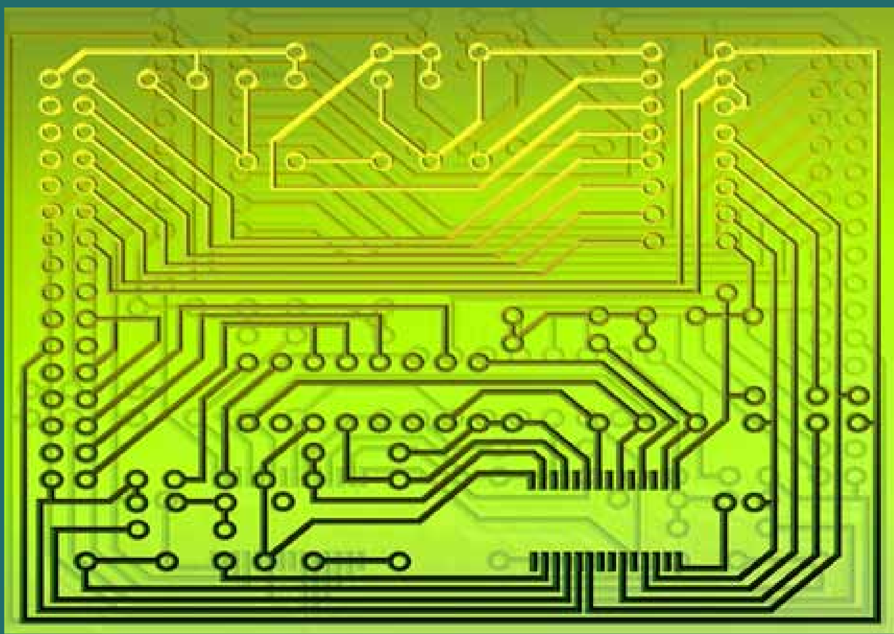
Electricity: circuits



Introduction

Household electrical installations are used to solve a problem: to provide energy to devices so that they work.

Household installations can be connected to a large supply network powered by electric power plants.

Likewise, the electrical installation in each home is a small network that can supply energy to the lights and appliances through electric current.

Current is like a fluid which flows wherever we want it to go without much difficulty. The paths used to carry the current are called **circuits**.

Electric circuits are the technology on which most devices that we use every day are based.

Circuits

Do you know why sockets always have two holes and batteries two connection terminals?

Try cutting and stripping the power cable of a device (one that does not work and is unplugged, of course). This simple experiment will reveal that inside there are two metal filaments separated by an insulating plastic cover. Why is this?

To answer this question, think about how an electric appliance works. Does it use electrons, or does it use the movement of the electrons?

Our appliances do not consume electrons. Electrons are matter and matter can neither be created nor destroyed, except in nuclear reactions. Neither can the charge be accumulated in excessive amounts without causing accidents.

The same electrons that reach the machine return to it, so they are neither created nor destroyed, nor accumulated.

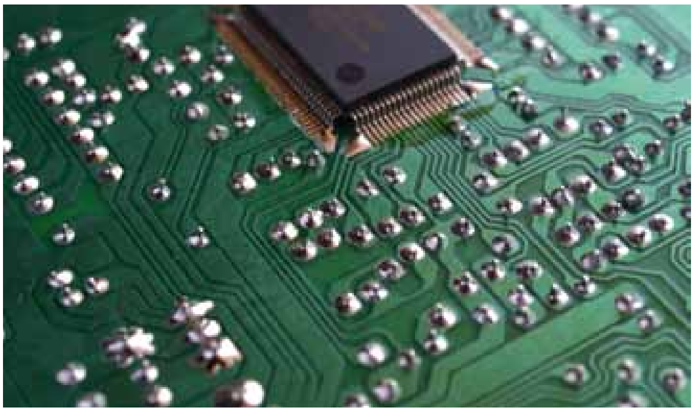
This occurs because there is a flow of electrons. This movement provides energy to the lightbulb to produce light.

Continuity of a circuit

If we want the current to reach a point and keep circulating, it needs a return path. For every electrical device to work properly, the circuit must allow the current to reach the destination and return. We are surrounded by electric circuits of all types and sizes.

Some are microscopic and others are hundreds of kilometers long.

A very simple circuit is like one made up of a lightbulb connected to a battery. There is only one possible path: the electrons leave the battery, pass through a conducting wire, next through the bulb filament, and then through the other conducting wire until they return to the battery, and so on.
Instead of only one path, a circuit may have several branches, although each one of them must have a return path.



Some circuits that are used repeatedly in electronic devices are not made with wires but rather printed using a conductive material. This facilitates their production on an industrial scale. In a printed circuit board, the connections maintain power to devices and microprocessors. Each element must be part of one of the closed paths, which may be several and very different.
Where does the current that powers our household appliances come from? From power plants. This means that there must be a route out from the power plant to our house, and another coming back to the power plant. From this perspective, a country's electrical grid could be considered a very complex circuit, with a great number of possible paths.

Open and closed circuits

For current to circulate through a circuit (and for the devices connected to it to work) it is necessary for it to travel circularly without disruptions.
In this case we say it is **closed**.
If, on the other hand, it has one or more points where the current cannot pass through, we say that the circuit is **open**. In this case the machines or devices do not receive current and do not work.
There are many ways to open a circuit; some are accidental and others are voluntary. Some examples of open circuits are:

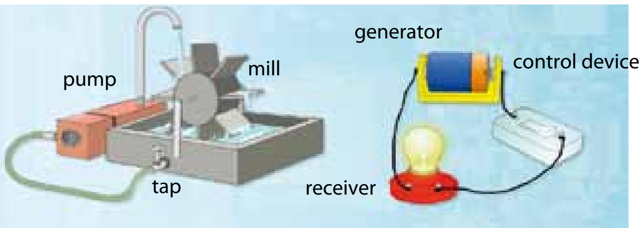
- An open switch.
- A plug taken out of the socket.
- A lightbulb or fuse which has burned out.
- A cut or poorly-connected cable.

Frequently we associate the word *open* to a machine which is working and *closed* to one that is turned off. However, when we talk about circuits it is exactly the contrary.

Elements of an electric circuit

Elements of a circuit (I)

A hydraulic circuit is not just a closed path of pipes full of water. The water must be moved with a pump and its movement harnessed through jets or some other way. It is also necessary to install taps and valves to control the flow.
Likewise, an electric circuit is not just a closed path made up of cables and connections. First, the charges



must be moved by **generators** to make the current work with receivers. **Control and safety devices** must also be installed.

Elements of a circuit (II)

The elements we can find in an electric circuit are:

- Electric generator: makes the current flow, energizing the electrons. (Its equivalent in a hydraulic circuit would be a water pump.)
- Conductors and connections: the electric current passes through them. (In a hydraulic circuit they would be the pipes and fittings.)
- Receiver: consumes electric energy, converting it into useful work. (In a hydraulic circuit it would be a fountain or a mill driven by water flow.)
- Control element: used to regulate the current flow; if it should pass through or not. (Its equivalent in a hydraulic circuit would be a shut-off valve.)

Generators

A generator works like a water pump: it is the element that energizes the electrons to make them move and create an electric current in the circuit.

A generator transforms mechanical, chemical, or light energy into electric energy.

Regardless of the source from which the energy is taken, a generator is characterized by:

- The **type of current:** creates direct current (DC) or alternating current (AC).
- The **voltage** it supplies.

Conductors

The function of conductors in a circuit is to let the electric current flow wherever we want. Most metals are good conductors.

- Cables: an electric cable is similar to water pipes (except that it carries charges instead of water).

When we install a cable, we establish the path through which the current will flow. High tension power lines carry great amounts of current. They must be thick and for safety purposes, located either high up or buried underground. All electric cables are made of a metal inside through which the current flows, and for safety purposes, a non-conducting plastic covering.

- Connections: a connection is the place where cables carrying current are joined. Connections not only join paths, but also branch them off like at an intersection. A soldering is a fixed connection. A terminal strip is a semi-fixed connection. A plug or a USB connection are non-fixed connections.

Receivers

A receiver converts electric energy into other forms of energy, producing useful work.
For example: a lightbulb (light energy), a motor provides movement (mechanical energy), an electric heater provides heat (heat energy), a doorbell produces sound (sound energy), etc.
Each receiver requires a certain voltage to work. This is supplied by the generator to which it is connected, even though it may also depend on the layout of the circuit.
You have probably heard about a machine using a lot of electricity, calling it high-consumption. This refers to the amount of energy it needs to operate for a given amount of time. This is called power and it is measured in watts (W).

Control elements

If we had to unscrew the lightbulb every time we wanted to turn the light off, it would be very impractical. This is why there is a switch that lets the current pass through to the lightbulb.
The same thing happens when we press a button to call the elevator or when we turn the dial on the music player to turn up the volume.

You may also remember a stormy day when the circuit breaker in your house tripped and left you all in the dark. As you can see, most electric circuits around us are able to respond to our demands and also operate automatically (usually for safety reasons). This is because they have control elements.

Switches

Switches are a part of our everyday lives. They are on all electrical devices.

Switches allow us to manually select between two different states: on/off.

But when talking about circuits, what does a switch really do? A switch has two possible states:
- **Open:** a point in the circuit is disconnected. (The circuit is open and current cannot pass through.)
- **Closed:** there is contact. (The circuit is complete and current can pass through it.) Normally, every machine has its own switch to turn it on or off. Also, every electrical installation has a circuit breaker which shuts off the power supply to the entire installation in case of an emergency.

Push-buttons

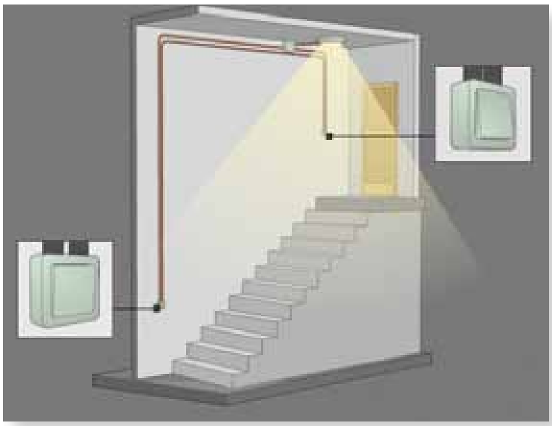
When we want to ring a doorbell, we do not close a switch until we think it has rung enough and then open it again. This would not be very practical.
This is why we use a push-button.
Push-buttons, like switches, can open or close a circuit. Nevertheless, they have an important difference: **their natural state is always open** (not letting current pass through). When pushed, the circuit is closed, letting current flow as long as it is pressed down. Once we let go of the push-button, it will automatically go back to its open state.

Push-buttons are very convenient for devices that only need to be activated for a certain period of time, usually short periods.

Changeover switches

Sometimes it is necessary to be able to turn a light on and off from different switches located at different points of the installation, for example, at the top and at the bottom of a flight of stairs.

To achieve this, the switches must be connected in a certain way: we say the **switches are commuted**.

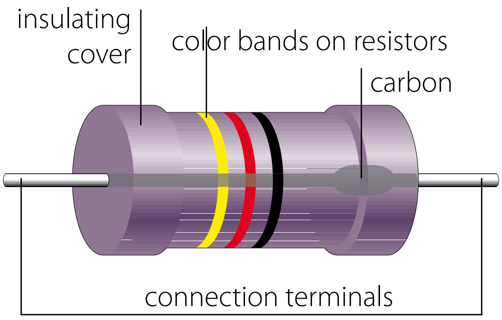


Current intensity control

Many times, the need for control does not have to do with turning a receiver on or off, but instead with regulating the current that we want to reach the receiver.

- **Resistors:** a resistor is made up of a small conductive filament with a known resistance to the current flow. It is covered by an insulating material which protects it and indicates the resistance value through color coding. The higher the value, the lower the current intensity allowed to flow through the segment to which it is connected.
- **Potentiometers:** Surely you have seen light dimmers or dials to turn up or down the volume on music speakers. Potentiometers are control elements that make this possible. The resistance is regulated manually and therefore, the current intensity in that part of the circuit is also regulated indirectly.

Structure of a resistor



Safety devices

A sudden increase in the current intensity can cause appliances connected to it to break down. To avoid this, there are **safety devices** which automatically interrupt the current flow.

- **Fuse:** some electrical appliances have filaments that burn out when they are exposed to high current intensities, as occurs in a short circuit. When it burns out, the conductive filament (which is inside a protective case) breaks and will not let current flow. The inconvenience of fuses is that they need to be replaced with new ones when they burn out.
- **Automatic switches:** there are switches that automatically change from closed to open when a large amount of current flows through them. Compared to fuses, their advantage is that it is possible to manually return them to their closed state and they will continue working. The most common automatic switches are circuit breakers and residual current devices, which control the power supply to an entire installation. The circuit breaker trips when there is a short circuit or overload (too many machines connected at the same time).The residual current device trips when it detects an accidental discharge.

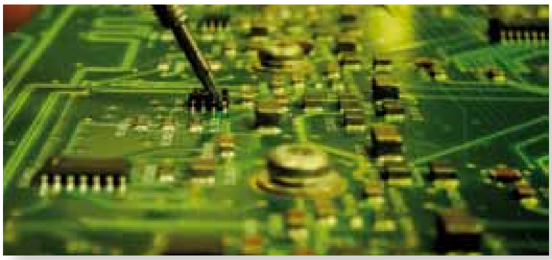
Circuit analysis

Two electric circuits could be made up of the same types of elements, connected in the same way, but have very different effects. For example: a motor connected to the circuits could turn very quickly or very slowly.
To understand why, we must know about the basic electrical properties: **voltage**, **current intensity** and **resistance**.
In this topic there will be a review of these properties, and the relationships between them in an electric circuit will be studied in detail.

Review of electrical properties

Whenever there is a **potential difference (pd)** between two points, and they are connected to a conductor, an electric current will appear. This means that the charges (electrons) will move from the point with the higher potential to the point with the lower potential.
Let's continue with the water analogy: If we join two tanks at different heights with a pipe, we can identify different elements.

- The difference in height will be equivalent to the pd of a circuit.
- The obstacles in the pipe can be compared to the resistance to the current flow.
- The amount of water that passes through the pipe will correspond to the current intensity.



Without a difference in the levels, the water does not flow. Likewise, without pd in the circuit, the current intensity is zero. When there is a small difference in the levels, the difference in pressure inside the pipe is small and the water will flow slowly. There is not a lot of water current.
Likewise, when the pd between two points is small, the current intensity is small. If the difference in levels is increased, the difference in pressure inside the pipe will increase as well as the speed of the water flow. When the pd between two points increases, a higher current intensity is obtained. With the same difference in levels in the tanks, if the pipe has more obstacles in the water flow, less current will flow. Following the analogy, although the same pd is maintained between the two points, if the resistance is increased in the path that joins them, the current intensity will be lesser.

Measuring instruments

When designing circuits, it is essential to know the basic electrical properties associated to each one of the parts. To do this, it is necessary to know how and where to measure them, and with which instruments.
The measuring instruments that must be used for each electrical property are:

- The ammeter for measuring current intensity. The unit of measurement in the International System of Units (SI) is the ampere (A).
- The voltmeter for measuring pd, also called tension or voltage. The unit of measurement in the SI is the volt (V).
- The ohmmeter for measuring resistance. The unit of measurement in the SI is the ohm (Ω).

Nowadays all these instruments can be found in one device called a *multimeter*. It may analog or digital.

- **Analog multimeter:** Besides the connections for taking measurements of the circuits, it has a selector for choosing which property needs to be measured and with which unit, and a graduated scale where a needle indicates the result of the measurement.
- **Digital multimeter:** In this case, the graduated scale and the needle are replaced by a display where the result of the measurement is expressed numerically. The digital multimeter is the most commonly used today due to its readability.

The multimeter

The multimeter has four operating modes with which the following properties can be measured, and in the following conditions:

- DC current intensity (direct current)
- DC potential difference (direct current)
- AC potential difference (alternating current)
- Resistance

The selector is usually a rotating wheel, surrounded by the symbols of the available options. On the rotating wheel there is an arrow or another mark to indicate the selected option.

Measuring voltage

To take a safe measurement, before preparing the necessary connection, the current flow must be stopped with the appropriate switch or control element. To measure the pd between two points, they must be connected to the connection cables of the voltmeter. If the red cable is connected to the point with the higher potential and the black cable is connected to the point with the lower potential, then the reading will be positive. Otherwise, it will be negative. The measurement will be taken in volts (V) or any of its multiples or submultiples.

The pd on the terminals of a battery must coincide with the voltage indicated by the manufacturer on the label.

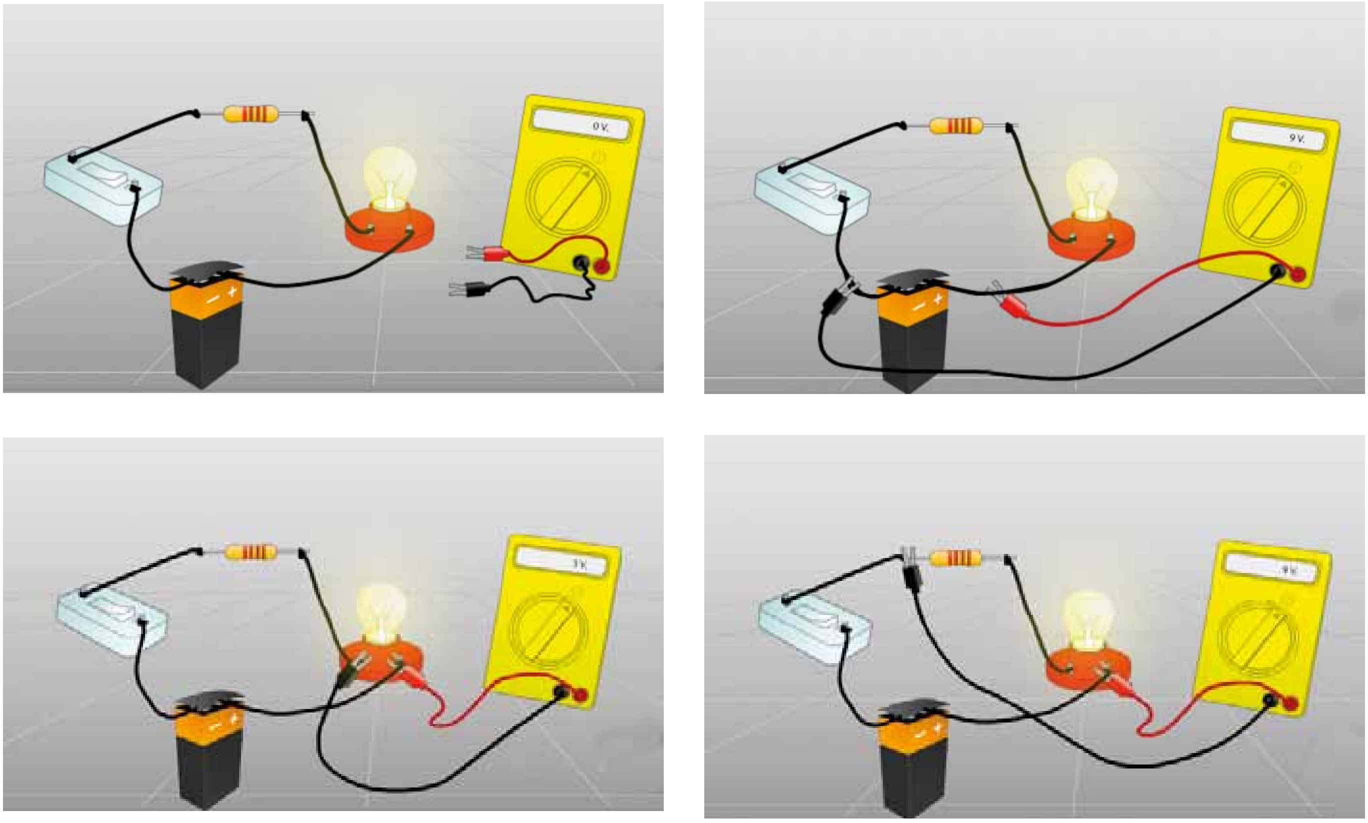
The pd or voltage that powers a receiver can be measured by connecting the cables to its two terminals.

There are no restrictions on the points between which we wish to measure the pd. It is often useful to measure it between two points separated by more than one device.

The pd between two points on a cable that is not separated by any device is zero. (Actually it is not zero, but it is small enough for us to consider it so.) This means that it does not matter where the cables are connected along the cable or connection. It only matters which devices there are between the points where they are connected.

Measuring resistance

The ohmmeter measures the resistance to the current flow between two points. The measurement is taken in ohms (Ω) or any of its multiples or submultiples.



Measurement of the voltage in different points of a circuit.

It is important to take the measurement with the receiver disconnected and removed from the circuit, as the presence of voltage or alternative paths for the current flow could affect the reading. Commercial resistor values vary widely. There are resistors from milliohms (10-3 Ω) to others with megaohms (106 Ω).

Measuring current intensity

The ammeter measures the current intensity that flows through a certain point of a circuit. The measurement is taken in **amps (A).** Usually one of its submultiples is used, like the **milliamp (mA)**, because one ampere is a very high current.

The connection of the device is different from that used to measure voltages or resistances, in which the measurement is taken between two points.

Current intensity must be measured at only one point: the point where it passes through.

In order to make the current pass through the instrument, it is necessary to open the circuit at the point where we want to take the measurement (disconnecting the cable) and connect one terminal to a cable and the other terminal to the other cable. This way we make sure that all the current flows through the measuring instrument.

Summary: how to take measurements

To take a measurement correctly, follow these steps in this order:

1. Actuate the control element of the circuit so that no current flows while we make the connection with the instrument (for safety reasons).
2. Turn the selector to the operating mode and the smallest scale.
3. Connect the multimeter appropriately to the circuit or device: between two points for the voltage or the

resistance, and opening the circuit at a certain point for the current intensity.
4. Actuate the control element so that the current flows when measuring voltages or current intensities.
5. Read the display and regulate the scale if necessary.

Ohm's law (I)

What relationship is there between the three properties presented on the previous pages? Think about a lightbulb connected to an electric circuit. We measure the voltage between the terminals, the resistance and the current intensity that goes through it. If one of these properties is modified, how will the other two be affected? Or if one changes and the other stays the same, how will the third be affected?
The following can be observed:

- When the resistance is fixed, if the voltage increases, the current intensity increases. Also, it does this proportionally (if the voltage doubles, the intensity doubles; if the voltage triples, the intensity triples; and so on).
- When the voltage is fixed, if the resistance increases, the current intensity decreases. It does this in an inversely proportional way (if the resistance doubles, the intensity is reduced to half; if the resistance is tripled, the intensity is reduced to a third; and so on).

Ohm's law (II)

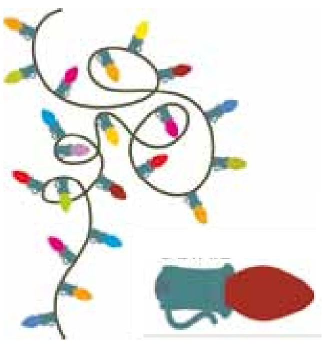
We can summarize the observation of the previous section in the following way: the current intensity that goes through a receiver such as a lightbulb is proportional to the voltage that is applied and is inversely proportional to its resistance. The relationship we have just described can be expressed mathematically in this way:

$$I = V / R$$

This relationship between the basic electrical properties is extremely important and is known as *Ohm's law.*

Series connection

To carry current to a string of lights on a Christmas tree, for example, a circuit with a connection between the lightbulbs is very simple to make. It entails connecting them one after another, all in a row. This is called a series connection. To simplify it, let's say there are only three lightbulbs. What properties does this connection have? Think about these two important questions. Firstly, what happens if one of the lightbulbs burns out?
As the circuit will have been interrupted (opened), the current will not flow through it, and all the lights will be turned off, not only the one that burned out



And secondly, what will happen if we add more lightbulbs in a series connection? Will they shine with the same intensity? Or will they shine less?
They will shine less! This means that less current intensity will pass through each one of them. To understand why, we should learn more about how circuits with devices behave in a series connection.

Potential difference in a series connection

In the model of the Christmas lights mentioned previously, we can add a resistor in series with the lightbulbs. It would be a control resistor, to ensure that the current intensity that flows through the circuit, and therefore through each lightbulb, is adequate. (If it is too weak, the lightbulbs will not shine, and if it is too strong, they could burn out.) The result is a circuit with a battery, a control resistor, a switch and three lightbulbs with the same resistance.

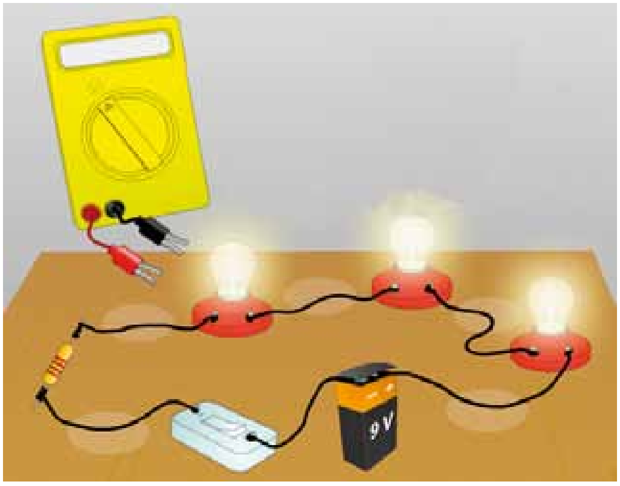
Will the potential difference between the terminals of the lightbulbs be the same for all of them? It has to be, because they all have the same resistance, and the same current intensity passes through each of them. Therefore Ohm's law indicates that the potential difference in each one will be the same.

What happens if we include more and more lightbulbs between the terminals of the multimeter?

Look at the following table, where the results are shown in various measurements.

Can you identify any relationship between the values obtained for each lightbulb and the potential difference between the terminals of the multimeter?

MULTIMETER CONNECTION ON THE TERMINALS OF…	PD
one lightbulb	2 V
two lightbulbs	4 V
three lightbulbs	6 V
the resistor	3 V
three lightbulbs and the resistor	9 V



Potential drop

In the previous exercise we saw that the pd between the left terminal of the first lightbulb and the right terminal of the second lightbulb is the sum of the separate potential differences of the two lightbulbs. Likewise, the total pd between the first terminal of the first lightbulb and the second terminal of the last lightbulb is the sum of the pds of all the lightbulbs. In a circuit in which all the devices are in series, i.e., connected one after another, the sum of the potential differences in all the components is the same as that of the battery. We can interpret this as a progressive **potential drop** of the battery's capacity to supply energy through the different components of the circuit.

Current intensity in a series circuit

What happens to the current intensity in series connections? As the circuit is closed and the current flows through the devices one after another, the current intensity is the same in all the points of the connection, in the cables as well as in the receivers.

Equivalent resistance in series

If we replaced the three lightbulbs with only one, what resistance should it have for the current intensity circulating through the circuit to be the same?

Remember that the charge cannot leak out anwhere, because charge can neither be created nor destroyed, and goes around the whole circuit without accumulating in any part of it.

This is called equivalent resistance of a series connection. In general, there are equivalent resistances of many types of connections. It is the overall resistance that an entire connection of receivers has to the current flow. For resistances connected in series, it is easy to calculate the equivalent resistance: it is done by adding the resistances of the individual receivers connected one after another.
If we have three devices, the values of three resistance values must be added:

$$R_{total} = R_1 + R_2 + R_3$$

If we have n devices, then:

$$R_{total} = R_1 + R_2 + R_3 + \ldots + R_n$$

Let's discover which is the total equivalent resistance of the three Christmas lightbulbs and the resistor.
First we have to know the individual resistance of each element of the series connection. Let's say that the resistance of each lightbulb is 50 Ω and that of the resistor is 100 Ω.
The equivalent resistance of the three lightbulbs in series is equal to the sum of its individual resistances.

$$R_{lightbulbs} = 50\ \Omega + 50\ \Omega + 50\ \Omega = 150\ \Omega$$

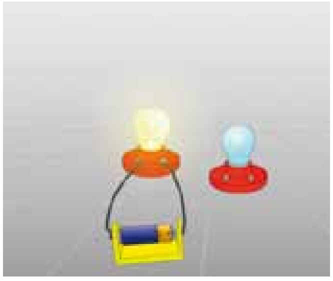
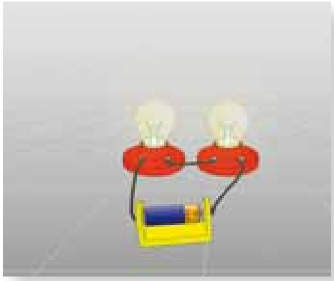
A single 150 Ω resistor provides a resistance equivalent to that of the three lightbulbs in series. Let's suppose that we replace them with a 150 Ω resistor, connected in series with the 100 Ω resistor that we already had.
The equivalent resistance of the two resistors is equal to the sum of the resistances of each one of them, as they are connected in series.

$$R_{total} = 150\ \Omega + 100\ \Omega = 250\ \Omega$$

This coincides with the total equivalent resistance of the connection, because there are no more elements connected in series to simplify.

Parallel connections (I)

At the beginning of this section we asked what would happen if we connected more lightbulbs in series, and we saw that the intensity of the light would diminish.
Now we can understand why this happens: If we add more lightbulbs in series, the total equivalent resistance of the connection, which is the sum of all the individual ones, increases. Ohm's law tells us that, given a certain voltage, when the resistance increases, the intensity decreases. Therefore, the intensity that passes through the lights will also decrease and each one will shine less.
Notice that this raises an important technological problem: What would happen if the houses on a street were connected in series? As more houses were added, there would be less and less light.

Connection in parallel.

Parallel connections (II)

The problem raised in the previous section can be solved by connecting the devices in a different way: a **parallel connection.**

Suppose we have a lightbulb that gives us enough light if we connect it to 1.5 V.

We have seen that the light intensity diminishes when another lightbulb is connected because the total resistance increases. Several lightbulbs connected this way do not provide enough light.

But, if the circuit is subdivided in several branches, i.e., multiple parallel paths where current flows, all the lightbulbs will glow at the same time and in the same way as the first one connected individually.

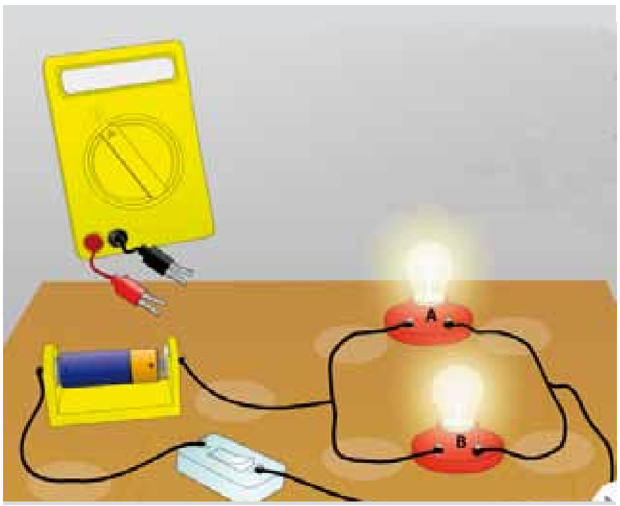
When one of the lightbulbs burns out, one of the paths is cut off, but the current continues flowing through the others. Remember that in a series connection all the lightbulbs turned off when one burned out.

Measurement of potential difference in a parallel connection

What are the potential differences in the circuit with two lightbulbs in parallel?

Look at this table of measurements:

Measurement taken	Voltage
between the terminals of lightbulb A	1.5 V
between the terminals of lightbulb B	1.5 V
between the terminals of the battery	1.5 V
between the right terminal of the battery and the left terminal of a lightbulb	0 V



Do you notice anything significant?

Potential difference in parallel connections

The previous measurements show that two lightbulbs connected in parallel are subjected to the same voltage.

Moreover, this voltage is also exactly the same as that supplied to the circuit by the battery.

This result can be applied to any branch in parallel, no matter the number of branches. The pd is the same between the ends of all the branches and must coincide with the pd supplied to the whole set of branches.

This is how the problem we mentioned before about the electric power supply to the houses is solved.

The solution is to connect the houses in parallel instead of in series. Inside each house, the lights and electrical appliances must also be connected in parallel. So, if a lightbulb burns out, for example, the washing machine will continue working.

Current intensity in a parallel connection

We have just learned about the voltage between different points in a parallel circuit. What can we learn about current intensity?

Intuitively, and keeping in mind what we know about current, what do you think could happen if all the current supplied by the battery from one of its terminals reaches the other terminal after completing the circuit?

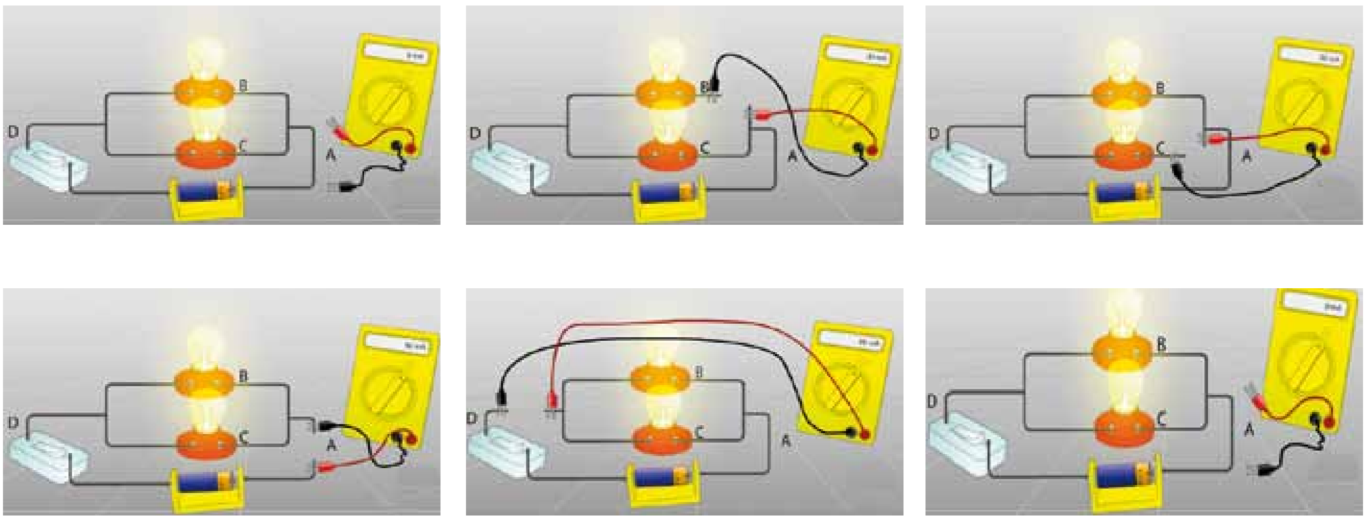
It is a problem which is similar to dividing up a cake for all the guests at a party.

Think of the current intensity as if it were a cake, and each one of the branches of the circuit, a guest.

Maybe some guests are very hungry and others not so much. The pieces do not have to be the same size.

Like in a canal, when the current comes to a branch, it must divide itself.

What simple mathematical relationship is there between the current intensity of the branches and the current intensity that enters and leaves the generator that powers them?



Notice that the current intensity that reaches the parallel connection must divide itself up among the branches. Then the sum of the current intensities in all the branches would be equal to the current intensity before the junction. Likewise, after the junction, the current intensity should have the same value as before, because all the current that enters must leave. (As we already know, it is neither lost nor accumulates anywhere in the circuit.)

Distribution of the current intensity

The previous observation can be applied to any branched circuit with parallel connections.

We say that at the branching point, also called a node, the sum of the current intensities entering is equal to the sum of the current intensities leaving.

In a parallel connection with n branches, the sum of its intensities is equal to the total intensity that flows through the generator that powers them.

$$I_T = I_1 + I_2 + \ldots + I_n$$

Notice that the same thing happens with the water flow in branched pipes.

Power strips

The power strips that everyone uses to plug in more than one machine or appliance to the same 220 V socket are a clear example of branch nodes that allow different receivers to be connected in parallel.
As we already know, parallel connections allow each branch (in this case, each plug in the power strip) to have the same voltage, 220 V, which is what our appliances need. If we also want to know how much total current intensity there is flowing through the power strip cable, we have to know the current intensity which powers each one of the appliances connected and add them up.

Equivalent resistance in parallel

In the analysis of series connections, we introduced the concept of equivalent resistance of a set of devices. Remember that equivalent resistance is the individual resistance that provides the same resistance to the current flow of all the devices together.
The resistance of two devices connected in parallel can be calculated with the following formula:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2}$$

For three devices, the formula will be:

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

And in general, for n devices, the formula will be:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$$

So the equivalent resistance of devices in parallel is less than any of its individual resistances.

Mixed connections

In a mixed connection we can find parts of a circuit in series and others in parallel.
To determine the current intensity or the voltage in different points of the circuit we have to break it down into parts where there are only series or parallel connections, and apply the formulas that we already know for each case.

Equivalent resistance of a mixed connection

Let's see how to obtain the equivalent resistance of a set of devices in a mixed connection. We should go step by step. We have already learned the formulas to find the equivalent resistance of series connections and parallel connections. For a mixed connection, they must be applied in steps.
If in one part of the circuit we have three resistances in series —R_1=100 Ω, R_2=200 Ω and R_3=300 Ω—, we know how to find the equivalent resistance: just add them up.

$$R_{series} = R_1 + R_2 + R_3$$

If we use the indicated values:

$$R_{series} = R_1 + R_2 + R_3 = 100\ \Omega + 200\ \Omega + 300\ \Omega = 600\ \Omega$$

We obtain:

$$\mathrm{R}_{\mathrm{series}} = 600\ \Omega$$

The remaining resistance, R_4= 300 Ω, is in parallel, and we know how to find its equivalent: just add up the reciprocals. This will give us the total resistance.

$$1 / R_{\mathrm{total}} = 1 / R_{\mathrm{series}} + 1 / R_4$$

Using the indicated values:

$$1 / R_{\mathrm{total}} = 1 / R_{\mathrm{series}} + 1 / R_4 = 1 / 600\ \Omega + 1 / 300\ \Omega = 1 / 200\ \Omega$$

We obtain:

$$1 / R_{\mathrm{total}} = 1 / 200\ \Omega$$

Inverting the fractions:

$$R_{\mathrm{total}} / 1 = 200\ \Omega / 1$$

We obtain the final result:

$$R_{\mathrm{total}} = 200\ \Omega$$

Now we can apply Ohm's law to find the current intensity that flows through the battery which powers the circuit:

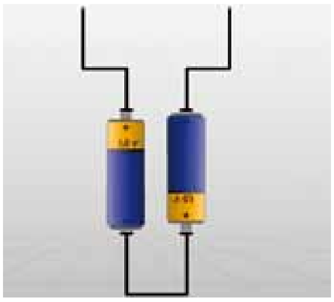
$$I_{total} = V_{battery} / R_{total} = 4.5\ V / 200\ \Omega = 0.0225\ A = 22.5\ mA$$

Recap

Series connections	Parallel connections
The current intensity is the same in all the elements.	The potential difference is the same in all the elements.
The potential difference is divided among the different elements.	The current intensity is divided among the different elements or branches.
When more elements are added, the total resistance increases, and with a fixed voltage, the current intensity flowing through the circuit decreases.	When more elements are added, the total resistance decreases, and with a fixed voltage, the total current intensity increases.
The more Christmas lights connected to the same voltage, the less they will shine and the slower they will wear down the battery.	The more Christmas lights connected to the same voltage, the faster they will wear down the battery, because each light will shine as brightly as if there were only one light in the circuit.

Connecting DC generators

Series connection of DC generators (I)



If you have ever needed to change the batteries in a device, you will have noticed that the flashlight, the remote control, and the music player all need more than one battery. Have you noticed how the batteries are connected to each other? Which terminals touch each other? Do you think this is coincidence that they are placed this way?

Why are the batteries connected to each other? When we connect two batteries one after the other, they make a series connection, in which we make sure that the positive terminal of one is connected to the negative terminal of the other. This is also shown in the circuit diagram. What is the advantage of connecting generators like this?

Series connection of DC generators (II)

We have already seen how the total pd is the sum of the pds of each receiver in a series connection of receivers. The same thing happens when we connect batteries or generators in series. The resulting voltage is the sum of the voltages that each one of them creates independently.

That is why it is so common to connect batteries in series. It creates higher potential differences than that of each individual battery.

For example, a remote control which operates on 3 V needs two 1.5 V batteries connected in series.

The most common 1.5 V batteries in everyday appliances are commercially known as AA or AAA.

Parallel connection of DC generators

What would happen if the batteries in the remote control were connected in parallel instead of in series? Are there any advantages to this?

In order to answer this question, remember what happened in the parallel connection of receivers. The voltage was the same in each branch, but the current intensity was divided.

When connecting batteries of the same voltage in parallel the voltage supplied does not increase, but the work is distributed. This way, the work of creating current in the circuit is shared. The batteries last longer, as they share the energy consumption.

If the batteries did not all have the same voltage, energy would be lost because some would act as receivers, consume energy unnecessarily, heat up and even become damaged.