I. Basic Electricity

Prepared by Belgian BioElectroMagnetics Group (BBEMG)

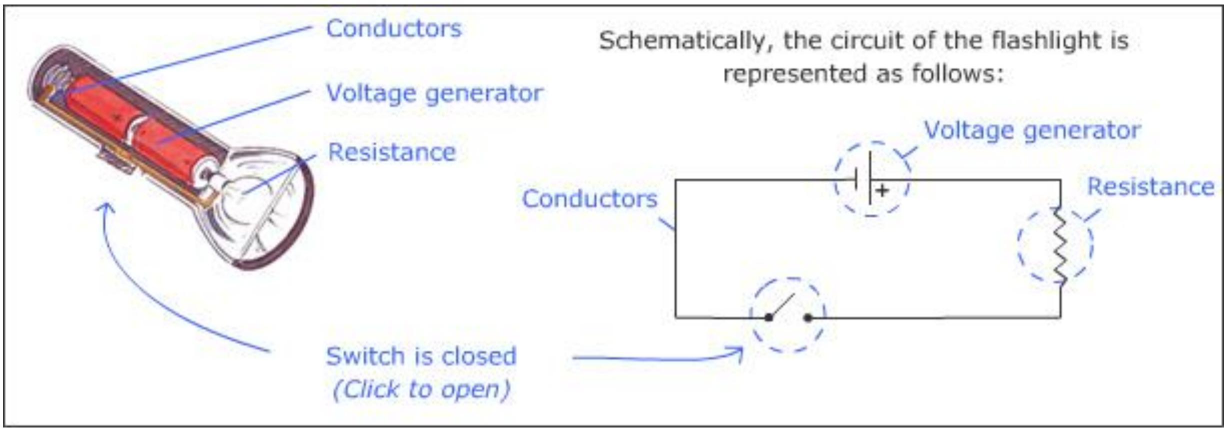
Note:
All the information on this page is available as Flash animation at the following address: http://www.bbemg.be/en/main-emf/electricity-fields/electrical-concepts.html

Introduction

We use everyday numerous forms of energy: petroleum, wind, water, the sun are all energy vectors, just like our own body energy and that of animals. This energy gives us the means to produce work (e.g. movement, light or heat).

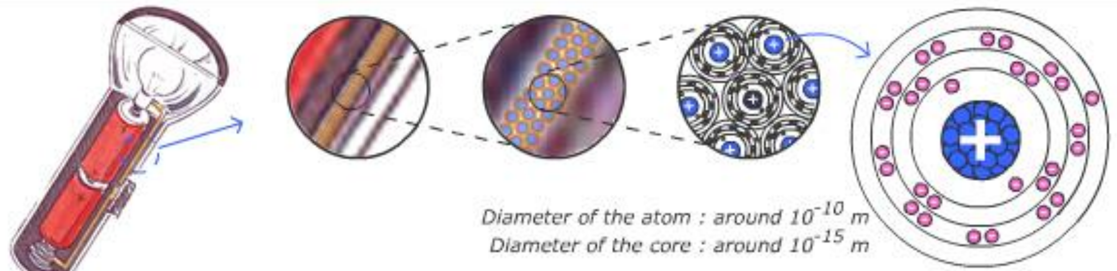
Among these different forms of energy, there is one which uses the energy of electrons: it is called Electricity. Its generation, its transmission and its use are possible because of its electromagnetic characteristics. Electricity and electromagnetism are tightly linked. In this module, we intend to have you (re)discover the basic concepts in electricity that you need to have in mind in order to tackle the subject of electromagnetism and electric and magnetic fields without apprehension.

To get started, here is an illustration of a very simple electrical circuit: that of a flashlight.



Electric current

To better understand the origin of the electric current, one must penetrate into the heart of the copper wires of the flashlight circuit. Let's imagine a powerful magnifying glass allowing us to see the infinitely small.

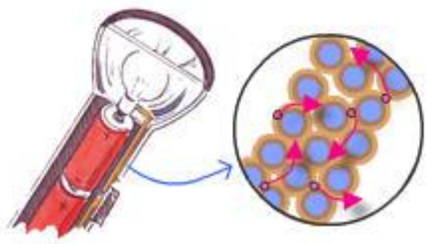


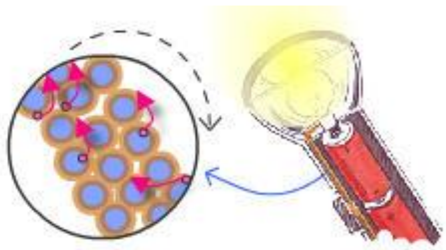
Electrons, distributed in layer around the core, form the electronic cloud. The atom is electrically neutral: it contains as many protons as electrons.

A copper wire consists of an ordered tangle of copper atoms. Each atom is itself composed of a core (composed of neutrons and positively charged protons) and electrons (negatively charged) moving around the nucleus.

When the flashlight is OFF, there is a natural agitation and random movements in the copper strips.

When the flashlight is ON, the movements are now coordinated. These movements are at the origin of the electric current.





The particles in motion are the electrons.

Each electron is electrically charged. The current through a cross section of the circuit is the quantity of electric charges that cross that surface in one second.

Intensity of the electric current (in ampere, A) ← $I = \frac{q}{t}$ → **Electric charge** (in coulomb, C); Time (in second, s)

The electric charge of an electron is equal to 1.6 x 10^{-19} C. From the formula above, a current of 1 ampere (usually abbreviated amp) corresponds to flow of 6.25 x 10^{18} electrons per second.

The electric charge **q** is equal to **1,6 x 10^{-19} C** multiplied by the number of electrons **n**.

Thus, $I = \frac{1{,}6 \times 10^{-19}\ C \times n}{t}$

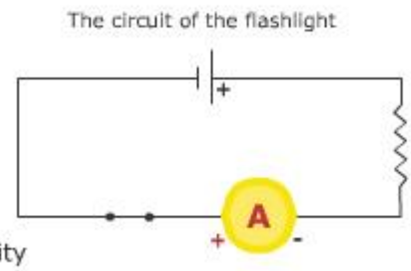
after transformation of the formula, we have: $n = \frac{I \times t}{1{,}6 \times 10^{-19}\ C}$

if I = 1 A and t = 1 s, then **n = 6,25 x 10^{18} électrons**

The electric current is measured with an ammeter. There are different types, but let's look at the basic principle at work:

How to measure a current with an ammeter?

- The ammeter is placed in series in the circuit
- It is needed to take into account the direction of the current
- The ammeter can be placed anywhere in the circuit
- In our flashlight, the intensity of the current is 700 mA



The electric current is:

- A few hundred milliamperes (mA) in a flashlight,
- A few amperes (A) in a kitchen appliance,
- Several hundred amps in a high-voltage power line.

Note:

The intensity of the current plays an important part in the seriousness of an electrocution, but other factors must be taken into consideration. Actually, the risk of electrocution depends on the voltage of the source being touched and on the resistance to the flow of electricity of our body.

This voltage in a flashlight is supplied by two 1.5 V batteries, so it is 3 V. The electrical resistance of our skin is very high, so the current is extremely low.

Other factors are also at work that can aggravate an electrocution, as the frequency of the voltage for example. We will introduce these various concepts in following modules.

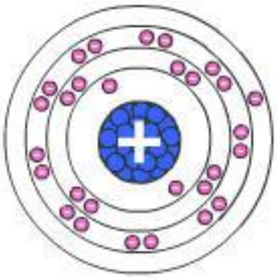
Conducting and insulating materials

In our flashlight, the electric current flows through copper wires: copper is a conductor of electricity. Since there is no risk of electrocution, the wires have no protecting cover (such as PVC) as you find on ordinary wiring connected to the power grid.

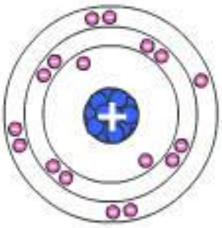
Let's examine where the difference between conducting and insulating materials comes from.

The chemical, physical and electrical properties of an atom or molecule are determined by the number of electrons and their distribution among different layers (see the Mendeleev periodic table and additional information in appendix).

The electrons on the outer layer, also known as valence layer, participate in the bonds between atoms. It has a maximum of 8 electrons. The number of electrons on the outer layer determines whether a material is a conductor or an insulator.



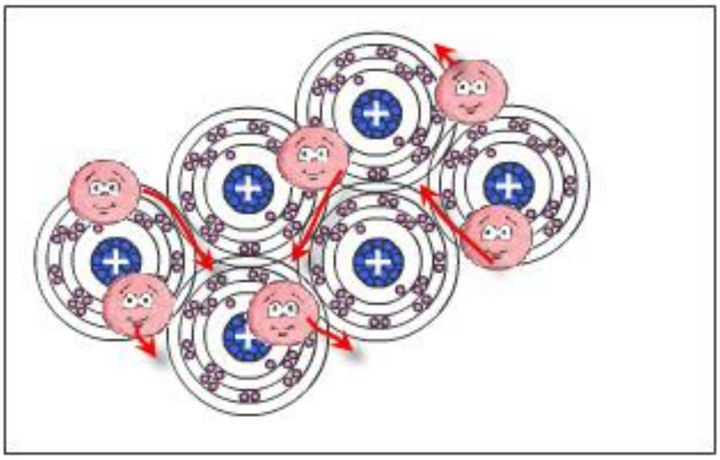
When there are fewer than 4 electrons on the outer layer (a single electron in the example shown at left), they are free to move from atom to atom and thus participate in the current generation. The material is said to be conducting the electricity.



When there are more than 4 electrons on the outer layer (7 electrons in the example shown at left), these electrons are more tightly bound to their atom/molecule and they are involved in stronger bounds with neighbouring atoms/molecules. There are no free electrons, or at least very few, thus no transfer of electrons between atoms/molecules occurs; within an insulating material, the electrons can't move, but the separation of positive charges from negative ones is possible. Insulating materials play an important role in static electricity. The material is said to be an insulator.

The copper atoms in the flashlight wiring have 29 electrons.

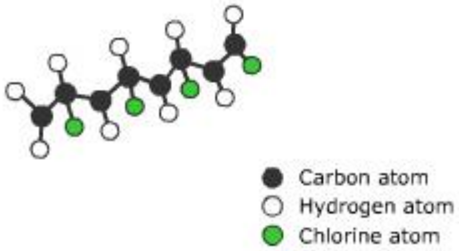
Their outer layer contains one electron. This electron is free to move about from one copper atom to another. It is that electron that participates to the conduction of the electric current.



Gold, iron and aluminium are examples of conducting materials.

PVC (Polyvinyl chloride) is composed of chains of carbon atoms to which hydrogen and chlorine atoms are attached (see figure below). The outer layers of all three atoms are strongly involved in the intermolecular bounds: they do not move.

PVC (polyvinyl chloride), unlike copper, is composed of long chains of organised atoms of carbon, hydrogen and chlorine.

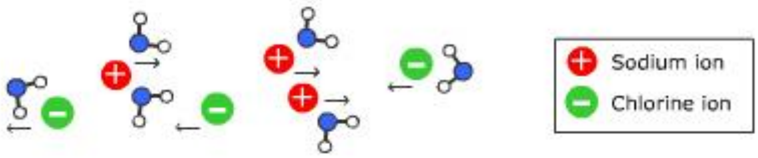


Wood (when dry), paper, pure water and ice are examples of insulating materials. The insulation prevents unwanted contact with conductors: as our body is conductor, a worn out or insufficient insulation can increase the risk of electrocution.

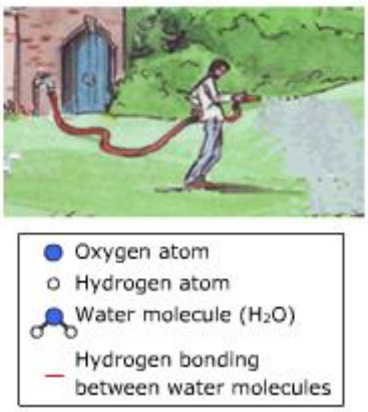
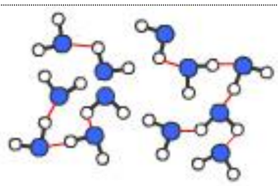
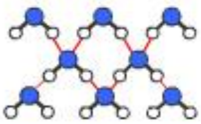
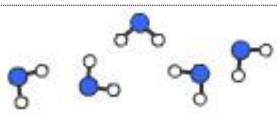
In a copper wire, the electrons participate directly in the conduction of the current. In a liquid, the current is caused by the ions. An ion is an atom that has either gained (negative ion) or lost (positive ion) an electron.

Pure water or ice is a good insulator: both hydrogen atoms are strongly tied to the oxygen atom (covalent bond); there are neither free electrons nor ions... thus no conduction of electricity.

However, “impurities” such as salt or lead for example turn it into a conductor: it is those elements, in the form of ions, which provide the necessary electric charges to conduct the current.



Water, whether tap water, bottle water or surface water (lakes and rivers) is therefore conducting electricity. It is also the presence of ions which is responsible for the electric conductivity of the human body.

		In liquid water, the molecules are not frozen in place. They are randomly moving about and the hydrogen bonds between molecules are continuously broken and reformed.
		In ice, the water molecules are organised into a crystalline lattice. The hydrogen bonds are permanent.
		Conversely, in water vapour, the water molecules are free from each other.

At the atomic level, the concept of conducting and insulating materials is complex. The appendix “Conducting and insulating materials” will allow you to further your understanding of the difference between these materials.

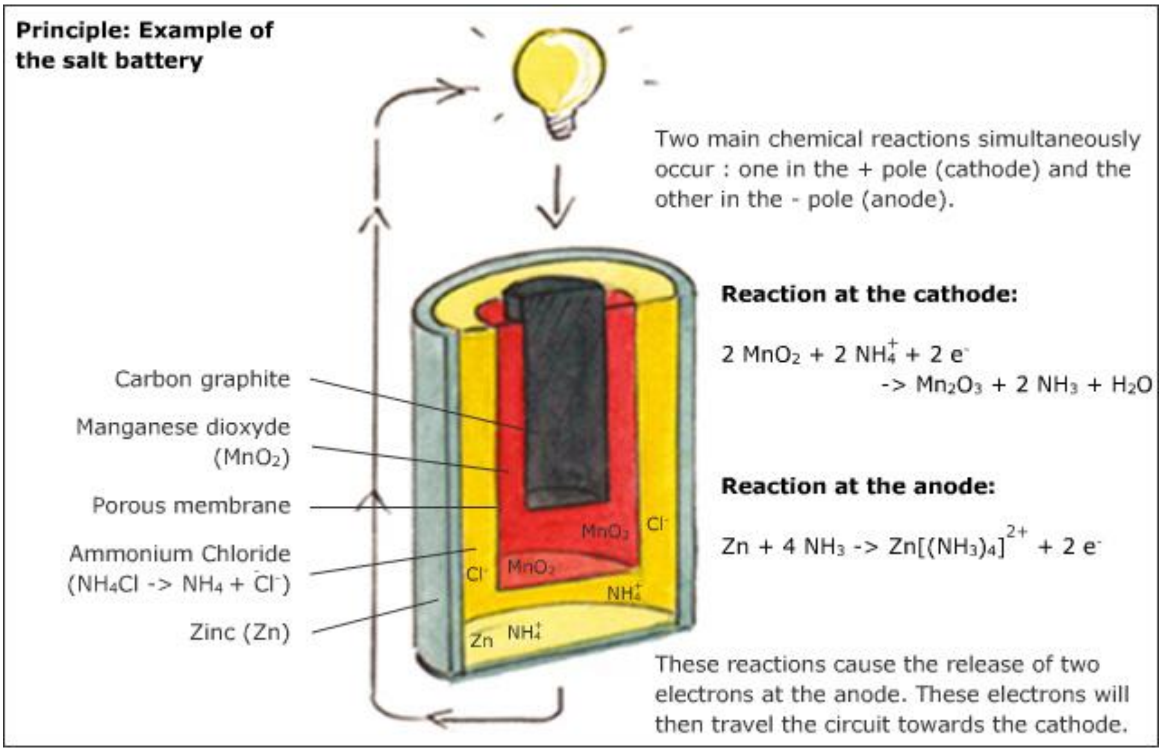
Note: Semiconductors have intermediate properties between conductors and insulating materials. For more information on this subject, see the relevant appendix.

Voltage generators

Electric generators are devices that produce electric energy from another form of energy. As we saw earlier, when the flashlight is off, the movement of the free electrons is random and in all directions. When the flashlight is on however, it is quite different: the electrons all move in the same direction from the negative pole to the positive pole (*).

(*) This is the actual direction of movement of the electrons. Nevertheless, electricians use the convention that the current goes from the + pole to the – pole. This convention that seems erroneous is due to the fact that 19th century physicists were not aware of the structure of matter and postulated that the current was a flow of positive charges.

The chemical reactions that take place in the cell provide the electrons with the energy required to propel them through the flashlight circuit. This energy is called the electric potential. The difference of potential between the + pole and the – pole of the cell is maintained until exhaustion of the chemicals.

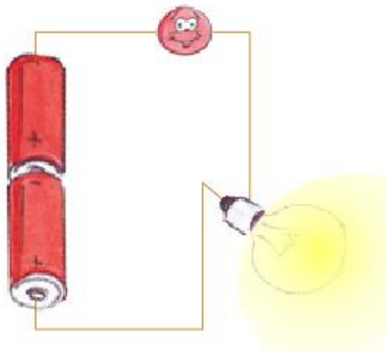


In order to understand what the electric potential is, let's compare the electric charges in the flashlight batteries to the water stored in a water tower.

"Let's say that ..."
The electric potential is the difference in elevation between the highest level of the water and that of the garden hose nozzle.
The batteries would be the water tower.
The electrons would be the water molecules.
The current would then be the flow of water at the nozzle of the garden hose.

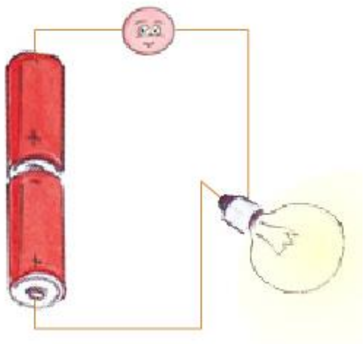
The storage tank is completely full. The water molecules hurry down the pipe. The flow of water is maximal.

The batteries are new, and they contain the necessary chemicals. At the outlet of the battery, the electrons are present in large numbers with the energy required to travel the entire circuit. The current is maximal; the bulb emits a bright light.



The storage tank is almost empty. The water flow is weak.

The batteries are worn out; the chemicals are no longer reacting; the energy of the electrons is no longer capable of propelling them through the circuit. The bulb doesn't shine anymore.



The difference in electric potential between two points of a circuit is expressed in volts (V).

Each battery of the flashlight has the capacity to maintain a difference of potential of 1.5 V between its + and – poles: it is also called electromotive force (EMF). The difference of potential is small: the cell is a low voltage generator (*).

(*) "Voltage/electric potential", "difference of potential", and even "electromotive force"... how to navigate this seemingly haphazard vocabulary which represents the same concept!

A little vocabulary lesson:

The electric potential, that's the potential electric energy per unit of charge.

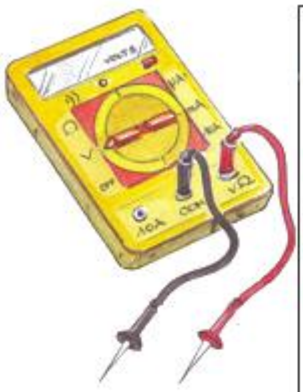
The electromotive force (EMF) often represents the voltage supplied by an electric generator.

The voltage represents the evolution of an electric field along a circuit:

- When the operating conditions are stable, the voltage is equal to the potential difference.
- In variable operating conditions, it's mathematically more complicated! We will not go any further along these lines in this module.

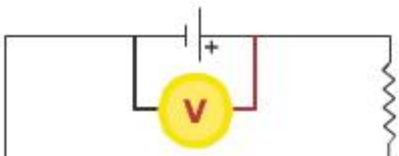
The potential difference in a flashlight supplied by 2 1.5 V batteries is 3 V. The potential difference between two points is related to the energy required by an electron to travel between these two points.

Voltage is measured with a voltmeter. There are different types, but let's look at the basic principle at work:



How to measure a voltage with a voltmeter?

- The voltmeter is placed in parallel in the circuit.
- It is needed to take into account the direction of the current.
- It should be placed across the terminals of an electric element. If it is connected to the copper wire, it will show 0.
- In our flashlight, the voltage is 3 V.



The order of magnitude of voltages is:

- a few volts (V) in electronic circuits and in flashlight batteries;
- about 230 V between phase and neutral of our wall receptacles (120 V in the USA)
- from 15 to 380 kilovolts (kV) between phases of a high-voltage power transmission line.

Note:

The potential, as high as it might be, is not a factor to consider with regard to the risk of electrocution. It's the potential difference that one must watch for.

To convince yourself, take the case of a bird landing on a high voltage power line.

Why is it not electrocuted?

For electrocution to occur, there must be a current through the body, therefore there must be a potential difference between two points. Both feet of the bird are on the same wire, thus at the same potential. No difference, no current. But if by flapping its wings, the bird touches another wire, there will be a difference of potential between its wing and its feet, therefore a current. Similarly, the bird will be electrocuted if it makes contact with a cable and the tower simultaneously, since the cable is isolated from the tower and the tower is earthed (or grounded), that is at the potential of the earth.

It is not the potential by itself which is dangerous, but the potential difference, because the current that travels through the body is proportional to the difference of potential between the two points of contact.

Another example is the hair-raising experiment: the voltage reached by our body may also be very high while we don't even feel any effect.

(*Source*: Maison de la Science, Université de Liège)

Direct and alternating current

There are two large families of electric generators: direct current (DC) and alternating current (AC).

The current (as well as the voltage) is said to be direct when the electrons always flow in the same direction from the negative to the positive pole of the generator. It's the case of the flashlight batteries. Those are direct voltage generators.

The situation is quite different for appliances connected to the power grid: in this case, the electrons reverse their movement 100 times per second (120 in the USA); the voltage (and the current) is said to be alternating at the frequency of 50 Hz (hertz). In 50 Hz, the voltage goes from a maximum positive value, through zero, to a maximum negative value, then through zero and back to a positive value and so on... 50 cycles per second, following a sinusoidal curve.

What happens to the electrons?

When we flip a switch, the light comes on instantly. From that to claim that the current (and thus the electrons) moves at the speed of light is a small step... that we will not take when we think at the level of the atom.

The electrons actually do not travel along the direction of the current more than a metre per hour, in direct current. But, when the electrons enter the circuit, “pushed” by the generator, a chain of shocks between electrons takes place. The electron may not have moved much, but it hits another one which in turns hits the next, propagating the movement at actually close to the speed of light... though it has nothing to do with the movement of the electrons themselves along the path of the current.

Note: the motion of the electrons is actually very fast, but in many directions, and running into each other. Only on average do they move with the current.

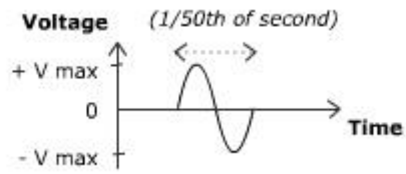
In alternating current, the electrons oscillate at 50 Hz and stay practically in place. Their motion is akin to a vibration.

The frequency can be visualised with an oscilloscope. This instrument is a sophisticated voltmeter with which one can follow the evolution of the voltage over time. Shown below is the voltage across the chandelier varying in a sinusoidal way at a 50 Hz frequency.

When the voltage is null, light bulbs "go off". However, there is no difference when the voltage is positive or negative. At the frequency of the power distribution network (50 cycles per second), we do not detect the light going on and off because the filament doesn’t have time to cool. In addition, retinal persistence doesn’t allow the eye to detect such rapid changes.

Evolution in a sinusoidal way at a 50 Hz frequency?

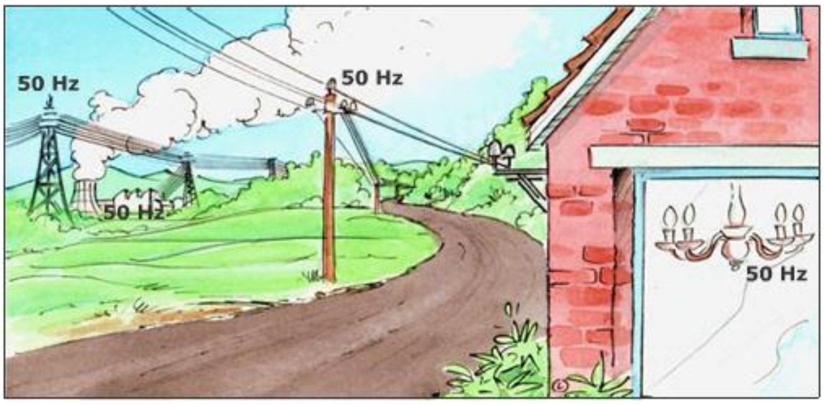
This means that voltage goes through cycles from 0 V to the maximum positive through 0 V again and to the maximum negative and back to 0 V 50 times per second.



Attention: The electrical appliance subjected to the alternating voltage has little use of the peak values or of the zero values. This is why an effective voltage is defined which is more useful. The effective value represents the equivalent continuous value of an alternating value. For a sinusoidal variation, the effective value is the peak value divided by the square root of 2 (1.41). This is why it is also called root mean square value (RMS). The voltage ratings of common power supplies or receivers are effective values.

230 V between phase and neutral of our wall receptacles is the effective voltage. The peak (maximum) voltages are +325 and – 325 V.

Alternating voltage is produced in power plants. It is maintained throughout the entire grid along the path followed by the electricity on the way to our dwellings.



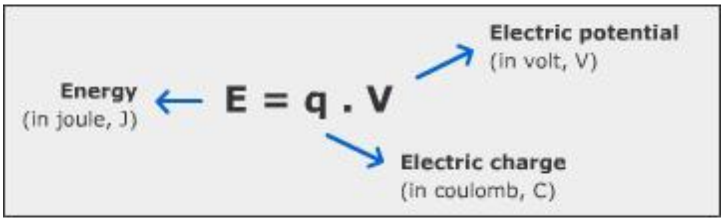
The electric current is produced at a frequency of 50 Hz in power plants by high voltage generators which consist of a turbine and of an alternator:

- The turbine is driven by the force of water (hydroelectric plants), of the wind (wind farms), steam pressure (thermal and nuclear plants), etc. The mechanical energy at the output shaft of the turbine is then transformed into electrical energy by the alternator.
- The alternator contains a fixed part, the stator, and a rotating part, the rotor. We can say, simplifying matters a bit, that the rotational speed of the rotor causes the generation of a sinusoidal voltage in the stator windings at a 50 Hz frequency.

Energy and power

Energy

The energy required to light a lightbulb or run any electrical appliance is supplied by the charges that go through them and by the electric potential of these charges:



The amount of energy released by an electric charge in any electrical appliance is proportional to the potential difference between its input and output. The energy of an electron at the output of two 1.5 V batteries in series, that is 3 V, is twice that of an electron at the output of a single 1.5 V battery.

The official unit of energy is the joule (J).

What is shown by our electric bill is the energy consumed during some period of time, or the quantity of charges passing through times the electric potential. Our electric consumption is calculated in kWh.

Where does the calculation of electricity consumption in kWh come from?

The energy E released by an electric charge q undergoing a potential difference V is expressed by **E = q . V**

As we have seen that the current is equal to the charge running through a circuit per unit of time : **I = q / t**

Thus, we have : **E = I . t . V**

This formula shows that energy depends on current, time and potential difference.

Since the power depends on voltage and current (P = V . I), then :

E = P . t (en W . h ou kW . h)

Consider an example:
A chandelier with four 60 W bulbs on for 2 hours uses 4 . 60 W . 2 hours = 480 Wh. Over the same period, the flashlight will consume 4.2 Wh.

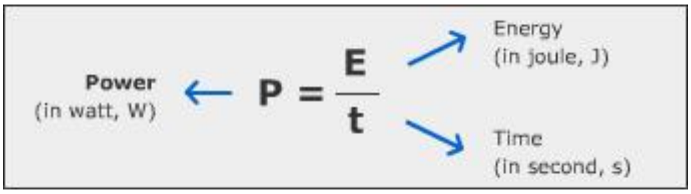
Note:

In an incandescent lightbulb, the electrical energy is converted to light and heat (thermal energy). Technically, there is no loss of energy, simply transformation from one form to another. However, we often speak of “energy loss” when a portion of the energy is not converted into the primary form useful for the device. In this case, we say that the thermal energy is a loss since the purpose of the lightbulb is to produce light.

A high efficiency lightbulb looses less thermal energy, it produces less heat. The efficiency of the lightbulb depends on the ratio between light and heat energies. We will revisit this later.

Power

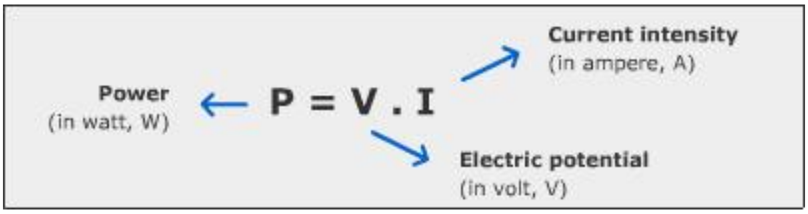
The power of an electrical appliance is defined as the flow of energy, that is the quantity of energy consumed per unit of time. It is expressed in watts (W).



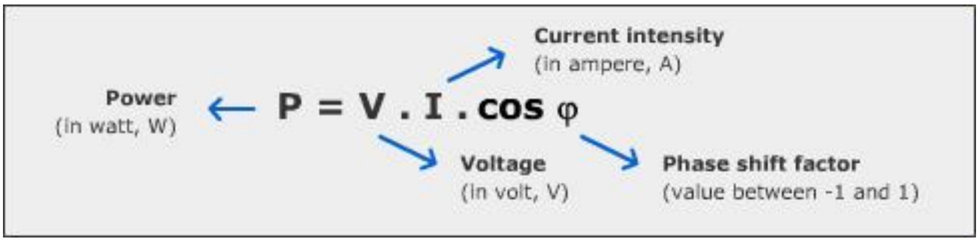
The power of a heater is the amount of heat that it can produce per unit of time. A 2200 watt electric oven consumes 2200 joules every second.

The power of a motor driven device tells us the amount of work that it can do per unit of time. A 500 W drill (that is 500 joules/second) will not make a hole through a stone wall as easily as another of 1000 W (1000 J/s) would.

In direct current (*), the power is proportional to the voltage (V) and to the current (I):



(*) In alternating current, the formula is slightly different, as the phase difference between current and voltage must be taken into account. Depending on the type of device (for example an electric motor), voltage and current do not necessarily reach their peak at the same time. The relation becomes:



We will revisit the subject when discussing motor operation

Let's go back to our flashlight example: it is subjected to a potential difference of 3 V (two 1.5 V batteries in series). If the current through it is 0.7 A, its power is 3 x 0.7 = 2.1 W. The intensity of the light depends on the electrical power.

The power is supplied by the electric generator: the batteries (rechargeable or not) in the flashlight, the power plant alternator for the chandelier and any appliance connected to the grid.

Power of batteries

The type of batteries used in a flashlight is often alkaline or rechargeable batteries. Their power is in the range from a few watts to a few tens of watts.

The choice of battery depends on their respective characteristics which have to match the requirements for their intended use.

Among the electric characteristics, let's count their voltage (in V), their capacity (in mA.h), and the maximum current they can supply (in A). Other features such as their size and weight or for rechargeable batteries, their time of self-discharge or the number of allowed charge/discharge cycles are also determinants of the choice of one over the other.

Battery characteristics, rechargeable or not, depend mainly on the chemicals involved.

Power of the electric network

In 2004, the production capacity in Belgium reached more than 15,000 megawatts (Source : Synergrid)

The following table gives an idea about the **capacity of production by primary energy source**

(in MW or megawatts, ie millions of watts)

By primary energy source — * Provisional figures — MW

	2004*	2003	2002	1999	1994
Nuclear	5.801,5	5.761,0	5.761,0	5.713,0	5.528,0
Conventional thermal	6.800,3	6.800,1	6.845,9	7.226,4	7.427,5
Biogas	25,9	25,9	25,9	11,8	1,8
Waste and vapor recovery	201,3	200,1	196,9	147,1	124,0
Combined heat and power, CHP	1.340,8	1.339,6	1.272,7	1.057,4	410,1
Lake and stream water	107,6	107,6	106,0	97,0	95,5
Pumping	1.307,0	1.307,0	1.307,0	1.307,0	1.307,0
Wind	92,8	66,9	31,0	9,3	5,2
Belgium	**15.677,2**	**15.608,2**	**15.546,4**	**15.569,0**	**14.899,1**

Since electric power cannot be stored, the supply must adapt to the demand: the production must match the consumption. The national power transmission grids are interconnected. This allows each country to quickly meet any unbalance between production and consumption by exchanging electric power between countries.

Note:

Any unbalance between production and consumption leads to a change in the alternators operating speed at the power plants within the interconnected network.

Even though it is a simplification, we can say that the balance between production and consumption is controlled by the frequency (50 Hz in our region). A change in frequency indicates an unbalance: when the frequency increases above 50 Hz, it means that the production exceeds the consumption, when it decreases below 50 Hz, the consumption is higher than the production. The unbalance causes a minute change in frequency, and to return to a balanced state, the alternators speed is continuously adjusted up or down by controlling the speed of rotation of the turbines.

We will come back to this in more detail in the production and transmission module ("Power distribution")

Resistance

In direct current (*), there is a relation between the difference of electric potential and the current involving the electric resistance of the conducting material. It is called Ohm's law:

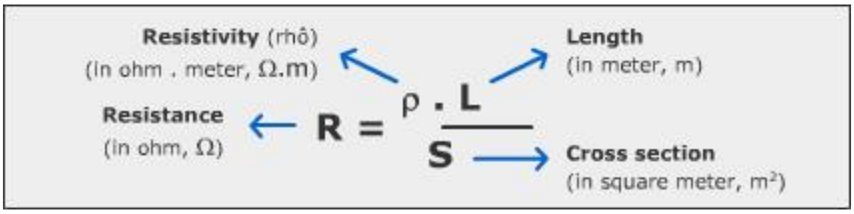
(*) In alternating current, Ohm's law still applies, but this time we use the impedance rather than the resistance:

The electrical impedance is a measure of the opposition to a sinusoidal alternating current in an electric circuit.

We'll come back to this when we discuss motors.

For an identical potential difference, the motion of the electrons is not identical in all materials: a more resistant material will not let the electrons through as easily. Materials have different resistances to the current. In a more resistant material, the electrons hit each other more, which slows them down. They lose their energy and the lost energy is transmitted to the material in the form of heat.

The resistance of a circuit depends on several factors, according to Pouillet's law:



- The resistivity which depends on the nature of the material: the higher the resistivity the higher the resistance;
- The length: the longer the circuit the higher the resistance;
- The cross section: the larger the section the lower the resistance.

Depending on the intended application, either a low or a high resistance will be required.

Low resistance requirement

The requirement for a low resistance is particularly significant when one considers power input cables, say to a large appliance: a cable that is too resistant (electrically) would overheat, leading to the deterioration of the insulation, seriously increasing the electrocution and fire risks.

In our flashlight, the energy loss due to the resistance of the wire is extremely low, but if the contact between the battery and the wire is of poor quality, the resistance at that point may be so high that the current will not reach the bulb.

High resistance requirement

The operating principle of an incandescent lightbulb makes use of thermal energy. The design must maximise the energy loss in the filament:

- It is made of tungsten, a material which has a higher resistivity than copper and a high melting temperature (3410°C);
- Its length is increased by making it into a spiral, and this also increases the luminous surface and thus the intensity of the visible light;
- It is very thin (not too thin though, it would otherwise melt quickly when heated by the current).

The filament is highly resistant to the current. The electrical energy is converted to thermal energy. The heat is so intense that the air must be evacuated from the bulb (vacuum or inert gas) or the filament would deteriorate and eventually burn.

A large part of the filament incandescent radiation is in the infrared... which heats without lighting.

Only a few percent (5%) of the electrical energy that reaches the filament is converted into visible light, the balance is dissipated into heat. Incandescent light bulbs are actually more a heating than lighting device! Nowadays, there are other types of light bulbs which do not make use of thermal energy, such as high efficiency bulbs, LEDs ... we'll come back to that in the "Uses of electricity" module.

Static electricity

So far, we've been talking about electricity as an organised movement of electrons, but there is another form of electricity: it is called static electricity because in this instance the electrons can't move. It is the case in insulating materials (*): when two insulating materials are rubbed against each other, electrons are stripped from one and transferred to the other.

(*) This happens in conducting materials as well, when they are isolated from other conductors. The charges are then evenly distributed throughout the material. This is for example what occurs in a moving car in dry weather: it charges itself with static electricity by friction with the air. The body is a conductor, but it is isolated from the ground by the tyres.

The quantity of exchanged charges depends on the materials put in contact, their surface and the percentage of humidity. Some materials can lose or acquire charges very easily, thus becoming more positive or negative respectively.

Classification of materials according to their propensity to become positively charged (from + to –): Rabbit fur – glass – nylon – wool – cat fur – cotton – silk – Dacron – polyvinyl chloride – polyethylene – rubber – Teflon

Note:
Friction is not necessary for the transfer of charges from one material to another. In fact, friction only amplifies the transfer process which otherwise naturally occurs by simple contact between the two materials.

Let's look at the balloon example.

(1) Both the balloon and the hair are initially neutral (before friction), that means they contain just as many negative charges as positive;

(2) Friction between the balloon and the hair causes a transfer of electrons from the hair to the balloon: the balloon is then negatively charged;

(3) When the negatively charged balloon is placed near the ceiling, it will locally modify the charge distribution on the ceiling: positive charges get closer, negative charges further away. The balloon will then stick to the ceiling by electrostatic attraction.

Both balloon and ceiling will slowly return to neutrality of charge and the balloon will progressively detach itself from the ceiling.

The neutralisation of charges can take different paths, depending on the conductivity of the medium separating the charged surfaces and that of the surfaces themselves. In our example, the humidity in the air allows the negative charges to flow from the balloon to the water molecules in the air. When the air is dry, the balloon remains attracted to the ceiling longer.

When the neutralisation of the charges occurs practically instantly, we speak of electrostatic discharge.

During the discharge, the electric potential of the two materials which were different because of the accumulation of negative charges on one and positive charges on the other, are equalised.

What happens when we feel an electric shock when we get out of a car and touch the body, especially when it's freezing outside ?*

The friction of the air on the car's body when in motion charges the body with static electricity. Since the tyres isolate the car from the ground, the car will reach a higher electric potential than the earth. Being inside the car, we are subjected to that same potential.

When we put our feet on the ground to get out of the car, assuming that the resistance of the sole of our shoes is not too high, the charges will drain to the ground, and we'll now be at the same potential as the earth.

If after having our feet on the ground, we touch the car's body, the electric charges on the car will also drain to the ground, following the path of least resistance, this time our own body. The circuit can close shortly before actual physical contact with the car, through the breakdown of the air gap: a good electrical contact with the car's body (low resistance) coupled with a very small surface (here the end of a finger) produces an intense and localised current (a few amps) which causes this well known unpleasant sensation, but which is actually benign. The discharge is quasi-instantaneous (a few nanoseconds).

On the other hand, if we touch the car's body before we put our feet on the ground, there is very little exchange of charges as our body's potential is nearly identical to that of the car. When we put our foot on the ground, all the charges, ours and the car's will drain to the ground. No sensation will be felt either in our hands or our feet since the contact between car and earth is already established.

*In freezing weather, the car will accumulate more charges because there is generally less humidity in the air, humidity that could otherwise neutralise the charges.

And in our body?

In the preceding sections, we have reviewed the concepts of current, conducting and insulating materials, potential difference, energy and power, resistance etc. We will revisit these concepts with regard to the human body as we also run on electricity!

For one, the nervous system is a formidable electrical communication network. Communication between the brain and the rest of the body takes place by means of electrical and chemical signals. An electroencephalogram (EEG) records the electrical activity in our brain.

The heart as well features specialised cells that automatically generate electrical impulses. These are the triggers of the electrical activity in the various heart cells, including those that are responsible for heart contractions. An electrocardiogram (ECG) records the overall electrical activity within the heart.

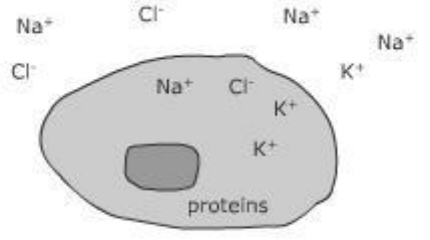
In a copper wire, the current is due to the movement of electrons. In the human body, which consists of water for the most part, the current is caused by the movement of ions.

The transmission of an electrical signal from one cell to another is obtained because the distribution of ions is different on either side of the cell wall.

The concentration in positive ions and negative ions is different on either side of the cell membrane:

- Na+ and Cl- ions are more numerous on the outside of the cell;

- K+ ions and negatively charged proteins are more numerous inside the cell.

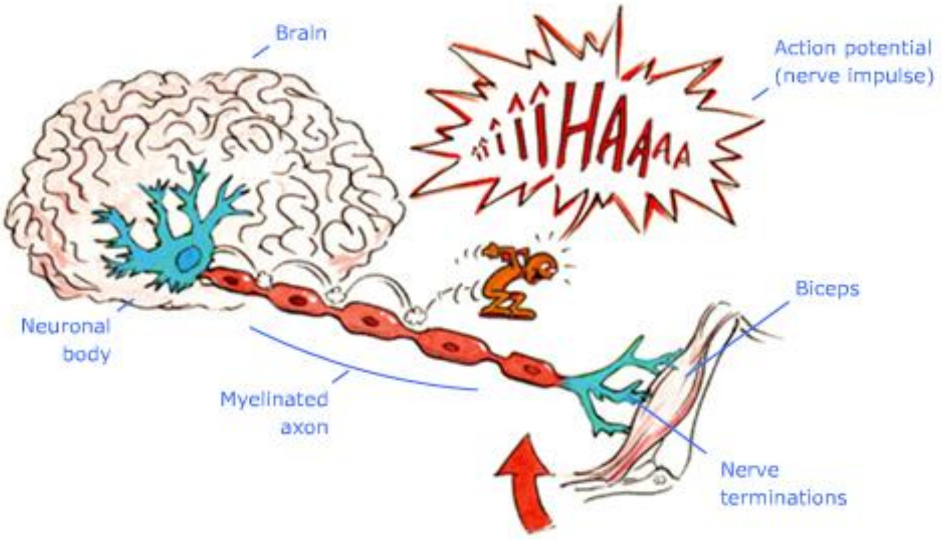


By placing a microsensor inside a cell and another one outside, a potential difference can be measured: at rest, the interior of the cell is more negative than the exterior (between -20 and -100 mV). It is the **at rest potential**.

Depending on the state of stimulation of the cell, few, many or no ions go through the cell membrane. The difference of potential between the inside and the outside of the cell vary with the movement of the ions. Beyond a certain threshold, the cell triggers the **action potential**.

Excitable cells (such as neurons, heart and muscle cells) have the ability to quickly change the intra- and extracellular ionic concentrations, thus initiating cycles of depolarisation and repolarisation.

In the neuron shown below, the action potential triggered in the body of the neuron travels along the axon in order to signal to the biceps that it must contract.



At the nerve terminations in contact with the muscle (synapses in this case), the electrical signal is converted to a chemical signal: the action potential releases certain molecules (called neurotransmitters) which represent information the muscle can understand.

The intensity of the action potentials is very low, but thousands of them travel through the human body neurons all the time. Their travelling speed (*) depends on the axons characteristics, such as their cross section and whether or not they have a myelin sheath.

(*) In order to conduct the nerve impulses more rapidly, some axons feature performance enhancements, such as:

- a larger cross section which allows the ions to move more freely and quickly (remember the electrical resistance of wires?);
- a myelin shield which covers the axon: the axon is said to be myelinated (see figure above). This sheath is electrically insulating. The action potential is not transmitted in a continuous manner down the myelinated axons. It literally 'jumps' at the gap where there is no or thinner myelin, called "Nodes of Ranvier". This type of conduction, said to be saltatory accelerates greatly the propagation of the action potential.

Note: In multiple sclerosis, the myelin sheath is destroyed, which leads to a slowdown or even loss of impulse conduction.

In case of contact with a voltage source (a badly insulated electrical cable for example), a current flows through the body: it is called electrocution (not necessarily lethal). The current seeks the ground via the path of least resistance.

The resistance of the human body depends on the conductivity (or its inverse, resistivity) of the tissues encountered by the current. Here are examples of human body resistance values (Source : Dawson et al, 2001)

Resistance value between ...	... one hand and one foot	... from one hand to the other
Child 1.10 m and 18 kg	**1,9 kΩ**	**2,5 kΩ**
Adult 1.77 m and 77 kg	**1,2 kΩ**	**1,6 kΩ**

Examples of resistance value of various tissues (Source: Dawson et al, 1997)

	Conductivity in siemens/metre (S/m)
Skin	**0,1**
Bones	**0,04**
Fat mass	**0,04**
Muscle	**0,35**
Heart	**0,1**

Note: The higher the conductivity, the easier it is for the current to go through the tissue. The above values show that muscles are good conductors when compared to bones for example.

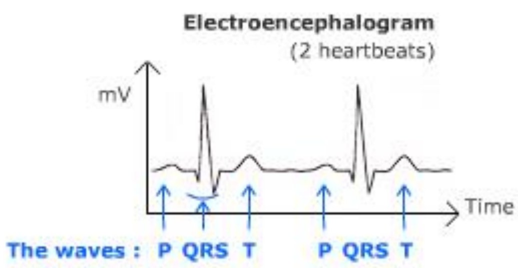
This current acts very much like the action potentials: the muscles contract and may even be tetanised (*), preventing the victim to let go of the voltage source.

(*) Beyond 40 contractions per second, the muscle doesn't have time to relax: it is tetanised. An electrocution with 50 Hz AC can thus lead to tetanisation. This is completely reversible as soon as the contact with the voltage source is broken.

Note: The situation is different regarding the cardiac muscle, because of the longer duration of the refractory period, that is the period during which the cardiac muscle cannot be re-excited. Therefore, it cannot contract again, it cannot be tetanised.

However, an electrocution at the heart level can quickly turn tragic, especially if it happens at the T-wave because the ventricular fibrillation risk is very high at that moment, which can stop the blood circulation. The ventricular fibrillation threshold is approximately 50 mA maintained for 1 second.

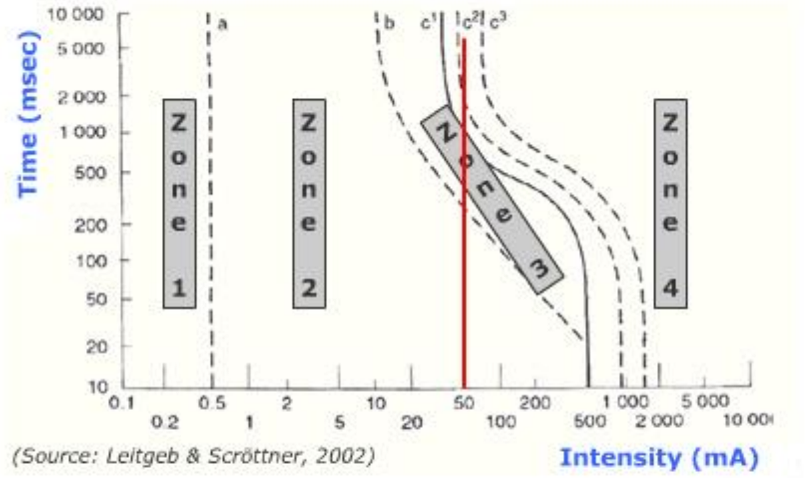
Ventricular fibrillation is an abnormally irregular heart rhythm caused by rapid, uncoordinated and ineffective contractions of the heart.



The T-wave occurs at that instant in the cardiac cycle when the ventricles relax and the blood enters the atria. It is the start of the cardiac cycle (see complete cycle in the ECG description).

Another danger of electrocution is the risk of electrical burns: subjected to a difference of potential, the ions move through the body and generate heat, very much the same way that electrons heat a tungsten filament.

The seriousness of an electrocution depends on the intensity of the current and on the duration of the contact, the type of skin and its moisture level.



Zone 1: No perception
Zone 2: Perception
Zone 3: Pain (not irreversible)
Zone 4: Risk of ventricular fibrillation

When an electrocution causes a muscle contraction and thus prolongs the contact (the hand closes on the wire), the risk of more serious injury increases. The seriousness of an electrocution depends on the intensity of the current and the duration of the contact.

The amount of current going through the body also depends on skin type and moisture level. Barefoot in a bathroom, directly in contact with water, we are more vulnerable.

This is why the building regulations requires higher protection standards in that room (see “Power transmission and distribution").

Note:

Our body may also be traversed by a current without being even noticed, namely the **contact current** or **touch current**. This current flows through the body between two points of contact (usually between hand and foot, between both hands or both feet) with conducting materials that are at different potentials (a machine and the ground, a faucet and the ground, etc.) whilst this difference of potential is not obvious a priori since none of the objects are connected to a voltage source (*).

(*) The contact current has nothing to do with contact with energised components (as is the case with electrocution), nor with electrostatic discharges.

It is a 50 Hz current, but unlike the current responsible for an electrocution, is very much below the threshold of perception: we do not feel it going through us.

These contact currents are the subject of in depth studies by our research team (see the link ‘Research teams’ on our website).

The contact currents are generally very low when the electric system is correctly designed, installed and maintained.

Quiz (Flash)

To access the Quiz, click on the link: http://www.bbemg.be/en/main-emf/electricity-fields/electrical-concepts.html

Appendices

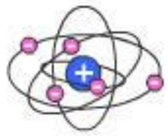
Evolution of the atom model

Contrary to popular belief, the electrons' trajectory around the nucleus is not elliptical like that of the planets around the sun. The motion of electrons obeys the laws of quantum mechanics. Thus it is not possible to exactly determine the position of electrons, but only the probability that one can be found in a given zone. To describe the position of electrons in this electronic cloud, we speak of atomic orbitals. The atomic orbitals theory proceeds from quantum mechanics research.

The atomic model has evolved over time, whenever new properties of matter were discovered. In Antiquity, it was postulated that matter could be divided into smaller and smaller fractions up to the smallest uncuttable grain called atom (from the Greek atomos which means uncuttable, indivisible).

In 1897, J.J. Thomson describes the electrons as corpuscles separate from the atom. The atom is represented by a positive sphere strewn with negative corpuscles (as prunes in a pudding… whence the name of "plum pudding" given to the model), the whole being neutral.

Later experiments showed that the positive charges are actually concentrated in the nucleus, and this model was then abandoned.

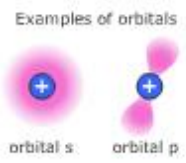


In 1911, E. Rutherford proposed the planetary atomic model: the negative electrons gravitate around the positive nucleus like the planets around the sun. Between electrons and nucleus is simply a vacuum. His model derives from classical mechanics.

The problem is that according to classic mechanics, an electron in orbit progressively loses energy. It would get closer and closer to the nucleus and eventually collide with the latter. But it's definitely not the case!

In 1913, N. Bohr describes the hydrogen atom as a positively charged nucleus around which one electron revolves. His model remains planetary, but he completes it by locating the electron on constant energy orbits. The electron thus conserves its energy as long as it stays on a defined orbit, and it can jump from one orbit to another by absorbing or emitting energy. This model explains observed behaviour of the hydrogen atom, but not the motion of electrons in atoms with more than one electron.

Since the nineteen fifties, with the Schrödinger model, quantum mechanics established itself as the better explanation.



In the Schrödinger model, the well defined orbits of the Bohr model become probability clouds: the electronic orbitals. These represent the probability of the presence of an atom at a given distance from the nucleus.

Unlike classical mechanics, quantum mechanics doesn't lend itself to an easy visual representation. This is why the planetary model is still in use today.

Number and distribution of the electrons in an atom: Mendeleev's periodic table

Anyone having taken beginner's chemistry at school will certainly remember this famous periodic table!

It is called "periodic" because it is organised to illustrate the recurring nature of the elements properties. In 1869, Dmitri Mendeleev finalised his classification of the then known 63 elements. The elements, placed in 8 columns in order of their atomic mass presented similar chemical, physical, and electrical properties column after column. The periodic table of the elements was thus born.

However, in Mendeleev's table, the atomic mass of some elements didn't allow them to be classified among elements with like properties. It was discovered early in the 20th century that the atomic number was a better predictor of the periodicity of the elements properties.

The atomic mass is computed from the nucleus mass which contains protons and neutrons. Each has a mass of 1 atomic unit (in the 10^{-24}g range). The mass of the electrons is so small that it can be neglected, it needs not enter into the calculation of atomic mass.

The atomic number represents the number of protons in a given atom. For example, hydrogen, element no. 1 has one proton in its nucleus, carbon has 6, silicon has 14 and copper 29. An atom is neutral if it has the same number of electrons and protons. Therefore, the atomic number is also the number of electrons gravitating around the nucleus.

The current periodic table includes more than 100 elements, 92 of which are natural (the rest have been artificially produced by nuclear reaction). The elements are organised as follows:

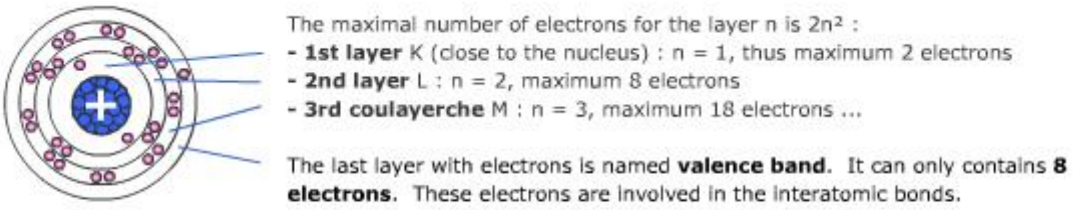
- The columns group the elements that have the same number of electrons on their outer layer (valence layer).
- The rows group the elements according to the number of electron layers.

Isolating and conducting materials: allowed and forbidden energy bands

In order to fully understand the difference between insulating and conducting materials, we must take another stroll through quantum mechanics. With Bohr's model, and then Schrödinger's, we saw that within the atom, the electrons can only be at defined energy levels.

The electrons gravitating around a nucleus position themselves on different layers precisely following rules (*). When atoms are assembled together to form a material, they influence each other, and we no longer speak of energy layers but of energy bands, characterising the entirety of the material.

(*) In an atom, the electrons position themselves on defined energy layers. These layers are labelled by the principal quantum number (n) starting from the nucleus:



Note:

The distribution of electrons among the various layers and sub-layers is governed by the following filling rules:

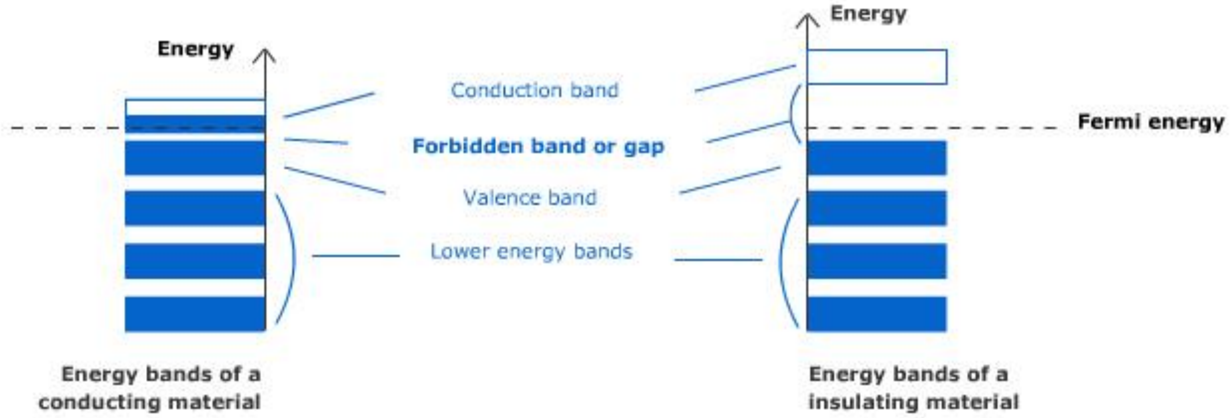
- The Pauli's exclusion principle: two electrons with the same quantum state cannot be on the same orbital.
- The increasing energy principle ("aufbau"): the lesser energy orbitals must be filled first.
- The Klechkowsky's rule
- Hund's law

These rules determine the placement of the electrons in an atomic orbital (in non excited state).

The common unit of energy is the electron-volt (eV), the energy acquired by an electron subjected to a 1 V difference of potential: 1 eV = 1 Volt x 1.6 10^{-19} Coulomb = 1.6 10^{-19} Joule

Example of conducting material: copper wire

When a copper wire is connected to the poles of a battery, the peripheral electrons acquire energy, move to the conduction band and participate in the production of current. This is possible because the required energy is low (the Fermi level is in the conduction band) and also because the last band of a copper atom contains only one electron. There is plenty of room to accept new electrons.

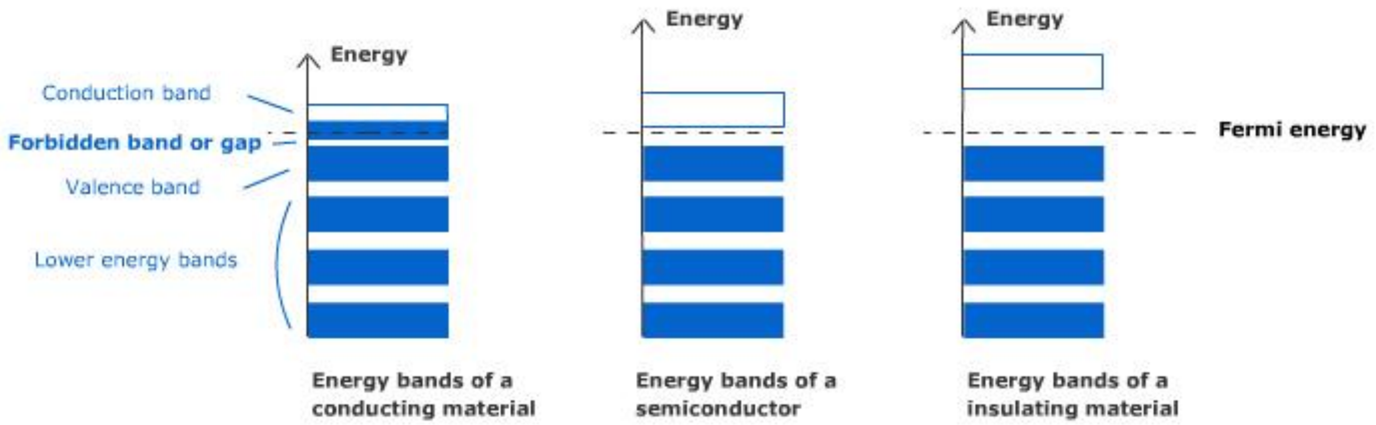


Example of insulating material:

Conversely, in an isolating material, the valence bands are complete. The electrons are highly involved in the interatomic bonds and the conduction band is empty. Moreover, the forbidden band is very wide. An insulating material could conduct electricity only if provided with a large amount of energy, by heating it for example. In practice however, the required temperature is so high that the material would melt before becoming a conductor.

Semiconductor materials

Semiconductors have intermediate properties between conducting and insulating materials.



Germanium and silicon are examples of semiconductors. Their valence band is not complete as it contains only 4 electrons and their forbidden band is relatively narrow. This means that the energy required to go from the valence band to the conduction band is not prohibitively high, the electrons can acquire that energy. With the acquired energy, the valence band electrons break the covalent bonds and reach the conduction band. When in the conduction band, they behave like the free electrons in metal: subjected to a difference of potential, they participate in the conduction of the current. The energy may be supplied by an increase in temperature, by light photons, etc. The latter come into play in photovoltaic panels and generate a direct current. We'll come back to this later.

How to generate a direct voltage?

Electrochemical generators

They maintain a difference of potential generated by the simultaneous chemical reactions that occur at the anode and cathode. Among these electrochemical generators, we've already spoken of batteries. However, those have the disadvantage of having a limited amount of reactants. When they are exhausted, the battery is useless.

Rechargeable batteries are also electrochemical generators. But they offer the advantage of being rechargeable, as the chemical reaction that generates the electrons can be reversed. The electrons now flow in the other direction and after a while, the battery is recharged.

Photovoltaic generators

They utilise the semiconductor properties of the materials they are made of. Photovoltaic solar cells are semiconductors that are able to convert light directly into electric current. When photons, that is light particles hit a semiconductor, the energy they supply can cause electrons on the valence band to move to the conduction band and thus increase the conductivity of the material.

Semiconductors such as silicon in their neutral state are not immediately and solely by themselves able to generate an electric current. In fact, they must contain impurities, which is done through a process called “doping”. This means that elements such as phosphorus are introduced to create a globally negative charge (n-type dopant) or boron to create a globally positive charge (p-type dopant).

If one side of the cell is a p-type semiconductor and the other n-type, the recombination of free charges (electrons and holes) generate an intrinsic potential difference. The electrons that were sent to the conduction band by the photon’s energy are carried from the n-side to the p-side. The result is a direct electric current which can be used to power electric appliances (after going through an inverter which converts DC into AC)

The dynamo

A dynamo is a machine that converts mechanical energy into direct current. The first industrial use dynamo was designed by Zénobe Gramme at the end of the 19th century. In spite of the name and the apparent similarity, a bicycle dynamo is actually an alternator, not a DC generator.

What is a joule?

A joule is the amount of the energy required to lift a 102 gram book 1 meter, on our good old earth (*). It is also the amount of energy required to raise the temperature of 1 gram of water by 1 degree Celsius.

(*) *For the curious! Where does the 102 g come from?*

The energy (E) required to lift the book can be calculated with the formula:

$E = m \cdot g \cdot h$

where

- m is the book's mass in kg, our unknown;
- g is the acceleration of gravity, 9.81 m/s^2 at the surface of our earth;
- h is the elevation in meters of the book above its initial position.

$m = E / g \cdot h = 1 / 9.81 \cdot 1 = 0.102$ kg = 102 g .... QED :-)

In short, a joule is rather small!

The order of magnitude of typical energy values varies greatly with the field of endeavour considered, so much that each has adopted its own energy unit, and that we are not always aware that we are talking about the same thing. For example:

- Nutritionists speak in calories or kilocalories (1 kcal = 4186 joules = 4.186 kJ). We need on average from 2000 to 2500 kcals per day (8.4 to 10.5 million joules or megajoules, MJ). A medium build person will burn approximately 550 kcal (about 1400 kJ) jogging (lightly) for half an hour.
- In the petroleum industry, they use the "ton of oil equivalent" (1 toe = 42 million kilojoules or 42 GJ). Environmentalists (and the World Bank) speak of kg of oil equivalent per capita to compare energy consumption from region to region; if you fill up once a week, 50 litres of petrol, you use about 7 litres per day, or 7 koe (approx. 250 MJ). Petrol and diesel have practically the same energy content, 1.05 vs 1 toe.
- In the power distribution industry, the most common unit is the kilowatt-hour (power x time) or kWh which is equal to 3.6 MJ. In Belgium, a 4 people household consumes on average 3500 kWh per year. Per day, that is 10 kWh (equivalent to seven 60 W light bulbs continuously lit), or 36 MJ of electrical energy.

The amount of energy contained in 1 l of petrol or diesel is approximately 10 kWh.

Summarising, in amount of energy...

1l of petrol = 1 koe = 35 MJ = 8000 kcal (8 Mcal) = 10 kWh

Common battery reactants and some of their characteristics

	Saline	Alkaline	Ni-Cd	Ni-MH	Li-ion
Cathode reactant	Manganese dioxide	Manganese dioxide	Nickel oxyhydroxide	Nickel oxyhydroxide	Lithium oxide
Anode reactant	Zinc	Zinc	Cadmium	Nickel alloy	Nickel alloy
Electrolyte	Ammonium chloride	Potassium hydroxide	Potassium hydroxide	Potassium hydroxide	Lithium salt (LiPF6...)
Nominal voltage per cell	1.5 V	1.5 V	1.25 V	1.25 V	3.6 V
Advantages / disadvantages	Price/Short life, not rechargeable	Price/Not rechargeable	Long life, relatively inexpensive/Low energy density, toxic metals	High energy density, no toxic metals/Reduced life cycle	Very high energy density/ Expensive, safety in use?
Typical usage	**Toys, etc...**	**Radio, toys...**	**Camera, portable medical devices,...**	**GSM, laptop, digital camera, cordless phones...**	**GSM, laptop, digital camera, mobile phones, electric vehicles...**





There are many types of batteries on the market, each with their own characteristics. All do not always fit all applications. This is why it is important to understand their differences in order to choose the most suitable type.

Note: The memory effect

When Ni-Cd batteries (and to a lesser Ni-metal hydride batteries) are charged before they are completely discharged, they keep in “memory” the intermediate charge threshold. This means that they will no longer discharge beyond that point, thus “wasting” the energy remaining in the cell. This memory effect can significantly shorten the effective autonomy of the powered device.

It is imperative that Ni-Cd batteries should be completely discharged before they are recharged.