Module

1

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Circuits & Resistors

Conductors & Insulators

What you'll learn in Module 1

Section 1.1 Conductors & Insulators.

- Recognise common electrical conductors and their uses.
- Recognise common electrical Insulators and their uses.

Section 1.2 Materials in Circuits.

- Identify electrical conductors on a PCB.
- Identify common insulating and conducting materials and their uses on a PCB.

Section 1.3 Resistance in Conductors.

- Calculate the dimensions of a conductor.
- Describe the effect of length and cross sectional area on the resistance of a conductor.

Section 1.4 Resistivity.

- Describe the property of resistivity.
- Carry out calculations involving resistivity.
- Use appropriate electrical units (Ωm) to describe the resistivity of common conductor & insulator materials

Section 1.5 Temperature Effects

- Describe the effect of temperature on the resistance of a conductor.
- Describe the effect of temperature on the resistance of a insulator.
- Define negative and positive temperature coefficients.

Section 1.6 Resistivity Quiz

- Calculations on Resistivity.

Fig.1.0.1 A Complex Circuit The Raspberry Pi

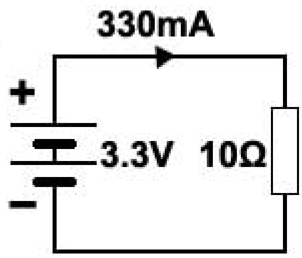


Fig.1.0.2 The Raspberry Pi - Simplified!

Introduction.

Electronic circuits range from quite simple arrangements of a few connected components to vast and very complex networks. This module provides a basic introduction to circuits and their properties.

However even a complex circuit, such as the Raspberry Pi shown in Fig. 1.0.1 can for some analysis purposes be illustrated by a simple diagram such as that shown in Fig. 1.0.2.

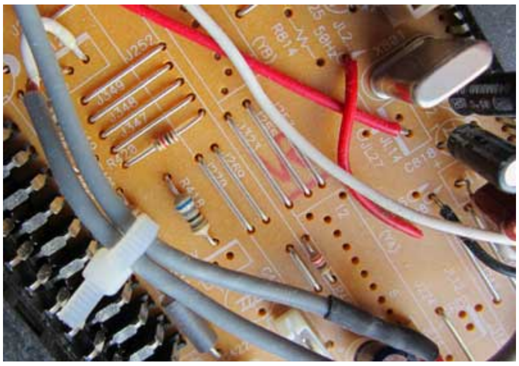
This is because all of the complexity of a circuit can be replaced (in theory) by a single resistor.

The Raspberry Pi can be powered by a 3.3V DC supply, from which it draws around 330mA of current (depending on what mode it is operating in). This means that theoretically the Pi could be replaced by a resistor whose value would be 3.3V divided by 330mA = 10 ohms.

Why? Admittedly the resistor would not do as much as the Raspberry Pi, but it will make circuit calculations much simpler! Any electrical or electronic circuit, however complex, supplied with a driving voltage from some sort of power supply, will pass a certain amount of current, and that is the same action as if a power supply (mains/line, battery, radio signal or whatever) were supplying a single resistor having a particular value of resistance.

Using just the basic properties of simple circuits containing only power supplies, conductors, insulators and resistors can greatly simplify the understanding of more complex circuits. This initial module will therefore study the basic properties of conductors and insulators and show you how to calculate their important values. Later modules in this series will introduce resistors, both as single components and as part of more complex networks.

1.1 Conductors & Insulators



What you'll learn in Module 1.1

After studying this section, you should be able to:

- Recognise common electrical conductors and their uses.
- Recognise common electrical Insulators and their uses.

Conductors

In electrical and electronic circuits and components, CONDUCTORS are materials that allow electric current to flow through them because their atomic structure allows the outermost (free) electrons to easily move from one atom to another, and because the electrons carry a negative electric charge they are easily repelled by an applied negative electric charge, and attracted by a positive charge. Therefore applying a voltage between the two ends of a conductor causes an 'electron drift' from negative to positive giving rise to an electric current. Suitable materials to act as conductors include:

Most Metals

Some Gases

Solutions of Acids, Alkalis & Salts in water

Metal Conductors

Metals such as copper, aluminium, and some alloys (mixtures of two or more metals), e.g. brass, phosphor-bronze and manganin are widely used in electrical and electronic circuits. Electric connectors in switches or in a mains 13A plug use a good conductor such as brass for their main contacts. Phosphor bronze, an alloy of copper and tin with some phosphorous, is springy in nature and useful for contacts such as the fuse holder in a mains plug, as well as "brushes" used to carry current between the stationary and rotating parts in some electric motors.

The best metal conductor of all is pure silver; however it has two drawbacks. Its surface readily tarnishes when exposed to air, this creates a high resistance surface that reduces its conductivity. Although this doesn't cause a great problem in high voltage conductors, it can significantly reduce conduction in low voltage applications such as switch or plug/socket contacts. Silver is also expensive compared to other metals such as copper (the second best metal conductor). Although Copper is the most popular metal for electrical conductors,it also tarnishes, so copper conductors are often plated with less tarnishable metals such as nickel. For optimum contact conduction in low voltage applications however, gold plating is used because, although slightly less conductive than pure copper, gold does not tarnish.

Gold plating is commonly used to reduce 'skin effect' in conductors used for high frequency current applications. Skin effect is the tendency of high frequency currents to flow mainly close to the surface of the conductor. Using gold plating therefore provides a current path with a resistance only slightly worse than copper in the body of the cable, but considerably better that the tarnished outer layer of the cable or connector. Hence it is common to see gold plated sockets and connectors in devices such as mobile phones and even audio equipment.

Manganin is another copper-based alloy but with higher resistance, used in the construction of wire wound resistors and heater elements for high power applications.

Aluminium is commonly used as a conductor. Though not as good a conductor as copper, it is much lighter and useful for applications such as the large power distribution cables crossing the landscape strung on electricity pylons. Copper cables would be too heavy for this job. Aluminium also has some properties, useful in the construction of transistors and diodes.

Silver is an even better conductor than copper, but since it is more expensive, it is only used in very small amounts.

The conductivity of metals used for electrical purposes may be compared to an internationally agreed standard value, as shown in Fig 1.1.1. That of annealed copper, that is copper that has been heated and cooled at a controlled rate to soften the metal and remove any stresses present. Other commonly used metals can therefore be compared to this standard where a 100% rating indicates the same conductivity as copper, over 100% indicates a better conductor and less that 100%, a worse conductor. Note that the table only compares standard samples of metals and does not take into consideration effects due to tarnishing or different frequencies of current etc.

Conductivity of Metals	
Silver	105%
Copper	100%
Gold	70%
Aluminium	61%
Brass	28%
Zinc	27%
Nickel	22%
Iron	17%
Tin	15%
Phosphor Bronze	15%

Fig. 1.1.1 Conductivity of Metals

Conductive Gases

Some gases can pass current, such as neon for example, which produces a typical orange glow when a small electric current is passed though it at a high voltage. Neon indicator lamps have many uses and can be used with either AC or DC current.In neon (fluorescent) lighting, colours other than orange can be produced by adding gases such as argon, mercury, or helium at low pressure. Light is produced by applying a high voltage between two electrodes at either end of the tube, which causes the gas molecules to ionise and so emit photons, giving light either directly through the clear glass tube, or indirectly by exciting a phosphor coating on the wall of the tube to give a greater range of colours.

Neon & Fluorescent Lighting on Hong Kong Waterfront

Insulators

Materials that prevent the flow of electric current are called INSULATORS. These are mostly solid materials in which the outer electrons of each atom are tightly bonded to the nucleus of the atom, preventing any electron movement within a 'normal range' of applied voltage. Materials commonly used in electronic circuits include:

Plastics (e.g Polystyrene, P.V.C. Bakelite and Polythene)

Glass (including Fibre Glass)

Ceramics

Resins (e.g. epoxy resins)

Paper (usually impregnated with wax, resin etc.)

Rubber (Natural or synthetic)

Air

Insulated Tool Handles

Both the terms 'Insulator' and 'Conductor' are relative. That is, they each have some properties of the other as well as their own. For example an insulator may pass very small currents, but not sufficiently to be called a conductor. An insulator can work well at low voltages, such as those found in battery operated equipment, but fail totally and pass large currents if connected to a much higher voltage.

1.2 Materials in Circuits

What you'll learn in Module 1.2

After studying this section, you should be able to:

- Identify electrical conductors on a PCB.
- Identify common insulating and conducting materials and their uses on a PCB.

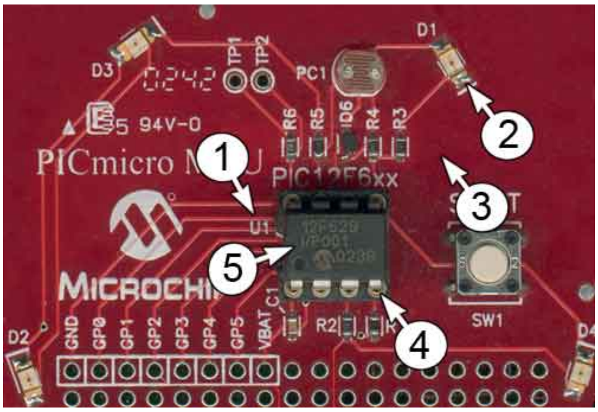


Fig. 1.2.1 Micro-controller Circuit Board

Conductors and Insulators in circuit boards.

A good example of how various materials are used for conductors and insulators in electronics can be seen on the printed circuit board shown in Fig. 1.2.1.

1. The conducting strips are made from copper, which is a very good conductor.

2. Electrical connections between the components and copper strips are made with solder (mainly tin), which is another good conductor, and has the advantages of being easy to melt, as well as making good electrical and mechanical contact.

3. The board itself is made from a good insulator, usually paper impregnated with resin, which is known as SRBP (synthetic resin bonded paper), or in high quality boards from glass-fibre board. Glass, paper and resin are all very good insulators.

4. The contacts of the chip holder are gold plated. This gives an excellent low resistance contact and also prevents tarnishing (oxidisation), which would otherwise increase the contact resistance over time.

5. The chip is encapsulated in black resin; this gives good electrical insulation and, being black, provides good heat conduction to disperse heat generated within the chip.

1.3 Resistance in Conductors

What you'll learn in Module 1.3

After studying this section, you should be able to:

• Calculate the dimensions of a conductor.

• Describe the effect of length and cross sectional area on the resistance of a conductor.

How the Dimensions of a Conductor Affect its Resistance

The ability of any conductor in an electrical circuit to pass current is judged by its electrical RESISTANCE. Resistance is the ability to OPPOSE the flow of electric current. The greater the value of resistance of any conductor, the less current will flow. The resistance of a conductor depends mainly on three things:

1. The LENGTH of the conductor.
2. The CROSS SECTIONAL AREA of the conductor.
3. The MATERIAL of which the conductor is made.

Because the resistance is greater in longer conductors than in shorter ones, then:

RESISTANCE (R) IS PROPORTIONAL TO LENGTH (L) and is written as R ∝ L (∝ means proportional to...) Therefore the longer the conductor, the more resistance is present and so less current flows.

Also, because resistance is less in conductors with a large cross sectional area:

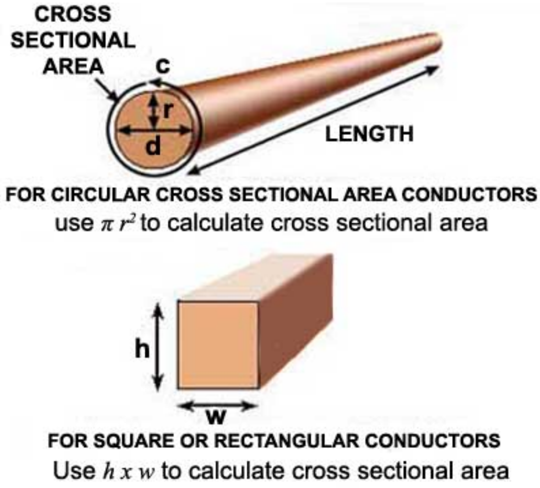


Fig. 1.3.1 Calculating the Dimensions of a Conductor

RESISTANCE (R) IS INVERSELY PROPORTIONAL TO CROSS SECTIONAL AREA (A)

Which is written as R ∝ 1/A (or R ∝ A^{-1}).

The greater the cross sectional area, the more current can flow along the conductor, so the lower the value of the conductor's resistance.

Circular Conductors

When the conductor has a circular cross section, the area of a circle can be found by using the formula:

πr^2 Where π = 3.142 and **r** is the radius of the circle.

If the cross section of the conductor is square or rectangular, the cross sectional area of the conductor can still be found by simply multiplying the width by the height. Most conductors, found in cables etc. are of course circular in cross section.

The Material from which the conductor is made also affects its resistance, by an amount depending on the RESISTIVITY of the material, described in Resistors & Circuits Module 1.4.

1.4 Resistivity

What you'll learn in Module 1.4

After studying this section, you should be able to:

- Describe the property of resistivity.
- Carry out calculations involving resistivity.
- Use appropriate electrical units (Ωm) to describe the resistivity of common conductor & insulator materials

How Materials Affect Resistance

Provided that the dimensions (length and cross sectional area) of any conductor do not change, its resistance will remain the same. If two conductors of exactly the same dimensions have a different resistance, they must be made of different materials.

One way to describe a material (any material) is by its RESISTIVITY. This is the amount of resistance present in a piece of the material OF STANDARD DIMENSIONS. Every material can be defined in this way. The resistivity of any material is defined as the resistance of a piece of that material having a length of one metre and a cross sectional area of one square metre (i.e. a cube of material one metre square); the resistivity of the material being the resistance across opposite faces of the standard cube.

Resistivity is given the symbol **ρ.** This is not a letter p but a lower case Greek letter r (called rho) and is measured in a unit called the OHM METER, written ΩM. (Note: this is not the same as ohms/metre or ohms per metre)

So the resistance of any conductor can be found by relating the three factors;

Length: = L Cross Sectional Area: = A Resistivity: = ρ

The following formula can be used to find the resistance of any conductor, providing that its dimensions and its resistivity are known.

$$R = \frac{\rho L}{A}$$

Remember that, as conductors are usually circular in section, the cross sectional area may need to be found using the basic formula for the area of a circle. i.e. $A = \pi r^2$ or $A = \pi(d/2)^2$ where r and d are the given radius and given diameter, respectively, and $\pi = 3.142$.

Important.

When using this (or any) formula you must convert any sub-unit (mm, cm etc.) into its STANDARD SI UNIT e.g Metres (M). Otherwise your result may be out by a factor of 100 or 1000 or more.

Resistivity problems can be tricky to work out since you have to remember several things at once, using the cross sectional area formula AND the resistivity formula together, converting to standard SI units, and using resistivity constants. Maybe you could use a little practice? Try a short Resistivity Quiz and if you need a little help with the maths, download our "Maths Tips" booklet to get you started.

Approximate Resistivity of some common materials. (in Ωm)

CONDUCTORS	INSULATORS
Aluminium 2.7×10^{-8}	P.V.C. 5.4×10^{15}
Copper 1.7×10^{-8}	Glass 10^{4}
Iron 10.5×10^{-8}	Quartz 10^{12}
Mercury 96×10^{-8}	P.T.F.E 10^{12}

(P.T.F.E.= polytetrafluoroethylene, used to insulate high voltage cables.)

It can be seen from this list that the resistivity of insulators is much higher than that of conductors.

1.5 Temperature Effects on Resistance

What you'll learn in Module 1.5

After studying this section, you should be able to:

• Describe the effect of temperature on the resistance of a conductor.

• Describe the effect of temperature on the resistance of an insulator.

• Define negative and positive temperature coefficients.

How Temperature Changes Resistance

Although the resistance of a conductor changes with the size of the conductor (e.g. thicker wires have less resistance to current flow than thinner wires), the resistance of a conductor also changes with changing temperature. This may be expected to happen because, as temperature changes, the dimensions of the conductor will change as it expands or contracts.

However, materials that are classed as CONDUCTORS tend to INCREASE their resistance with an increase in temperature. INSULATORS however are liable to DECREASE their resistance with an increase in temperature. Materials used for practical insulators (glass, plastic etc.) only exhibit a marked drop in their resistance at very high temperatures. They remain good insulators over all temperatures they are likely to encounter in use.

These changes in resistance cannot therefore be explained by a change in dimensions due to thermal expansion or contraction. In fact for a given size of conductor the change in resistance is due mainly to a change in the resistivity of the material, and is caused by the changing activity of the atoms that make up the material.

Temperature and Atomic Structure

The reasons for these changes in resistivity can be explained by considering the flow of current through the material. The flow of current is actually the movement of electrons from one atom to another under the influence of an electric field. Electrons are very small negatively charged particles and will be repelled by a negative electric charge and attracted by a positive electric charge. Therefore if an electric potential is applied across a conductor (positive at one end, negative at the other) electrons will "migrate" from atom to atom towards the positive terminal.

Only some electrons are free to migrate however. Others within each atom are held so tightly to their particular atom that even an electric field will not dislodge them. The current flowing in the material is therefore due to the movement of "free electrons" and the number of free electrons within any material compared with those tightly bound to their atoms is what governs whether a material is a good conductor (many free electrons) or a good insulator (hardly any free electrons).

The effect of heat on the atomic structure of a material is to make the atoms vibrate, and the higher the temperature the more violently the atoms vibrate.

In a conductor, which already has a large number of free electrons flowing through it, the vibration of the atoms causes many collisions between the free electrons and the captive electrons. Each collision uses up some energy from the free electron and is the basic cause of resistance. The more the atoms jostle around in the material, the more collisions are caused and hence the greater the resistance to current flow.

In an insulator however, there is a slightly different situation. There are so few free electrons that hardly any current can flow. Almost all the electrons are tightly bound within their particular atom. Heating an insulating material vibrates the atoms, and if heated sufficiently, the atoms vibrate violently enough to actually shake some of their captive electrons free, creating free electrons to become carriers of current. Therefore at high temperatures the resistance of an insulator can fall, and in some insulating materials, quite dramatically.

In a material where the resistance INCREASES with an increase in temperature, the material is said to have a POSITIVE TEMPERATURE COEFFICIENT.

When resistance FALLS with an increase in temperature, the material is said to have a NEGATIVE TEMPERATURE COEFFICIENT.

In general, conductors have a POSITIVE temperature coefficient, whilst (at high temperatures) insulators have a NEGATIVE temperature coefficient.

Different materials within either group have different temperature coefficients. Materials chosen for the construction of the resistors used in electronic circuits are carefully selected conductors that have a very low positive temperature coefficient. In use, resistors made from such materials will have only very slight increases in resistivity, and therefore their resistance. Using such materials for the manufacture of resistors creates components whose value changes only slightly over a given range of temperature.

Materials chosen as insulators will have a very low NEGATIVE TEMPERATURE COEFFICIENT over their working range of temperature.

1.6 Resistivity Quiz

What you'll learn in Module 1.6

After studying this section, you should be able to:

- Descibe common materials used in electronic circuits.
- Relate resistance to the dimensions and resistivity of a conductor.
- Calculate the cross sectional area of conductors.
- Carry out calculations involving resistivity & resistance.

Try a few calculations based on Resistivity. For these you just need to use the information in Module 1.4 "Resistivity" and Module 1.3 "Resistance in Conductors" pages, hopefully it'll be a breeze.

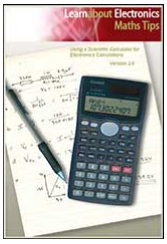
Because you may be using more than one formula for any problem it is important to remember to use the correct formula at the right time.

Before you start, these few tips may make the problems easier if you follow them carefully.

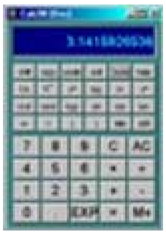
1. Work out the answers using pencil and paper; if you don't write out the problem you WILL get mixed up half way through and end up with the wrong answer.

2. Of course the answer is not just a number, it will be a certain number of Ohms or metres, don't forget to show the correct unit (e.g. Ω) or your answer is meaningless.

3. Convert all sub units such as mm to metres when you put them into the appropriate formula. If you slip up here you'll get really stupid answers, thousands of times too big or too small.



To help you on the right track why not download our "Maths Tips" booklet, which shows how to use your calculator with exponents and engineering notation to deal with those sub-units and get the right answer every time.



Not got a scientific calculator? The "Maths Tips" booklet explains what you need (and what you don't need so you don't spend your money unnecessarily). If you don't want to buy a scientific calculator, you can always pick up a free one on the net. PC users can try Calc98 from www.calculator.org/download.html. Whichever calculator you choose remember that you should read the instructions to become familiar with the working methods you should use as these do vary from calculator to calculator.

OK so now you have read these instructions, you are ready to start. Here is a way to set out a typical problem on paper so you (with practice) don't get confused.

Firstly list all the values given in the problem, followed by the value that needs to be found for the answer. For example if the problem asks for the resistance of a cable of given dimensions and material, the following list can be made:

ρ (of copper) = 1.7 x 10^{-8} Ωm (17 E-9 or 17 EXP-9 when entering it into your calculator in Standard Form, depending on which model you use)

L (Length of cable) = 7m

d (Diameter of cable) = 0.5mm (500 E-6 or 500 EXP-6 metres in Standard Form)

A (Cross Sectional Area of cable in square metres) = $\pi(d/2)^2$ = 3.142 x ((500 $\text{EXP}^{-6}/2)^2$)

= **196.4 $\text{EXP}^{-9}\text{m}^2$**

Therefore R = (ρL) / A = (17 EXP^{-9} x 7) / 196.4 EXP^{-9} = 605mΩ

Note that when the diameter (or the radius) of a cable is given it is necessary to firstly work out its cross sectional area in square metres (m^2) before the formula relating R, to ρ, length and **cross sectional area** can be used. Look at the "Resistivity" page for more help in working out the cross sectional area.

Note: If you are using Calc98 for your calculations you need to set the View>Option>Display menu to Engineering (under the "Decimal" choices) and it would be a good idea whilst you are in this menu to select 2 from the Decimals drop down box, to set the number of digits after the decimal place. This will round your answer down to two decimal places, which is sufficiently accurate for most uses and stops you getting silly answers such as 4.66666666667mm, which would be far too accurate for any practical scale of measurement.

Resistivity Calculations Practice

(Calculate your answers with pencil, paper and calculator; you can check your answers on line at. http://www.learnabout-electronics.org Resistors Module 1)

1.

A wire 12m long has a resistance of 1.5 Ω. What will be the resistance of 16m of the same wire?

a) 1.6Ω b) 2 Ω c) 12Ω d) 1.4Ω

2.

A sample of copper wire of 0.2mm radius has a length of 5m. If the resistivity of the copper is 1.7×10^{-8}, what would be the resistance of the wire?

a) 60.49Ω b) 42.5Ω c) 4.25Ω d) 0.676Ω

3.

What is the resistance of 100m of copper wire, having a diameter of 1.024mm?

a) 2.06Ω b) 5.15Ω c) .515Ω d) 3.7Ω

4.

The resistance of a 50m length of wire is found to be 0.83 ohms. Its diameter is 1.15mm. What is its resistivity and from what metal is it most probably made?

a) 2.7×10^{-8} aluminium b) 10.5×10^{-8} iron c) 17.2×10^{-9} aluminium d) 1.72×10^{-8} copper

5.

What is the length of a copper wire having a radius of 0.25mm if its resistance is found to be 0.2 Ω?

a) 2m b) 2.31m c) 16.96m d) 1.7m

