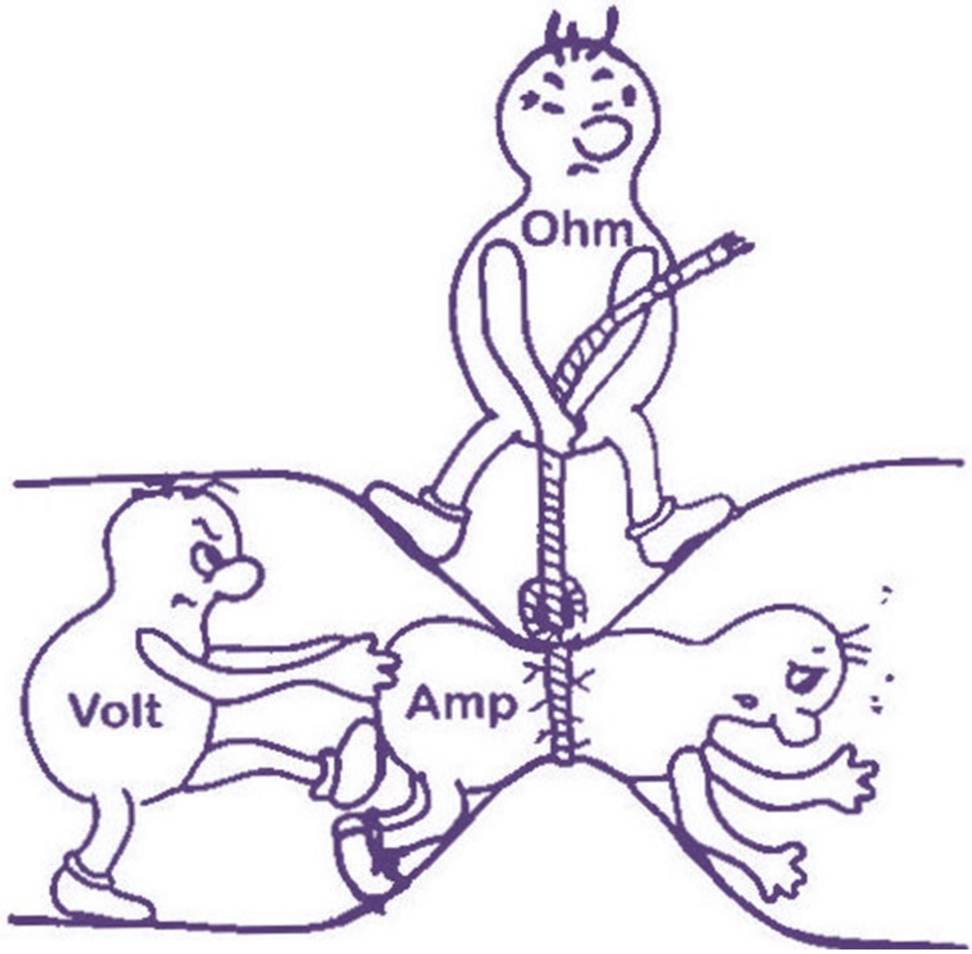
Physics

Unit 1 - Area of Study 2

How do electric circuits work?



INTRODUCTION

Humans have known about electricity for thousands of years, however it is only in the last few centuries that we have come to understand it. Electricity is a term used to describe the energy produced by electrically charged particles, like electrons and protons. Usually in a piece of matter there are equal numbers of electrons and protons, so that all the charges balance out to zero. However, when two materials are brought into close contact, eg. by vigorous rubbing, electrons can transfer from one material to the other. The material that loses the electrons is now positively charged, the material that gains the electrons is now negatively charged. This is called static electricity, as the charges are stationary as opposed to when charged particles flow in a common direction creating an electrical current.

CHARGE

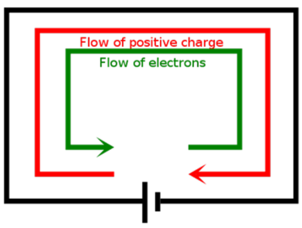
Charge (Q) cannot be created nor destroyed, but it can be transferred from one object to another. The number of electrons in an electrically neutral body is equal to the number of positive charges. The size of the charge on the electron is the same as the size of the charge on the proton. The **elementary charge** (e) is the magnitude of the charge on a proton or electron. It is the smallest charge found in nature. Because it is so small, we have a measure of charge, called the Coulomb (C), which is a standard number of elementary charges.

$$1\ \text{C} = 6.25 \times 10^{18}\ \text{e, or}$$

$$\text{e} = 1.6 \times 10^{-19}\ \text{C}$$

CURRENT

Electric currents (I) are moving charges; they can flow in solids, liquids and gases.
In gases an electric current can flow if the potential difference is large enough, eg. spark plug, lightning. Electrons have been stripped from the gas molecules, forming free electrons and positive ions. The movement of these particles makes up the electric current.
In liquids a current can flow if there are ions present. This may happen in solutions of electrolytes.
In solids electric current is due to the movement of electrons. Only substances made up of atoms with a weak hold on some of their electrons allow electrons to move through them. Such substances are called **conductors.** Substances that are made up of atoms that have a very tight hold on all their electrons are called **insulators.**
The convention is that electric current always flows from the positive to the negative. In other words, the direction of the current is the opposite direction to the movement of the electrons in the solid. So when you see an arrow giving the direction of the current in a wire, remember that the electrons are going in the opposite direction. The direction of electrical current (conventional current) is the direction of flow of positive charge. Positive charge can be transferred either by positive charges moving in the direction of the current or by negative charges moving in the opposite direction.



The unit of electric current is the ampere, A. (after André Marie Ampère, 1775 - 1836) often shortened to “amp” or “amps”. A current of one ampere is flowing if one coulomb of charge passes a particular point every second. The total charge (*Q)* passing a given point when a current *(I)* flows for a time *(t)* is given by *Q = It*

Electric current is the rate of transfer of charge $$I = \frac{Q}{t}$$ 1 mA = 10^{-3} A, 1μA = 10^{-6} A

CONDUCTORS AND INSULATORS

A conductor allows the flow of charged particles through the material. Metal is a good conductor of electricity, because the structure of metals is such that the outermost electrons are free to move around in the fixed crystal lattice made up of the atoms.

Insulators don't allow the free movement of charged particles, materials such as plastic and glass are good insulators.

Semiconductors, used in electronics, can be doped to allow them to significantly improve their conduction qualities.

AC or DC

In a direct current, or DC circuit, the polarity of the voltage stays constant. In other words, the positive terminal is always positive and the negative terminal is always negative, as is the case in a battery. When a battery is connected in a circuit, the current always flows along the wire in the one direction.

In an alternating current, or AC, circuit, the polarity of the voltage can change in a regular way, so that the charge first flows in one direction, then in the other.

The Australian mains electricity supply is AC, changing polarity first one way and then back again 50 times per second, i.e. 50 Hz. There is no difference in the charge carried in AC or DC.

EMF AND ELECTRIC POTENTIAL

If charges are moving, they have energy, a battery or generator is the usual source of this energy. When electrons flow through a battery or other power supply, they gain electrical potential energy. As the electrons flow around a circuit, they lose this energy when passing through components that have resistance, eg. globes.

The energy transferred to one coulomb of charge within the battery is called the **electromotive force** (EMF or ε) of the battery. The unit of electromotive force is the volt (V). EMF can be considered as a 'concentration of charge'. The work done in pushing the charges together is stored as electrical potential energy. A battery with an emf of 6V transfers 6J of energy to each coulomb of charge, when charge moves through the battery.

The energy transferred to a circuit component per unit charge is called the **potential difference** (PD) or **voltage** or **voltage drop** between the two terminals of the component. The unit for potential difference is also the volt.

$$V = \frac{E}{Q}$$

One volt equals one joule per coulomb.

1 V = 1 J/C = 1 J C^{-1}

EMF and PD are often simply referred to as **voltage** (V) although they are different. The SI unit for electrical potential is *joules per coulomb*, this is given the name volt after Alessandro Volta, the inventor of the first chemical battery.

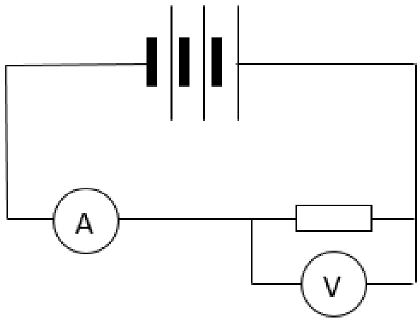
RESISTANCE

There is resistance *(R)* in all conductors and electrical components (apart from super conductors). Resistance is the hindrance to the flow of charge. The higher the resistance, the harder it is for the current to flow. Resistance is measured in ohms *(Ω)*. When the resistance of a circuit element is constant it is said to be ohmic. The resistance of metals depends on its length *(L)*, area *(A)*, and the resistivity of the material *(ρ)*.

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

RESISTORS

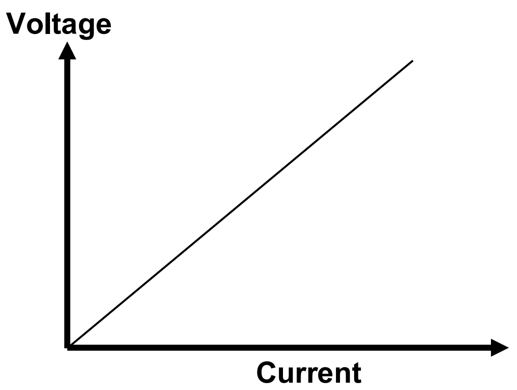
If a resistor is connected to a power supply, then it is possible change the voltage of the power supply and to measure both the voltage across the globe and the current flowing through the globe.



Voltage, current and resistance are connected by **Ohm's law.**

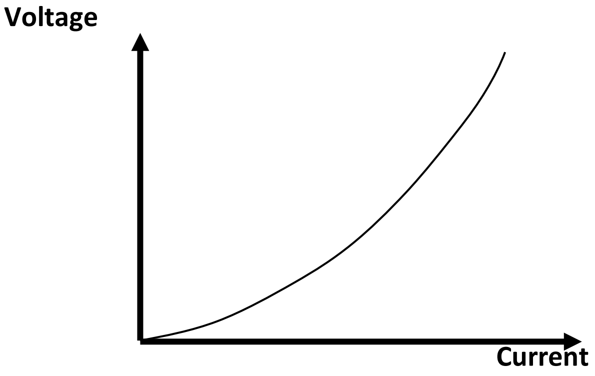
$$I = \frac{V}{R}$$

When relation between current and voltage is linear, resistor called **Ohmic** and V-I graph looks like:



Resistance is the gradient of this graph.

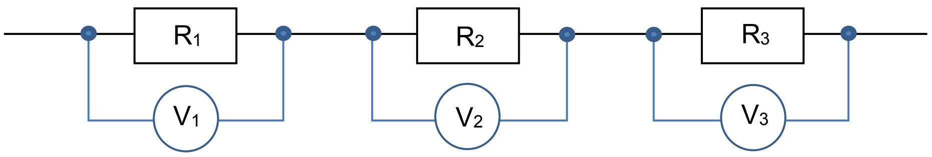
All conductors that do not give a straight voltage versus current graph are called **non-Ohmic** as the resistance changes depending on the voltage/current. Not all non-ohmic devices produce the graph shown below.



Resistance at any point can be found as gradient of the graph. For simplicity in year 11 physics course you may find resistance just dividing voltage by current.

<u>SERIES CIRCUITS</u>

In a series circuit the current is constant throughout the circuit, which is why we measure current in series with the components.



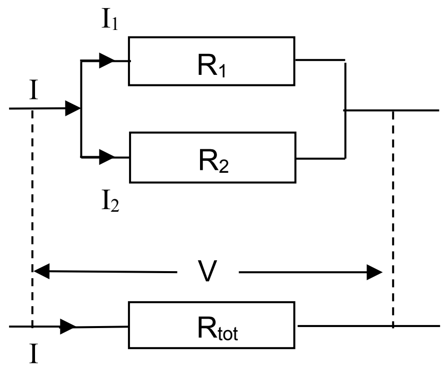
The total resistance and voltage in series are the sum of the components.

$R_{tot} = R_1 + R_2 + R_3 + etc$

$V_{tot} = V_1 + V_2 + V_3 + etc$

The total current is constant in a series circuit as there is only one path that the current can possible take. ***$I_{tot} = I_1 = I_2 = I_3 = ...$***

PARALLEL CIRCUITS



In parallel circuits the same voltage drop occurs across both elements.

The total current that flows is the sum of the two individual currents.

$I_{tot} = I_1 = I_2$

To find the total or effective resistance is a parallel circuit we need to use the following relationship

$$\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} + ...$$

The voltage in a parallel circuit is constant as the amount of energy each electron is carrying does not change.

$V_{tot} = V_1 + V_2 + V_3 + etc$

KIRCHHOFF'S LAWS

In 1845, whilst still in University student, Gustav Kirchhoff formulated two laws, based on conservation of charge and energy.

Law 1 Conservation of charge

At any point in a conductor, the sum of the charges flowing into the point must equal the sum of the charges moving out of the point.

Another way of saying it is 'the sum of the electric currents that meet at any point in a circuit is zero'.

Law 2 Conservation of electrical energy

This can be summarised as 'in any closed loop of a circuit, the sum of the voltage drops must equal the sum of the emf's in that loop'.

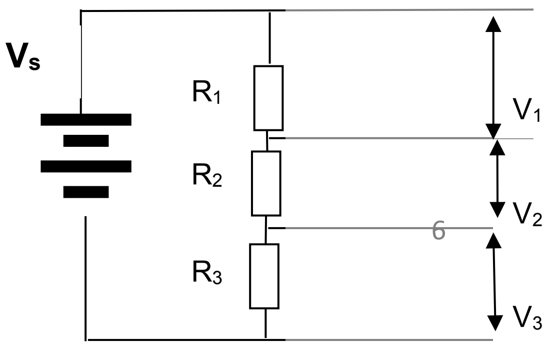
VOLTAGE DIVIDERS

The backbone to most electronic circuits is the voltage dividers. A voltage divider is a circuit which accepts an input of a large voltage and only puts out part of that voltage. Whenever components are in series in a circuit the voltage is being divided amongst them. A common use of resistor combinations is to divide or *attenuate* voltages.

The resistors are placed in series.

The current through each resistor is the same,

so the voltage across each one depends on its resistance.



ELECTRICAL ENERGY AND POWER

ELECTRICAL ENERGY

When a current passes through a resistor, the resistor gets hot. Electrical energy is being converted to thermal energy. Electrical energy can also be converted into mechanical energy.

If a charge (Q) passes through a potential difference (V), the electrical energy (E) is:

$$E = Q\,V$$

So if it takes 'V' joules of energy to get '1' coulomb of charge form one place to another, then it takes 'VQ' joules to get 'Q' coulomb from one place to another

As the current (I) is the rate at which charge is moving, the total charge Q = I t.

$$\Rightarrow \quad E = V\,I\,t.$$

ELECTRIC POWER

The rate of energy transferred or the rate of work done is called **power**. In a circuit component the power can be calculated in terms of potential difference and current

$$P = \frac{E}{t} = \frac{VIt}{t} = VI$$

The unit for power is the watt (W).

One watt is equal to one joule per second. $1\ W = 1\ J\ s^{-1}$

In terms of the volt and ampere $1\ W = 1\ V\ A$

A larger unit for power is the kilowatt (kW). 1 kW = 1000 W.

Since P = I V and V = I R

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

The energy supplied in time 't' is

E=Pt

UNITS FOR ELECTRICAL ENERGY

The unit for electrical energy is the joule. In industry and in household consumption of electricity the unit kilowatt hour (kWh) is used. One kWh is the energy delivered in one hour at a rate of 1000 W.

$$\Rightarrow \quad 1\ kWh = 1000 \times 3600\ s$$

$$\Rightarrow \quad = 3.6 \times 10^6\ J$$

Thermistor

This is a temperature dependent resistor. When the temperature is high the resistance is low and when the temperature is low the resistance is high. These resistors are often used in temperature-controlled environments.

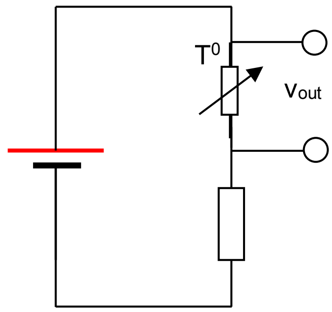
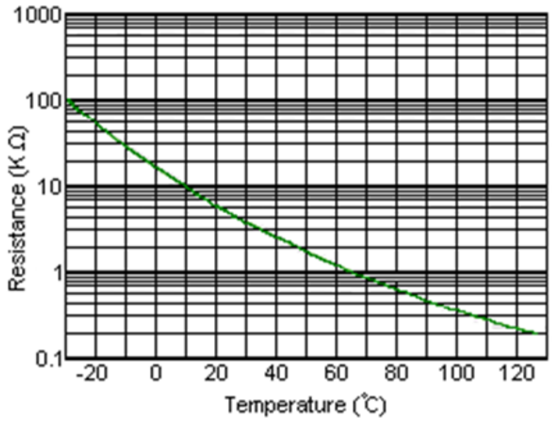


Figure 2



If you take the voltage out over the thermistor as seen in figure 2 then as the temperature increases the voltage out will decrease. If you take the voltage out over the other resistor the voltage will increase as the light intensity increases.

Diodes

Diodes are devices that only allow current to flow in one direction. The diode can be in two states, forward biased (current in forward direction) and reversed biased (current in reverse direction). When forward biased (Figure 3) the diode takes 0.7V and leaves the rest for the other resistor no matter the voltage supplied.

If the supply voltage is less then 0.7V the diode will take all of the voltage and allow only a very little current to flow.

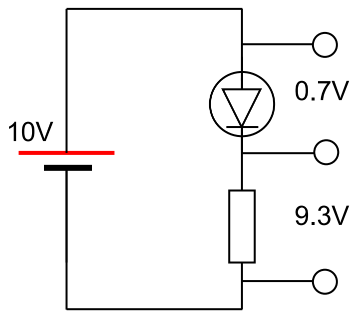


Figure 3

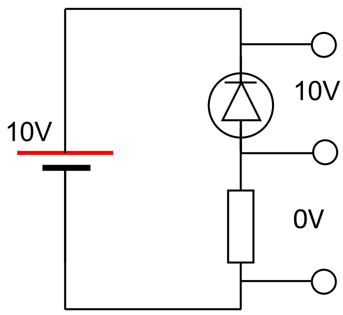


Figure 4

When reversed biased (Figure 4) the diode will have the full supplied voltage and not allow any current to flow.

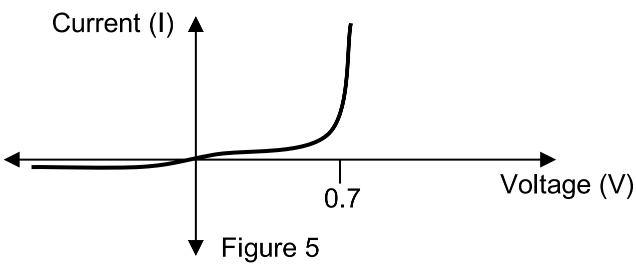
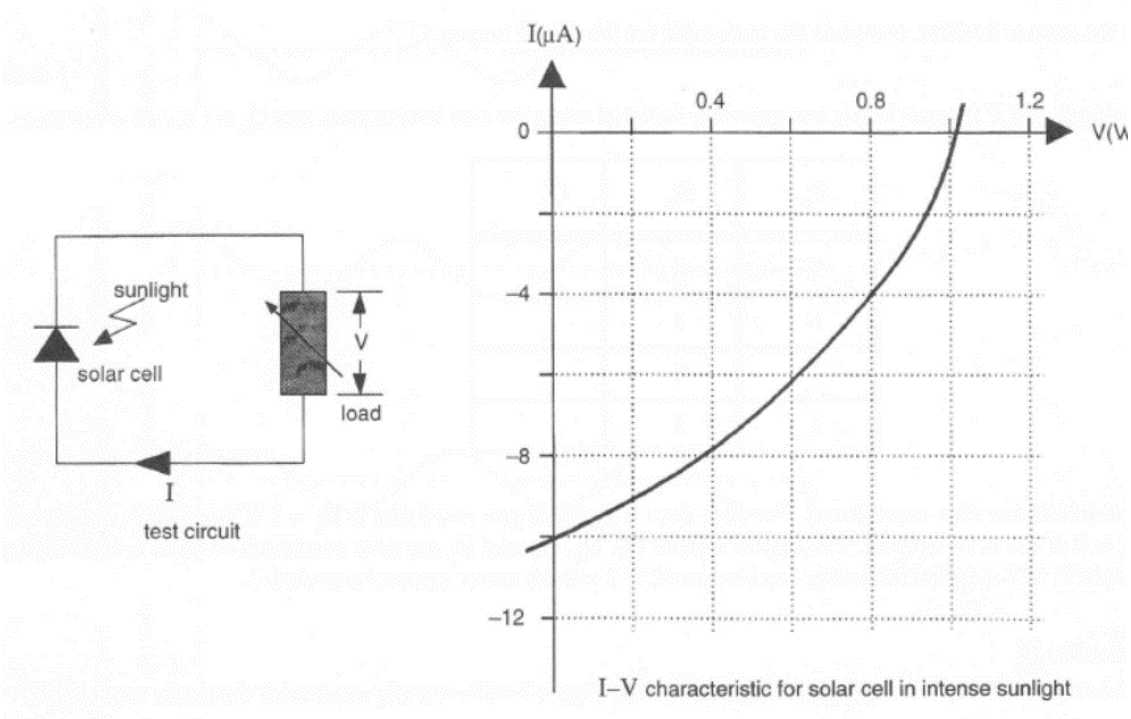


Figure 5

A solar cell is a photodiode, with a non-linear I-V characteristic connected reverse biased. It is used to provide electrical energy to a load. The amount of electrical energy provided is dependent upon the intensity of the sunlight incident on the solar cell.

The figure below shows the relation between the current through, and the voltage across, a solar cell in intense sunlight. The circuit shown allows the electrical energy generated by the solar cell to be dissipated in the load. The load has a resistance that may be varied. The current through the load is represented by I, and V represents the voltage across the load.

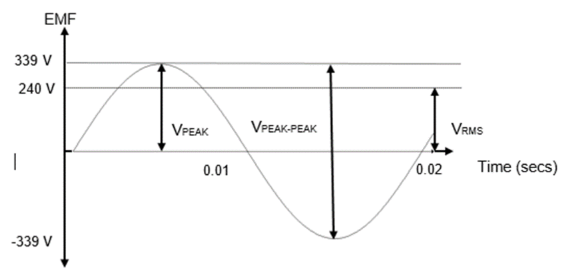


HOUSEHOLD ELECTRICITY

In typical houses, parallel circuits are usually preferred over series circuits, because each device in a parallel circuit can be turned on and off independently. All appliances/devices also have 230 V across them. In Australia, in theory, we have 230 V, 50 Hz, AC supply, in practice it is somewhat different. In fact, different states have different standards. For example in Victoria, NSW and Queensland it is 240V.

MEASURING AC VOLTAGE

When comparing DC and AC power supplies, it is necessary to carry out conversions to make a true comparison. Below is a regular sinusoidal AC voltage.



The **Root Mean Square (RMS)** voltage is the square root of the mean of the square of the potential difference. This complicated value is used because it gives the value of the DC potential difference that provides the same power as the alternating current.

To convert:

RMS to Peak $\times\sqrt{2}$

Peak to Peak-Peak $\times 2$

RMS to Peak-Peak $\times 2\sqrt{2}$

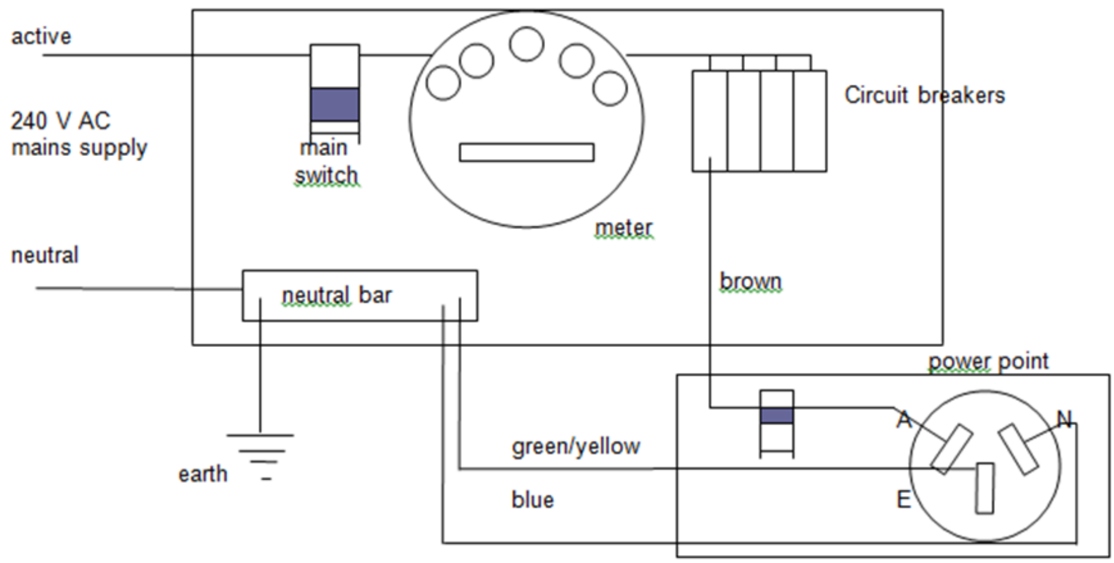
Peak to RMS $\div\sqrt{2}$

Peak-Peak to Peak $\div 2$

In formulas you need to use all values in the same unit, i.e. **all** RMS, or Peak, or Peak - Peak.

Any AC current can be given an RMS equivalent value in exactly the same manner. When doing calculations involving power **always** use the RMS values, unless otherwise stated.

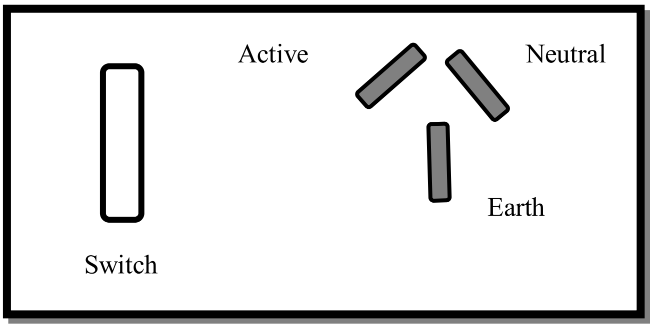
DOMESTIC WIRING



Two wires come from the power pole to the house. The ACTIVE wire is 240 V_{RMS}. The NEUTRAL wire is 0 V and is connected to the ground. The cable from the pole goes first to a mains connection which contains a fuse in the active wire. Then it is connected to the switchboard or fusebox. A main switch is placed in the active wire so that the power can be easily cut in case of emergency. Several lighting and power circuits originate at the switchboard and each has a fuse or circuit breaker (again in the active wire) so that individual circuits can be isolated and cut.

The neutral is connected to the neutral bar in the switchboard which is earthed. The neutral bar has connections to each power and lighting circuit. A third wire, an earth, also goes to each circuit.

The earth wires are connected into the ground, often by a water pipe or metal stake. They serve as a safety feature in that the earth wire is connected to the metallic case of an appliance. If this case accidentally becomes electrified, the current flows harmlessly to earth and possibly blows a fuse in the process. The current will flow to the earth, because it will always take the path of least resistance.



The potential differences are: active and neutral = 240 V, active and earth = 240 V, neutral and earth = 0 V

The fuse is designed to 'blow' (break), and break the circuit if too much current flows at any time.

ELECTRIC SHOCK

Electric shock and electrocution (death by electric shock) will occur if current finds a path through the body. The human nervous system runs on electrical signals, running a current through the body interferes with these signals which can result in fibrillation of the heart and nerve damage and tissue damage. Electric shocks can also cause muscles to seize, either throwing the victim across the room, or making their hand clamp down around the electrical source – preventing them from letting go.

Different parts of the body have different amounts of resistance; dry skin has the most resistance whereas blood lines have fairly low resistance, therefore if you have wet skin this will reduce your resistivity considerably. In general, the resistivity of skin varies from about 10^6 Ω for dry skin, to about 1500 Ω for someone with wet hands, and all the way down to about 500 Ω for someone sitting in a bath.

How much damage is done depends on four things:

- The resistivity of the path – the less resistance the more damage done, which is why being wet increases the damage done
- The path of the current through the body (going through the heart can cause fibrillation)
- The current
- The time the current is flowing though the body

The following table shows the effects for different currents and time periods

Current (mA)	Time (ms)	Effect
50	10–200	Usually no dangerous effect
50	> 4000	Fibrillation possible
100	10–100	Usually no dangerous effect
100	> 600	Fibrillation possible
500	> 40	Fibrillation possible

If you find someone who has collapsed from an electric shock:

- Call 000
- Switch off main power (if possible)
- Do not touch the person (otherwise you will get a shock)
- You may be able to move the person if you use an insulating material (plastic rope, garden hose)

FUSES AND CIRCUIT BREAKERS

A fuse is a thin metal wire, that breaks when too much current passes through it. Fuses are rated according to the amount of current that causes them to melt. Therefore, a 5 amp fuse will melt at a current of 5 or more amps.

Fuses used to be the most common method for protecting circuits within a house. These days new houses are built with circuit breakers instead. Circuit breakers are special switches that 'trip' (turn off) the circuit if too much current flows through. These can either be thermal or electromagnetic.

EARTHING

Earthing is another safety feature. This connects the outer metal casing of an appliance to the earth. This allows any charge that reaches the outer casing due to electrical faults (for example if the active wire came into contact with the casing) to be drained directly to the earth. If a case was not earthed and came into contact with the active wire it would build charge on the surface until it could be discharged in some way, which could be though a person next time they touch the appliance.

If current flows through the earthing wire this will also blow a fuse (or flip a circuit breaker) in the active wire, cutting off power to the appliance. It should be noted that although this is a safety feature, fuses and circuit breakers often don't act quickly enough to stop someone getting an electric shock, they are their primarily to stop fires that can be caused by the large current flow.

RESIDUAL CURRENT DEVICES (RCDS)

RCDs quickly disconnects the current to an appliance or circuit when a fault develops, in order to prevent harm from an electric shock. RCDs detect when the current in the active wire is not equal to the current in the neutral wire. The way they operate is similar to transformers, except they have the same number of coils on each side, so when the current is the same in the neutral and active wires they cancel each other out, but when the current is different the RCD generates a magnetic field, and therefore a current in the relay circuit. This triggers switches in both the active and neutral wires.

DOUBLE INSULATION

An extra layer of insulation between the active wire and the outer shell. This means that the outer shell can only become live if two independent layers of insulation fail. This is used for appliances that do not have an earthing wire (two pin plugs).