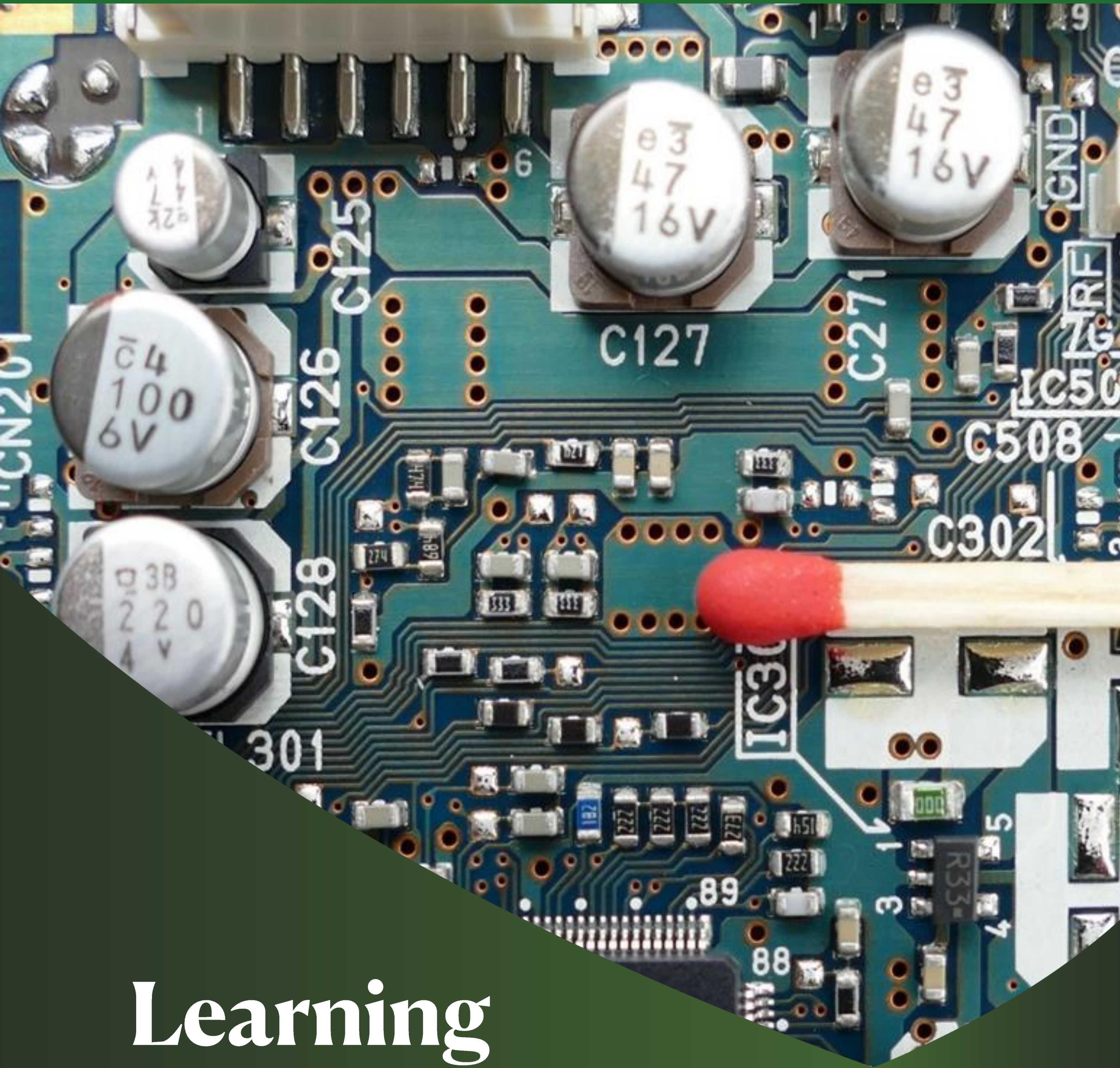


Learning resource

Explain the properties of conductors, insulators and semiconductors and their effect on electrical circuits

Level 2 | Credits 7

Te Pūkenga

Contents

Part 1: Conductors, Insulators and Semiconductors

To understand electricity, you will need to have some understanding about matter and what makes up matter. You will need to know this so that you can understand how to put one of the most amazing power sources on the planet to use.

Matter

Matter is anything that has mass and occupies space. Matter can exist in numerous states with the three most commonly known being solid, liquid and gaseous. Some types of matter can readily be observed to exist in all three states; water for example exhibits all three states over a relatively small temperature range.

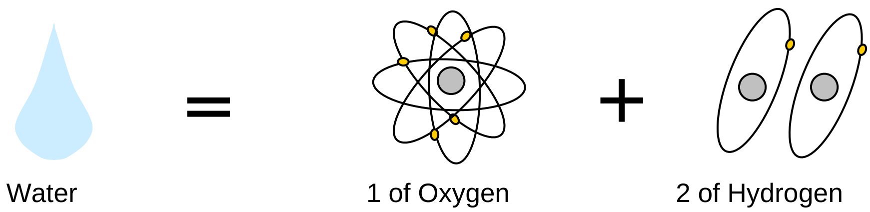

Photo by Graeme Jeffrey

Elements

Elements are the basic building blocks of all matter in the universe as we know it. Ninety-two elements occur naturally, and several other man-made elements have been added to this list.

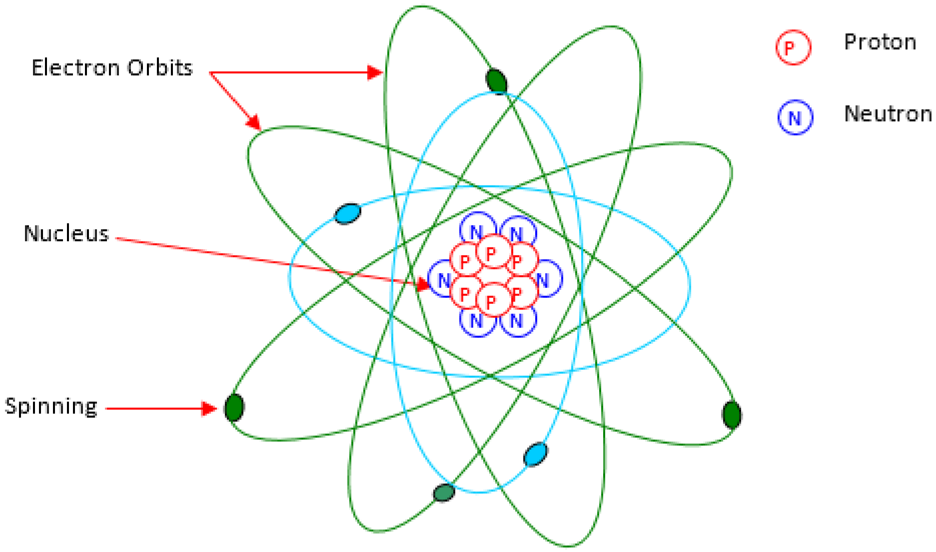
Compound

When two or more elements combine they form a compound. All matter is made of compounds. Water is a compound of two hydrogen atoms for every atom of oxygen.



Atom

Every element is unique in that, the number of protons, (positive charges) the number of electrons (negative charges) and the number of neutrons (no electrical charge) for every element is different. The protons and neutrons form the nucleus of an atom and the electrons orbit around the nucleus in much the same way as the planets in our solar system orbit the sun. The Bohr model of an atom is shown below:



Orbital shells

The orbital paths occupied by electrons are commonly called shells.

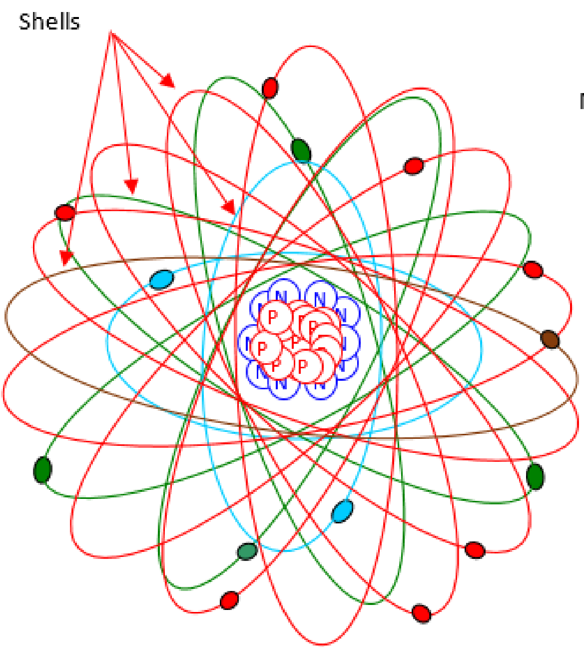
Each shell is labelled with the letters of the alphabet, starting at the letter 'K'. Each shell can hold a certain number of electrons before it becomes full. All shells, except for the 'K' shell, can have sub-shells.

On occasions, a new shell may be started before the previous one is completely filled.

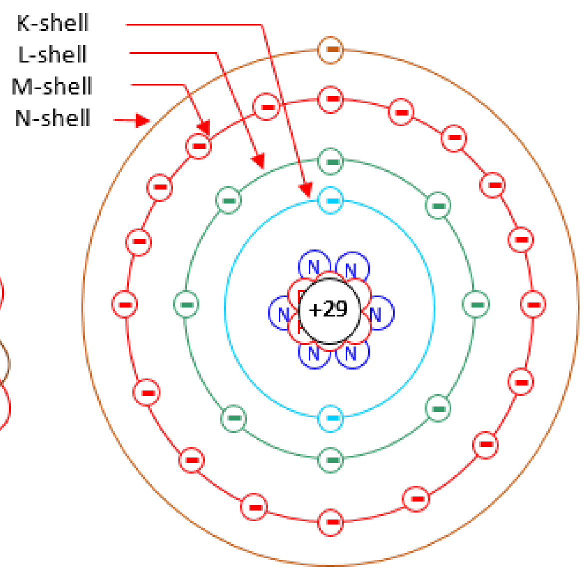
The sub-shells (below the valence shell) are largely responsible for the magnetic properties of a material as they hold most of the electrons of the atom.

For example:

- **K-shell can hold a maximum of 2 electrons**
- **L-shell 8 electrons**
- **M-shell 8 or 18 (depending on sub-shells)**
- **N-shell 8, 18 or 32 (depending on sub-shells)**
- **O-shell 8 or 18 (depending on sub-shells)**
- **P-shell 8 or 18 (depending on sub-shells)**
- **Q-shell 8**



Model of a Copper Atom

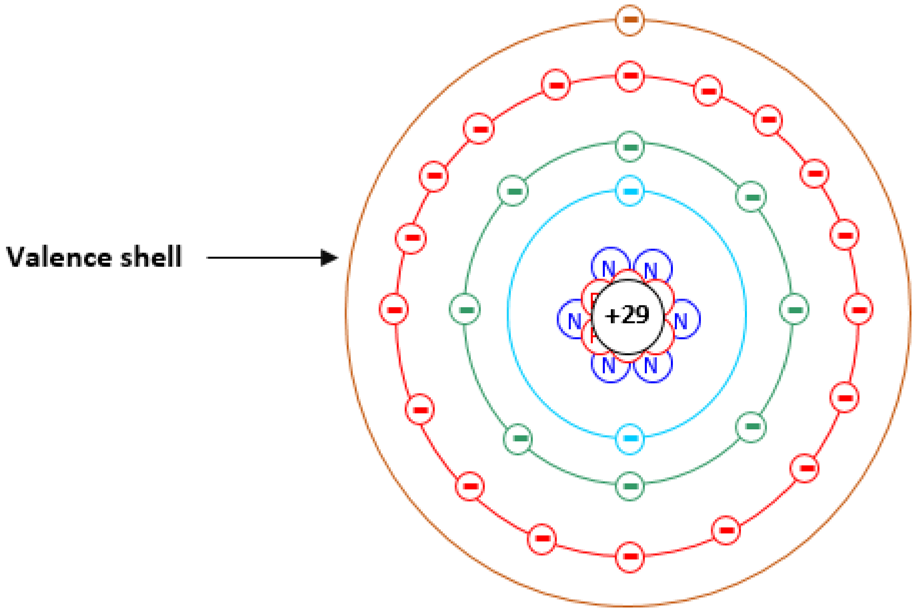


Model of a Copper Atom

Although both diagrams above represent models of the same atom, the one on the left shows the formation in a three-dimensional form as it would appear if the atom was viewed under a very powerful microscope. The one on the right shows all shells and their electrons in the same plane.

Valence shell

The outer-most shell of an atom is called the valence shell and cannot hold more than eight electrons. The electrons in this shell are called valence electrons and are not bound as tightly to the nucleus as are the electrons located in the inner shells.



Free electrons

Electrons are held in place ("bound") to the atom by attraction between the negative electrons and the positive protons of the nucleus.

Although all electrons carry the same negative charge they do not have the same energy level. The energy level increases the further away the electron is from its nucleus. Valence electrons have the greatest amount of energy in an atom.

Depending on the strength of the bond and the energy of the electron, electrons can be dislodged from their orbits and may move on to other atoms.

Tightly bound electrons are very hard to move and loosely bound ones much easier.

Loosely bound valence electrons don't take much extra energy to get them to move from their atom to another atom.

The electrons that are capable of moving from one atom to the next are called free electrons. Free electrons are the building blocks of electrical current.

Conductor and insulators

The makeup of the valence shell of an atom determines if a material is a good conductor or good insulator. This is because it is the electrons in the valence shell that determine how that atom will bond with others and if there are free electrons available for current flow or not.

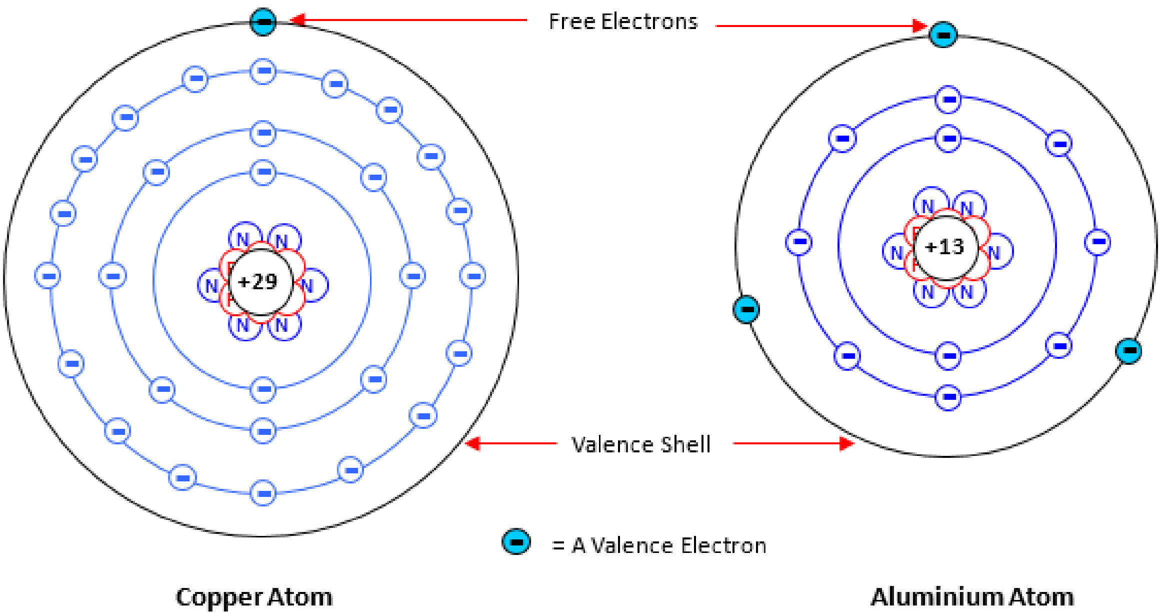
Electrical conduction

In a solid material, the atoms are fixed relative to each other and cannot move. However, when there are free electrons that can move from atom to atom current can flow through the material. This is current flow - when the free electrons are caused to flow along from atom to atom in a material.

Good conductors

Atoms that have less than half the maximum possible electrons in their valence shell will lend their electrons to other atoms in close proximity to them. The more freely this lending takes place, the better the element is as a conductor.

Good conductors will have one, two or three electrons in their valance shell. These electrons can be readily moved and when this happens, they are called free electrons

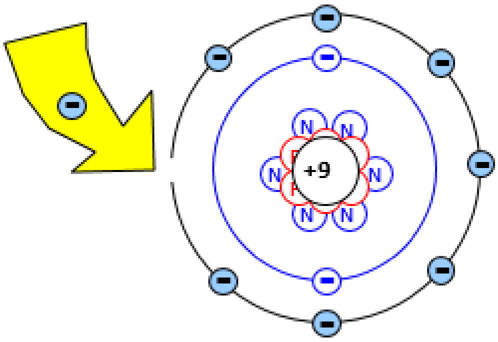


because they can take part in current flow. Conductors have loosely bound valence electrons.

Good insulators

Non-metals are borrowers (or keepers) of electrons because their valence shells are almost complete, they have tightly bound valence electrons. Very good insulators will have seven or more electrons in their valence shells and are stable because the electrons have strong bonds to their atoms, that makes them chemically stable.

This atom has 7 electrons in its valence shell and tries to become more stable by borrowing one to fill the space



Once filled, it is very difficult to free an electron. These atoms make very good electrical insulators

This will mean they are very resistant to electron /current flow, and that makes the material an insulator.

Below is a list of common insulators found in the electrical industry and their typical uses. They are in the order of best to worst insulators, although even the worst is still a very good insulator.

Fused quartz glass is the best insulator i.e. has the highest resistivity to current flow, and the list works down in approximate order to silica glass which has the lowest resistivity on the list.

Note: we will explain resistivity later on in this resource.

1. **Fused quartz glass (HV power line insulator)**
2. **Polyethylene terephthalate (PET) (High heat, chemical and impact resistance, MCB cases)**
3. **Quartz (HRC fuse filler powder)**
4. **Transformer Oil (Insulator and coolant for transformers, High Voltage switching)**
5. **Hard Rubber (Plug tops, battery cases)**
6. **Soft rubber (Cable insulation)**
7. **XLPE (Cross-linked polyethylene, cable insulation)**
8. **Air (Power lines, dielectric for capacitors)**
9. **Ceramics - Porcelain (Power line insulators, where a more rigid insulator is needed)**
10. **Mica (High quality dielectric for capacitors, stable insulator)**
11. **PVC (Cable insulation, electrical enclosures)**
12. **Glass - silica (HV power line insulator)**


Photo by Graeme Jeffrey

Semiconductors

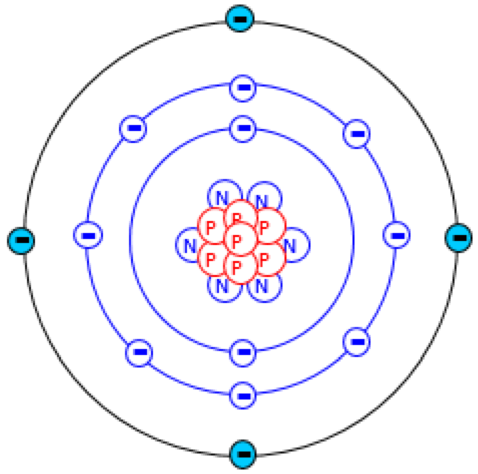
As we have discussed previously, conductors have their valence shells less than half filled and insulators have their valence shell more than half filled.

There are some elements that have their valence shells half-filled i.e. they have four electrons in their valence shell. Those electrons are shared with (bound to) neighbouring atoms.

These types of materials conduct better than insulators but not as well as conductors. For this reason, this group of elements is given the name of semiconductors. Naturally occurring silicon and germanium are semiconductor elements.

Both germanium and silicon are tetrahedral crystalline lattice structures where each atom shares one of its valence electrons with four neighboring atoms to form good bonds between their electrons and the other atoms.

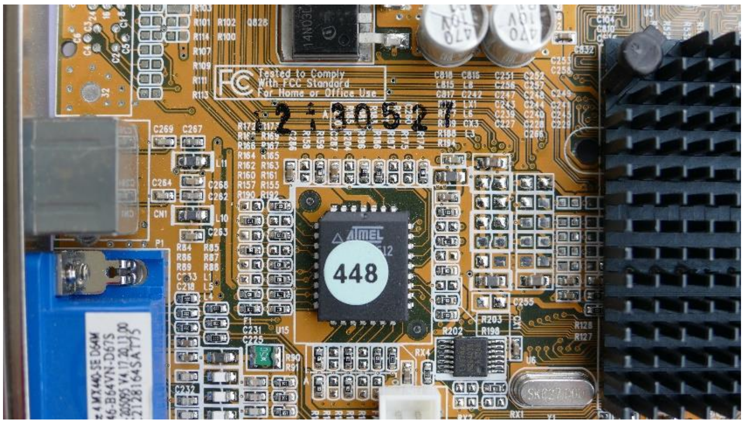
Even though these materials have good bonds, when enough energy is applied, a single valence electron can still gain enough energy to break free of its bond and move through the material as a free electron.



This gives semiconductors two possible states, naturally "insulating" against current flow and then eventually when enough energy is applied, they turn into a conductor.

The point at which this change occurs is dependent on the temperature of the material. This temperature characteristic can be used to our advantage in the design of electronics.

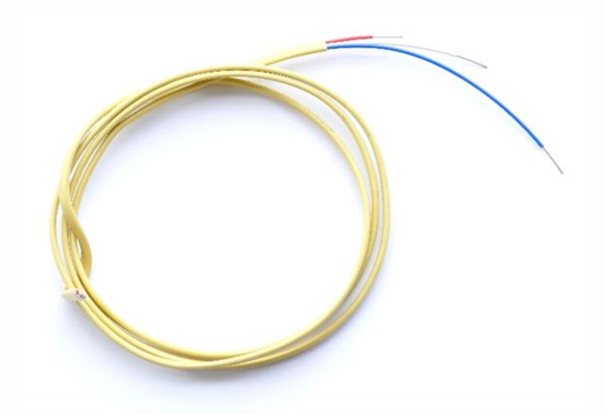
Semiconductors are an extremely important group because all modern electronic



devices are designed around them.

Conductors and insulators in electrical industry

You will use both conductors and insulators in the electrical industry.



A cable is a classic example of where you will need to understand and use both conductors and insulators in the same application.

In a cable, the conductors are used to efficiently transmit electrical current from one point to another and the insulator (i.e. plastic around the outside) is used to stop the current going anywhere else.

There are a huge variety of different uses for conductors and insulators in the electrical industry.

The main use of conductors is to carry current but sometimes some conductors - due to their higher resistances, are used to produce heat or light.

The following tables list the most common conductors and insulators and some of their typical uses in the electrical industry.

Table 1.1 – Common conductors

Table 1.2 - Common insulators

Table 1.1a – Common conductors

Conductor	Some typical uses in the electrical industry	Advantage	Disadvantage
Copper	General purpose wiring, cable cores, bus bars, aerial conductors.	Very low resistance, economical to produce, ductile and can be easily formed into wires. Can be soldered, low temperature co-efficient, Tolerant to atmospheric changes.	Thins out if stretched too far. Corrodes easily when in acidic or alkaline environments, cannot be machined.
Hard drawn copper	Aerial conductors, bus bars.	Strong tensile strength for long aerial spans	Hard to work, not very flexible, harder to work with than soft copper.
Stranded copper	Cable conductors and flexible cable cores.	Flexible to cope with movement, less likely to fracture when bent.	Can shear off if terminals are over-tightened, can "rearrange" in terminals over time and loosen.
Silver	Low voltage contacts, switches, fuses, electrical contacts in computers phones etc.	Best conductor, Low skin effect, suitable for higher frequencies, low corrosion.	Soft and cannot be stretched, costly.
Aluminium	Bus bars, overhead power transmission lines (when supported with a strain wire), conductors in distribution cables.	Light weight and economical so can be used in longer spans, high tolerance to weather and resistant to corrosion.	Less conductive than copper - higher power losses. Will stretch, needs a strain wire for long overhead spans, reacts with other metals so special jointing techniques are needed.

Conductor	Some typical uses in the electrical industry	Advantage	Disadvantage
Tungsten	Lamp filaments, heating elements, welding electrodes, switch contacts.	Tough, durable, high working temperatures, can be drawn into fine wire.	High resistance -produces heat, brittle, not used as cables.
Carbon	Motor brushes, resistors, switch contacts, batteries.	Non-metal, self-lubricating, corrosion free.	High resistance, ignitable, limited specific uses, brittle.
Nichrome (nickel, chromium alloy)	High power resistors, heating elements.	Very high working temperatures, low temperature co-efficient, runs hot without corroding in air.	Very high resistance, high cost, can be problematic to terminate.
Brass (copper and zinc alloy)	Earth/neutral bus bars, electrical terminals, electrical connectors.	Strong, machinable, can be cast into shapes, resistant to atmospheric conditions and corrosion.	Corrodes easily when in acidic or alkaline environments, higher resistance than copper, brittle.
Gold	Low voltage contacts, switches, fuses, high tech electronic components and circuit boards.	Very good conductor, can be drawn to fine wire, non-corroding.	High cost, soft, higher resistivity than silver and copper.
Lead	Lead acid batteries, alloying material, solder, protective sheath for underwater cables	Relatively inexpensive and inert, corrosion resistant, low melting point.	Toxic to humans and harmful to the environment, very soft, stretches, low melting point.

Conductor	Some typical uses in the electrical industry	Advantage	Disadvantage
Tin	Alloying material for brass, bronze, and solder, negative electrodes in advanced Li-ion batteries, stabilization of PVC, specialised semi-conductors.	Low melting point, stable, malleable.	Not a good conductor on its own, can become brittle, low melting point.

Table 1.2a - Common insulators

Insulator	Some typical uses in the electrical industry	Advantage	Disadvantage
Glass	Insulator strings on H.V lines, fibre glass insulation and construction.	Waterproof, heat resistant, self-cleansing (because it is so smooth).	Fragile, costly.
Mica	Heating element supports (toasters, irons), capacitor dielectrics.	Can easily be split, fairly flexible, can be stamped into shapes, high resistance to current and heat.	Can split, natural product so can vary in quality, can be hazardous to health.
Oil	Insulation in transformers and oil circuit breakers.	Non-oxidiser, excellent insulator, fluid, transfers heat, quenches arcs.	Can be costly, can be contaminated by water from environment, very penetrating, risk to the environment.
Ceramics (Porcelain)	Cooker element insulator beads, overhead line insulators, cable supports and standoffs.	Heat resistant, made into any shape, strong, resistant to oils, petrol and acids etc. Impervious to dust and weathering,	Brittle, not as strong as alumina ceramic,
Ceramics (Alumina)	High temperature insulators, electronic substrates, HV Insulators.	Heat resistant, made into any shape, strong, resistant to acid and alkali attack, High strength and stiffness, good thermal conductivity.	Brittle, higher cost than porcelain
Hard rubber and rubber compounds	Plug tops, flexible cord sheaths, insulating mats.	Good insulator, flexible, waterproof, resistant to weathering and aging, resilient to rough treatment.	Flammable, damaged by oil, petrol, gases, acids and alkalis.

Insulator	Some typical uses in the electrical industry	Advantage	Disadvantage
PVC	Conduits, cable and cord sheaths, electrical enclosures, insulating components.	Rigid or flexible, waterproof, resistant to petroleum products, excellent insulator, heat resistant, economical.	Brittle at low temperatures, can be damaged by UV, breaks down when in contact with polystyrene.
Hard plastic	Plug tops, battery cases, electrical enclosures, electrical fittings.	Rigid, waterproof, excellent insulator, non-corroding, easy to drill and work with, economical.	Brittle at low temperatures or old age, can be damaged by UV unless specifically manufactured to resist UV, can snap/crack.
Magnesium oxide	Insulation in high temperature range elements, heater elements and MIMS cable.	Excellent heat resistant properties, very good insulator when compressed, in powder form.	Draws in moisture, conducts when damp, costly, requires specialised terminations.

The following tables show common conductors and their typical performance in different environmental conditions.

Table 1.1b – Common conductors

Conductor	Crimp links and lugs can be used	Resistant to corrosive materials	Unaffected by dust	High melting point	Water resistant	High tensile strength	Withstands vibration
Copper	P		P	P	P		
Hard drawn copper	P		P	P	P	P	
Stranded copper	P		P	P	P		P
Silver			P		P		
Aluminium	P		P		P		
Tungsten		P	P	P	P		
Carbon			P	P			P
Nichrome (nickel, chromium alloy)		P	P	P	P		
Brass (copper and zinc alloy)			P	P	P		P
Gold			P		P		
Lead		P	P		P		
Tin			P				

Table 1.2b - Common insulators

Insulator	Can cope with compression	Resistant to corrosive materials	Unaffected by dust	High melting point	Water resistant	High tensile strength	Withstands vibration
Glass	P	P	P	P	P	P	P
Mica				P			
Oil							
Ceramics (Porcelain)	P	P	P	P	P	P	P
Ceramics (Alumina)	P	P	P	P	P	P	P
Hard rubber and rubber compounds	P		P		P		P
PVC	P		P		P		P
Magnesium oxide	P			P			P

Practical 1.1

Aim

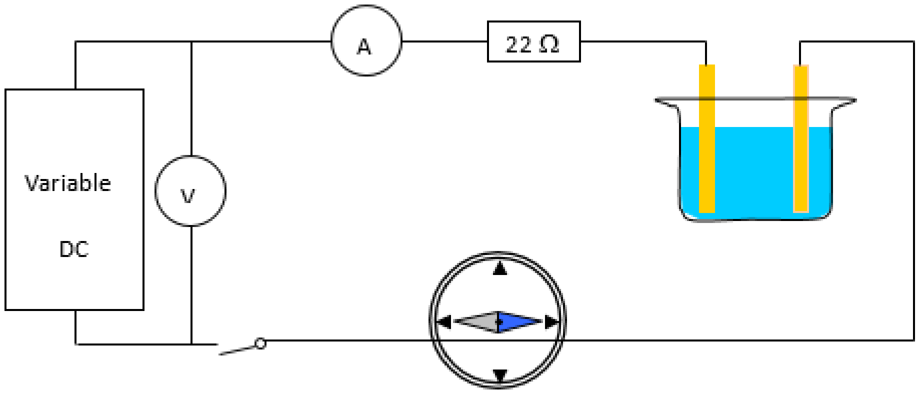
To demonstrate that electric current can be conducted by a solid or liquid and when electric current flows, it produces both heating and magnetic effects.

Equipment

Item	Quantity
Magnetic compass	
Glass beaker or jar	
Two copper strips approximately 15 mm wide and 60 mm long	
22 Ω 10-Watt wire wound resistor	
Variable DC power source 0 to 25 V	
Table salt	
Ammeter	
Voltmeter	
Multi-meter	
Switch	

Procedure

1. Fill the beaker approximately ¾ full with tap water.
2. Insert the two copper strips so that they are immersed in the water but do not touch one another.
3. Set the multi-meter to a suitable ohm range and measure the resistance of the tap water between the two copper electrodes recording the reading in table 3. Measure and record the resistor value also.
4. Connect the copper strips and resistor to the DC power supply as shown but do not turn the power source on. Position the compass so that its needle is in line with a straight section of the circuit conductor.



5. **Set the power source to its minimum level then turn it on and adjust the output to 5 volts. Observe the ammeter, beaker of water, and compass.**
6. **Leave the voltage at this setting for two minutes and then touch the resistor body and the side of the beaker to feel their temperature.**
7. **Record your observations by writing in the value of current and ticking the appropriate sections for the resistor, compass and water activity in table 3.**
8. **Increase the voltage in 5 volts steps. For each step, repeat steps 5 and 6 for all 5 voltage settings.**
9. **Turn the power supply off, remove the copper strips from the water and add salt, stirring it in until to dissolves. Keep adding the salt until the liquid is saturated. (That is, until no more salt will dissolve). Measure the resistance of the liquid using the multi-meter and record this value in table 4.**

Replace the copper strips, turn on the power source and repeat steps 4 to 7. Record your findings in table 4.

⚠ **Caution:**

The resistor can dissipate significant amounts of heat that could burn skin on contact.

10. **Disconnect the circuit and return all equipment to its proper place. Using the information recorded in both tables, write a discussion on your observations and include in it, the points listed below.**
    - **The conductivity of ordinary tap water.**
    - **The effect the salt had when added to the water. Support this by the recorded current readings.**
    - **The reason for the change in temperature of the water and resistor.**
    - **The way in which the compass reacted and the reason for that reaction.**

Your discussion should conclude by stating the two effects current has when it flows in a circuit.

Table 1.3

Table 1		Water activity			Resistor value Ω			Compass				Liquid resistance
Voltage	**Current**	**None**	**Slight**	**Heavy**	**Cold**	**Warm**	**Hot**					
5V												
10V												
15V												
20V												
25V												

Table 1.4

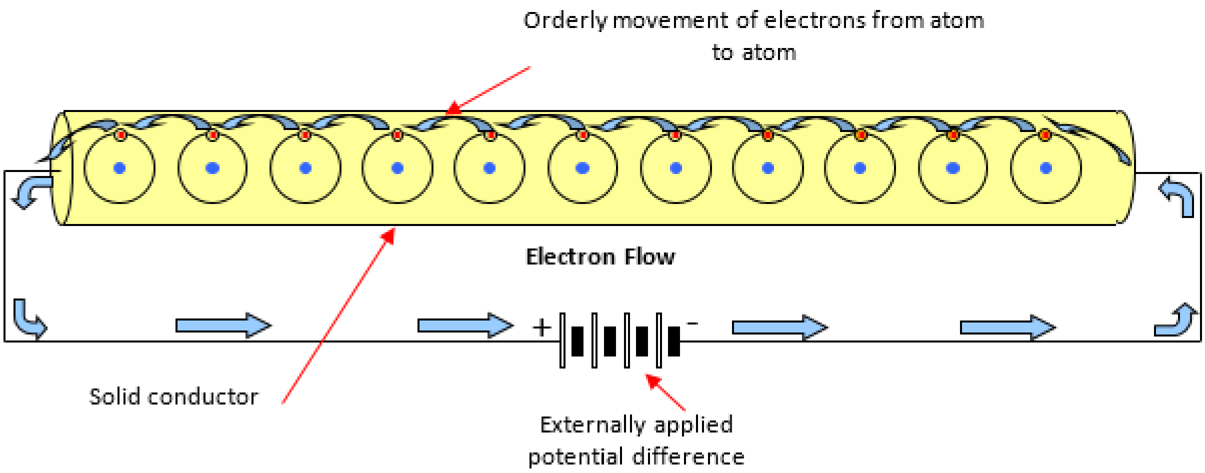
Table 2		Water activity			Resistor value Ω			Compass				Liquid resistance
Voltage	**Current**	**None**	**Slight**	**Heavy**	**Cold**	**Warm**	**Hot**					
5V												
10V												
15V												
20V												
25V												

Part 2: Resistance, Resistivity, and Resistors

Electrical resistance is the opposition to current flow. To understand this, we will need to spend a short amount of time looking at voltage and current to see how these three all fit together. Let's start with having a look at electron flow.

Electron flow

Since electrons are negatively charged, they are attracted to the positive terminal of a voltage supply source. They will leave the negative terminal and flow through the conductor of a circuit back to the positive terminal of the source. Current that flows from negative to positive is called (actual) electron flow.

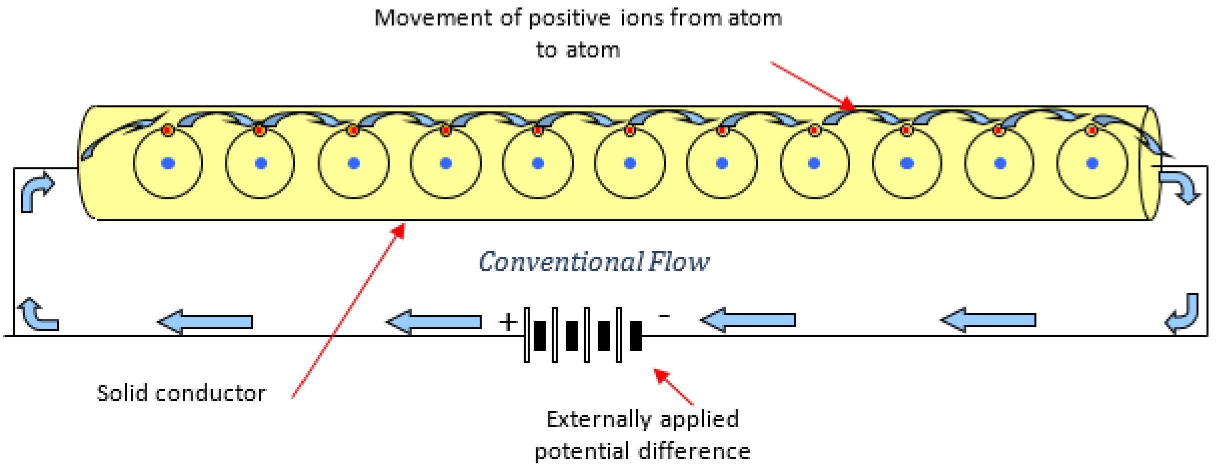


Conventional current flow

In early days when discoveries were being made in the electrical field, scientists observed current flow and its chemical effects in liquid. As a result, it was mistakenly thought that electrons flowed from positive to negative. This is now referred to as *conventional* current flow.

It was too late when they discovered that electrons actually flow from negative to positive, they had already established electrical formulas and rules based on the conventional current flow model.

So we still use conventional current flow (from positive to negative) in explanations of electrical concepts today but you will know that in reality, true real life current (electron flow) is in fact from negative to positive.



Let's have a look at current flow from the point of view of electrical circuits. We use the flow of current to do electrical work. There are two main types of current flow we will look at here:

1. Direct current (DC).
2. Alternating current (AC).

Each type of current flow has its uses as you will learn.

DC current flow

When electrons flow in one direction only, it is called direct current or simply DC.

Batteries are one common source of DC. DC is a continuous stream of electrons flowing in one direction. DC is an effective source of power to run a lot of electrical equipment.

AC current flow

There is another type of current flow that we commonly use in the electrical industry. It can take a little bit of getting your head around at first, but you will need to understand it. It is called alternating current or AC.

Just to help you start getting your head around alternating current – the current could be likened to the action of a Japanese hand saw. The teeth are designed to cut either way, if you push the saw through wood or pull it, the teeth cut either way. The saw cuts on both your forward thrusts and backward pulls, a very efficient use of your sawing action.

In alternating current, firstly electrons flow from left to right (for example). Then they stop, reverse direction and flow back right to left. The current continues to swap direction over and over and this cycle continues to repeat continuously as long as the AC energy source is applied to the conductor.

The backward and forward “sawing” motion (a crude term for explanation purposes) of the electrons is used to do electrical work. It doesn’t matter which way the electrons are flowing, the fact that they are flowing does the work to run an electrical load.

Why? Why bother having current alternating its direction all the time? Because this is the natural output of an AC alternator. An alternator is a simple and cost-effective machine for producing current and the current it produces is AC.

AC also has other very useful benefits that you will harness in your work in the electrical industry. One significantly large benefit of AC is that it causes transformers to work. It allows the very simple but very clever transformation of voltage up or down using a transformer whereas DC doesn’t.

The measurement of current

The SI unit of electrical charge is called a coulomb. This is named after the French physicist Charles Augustin de Coulomb, who in 1806 discovered the law of force between two electrically charged bodies.

The quantity of current flowing through a conductor at any time is the measure of the rate of flow of electrons that pass a given point in one second.

Current flow is measured in Amperes where 1 ampere = 1 coulomb per second. The quantity symbol for current is I and the unit symbol is A. This unit was named after the French physicist Andre Ampere.

Electromotive force

Electro (electrical) motive (driving) force

The unit of electrical pressure is called the volt and is named after an Italian physicist Count Alessandro Volta (1745-1827).

Electromotive force is the “electrical driving force” that causes the free electrons to move along a conductor. It is the electrical “pressure” developed by an electrical energy source that causes electric current in a circuit.

A simple AA battery is a source of EMF (voltage). A very simplified explanation of the EMF (voltage) developed by a battery is that a chemical reaction has caused the electrons in the battery to be taken from one end and pushed to the other.

So, you end up with heaps of electrons at one end and missing electrons at the other end where they came from. The electrons have a strong attraction to go back to where they used to be, but they can’t. There is now an electrical tension set up in the battery - electrons straining with force to flow back and join with the atoms that have missing electrons (holes for electrons).

If we connect that same battery to an external circuit, the electrons now have a path to get back around to the other end of the battery via the external conductor - and they do, with enthusiasm!

We take advantage of that current flow and put some useful load in the circuit, something like a lamp that produces light as the electrons flow through it. And there you have it! Your torch is producing light and you can see to clip that cable in the ceiling!

Electromotive force can be produced in quite a few different ways such as an electrical generator, electrochemical cells (batteries), solar cells, fuel cells and thermocouples.

Unit of EMF

When electric current flows, work is done. The amount of work done is measured in joules.

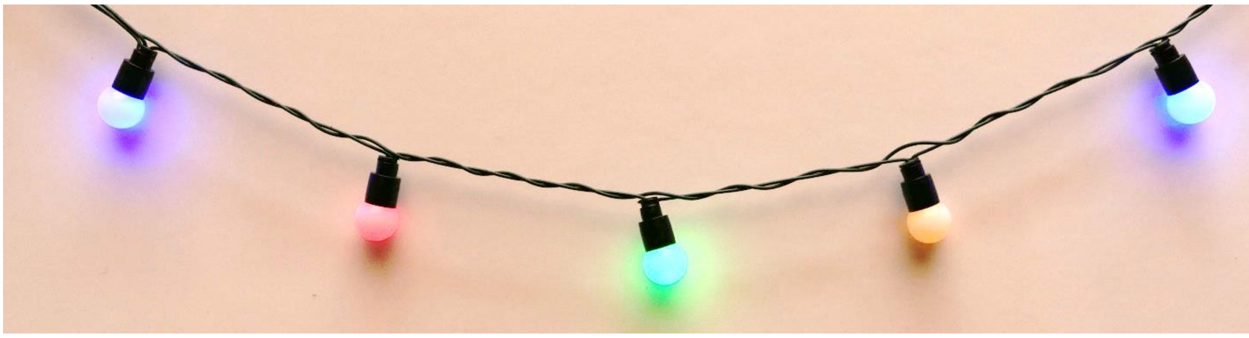
How the measurement of one volt is worked out is as follows:

One volt of electromotive force will produce the right amount of force to cause one ampere of current to flow long enough to cause one joule of work to be done.

The quantity symbol for electromotive force is E measured in volts and the unit symbol is V.

Unit of potential difference

The difference in the number of electrons between two points is called *potential difference*.



If you have a set of Christmas tree lights with the lamps connected in series (the circuit current flows first through one lamp and then the next and then the next etc), a portion of the supply voltage to the circuit is used up getting the current to flow through each individual lamp.

If you wanted to know how much voltage each lamp uses (drops), you could measure the voltage across one lamp. This type of voltage measurement is measuring the “potential difference” between two points in a circuit.

When measuring potential difference, the symbol for voltage is V and the unit symbol is also V.

Resistance

Resistance is the opposition to current flow and is measured in ohms (Ω). All materials have a certain amount of resistance to current flowing through them.

The unit ohm is named after the German physicist Georg Simon Ohm, who in 1826 discovered the relationship between the flow of current, the voltage, and the resistance in a closed circuit.

In our learning journey through the area of resistance we are going to start by looking at the electrical resistivity of materials.

Electrical resistivity

Conductors allow the easy flow of electrons and insulators do not.

Electrical resistivity of a material is the measure of the material's resistance to current flow for a standard amount of that material.

Resistivity is represented by the Greek Letter ρ (rho). The SI unit of measure is the ohm-metre (Ωm).

$f(x)$

Formula

To work out the resistivity of different types of materials you can use this formula:

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

Where:

R is the electrical resistance of the material in ohms.

A is the cross-sectional area of the material in square metres.

l is the length of the piece of material you are dealing with in metres.

You may have noticed that the units of measurement used in the formula for resistivity are metres.

The standard size of material this formula is based on is a cubic metre. Imagine paying for a cubic metre of silver, let alone putting it on the bench!

More than likely you are going to use the formula for working out the resistivity of a copper cable that is measured in millimetres.

You need to remember to convert your measurements of millimetres to metres when using this formula.

Electrical resistivity and insulators

Thinking about the resistivity of a material can be tricky - as all insulators and conductive material have resistivity. It's just how much they have that makes the difference.

The higher the resistivity a material has, the more it "resists" current flow and the better insulator it is.

So, if your job was to choose the best insulator and you were given the choice of PVC with a resistivity of 1.00×10^{12} or XLPE with a resistivity of 1.00×10^{15}, which one is the best insulator?

To work it out, you first need to understand what 1.00×10^{12} actually means. 1.00×10^{12} very simply means take the number (1.00) and move the decimal place 12 times to the right. It is a way to write a very big number simply and compactly.

PVC = 1.00×10^{12} = 1000000000000.0 Ωm

XLPE = 1.00×10^{15} = 1000000000000000.0 Ωm

Which is the better insulator? It's the material that has the most resistivity (opposition to current flow).

The one with the highest resistivity, and is the best insulator is XLPE with a resistivity of 1.00×10^{15}.

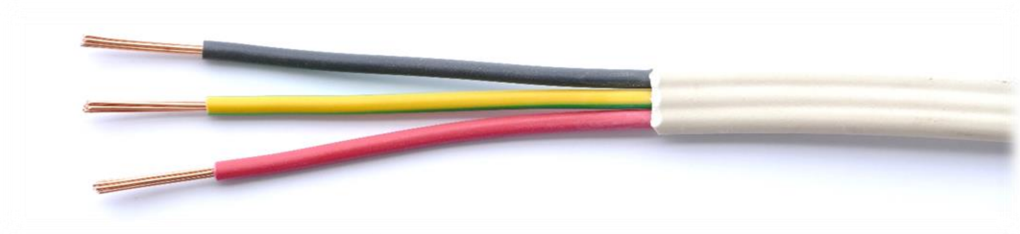
The higher the resistivity a material has, the more it "resists" current flow and the better insulator it is.

Electrical resistivity and conductors

If you want a good conductor, you need to choose a material with as low a resistivity as possible.

> **The lower the resistivity a material has, the less it "resists" current flow and the better conductor of current it is.**

You can use the resistivity of copper and compare it to the resistivity of silver.



Resistivity of copper = 1.68 x 10^{-8}

Resistivity of silver = 1.59 x 10^{-8}

x 10^{-8} means move the decimal place to the left (minus) 8 places. It is a way to write a very small number with lots of zeros simply and compactly.

Copper = 1.68 x 10^{-8} = 0.0000000168 Ωm

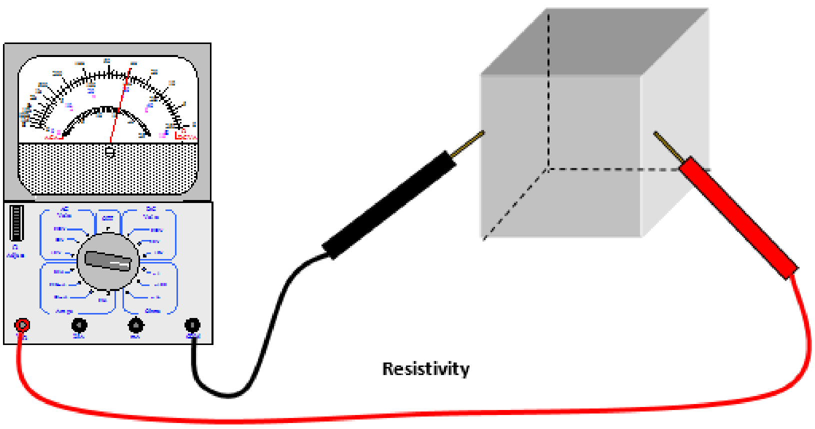
Silver = 1.59 x 10^{-8} = 0.0000000159 Ωm

Silver is a better conductor than copper as it has less resistivity, i.e. the free electrons are freer and easier to get to move in silver than in copper. If we were to compare the resistivity of copper to PVC, copper has far far less resistivity than PVC.

Copper = 1.68 x 10^{-8} = 0.0000000168 Ωm

PVC = 1.00 x 10^{12} = 1000000000000.0 Ωm

A material that has low resistivity will be a good conductor, the lower the better.



Note: the temperature of the material has an effect on the resistivity of the material. The standard resistivity for a material is measured at 20ºC, (although some are measured at different temperatures for special situations).

Electrical resistivity values

Some common materials and their values are given in the order of best to worse the table below:

Table 2.1 – Material resistivity - Conductors

Material (conductors)	Resistivity in Ohm metres @ 20ºC
Silver	1.59×10^{-8}
Copper	1.68×10^{-8}
Annealed Copper	1.72×10^{-8}
Gold	2.44×10^{-8}
Aluminium	2.82×10^{-8}
Tungsten	5.65×10^{-8}
Platinum	1.06×10^{-7}
Tin	1.09×10^{-7}
Carbon Steel (1010)	1.43×10^{-7}
Lead	2.20×10^{-6}
Brass - 58% Cu	5.90×10^{-8}
Brass - 63% Cu	7.10×10^{-8}
Nickel Silver (German silver)	3.3×10^{-7}
Manganin	4.82×10^{-7}
Nichrome	1.1×10^{-6}
Carbon (graphite)	3.00 to 60.00×10^{-5}

Table 2.2 – Material resistivity – Semi-conductors and Insulators

Material (semiconductors)	Resistivity in Ohm metres @ 20ºC
Germanium	4.6×10^{-1}
Silicon	6.40×10^{2}

Material (Insulators)	Resistivity in Ohm metres @ 20ºC
Glass – silica	1.00×10^{11}
PVC	1.00×10^{12}
Ceramic (Alumina)	1.00×10^{13}
Mica (Glimmer)	1.00×10^{13}
Ceramic (Porcelain)	1.00×10^{14}
Air	1.30×10^{14}
XLPE	1.00×10^{15}
Hard Rubber	1.00×10^{15}
Fused Quartz (Glass)	7.50×10^{17}
Polyethylene terephthalate (PET)	1.00×10^{21}
Teflon	1.00×10^{23}

Resistance (R)

Resistance is related to, but, slightly different to resistivity.

If you remember, resistivity is the inherent amount of resistance to current flow something has for every cubic metre of material. Resistance is the total opposition to current flow of an object, the object could be any size.

If you have an object made of a certain material, and If you know the resistivity of your material, its physical length and size, you can then work out the total resistance of your object.

We use resistance in various forms all the time to achieve our electrical goals for circuits.

In electronic circuits we use components designed specifically to resist current in various ways. Guess what they are called? Resistors! Amazing!

We will spend some time later in this resource looking more specifically at those actual resistors.

Resistance in a circuit

We want conductors to have a low resistance to get the current to and from the load without wasting energy and costing us extra money.

At the same time, we want insulators to have a high resistance to stop any current leaking out of a cable and burning the house down or electrocuting you.

We also want the load in a circuit to have the right amount of resistance to do a job.

The load might be a heater for your bathroom for example. We send the current to the heater through the cable, then the current flows through the heater element.

The heater element is made of a material that is designed to allow current to flow through it, but it has a much higher resistance to current flow than the copper supply conductor.

As the current forces its way through the element the element gets hot. There is a fan that blows over the element and the heat the element produces makes you toasty and warm!

There is one other benefit of the resistance of the load. Without a load in a circuit, you will have a low resistance conductor connecting the ends of the supply source together.

This would be a short circuit and all of the electrons would have a super highway to get where they want to be.

The current flow would go sky high. The very high current flowing through what little resistance the cable has will cause heaps of heat.

The cable insulation could melt or burst into flames! It would be all downhill disaster from there.

The resistance of the load in a circuit keeps the circuit current under control. It provides enough opposition to current flow to produce the work the circuit is designed to do and at the same time keep the overall circuit current down to a safe level.

Can you see that all three components of our circuit have different requirements for resistance?

- Resistance is undesirable in a cable conductor, we keep it as low as possible.
- Resistance is very desirable in a cable insulator, we keep it as high as possible.
- Resistance is necessary for the load, we set it at the correct level to make the circuit work.

Unit for resistance

The SI unit symbol for resistance in electrical circuits is (R). Electrical resistance is measured in ohms which has the symbol (Ω).

How the unit of resistance was originally decided on was: when 1 volt is applied to a circuit, a current of 1 ampere will flow when the circuit has a resistance of 1 ohm. So, there you have it!

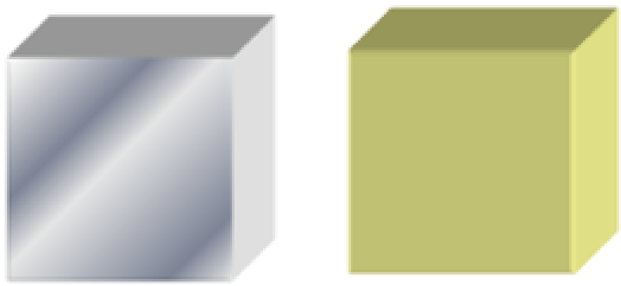
Factors affecting conductor resistance

There are a few factors that affect the resistance of a conductor. You may need to work out the resistance of a particular cable conductor, so it is important that you understand what factors you need to take into account.

Resistance will depend on the following factors:

1. **The material the conductor is made of, i.e. the resistivity (ρ) of the material.**
   - **The lower the resistivity, the lower the resistance.**
   - **The higher the resistivity, the higher the resistance.**

Resistance is proportional to the resistivity of the conductor, $R \propto \rho$**.**



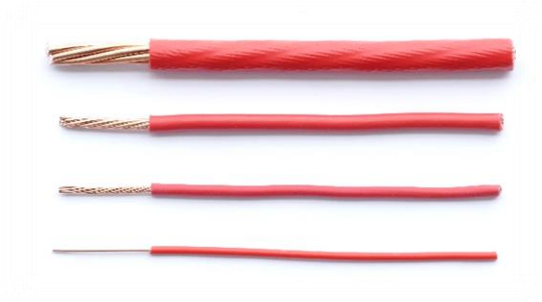
SILVER
Low resistivity
(1.63×10^{-8} Ωm)

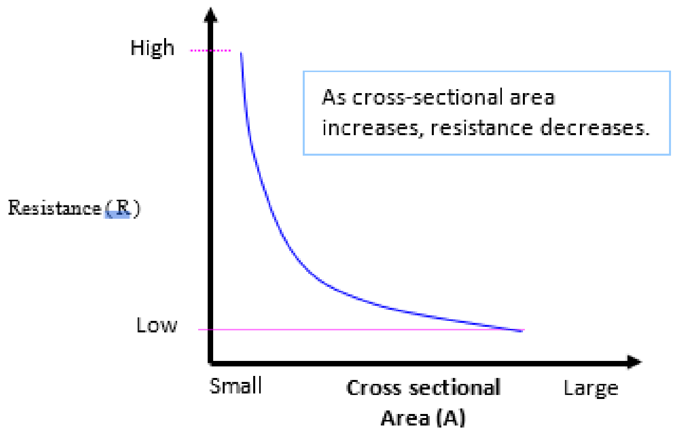
NICHROME
High resistivity
(112×10^{-8} Ωm)

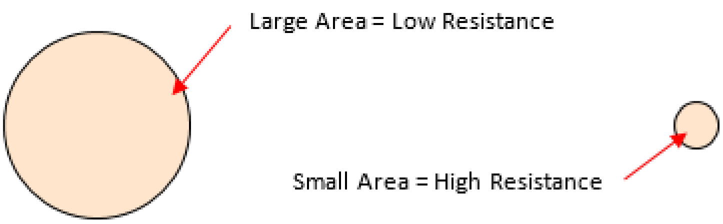
2. **The cross-sectional area of the conductor.**
    - **The greater the conductor area, the lower the resistance.**
    - **The smaller the conductor area, the higher the resistance.**

Resistance is indirectly proportional to the cross-sectional area of the conductor,

$R \propto \frac{1}{A}$





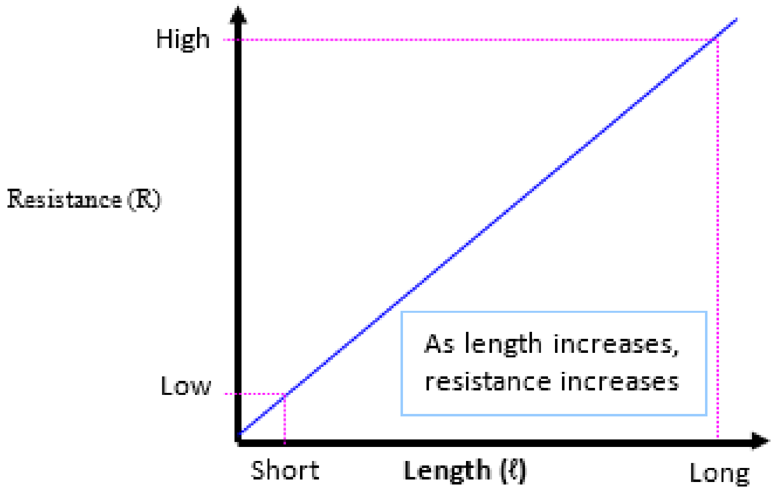


3. The length of the conductor.

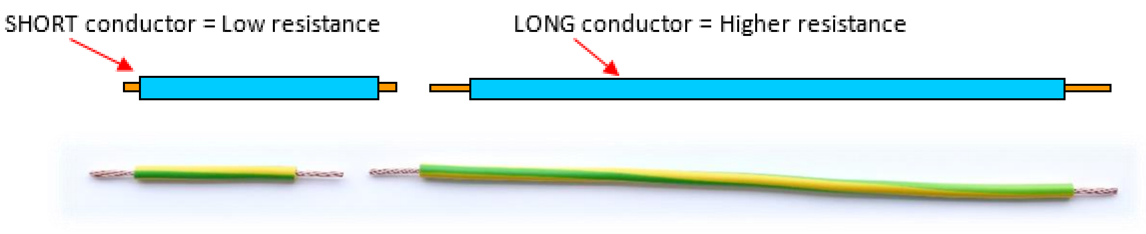
- The shorter the conductor, the lower the resistance.
- The longer the conductor, the higher the resistance.

Resistance is proportional to the length of the conductor

$R \propto l$



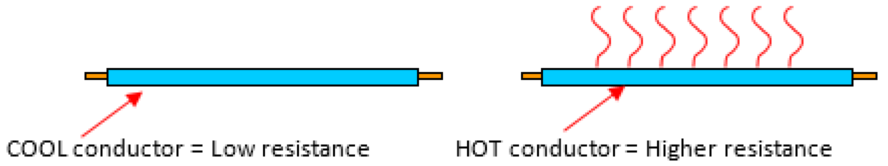
The graph above shows that as the length of a conductor increases, the resistance also increases.



The change in resistance with a change in length is linear so it is possible to estimate the length of a conductor from its resistance (as long as its temperature remains the same).

4. **The temperature of the conductor.**
   - **The higher the conductor temperature, the higher the resistance.**
   - **The lower the conductor temperature, the lower the resistance.**

Resistance is proportional to the temperature
$R \propto l$



You may have a length of copper cable for example, it has a length and a cross sectional area and you know the resistivity of a cubic metre of copper.

You can then work out what fraction of a cubic metre of copper your conductor is, and then use the resistivity of copper to work out the total resistance your piece of copper has. This will be the resistance at 20˚C as this is the temperature for standard resistivity.

The snag is, you may be installing that conductor in a cool store at -20˚C. Or it may be in a bakery above the ovens. The temperature will make a difference to the resistance of the conductor as well.

The shorter, fatter and colder a conductor is the less resistance it will have.

The longer, skinnier and hotter a conductor is the more resistance it will have.

Calculating conductor resistance

By combining all of the resistance factors above into a formula, it is possible to calculate the resistance of any conductor.

$\boldsymbol{f(x)}$ $$\boldsymbol{Resistance\ (R) = \frac{Rho\ (\rho) x\ Length\ (\ell)}{Area\ (A)}}$$

R = resistance of material (Ω)

ρ = the conductor's resistivity [pronounced row] (Ω m)

ℓ = Length (m)

A= Cross sectional area (m2)

Important note

As with any formula, pay careful attention to the units the formula uses.
In this formula the cross-sectional area of the conductor must be in or converted to metres squared.

To convert millimetres squared to metres squared multiply the millimetres squared by 10^{-6}

If you know the resistance of a conductor, it is also possible to calculate the resistivity of the conductor by transposing the formula.

$\boldsymbol{f(x)}$ $$\rho = \frac{R\ x\ A}{\ell}$$

Example 2.1

Determine the resistance of a 100-metre length of copper conductor if its cross-sectional area is 0.5 mm^2. Use 1.72 x 10^{-8} ohmmeter for the resistivity (ρ) of copper.

$$R = \frac{\rho \times \ell}{A}$$

$$R = \frac{1.72 \times 10^{-8} \times 100}{0.5 \times 10^{-6}}$$

$$R = 3.44\ \Omega$$

Example 2.2

Determine the resistivity of a material that has a total resistance of 8.6 Ω, its length is 1000 metres and its cross-sectional area is 2 mm^2.

$$\rho = \frac{R\ x\ A}{\ell}$$

$$\rho = \frac{8.6 \times 2 \times 10^{-6}}{1000}$$

$$\rho = 1.72 \times 10^{-8}\ \Omega m$$

Example 2.3

Calculate the length of a conductor that has a cross sectional area of 0.2 mm^2 if its resistivity is 50 x 10^{-8} ohmmeter and it has a resistance of 15 Ω.

$$\ell = \frac{R\ x\ A}{\rho}$$

$$\ell = \frac{15\ x\ 0.2 \times 10^{-6}}{50 \times 10^{-8}}$$

$$\ell = 6\ m$$

Example 2.4

Calculate the area of a conductor in square millimetres if it has a resistivity of 1.72 x 10^{-8} ohmmeter, a length of 1000m and a resistance of 8.6 Ω

$$A = \frac{\rho \times \ell}{R}$$

$$A = \frac{1.72 \times 10^{-8} \times 1000}{8.6}$$

$$A = 2\ x\ 10^{-6}\ m^2$$

$$A = 2 \div 10^{-6}\ mm^2$$

$$A = 2\ mm^2$$

Temperature co-efficient of resistance

You need to know what "temperature co-efficient of resistance" is. It's a mouthful but don't freak out as it isn't too bad when it is explained.

The resistance of a conductor varies with temperature. The temperature co-efficient of resistance is a number that defines how much.

"Temperature" - indicates that we are working out what difference a change in temperature is going to make.

"Co-efficient" - is the number that tells us by how much.

"Resistance" - is the thing that is going to change.

One of the most common conductor materials used in the electrical industry is copper, as it is a very good conductor and relatively cost effective.

- **The temperature co-efficient of resistance of copper is given as 0.00427 at 0˚C.**
- **The temperature co-efficient of resistance of copper is given as 0.00393 at 20˚C.**

Using a TCR of 0.00427, it means that for every 1˚C change in temperature the resistance of copper will change by 0.00427Ω which can also be written as 4.27 $\times 10^{-3}$ or even as a percentage 0.427%.

PTC / NTC

There is another thing you will need to know about temperature co-efficient of resistances, - there are positive ones and negative ones.

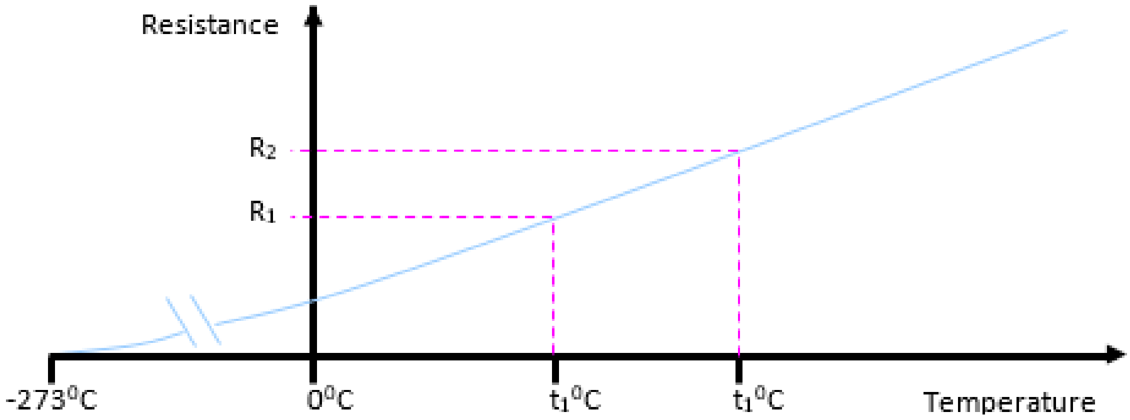
You already know that as the temperature of copper increases, so does its resistance. There are some materials that we use (in particular in electronics) that actually have a decrease in resistance when the temperature increases.

Definition

Positive temperature co-efficient of resistance (PTC):	The resistance of a material increases as the temperature increases.
Negative temperature co-efficient of resistance (NTC):	The resistance of a material decreases as the temperature increases.

Calculating conductor resistance with change of temperature

If the temperature change over which the resistance is measured is relatively small, the relationship between temperature and resistance is close to linear and the resistance at a given temperature can be readily calculated.



A simple scenario might be that you have a copper conductor in a roof space and it has a resistance of 2Ω at 28˚C. What will be the new resistance of the conductor be if the temperature in the roof increases to 40˚C?

There are several formulas that can be used for working out the answer to this question. We will take a quick look at two.

Note: The information you are given in a question will determine which formula you would choose to use.

The formula below calculates the resistance at a new temperature with reference to the resistance of the conductor material at 0 ˚C.

$f(x)$ $$R_t = R_0(1 + \alpha_0 t_1)$$

Where;

R_t *= Resistance at the new temperature (Ω)*

R_0 *= Resistance at 0℃ (Ω)*

α_0 *= Temperature coefficient of resistance at 0℃*

t_1 *= New temperature (℃)*

Example 2.6

A copper conductor in a roof space has a resistance of 2Ω at 28˚C. What will be the new resistance of the conductor if the temperature in the roof increases to 40˚C? The temperature co-efficient of resistance of copper at 0˚C is 0.00427 (4.27 x10^{-3}).

Firstly, using the information you have, work out what resistance the conductor would have at 0 ^{0}C.

$$R_t = R_0(1 + \alpha_0 t_1)$$

Transpose formula to find R_0

$$R_0 = \frac{R_1}{(1+\propto_0 t_1)}$$

$$R_0 = \frac{2}{(1+0.00427 \times 28)}$$

$$R_0 = 1.79\Omega$$

Now that you have the R_0 figure you can work out the new resistance at 40˚C.

$$R_t = R_0(1 + \alpha_0 t_1)$$

$$R_t = 1.79(1 + 0.00427 \times 40)$$

$$R_t = 2.09\Omega$$

The resistance of the conductor has gone up a little from 2Ω to 2.09Ω because of the higher temperature of the copper.

We will now look at a second formula to work out the increase in resistance. This equation is a one step process for the same example. For this equation to be accurate, you need the temperature co-efficient of resistance of the conductor at the temperature range in the question.

$f(x)$	$R_2 = R_1\,[1 + \alpha\,(t_2 - t_1)]$

Where;

R_2 = Resistance at the new temperature (Ω)

R_1 = Resistance at the original temperature (Ω)

α = Temperature coefficient of resistance

t_1 = Original temperature (˚C)

t_2 = New temperature (˚C)

Example 2.7

A copper conductor in a roof space has a resistance of 2Ω at 28˚C. Using the temperature co-efficient of resistance for copper of 0.00393, what will the new resistance of the conductor be if the temperature in the roof increases to 40˚C?

$$R_2 = R_1\,[1 + \alpha\,(t_2 - t_1)]$$

$$R_2 = 2\,[1 + 0.00393\,(40 - 28)]$$

$$R_2 = 2\,[1 + 0.00393\ \times 12]$$

$$R_2 = 2\ \times 1.04716$$

$$R_2 = 2.09\Omega$$

Example 2.8

A cable conductor has a resistance of 10 Ω at 0 ^{0}C. determine its resistance at 25 ^{0}C if α_0 for copper is 0.00427.

$$R_t = R_0(1 + \alpha_0 t_1)$$

$$R_t = 10\left(1 + (0.00427 \times 25)\right)$$

$$R_t = 10\ \times 1.10675$$

$$R_t = 11.07\ \Omega$$

Example 2.9

If the start winding of a single-phase motor has a resistance of $11.0675\ \Omega$ at 25 ^{0}C, find the resistance of the winding when the motor is running hot and the winding is at 60 ^{0}C, use α_0 for copper is 0.00427.

First, we transpose $R_t = R_0(1 + \alpha_0 t_1)$ to find the resistance at 0^{0}C (R_0)

$$R_t = R_0(1 + \propto_0 t_1)$$

$$R_0 = \frac{R_t}{(1+\alpha_0 t_1)}$$

$$R_0 = \frac{11.0675}{(1+(0.00427\times 25))}$$

$$R_0 = 10\ \Omega$$

Then using $R_t = R_0(1 + \alpha_0 t_1)$ we find the conductor's resistance at 60 ^{0}C.

$$R_t = R_0(1 + \alpha_0 t_1)$$

$$R_t = 10\big(1 + (0.00427 \times 60)\big)$$

$$R_t = 12.56\ \Omega$$

Example 2.10

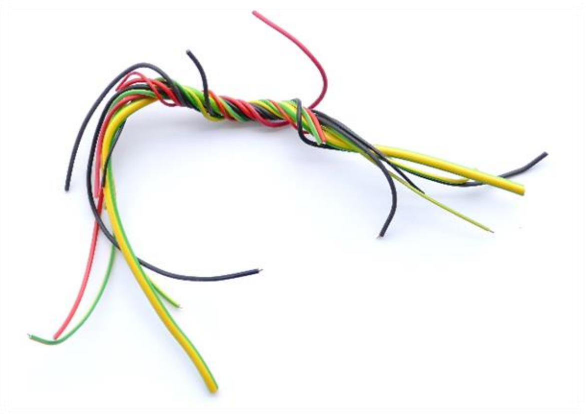
If the start-winding resistance of a single-phase motor is 16.9215 Ω at 30 ^{0}C, find the resistance of this winding at 60 ^{0}C if α for copper is 0.00393.

$$R_2 = R_1(1 + \alpha_1(t_2 - t_1)$$

$$R_2 = 16.9215(1 + 0.00393(60 - 30)$$

$$R_2 = 18.92\ \Omega$$

Insulation resistance



As we said earlier in this resource, in a cable we want the conductor resistance to be as low as possible and the insulation resistance to be as high as possible. The conductors and the insulation have opposite jobs.

The conductor needs to allow the current to flow as easily as possible and the insulator must stop current flow, if you are using your drill you do not want the current to flow out through the handle or out through the plastic on the cord.

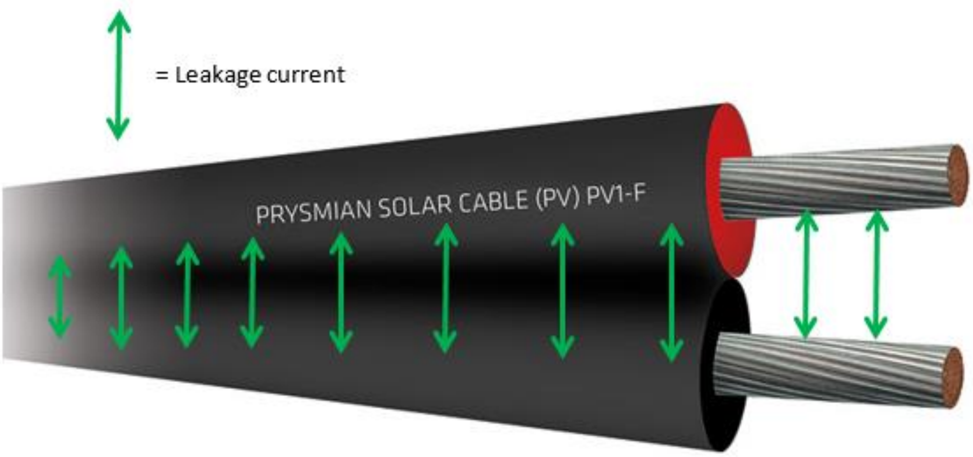
Insulation resistance is inversely proportional to length

The accepted industry standard for insulation resistance is that an insulator should have at least 1MΩ (1 million ohms) of resistance against current flow.

> **Note: according to AS/NZS 3000 this is the minimum acceptable insulation resistance. Iif a cable or installation is at this low end of the insulation scale, you should be checking for problems. Billions of ohms would be much better.**

Insulation should have a resistance of at least 1MΩ, heaps more if possible.

You have already discovered that the resistance of a conductor will increase as the length is increased. The opposite is true of the insulation, as the length of cable insulation is increased, the insulation resistance is reduced. Generally, if the length of the cable is doubled its insulation resistance is halved, crazy! Why?



Insulators do actually leak a small amount of current. As we wrap the insulation around a conductor, the longer the conductor is, the greater the surface area of the conductor that is in contact with the insulator.

If you have a think about one 10mm length of insulation, it is slightly (very slightly) leaky to current. Now, add another 10mm and you have double the amount of leakage. Add another one and you have three times the leakage for the cable.

Can you see that there is more and more insulation leakage current the longer the cable is? And if you think about it, that actually means the overall insulation resistance figure for the cable is reducing the longer it gets.

The thinner the insulation is the leakier it will be too. It is probably obvious that if you make the insulation thicker it will have less current leakage and therefore insulate better.

In summary it can be said that the insulation resistance of a cable is inversely proportional to the length of insulated cable and directly proportional to the thickness of its insulation.

$\boldsymbol{f(x)}$

$$\textit{Insulation Resistance (IR)} \propto \textit{Thickness of Insulation (d)}$$

$$\textit{Insulation Resistance (IR)} \propto 1/(\textit{Length of cable (l)})$$

A formula that you can use to work out changes in insulation resistance with changes in the length of cable is as follows:

$$\frac{IR_1}{IR_2} = \frac{l_2}{l_1}$$

Where;

$IR_1 = \textit{Insulation resistance of the first cable length}\ (\Omega)$

$IR_2 = \textit{Insulation resistance of the new cable length}\ (\Omega)$

$l_1 = \textit{length of the first cable}$

$l_2 = \textit{length of the new cable}$

Example 2.11

An underground cable with a length of 100 metres has an insulation resistance of 100 MΩ. If 1.2Km of the same cable was to be used to supply a farm what would be the expected insulation resistance of the cable?

$$\frac{IR_1}{IR_2} = \frac{l_2}{l_1}$$

Transpose the formula to give IR_2

$$IR_2 = \frac{IR_1 \times l_1}{l_2}$$

$$IR_2 = \frac{100M\Omega \times 100m}{1200m}$$

$$IR_2 = 8.33M\Omega$$

Obviously, it is important to have good effective insulation Ion a cable but there are some other considerations for insulation too.

Other cable insulation considerations can be its ability to withstand:

- **Heat and or cold and or freezing**
- **Sun light and ultra violet rays**
- **Other environmental conditions like salt and moisture**
- **Impact**
- **Wear**
- **Flexing**
- **Shock**
- **Vibration**
- **Fire**
- **Oil and chemicals**

Practical 2.1

Aim

To demonstrate what effect length and cross-sectional area has on a conductor material's resistance.

Equipment

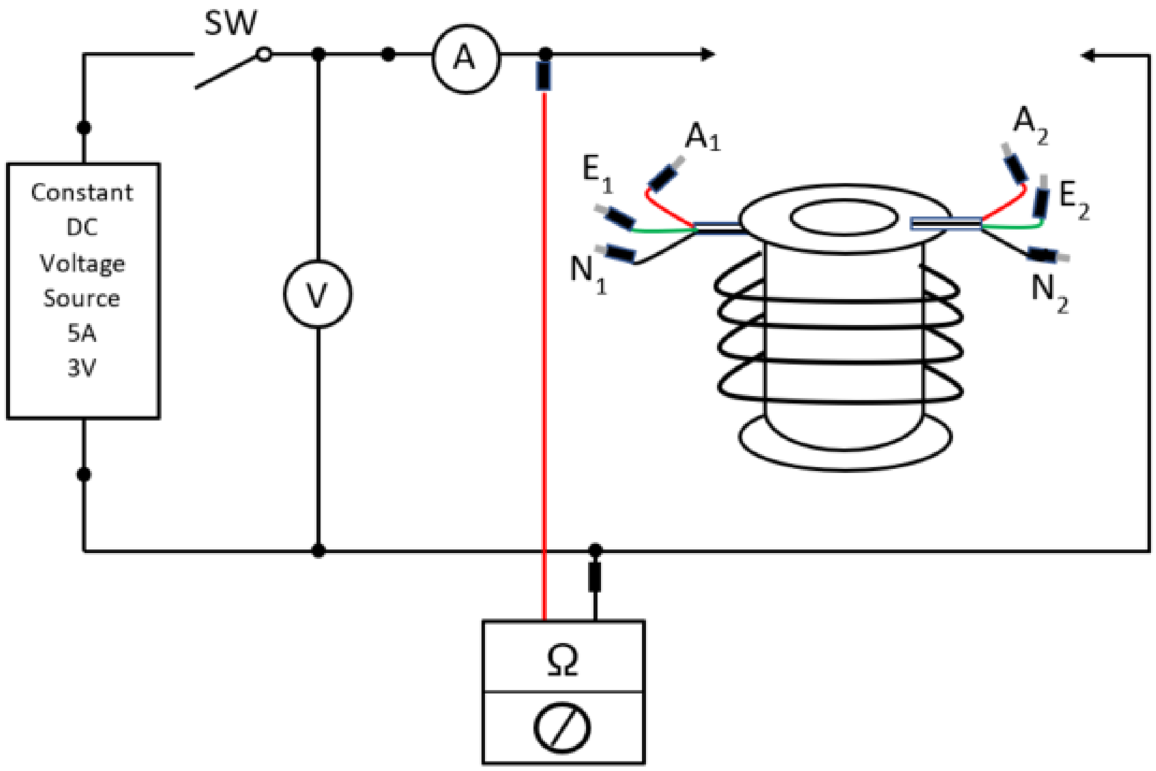
Item	Quantity
Variable DC power source 0 to 25V	1
Ammeter 0 – 10A DC	1
Voltmeter 0 – 50V DC	1
Ohm meter	1
Switch	1
Connecting leads	As required
A 100m drum of 1.5mm2 T+E cable	1

Note: Any size cable can be used; however, 1.5mm^2 T+E cable has 3 conductors of the same size and is small enough to show a significant amount of resistance.

Procedure

1. **Referring to the circuit diagram below setup the circuit. Ensure the switch is open (OFF position) and the ohm meter is not permanently connected. Adjust the voltage source output to 0.0 V to avoid accidental short circuits.**

2. **You will be making multiple connections and measurements by connecting the two flying ends of the leads (shown as arrows) according to the tables below:**



3. **Have your circuit checked by your instructor for correct connection.**

4. **Set the multi-meter to a suitable ohm range, and measure the resistance of the conductors as per table below and record these readings in the same table. Make sure you connect the links as required and check with your instructor to ensure the connections are correct.**

5. **Remove the ohm meter and close (Turn ON) the switch and adjust the supply source voltage to 2.0V (the current may reach 1.6A to 2.0A) Monitor the supply voltage (V), and Current through the circuit (I). When the values are stabilised, record them in the Table 5 below for that setting.**

6. **Turn off the switch and adjust the links as necessary. Each time you adjust the links you will be increasing the length of the conductor while its CSA is kept the same.**

7. **Repeat steps 4 to 6 above for each link setting ensuring the supply voltage remains the same. Any change in current will be a result of resistance change.**

Table 2.3

Testing points	Links		Measured		Calculated		
			(R_W) Wire Resistance (Ω)	Wire length* (m)	Current (I) (A)	V	Wire Resistance $R_W = \frac{V}{I}$
$A_1 – A_2$	-	-					
$A_1 – E_1$	$A_2 – E_2$	-					
$A_1 – N_2$	$A_2 – E_2$	E_1- N_1					
*Wire length would be the multiples of the cable length (e.g. 100m, 200m and 300m)							

8. **Turn off the switch and make it safe. Calculate the conductor resistance using the values you have recorded for voltage and current of the circuit in the table.**
9. **Compare the calculated and measured values for conductor resistance and related them to Ohm's Law.**
10. **Using the values in the table draw a graph below indicating the relationship between the conductor's length and its resistance.**
11. **Remove the links and setup the circuit as per table below. In this part you will be connecting the conductors in parallel that is increasing the CSA at each step.**
12. **Set the multi-meter to a suitable ohm range and measure the resistance of the conductors as per table 6 below recording these readings in the same table. Make sure you connect the links as required and check with your instructor to ensure the connections are correct.**
13. **Remove the ohm meter and close (Turn ON) the switch and adjust the supply source voltage to 2.0V (the current may reach 1.6A to 6.0A) Monitor the supply voltage (V) and Current through the circuit (I). When the values are stabilised record them in the Table below for that setting'**

Table 2.4

Testing points	Links		Measured		Calculated		
			(R_W) Wire Resistance (Ω)	Wire CSA* (mm^2)	Current (I) (A)	V	Wire Resistance $R_W = \frac{V}{I}$
$A_1 - A_2$	-	-					
$A_1 - A_2$	$A_2 - E_2$	$A_1 - E_1$					
$A_1 - A_2$	$A_2 - E_2 - N_2$	$A_1 - E_1 - N_1$					
*Wire CSA would be the multiples of the individual wire CSA (e.g. 1.5 mm^2, 3.0 mm^2 and 4.5mm^2)							

14. **Turn off the switch and adjust the links as necessary. Each time you adjust the links you will be increasing the CSA of the conductor while its length remains the same**

15. **Repeat steps 12 to 14 above for each link setting ensuring the supply voltage remains the same. Any change in current will be a result of resistance change.**

16. **Turn off the switch and make it safe. Calculate the conductor resistance using the values you have recorded for voltage and current of the circuit in the table.**

17. **Compare the calculated and measured values for conductor resistance and related them to Ohm's Law.**

18. **Using the values in the table draw a graph below indicating the relationship between the conductors' CSA and its resistance.**

19. **Disconnect the circuit and return all equipment to its proper place.**

20. **Write up your conclusion discussing the relationship between conductor's length, CSA and its resistance.**

Practical 2.2

Aim

To demonstrate how a change in temperature affects the resistance of a conductor.

Equipment

Item	Quantity
Glass beaker or jar	1
Long length of coiled insulated wire (e.g. 12V contactor coil)	1
22 Ω, 5 Watt wire wound resistor	1
Variable DC power source 0 to 25V	1
Ammeter 0 – 10A DC	1
Voltmeter 0 – 50V DC	2
Ohm meter	1
Switch	1
Thermometer	1

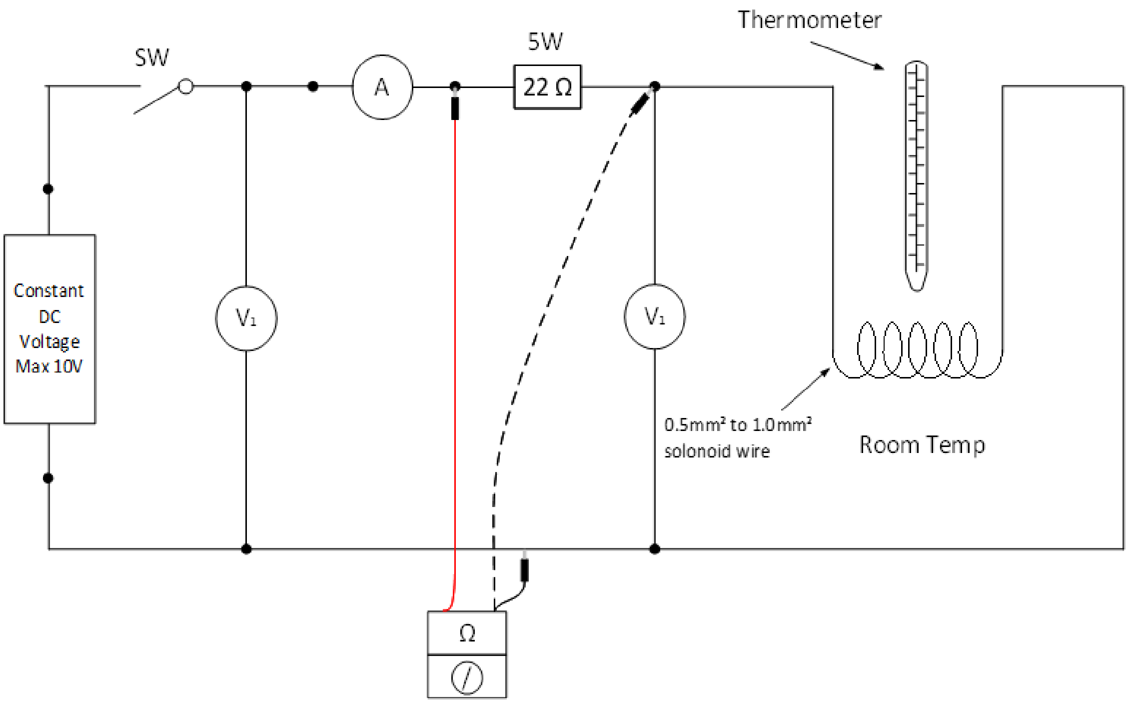
Procedure

1. **The circuit diagram below setup the circuit. Ensure the switch is open (OFF position) and the ohm meter is not permanently connected. Adjust the voltage source output to 0.0 V to avoid accidentally overheating the resistor.**

2. **Have your circuit checked by your instructor for correct connection.**

3. **Set the multi-meter to a suitable ohm range and measure the resistance of the (22Ω) resistor first then the total resistance of the resistor and the coil together. Record these readings in Table 7 below in the (Room Temp) row.**

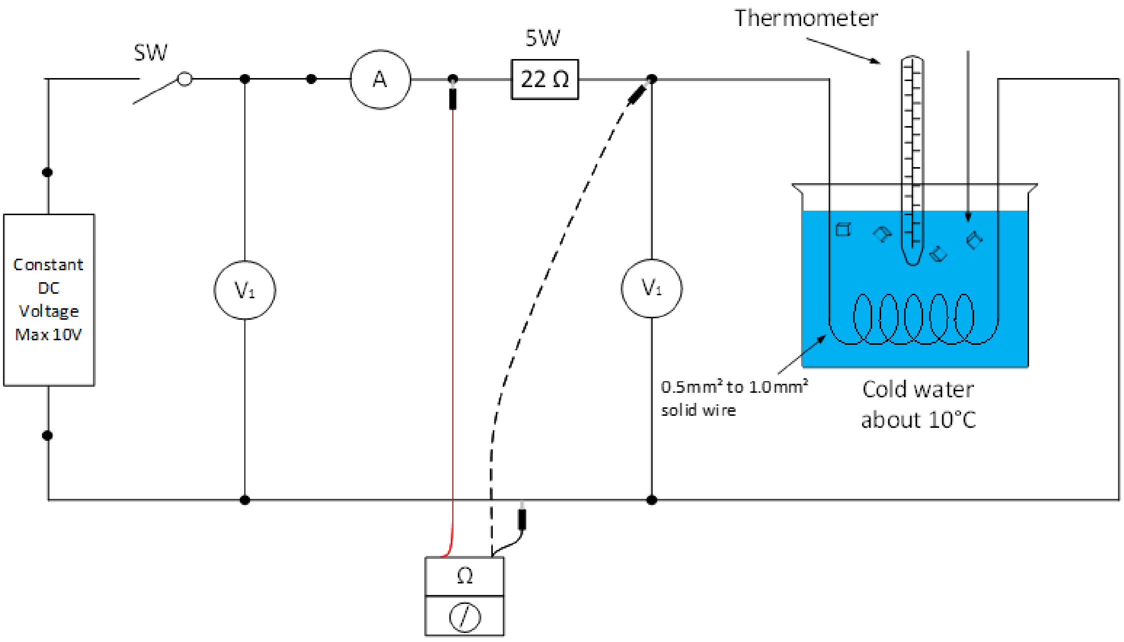
4. **Remove the ohm meter and close (Turn ON) the switch and adjust the supply source voltage until the current reaches 0.4A (400mA). Monitor the supply voltage (V_1), current through the circuit (I) and the voltage across the coil (V_2). When the values are stabilised record your readings in the (Room Temp) row.**



5. **Turn off the switch and place the coil in the beaker filled with cold water and ice. Use the thermometer to record the temperature of the water. Wait until the temperature goes below 10 0C.**

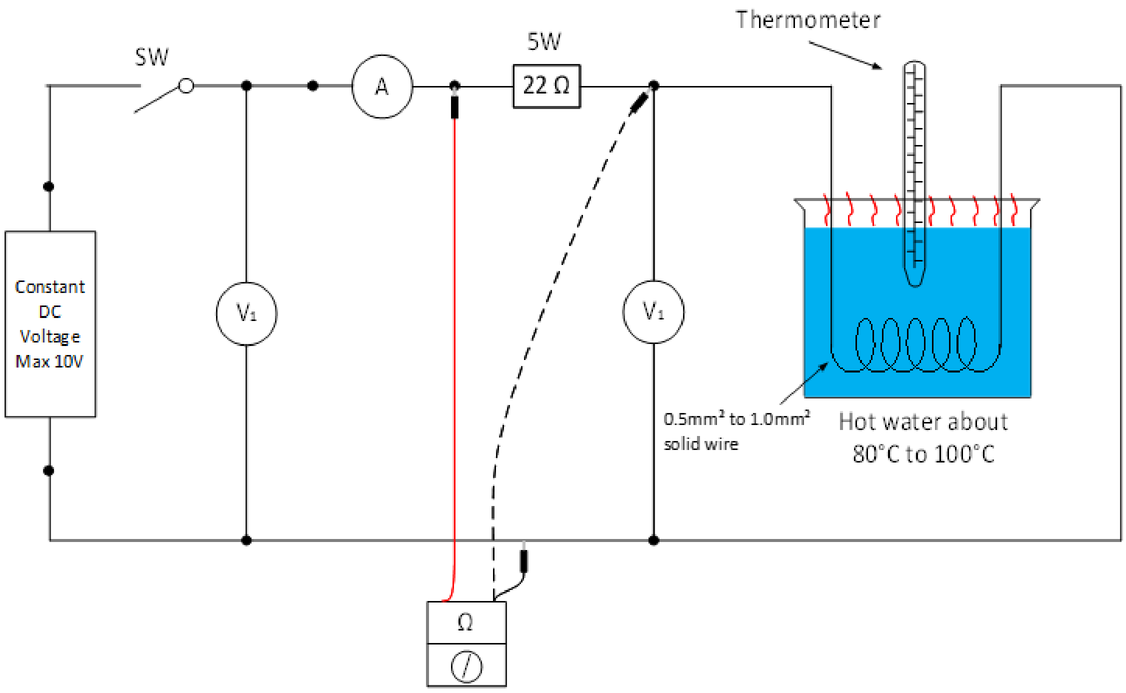
6. **Measure the resistance values as in step 3 and record readings in the Cold Temp. row. Make sure you record the temperature.**

7. **Remove the ohm meter and close (Turn ON) the switch. Ensure the supply source voltage (V1) is the same as in step 5. Monitor the current through the circuit (I) and the voltage across the coil (V2). When the values are stabilised record them in the Table row for Cold Temp.**



8. **Turn off the switch empty the beaker and wait until it warms up to room temperature. Then place the coil in the beaker and fill up with hot water around 80 0C to 100 0C. Use the thermometer to record the temperature of the water.**

9. **Measure the resistance values as in step 3 and record readings in the (Hot Temp) row. Make sure you record the temperature.**



10. **Remove the ohm meter and close (Turn ON) the switch. Ensure the supply source voltage (V1) is the same as in step 5. Monitor the current through the circuit (I) and the voltage across the coil (V2). When the values are stabilised record readings in the (Hot Temp) row.**

Table 2.5

	Water temp (°C)	Measured						Calculated	
		Total Resistance (Ω)	R_1 Resistance (Ω)	(R_W) Wire Resistance $R_W = R_T - R_1$	Current (I) (A)	V_1	V_2	Wire Resistance $R_W = \frac{V_2}{I}$	Total Resistance $R_T = \frac{V_1}{I}$
Cold temp									
Room temp									
Hot temp									

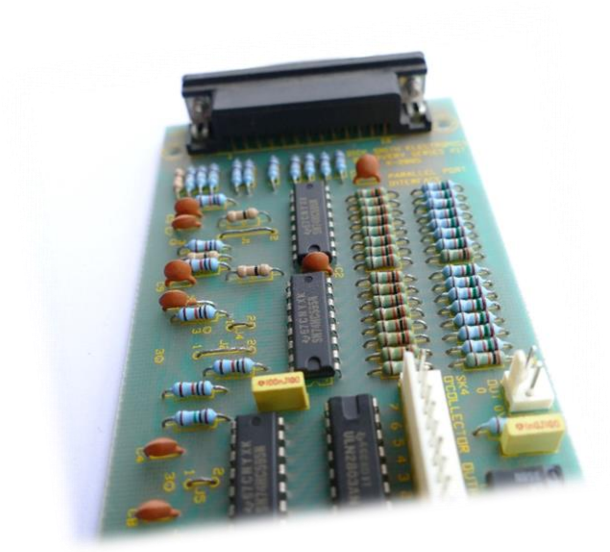
11. Disconnect the circuit and return all equipment to its proper place. Using the information recorded in the table calculate the coiled wire resistance and the total resistance of the circuit.

12. Compare the calculated and measured calculated value and related them to Ohm's Law.

13. Using the values in the table draw a graph below indicating the relationship between the conductors' temperature and its resistance.

Part 3: Resistor Characteristics

Resistors



A resistor is a component specifically designed to oppose current flow.

Voltage is used up (dropped) pushing the current through a resistor as resistors make it difficult for current to flow.

The result of current forcing its way through a resistor is heat, power is used (dissipated) by a resistor to create the heat.

In electronic circuits, resistors are often designed and installed to control the current flow to particular parts of a circuit or drop a certain amount of voltage. The design of resistors and the materials used to manufacture them is largely governed by their function and the amount of power they are expected to dissipate.

Resistor terms

As with any field of technical study, there are terms and jargon associated with resistors.

You will need to be familiar with the following terms:

Term	Definition
Tolerance	In the process of manufacturing resistors there is some margin for inaccuracies in the resulting value. The tolerance is the percentage difference between the required value and the manufacturers' achieved value.
Preferred values	It would be too huge to have a range of resistors going up in 1-ohm or smaller steps. There are a set of preferred values of resistors that is the internationally accepted range of manufactured values commonly made and used.
Stability	How much the resistance might change if the temperature changes. Also, as a resistor ages it may vary in its value, how stable the resistor is over time may also be referred to as its value stability.
Power rating	The maximum value of power a resistor can cope with continuously, if this value is exceeded then the resistor might be destroyed. This rating is usually given by the manufacturer in watts.
Power dissipation	The heat generated by the current flowing through the resistor. This value will vary with changes in current flow.
Voltage rating	The maximum voltage that can be used without causing damage to the resistor. Different resistors may have different voltage ratings.
Current rating	The maximum current that can flow continuously through a resistor without causing damage to the resistor.
Temperature coefficient ppm	How much the value of a resistor will change with a change in temperature, ppm/°C = parts per million per degree centigrade temperature change.

Resistor ratings

There are two ratings associated with all resistors. These are,

- **Resistance value.**
- **Power dissipation (rating).**

Resistance value

Resistors are made to have a certain value of resistance, obviously this is the resistance value of the resistor.

Resistor values can be fractions of an ohm up to many millions of ohms. The actual range available will depend on the construction and process used in their manufacture.

When resistor values are written, they are often written using a multiplier (R, k, M etc.) and the multiplier is written to indicate the position of the decimal point.

- **R = resistance**
- **k = kilo (x 1000)**
- **M = Mega (x 1 000 000)**

For example, Resistor values from 0 Ω to 999 Ω are often written as follows,

33 Ω is written as 33 R

3.3 Ω is written as 3R3

0.33 Ω is written as 0R33

Power rating

Power used by a resistor is calculated by multiplying the voltage dropped across the resistor and the current flowing through the resistor together.

That is;

$f(x)$	$Power\ (P) = Voltage\ (V)\ x\ Current\ (I)$ $P = V\ x\ I$

Power can also be calculated if only the current flow and the value of the resistive path are known.

$f(x)$	$Power\ (P) = I2\ (current)\ x\ R\ (resistance)$ $P = I^2R$

Since the power dissipated by a resistor is in the form of heat, it is really important that the resistor is able to handle the temperature rise it is going to have or, there will be damage to itself or the components around it.

Resistors designed to cope with more than 1-watt of power should be mounted in such a way as to allow adequate airflow around the body of the resistor because, they are going to get hot and need the air to cool them.

Resistor categories

All resistors, no matter what their design or application will fall into two broad categories which are:

- **Fixed resistors, and**
- **Variable or adjustable resistors.**

Resistors are also either linear and non-linear.

- **Linear resistors.**
  - **The resistance of these resistors stays the same, once set, the resistance doesn't change significantly with changes in temperature or voltage.**
- **Non - linear resistors.**
  - **Non-linear resistors are manufactured to change resistance value depending on temperature, applied voltage or other variable conditions like dark or light.**

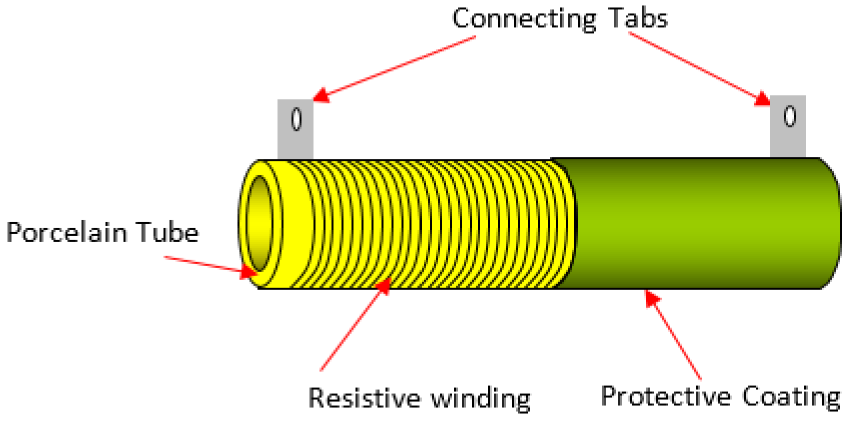
Fixed resistors

Fixed resistors are manufactured to have a fixed resistance value that cannot be altered by the user. They are available in six main types:

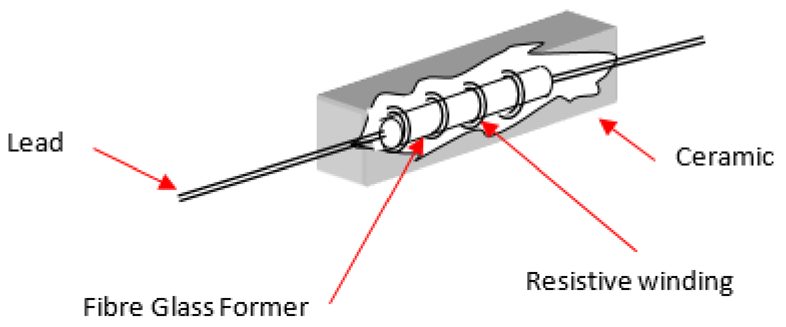
- Wire Wound
- Carbon Composite
- Carbon Film
- Metal Film
- Thick / Thin Film
- Surface Mount

Wire wound resistors

Wire wound resistors are constructed by winding a resistive conductor such as Manganin or Nichrome on a former, which can be made from Bakelite or porcelain. Early versions used a tube former to improve surface area and cooling air flow. Once wound, the resistive wire is coated with vitreous enamel to reduce oxidation and general deterioration from corrosion.



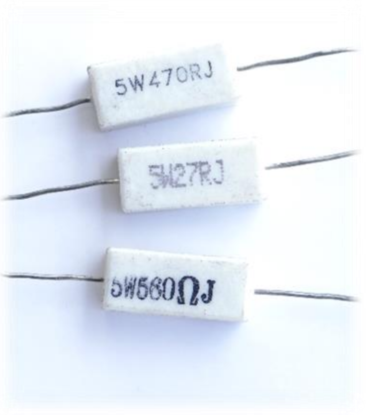
An alternate form of the wire wound resistor is a solid rectangular construction. Here the resistance wire is wound on an insulating fibreglass core, terminated to bare copper leads at each end and then encapsulated in ceramic material.

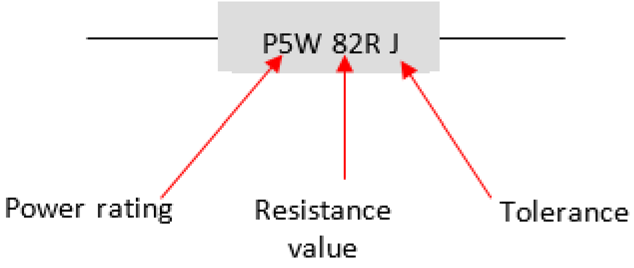


If the resistance wire is wound so that adjacent turns touch (close wound) the wire will be insulated against short circuits by a suitable oxide layer. Where the turns do not touch, the wire may be bare.

This type of construction can be made in a wide range of resistance values (fractions of an Ohm to many thousands of Ohms) as well as a wide range of power ratings (5 Watts to 30 Watts). The actual resistance value will depend on;

- **The type of material used.**
- **The gauge of the resistance wire (Its cross-sectional area).**
- **The length of the wire used.**

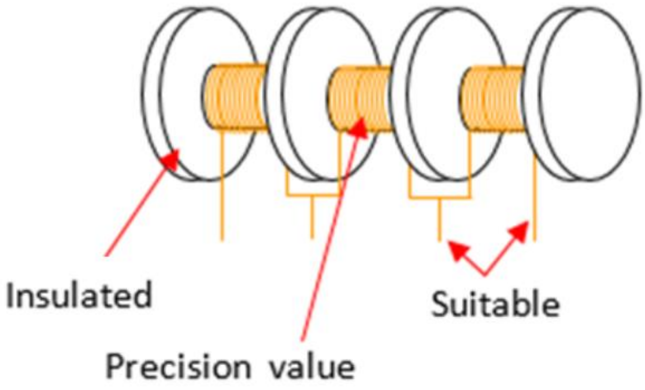




The body of these types of resistor is physically large enough for the resistance value and power rating to be printed directly on it.

Bobbin wire wound resistors

These are precision wire wound resistors designed for applications that require exact values and total temperature stability, such as, shunts and multipliers for multimeters.

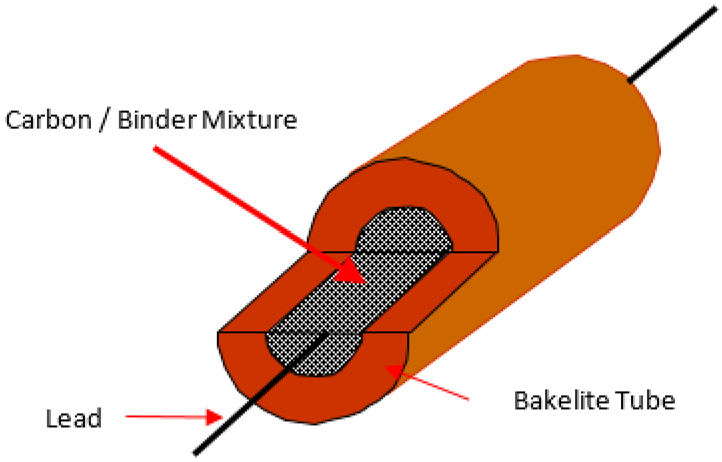


Carbon composite resistors

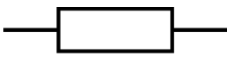
Carbon composite resistors were once the most widely used type of construction for mass-produced resistors.

The resistor consists of fine carbon granules mixed with powdered refractory clay which acts as a binder. The ratio of binder to carbon determined the final resistance value. The mixture was compressed into a Bakelite tube and leads were inserted at each end.

After baking and curing the composition becomes hard and mechanically stable. The resistor was then coated and marked with the appropriate colour bands to indicate its value and tolerance.



This construction allows resistance values of a few Ohms to several mega ohms to be made in power ratings from 0.5 to 2 Watts.

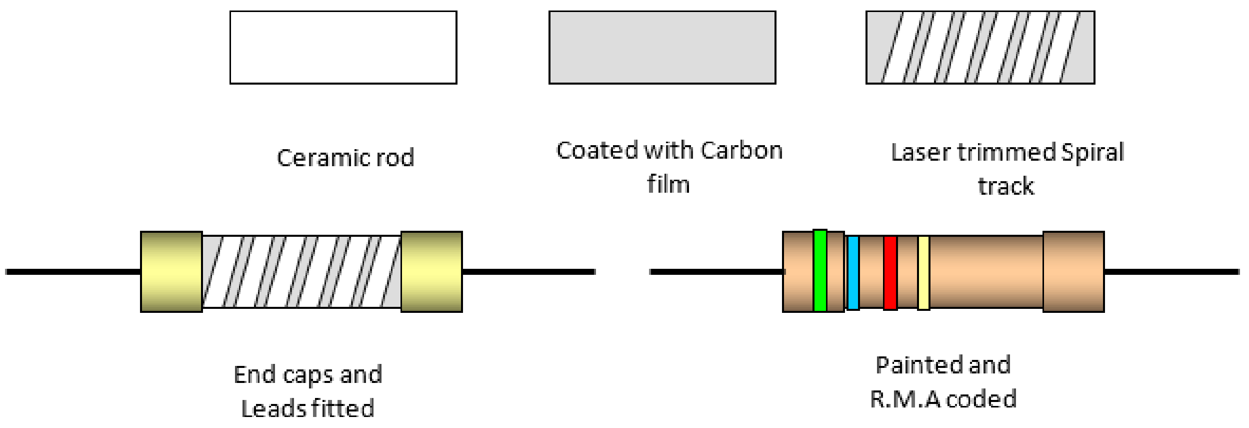
	Symbol	Characteristics	Construction	Application
Carbon Resistor		Fixed value resistances. Can change with heat, degrades over time.	Carbon particles mixed with a binder material such as clay which is baked to form a solid resistor, the resistance depends on the mixture ratio.	Many electronics, surge protection circuits, welders, strobe lighting, high voltage power supplies.

Carbon film resistors

A thin layer of pure carbon is deposited on the surface of a ceramic rod. This is then fitted with metal end caps connected to copper connection wires. A helical groove is laser cut into the carbon, forming a spiral like winding. The completed assembly is then baked at high temperatures and coated with a protective layer of light tan paint. Coloured bands are added to indicate the resistance value.

This type of resistor can be produced with a much higher accuracy than composite types and are the most commonly used for general purpose electronic applications. They are cheap to produce and are stable enough for most applications.

Carbon film resistor values are available from fractions of an Ohm to several mega ohms at power ratings ranging from 0.125 to 2 Watts.



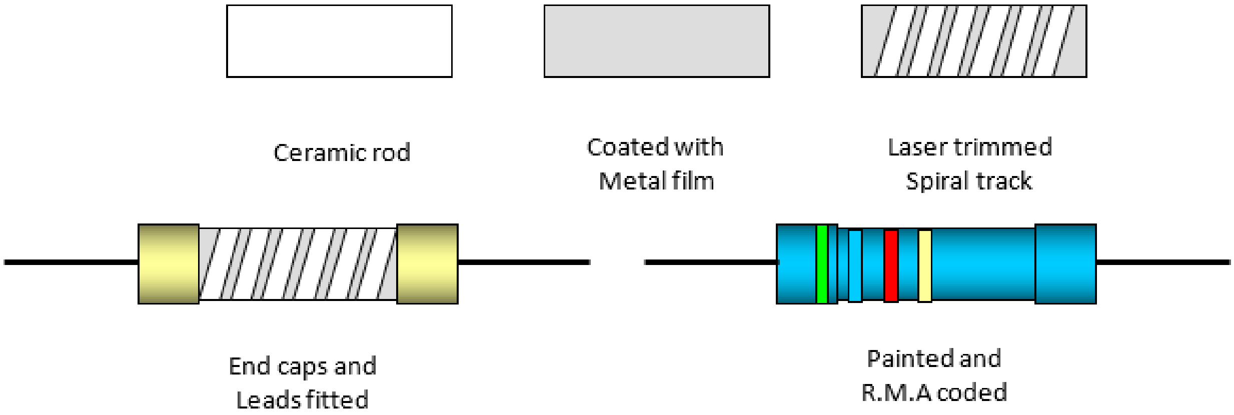
(Green, Blue, Red, Yellow)

Metal film Resistors

The construction of metal film resistors is very similar to the carbon film type except that a composition of suspended metal in glass is applied to the ceramic rod.

The combined assembly is the heated to between 750ºC and 930ºC to form a thick film fused to the surface of the ceramic rod. This forms a resistor that is almost fully resistant to moisture, temperature, mechanical shock and vibration.

The required resistance is obtained by trimming the resistive deposit in a spiral. Metal film resistors are generally smaller than carbon film of the same rating, the 0.5-Watt version being only 5mm in length and 2mm in diameter. Metal film resistors have a body colour that may range from light blue to a medium shade of green.

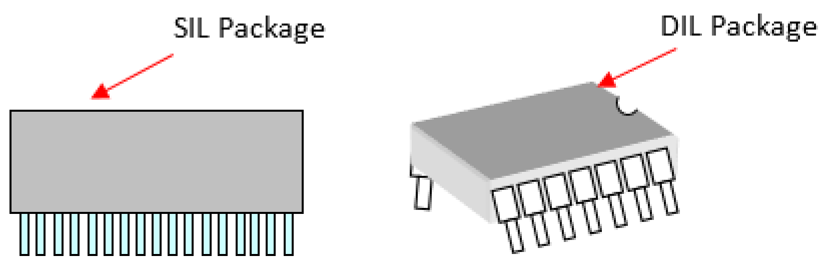


(Green, Blue, Red, Yellow)

Thick / film resistors

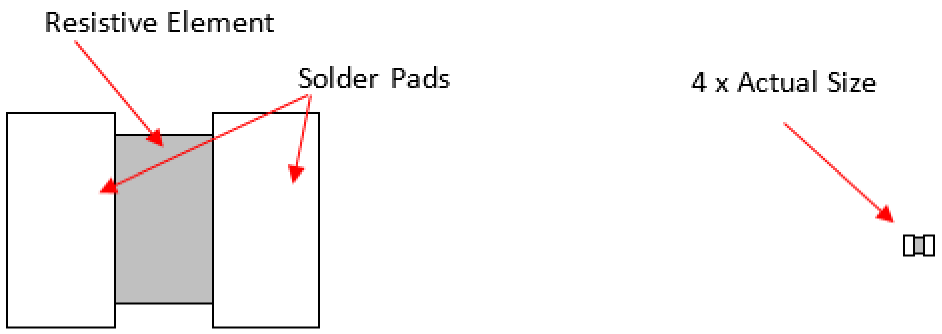
These are specially designed for application in high-density circuit board applications. The type of construction allows several resistors to be combined in a single package. The resistance value of the resistors in the single package is the same.

The packaging can be DIL (Dual In Line) or, identical to ICs (Integrated Circuits) or, a SIL (Single In Line) a flat rectangular wafer. The wafer packaging is provided with a single row of equally spaced pins for using on a printed circuit board.

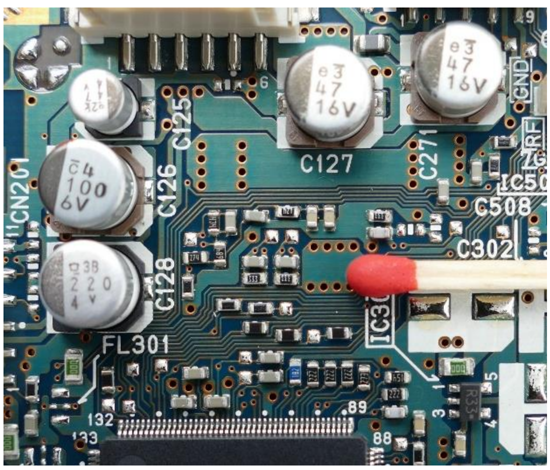


Surface mount resistors

Surface mounted resistors are specifically designed to be mounted directly to the copper pads of a printed circuit board in miniaturised electronic applications. Because they are so small, replacing them requires a high degree of soldering skill.



Using colour stripes to identify their resistance value is just not feasible because they are so small. Instead; an alpha-numeric micro code is used to identify values.



Their package style and relative size is shown in the diagram above.

Adjustable / variable resistors

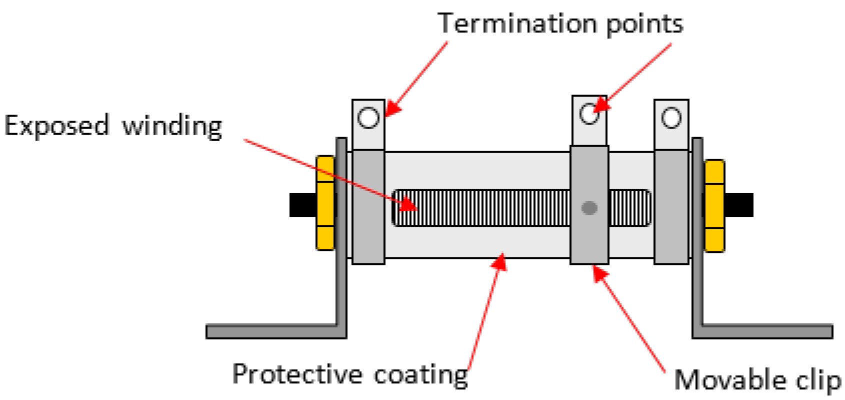
Like the fixed version of resistors, variable resistors are made using a variety of materials and in a variety of designs. The resistive path can be made from;

- Carbon composition
- Carbon Film
- Hot-moulded carbon
- Cermet
- Wire wound

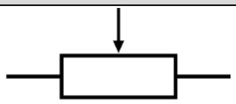
The resistance of adjustable resistors is usually able to be altered by a clip or slide.

Some are designed for high power applications where it is necessary to fine tune current flow to suit the application. Others are designed for very low power applications such as bias adjustment in electronic circuits.

High power resistors are usually wire wound. The simplest of these is a standard wire wound resistor with a tapping point in the winding. This can be adjusted to the value required.



You can see in the picture above, part of the protective coating has been removed to expose a portion of the resistive winding. As it can also be seen, a moveable clip is positioned to make contact with the winding and locked into place at the required resistance value. Once fixed in position, the clip does not move. The connections are made to only one of the two end terminals and the movable terminal.

	Symbol	Characteristics	Construction	Application
Variable Resistor		Variable medium to high power resistance, A tool such as screw driver is used to adjust current flow, various designs for different applications.	Wire wound on an insulating tube with terminations at each end and an adjustable	Circuitry where fine tuning is required such as railway signalling, adjustable power supplies

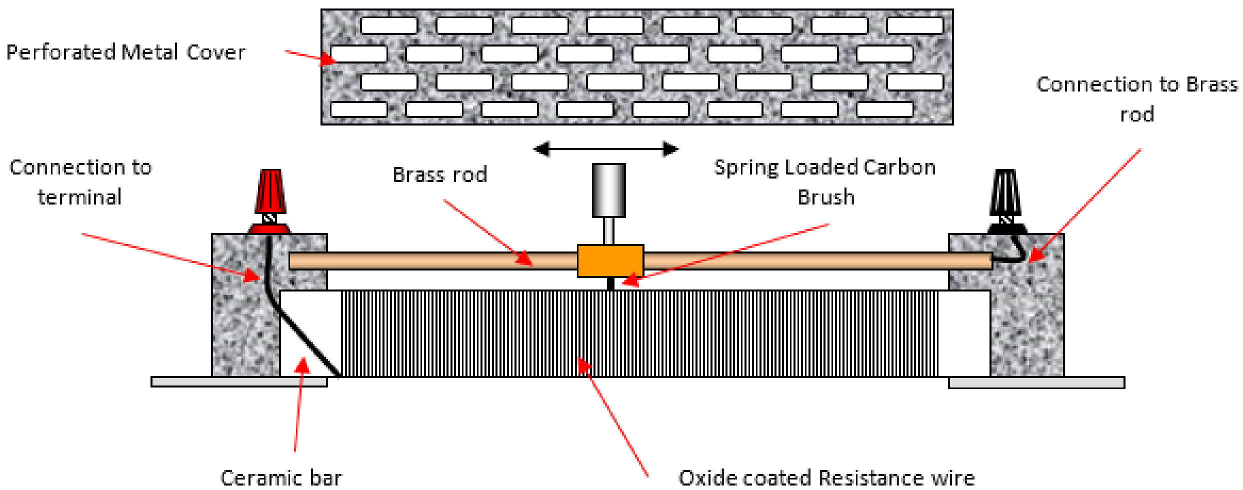
			terminal in the middle.	and motor drive circuits.

Rheostat

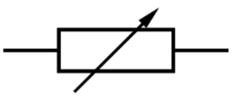
Two terminal, continuously variable resistors of high-power rating are often called rheostats.

Oxide coated resistance wire is close wound on a large ceramic bar and connected at one end (left-hand side of the diagram shown below) to a terminal. The other end of the resistive winding is not terminated. Once wound, the oxide layer is removed from a strip on the top surface that will make contact with a spring-loaded brush assembly.

The brush (usually made of bronze) makes contact with the bared winding and slides on a brass rod that is connected to the second terminal. The resistance between the two terminals is adjusted by sliding the brush on the bared surface. Large laboratory rheostats are available that are up to 400 mm in length and able to dissipate up to 300-



watts of power.

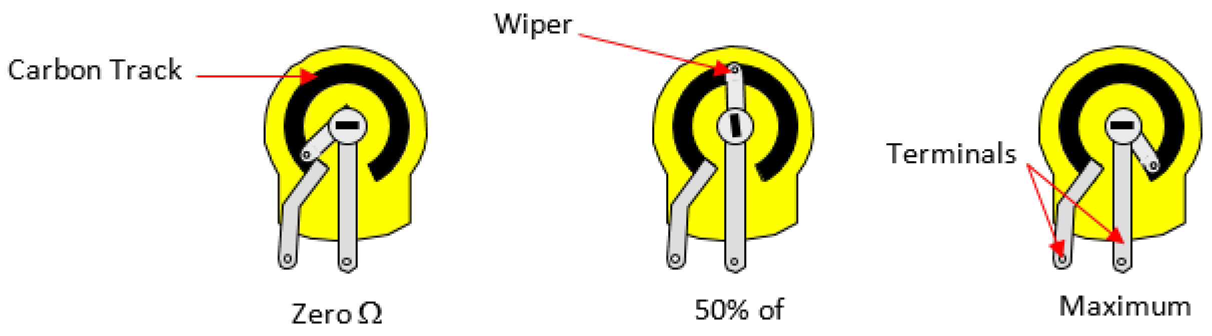
	Symbol	Characteristics	Construction	Application
Rheostat		Variable resistance, used to adjust current flow, medium to high power rating. Usually freestanding and readily adjusted by hand.	Wire wrapped around an insulating core, similar to a wire wound resistor but with heavier gauge wire to allow for the higher currents, the wiper slides along in contact with the wrapped	Older light dimmers, motor speed controllers, tuning circuits benchtop laboratory power supplies.

			wire to give the desired value.	

Miniature rheostats

Any two-terminal variable resistors may be called a rheostat. This includes some miniature devices found on printed circuit boards.

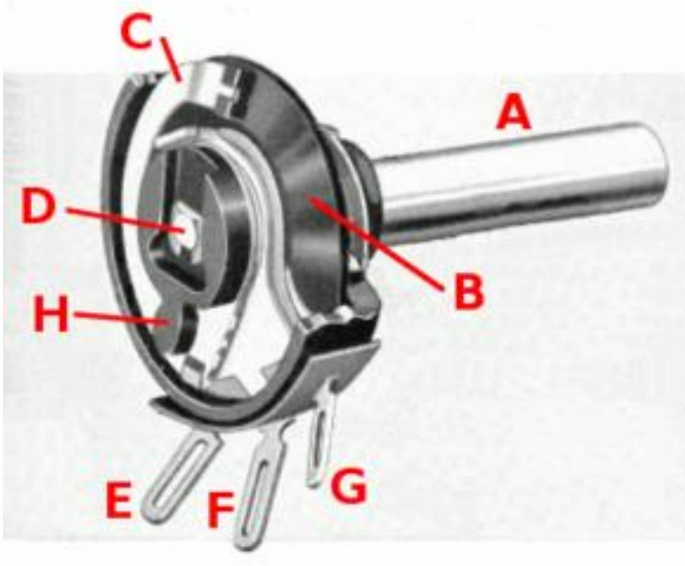
The resistive path is a carbon track deposited on an insulated base. One end of the track is connected to a terminal and the second terminal connects to a movable arm (called a wiper) that makes contact with the track. A screwdriver slot in the wiper mechanism allows it to be positioned anywhere on the track. Once positioned, the wiper is usually glued in position. One common type is pictured below.



Potentiometers

These are similar to rheostats except that they have three terminals, one terminal at each end of the resistive path (this can be a wire winding or a track) and the third terminal connects to the wiper. Depending on their design, the wiper action may be rotary or linear.

Rotary action potentiometer



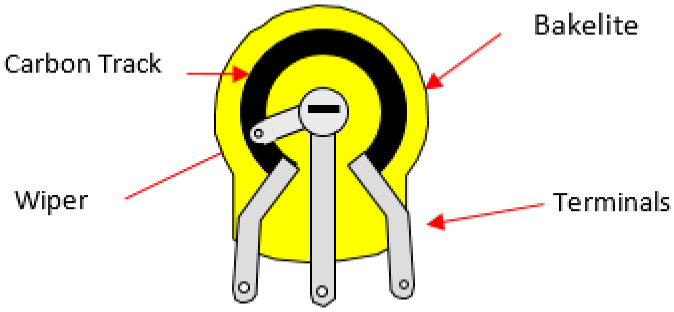
Cutaway drawing of a potentiometer

Drawing of potentiometer with case cut away, showing parts: (*A*) shaft, (*B*) stationary carbon composition resistance element, (*C*) phosphor bronze wiper, (*D*) shaft attached to wiper, (*E, G*) terminals connected to ends of resistance element, (*F*) terminal connected to wiper. A mechanical stop (*H*) prevents rotation past end points.

Carbon composite potentiometers

They are made in a wide range of power ratings from 100-milliwatts to 30-watts. The base is made of Bakelite moulded into the required shaped and then coated with a composite

carbon material. A metal wiper is attached to the shaft and makes a sliding contact with the carbonized surface.



Carbon composition potentiometer

Carbon film potentiometers

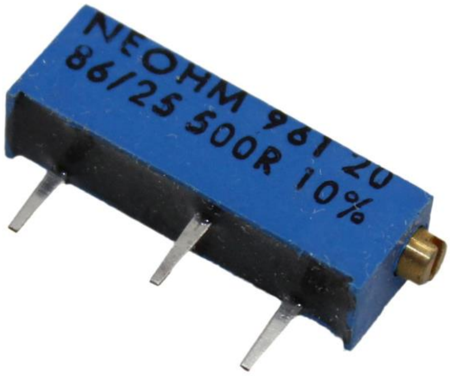
Construction is similar to the carbon composite type except that a carbon film is spayed or evaporated onto the moulded base.

Hot moulded carbon potentiometers

The resistive element, base and terminations are moulded as one integral part. The wiper is usually made of carbon. These are more expensive than the carbon composite types but are more adjustable, accurate and they are generally used in high precision applications.

Cermet potentiometers

These are high stability, high precision devices and are mainly used where very high precision is required.

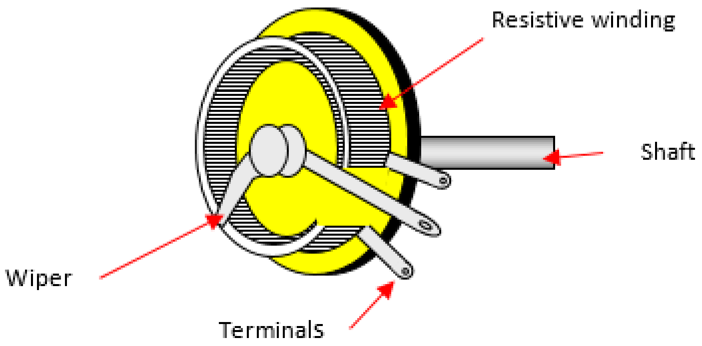


Cermet 830p500-0

Cermet 3362p series

Wire wound potentiometers

Wire wound potentiometers use resistance wire wound around a former of high temperature insulating material such as Teflon, mica or ceramic. Wire wound resistors tend to be electrically "noisy" because the resistance changes in very small but discrete steps as the wiper moves from turn to turn. They can be manufactured with resistance values ranging from a few ohms to 100k ohms and power ratings from 1 to 5 watts.



Variable (semiconductor) resistors

These resistors are a special group of resistive devices designed around semiconductor technology and, can alter their resistance value as a result of changing environmental conditions.

For example, changes in:

- **Temperature.**
- **Light.**
- **Voltage supply.**

Non-linear resistors

Non- linear resistors are variable resistors that change in resistance due to environmental changes, but the change in resistance is not linear, i.e., they do not change according to Ohms law.

Thermistor is an example of a trade name for a range of non-linear resistors used to detect a temperature rise in a variety of circumstances, like in electric motor windings or the batteries in battery operated hand tools.

Thermistors are manufactured to produce a sudden large sharp increase or decrease in resistance at a predetermined temperature.

Thermistors

The word thermistor is a contraction of the two words thermal and resistor. Thermistors are designed to alter their resistance depending on their temperature.

Two types available are:

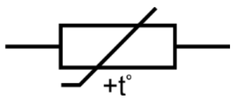
- **Positive temperature coefficient (PTC)**
- **Negative temperature coefficient (NTC)**

P.T.C.

Positive temperature coefficient devices increase in resistance as temperature increases.

They can be used as:

- **Solid-state thermal relays.**
- **Thermal protection devices.**

	Symbol	Characteristics	Construction	Application
PTC Thermistor		**Resistance increases with an increase in temperature**	**Depending on the range or resistance required they may be constructed of barium oxide or a silicone-based material.**	**Over current protection, time delays, self-regulating heaters.**

Thermal relay

An example of where a PTC device is used is in a solid-state start relay for single-phase induction motor driven refrigeration compressors.

The PTC is connected in series with the start winding of the motor. Its resistance at 20^{o}C is about 30Ω. The motor starts and current flows through the PTC and start winding.

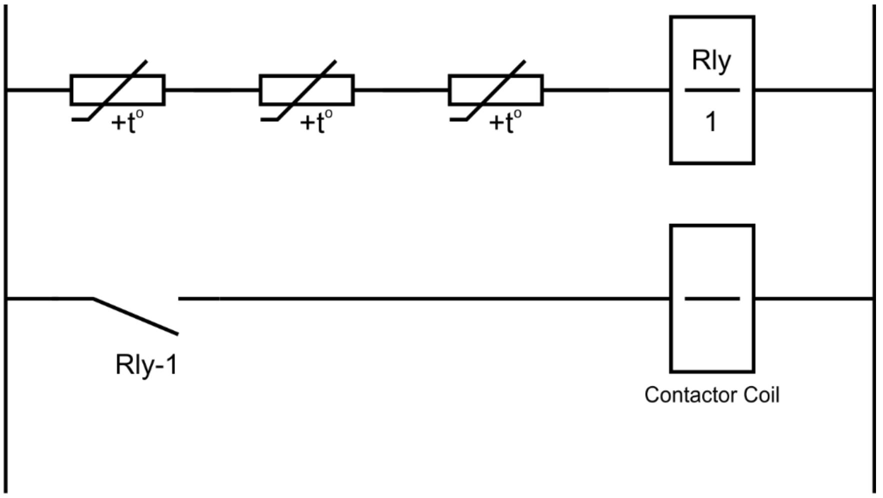
As current flows through the PTC, the PTC temperature increases very rapidly and in 2 to 3 seconds, its resistance changes from 30 Ω to 30 kΩ, effectively disconnecting the start winding.

Motor protection

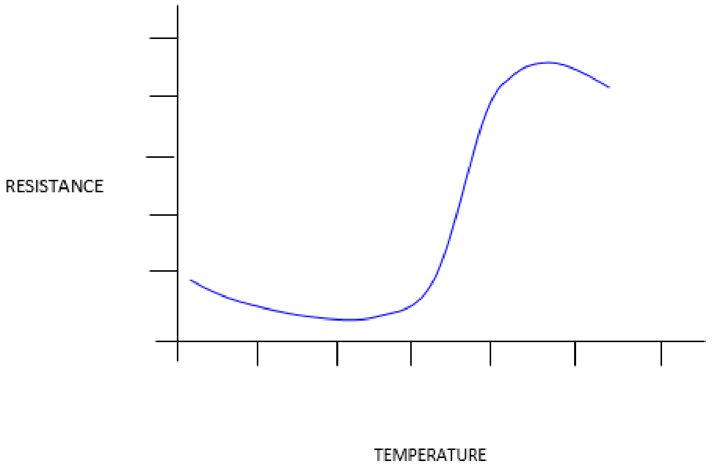
Three PTC thermistors are placed, one into each of the phase windings of a 3-phase motor.

The thermistors are connected in series with each other and to the motor controller.

If the winding temperatures increase too much the resistance of the PTC sensors rise to a set point where the control circuit alarms and shuts down the motor.



A characteristic curve for a PTC device is shown below



N.T.C.

The resistance of a negative temperature coefficient device decreases as its temperature rises.

NTC applications include:

- **Automatic current limiting.**
- **Temperature measurement.**
- **Power measurement.**

NTC Thermistors are electronic temperature-sensing devices that are made of semiconductor material that has been produced by a process of sintering. They are highly temperature sensitive and are ideal for detecting small changes in temperature.

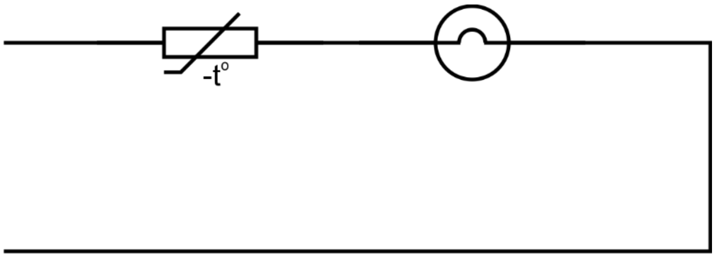
A thermistors resistance has a large change in resistance in proportion to small changes in temperature.

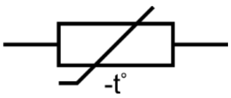
The resistance of an NTC thermistor will decrease as it's temperature increases. The manner in which the resistance decreases is related to a constant known in the electronics industry as beta, or ß. Beta is measured in °K.

An NTC resistor is often placed in series with expensive incandescent lamps to limit their inrush current and prevent premature lamp burnout.

On start-up, the NTC starts with a high resistance which limits the current to the lamp.

As the current through the NTC heats it up, its resistance reduces more and more - gently increasing the current until the full operating current of the lamp is reached.



	Symbol	Characteristics	Construction	Application
NTC Thermistor		Resistance decreases with an increase in temperature, Large band, very accurate, good stability	Made up of Chromium or Nickel oxides with small amounts of semiconductor material added. Can be manufactured for different applications such as disc, bead shape or enclosed in a glass envelope which provides good	Temperature sensors, high temp sensors or automotive applications

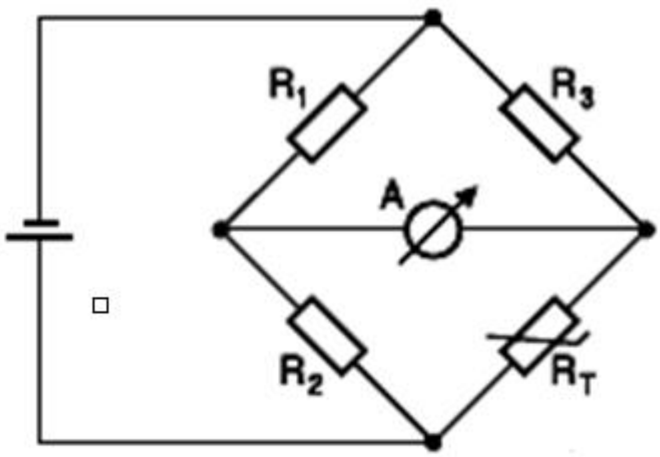
			temperature and durability.	

NTC Temperature measurement

One common circuit where thermistors are used for temperature measurement is a Wheatstone bridge, shown below, with an NTC thermistor used as one bridge leg.

With the bridge being balanced, any change in temperature will cause a resistance change in the thermistor and a significant current will flow through the ammeter which will in turn indicate a change in temperature.

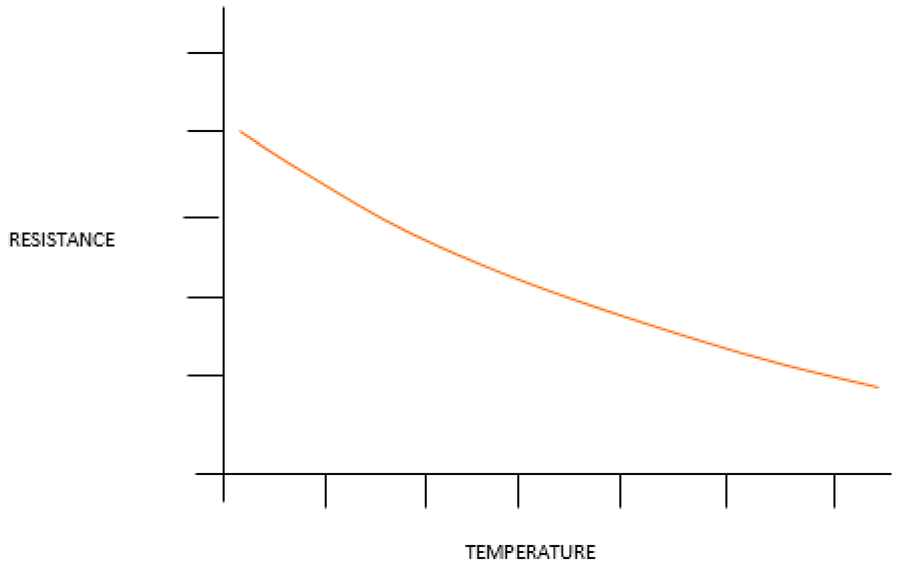
It is also possible to use a variable resistor in position R3 to adjust back to a balanced condition when there is a temperature change and work out the temperature from its new resistance value.



NTC Power measurement

Since the resistance of a thermistor is dependent on its temperature, assuming the ambient temperature remains the same, the temperature of a NTC thermistor is determined by the power the circuit is using. This makes it suitable for measuring power use in electrical circuits.

A characteristic curve for an NTC device is shown below.

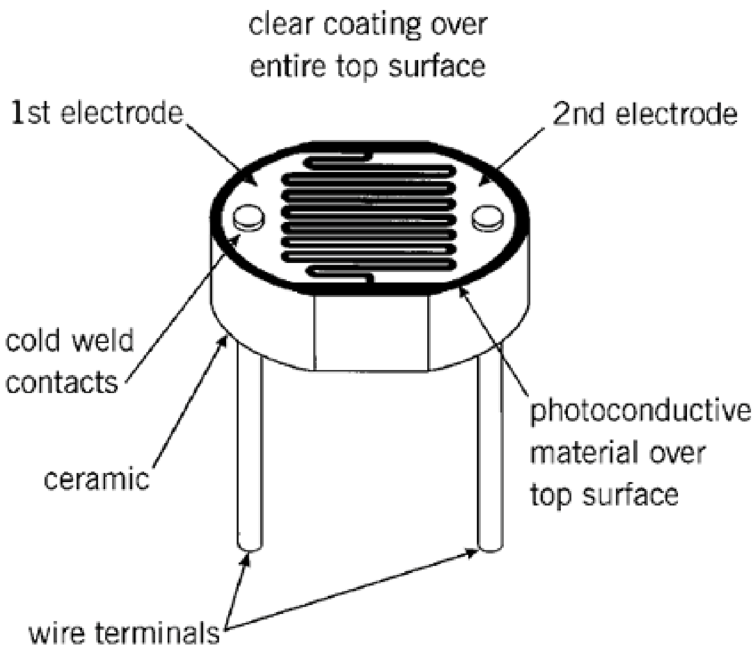


Light dependant resistors

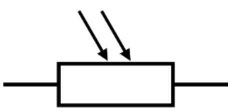
A Light Dependant Resistor (L.D.R) is a photoconductive cell that shows a drop in resistance when exposed to a source of visible light.

These are sometimes called CdS cells because they are often made by plating two sets of gold electrodes on a Cadmium Sulphide base.

The terminal resistance of the cell goes down as the light intensity falling on it increases.



Typical Construction of a Plastic Coated Photocell

	Symbol	Characteristics	Construction	Application
Light Dependent Resistor		**Resistance drops when exposed to visible light**	**Two gold electrodes on a cadmium sulphide base.**	**Daylight switches, security light motion sensors, street lighting, traffic hazard lamps.**

Applications

An LDR can be used to detect ambient light level to:

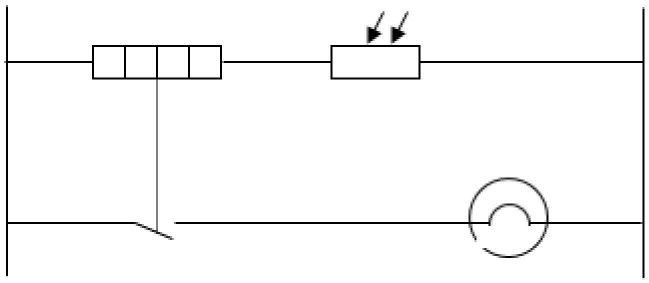
- **Automatically turn on street lighting at night.**
- **Automatically turn on hazard warning lamps at dusk.**

Street lighting

The resistance of an LDR changes as ambient light levels change. This can be used to control artificial lighting. In the circuit below, the LDR is connected in series with the heater to a bimetallic relay.

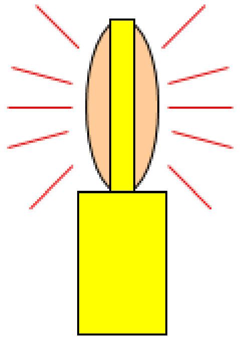
As the LDR's resistance is low during daylight conditions, the current flow through the heater is sufficient to keep a bimetal relay bent and its contact open, hence the lights are OFF.

When it gets dark, the increased resistance of the LDR causes the relay contact to close and the light turns on.



Hazard lamp

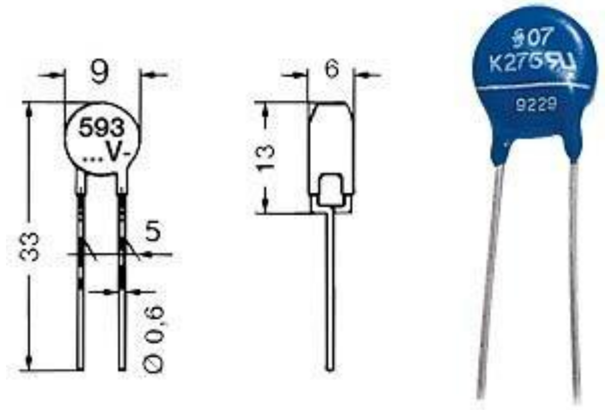
Roadwork hazard lamps are used to warn motorists of dangers at night by starting up the lamps when dusk falls. Inside the lamp lens an LDR monitors the ambient light conditions. As the light level falls the LDR enables the battery powered lamp circuit to flash the lamp.

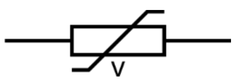


Traffic Hazard Lamp

Voltage dependant resistor

This device suddenly changes its resistance if the voltage across it increases above a pre-set level. The resistance of a Voltage Dependant Resistor (VDR) is normally very high - almost infinity. When the voltage supplied to it goes above a set level, the VDR's resistance drops very sharply to almost zero ohms.



	Symbol	**Characteristics**	**Construction**	**Application**
Voltage Dependent Resistor		**Resistance decreases with an increase in voltage**	**Constructed of two semiconductor materials that reduce in resistance as the voltage increases, depending on the application this rise in voltage may destroy the VDR**	**Surge protection, voltage regulation**

VDRs are sometimes known as varistors or MOVs (metal-oxide varistors), or by their brand name such as Metrosils.

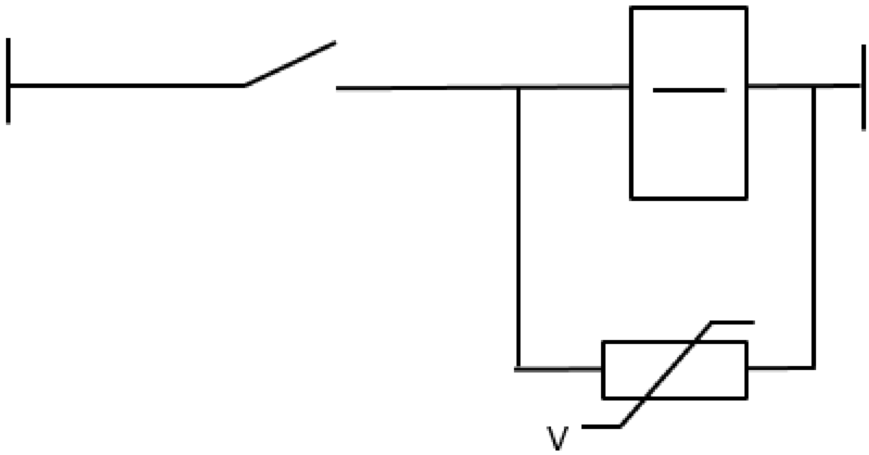
Applications include:

- **Transient voltage suppression.**
- **Electrical contact protection.**

Transient voltage suppression

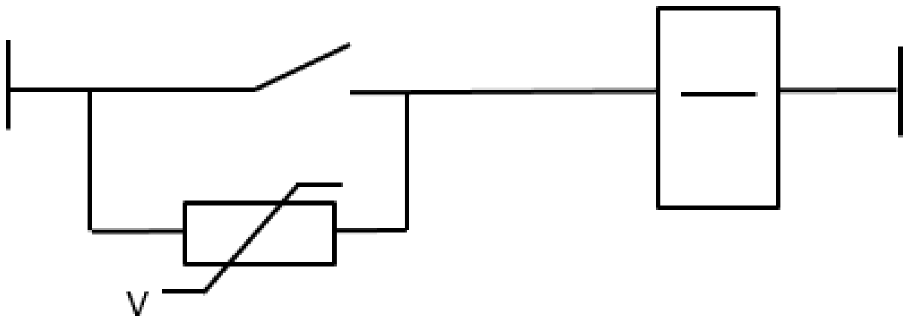
When current flows through any inductive (something with a coil in it like a relay coil) circuit, energy is stored in the form of a magnetic field. When the current to the circuit is switched off, the magnetic field collapses and induces a spike of voltage ten to twenty times greater than the supply voltage to the circuit. This high voltage can cause insulation breakdown and component failure.

By placing a VDR across the inductor, any induced voltage spikes cause the VDR to conduct and divert the high induced voltage safely away from the inductor. This is called transient protection or transient suppression.



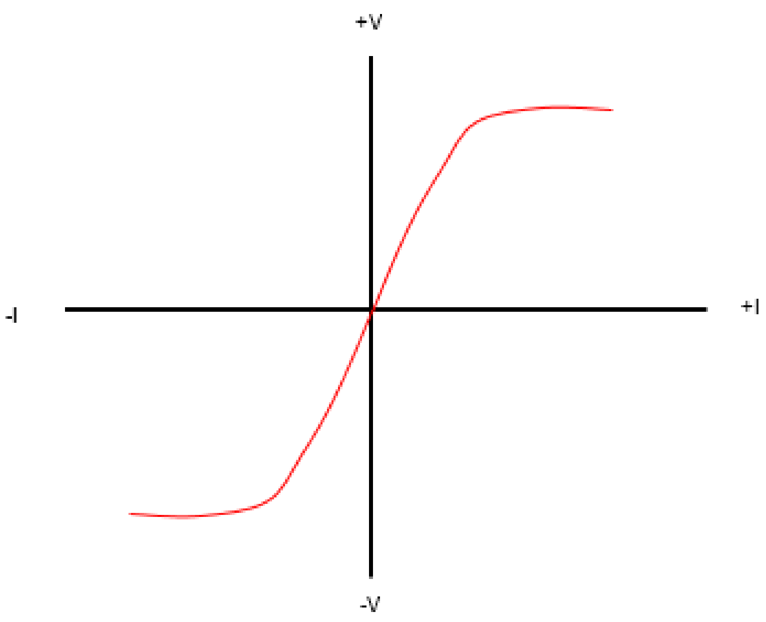
Electrical contact protection

A VDR can be connected across electrical contacts that control current to inductive circuits. The VDR is used to divert energy from the collapsing field when the circuit is switched off, and prevent damage to the contacts that would otherwise be caused by



arcing.

A characteristic curve for an VDR device is shown below:

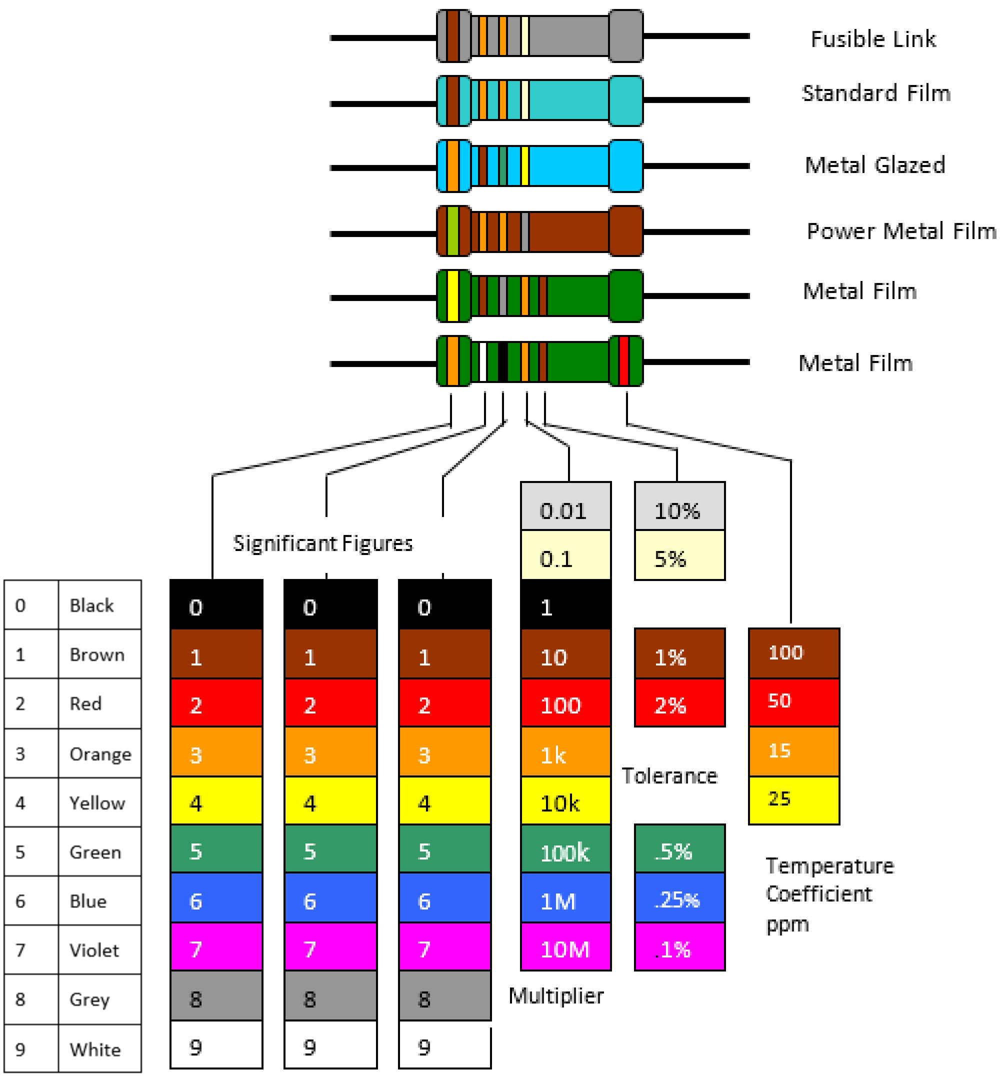


Resistor colour codes

Resistors are small and hard to write numbers on so coloured bands are put around the resistor body that show the value of the resistor. This code was initially defined by the Radio Manufactures Association (R.M.A) and is internationally accepted worldwide as the means of identifying resistor values.

Each colour is assigned a number value. Resistors using this method of value identification may be marked with 4 to 6 coloured bands. Before reading these bands, it is important to have the resistor around the right way because the bands are read from left to right.

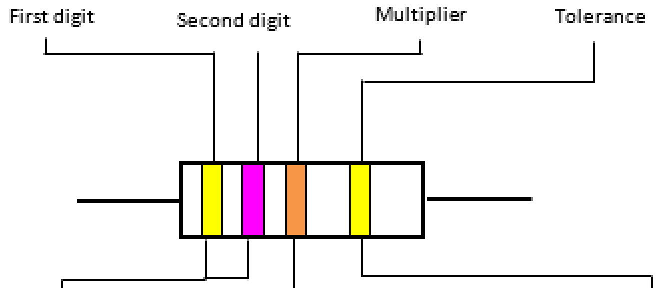
Hold the resistor with the colour bands on the left-hand side as shown in the diagram below.



R.M.A Colour Code Chart

Example 3.1

Consider the 4-band resistor shown below. Reading the colour bands from left to right we have: yellow, violet, orange and gold.



0	Black
1	Brown
2	Red
3	Orange
4	**Yellow**
5	Green
6	Blue
7	**Violet**
8	Grey
9	White

$\times 10^0$	Black
$\times 10^1$	Brown
$\times 10^2$	Red
$\times 10^3$	**Orange**
$\times 10^4$	Yellow
$\times 10^5$	Green
$\times 10^6$	Blue
$\times 10^7$	Violet
$\times 10^{-2}$	Silver
$\times 10^{-1}$	Gold

20%	None (M)
10%	Silver (K)
5%	**Gold (J)**
2%	Red (G)
1%	Brown (F)

In this example, the colours represent:

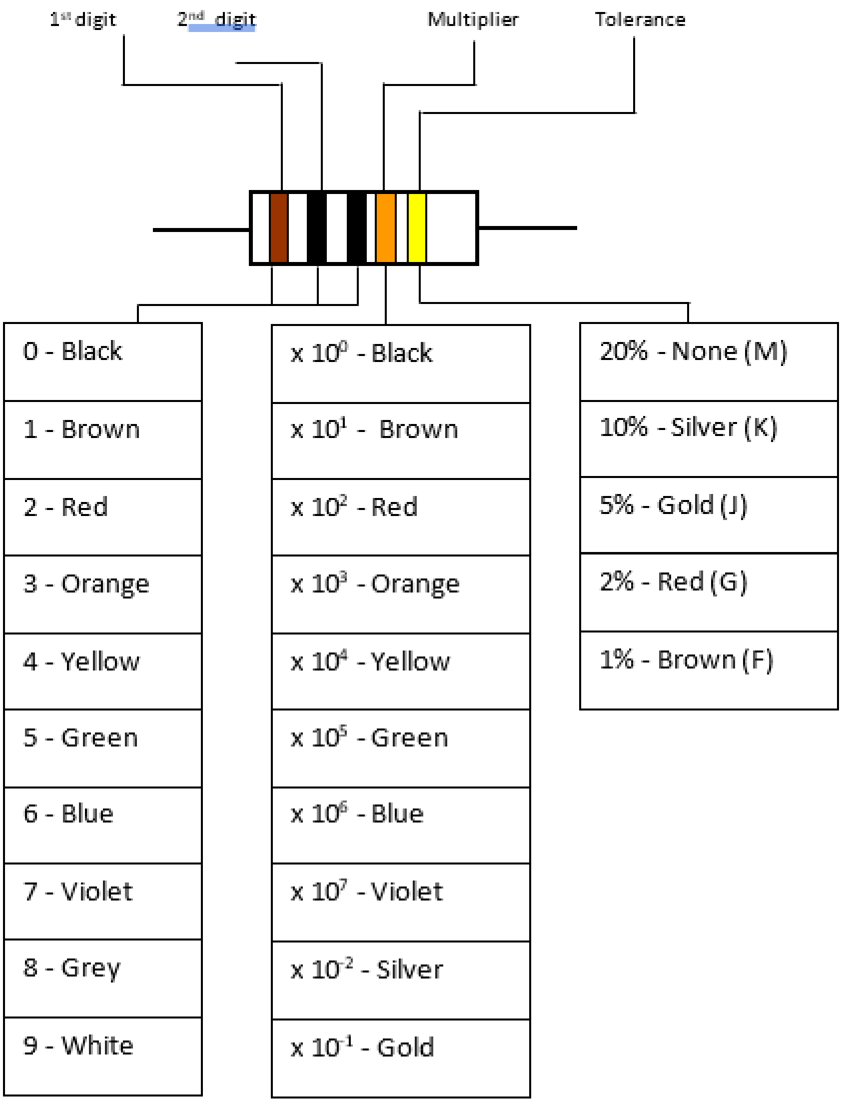
1st - Yellow = 4
2nd - Violet = 7
3rd - Orange = x 10^3 (or in other words, add 000, or k)
4th - Gold = 5%

The resistance value is 47 x 10^3 Ω (47000Ω) written as 47kΩ with a tolerance of 5%.

5% tolerance means that when this resistor is measured with an ohmmeter it could have a value anywhere between 49.35 kΩ and 44.65 kΩ.

Example 3.2

5-band resistors are treated in the same way except that the first three bands represent significant digits instead of just two. In this example, we have the colours brown, black, black, orange and gold.



In this example, the colours represent:

1st -	**Brown = 1**
2nd -	**Black = 0**
3rd -	**Black = 0**
4th -	**Orange = x 10^3 (or in other words, add 000, or k)**
5th -	**Gold = 5%**

The resistance value is 100 x 10^3 (100 000Ω) written as 100kΩ with a tolerance of 5% or 100kΩ ± 5.0kΩ.

Part 4: Calculated vs. measured values in a circuit

Controlling flow

Electric circuits are designed to work at their best when a specific level of current flows. If too little current flows, the load will not produce the required output or may not work at all. If too much current flows, parts of the circuit could be damaged.

Two significant factors that determine the amount of current flow in a circuit are:

1. **The amount of voltage applied to the circuit.**
2. **The resistance of the circuit through which current flows.**

Ohm's law

Way back in 1826, Georg Simon Ohm worked out the mathematical relationship between voltage (V), current (I), and resistance (R).

He found that if the resistance of a DC circuit does not change, then the current flow through that circuit depends directly on (directly proportional to) the voltage connected to the circuit.

Ohm also found that if you keep the voltage to the circuit the same and increase the resistance of the circuit then the current flowing will decrease, i.e. the current flow is indirectly or inversely proportional to the resistance.

Directly proportional

Directly proportional in this example means, that if voltage goes up, the current also goes up. When voltage goes down, the current goes down.

$f(x)$	$V \uparrow \Rightarrow I \uparrow \quad or \quad V \downarrow \Rightarrow I \downarrow$

Indirectly (Inversely) proportional

As the resistance goes up the current goes down and as the resistance goes down the current goes up, = (they change in the opposite way).

$f(x)$ $R \uparrow \Rightarrow I \downarrow \quad or \quad R \downarrow \Rightarrow I \uparrow$

Ohms law in words:

Definition

Ohms law

The current flowing in a circuit is directly proportional to the applied voltage, and inversely proportional to the resistance of the circuit.

Ohm's Law Equation

The relationship between voltage, current and resistance can be expressed in a very simple equation which states that voltage is a product of current and resistance.

$f(x)$ $V = I \times R$

This basic equation can also be transposed to work out either resistance 'R' or current 'I'.

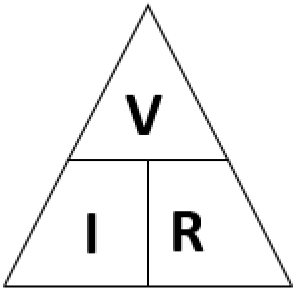
$f(x)$ $R = \frac{V}{I} \quad and \quad I = \frac{V}{R}$

Ohm's law triangle

The following triangle information is useful for coming to terms with the simple transposition of ohms law but, comes with some cautions:

- **Ohms law is a very important formula in your study and you should commit all three variations of it to memory, starting right now.**
- **Do not rely on the triangle to short cut learning to transpose a formula. The triangle is useful very short term, but it is vital to your success in electrical theory that you learn how to transpose electrical formulas mathematically.**

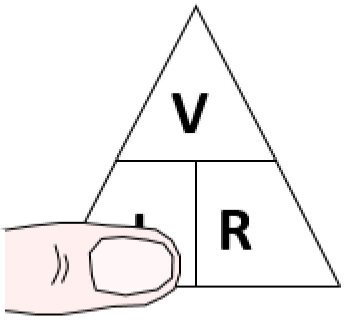
A visual representation of the ohms law relationship between voltage, current and resistance can be made using a triangle.



This triangle can be used to determine the relationships between V, I and R.

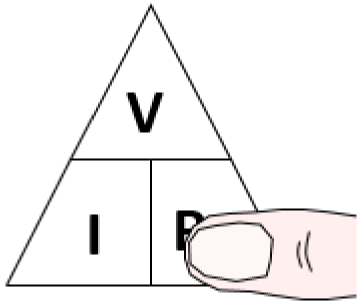
For example, to make 'I' the subject of the equation, (to work out what the value of 'I' is), cover the 'I' up with your finger, and then from the triangle, look to see what is left showing, this will be the formula to use to work out 'I' (current).

$$I = \frac{V}{R}$$



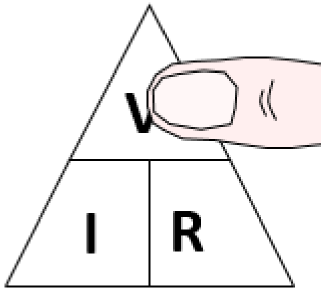
To make ‘R’ the subject of the equation, cover it up, and then from the triangle find the formula.

$$R = \frac{V}{I}$$



To make ‘V’ the subject of the equation, cover it up, and then from the triangle find the formula.

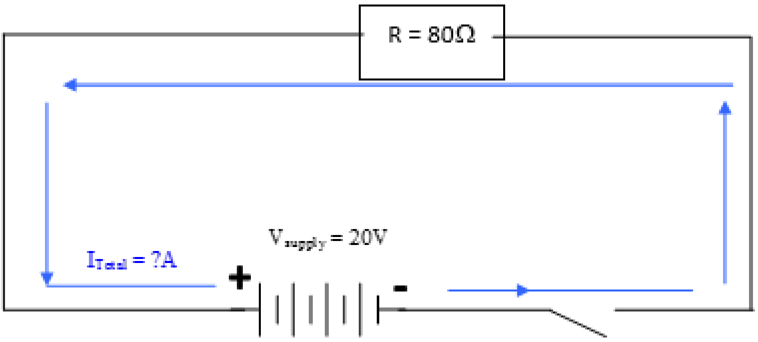
$$V = I \times R$$



Calculating current using ohms law

In a DC circuit the value of voltage, current or resistance can be calculated using ohms law if any two of the three values are known.

For example, in the circuit diagram below shows a 20V source connected across an 80Ω resistor. To calculate the current that would flow in the circuit use ohm's law, (on the triangle, cover up 'I' to help figure out the formula).



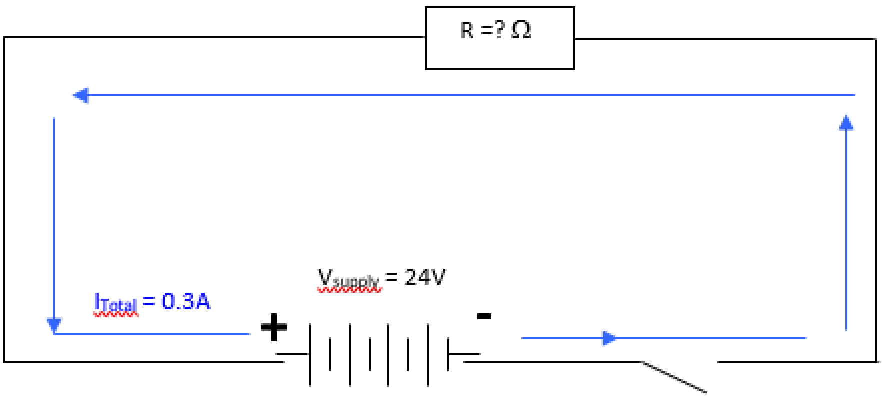
$$I = \frac{V}{R}$$

$$I = \frac{20}{80}$$

$$I = 0.25\,A$$

Calculating resistance using ohms law

To calculate the resistance in the circuit use ohm's law (cover up 'R' to determine the formula).



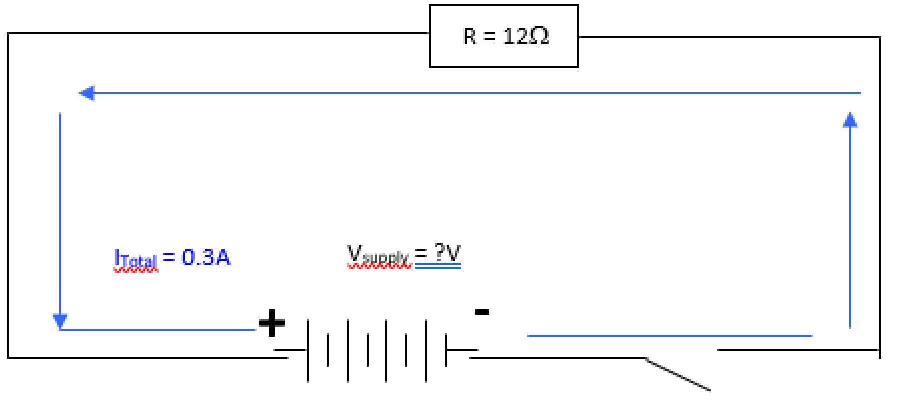
$$R = \frac{V}{I}$$

$$R = \frac{24}{0.3}$$

$$R = 80\,\Omega$$

Calculating voltage using ohms law

Calculate the voltage in the circuit using ohm's law (cover up 'E' to determine the formula).



$$V = I \times R$$

$$V = 0.3 \times 12$$

$$V = 3.6\,V$$

Variations in circuit calculations vs readings

You may be designing a circuit and need to calculate the values of current and resistance, or the required voltage. Next you might build the circuit and take the actual readings of current resistance and voltage.

Sometimes there can be a variation between the theory and reality and you may need to be able to pinpoint or explain the differences.

Here are some explanations and differences you may need to look for in this situation.

Factor	Explanation
Component tolerance / stability.	**Component values may be manufactured slightly different to intended values or change during their lifetime because of external stresses such as temperature, aging, humidity, mounting, dust, etc.**
Supply variations	**Supply voltage varies depending on many things including the load on a supply. The supply voltage to the circuit may be different to the supply voltage used in the circuit calculations. This will cause readings to be different to test results.**
Non-linear components	**Some components used in circuits are non-linear which means their effect in a circuit is not always proportional to current or voltage. This can cause differences between calculations and readings if not taken into account. Examples of non-linear components are diodes, transistors and amplifiers.**
Instrument and measurement accuracy	**Specified instrument accuracy, faulty calibration of measuring instruments, and poorly maintained instruments can cause inaccuracy in readings.**

% variations in circuit calculations vs readings

Using the formula below, you can work out the difference between measured values and calculated values as a percentage:

$$f(x) \qquad difference\ in\ \% = \frac{measured - calculated}{calculated}\ x\ 100$$

Note: If the calculated result is higher than the measured result, the result will be a negative figure.

Part 5: Electrical Power and Energy

Work

Work is done when a force moves a body through a distance, you pull a sliding door open for example.

$f(x)$

$$Work = Force \times distance$$

$$Work = F \times d$$

Work is measured in Joules; 1 Joule of work is done when a force of 1 Newton moves a mass 1 metre.

This may be reasonably easy to understand for a mechanical force and a physical body that can be seen to move. But there are other forms of work besides mechanical work, such as the work a battery does internally as it separates electrical charges by chemical means.

Then when an external circuit is connected to the battery, work is also done by the battery causing electrons to move through the external circuit.

Power

Power is defined as the rate at which work is done, let's face it some of us do more work in the same time as someone else, that means you are producing more power!

$f(x)$

$$Power = \frac{Joules}{Seconds}$$

Since work done is measured in joules, then power is measured in joules per second.

Electrical power

In the electrical industry we are obviously mainly interested in electrical power. Electrical power is the ability of voltage to do work causing current to flow in a circuit and doing it at a particular rate.

The formula for electrical power is:

$$f(x) \qquad Power(electrical) = V \times I$$

Two other power formulas are:

$$f(x) \qquad P = I^2 \times R$$

$$P = \frac{V^2}{R}$$

Watts / kilowatts / megawatts

Electrical power is measured in watts. In electrical calculations, watts are a far more useful unit than joule/seconds.

One Watt (W) is one joule per second.

One Watt is a fairly small unit in the scheme of things so we normally state power in bigger units:

- **Kilowatt (kW), each kilowatt is 1 000 watts or,**
- **Megawatt (MW) which is 1 000 000 watts.**

Horsepower

Some older electric motors and motors that currently originate from the US are rated in the old imperial unit for power, called horsepower (HP).

It is often necessary to convert this imperial unit to the SI equivalent. The relationship between watts (SI unit) and the horsepower (imperial unit) is 1 HP = 746 watts

1HP = 746 watts

Energy

Energy is a product of power and time. The faster a certain amount of work is done; the more energy is required to do it.

(FYI, and just to be slightly confusing, the unit of energy is the same as the unit for work, the joule).

$f(x)$

$$Energy = Power \times Time$$

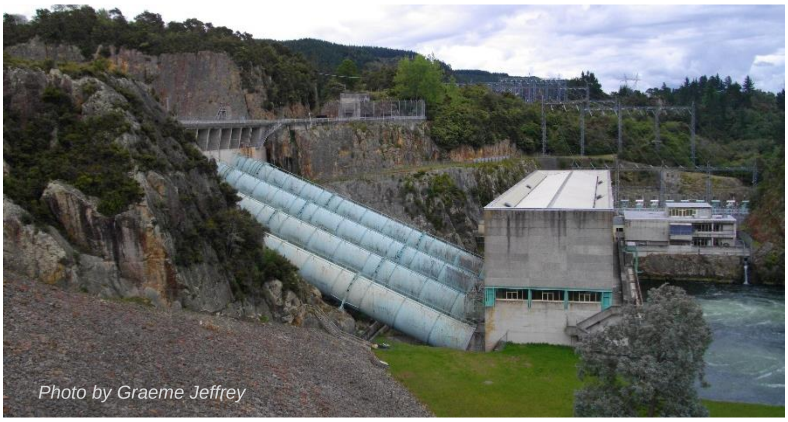
Energy is the ability or capacity to do work, or a measure of work done. It is measured in the same units as work, the joule.

There are two kinds of energy:

- Potential energy.
- Kinetic energy.

Potential energy

Potential energy is stored energy. Water stored in a dam, steam or air under pressure, a bullet, electrical energy stored in a battery are all examples of potential energy.



Kinetic energy

Kinetic energy is the energy possessed by a body when it is in motion. A bullet being fired from a rifle, expanding steam, water released from a dam, a battery supplying a load are all examples of kinetic energy.

Electrical energy

As you already know, the formula for energy is:

$$\boldsymbol{Energy = Power \times Time}$$

To work out formulas for electrical energy:

$\boldsymbol{P = I \times V \text{ or } P = I^2 \times R}$ so, if $\boldsymbol{Energy = Power \times Time}$ then;

$\boldsymbol{f(x)}$	$\boldsymbol{Electrical\ energy = I^2 \times R \times t}$ $\boldsymbol{Or\ Electrical\ energy = I \times V \times t}$ $\boldsymbol{Or\quad Energy = P \times t}$

A unit of electrical energy is expressed as 1 Watt Second (Ws), (which is the same amount as 1 Joule).

Because this unit is so small, it is not a useful amount to measure energy by when it comes to energy consumption in a standard electrical installation.

kWh

In the electrical industry, electrical energy is normally measured in chunks of 1000 watts per hour or 1 kWh.

Electrical supply companies charge their customers per unit of (kWh) of electricity.

The kilowatt-hour is used to measure electrical consumption instead of the watt second because watt seconds are too small to be useful.

An electric water urn rated at 1500 W is installed at the lunchroom of a worksite. The urn is switched on for 8 hours a day, 5 days a week and 48 weeks in a year.

Assuming the urn is using energy for 80% of the time; calculate the cost of the electrical energy to operate this urn in a year if the electricity price is $0.26 per unit.

Total time the energy is used in a year is:

$$t = 8 \times 5 \times 48 \times 0.8$$

$$t = 1536 \ Hours$$

$$Energy = P \times t$$

$$Energy = 1.5 \ kW \times 1536 \ Hours$$

$$Energy = 2304 \ kWh$$

$$Cost = 2304 \times 0.26$$

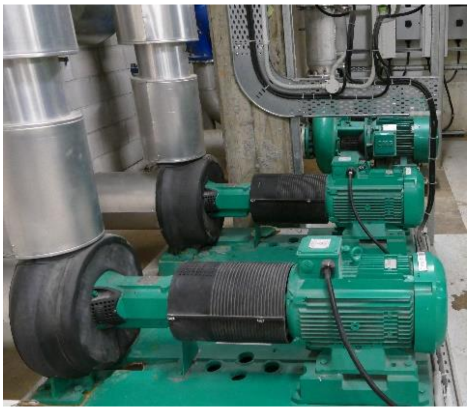
$$Cost = \$599.04 \ \textit{(for a year)}$$

Efficiency

We all suffer from inefficient electrical equipment, at home we may not be too worried about it, but larger equipment and bigger, busier electrical installations stand to loose large amounts of money due to inefficiency and money paid for power wastage becomes significant.

Efficiency is how much you get out compared to what you put in and is often said as a percentage.

As an electrician it may be your job to improve the efficiency of an installation. It may be for a domestic installation going off grid with solar power or a factory wanting to increase profitability. Either way you will need to know and understand efficiency.



Take an electric motor for example, in the process of converting electricity to movement, some of the energy is wasted in noise, heat, wind resistance on the load and/or rotor, friction, copper and iron losses in the motor.

Consider the following equations:

$f(x)$

$$Output = Input - losses$$

Or:

$$Input = Output + Losses$$

Efficiency can be calculated as a number by using the following formula:

$f(x)$

$$Efficiency\ (h) = \frac{Output}{Input}$$

Where;

$h = Efficiency$

$$Output = output\ power\ of\ equipment$$

$$Input = input\ power\ of\ equipment$$

Percentage efficiency

Efficiency is often written as the percentage difference between the input power and the output power.

The percentage efficiency of an electrical machine can be calculated by dividing the power output by the power input and multiplying the answer by 100% to obtain a percentage value.

$f(x)$

$$h = \frac{Output}{Input} \quad x\,100$$

Where;

$h = Efficiency\ in\ \%$

If the output power and the efficiency of an electrical machine is known, the equation can be transposed to calculate the input power of the machine.

$f(x)$

$$Input\ = \frac{Output \times 100}{h}$$

Example 5.1

A customer is planning to replace a burnt-out pool pump with a new one. The original pump is rated 2.0HP and has an efficiency of 70%. However, there is a choice of another pump of the same power rating that is 90% efficient. The second pump is $150.00 dearer, but the sales person says the pump will pay for the difference in just one year.

Is this true?

The pump will be used 2.0 hours a day every day of the year and the electricity price is $0.26 per unit.

$$t = 2 \times 365$$

$$t = 730\ Hours\ (for\ a\ year)$$

$$P = 2\ HP \times 0.746\ (To\ convert\ horse\ power\ to\ KW)$$

$$P = 1.492\ KW\ \ (This\ is\ the\ output\ of\ both\ pumps)$$

Input power and cost for Pump 1 with 70% efficiency;

$$Input\ = \frac{Output \times 100}{h}$$

$$Input\ = \frac{1.492 \times 100}{70}$$

$$Input = 2.131\ KW$$

$$Energy = P \times t$$

$$Energy = 2.131\ KW \times 730\ Hours$$

$$Energy = 1555.9\ KWH$$

$$Cost = 1555.9 \times 0.26$$

$$Cost = \$404.55\ \textit{(Cost of running the original pump for a year)}$$

Input power and cost for Pump 2 with 90% efficiency;

$$Input = \frac{Output \times 100}{h}$$

$$Input = \frac{1.492 \times 100}{90}$$

$$Input = 1.658\ KW$$

$$Energy = P \times t$$

$$Energy = 1.658\ KW \times 730\ Hours$$

$$Energy = 1210.2\ KWH$$

$$Cost = 1210.2 \times 0.26$$

$$Cost = \$314.65\ \textit{(Cost of running the more efficient pump for a year)}$$

Running cost saving after a year is:

$$Cost\ difference = \$404.55 - 314.65$$

$$Cost\ difference = \$89.90$$

Alternatively, the difference in energy consumption (kWh) can be determined for the year. Then the difference in energy between the first and second pump would be:

Energy saved = energy pump 1 – energy pump 2

= 1555.92 – 1210.18

= 345.74 kWh

Running cost saving = Energy saved x cost/unit

= 345.74 x 0.26

= $89.89

That means there is a saving of $89.90 per year using the more efficient pump, which will pay the difference in 20 months and not in a year.

Part 6: Analyse Resistive Circuits

Kirchhoff's voltage law

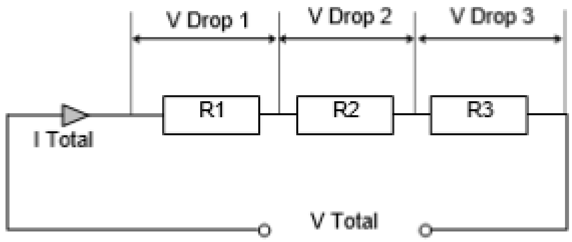
Kirchhoff's voltage law applies to voltage in series circuits, it is sometimes referred to as the voltage divider law.

Gustav Kirchhoff, was a German physicist (1824 to 1887). Gustav found that the components in a series circuit will divide the supply voltage between themselves. He found that if you add up the voltage used (dropped) by each component in a circuit the sum of the voltages will equal the voltage of the circuit supply.

When voltage is supplied to a series circuit, each component in that circuit will use (drop) a portion of the supply voltage. If there are two components, then the voltage will be dropped in two parts. If there are three components, there will be three smaller volt-drops, and so on.

The voltage dropped by each component is proportional to the resistance of the component.

The volt-drops, when added together, will equal the total applied voltage, see the diagram below.



Each component, R_1; R_2 and R_3, uses part of the applied voltage (V $drop_1$; V $drop_2$ and V $drop_3$) to create and maintain the circuit current I_{TOTAL}.

Kirchhoff's voltage law for series circuits:

$f(x)$ $V_{TOTAL} = Vd_1 + Vd_2 + Vd_3$.

In a series circuit, all of the loads have the full circuit current flowing through them.

Kirchhoff's current law

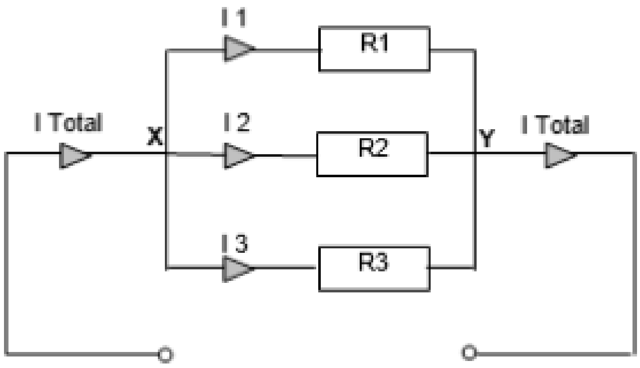
Kirchhoff also discovered another rule about currents in parallel circuits.

If you have a circuit with loads wired in parallel, the current flowing in the circuit divides up between the parallel paths (branches). If you add all of the currents together, they will equal the total current flowing from the power source.

This is sometimes referred to as the current divider law.

It means that when the current flow reaches a junction point in a circuit where the circuit divides into two or more parallel branches, the current will split up into two or more currents.

These currents, when added together, will equal the current flow entering the junction point (the total current drawn by the circuit). If these same branch currents reach a junction point where the two or more branches join to form a single circuit again, the currents combine into one total again.



The total current flow in the circuit (I_{TOTAL}) can be measured at point X.

At point X the current splits into the three branches towards the loads R_1; R_2 and R_3 as three currents I_1; I_2 and I_3.

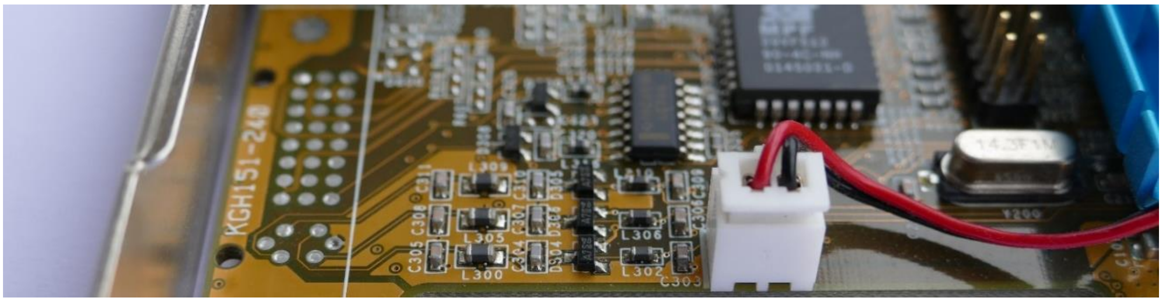
Kirchhoff's current law for parallel circuits:

$f(x)$	$I_{TOTAL} = I_1 + I_2 + I_3$

At point Y the currents from the three branches I_1; I_2 and I_3 join again to form the same single current I_{TOTAL}.

$$I_1 + I_2 + I_3 = I_{TOTAL}$$

With voltage in a parallel circuit, all loads have the same voltage across them which is the full supply voltage.

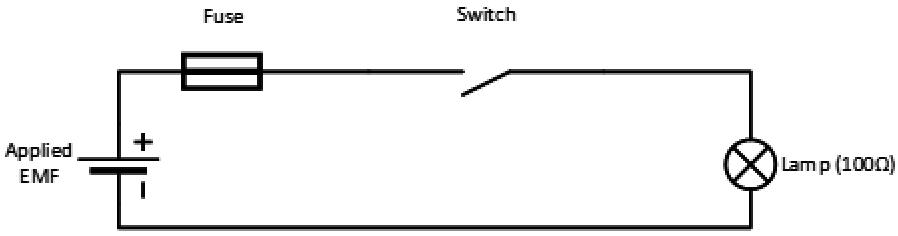


Resistance in a series circuit

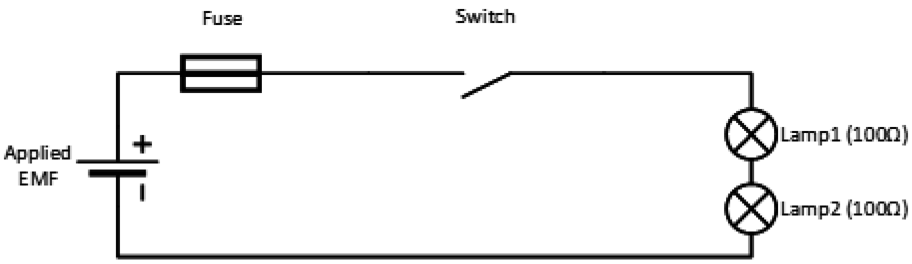
In an electrical circuit, conductors, control equipment and protection devices all have very little resistance, so we generally ignore them when it comes to resistance calculations.

We just use the load resistance (i.e. the lamp in the circuit below) in calculations as the total resistance for the circuit because it is the only component that has a significant opposition to current flow.

For example, if a single incandescent lamp with a resistance of 100 Ω is connected in a circuit as shown below, the total resistance for that circuit is considered to be 100 Ω and is written as R_{total} = 100 Ω.

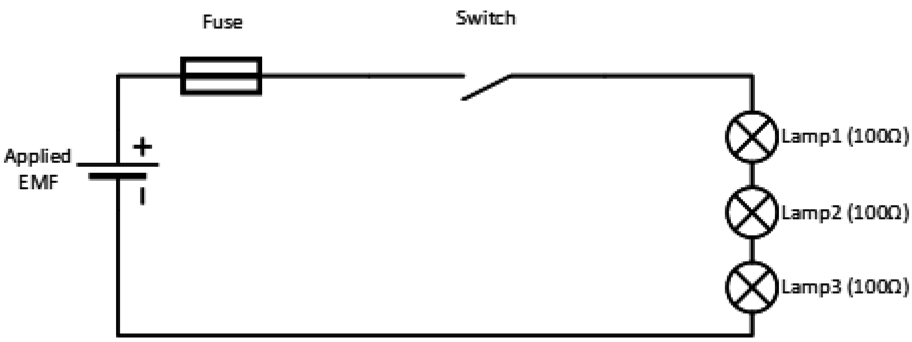


If a second lamp is connected in series with the first, the total circuit resistance will increase by the resistance value of the second lamp.



The total circuit resistance is now 100Ω + 100Ω so R_{total} = 200 Ω.

If a third identical lamp is connected in series with the previous two, the total circuit resistance will be 100Ω + 100Ω + 100Ω so then R_{total} = 300 Ω.



The total or equivalent resistance for a series circuit will be the sum of the resistances of the individual loads. That is;

$f(x)$	$R_{total\,(series)} = R_1 + R_2 + R_3 + \cdots$

Example 6.1

Determine the total resistance of four resistors connected in series if their values are 82 Ω, 33 Ω, 12 Ω and 133 Ω.

$$R_{total} = R_1 + R_2 + R_3 + R_4$$

$$R_{total} = 82 + 33 + 12 + 133$$

$$R_{total} = 260\,\Omega$$

If the total resistance and the sum of all the other resistors are known, the value of an unknown resistor in a series circuit can be found by transposing the equation.

Example 6.2

The total resistance of three resistors connected in series is 50Ω. If resistance of R_2 is 13Ω and of R_3 is 15Ω, calculate the resistance of R_1.

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

$$R_1 = R_{total} - (R_2 + R_3)$$

$$R_1 = 50 - (13 + 15)$$

$$R_1 = 22\,\Omega$$

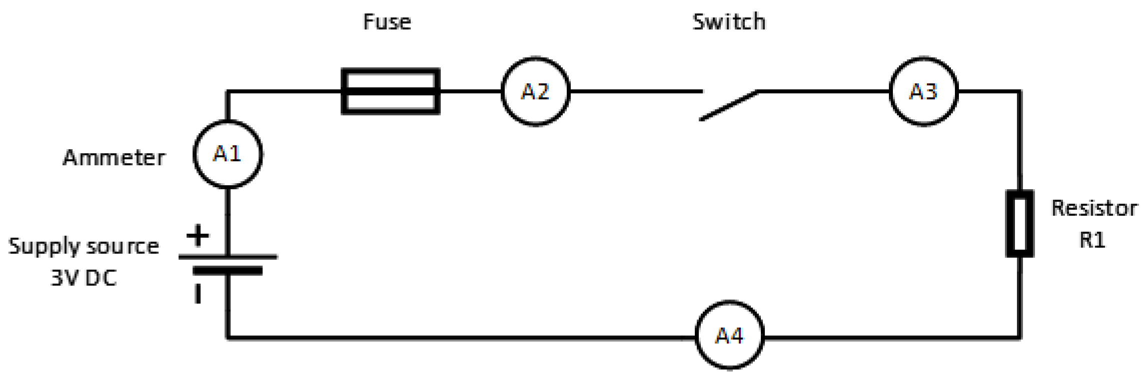
In summary, as we add resistors in series, the total resistance is the sum of all the resistors in series. This in turn will have an impact on the current flowing in the circuit.

Current in a series circuit

In a series circuit there is only one path for the current to flow and so the current that flows is limited by the total resistance of the circuit. If that current path is broken by opening a switch for example, all circuit current will stop and none of the components will work.

If an ammeter is connected in series, no matter where the ammeter is put in the circuit it would show the same amount of current.

The diagram below shows a circuit with one resistor (R_1) in series with a switch, fuse and 4 ammeters (A_1 to A_4).



In this example, the 4 ammeters would show exactly the same current (assuming they are calibrated and working properly).

Note: It wouldn't be a good situation if putting an ammeter in a circuit changed the current flow of the circuit. You wouldn't get an accurate current reading. Ammeters are manufactured to have a very low resistance so they affect the current flow of the circuit as little as possible.

Generally, an ammeter capable of measuring 10A has a resistance of around 0.01Ω. In the example above if R_1 is 2Ω and each ammeter 0.01Ω the total resistance and the current of the circuit are:

$$R_{total} = 2.0 + 0.01 + 0.01 + 0.01 + 0.01$$

$$R_{total} = 2.04\ \Omega$$

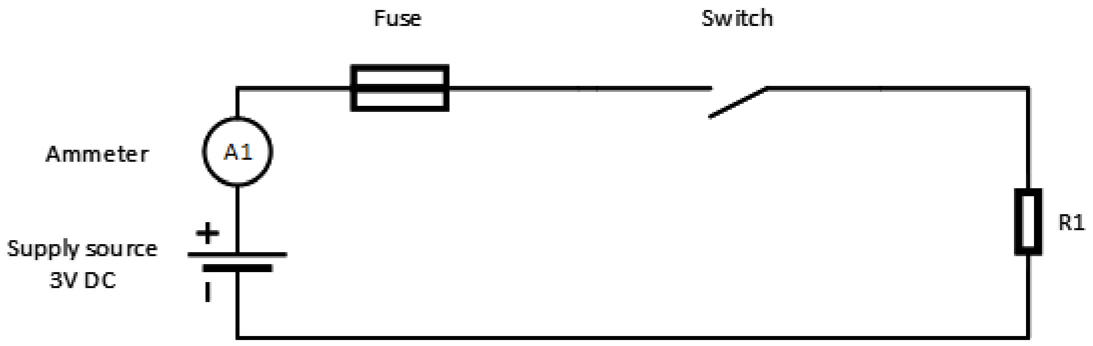
$$I = \frac{V}{R}$$

$$I = \frac{3}{2.04}$$

$$I = 1.47\ A$$

We put 4 ammeters in the circuit to demonstrate the point that the current stays the same throughout a series circuit. In reality, you only need one ammeter to measure the current through the circuit.

In the circuit below, for example, if we use the same values for R_1, the ammeter and the Supply voltage, then the total circuit current will increase slightly due to less resistance in the series circuit.



$$R_{total} = 2.0 + 0.01$$

$$R_{total} = 2.01\ \Omega$$

$$I = \frac{V}{R}$$

$$I = \frac{3}{2.01}$$

$$I = 1.493\ A\ \text{(a rise of 0.022A)}$$

Usually in calculations, the resistance of an ammeter is so small that we disregard the ammeter's resistance as its effect on the current is not significant. So for the rest of our calculations we will not include ammeter resistance unless it is specifically asked for. In that case, for the above example the calculated circuit current would be:

$$I = \frac{V}{R}$$

$$I = \frac{3}{2}$$

$$I = 1.5\ A$$

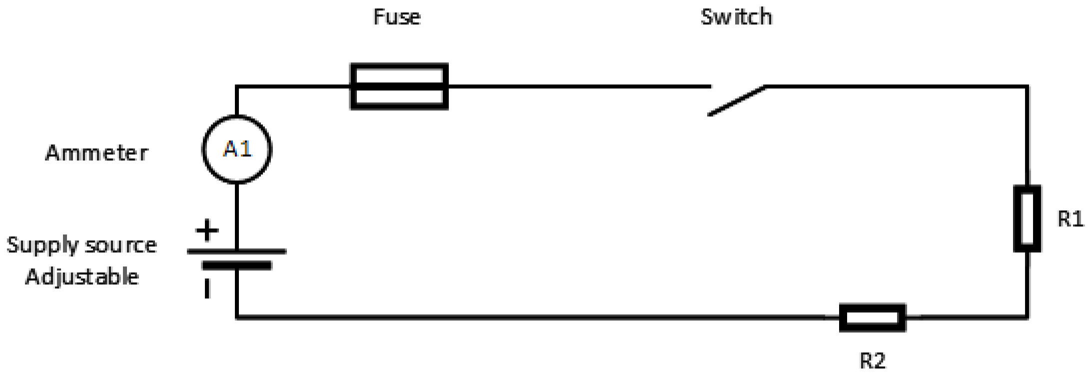
The power dissipated by the resistor would be:

$$P = V \times I$$

$$P = 3 \times 1.5$$

$$P = 4.5\ W\ \text{(power dissipated by the resistor R1)}$$

In the circuit below a second resistor of 1.5Ω (R_2) is put in series with R_1. The total series resistance of the circuit increases to 3.5Ω. In this circuit we can adjust the applied EMF (supply voltage) to vary the current if necessary.



If the voltage is set at 4.0 V the current of the circuit would be:

$$I = \frac{V}{R}$$

$$I = \frac{4}{3.5}$$

$$I = 1.143\ A$$

We can now use the calculated current through the resistors and their resistance values to calculate the voltage dropped across each of the two resistors V_{R1} and V_{R2}.

Because the resistors are different values, the voltage dropped across each of them is different.

Remember though, as we mentioned previously, that the sum of the volt-drops would add up to the supply voltage (Kirchhoff's voltage law).

Therefore:

$$V_{R1} = I \times R_1$$

$$V_{R1} = 1.143 \times 2$$

$$V_{R1} = 2.286\ V$$

$$V_{R2} = I \times R_2$$

$$V_{R2} = 1.143 \times 1.5$$

$$V_{R2} = 1.715\ V$$

The total voltage drop for the circuit is:

$$V_T = V_{R1} + V_{R2}$$

$$V_T = 2.286 + 1.715$$

$$V_T = 4\ V$$

As expected, the total voltage dropped by the two resistors equals the supply voltage.

The power dissipation for each of the resistors, can also be calculated.

$$P_{R1} = I \times V_{R1}$$

$$P_{R1} = 1.143 \times 2.286$$

$$P_{R1} = 1.961\ W$$

$$P_{R2} = I \times V_{R2}$$

$$P_{R2} = 1.143 \times 1.715$$

$$P_{R2} = 2.613\ W$$

$$P_{total} = 1.961\ + 2.613$$

$$P_{total} = 4.574\ W\ \textit{(Power of both resisters together)}$$

The total power, (P_{total}), can also be determined by using the circuit's total current (I_{total}) and the supply voltage, (this is a good way to check that you have the previous answer right).

$$P_{total} = I_{total} \times V_{supply}$$

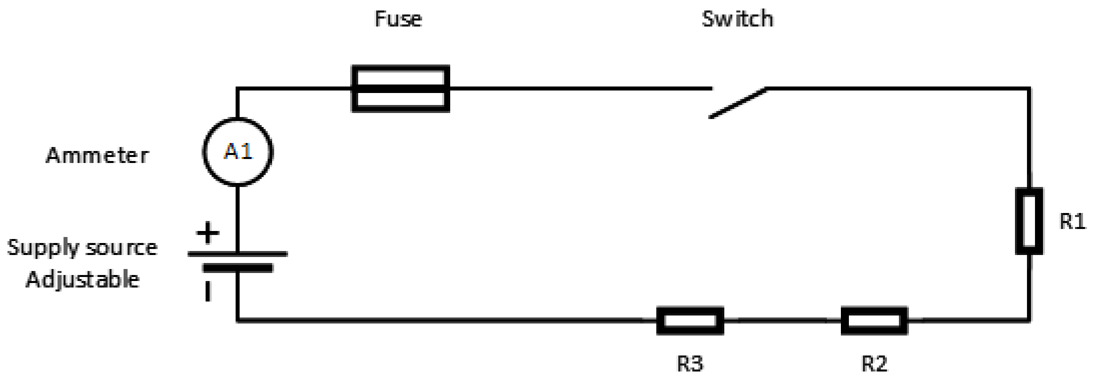
$$P_{total} = 1.143\ \times 4$$

$$P_{total} = 4.572\ W$$

Different value resistors in series

Consider the circuit below that has three resistors in series. R_1, R_2 and R_3, valued at 5Ω, 10Ω, and 15Ω respectively. If the supply voltage is set at 35 V and the switch is closed, calculate the:

- **a) Total current of the circuit (and therefore each resistor).**
- **b) Volt-drop across each resistor.**
- **c) Power dissipated by each resistor.**
- **d) Total power of the circuit.**



Using $R_{total} = R_1 + R_2 + R_3$ **we can calculate the total resistance of the circuit,**

$$R_{total} = 5 + 10 + 15$$

$$R_{total} = 30\ \Omega \text{ (total resistance of the circuit)}$$

Using $I = \frac{V}{R}$ **we calculate the total current of the circuit,**

$$I_{total} = \frac{35}{30}$$

$$I_{total} = 1.167\ A \text{ (Circuit current and through each resistor)}$$

Using $V = I \times R$ we calculate each resistor's volt-drop;

$$V_{R1} = I \times R_1$$

$$V_{R1} = 1.167 \times 5$$

$$V_{R1} = 5.835\,V \text{(volt-drop of resistor R1)}$$

$$V_{R2} = 1.167 \times 10$$

$$V_{R2} = 11.67\,V \text{ (volt-drop of resistor R2)}$$

$$V_{R3} = 1.167 \times 15$$

$$V_{R3} = 17.505\,V \text{(volt-drop of resistor R3)}$$

Using $P = I \times V$ we calculate the power of each resistor and the total power of the circuit;

$$P_{R1} = I \times V_{R1}$$

$$P_{R1} = 1.167 \times 5.835$$

$$P_{R1} = 6.809\ W \text{(Power dissipation by resistor R1)}$$

$$P_{R2} = 1.167 \times 11.67$$

$$P_{R2} = 13.619\ W \text{(Power dissipation by resistor R2)}$$

$$P_{R3} = 1.167 \times 17.505$$

$$P_{R3} = 20.428\ W \text{(Power dissipation by resistor R3)}$$

$$P_{total} = 1.167 \times 35$$

$$P_{total} = 40.845\ W \text{(Total power dissipation by the circuit)}$$

Internal resistance of a battery

A battery has an internal resistance that, (when load current is flowing), causes volt drop internally in the battery. This is because the load current has to flow through the internal battery resistance also.

The voltage used internally by the battery results in a voltage drop across the battery terminals which reduces the available terminal voltage of the battery (the voltage supplied to the external circuit).

Note: A battery will have a higher terminal voltage while sitting “idle” than when current is flowing through the battery. This is due to the voltage dropped internally across the resistance of the battery when current starts to flow.

In some circuit calculations you may be required to take the internal battery resistance and voltage drop into account.

If you are given the internal resistance of a battery you can simply use the circuit current and ohms law to calculate the voltage dropped across the battery.

The battery terminal voltage applied to the circuit will be the no load battery voltage less the full load battery voltage drop.

$f(x)$

$$V_{terminal} = V_B - (R_B \times I_{Total})$$

In summary:

In a series circuit:

- There is only one path for the current and the same current flows through each resistor.
- The total resistance of the circuit is equal to the sum of all the individual resistors connected in series.
- The supply voltage will be divided across all the resistors of the circuit directly proportional to the resistance of each resistor.
- The power dissipated by each resistor is directly proportional to the resistance of the resistor.

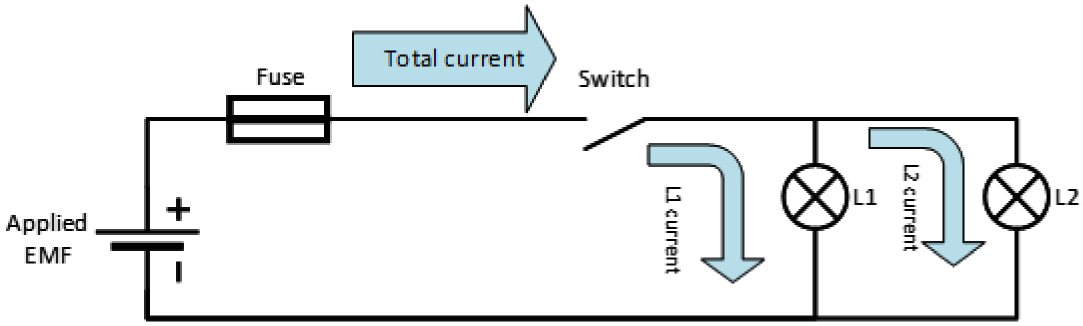
- **The sum of the power dissipated all of the resistors is equal to the total power of the circuit.**

Resistance in a parallel circuit

Parallel paths are very common in electrical circuits. A parallel path is where a circuit splits into two or more branches, i.e. there is more than one path for current to flow, there are parallel paths or “branches” in the circuit.

Most loads in the electrical industry are connected in parallel to the supply so they can operate independently from each other. In some cases, supply sources are even connected together in parallel to increase the output capacity of the supply.

Putting resistors in parallel can (for the sake of explanation) be thought about as increasing the surface area of the conductor and will cause the overall resistance of the circuit to be lowered. Have a look at the circuit below, it shows two lamps connected in parallel to a supply.



As you can see, when the switch is closed both lamps will be connected to the full supply voltage and there will be two current paths. As the supply voltage is directly connected to each lamp, the voltage across each lamp is the same value and will be the voltage of the supply.

Note: In a parallel circuit, the voltage dropped across parallel paths is equal.

These two paths or branches are independent of each other, so unlike a series circuit, the current through each resistor path may have a different value.

Since both of the currents flowing in the parallel parts of the circuit come from a single conductor (from the supply), the current in the supply conductor will be the sum of the parallel currents.

Equivalent resistance in parallel circuits

The total resistance of a circuit, or part of a circuit, is referred to as the equivalent resistance of that circuit. If you recall, in a series circuit the equivalent resistance is the sum of the individual resistors.

When adding resistances in parallel circuits, the total equivalent circuit resistance reduces as more paths are added. The equivalent resistance of a combination of parallel resistances will always be lower than the lowest individual resistance in the group.

$f(x)$

The total or equivalent resistance for a parallel circuit can be calculated using the following formula;

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

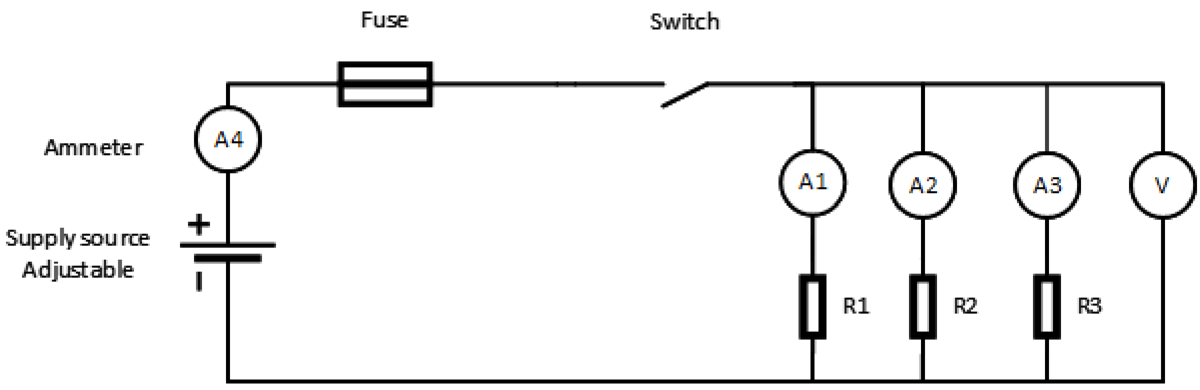
Since you will often need to work out the equivalent resistance of a circuit, you can transpose the formula to;

$f(x)$

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

These equations can be used to determine the equivalent resistance of any parallel path when the voltage or the current of the circuit is unknown.

Consider the example below:



If R_1, = 5Ω, R_2 = 10Ω, and R_3 =15Ω, calculate the equivalent resistance of the parallel portion of the circuit.

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

$$R_{total} = \frac{1}{\frac{1}{5} + \frac{1}{10} + \frac{1}{15}}$$

$$R_{total} = 2.72\,\Omega$$

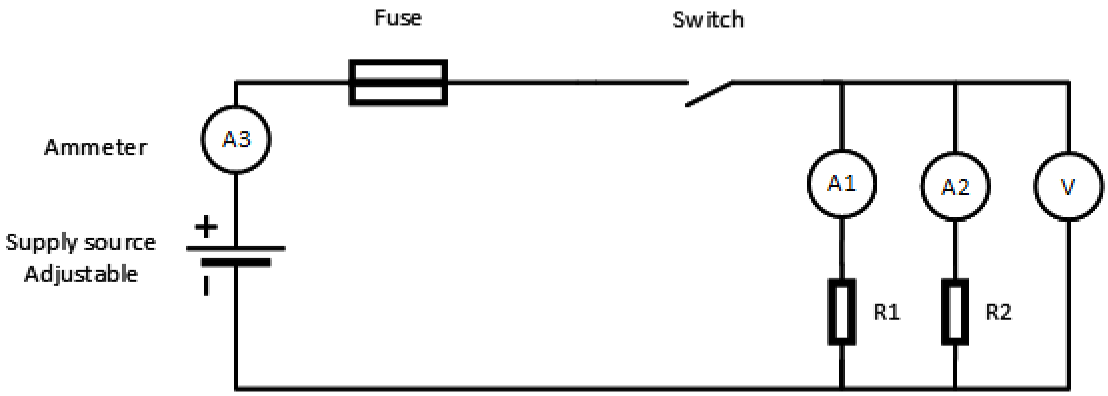
If the supply voltage is set at 30V, calculate what the supply current would be in this circuit. This current will show on ammeter A_4.

Using $I = \frac{V}{R}$ we can calculate the total current of the circuit.

$$I_{total} = \frac{30}{2.72}$$

$$I_{total} = 11.294A$$

Now consider the following example:



For the circuit above, R_1 and R_2 are 1Ω each and the supply voltage is set to 3V.

The ammeter A_3 shows the total current through the entire circuit while A_1 and A_2 show the currents through each of the parallel branches of the circuit.

A voltmeter V will measure the voltage across the resisters and the supply voltage. When the switch is turned on, the voltmeter will read 3V.

Using $I = \frac{V}{R}$ we can calculate the total current of the circuit. Firstly, we find the current flowing in each of the parallel branches of the circuit;

$$I_{R1} = \frac{3}{1}$$

$$I_{R1} = 3.0\ A \text{ (Current through R1)}$$

$$I = \frac{V}{R}$$

$$I_{R2} = \frac{3}{1}$$

$$I_{R2} = 3.0\ A \text{ (Current through R2)}$$

Now by adding the two currents of the parallel branches together, we find the total current flowing in the circuit;

$$I_T = I_{R1+} I_{R2}$$

$$I_T = 3 + 3$$

$$I_T = 6\ A$$

Alternatively, we can find the total equivalent circuit resistance and then calculate the total current flow from that.

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

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

$$R_{total} = \frac{1}{2}$$

$$R_{total} = 0.5\Omega \text{ (Total equivilent resistance of the parallel circuit)}$$

The equivalent circuit resistance for this circuit is half the resistance of the resistors in this example. This is true for two resistors that have an equal value of resistance and are in parallel. If the resistance of the parallel paths is not the same, the equivalent result will be lower than the lowest of the parallel branch resistances.

Using $I = \frac{V}{R}$ we can calculate the total current of the circuit;

$$I = \frac{V}{R}$$

$$I = \frac{3}{0.5}$$

$$I = 6A$$

Using $P = I \times V$ we can calculate the power of each resistor and the total power of the circuit;

$$P_{R1} = I_{R1} \times V$$

$$P_{R1} = 3 \times 3$$

$$P_{R1} = 9\ W \text{(Power dissipated by resistor R1, which is the same for R2)}$$

$$P_{total} = I_{total} \times V$$

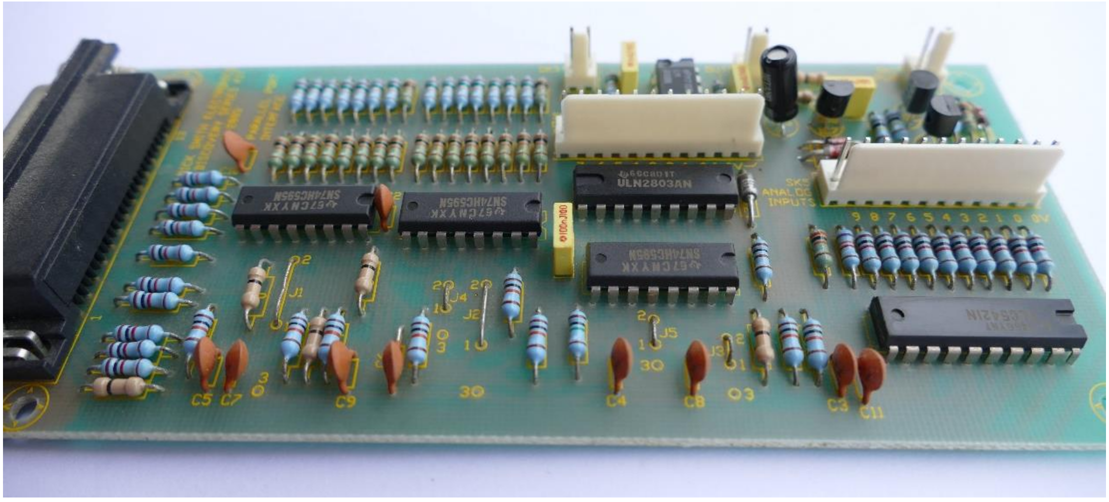
$$P_{total} = 6 \times 3$$

$$P_{total} = 18\ W \text{(Total power dissipation by the circuit that is the sum of } P_{R1} \text{ and } P_{R2}\text{)}$$

In summary:

In a parallel circuit:

- Branches in a parallel circuit are where there are alternative paths for current flow, where the circuit current splits and flows down multiple paths.
- The total equivalent resistance of a parallel circuit network is less than the value of the lowest resistance path in the parallel circuit.
- The voltage measured across each parallel path in the circuit is the same.
- The total circuit current is the sum of the individual currents in the parallel branches of the circuit.
- If one of the parallel circuits goes open circuit, it has no effect on the operation of the other parallel portions of the circuit.



Series or parallel circuits

Series or parallel circuits are not very often used on their own but are frequently found in combinations that make more complex circuits.

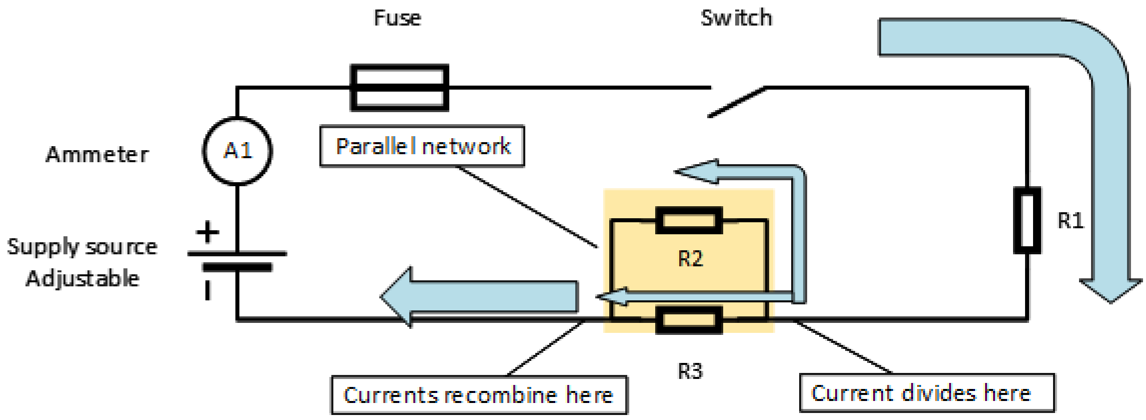
To work with combined series parallel circuits, you will need to be able to work out various things like the equivalent resistance, total current and total power dissipation.

Before any of the circuit parameters can be determined, it is necessary to establish which parts of the circuit are connected in series and which are in parallel. It is often quite easy to recognise component configurations but, in some cases, it will be necessary to look at a circuit carefully to figure it all out.

For complex configurations, redrawing the circuit often helps in clarifying series and parallel paths. Once series and parallel paths have been identified, it is simply a matter of applying the rules we have already looked at to solve the problem.

One way of identifying series and parallel paths is to trace the path that current would take when flowing from one terminal of the source through the circuit components. If the current does not divide, the components are in series. If current does divide into a number of branches, then components in that part of the circuit are connected in parallel.

Examine the circuit shown in the diagram below:



When tracing the path from the positive terminal of the battery, current flows directly through R_1 but when it gets to the other side of R_1, it divides. One path leads through R_2 and the other through R_3.

The point at which current divides marks the start of the parallel branch. Where the current recombines into a single path, this marks the end of that parallel branch. Now that the series and parallel paths have been identified, the total circuit equivalent resistance can be calculated.

If the supply voltage is set at 30V and the three resistors have a resistance value of 10Ω each we could calculate the equivalent resistance of the circuit:

Since R_2 and R_3 are in parallel then we apply the parallel path rules:

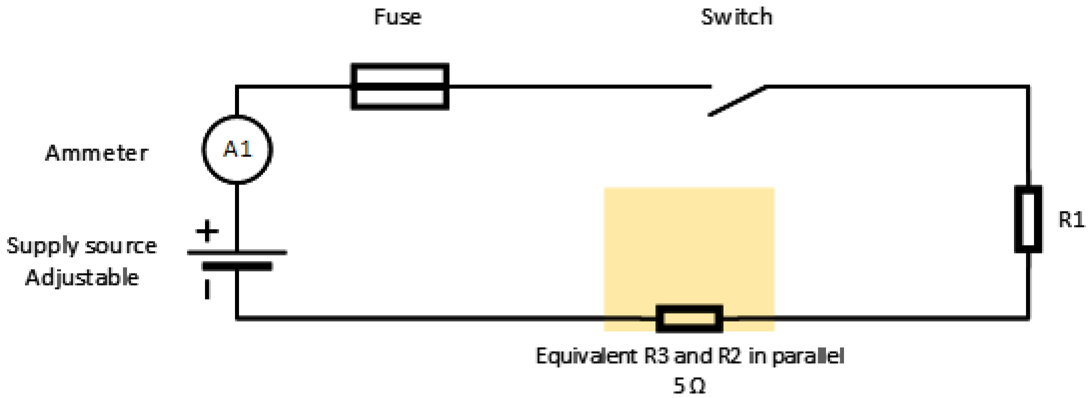
$$R_{total} = \frac{1}{\frac{1}{R_2}+\frac{1}{R_3}}$$

$$R_{total} = \frac{1}{\frac{1}{10}+\frac{1}{10}}$$

$R_{total} = 5\ \Omega$ (Equivalent resistance of the parallel branch R_2 and R_3. We will call it R_{ER})

If we redraw the circuit, by replacing the parallel branch with its equivalent resistance, the circuit can be shown in a simplified series configuration. This step is not essential but helps to simplify the circuit and focus you on how to deal with it.

We can now apply the series path rules to this equivalent circuit.



$$R_{total} = R_1 + R_{ER}$$

$$R_{total} = 10 + 5$$

$R_{total} = 15.0\ \Omega$ (Total resistance of the circuit)

Using $I = \frac{V}{R}$ **we can now calculate the total current of the circuit**

$$I_{total} = \frac{I_{Supply}}{R_{total}}$$

$$I_{total} = \frac{30}{15}$$

$$I_{total} = 2.0\ A$$

Using $P = I \times V$ we can now calculate the total power of the circuit;

$$P_{total} = I_{total} \times V_{Supply}$$

$$P_{total} = 2 \ \times 30$$

$$P_{total} = 60 \ W$$

Using $V = I \times R$ we can also calculate the volt-drops across R_1 and the parallel network;

$$V_{R1} = I_{total} \times R_1$$

$$V_{R1} = 2 \times 10$$

$$V_{R1} = 20 \ V (\text{Voltage across R1})$$

$$V_{RER} = I_{total} \times R_{ER}$$

$$V_{RER} = 2 \times 5$$

$$V_{RER} = 10 \ V (\text{Voltage across the parallel network})$$

Notice that if you add the two voltages V_{R1} and V_{R2}, the result is the same as the supply voltage.

We can use the voltage across the parallel network to calculate the current through each resistor in the network.

Using $= \frac{V}{R}$:

$$I_{R2} = \frac{V_{RER}}{R_2}$$

$$I_{R2} = \frac{10}{10}$$

$$I_{R2} = 1A \text{ (Current through R1)}$$

$$I_{R3} = \frac{V_{RER}}{R_3}$$

$$I_{R3} = \frac{10}{10}$$

$$I_{R2} = 1A \text{ (Current through R2)}$$

Notice also that the sum of the currents through R_1 and R_2 is the same as the current through the whole of the network.

Nested branches

The term nested means one network is contained within another.

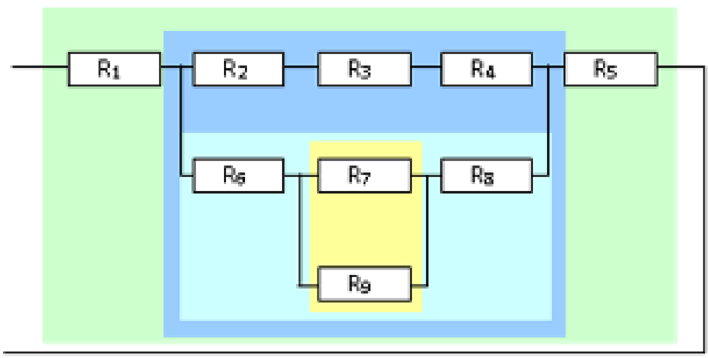
When solving a problem that has nested networks, the inner most network must be solved first, then the next and the next until the whole circuit is solved.

It is important to redraw an equivalent circuit after resolving each network to keep track of progress through the problem.

Example 6.3

The circuit below has a number of nested networks. For example;

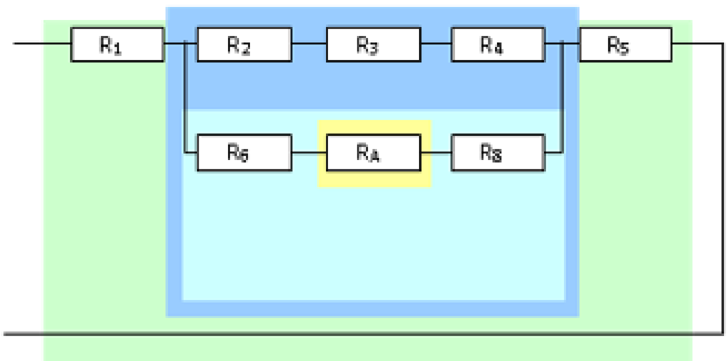
- **The R_7 - R_9 is a parallel pair.**
- **The R_7 - R_9 pair is nested within the R_6, R_7 and R_8 branch.**
- **The R_6, R_7, R_8, (and R_9) branch is, in turn, paralleled with R_2, R_3 and R_4.**
- **The R_6, R_7, R_8, (and R_9) and R_2, R_3 and R_4 group is nested within the R_1 through to R_5 group.**



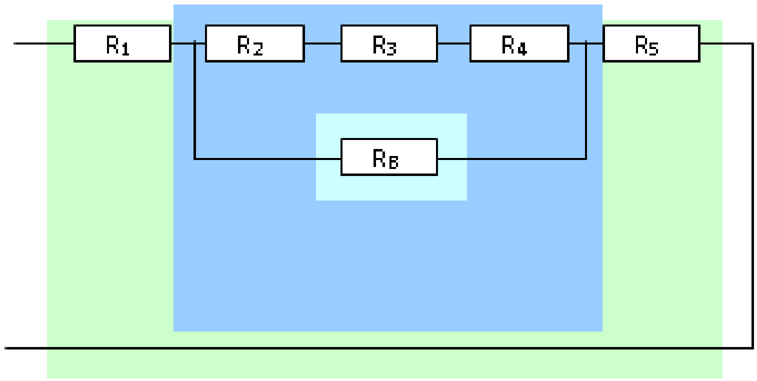
This problem must be solved by starting with the inner most network consisting of R_7 and R_9.

The steps below are a suggestion to systematically solve this type of problem.

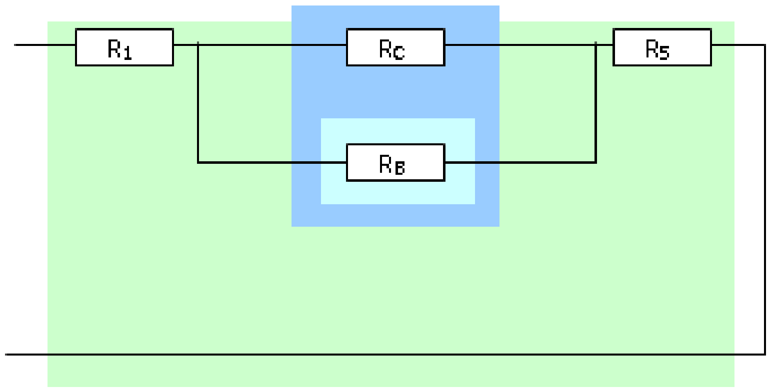
1. **Combine the R_7 - R_9 group into an equivalent resistance and redraw the circuit. The combination of this pair is labelled R_A in the circuit below:**



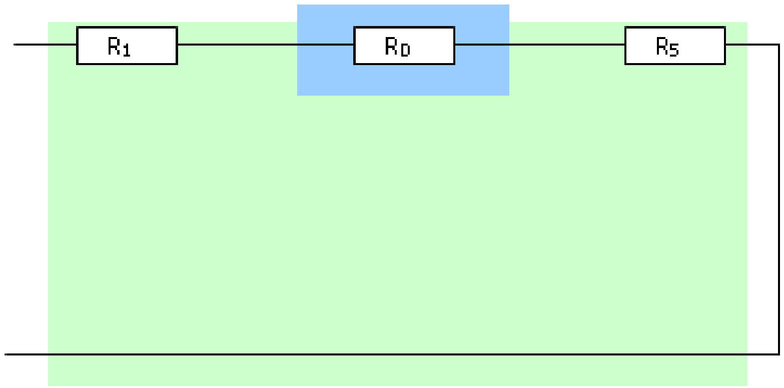
2. **Next, resolve the series group R_6, R_A and R_8. This combination is labelled R_B in the circuit below.**



3. **Now deal with the series network R_2, R_3 and R_4 and resolve this to a single value. This is labelled R_C in the circuit below.**



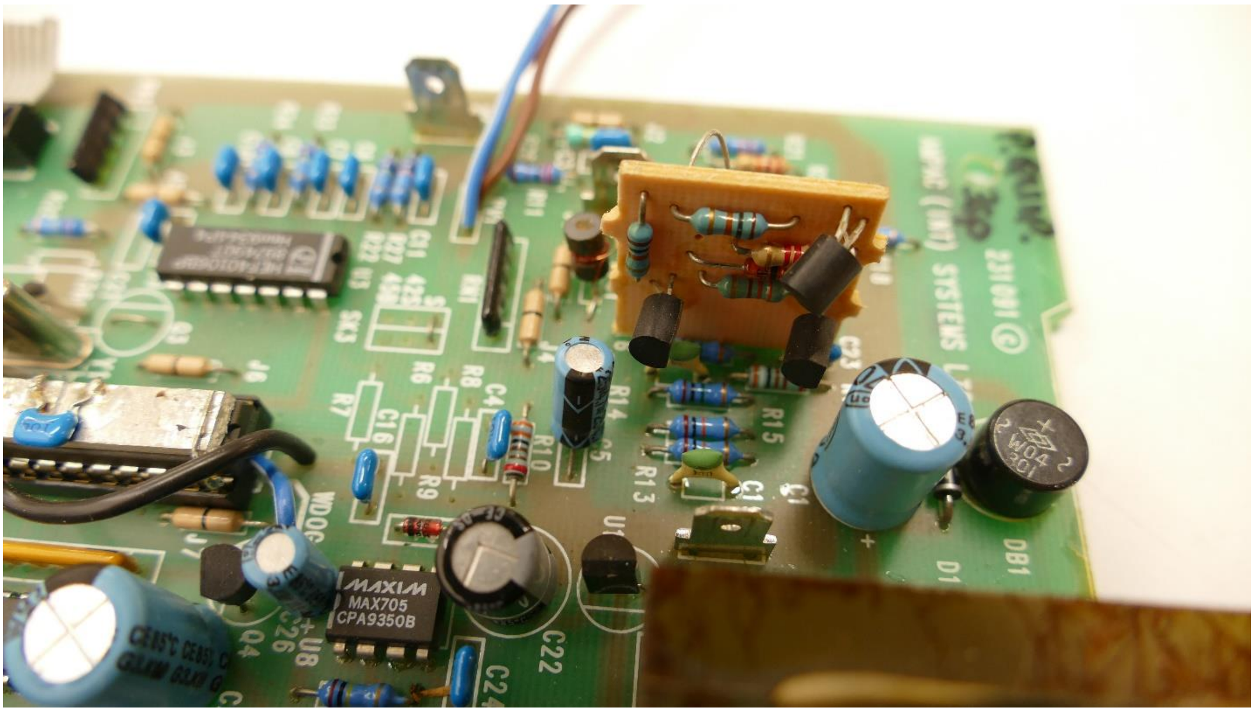
4. **Next, resolve the R_B - R_C network and call this R_D.**



5. **Finally resolve the series network R_1, R_D and R_5. This is the total equivalent resistance of the entire circuit.**

In summary

- When dealing with complex series and parallel circuits, identify the inner most network first to simplify the circuit.
- Next, within that network solve any series elements first and redraw the equivalent circuit.
- Still within that network, solve any parallel elements next and redraw the equivalent circuit.
- Progress to the next network and repeat the above steps.
- Continue the process for any remaining networks until the circuit resolves to one element only.
- Use the source voltage and total resistance to calculate total circuit current by applying Ohm's law.
- Use the total circuit current and source voltage to calculate total power dissipation.
- Use the voltage across an individual component to calculate current flow through it.



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