

For many conductors, including most metals, when a potential difference is applied across the ends of the conductor, **the current in the conductor is proportional to the applied potential difference**:

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

where the proportionality constant *R* is called the **resistance** of the conductor.

This statement is known as **Ohm's first law**, after the German physicist Georg Simon Ohm (1789–1854), who was the first to demonstrate experimentally this fundamental relationship.

The ohm

Rearranging $I = \frac{\Delta V}{R}$ gives $R = \frac{\Delta V}{I}$,
so the SI unit of resistance is the volt per ampere, which is called the **ohm (Ω)**:

$$1\Omega = 1\frac{\mathrm{V}}{\mathrm{A}} .$$

If a potential difference of $1\ \mathrm{V}$ across a conductor produces a current of $1\ A$, the resistance of the conductor is $1\ \Omega$.

A **resistor** is a conductor that provides a specified resistance in an electric circuit. In a circuit diagram, a resistor is represented by a zigzag line:

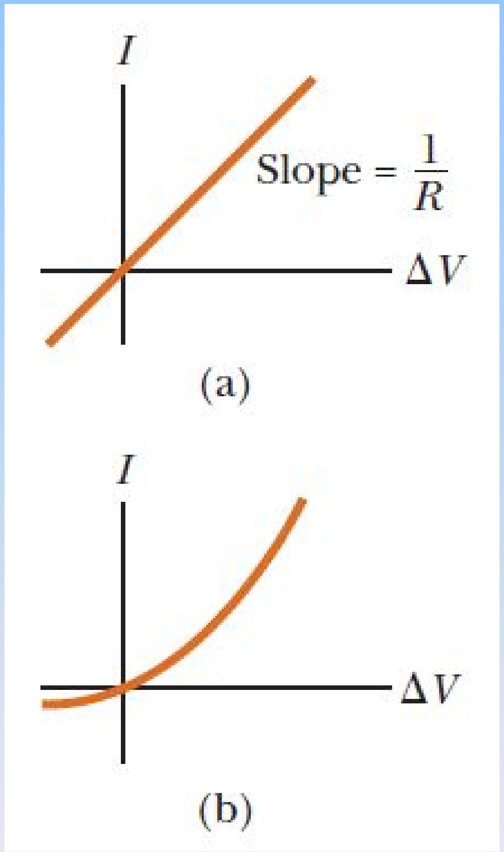
Ohmic and non-ohmic conductors

The first Ohm’s law is an empirical relationship valid only for certain materials, which are said to be **ohmic**.

Ohmic materials have a constant resistance over a large range of applied voltages, thus they have a linear current–voltage relationship (a).

Materials that don't obey Ohm's first law are referred to as **non-ohmic**.

Non-ohmic materials have a resistance that changes with voltage, hence they have a nonlinear current-voltage relationship (b).



Resistance depends on…

The resistance R of a conductor depends on its dimensions and on the material it is made of.

- It increases with the length L of the conductor,

because the electrons going through a longer conductor must undergo more collisions with the ions of the material.

- It decreases as the cross sectional area A of the conductor is increased.

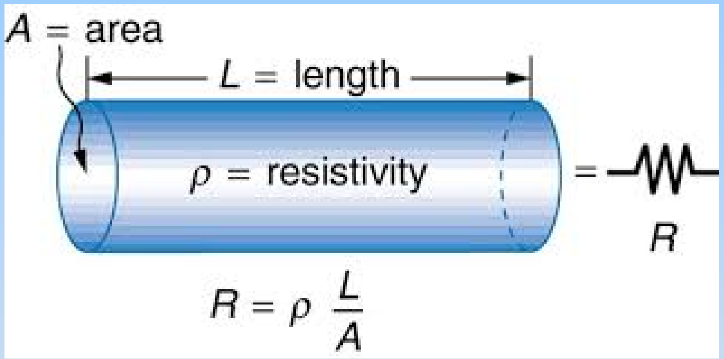
In fact, a narrow conductor has few paths available for the electrons to move through, whereas a larger conductor has many more routes they could take, making conduction easier.

- Resistance also depends on the particular material the conductor is made of.

The quantity that characterizes the resistance of a given material is its **resistivity** ρ. The greater the resistivity, the greater the resistance.

Ohm's second law

The resistance R of a conductor is directly proportional to its length L and inversely proportional to its cross-sectional area A:



$$R = \varrho \frac{L}{A} \ ,$$

where ϱ is the **resistivity** of the material.

This relationship is known as **Ohm's second law**.

Since $\rho = R\frac{A}{L}$, the SI unit of resistivity is the **ohm-meter** $(\Omega \cdot \mathrm{m})$.

Resistivity

Every material has a characteristic resistivity that depends on its atomic structure and on temperature.

Good electric conductors have very low resistivities, and good insulators have very high resistivities.

Resistivities	
Material	Resistivity ρ (Ω·m)
Insulators	
Teflon	1.0×10^{23}
Quartz	7.5×10^{17}
Rubber	7.5×10^{17}
Glass	7.5×10^{17}
Conductors	
Nichrome alloy	1.6×10^{-6}
Lead	2.2×10^{-7}
Iron	9.7×10^{-8}
Tungsten	9.7×10^{-8}
Aluminium	2.7×10^{-8}
Gold	2.2×10^{-8}
Copper	$\mathbf{1.7 \times 10^{-8}}$
Silver	1.6×10^{-8}
Graphene	1.0×10^{-8}

Resistivity variation with temperature

The resistivity, and hence the resistance *R*, of a conductor depends on its temperature.

For most metals, resistivity increases with increasing temperature.

As the temperature of the material increases, its constituent ions vibrate with higher speeds and greater amplitudes. Consequently, the electrons find it more difficult to avoid collisions, and this increases the resistivity of the material.

Over a large temperature range, the resistivity of most metals increases linearly with increasing temperature according to the following relationship:

$$\rho_t = \rho_0[1 + \alpha(t - t_0)]\,,$$

where ρ_t is the resistivity at some temperature t (in Celsius degrees), ρ_0 is the resistivity at some reference temperature t_0 (usually taken to be 20 °C), and α is a parameter called the temperature coefficient of resistivity.

Joule effect

When an electric current passes through a resistor, it gets hot, so it dissipates energy in the form of heat.

This heating effect is called **Joule effect**.

We want to calculate the amount of energy dissipated per unit time by a resistor, that is the electric power.

As an amount of charge ΔQ moves through a resistor, it loses a potential energy

$$\Delta U = \Delta V \cdot \Delta Q,$$

where ΔV is the potential drop across the resistor.

Joule effect

So the electric power dissipated by the resistor is:

$$P = \frac{\Delta U}{\Delta t} = \frac{\Delta V \cdot \Delta Q}{\Delta t} = \Delta V \cdot I\ .$$

This equation is valid for any device carrying a current I and having a potential difference ΔV between its terminals.

Joule effect

In the special case of a **resistor**, applying Ohm's first law, we can write the power dissipated in the form of heat as

$$P = \Delta V \cdot I = (R \cdot I) \cdot I = R \cdot I^2 \ ,$$

or

$$P = \Delta V \cdot I = \Delta V \cdot \frac{\Delta V}{R} = \frac{(\Delta V)^2}{R} \ .$$

Joule effect

On a microscopic level, the power dissipated by a resistor is the result of incessant collisions between electrons moving through the metal and the ions making up its crystal lattice.

The electric potential difference produced, for instance, by a battery, causes electrons to accelerate until they *bounce off* an ion of the resistor. At this point the electrons transfer energy to the ions, causing them to *jiggle* more rapidly.

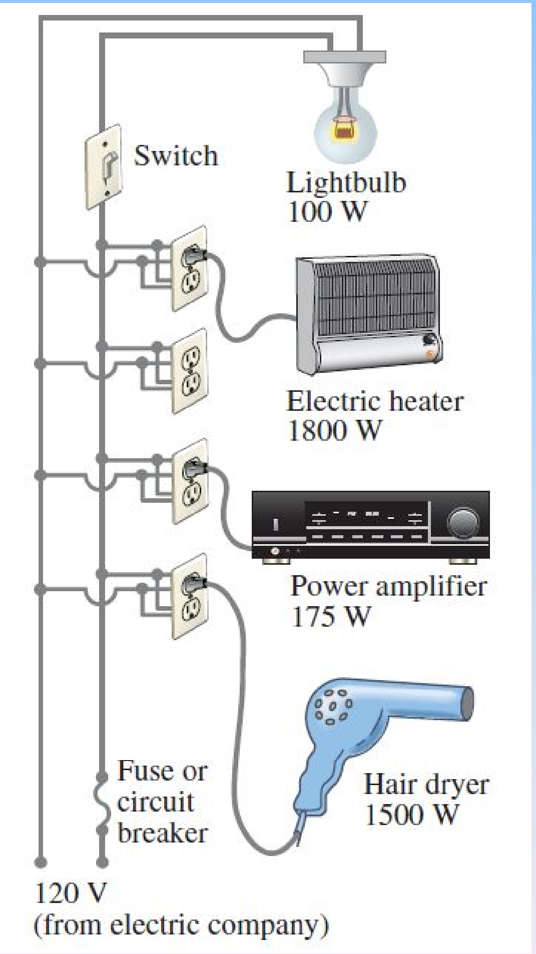
The increased kinetic energy of the ions is reflected in an increased temperature of the resistor.

After each collision, the potential difference accelerates the electrons again and the process repeats, resulting in a continuous transfer of energy from the electrons to the atoms.

Joule effect

The Joule effect is used in many household appliances.

A fuse is a safety device installed in circuits. When current exceeds a certain value, the metallic wire inside the fuse melts and the circuit opens preventing the start of a fire.



Energy and power in the electricity bill

When you get a bill from the local electricity company, you will find the number of kilowatt-hours of electricity you have used. What does kilowatt-hour stand for?

Whereas the watt and its multiple, the kilowatt, are units of power ($1\mathrm{W} = 1\,\mathrm{J/s}$), the **kilowatt-hour** is a unit of energy.

One kilowatt-hour (kWh) is the energy consumed in 1 h at the constant rate (power) of 1 kW:

$$1\ \mathrm{kWh} = 1\ \mathrm{kW} \cdot 3600\ \mathrm{s} = 3.6 \cdot 10^{6}\ \mathrm{J}$$

Energy and power in the electricity bill

Power is also important in your electricity bill:

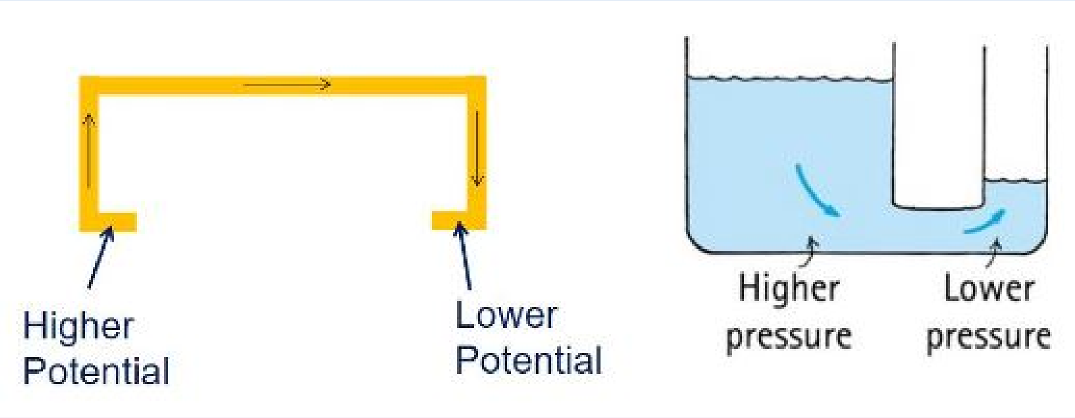
committed power capacity is the maximum power you have agreed to be delivered to your household by your electricity company (usually 3 kW for residential users).

The more committed power capacity is, the more fixed costs and energy costs are.

If the power demand of your electric appliances exceeds the committed power capacity at any time, energy delivery to your household will be temporarily interrupted.

Electric circuits

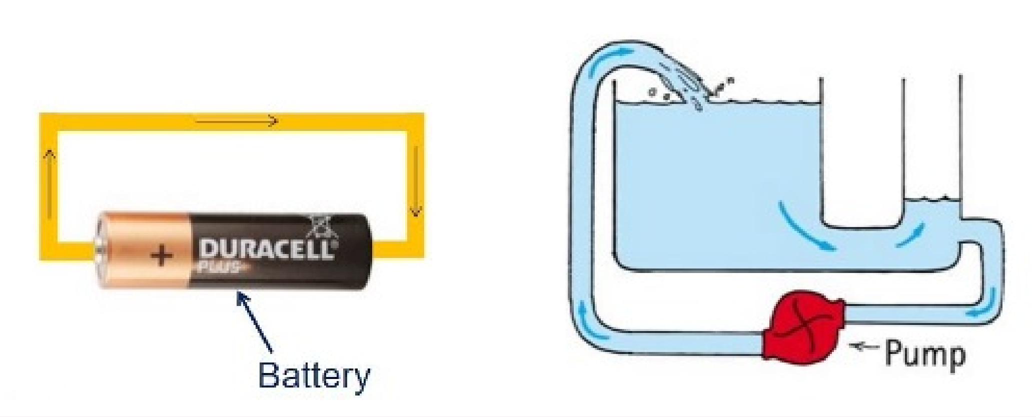
An electric current through a conductor is generated by a potential difference between its ends, just like a water flow in a pipe is determined by a pressure difference between two points.



Electric circuits

To maintain a continuing flow of water in the pipe, a pump must be provided to maintain the pressure difference.

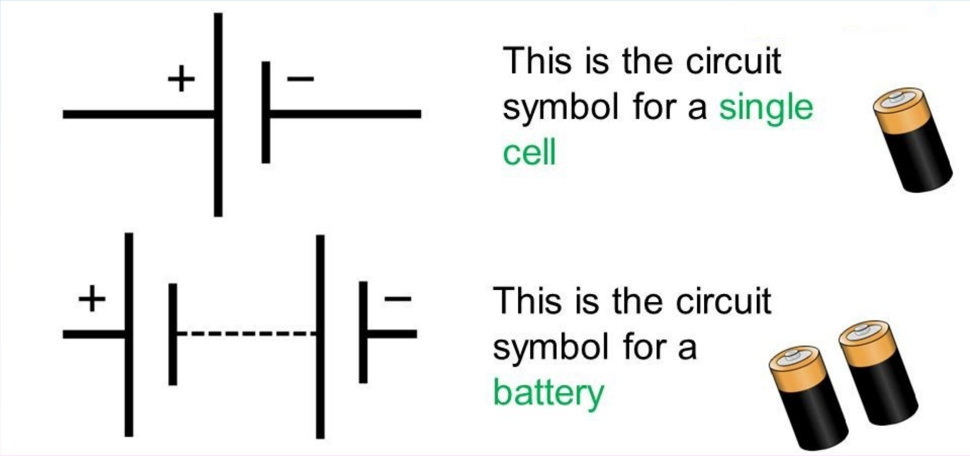
In the same way, to maintain an electric current in a conductor, a voltage source (e.g. a battery) must be provided to maintain the potential difference.



Electric circuits

A battery uses chemical reactions to produce a difference in electric potential between its two ends, or terminals.

A battery may be made up only of a single cell or of several cells in series, for example a 3 V battery contains 2 x 1.5 V cells.



Electric circuits

The terminal corresponding to a high electric potential is denoted by a $+$ and the terminal corresponding to a low electric potential is denoted by a $-$.

When both terminals of a battery are connected to a conductor, electrons move in a closed path from the negative terminal of the battery, through the conductor, to the positive terminal.

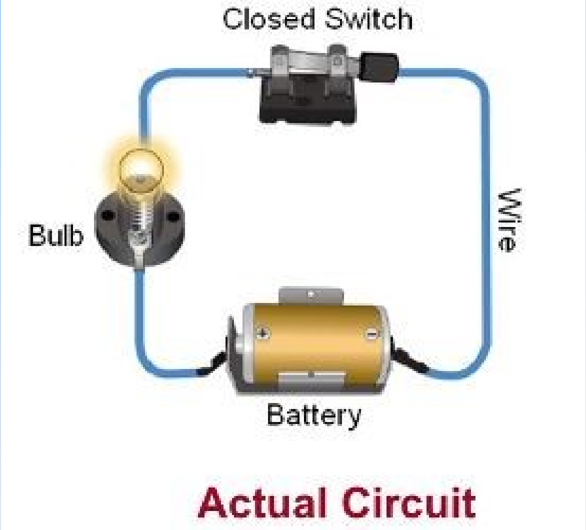
On the contrary, the conventional direction of the current is from the positive to the negative terminal.

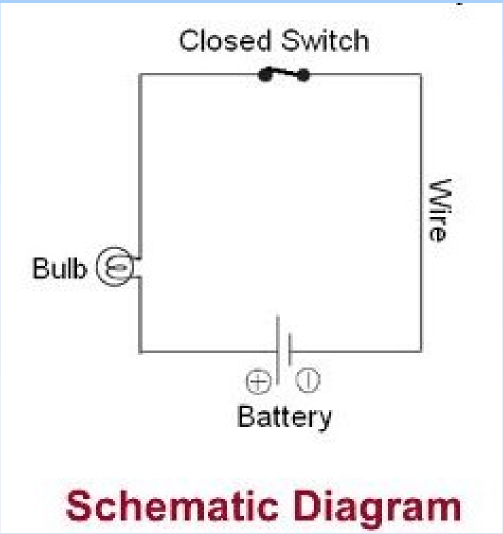
When current flows through a closed path, the closed path is called an **electric circuit**.

Electric circuits

A simple example of an electric circuit with a battery, a switch and a lightbulb, connected by a conductive wire.

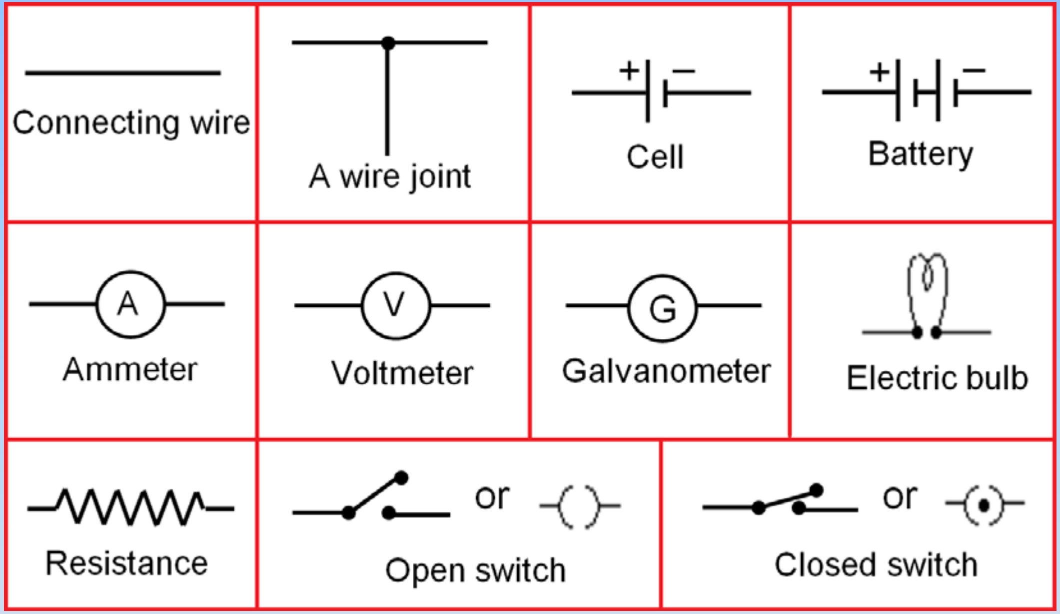
Schematic diagram of the circuit, in which symbols are used to represent each part of the circuit.





Note that the switch needs to be closed in order to let the current flow in the circuit and the lightbulb glow. When the switch is open, however, there is no closed path through which electrons can flow, therefore no electric current.

Circuit symbols



A **voltmeter** is an instrument used for measuring electrical potential difference between two points in an electric circuit.

An **ammeter** is a device used to measure the electric current in a circuit.

A **galvanometer** is a type of mechanical ammeter, that measures current flow using the deflection of a needle. The needle deflection is produced by a magnetic force acting on a current-carrying wire.