Crystal Clear Electronics

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02 - Revision of Basic Physics

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In order to understand the inner workings of electronic circuits, we need to have a solid understanding of some basic concepts and refresh our Physics knowledge. In this chapter we will revise few definitions and derivations as well, but you don't have to remember them, it is enough if you understand the trail of thought behind them and try to remember the bigger picture.

The concept of energy

When fat is placed into a heated frying-pan, it melts. This means the hot pan has the ability to alter its contents, and this ability is connected to temperature. A bow only can shoot arrows, if it was stretched, so a stretched bow also has some kind of ability to change things. It is useful to describe the changing abilities of things with some kind of common physical quantity. This physical quantity is called energy. The common symbol is *E*, its unit of measurement is Joule, which is represented by J.

Several forms of energy (the ability to change things) can be observed in the nature. If we roll down a hill with a bicycle, and stop by braking at the bottom, then we will experience, that the brake shoes warmed up. If we want to get back to the hilltop, then we have to invest energy, because we change our and the bike's position.

This energy is provided by our cells from the chemical reaction of the food we have eaten and the oxygen we are breathing. The energy invested during the climb enables our body and the bicycle to change its state of motion at the time of going down. Our speed is increasing while going downhill, so our kinetic energy also increases. When braking, our speed is reduced, which means our kinetic energy is reduced as well. Energy doesn't disappear, it is converted to heat in the brakes instead. This process illustrates the most important feature of the energy: we cannot destroy it; we can only transform it into different forms. In our case the chemical energy of nutrition was converted into potential energy by our own body and then, while riding the bicycle, it became kinetic energy and finally it warmed up the brake-shoes at braking.

Work

Work is the process of changing a body's energy (for example when a car is accelerating). The energy change is called work, its symbol is *W*, and the unit of measurement is Joule (it equals with the unit of measurement of energy, since it is energy difference.)

$$W = \Delta E \ [\mathrm{J}]$$

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Energy can also be interpreted as a body's ability to do work. It can be verified through measurements that work is directly proportional to body force and displacement.

$$W = F \cdot s$$

Power

From the point of view of our tiredness, it is not the same, whether we walk up or run up a hill. Although the energy change is the same in both cases, there is a slight difference between the two processes: we did the same work in different amount of time. It is worth to introduce a physical quantity that takes into account the time during the processes of energy change. This is called power, its symbol is *P*, its unit of measurement is Watt, which is represented by W (don't confuse with the symbol of work!). It shows us, how much energy has been changed in unit time.

$$P = \frac{\Delta E}{\Delta t} = \frac{W}{\Delta t} [\mathrm{W}] = \frac{[\mathrm{J}]}{[\mathrm{s}]}$$

If a light bulb has a power of 100 watts, then it means that during operation it converts 100 J of electricity into light and heat every second.

The electric charge

The electric charge is a basic quality of certain particles that determines the extent how they participate in electrical interactions. Charge as a physical quantity is usually denoted by the letter *Q*, its unit of measurement is Coulomb, which is represented by C. Atoms, molecules, and extensive bodies can be charged as well. The charge of extensive objects is caused by the excess or lack of an elementary particle called the electron. The electron has a low negative charge. In materials, normally, each electron has a single positive-charged particle pair (called the proton), so when looking from the outside the material appears neutral, and its total charge is zero. Occasionally, there can be cases when there are excess electrons or lack of electrons, for example, when two bodies are rubbed together. The positive protons cannot move, but some of the negative electrons can, so through rubbing the electrons can move from one body to another, disrupting the balance of charges.

Electrostatic force (Coulomb-force)

Experience has shown that bodies with the same sign of charge are repelled, but those with the opposite sign of charge attract each other, thereby, in both cases they act on each other by force.

The electrostatic force is one of the fundamental interactions of physics, its size is described by the formula

$$F = k \bullet \frac{Q_1 \bullet Q_2}{r^2}$$

(called Coulomb's Law) in case of point charges.

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Interpretation of Coulomb-force

The number *k* is a constant (its value is approximately $9 \bullet 10^9$) Q_1 and Q_2 are the signed charge of the two bodies (negative for negative charge, and positive for positive charge), and *r* is the distance between the two charges. It is obvious that the higher the charging of the two bodies, the greater the attracting or repulsive force between them. Increasing the distance reduces the effect squarely, that is, at twice the distance, only a quarter of the force between the two bodies awakes.

ELECTRIC FIELD

Take a charged point-like body and place it somewhere in space, far away from other bodies, and place a positive charge near to it, called test charge, and measure how much force it exerts. If the resulting force is divided by the charge of the test charge, then a physical quantity is obtained, which is characteristic of this point of the space. This quantity is called electrical field, it is denoted by *E*, and its unit of measurement is V/m.

$$E = \frac{F}{q} = \frac{k \bullet \frac{Q \bullet q}{r^2}}{q} = k \bullet \frac{Q}{r^2} \; [\mathrm{V/m}]$$

If the Coulomb-force formula is substituted for F, then we get, that the electric field strength is independent of the charge of the test charge, it is dependent only of the charge of the charged body and the distance of the measurement. A field strength value can be assigned to all points of the space with this thought.

The electric charges create an electric field around them, which „extent” is indicated by the value of electric field strength. Where the value of electric field strength is higher, there is a greater force on a charge placed there.

ELECTRICAL VOLTAGE

Take a case when the electric field strength at all points of the space is the same in size and direction, but not zero. Put a positive test charge in this space. Because the Coulomb-force affects it, it will move. The starting point of the displacement is marked with A, and the end point is marked with B. The electric field is working on it during its movement.

$$W_{AB} = F \bullet s = E \bullet q \bullet s_{AB}$$

It can be seen that the work, which has been done, is directly proportional to the size of the test charge (*q*), electric field strength(*E*), and the displacement (s_{AB}).

If you want to get a quantity that gives you the ability to produce work at a particular point in the space, then it should be independent of the test charge. Dividing the work by the charge of the test charge we get this amount. Its name is electrical voltage, it is denoted by the letter *U*, and its unit of measurement is Volt (V).

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$$U_{AB} = \frac{W_{AB}}{q} = \frac{E \bullet q \bullet s_{AB}}{q} = E \bullet s_{AB} \; [\mathrm{V}]$$

Based on the above, the voltage can only be interpreted between two points. If we agree on a zero point, then all the other voltages are understood to that point, and in electrical circuits the zero point is the ground (often just GND, for short).

When we say in everyday life that a galvanic cell is „9 volts”, then it means, that we can measure a voltage of 9V between the positive and negative terminals. So, the galvanic cell (cell, battery) is a device that has the ability to produce work. The chemical processes in it results in the so-called charging separation: electrons accumulate at the negative terminal, while lack of electrons occurs at the positive terminal. When conducting material is placed between the two terminals, the electrons accumulated at the negative terminal pass through the conductor to the positive terminal.

CONCEPT OF CAPACITY (CAPACITOR)

The capacitor is a device for accumulating electrical charge. Many types are made, the simplest is the so-called plate capacitor, which has a double-sided metal plate (arms) and insulating material (for example air) between them.

If a positive terminal of a galvanic cell is connected to one of the arms, the negative is connected to the other by a wire, then the plates will have an equal but opposite sign charge i.e., an electron excess on the negatively charged plate, and a lack of electrons on the positive plate.

If we were able to measure the charge level of the capacitor’s arms while charging, then we would experience that the measured charge is directly proportional to the voltage between the arms. In other words, if you connect twice as high voltage to the capacitor, then it will double the charge on the plates. The proportionality between the two amounts is the capacity (its symbol is C, and its unit of measurement is Farad [F]).

$$Q = C \bullet U$$

so

$$C = \frac{Q}{U}$$

which units are:

$$[\mathrm{F}] = \frac{[\mathrm{C}]}{[\mathrm{V}]}$$

Capacity shows the capacitor’s charge storage capacity. The higher the capacitor’s capacity, the more charge can be stored at the same voltage.

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About the capacitors

It can be verified through measurements and calculations, that the capacitor's capacity depends on the distance between the two plates (*d*), the surface of the two plates (*A*) and the type of insulating material (ε_r) between them.

$$C = \varepsilon_r \cdot \varepsilon_0 \cdot \frac{A}{d}$$

ε_0 is the so-called vacuum permittivity, whose value is

$$\varepsilon_0 = 8.85 \cdot 10^{-12} \, [\frac{\mathrm{C}^2}{\mathrm{N} \cdot \mathrm{m}^2}]$$

ε_r is the relative permittivity constant of the given material, which shows that in case of a given capacitor arm arrangement how many times the test substance increases the capacity value compared to vacuum.

The capacity formula shows us, that the closer we place the arms, the greater the capacity will be. The same happens if we increase the surface of the armaments. In practice, the capacitor with a capacity of 1F is rare, it is a high value, the usual value of magnitude is nF, µF.

This correlation is also used in case of making of capacitors. The smaller the insulation thickness and the larger the surface area, the capacitor fits in a smaller place. The thickness of the insulator cannot be reduced with impunity, since the thinning of the insulating layer also reduces the maximum voltage that can be applied, or an electrical discharge can occur that destroys the insulating layer and the capacitor.

When the capacitor is charged, it stores energy. When a capacitor is charging and its arms are suddenly short-circuited with a wire, we experience that the conductor gets warm. This means, that the energy of the wire has increased, which can only come from the capacitor.

It is worth to understand, that there is a difference between the concept of capacity and capacitor. A capacitor is a device, which has capacity, which stores electric charges in electronic circuits. Capacity is therefore a physical quantity and a capacitor is an object, whose most important parameter is its capacity.

Electric current

If we connect two different charged bodies with a metal wire, we can notice that electrons move from the more negative body towards the more positive body. The flow of charges is called electric current (I), whose unit of measurement is Ampere [A]. The electric current shows how much charge flows through the conductor in a given time.

$$I = \frac{\Delta Q}{\Delta t}, \qquad [\mathrm{A}] = \frac{[\mathrm{C}]}{[\mathrm{s}]}$$

If electric charge moves from one place to another, may it be any charged particle, then we are talking about electrical current. In liquids, for example, not only electrons can move, but also atoms that have

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electron deficiency or excess (they are the so-called ions). In any technical drawings, the direction of the current is indicated by an arrow.

The direction of electric current

The direction of current (for short current direction) can be selected optionally. For historical reasons, the current direction in which positive charges flow is called positive direction. This is the so-called technical current direction. Since the discovery of the electron we know that in metallic conductors negative charges are moving, yet in markings and calculations we use the technical direction, and so in the technical drawings the arrow does not point in the direction of electron migration, but in the opposite direction.

CONNECTION BETWEEN CURRENT AND VOLTAGE

If there is a current flowing through a body, we can be sure that a voltage can be measured between its two points, as the flow of the charges require work, and the ability to produce work is the voltage.

CONDUCTING PHENOMENON, RESISTANCE

Continuous electrical current can be generated by a circuit, which main parts are the battery, the conductor, and the consumer. At the negative terminal of the battery there is an electron excess, at the positive terminal there is a lack of electrons, because of the chemical processes taking place there. When connected to the consumer with wires, the electrons from the negative terminal flow through the conductor and the consumer reaching the positive terminal of the battery, trying to equalize the charge difference. The battery replaces the electrons at the negative terminal with the chemical processes taking place in it.

The atoms of the conductive materials are in a stable metal grid. The flowing electrons collide with them during their movement, so they pass on some of their motion energy to the bound atoms, which causes a rise in the temperature. The electrical energy of the battery is converted into the kinetic energy of the electrons, some of which are converted into thermal energy during the collision, leading to a rise in temperature. Conductors of different materials and geometries inhibit electrons in their motion to varying degrees, we use the concept of resistance to describe this property. Its symbol is R, its unit of measurement is Ohm (which is represented by the Greek big omega $[\Omega]$).

$$R = \frac{U}{I}, \qquad [\Omega] = \frac{[\mathrm{V}]}{[\mathrm{A}]}$$

The above mentioned and so-called Ohm’s Law states, that the resistance value can be determined as the ratio of the voltage on the conductor and the current flowing through it. It also follows that if current flows through a conductor and the resistance between two points is not zero, then a voltage drop can be measured between these two points.

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Resistance of different materials

If we measure the resistance of wire pieces of different lengths and diameters made of different materials, we find that the resistance depends on all three parameters in the following way:

$$R = \rho \cdot \frac{l}{A}$$

where ρ is the so-called specific resistance (its unit of measurement is $\Omega \cdot \mathrm{m}$), l is the length of the wire, A is the cross-sectional area of the conductor. This means that thicker wire has less resistance at the same length, and the longer wire has a higher resistance at the same cross-section. The value of the specific resistance of the materials can be found in tables, the resistance of most materials has been measured by humanity. The materials can be grouped according to the value of their specific resistance. If this value is small, then we call it conductors, if it is large, then insulators. It is worth to know, that the insulators have no infinite resistance, so there is very little current flowing through them, if we apply voltage to them.

In electrical circuits, there is often a need for a component, that has deliberately higher resistance than the wires. These components are called resistors (there is separate word for the component [resistor], and the physical quantity [resistance]). Resistor is a component often used in electrical circuits, often because of the limiting role of a constant current.

ELECTRIC POWER

We have already found, that if current flows through a conductor, then heat develops, which is called Joule heat. If we measure this current, and the voltage between the two points of the material, then from their product we get the heat output.

$$P = U \cdot I$$

However, it is worth to express the current and the voltage in the Ohm's Law, and replacing them into the formula of power:

$$P = I^2 \cdot R = \frac{U^2}{R}$$

This means for example, that 1.5 times higher the current, the heat loss is 2.25 times as high.

The wires also have resistance, and therefore heat develops. For example, when choosing the size of wires connecting household appliances to the network, it should be taken into account how much this heat generation will heat them up, as there may be a so high temperature, that the insulator surrounding the wire will melt and cause a fire.

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ELECTRICAL SOURCES

In electronics we distinguish voltage source and current source. A voltage source is a device, whose voltage is constant between its external terminals, even if current flows through it.

In contrast, the current source changes the voltage between its terminals so that the characteristic current flows through it.

These definitions assume an ideal case, in reality the voltage measured on the voltage sources will decrease slightly due to the load current. The terminals of the voltage source must not be short-circuited (connected with a low-resistance wire), because then a very high current will flow (due to its almost constant voltage), and this can lead to break the device, and also to personal injury.

In everyday language, the galvanic cells and batteries are commonly referred to as current sources, although they are much rather voltage sources, especially from an electrical point of view, as during load a near constant voltage can be measured on them. From an electronic point of view, we cannot produce a current source in real life with simple electrochemical methods (such as galvanic cells), but surely, we can with the help of a suitable electrical circuit.

So far, we have talked about direct current and direct voltage. Ideally, this means that the voltage and current in each case are unchanged at all times. In reality, such a situation does not exist for a long time, e.g. the voltage of a battery is also reduced during discharge.

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ALTERNATING VOLTAGE

The alternating voltage is a special case, where the voltage measured at the voltage source is positive, then awhile negative, and then it is periodically repeated. Why is this good? Our machines based on electromagnetic phenomenon (a large number of transformers, and motors) require sinusoidal alternating voltage and current. Without them, it would be difficult to imagine the production and supply of cheap and high-power electricity.

The figure below shows the representation of a sinusoidal alternating voltage in a Cartesian coordinate system. The time on the horizontal axis and the value of the voltage on the vertical axis can be read.

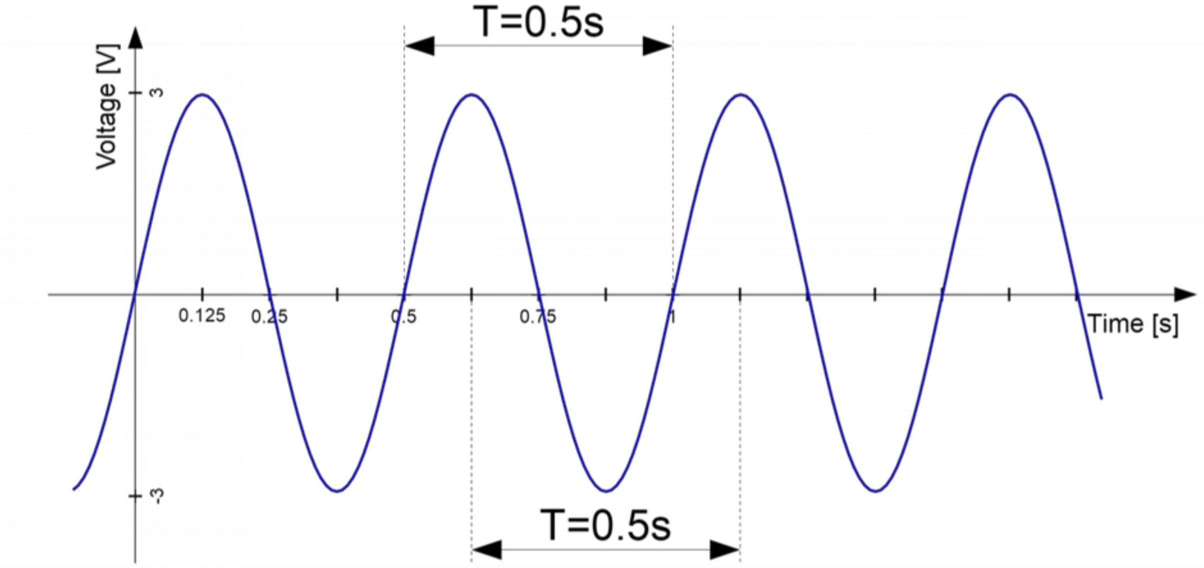

Figure 1 – Sinusoidal alternating voltage

Since the value of the voltage depends on time, such functions are called time functions. Periodic time functions have a period of time that shows how long a repetitive part of a function lasts. Typically, the period of time is denoted by the letter T. In the example above, the period of time is 0.5 seconds.

The rate of repetition of the function is usually characterized by the so-called frequency, which shows how many times the periodic function part is repeated in 1 second. Frequency is indicated by the letter f, the unit of measurement is Hertz (it is represented by Hz). Frequency is reciprocal of period of time, i.e. the frequency of the function in the above example is 2 Hz.

$$f = \frac{1}{T} = \frac{1}{0.5\ [s]} = 2\ [Hz]$$

The voltage-time function shown in the above example can also be described as an equation with the help of frequency or period of time:

$$U(t) = 3 \cdot \sin(2\pi f \cdot t) = 3 \cdot \sin(\frac{2\pi}{T} \cdot t) = 3 \cdot \sin(4\pi \cdot t)$$

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RESISTORS IN SERIES, RESISTORS IN PARALLEL

We are talking about serial connection, when we connect together only one of the terminals of the two components.

In case of parallel connection, both terminals of these components are connected.

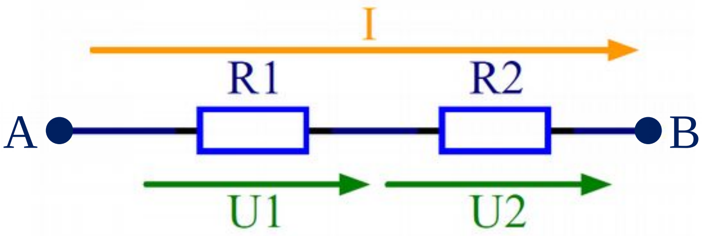

Figure 2 – Resistors in Series

In case of serial connection (see Figure), the same current flows through the two resistors, so their current equals. This follows that the voltage of the resistor R_1 is $U_1 = R_1 \bullet I$ while the voltage of the resistor R_2 is $U_2 = R_2 \bullet I$ and $U_1 + U_2 = U$.

The so-called equivalent resistance between points A and B can be obtained from the above and from Ohm's Law.

$$R_{AB} = \frac{U}{I} = \frac{U_1 + U_2}{I} = \frac{R_1 \cdot I + R_2 \cdot I}{I} = R_1 + R_2$$

Thus, in case of the serial connection of resistors, the value of the resulting resistance is the sum of the two resistances. If multiple resistors are connected in series, it is apparent from the above thought that the resulting resistance is the sum of all the resistors connected.

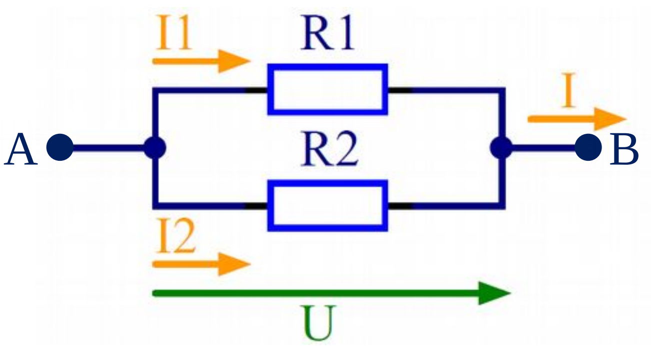

Figure 3 – Resistors in Parallel

In case of parallel connection, the voltage of the resistors will be the same, since both of their terminals are connected. Then the current of the two resistors is $I_1 = \frac{U}{R_1}$ and $I_2 = \frac{U}{R_2}$. The equivalent resistance in this case can be derived from Ohm's Law.

$$R = \frac{U}{I} = \frac{U}{I_1 + I_2} = \frac{U}{\frac{U}{R_1} + \frac{U}{R_2}} = \frac{U}{\frac{U \cdot R_2 + U \cdot R_1}{R_1 \cdot R_2}} = U \cdot \frac{R_1 \cdot R_2}{U \cdot (R_1 + R_2)} = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

In this way we got, how we can calculate the equivalent resistance of parallel resistors.

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KIRCHHOFF'S LAWS

The voltage and current conditions prevailing in the electrical circuits must be described by a mathematical apparat in order to calculate the values of each parameter. The so-called Kirchhoff's Laws provide a simple mathematical description of this problem with the help of the law of conservation of charge and energy.

KIRCHHOFF'S CURRENT LAW

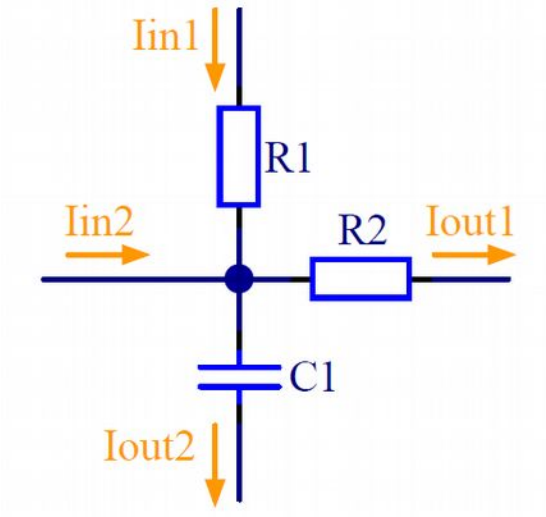

Figure 4 – Kirchhoff's first law

If more than two circuit components are connected together, the location of the connection is called a node. According to the law, the sum of the current entering a node is equal to the sum of the current flowing out of the node, which means

$$I_{in1} + I_{in2} + ... = I_{out1} + I_{out2} + ..$$

If the sign of the current, which flows into the node is considered to be positive, and the sign of the current which flows out of the node is considered to be negative, then the law can be reformulated: the sum of the currents entering and exiting the node is zero,

$$I_{in1} + I_{in2} + ... + I_{out1} + I_{out2} + ... = 0$$

If we think about it, the law is equivalent to the charge conservation. The current, as discussed earlier, indicates the number of charges that flow through the conductor over a single period of time, so the law says that the amount of charge that flowed into the node is exactly the same amount of charge that flows out of it.

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KIRCHHOFF'S VOLTAGE LAW

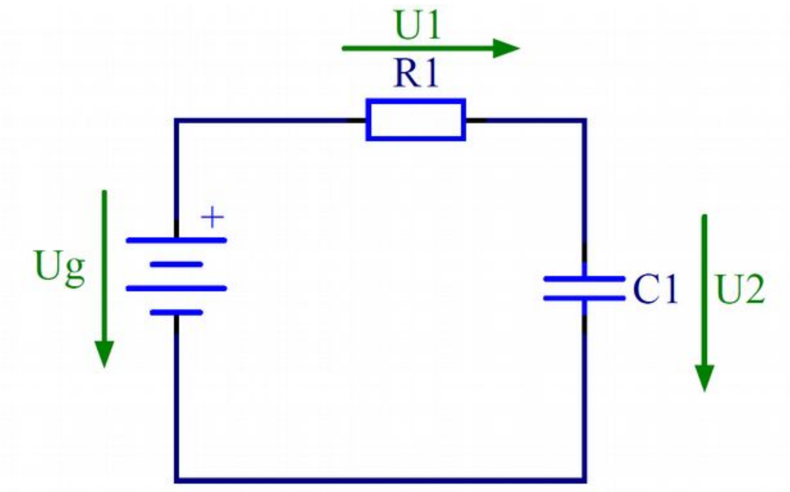

Figure 5 – Kirchhoff's second law

In each circuit we can find so-called loops, that represents closed curves and possible current loops (see Figure). According to the law, the sum of the voltage of each element in a closed loop is zero, i.e.

$$U_1 + U_2 + ... = 0$$

Relationship with the law of conservation of energy

In the circuit shown in the figure, the power of the source is $P_g = U_g \cdot I$, the power of the resistors $P_1 = U_1 \cdot I$, $P_2 = U_2 \cdot I$. Because power is equivalent to a change in energy over the unit time, we can declare, based on the law of conservation of energy, that the signed amount of power must be zero.

$$P_g + P_1 + P_2 = U_g \cdot I + U_1 \cdot I + U_2 \cdot I = I \cdot (U_g + U_1 + U_2) = 0$$

This is only possible, if the signed sum of voltage is zero, which is the same as Kirchhoff's voltage law statement.

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