Fundamentals of Electronics

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1 Introduction

Electric currents flow along wires to transmit energy for domestic and industrial purposes. To understand many electrical phenomena, it is only necessary to learn a few simple rules of circuit analysis and these will be the underlying theme of this guide.

This pre-course material establishes the basic definitions of electric charge, currents, voltage or electric potential energy. Secondly, it discusses the behaviour of currents in circuits and introduces some important circuit components.

Ultimately, all of these processes can be understood in terms of the simple model of the atom dating from 1910, Figure 1. This is an example of a Carbon atom with six "orbiting" electrons each with a negative charge, - e, six protons each with a positive charge of + e and six neutrons with zero charge. Here e is the smallest currently measurable amount of charge, equal to $1.6.10^{-19}$ coulombs. The net overall charge of the atom is zero. However, if any atom captures an extra electron its net charge becomes - e and is said to be negatively charged. Similarly, if a neutral atom loses an electron, its net charge becomes +e and is said to be positively charged.

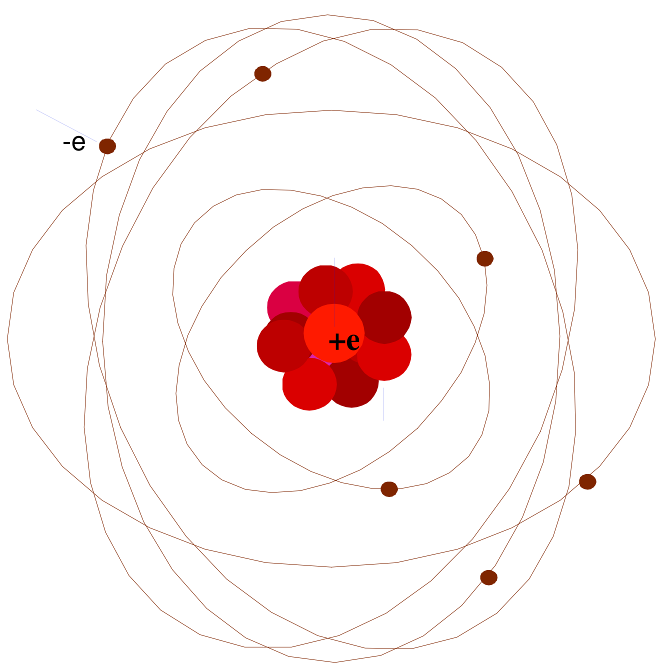


Figure 1 Atomic make-up of Carbon. Orbiting electrons each have a negative charge of $-e$, protons in the nucleus each have a positive charge $+e$. Neutrons have zero charge.

2 Charge

You are already familiar with one of the fundamental forces of nature, namely the gravitational force, which holds you securely to your seat. Now consider another force, the electrostatic force. This is the force responsible for binding atomic electrons to nuclei, the cores of atoms, and for holding atoms together to form microscopic molecules and macroscopic solids.

Electrostatic force is not as apparent as gravitational force. But it is easy to perform electrostatic experiments. As a child you may have rubbed an inflated balloon on your jersey and then placed the balloon against the wall of a room and seen that the balloon sticks to it, Figure 2(a). Here, the electrostatic attraction between the balloon and wall is so large that it exceeds the gravitational force on the balloon. A similar experiment involves rubbing a piece of plastic, such as your ruler, on a woollen cloth Figure 2(b). The ruler can then lift small pieces of paper, rather as a magnet lifts a paper clip. Another example of the action of electrostatic forces can be seen when brushing your hair. If your hair is dry and you brush briskly, you will see that your hair is attracted to the brush.

Under what circumstances do bodies like the balloon, the ruler and the hair experience electrostatic force? Something must have happened in each case during the rubbing process to make the bodies experience an electrostatic force.

(a) (b)

Figure 2 (a) Party balloons with electrostatic charge. (b) Your ruler can also be charged.

Well, the rubbing has removed some electrons from some of the atoms of one item and transferred them to the atoms of the other.

It is this imbalance of charge between the two bodies that causes them to experience electrostatic forces. Hence they are said to be charged with electricity. In Section 2.1 we discover some of the properties of this electric charge.

2.1 Electric charge

In 1785, a series of simple experiments similar to those discussed above, clarified the nature of electrostatic charge. These experiments were carried out by Charles Augustin de Coulomb. The unit of electrical charge, C, is named after him. The experimental results can be abridged as follows.

- The presence of electric charge on a body can only be detected by the forces that the electric charge causes the body to produce or experience. That is, the only way to detect charge is to see whether the body can produce an electrostatic force.
- Two types of electric charge exist. Like charges repel each other, unlike charges attract one another. Bodies carrying one type of charge become electrically neutral (i.e. exert no electric forces) after absorbing an equal quantity of the other type of charge. This quality of charge cancellation leads to the two types of charge being labelled positive (+) and negative (-).
- All matter contains electric charge. This charge is carried by fundamental particles. Electrons carrying a negative charge and protons a positive charge. The neutron, as its name implies, is electrically neutral. When two different materials are brought into intimate contact and energy is supplied, by rubbing, electrons may be transferred from one material to the other.
- In the rubbing process illustrated in Figure 2(b), no charge has been created: existing charges have simply been redistributed between the wool and the plastic. In other words, charge is conserved.
- Since bodies carrying opposite charges attract one another, any body that has a *deficit* of electrons will not only attract negatively charged macroscopic bodies in

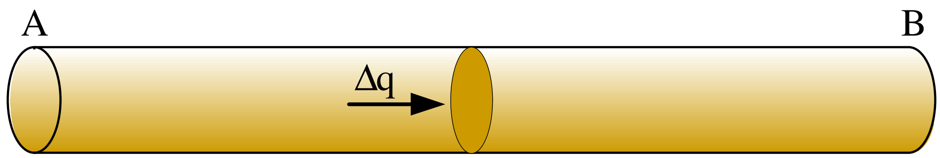
the vicinity, but will also attract any electrons that are close by. If these electrons are free to move, they will flow towards the positively charged body and neutralize it. This process of charge redistribution prevents us from detecting the electric charge on a hand-held rod of copper when it is rubbed. When copper is rubbed, it does acquire a charge. But copper has the property that electric charge can flow easily through it and so the imbalance of charge in the rubbed region can be made good by electrons flowing through the rod to or from the hand holding the end of the rod. Materials that allow electric charge to flow through them are called conductors and those that do not are called insulators. Glass and plastic are examples of insulators, whereas metals and salty-water are conductors.

Certain materials behave like perfect insulators for small electric forces only. When the electric force increases, there comes a point when electrons can be detached from the atoms of the material and these electrons can then flow a short distance. This flow of electrons is equivalent to a charge flow through the material. The material is said to have suffered breakdown and become conducting. This behaviour can theoretically occur in all insulators. In most solid insulators, however, the force required to produce breakdown is so large that the effect can often be neglected. In gases, on the other hand, the occurrence of breakdown is quite common. You may have seen sparks when you undress in a darkened room. Nylon clothes can become charged through the rubbing involved in everyday movement. When you undress, you separate oppositely charged regions. These regions come to equilibrium by the charge flowing through the air between them when the air breaks down. Some of the air molecules become excited by the charge flow and then lose this surplus energy by emitting visible radiation (light).

3 Current

The electric current is the rate at which charge is transferred, and it is represented by the symbol i. For example, if q units of charge go from A to B in t seconds, the average current $\bar{i}$ from A to B is

$$\bar{i} = \frac{q}{t} \tag{1}$$



$$i = \frac{dq}{dt}$$

Figure 3 The instantaneous current along a copper wire is defined as the net rate at which charge passes through an area perpendicular to the axis of the wire.

To cater for situations in which the current is not constant, we can modify equation (1) to define an instantaneous value of the current. For a wire, this is the rate at which charge passes through a plane perpendicular to the axis of the wire. If a net charge of Δq crosses the shaded area in Figure 3 in a time Δt, the instantaneous current is

$$i = \lim_{\Delta t \to 0}\left(\frac{\Delta q}{\Delta t}\right) = \frac{dq}{dt} \qquad (2)$$

So far I have not explicitly stated what is carrying the current. In normal circumstances, there are two possible mobile charge carriers; ions and electrons. Ions, atoms with either an excess or deficiency of electrons, are by no means uncommon. They exist in many chemical solutions, Figure 4, in certain solids, in plasmas and in the Earth's upper atmosphere. Ionic conduction can be very important. The messages in nerve cells are carried by pulsing currents of Na^+, K^+ and Cl^+ ions.

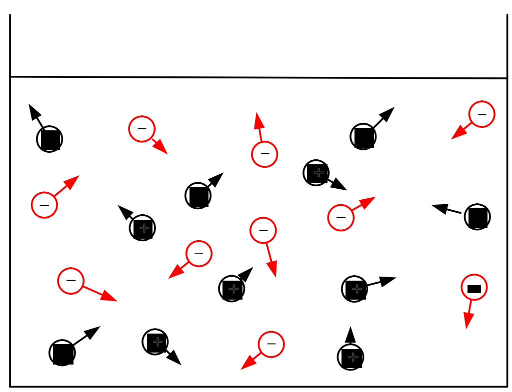


Figure 4 When salt or sodium chloride, NaCl, is dissolved in water it splits up into Na^+ ions and Cl^- ions. The Na^+ ion has a deficit of one electron and the Cl^- ion has gained an electron.

However, here we concentrate on the currents flowing in metal wires, and in a metal the ions are relatively immobile, fixed in a regular array known as a lattice. Metal ions are always positive, being formed from atoms that easily lose one or more electrons. These "free" electrons wander through the ion lattice, Figure 5, and it is the motion of these negative charges that gives metals their conducting properties.

In insulators, e.g. glass or plastic, there are no free electrons and current cannot be passed through such materials. Because the current in metals is carried by negatively charged electrons, there is a slight complication in defining the direction of a current in a wire. The negative sign of the electronic charge is the result of an arbitrary choice made by Benjamin Franklin in the eighteenth century between the "two types of electricity". The consequence of his choice is that a positive current flowing in a certain direction in a wire corresponds to a flow of electrons in the opposite direction. Fortunately, it is only when considering the microscopic aspects of currents that this anomaly becomes important. When indicating the direction of the current flow on a circuit diagram, we simply show the direction in which positive charge would flow, and bear in mind that the current is produced by electrons moving in the opposite direction.

3.1 S.I. Unit

The unit of current, the ampere, takes its name from André-Marie Ampere, a 19th century French scientist. In the SI system of units the ampere, A, is the fundamental unit of electromagnetism, and the unit of charge, the coulomb, is derived

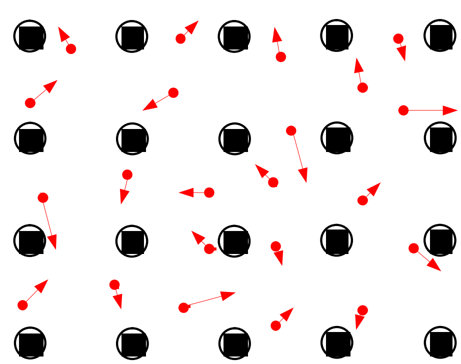


Figure 5 A schematic view of the crystal structure of a metal. The positive metal ions exist in a rigid lattice. Each atom, on forming an ion, gives up one or more electrons, which are then free to wander through the crystal.

from it. 1 ampere = a charge flow of 1 coulomb/second

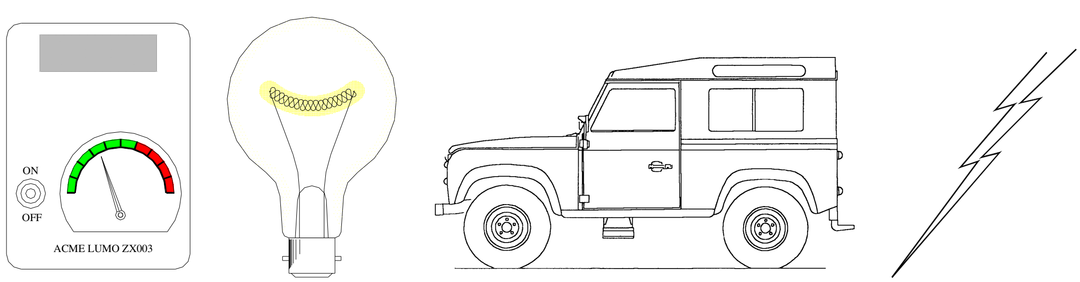
$$1\,\text{A} \quad = \quad 1\text{Cs}^{-1} \qquad (3)$$

The magnitudes of the currents involved in some common phenomena and devices are shown in Figure 6.

3.2 Why currents flow

In an isolated wire there is no net charge flow. The ions are immobile and the free electrons move randomly past the ions. Yet we know that it is possible to arrange for there to be a net movement of electrons towards one end of the wire. How is this done? The simplest answer follows from energy arguments, Figure 7. Electrons will flow from A to B in a wire if, by so doing, the potential energy of the system is reduced. Because electrons have a tiny mass, the amount of gravitational energy is too weak for them to sink to the lowest point in the wire. Rather it is the electrostatic potential energy here that dominates. If some means is found of arranging for electrons at A to have a higher electrostatic potential energy than at B, electrons will tend to flow from A to B. To maintain this current it is, of course, necessary to replenish the supply of electrons at the higher potential energy end of the wire. This will be elucidated upon later in the course.

An analogy between the flow of water in a pipe and the flow of charge in a wire, Figure 8, is useful. Water flows along the pipe when there is a height difference (and therefore a gravitational potential energy difference) between the ends of the pipe.



light meter	light bulb	car electrics	lightning
~ 10^{-5} amps	~ 1 amp	~ 10 amps	~ 10^{5} amps

Figure 6 The orders of magnitude of the currents involved in a variety of processes.

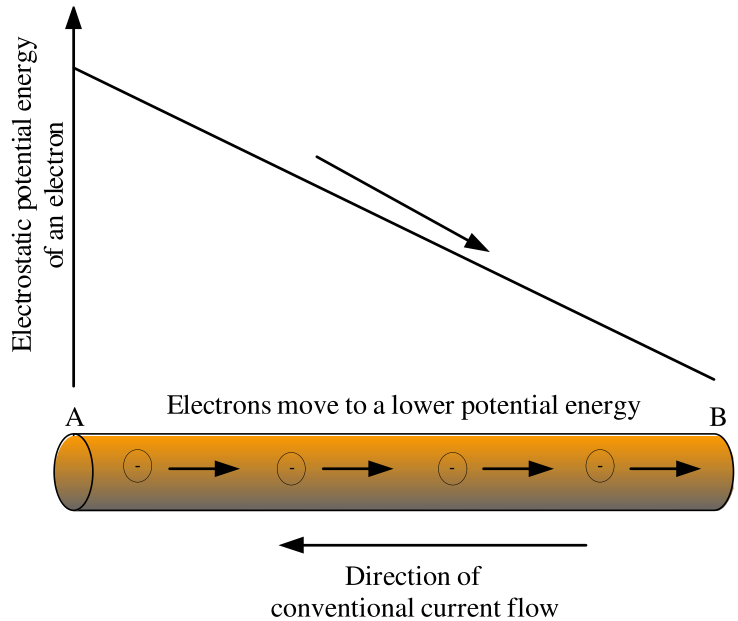


Figure 7 Electrons will move along a wire from A to B if there is a consequent reduction in electrostatic potential energy.

In terms of forces, it is the weight of the water, the gravitational force acting on it that pulls the water down along the pipe. Similarly, current flows in a wire if there is an electrical potential difference between the ends of the wire; each electron experiences an electric field that pulls it along the wire.

The comparison can be taken a little further. When water flows along a pipe, there are inevitably frictional losses. The water does not leave the pipe with kinetic energy equal to the gravitational potential energy it has lost. Some of the energy is

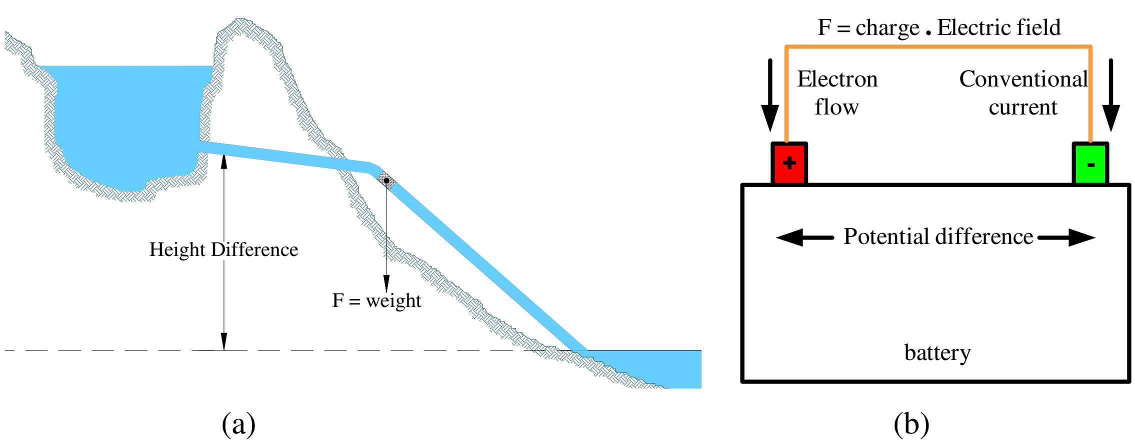


Figure 8 The analogy between the downhill flow of water and the flow of charge.

transformed into heating both the pipe and the water. Similarly, electrons do not steadily accelerate from one end of the wire to the other. They frequently "collide" with the ions past which they are moving and lose kinetic energy. This energy loss manifests itself as a rise in the temperature of the wire. The average speed with which electrons drift along a wire in response to a typical potential difference is no more than a few millimetres per second. The "frictional losses" in a wire are the basis of electrical resistance; this is the subject of the Section 4.

4 Ohm's law and resistance

The flow rate of water passing through a pipe is proportional to the height difference between the ends. In 1827 Georg Simon Ohm, found an equivalent relationship for charge flow in metal wires. He found that the current, *i*, through a wire is proportional to the potential difference, V, between the ends of the wire.

$$i \propto V \qquad (4)$$

This relationship is usually written in the form

$$V = iR \qquad (5)$$

and is known as Ohm's law. The constant of proportionality R is known as the resistance of the wire. The unit of resistance is the ohm, whose SI unit is given by the Greek capital letter Ω.

$$1\text{ohm} = 1\Omega = 1\text{VA}^{-1} \qquad (6)$$

Ohm's law is not a fundamental law of physics. It is an empirically tested and useful relationship which is obeyed by most metals in normal circumstances. It is not obeyed by all materials or by all components in electrical circuits, Figure 9. Broad pipes carry water more easily than narrow pipes. Similarly, thick wires carry current more easily than thin wires. In general, therefore, the resistance of a wire is determined both by its geometry and by the material from which it is made.

EXAMPLE: A light bulb is connected across a 9 volt battery. If the current through the bulb is 0.3 A, what is the resistance of the filament? Using equation (5)

$$R = \frac{V}{i} = \frac{9\,\text{V}}{0.3\,\text{A}} = 30\,\text{V}\,\text{A}^{-1} = 30\,\Omega\,.$$

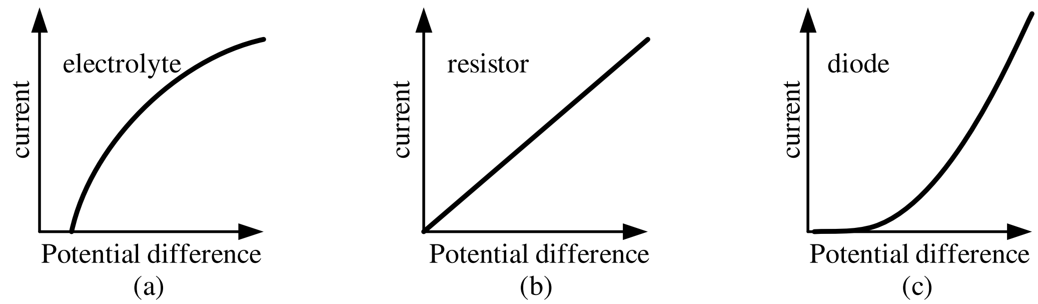


Figure 9 Current versus potential difference (a) an electrolyte, such as salty water, (b) resistor, and (c) a diode. Only current flow in the resistor shows direct proportionality to the potential difference.

What current will be drawn from the battery if a bulb of half the resistance replaces the first one? If R is reduced by half, then the current increases by a factor of two.

$$i = \frac{V}{R} = \frac{9\,V}{15\,\Omega} = 0.6\,V\,\Omega^{-1} = 0.6\ A\,.$$

5 Power in electric circuits

When a current is flowing in an electric circuit, each charge is moving towards a point where its potential energy is lower. This leads to a loss of potential energy. If Δq units of charge flow through a circuit across which there is a potential difference V, then there is a change in potential energy, ΔE given by

$$\Delta E = \Delta q . V \qquad (7)$$

This follows directly from the definition of potential. Here Δq is measured in coulombs (One coulomb of negative charge is defined as the combined charge of 6.10^{18} electrons) and V in volts. Then to satisfy equation (7) the units of ΔE must be joules.

Power is defined as the rate at which energy is transferred, $\frac{\Delta E}{\Delta t}$ and the unit of power the watt, W, is equal to one joule per second. In the electrical case, substituting from equation (7), power $= \frac{\Delta q}{\Delta t} . V$. But $\frac{\Delta q}{\Delta t}$ is simply the current *i*. So, electric power is given by

$$\text{power} = i\text{V} \tag{8}$$

If i is measured in amps and V in volts, then the power calculated from equation (8) will be in watts.

The “lost” energy ΔE cannot disappear! That would contravene the law of conservation of energy. It is converted into some other form of energy, the type depending on the circuit. The simplest form of circuit is a single resistor connected to a battery. A resistor, as was shown in Figure 9(b), is a circuit element that obeys Ohm’s law. One type takes the form of a piece of carbon or metal, with dimensions customised to give the required resistance, Figure 10. Here the drop in electrostatic potential energy is converted into internal energy. The electrons are accelerated by the electric field, gaining kinetic energy. This energy is subsequently transferred in collisions with the ions in the lattice, setting the ions into vibration. This increased vibration corresponds to an increase in temperature. So, the loss of potential energy leads to a corresponding increase in thermal energy. Because of this effect, lots of electrical equipment needs forced air cooling.

EXAMPLE: When current i is passed through a resistance R, what is the electric power dissipated in the resistor in terms of i and R. From equation (8) power = iV. But V = iR and so, substituting for V, power dissipated in resistor is given by

$$i^2\,\text{R} \tag{9}$$

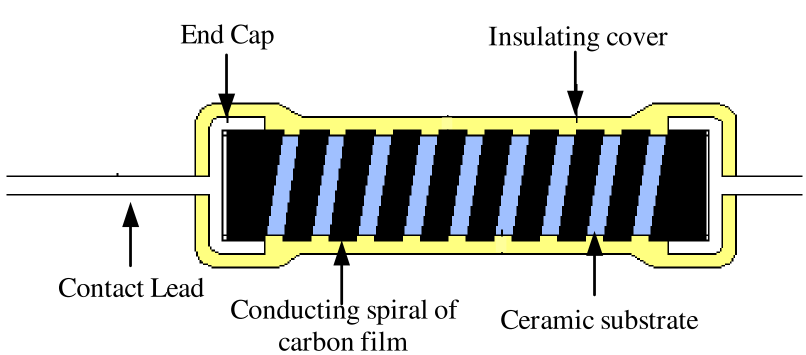


Figure 10 Internal structure of carbon film resistor.

Alternatively substituting for i,

$$\frac{V^2}{R} \tag{11}$$

ScottishPower charge their customers in kilowatt hours, kWh. This is just the product of the power and the duration of use. Their bills are written in terms of kWh rather than joules.

$$1 \text{ kWh} = 10^3 \text{ W} \,.\, 3600 \text{ s} = 3.6.10^6 \text{ J} \tag{12}$$

EXAMPLE: A kettle uses 2 kW of power when plugged into the mains. If it takes 3 minutes to boil 1 litre of water, and electricity costs 7.07p per kWh, estimate the cost of the electrical energy used to make a pot of tea.

Power used is 2 kW times 3/60 h = 0.1 kWh, $\therefore$ cost = 7.07p/kWh . 0.1 kWh = 0.707 p

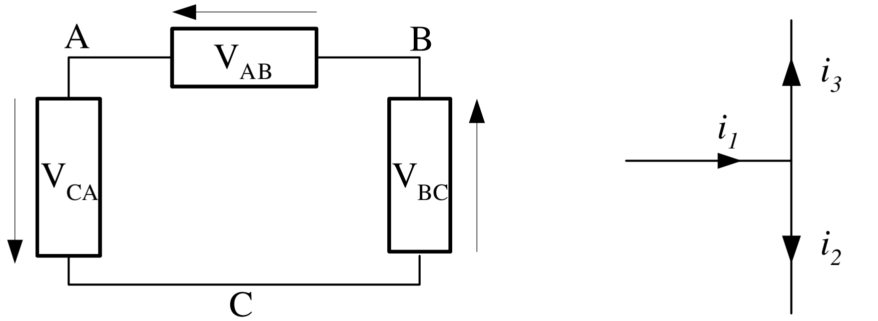
EXAMPLE: If an electric light bulb is rated at 100 W, 240 V, (a) what current does it draw? (b) What is the resistance of the filament?

(a) Power = iV $\rightarrow i \quad \dfrac{100\,\text{W}}{240\,\text{V}} = 417\,\text{mA}$. (b) $R = \dfrac{V}{i} = \dfrac{240\,\text{V}}{417\,\text{mA}} = 576\ \Omega$.

5.1 Series and parallel resistors

Many circuits, such as the wiring in a house or a car, contain only a few circuit elements and can be analysed on the basis of a few simple rules. This Section looks at one of these important circuit elements, the resistor, and examines the two ways in which resistors may be combined.

All circuits, irrespective of their complexity, adhere to the two principles summarized in Figure 11. These principles are known as Kirchoff's laws. If the first of these laws did not hold it would be possible to start from some point in the circuit where the electrical potential was known, and, having gone round the circuit adding up the potential differences, come back to the same point and find it had a different potential. Clearly this is impossible. Similarly, the second law could only be violated if charge



$$V_{AB} + V_{CA} + V_{BC} = 0 \qquad\qquad i_1 = i_2 + i_3$$

(a) Law 1 (b) Law 2

Figure 11 (a) the sum of potentials around a circuit sum to 0; (b) The currents entering a junction equal the currents leaving the junction.

were created or destroyed at the junction. The simplest resistor circuit consists of a source of electrical energy, such as a battery, and a single resistor, Figure 12. By convention, these are represented by the symbols shown in the figure. The longer line in the battery symbol represents the positive terminal, the one where the electrical potential is higher. In analysing this circuit, we shall assume that the battery has no resistance and maintains a potential difference of V between its terminals, irrespective of the current it supplies. The connecting wires are assumed to have zero resistance. Neither of these assumptions will ever be completely true, but usually the error involved will be small.

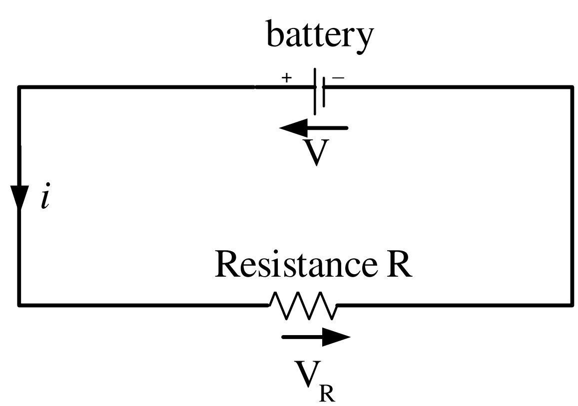


Figure 12 A simple circuit consisting only of a battery and a resistance R. The current *i* is maintained by the potential difference V across the terminals of the battery. A potential difference, V_R, develops across the ends of the resistor.

For this circuit the current flow is anticlockwise. Applying Kirchoff's first law, $V + V_R = 0$, but $V_R = -iR$, the minus sign indicating there is a voltage drop in the direction of current flow through the resistor. Consequently, $V = iR$ permitting the calculation of current if the battery voltage and resistance is known.

In analysing more complicated circuits, it is often useful to be able to return to a simple equivalent circuit like that of Figure 12. As an example of this approach, consider a circuit in which there are two resistors rather than one, Figure 13.

The two resistors may be placed in a line so that the same current goes through each. In this arrangement the resistors are said to be in series. From Kirchoff's first law, the sum of the potential differences around the circuit going in an anticlockwise direction must be zero,

$$V + V_1 + V_2 = 0 \tag{13}$$

Using Ohm's law for the two resistors (V = $-iR$ etc., where the minus sign again indicates a potential drop across the resistor) equation (13) can be rewritten as

$$V - iR_1 - iR_2 = 0 \quad \rightarrow V \quad = \quad i(R_1 + R_2)$$

A comparison with the equation for a single resistor, V = iR, shows that the effective resistance R_{total} of the pair of resistors in series is equal to the sum of their individual resistances.

$$R_{total} \quad = \quad R_1 + R_2 \tag{14}$$

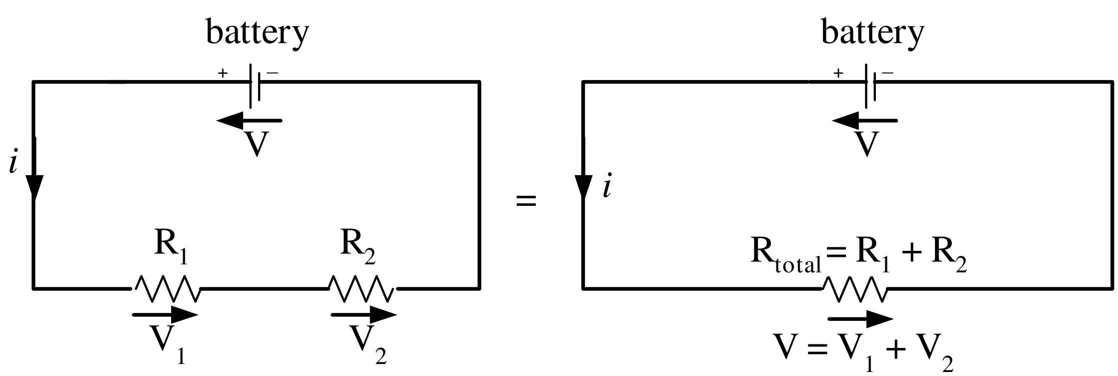


Figure 13 Series resistance, the effective value of the two resisters is equal to their sum.

With this equation the current through the circuit may be calculated by using the effective resistance in the equation $V = i R_{total}$

In another arrangement the resistors may be placed side by side, Figure 14. When their ends are connected to the same points in the circuit like this the resistances are said to be in parallel. Again the two resistances can be replaced by a single effective resistance.

Applying Kirchoff's second law at either point A or point B in Figure 14,

$$i = i_1 + i_2 \tag{15}$$

When the battery potential difference V is placed across the effective resistance, R_{total}, the current is given by

$$i = \frac{V}{R_{total}} \tag{16}$$

Similarly the currents i_1 and i_2 are produced with the same potential difference V across R_1 and R_2 respectively. Therefore, again using Ohm's law…

$$i_1 = \frac{V}{R_1} \quad \text{and} \quad i_2 = \frac{V}{R_2} \tag{17}$$

With these expressions for the currents, equation (15) can be rewritten as

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

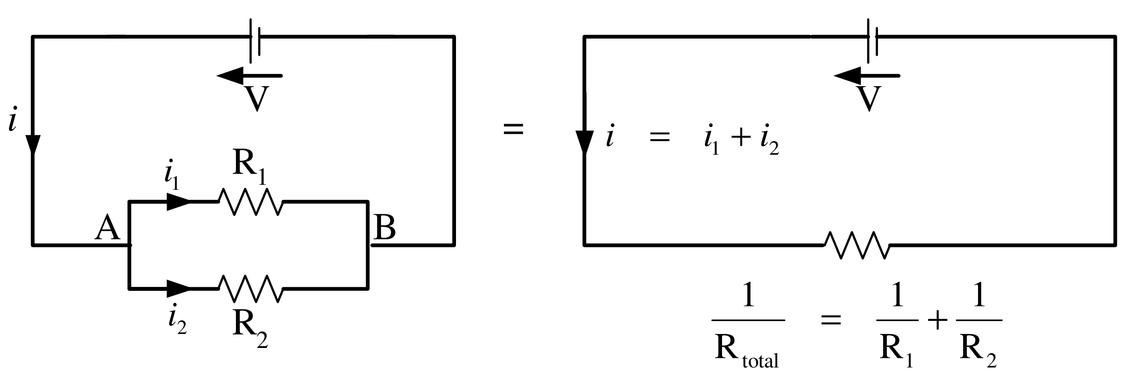


Figure 14 Parallel resistance, resistances R_1 and R_2 are equivalent to an effective resistance R_{total} that is given by $l/R_{total} = I/R_1 + l/R_2$.

Dividing by V gives

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} \tag{18}$$

This may be rearranged as

$$R_{total} = \frac{R_1 R_2}{R_1 + R_2} \tag{19}$$

These derivations may be generalized for any number of resistors, n, in series or parallel to give the following expressions

Series resistances $R_{total} = R_1 + R_2 + \cdots + R_{n-1} + R_n$ (20)

Parallel resistances $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_{n-1}} + \frac{1}{R_n}$ (21)

EXAMPLE: An engineer needs resistances of 5 kΩ, 2 kΩ, and 900 Ω but only has 1 kΩ, and 10 kΩ, resistors. How can he combine these to achieve the necessary values? Hint: these resistors have tolerances of ± 5% in their value and so the designer will be happy to achieve the required values to within ± 5%).

Using equation (19), two 10 kΩ resistors in parallel give $R_{total} = \frac{10\,k\Omega . 10\,k\Omega}{10\,k\Omega + 10\,k\Omega} = \frac{100\,(k\Omega)^2}{20\ k\Omega} = 5\,k\Omega$. Using equation (14), two 1 kΩ resistors in series give, $R_{total} = 1\,k\Omega + 1\,k\Omega = 2\,k\Omega$. Again using equation (19), a 1 kΩ resistor combined in a parallel network with a 10 kΩ give

$$R_{total} = \frac{1\,k\Omega . 10\,k\Omega}{1\,k\Omega + 10\,k\Omega} = \frac{10\,(k\Omega)^2}{11\ k\Omega} = 909\,\Omega = 900\,\Omega \pm 1\%.$$

6 Other Resources

6.1 Physics

This is an excellent reference site with good definitions and many worked examples. All aspects of physics are covered but you might be interested in the electricity, magnetism and electronics areas.

http://230nsc1.phy-astr.gsu.edu/hbase/hframe.html

6.2 Mathematics

6.2.1 Mathematica

Probably the best site around! There are thousands of worked examples and free downloadable notebooks you can run if you have the Mathematica software. There is a cheaper student edition of the software available.

http://www.wolfram.com/

Then click on "Services and Resources" for the examples.

6.2.2 Numericana

Another good reference site with lots of examples and explanations is...

http://home.att.net/~numericana/

6.3 Instrumentation

For a thorough description of how the C.R.O. works, the following hyperlinks give a wealth of information. Study of these sites will arm you with enough information for you to be quite confident in the use of the analogue oscilloscope, and introduce you to the Aladdin's cave of digital oscilloscopes.

http://www.tek.com/Measurement/App_Notes/XYZs/03W_8605_2.pdf

http://www.bkprecision.com/download/scope/HowScopeWork.pdf

http://www.cs.tcd.ie/courses/baict/bac/jf/labs/scope/

A more tongue in cheek, American, animation of scope operation is presented at the following site.

http://www.williamson-labs.com/scope1.htm