## Leaving Certificate Technology

## Energy, Electricity and Electronics

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## Energy and Energy Conservation

In this day and age with the threat of global warming there is a new awareness of the methods of producing energy and its effect on the environment. Some methods of production are environmentally friendly whilst others are exceedingly harmful.

A list of ways and means of producing energy are listed below with a brief resume of their advantages and disadvantages

## Renewable Energy

## Wind Power

A propeller is attached to an electric generator and with the rotation of the propeller electrical energy is generated. This is reckoned to be one of the most 'user friendly' methods of producing electricity. However each machine can produce only a limited amount of energy thus a large number of machines are required generally known as wind farms. As these farms due to their nature of operation must be placed on high ground they are unsightly.

## Solar Energy

A photovoltaic cell will generate a voltage when rays of light from the sun strike it. Used generally in calculators, satellites etc. they produce only a small amount of electricity per cell.

With the advance of technology solar panels are now used (usually fitted on roof tops) to supply sufficient energy to cope with the household need to produce warm water and power electrical appliances.

Solar energy is environmentally friendly and no toxic waste is generated.


## Wave/Tidal Energy

Experimentation with this form of energy is still at an early stage although some larger scale projects are in place, the Thames estuary is one example.

Movement of the waves cause paddles to move up and down and this movement is converted to rotary movement that rotates the turbine blades of the electric generator.


Wave energy is not used commercially to date but has potential, especially for island countries.

It is environmentally friendly and no toxic waste is generated.

## Non Renewable Energy

## Coal Fired Energy

Probably the most used system universally.
Boilers are heated using coal and the steam produced is used to drive a turbine which in turn drives an electric generator.

Unfortunately this produces adverse side effects harmful to the environment. It produces sulphur dioxide gas which in turn produces acid rain. It also produces carbon dioxide (green house gas) responsible for global warming.


## Oil Fired Energy

It uses the same system as coal to produce electrical energy. It is less pollutant than coal (does not produce acid rain) but it is still responsible for global warming.

## Nuclear Energy

As the supply of fossil fuels decrease the nuclear alternative is becoming more attractive and is purported to be the cheapest way of producing electrical energy. Nuclear energy is also the most contentious means of producing electrical energy - (it uses essentially the same system of production as a coal fired system).

Nuclear energy does not produce any green house gases or acid rain but does produce an extremely toxic waste. To date no satisfactory means for the disposal of this toxic waste has been found which is problematic as it will remain radioactive for a period bordering on two thousand years. Water which is used as a coolant within the nuclear reactor is pumped into the seas again causing radioactive pollution. Another concern is an accident which could produce a radiation leak or at its most violent a nuclear explosion - Chernobyl April 26th 1986.

## Biomass Energy

Biomass energy comes from a number of biological sources. There are a number of different sources of this type of energy including agricultural production of methane gas through to the growth and processing of willow which can then be burnt to produce steam in an electrical generating station. Willow can also be shredded and pressed into wood pellets suitable for a home fuel.

## Energy

Energy is the ability to do work. There are many forms of energy, some of the more important being: mechanical, heat, chemical, electrical and atomic. Any form of energy can be converted into another by means of a suitable apparatus. For example, a cell converts chemical energy into electrical energy and an electric motor converts electrical energy into mechanical energy.

## Types of Energy

## Mechanical Energy

Is the energy which is possessed by an object due to its motion or due to its position. Mechanical energy can be either kinetic energy (energy of motion) or potential energy (stored energy due to position).

Potential energy: energy due to position - e.g. water at a high level such as a waterfall which can be used to power a turbine.

Kinetic energy: energy due to motion - e.g. a jet of water directed against a moving blade of a turbine will cause the turbine to rotate. A moving car or the rotating blades of a windmill are further examples of kinetic energy.

## Heat

Heat stored in steam for use in the driving of a steam engine or turbine.

## Chemical

Coal contains energy which can be released by chemical combustion or burning. The energy in gunpowder/fireworks is also released in the same way but in a much shorter interval of time. Chemicals within a battery will produce electric energy.

## Sound Energy

All sounds are caused by vibrations which need a medium such as air to cause them to move. In the case of speech it is our vocal chords which are made to vibrate and in the case of a radio it is the forward and backward motion of a paper cone within the speaker which causes a sound to be transmitted.

## Conservation of Energy

There is a fundamental concept dealing with questions of energy which is known as the Principle of the conservation of energy. This states that energy can not be created or destroyed, it can however be transferred from one type of energy to another.

An example of this transference is shown.
The electric motor rotates and in so doing will raise the weight through a distance in a predetermined time. Electrical energy is converted to mechanical energy.


An illustration of the transference of energy.


Atomic energy stored in Uranium can be released by fission within the reactor and converted into heat in the heat exchanger. This energy is applied to the turbine which rotates (mechanical energy, kinetic). This energy in turn drives the alternator which converts the mechanical energy to electrical energy which is transmitted along the National Grid, network of cables, transformers and pylons which cover the country carrying electrical energy to our homes from any one of over twenty generating stations.


Due to the large amount of power involved, transmission normally takes place at a high voltage ( 110 kV or above) which is much more efficient than low voltage transmission. Underground power transmission is used only in densely populated areas due to its high cost of installation and maintenance.

This energy now dispersed to the various devices. The electric motor converts electrical energy to mechanical energy. Radiators convert the electric energy to heat energy. Lamps convert electrical energy to light energy and radios convert electrical energy to sound energy.

The law of conservation of energy states that energy can not be created or destroyed, this means that in any energy conversion process, the total energy coming out must equal the total amount of energy put in. Unfortunately the output energy is never all in the required form and we appear to have lost energy in the process.

For example when an electric motor is used to convert electrical energy into mechanical energy some of the electric energy input is used to produce magnetic fields within the motor but a percentage is "wasted" in the form of heat, noise, friction etc. It follows that useful energy output of a machine is always less than the input energy.

The EFFICIENCY of a machine is the ratio between the useful output and the input

$$
\text { Efficiency }=\frac{\text { energy output }}{\text { energy input }}
$$

This is usually expressed as a percentage:

$$
\text { Efficiency }(\%)=\frac{\text { energy output }}{\text { energy input }} \times 100
$$

## Example

The operating voltage of an electrical motor is 240 V and current drawn from the supply is 12 amps, if the power output of the machine is 2400 watts what is the efficiency (expressed as a \% ) of the machine.

Input power (in watts) $=$ V x I $=240 \times 12=2880$ watts

Efficiency $(\%)=\frac{\text { output power }}{\text { input power }} \times 100=\frac{2400}{2880} \times 100$

Efficiency $=83 \%$

## Electrical Energy

The energy dissipated in an electrical circuit element is given by the formula:
ENERGY $=\mathrm{V} \times \mathrm{I} \times \mathrm{t}$ (Joules or Watt seconds)
Where V is the voltage drop across the element
I is the current flowing through it t is the time current is flowing

## Example

In the circuit shown find the energy dissipated in the 10 ohm resistor if the current flows for a time of 20 second.

To find I use Ohm's Law:

$$
I=\frac{V}{R}=\frac{24}{10}=2.4 \mathrm{Amps}
$$

Energy $=24 \times 2.4 \times 20=1152$ Joules or watt seconds


In commercial terms the unit of energy the Joule is much too small a unit so the COMMERCIAL UNIT OF ENERGY is the KILOWATT HOUR (kWh). This corresponds to one kilowatt of power being consumed continuously for a period of one hour (called one unit of energy).

The meter used to record energy is called the ENERGY METER OR KILOWATT- HOUR METER. The meter shown on the right is now largely
 replaced by a digital read out type. This type of meter is used to measure the energy consumed in houses, factories etc over a predetermined period These meters are known as integrating meters as they "add up" the energy consumed on a continuous basis.

## Examples

1. What is the cost of operating a 3000 Watt immersion heater for 8 hours if electrical energy costs 14.5 cents per unit? 1 unit $=1 \mathrm{kWatt}$ hour

$$
\begin{aligned}
& \text { kWatts }=\frac{3000}{1000}=3 \\
& \text { number of units }=\mathrm{kWatts} \times \mathrm{hrs}=3 \times 8=24 \mathrm{kWh} \\
& \text { total cost }=24 \times 0.145=€ 3.48
\end{aligned}
$$

2. A small factory having the following equipment consumes the following amount of energy:

- 5 lathes each rated at 1200 watts
- 3 saws each rated at 1500 watts
- 4 planers each rated at 2400 watts
- 20 lamps each rated at 200 watts

If the factory operates on an eight hour day calculate the cost of energy over a 5 day period ( 1 unit of energy costs 14.5 cents). Remember to convert cents to euros i.e. 14.5 cents $=€ 0.145$

For 5 lathes energy consumed for 1 hour $=5 \times 1200 / 1000=6 \mathrm{~kW} \mathrm{~h}$
For 3 saws energy consumed for 1 hour $=3 \times 1500 / 1000=4.5 \mathrm{~kW} \mathrm{~h}$
For 4 planers energy consumed for I hour $=4 \times 2400 / 1000=9.6 \mathrm{~kW} \mathrm{~h}$
For 20 lamps energy consumed for 1 hour $=20 \times 200 / 1000=4 \mathrm{~kW} \mathrm{~h}$

Total energy consumed for I hour $=6+4.5+9.6+4=24.1 \mathrm{~kW} \mathrm{~h}$
Total energy consumed over a 5 day period $=5 \times 8 \times 24.1=964 \mathrm{~kW} \mathrm{~h}$
Total cost $=964 \times .145=€ 139.78$
3. An electrical heating element having a resistance of 24 ohms is connected to a 240 V supply for a period of 12 hours. Calculate the cost of operation if electrical energy costs 14.5 cents per kWh.

$$
\begin{aligned}
& \mathrm{I}=\mathrm{V} / \mathrm{R}=240 / 24=10 \mathrm{Amps} \\
& \begin{aligned}
\text { Power }=\mathrm{V} \times \mathrm{I}=240 \times 10 & =2400 \mathrm{Watts} \\
& =2400 / 1000 \\
& =2.4 \mathrm{kWatts}
\end{aligned}
\end{aligned}
$$

Energy consumed $=2.4 \times 12=28.8 \mathrm{~kW} \mathrm{~h}$
Total cost $=28.8 \times .145=€ 4.17$
4. Calculate the energy in kWh to lift a mass of 250 kg through a distance of 300 metres if the efficiency of the lifting gear is $30 \%$. A mass of $1 \mathrm{~kg}=9.8$ newtons $(\mathrm{N})$ and $1 \mathrm{kWh}=3600000$ Joules (J).

Force to lift the mass $=$ mass in $\operatorname{kg} \times 9.8=250 \times 9.8=2453 \mathrm{~N}$
Work done $=$ force (in newtons) x distance travelled (in metres)

$$
=2450 \times 300=735000 \text { joules }
$$

But as the machine is only $30 \%$ efficient Input to machine (in joules) $=735000 \times 100 / 30=2450000 \mathrm{~J}$
Input energy (expressed in kWh ) $=2453000 / 3600000=0.68 \mathrm{~kW} \mathrm{~h}$

## Electricity

It is hard to pinpoint its discovery but there is no doubt that people were aware of the effects of static electricity several hundred years BC. It was not until the 1800's that scientists began to realise how to harness the vast potential. Lighting was the first useful application to which electricity was used and the discovery of the light bulb by Thomas Edison marked the beginning of a new era and industrial revolution. Gas lighting was soon replaced and many of the jobs and task which had taken hundreds of people to carry out could be done more effectively and accurately using machines.

There is no doubt that life during the last century has been transformed by electricity and more especially in the last forty years by electronics. It is almost impossible to think of all the ways electricity affects our lives without leaving something out.

In our homes there is: electric lights, heating systems, food mixers, electric shower, washing machines, tumble dryer, television, PC etc

Methods of communicating have progressed rapidly in the last fifteen years, with the advent of an affordable mobile phone. We also have the internet which means world events or conflicts can be transmitted to our screens in seconds of their happening. Medical records, tax files and a host of similar information can be sent around the world in seconds. Biometric eye scanners may ensure more accurate identification of people for all sorts of purposes. Video conferencing allows a multidisciplinary team of surgeons to advise and comment on a complex operational procedure.

Transport in the future may rely heavily on low pollutant electrical transportation. GPS systems linked to post codes will come as standard in vehicles in the future.

Many products are designed on computer and manufactured with minimal human intervention on a world wide basis. It is worth noting that many of the above inventions have been a spin-off from wars or space travel. Radio communication was perfected so that generals could talk to soldiers on the front line and hence the mobile phone was born. Military aircraft perfected microwaves. Which five inventions do you think have made most impact on our lives over the last fifty years?

## Basic Concepts: Current, Voltage and Resistance

Consider the model shown below. You may wonder what the connection between this model and an electric circuit is. An understanding of the operation of this model will lead to a good understanding of the three parameters associated with an electric circuit.


As can be seen from the drawing opposite, no water flows around the system. The reason for this is simple - for water to flow in a system it must be forced to do so, this is usually achieved by a pump. In this example the pump does not rotate and hence no water flows.

A comparison is the circuit shown opposite. The bulb will not light as there is no power supply or battery connected. The battery therefore carries out the same function as the pump in the water circuit. The pumps forces the water around through the pipes, the battery forces the electricity through the wires and bulb. The battery can be thought of as applying the electrical pressure needed to make tiny charges called electrons flow in the circuit. This electrical pressure is referred to as VOLTAGE.


If the pump is switched on it begins to rotate and the water is forced around the system. The flow of electrons in an electrical circuit is called CURRENT.

An analogy can be useful but we must be careful how we make use of it. If we consider the above system containing water there is not a problem, this is not so however in the case of an electric circuit. If we assume the battery to be the pump and the pipe to be wires then we have a problem. We can not simply connect wires from one side of a battery to another with no components in between. What
 would happen if we connected one end of a battery to the other?

To work effectively components must insert into the circuit which reduce the current. As we can see from the diagram there is a restriction in the pipe after the pump. This restriction means that the flow of water is reduced. In electrical circuits components are inserted which act as RESISTORS to the flow of current. These components may be resistors which are used with LEDs to reduce current but equally motors and bulbs offer resistance to the flow of electrical current in a circuit.


What is the effect of increasing the pressure on the system by making the pump turn faster?
What would happen to the current if we increased the voltage in a circuit?
What is the effect of the restriction been made narrower or wider?
What would happen if we increase the size of the resistor in a circuit?

Ohm's Law (Relationship between Volts, Current and Resistance)
If the pump was made to run faster the pressure on the water would increase and more water would flow around the pipe, similarly if the restriction is made narrower then less water would flow around the pipe. So there is a relationship between the water pressure, size of restriction and the amount of water flowing around the pipe. This model equates very closely to the electrical circuit shown below.

This time instead of a water pressure an electrical pressure (measured in VOLTS) is produced at point A (electric pressure produced by the battery). This has the effect of causing an electrical current (measured in AMPERES, amps for short) to flow around the circuit. Remember there must be some electrical components in the circuit. In this case we have included a resistor (resistance measured in OHMS). The current flows out of the battery from the positive terminal around the circuit, through the 3 ohm resistor and back into the battery.


2 Amps

## Symbols

Voltage - Electrical pressure caused by the battery is measured in VOLTS - V
Current - flow of electricity is measured in AMPS - I
Resistance - opposition to current flow is measured in OHMS $-\Omega$
Points to remember:
Voltage at point A (termed VA) in this case equals 6 Volts
Voltage at point B (termed VB) is ZERO volts
Current always flows out of the positive terminal of the battery around the circuit and back to the negative terminal. Current flowing back into the battery must always equal the current flowing out of it.

## Applying Ohm's Law

When given any of the two values associated with an electrical circuit it is possible to calculate the third value using the OHM'S LAW TRIANGLE.


$$
\begin{aligned}
& V=I \times R \\
& I=\frac{V}{R} \\
& R=\frac{V}{I}
\end{aligned}
$$

## Example 1

In the circuit shown determine the current flowing in the circuit?


With reference to the Ohm's Law triangle, if the unknown value to be calculated is covered by the thumb then the required formula is obtained.

$$
I=\frac{V}{R}=\frac{12}{4}=3 \mathrm{amps}
$$

## Example 2

In the circuit shown below a 12 volt battery is connected to an unknown resistor, the ammeter records a current of 2 amps flowing around the circuit. Calculate the value of the resistance.

From the OHM'S LAW $R=\frac{V}{I}=\frac{12}{2}=6 \Omega$


Use a suitable electronic software package and include an ammeter (placed the correct way round) in your circuit to verify your answer.

## Example 3

A battery of unknown voltage is connected to a 3 ohm resistor and it was found that a current of 4 amps was flowing through the ammeter. Calculate the voltage of the unknown battery. Use an appropriate software package to verify answer.

From the OHM'S LAW

$$
V=I \times R=4 \times 3=12 \mathrm{~V}
$$

## Exercise

Design and build each circuit using a suitable electronics software package and verify your result.

1. A 24 volt battery is connected in series to a $3 \Omega$ resistor. Calculate the current flowing in the circuit
2. A 36 V battery is connected to an unknown value of resistor. It was found the current flowing through the circuit was 4 amps . Calculate the size of the resistor.
3. Calculate the value of the battery voltage required to cause a current of 5 amps to flow through an $8 \Omega$ resistor.
4. In a simple circuit containing a battery and a resistor in series, a current of 0.5 amps is flowing through a $20 \Omega$ resistor. Calculate the battery voltage.
5. Calculate the value of the battery voltage required to cause a current of 500 milliamps to flow through a $10 \Omega$ resistor.

## Summary

- There is a relationship between voltage, ohms and current which is summed by Ohms Law.
- If the resistance is large then less current flows and vice versa.
- The larger voltage causes more current to flow in the circuit.


## Calculating the Resistor Value for use with an LED



Most of the electronic circuits you will use at school will make use of an LED and it is therefore important to know how to calculate the value of a resistor if required and the correct way to install it in a circuit as electricity will only flow through the LED in one direction.

The following information about LEDs is often included in catalogues:

$$
\begin{array}{ll}
\text { Vf }=2 \text { volts } & \text { (Vf refers to the Forward Voltage) } \\
\text { If }=20 \mathrm{~mA} & \text { (If refers to the Forward Current) }
\end{array}
$$

Vf refers to the fact that when electricity flows through an LED when it is forward biased in a circuit, a voltage of approximately 2 volts is required across the LED. Therefore the voltage used in the calculation must be reduced by 7 volts.

If (Forward Current) means that the maximum current the LED is permitted to carry is 20 mA . Note that in all calculations mA must be changed to amps (mA /1000)

To calculate the resistor value to use with a 9 volt supply -

$$
R=\frac{\text { Voltage }-V f}{I f}=\frac{9-2}{0.02}=\frac{7}{0.02}=350 \Omega
$$

Why would a $390 \Omega$ resistor be used instead of a $330 \Omega$ resistor?

## Exercise

If LEDs are to be linked to power supplies the current that the LED can carry and the voltage to which it will be connected must be considered. Calculate the resistor values if an LED capable of carrying 20 mA is to be used with the following voltages assuming that Vf is 1.5 V in each case:

1. 6 volts
2. 12 volts
3. 5 volts

## Resistors

Resistors are used to control the flow of electricity in a circuit. Resistors are cheap and easy to use. Printed on each resistor is its own fixed resistance. This resistance is shown by a colour code. Resistance is measured in ohms, the symbol for which $\Omega$ is the symbol.

Look at the resistor shown below. Note that it has four colours. We can ignore the last colour, silver or gold, as this is simply to tell us how accurate the resistor is. The other three colours are used to find the value of the resistor. In the diagram below the resistor measures $330 \Omega$.

The following table is used to calculate resistor values.

| Colour | First Band | Second Band | Third Band |
| :--- | :--- | :--- | :--- |
| Black | 0 | 0 | - |
| Brown | 1 | 1 | 0 |
| Red | 2 | 2 | 00 |
| Orange | 3 | 3 | 000 |
| Yellow | 4 | 4 | 0000 |
| Green | 5 | 5 | 00000 |
| Blue | 6 | 6 | 000000 |
| Violet | 7 | 7 | 0000000 |
| Grey | 8 | 8 | 00000000 |
| White | 9 | 9 | 000000000 |

To calculate resistance:

First band (furthest away from gold band) $=$ orange $=3$
Second band $=$ orange $=3$
Third band = brown (brown $=1$, this tells you to add 1 zero)
By combining the three numbers we get $330 \Omega$.
Remember that all resistors have three colours to indicate their value. Can you see that a resistor which is coloured brown green black has a value of $15 \Omega$ ?

## Exercise

1. Complete the value of resistors with the following colour bands.

| 1st band | 2nd band | 3rd band | Resistance in $\Omega$ |
| :--- | :--- | :--- | :--- |
| red | red | brown |  |
| orange | orange | green |  |
| yellow | violet | orange |  |
| blue | grey | orange |  |
| brown | black | brown |  |
| orange | white | orange |  |
| brown | green | red |  |

2. Shade the resistors below and label them using the information in the table above.


## POWER

In the study of electricity the word power has a specific meaning, usually to do some form of work. Examples include:

- to move something
- to generate heat
- to produce sound
- to produce light

Power may be defined as the rate at which energy is converted into work and it is measured in watts, symbol W. Large electric motors are sometimes rated in horsepower in the same way that car engines are. One horsepower $=746$ watts.
There are three formulae which can be used to calculate power in an electrical circuit.

## Formula 1

$\mathrm{P}=\mathrm{Ix} \mathrm{V}$ Watts. Where I is the current flowing through an electrical component and V is the voltage across it.
(a) Calculate the power developed by the bulb if a current of 4 amps is flowing in the circuit.


Voltage across bulb $=\mathrm{V}=12$ volts Power $=I \times V=4 \times 12=48$ watts

## Formula 2

$\mathrm{P}=\mathrm{I}^{2} \times \mathrm{R}$ where I is the current flowing through a component and R is the resistance of the component.
(b) Find the power developed by the motor if the current flowing in the circuit is 3 amps and the resistance of the motor is 4 ohms?


## Formula 3

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

Where V is the voltage across the component and R is the effective resistance.
(c) Find the power developed by the motor in the circuit shown below.


$$
P=\frac{V^{2}}{R}=\frac{6 x 6}{9}=4 w a t t s
$$

## Exercise

1. A lamp is connected to a 10 volt supply and is drawing a current of 3 amps . Calculate the power developed by the lamp.
2. A lamp connected to a supply is drawing a current of 6 amps . If the resistance of the lamp is 2 ohms calculate the wattage of the lamp.
3. A motor of resistance $5 \Omega$ is connected to a 20 volt battery. Calculate the power output of the motor.
4. An 8 volt power supply is supplying a current of 250 mA to a relay. Calculate the power dissipated in the relay.
5. The current and resistance is known in a circuit. What formula can be used to determine the power dissipated in the resistor.
6. A resistor has 20 V dropped across it and 2 amps of current flowing through it. What power is dissipated in the resistor.
7. A circuit has 120 V applied to a motor that has $10 \Omega$ of resistance. How much power is developed by the motor?

## Power Dissipation

All components have resistance so when a current flows through them power is dissipated in most cases in the form of heat. It is something to be aware of in the selection of components to be used in a circuit that the power ratings are not exceeded, examples are bulbs and resistors.

## Example 1

Find the power dissipated by the bulb (Resistance of bulb $=100 \mathrm{ohms}$ )


To find the power dissipated in the bulb which has a resistance of $100 \Omega$.

If the formula Power = I x V watts is to be used the following data must be known: current flowing through the bulb and voltage across the bulb.


As the 200 ohm resistor and the lamp are in series then

$$
R_{t}=200+100=300 \Omega
$$

So now having one voltage and one resistance the current flowing in the circuit can be calculated:

$$
I=\frac{V}{R_{t}}=\frac{9}{300}=0.03 \mathrm{Amps}
$$

The voltage across the bulb can be found:

$$
\begin{aligned}
& \mathrm{V}(\text { bulb })=\mathrm{I} \times \mathrm{R} \text { where } \mathrm{R}=\text { the resistance bulb and } \mathrm{I} \text { is the current } \\
& \mathrm{Vd}=0.03 \times 100=3 \text { volts }
\end{aligned}
$$

We now have values for both the current through the bulb and the voltage across it.

$$
\mathrm{P}=\mathrm{I} \times \mathrm{V}=0.03 \times 3=0.09 \mathrm{~W} \text { or } 90 \mathrm{~mW} .
$$

The power could also be calculated using the formula

$$
\text { Power }=\frac{V^{2}}{R}=\frac{9}{100}=0.09 \mathrm{Watts}
$$

## Example 2

In the circuit shown calculate the power dissipated in the $3 \Omega$ resistor.


The first step is to find the total resistance of the circuit.

R2 and R3 are in parallel and this parallel arrangement is in series with R1

To calculate the parallel pair R2 || R3 (let equivalent resistance $=\mathrm{Rv}$ )

$$
\mathrm{Rv}=\frac{\mathrm{R} 2 \times \mathrm{R} 3}{\mathrm{R} 2+\mathrm{R} 3}=\frac{6 \times 3}{6+3}=\frac{18}{9}=2 \Omega
$$



Circuit now reads R1 and R2 in series.
Rtotal $=\mathrm{R} 1+\mathrm{Rv}=4+2=6 \Omega$


From having one voltage and one resistance the current flowing in the circuit can be found:

$$
\mathrm{I}=\frac{\mathrm{V}}{\mathrm{R}_{\text {total }}}=\frac{18}{6}=3 \mathrm{Amps}
$$

Knowing there is 3 Amps flowing in the circuit we can now calculate the voltage across the two resistors in parallel. Remember that their effective resistance is 2 ohms.

Voltage across parallel block: I x Rv $=2 \times 3=6$ volts


Voltage $=6 \mathrm{~V}$
Resistance $=3$ ohms
Power dissipated by the resistor.

Power $=\frac{\mathrm{V}^{2}}{R}=\frac{6 x 6}{3}=12 \mathrm{Watts}$

## Exercises

(a) In the circuit shown opposite the motor has an internal resistance of $10 \Omega$. Find the power developed by the motor.

(b) Calculate the power dissipated in the 12 ohm resistor.

(c) The bulb shown has a filament resistance of 12 ohms. Calculate the output power of the bulb.

(d) In the circuit below all bulbs have a resistance of 10 ohms find the output power of B3.


## Measurement of Current, Voltage \& Resistance

## To measure Resistance



Important - Either turn off the switch or remove the battery from the circuit before attempting to read resistance.

Arrange the multimeter as shown to measure ohms. Check the units, sometimes the answer will be displayed as $\mathrm{k} \Omega$, in other words the meter will read $.330 \mathrm{k} \Omega$. This differs across various meter manufacturers.

## To Measure Voltage



Arrange the multimeter as shown and measure the voltage value, in this case 9V. You can determine the range by turning the dial to select a different value.

Note the voltage is always measured across a component.

## To Measure Current



Care must be taken when measuring current otherwise the meter will be damaged. With the meter set to measure up to 200 mA it can be seen that the current passing through the bulb is 60 mA . Note that the multimeter has to be placed in series in the circuit itself in order to take a reading.

## VOLTAGE DC - AC

Direct current and voltage, i.e. the voltage is at a constant value and it causes a current to flow around the circuit in one direction only. Consider the simple circuit below.


The voltage causes a current to flow out of the positive terminal of the battery along the top rail from left to right, through the 1 Kohm resistor and hence back into the battery.

A voltmeter has been connected across the resistor to verify the battery voltage (in this case 9 volts)

A better method to depict the voltage plotted against time is to employ an oscilloscope which is included as standard in many software simulation packages. The diagram below depicts the circuit operating from a volt supply over a period of six seconds.

Note the trace produced by the oscilloscopes is a steady DC voltage.

DC voltage $=+9$ volts.


Let us now connect an AC source to the 1 k resistor and trace the voltage as before.


The voltage trace is completely different than before. AC or alternating current as the name suggests flows in one direction and then in the other as shown by the trace on the oscilloscope. We can see that the waveform flows from an initial value of 0 V to a maximum value of 9 V after half a second. The voltage value then drops to 0 V after a time of one second before reaching another maximum of 9 V (time = one and a half secs). Note that one complete cycle takes exactly two seconds.

Negative voltage can sometimes seem very confusing while really it is not. Just remember that in the minus part of the graph the current continues to flow only this time in the opposite direction.

In most cases many cycles of the waveform occur in one second and the number of cycles which occur per second is known as the FREQUENCY - Symbol (f) Frequency measured in HERTZ - (Hz).


There are five cycles occurring in one second and hence :- Frequency $f=5 \mathrm{~Hz}$
Relationship between frequency and period (time):-
(a) $\mathrm{f}=\frac{1}{\mathrm{~T}} \mathrm{~Hz}$

Where T is the PERIOD (i.e. time taken to complete one waveform)

## OR

(b) $\mathrm{T}=\frac{1}{\mathrm{f}} \mathrm{Sec}$

## Examples

1. A waveform has a frequency of 5 Hz , calculate the period of the waveform.

$$
\mathrm{T}=\frac{1}{\mathrm{f}}=\frac{1}{5}=0.2 \mathrm{sec}
$$

(This means 1 waveform will be traced every 0.2 seconds)
2. If the period of an AC waveform is 5 milli-seconds, find the frequency.

5 milli-seconds $=0.05$ seconds
$f=\frac{1}{T}=\frac{1}{0.05}=20$

## Exercise

1. Given the following frequencies, calculate the period of the waveform.
(a) $\mathrm{f}=100 \mathrm{~Hz}$
(b) $\mathrm{f}=5 \mathrm{~Hz}$
(c) $\mathrm{f}=20 \mathrm{~Hz}$
(d) $\mathrm{f}=100 \mathrm{~Hz}$
(e) $\mathrm{f}=1 \mathrm{~Hz}$
2. Given the following periods of each cycle calculate the frequency of the waveforms
(a) $\mathrm{T}=0.05$ seconds
(b) $\mathrm{T}=2$ seconds
(c) $\mathrm{T}=25$ milliseconds
(d) $\mathrm{T}=125$ milliseconds
(e) $\mathrm{T}=5$ milliseconds

## Transistor Operation

The transistor can be used in two modes:

- As an switch
- As an amplifier

Let us first consider the transistor as an electronic switch.


With the switch in the open position no current can flow around the circuit, the lamp is unlit.


With the switch is closed current can now flow around the circuit and the lamp is now lit.

A transistor can best be described as an electronic switch and performs the same operation as the mechanical switch in the above circuit. The transistor is controlled by applying a voltage to the base.

With less than 0.7 V on the base the transistor is switched off, no current can flow through from the collector to the emitter.

With more than 0.7 V applied to the base, the transistor is switched on and current can now flow easily from the collector to emitter.

The most common way to bias a transistor is to set up a potential divider arrangement. A typical arrangement is the variable resistor circuit shown below. The potential divider is explained in detail elsewhere but the principle of the circuit is that the junction between the1K fixed resistor and the 1 K variable will vary above and below 0.7 V .

As arranged the required voltage is exceeded switching on the transistor and hence the bulb will light


If the variable resistor is adjusted in the bottom half of the circuit we can see that the resistance is now just 50 ohms. Remember that 1 K ohm is 1000 ohms so the voltage should be approximately $1 / 20$ th the available voltage. In this case the 0.428 V is less than 0.7 and so the transistor is not switched and the bulb is unlit.


The inclusion of the 2.2 K resistor is very important. If we consider the circuit below then the base has been connected to the top rail which is in fact a 9 V supply rail via a resistor known as the BASE RESISTOR.

It is important to insert this resistor because if the base was connected directly to the top rail which is at 9 V the transistor would be damaged. (Assemble the circuit using appropriate soft ware, connect the base directly to the top rail, switch on and see result)

The base resistor is known as a voltage dropper resistor as the transistor will ensure a voltage of around 0.7 V or slightly larger will appear on the base. If we consider from the previous circuit the voltage dropped by the base resistor is approximately 8.2 V the then the voltage at the base of the transistor is around 0.8 V , this is acceptable. Please note that this resistor is necessary in all transistor circuits otherwise overheating will occur and the transistor becomes damaged.


## Transistor as a Current Amplifier

The circuit below is a simple yet effective method of demonstrating the gain of a transistor. Two ammeters have been included in the circuit, one to measure base current (IB) and the other to measure collector current (IC).

Note that one ammeter is reading in mA while the other is reading in $\mu \mathrm{A}$. Change all readings to mA :

$$
\begin{aligned}
& \mathrm{IB}=630.34 \mu=0.630 \mathrm{~mA} \\
& \mathrm{IC}=88.22 \mathrm{~mA}
\end{aligned}
$$



The current gain of a transistor is an important property of any transistor and is defined by:

$$
\begin{aligned}
& \text { hFE }(\text { gain })=\text { IC/IB } \\
& =88.22 / 0.630 \\
& =146.6 \approx 150
\end{aligned}
$$

Hence the gain of this particular transistor is around 150 and is typically between 80 and 500 depending on the type of transistor. Two important considerations therefore when selecting a transistor are:
(a) What current must it pass from collector to emitter? A bulb has a current rating of $60-100 \mathrm{~mA}$, a solenoid generally over 100 mA and a motor generally between $100-500 \mathrm{~mA}$ depending on the type used.
(b) What should the gain for the transistor be? If we expect a small base current then the transistor will need to have a high gain to allow it to switch a device that requires any amount of current.

All this information is include on datasheets which can generally be found in PDF format on a supplier's website.

## To verify the switch on voltage for a transistor



This is a very useful circuit which illustrates clearly the turn on voltage for a transistor.

- Arrange the circuit as above with a 1 K resistor and either a 1 K or 10 K potentiometer in the bottom position.
- Ensure SW2 is in the ON position.
- Adjust the potentiometer so that the red LED is unlit.
- Slowly adjust the potentiometer so that the LED comes on, measure the voltage across the potentiometer, you should find this happens at around $0.6 \mathrm{~V} / 0.7 \mathrm{~V}$.


## The Potential Divider

The potential divider forms the basis of many electronic circuits and allows us to use a variety of sensors such as LDRs (light), thermistors (heat) and moisture probes etc. The process can be thought of as three distinctive parts or blocks. Let us take as an example a situation whereby an alarm sounds if an LDR is placed in dark conditions. The problem could be considered as shown below.


The central part of this block is the process which determines whether the buzzer will sound or not, this is the function of the transistor.

If there are dark conditions then the buzzer will sound otherwise it is silent.

The device which is used to determine the presence or absence of light is called an LDR and it is connected to the base of a transistor as shown by the diagram opposite.

The transistor determines if the voltage at the base is greater or less than 0.7 V and as a result switches on or off the LED.

To study the principal of the potential divider build the following circuit placing a $1 \mathrm{k} \Omega$ resistor in the positions RES1 and RES 2 as shown.


Follow these instructions carefully:

- Place two resistors $1 \mathrm{k} \Omega$ in the positions RES (1) and RES (2).
- Record the values of the resistors in the table below.
- Using the multimeter adjusted to 20V DC measure the voltage across each resistor and record the value in the table below.
- Change the value of the resistors in positions RES (1) and RES (2) and record the values as before until table is complete.

| RES1 | Voltage 1 | RES2 | Voltage 2 | Total (Voltage 1 + Voltage 2) |
| :--- | :--- | :--- | :--- | :--- |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |

## Explanation

The important point to consider in this instance is the voltage value across RES (2). From the circuit board it is possible to see that RES (2) is connected to the base of the transistor. It is also clear that the bigger resistor always has the bigger voltage across it and that the value of the voltage over both resistors is always equal to the total input voltage.

Note that if the voltage over RES (2) is greater than 0.7 volts then the LED is on, otherwise it is off. This may be best considered by looking at the diagram below.


Let us consider a boy (resistor) standing on a pipe through which water is flowing. The effect of the resistor in a circuit is obvious in that it will slow down and restrict the current, allowing only a small current to flow.

At the same time as slowing the flow of water through the pipe it is noticed there is a bulge caused on the pipe. This bulge is caused by the build up of pressure that is necessary to force the water past the boy's foot. The measurement of electrical pressure in a circuit is call voltage.

## The key rule that must be understood is that if there is a big resistance then there is a corresponding big voltage.

No matter how complex a circuit may be it will consist of one or several potential dividers. Always recognise the potential divider in a circuit.

## LDR circuits

Various sensors can be used in a potential divider circuit to switch alarms and light indicators such as LEDs. The following exercises should help remove the mystery. Set up the components as shown in the diagram. Make sure that the ON-OFF switch is set to on.


A transistor can be thought of as a switch which is either turned off or on depending on whether the voltage level applied to its base is greater or less than 0.7 volts.

Allow a lot of light to fall on the $\operatorname{LDR}(\operatorname{RES} 1=15 \mathrm{k} \Omega)$. The LED is unlit and the voltage across the LDR is less than 0.7 V , just as expected. Ask your partner to slowly bring his/her hand close to and eventually cover the LDR. Notice how the voltage increases across the LDR. At a certain stage it will trigger the transistor and switch the LED on. What is happening is that the LDR is made from a substance called cadmium sulphate whose resistance increases in darkness. From the previous exercises (boy on the pipe) we noted that as resistance gets bigger so does voltage, switching the transistor when it reaches 0.7 volts.


The graph shows how an LDR responds when a hand is placed on or near it as shown by the circuit diagram below. At the start and up to five seconds there is a lot of light shining on the LDR. For this reason therefore the resistance of the LDR is low and hence the voltage across it. The horizontal line represents 0.7 volts and we can see that at the start the voltage is below this level and the transistor is off. At or about five seconds a hand covers the LDR and as we can see the voltage rises significantly, to about 2 volts and this in turn brings on the transistor.


LED comes on to indicate darkness

## Exercise

1. Why does the voltage rise?
2. Can you work out what happens over the 30 second period?
3. In the previous exercise we saw that the LED came on in darkness. By placing the LDR in position RES (1) the opposite effect may be achieved. It is recommended that the value of the resistor placed in position $\operatorname{RES}(2)$ be decreased to $4 \mathrm{k} 7 \Omega(4 \mathrm{k} 7$ is simply another way of saying $4700 \Omega$ ). It is sometimes a good idea to use a variable resistor for this purpose as it can be adjusted to suit different light levels. Build the circuit and place the components in the appropriate positions and see how the circuit operates. Draw a diagram of the above circuit in your exercise book and explain how it works.

## The Moisture Probe

Turn the ON-OFF switch to the off position. Build the circuit as shown below and measure the voltage across RES (1) and RES (2). Since there is a gap at the top containing air, which has extremely high resistance, there is a high voltage across RES (1) and zero level across RES (2). If we turn the ON-OFF switch to the on position the LED will not light - (less than 0.7 volts). Turn the switch to its previous off position.


Dip the terminals into water and measure the voltage values again. This time the voltage across RES (1) has fallen because water has much less resistance and this means a voltage increase over RES (2) occurs. Turn the switch to the on position and the LED comes on as expected as the voltage at the base of the transistor now exceeds 0.7 volts.

The moisture probe circuit. The LED indicates damp conditions.


## Resistors and Cells in Series \& Parallel

## Combination of Series and Parallel Resistors.

Consider the circuit shown below


The circuit consists of a parallel combination of resistors (R2 \& R3) which are connected in series to R1.

Let the equivalent resistance of R2 in parallel with R3 $=\mathrm{R} 4$

$$
R 4=\frac{R 2 x R 3}{R 2 x R 3}=\frac{4 x 4}{4 x 4}=2 \Omega
$$

(the above formula used above can be used to calculate the equivalent resistance of two resistors in parallel)

It is always a good idea in electronics to redraw the circuit after making a calculation. Circuit now reads.


There is now in effect two resistors in series the total resistance in the circuit is:

$$
R_{\text {Total }}=R 1+R 4=3+2=5 \Omega
$$



To find the value of three resistors in parallel.


The diagram above depicts three resistors in parallel
The formula below can be used to calculate the total resistance of the circuit

$$
\frac{1}{R_{\text {Total }}}=\frac{1}{R 1}+\frac{1}{R 2}+\frac{1}{R 3}
$$

The total resistance is:

$$
\begin{aligned}
& \frac{1}{R_{\text {Total }}}=\frac{1}{3}+\frac{1}{6}+\frac{1}{2} \\
& \frac{1}{R_{\text {Total }}}=\frac{6+3+9}{18}=\frac{18}{18} \\
& \frac{1}{R_{\text {Total }}}=1 \Omega \\
& R_{\text {Total }}=1 \Omega
\end{aligned}
$$

Thus the three resistors in parallel can be represented by a single resistor of $1 \Omega$. The above formula is quite suitable to calculate resistors of small values but with larger values it becomes difficult to find a common denominator. In the real world of electronics it is rare to see three resistors in parallel but quite often we do find two.

## Exercise

Find the total resistances of the circuit shown below
1.

2.

3.


## Cells in Series and Parallel

The cell mostly used in electronic circuits is called the LECLANCHE CELL. It produces an output voltage of 1.5 VOLTS and produces a finite amount of current. A number of these cells can be suitably interconnected (series case positive and negative connections fitted alternatively) to produce a much higher output voltage. The voltage of cells of any value or batteries of any voltage may be connected together in series to give a required output voltage.

## Cells in Series

When the cells are placed in series with respect to polarity the voltage can be increased incrementally. Consider the circuit opposite:-

Output voltage $=1.5+1.5+1.5+1.5=6$ Volts


## Cells in Parallel

Cells must be of the same voltage to operate correctly. When two identical cells are placed in parallel the current capacity of the arrangement is doubled.

Connections are as follows, positive terminals connected together, negative terminals connected together. Note the output voltage remains the same as the output voltage from a single battery but the current available to flow in the circuit has in fact doubled.


## Exercise

(The cells used produce a voltage of 1.5 V and can deliver a current of 1 AMP)

1. Design a voltage source, output voltage 9 V and capable of providing a current of 1 AMP
2. Design a power supply capable of outputting 3 V and capable of driving a motor which draws 2A
3. A torch is designed to hold 3 cells in series, what is the voltage of the bulb?
4. Provide a power supply unit to output a voltage of 12 V and provide a current of 3 AMPS

## Circuit Testing

There is nothing more disconcerting than having assembled a circuit and connected the battery to find the circuit does not work. First step is to carry out a visual check of the circuit and look for the following points:-

- Is the battery connected and is it the right way round?
- Is the circuit the same as the circuit diagram i.e. no components left out?
- Is there an obvious break anywhere in the wiring system?
- Do all solder joint look good i.e. bright and shiny?
- No excess solder shorting two tracks?
- Check colour coding of all resistor values?
- Are the transistors in the correct way and is the right type used?
- Are the diodes and LEDS fitted correctly (regarding polarity)?
- Are the capacitors fitted correctly?
- Has the battery sufficient power to drive the circuit?

If the ten points above have been checked out and no visible fault found then testing of the circuit must be carried out. The biggest percentage of testing is carried out using the voltmeter. Very rarely is an ammeter used in testing as it means the circuit has to be broken and the leads of the ammeter connected into the circuit. The following series of tests might be used to find out why a transistor circuit is faulty.

## Step 1

Using a multimeter set to read voltage (dc), we take a reading across the battery. This should be very close to 9 V.If it is not there are two distinct possibilities. Either the battery is no longer serviceable or it has been soldered incorrectly into the circuit. If the voltage reads 0 V then take the battery out of the circuit and test the battery voltage. Replace if necessary.


## Step 2

Assuming Step 1 is tested and found to be correct then we move onto this step. Close the switch and measure the voltage as shown. We would except to find a voltage of 9 V . If we do then we know that the switch and the copper track which forms the top rail are correct. If this is not the case then check the switch.


## Step 3

The potential divider consists of a 47 K resistor and a thermistor. By changing the temperature of the thermistor then the reading on the voltmeter should change accordingly. It should vary from about 0.5 V to just over 1 V . As the voltage increases to a value greater than 0.7 , this should trigger the transistor and LED should light. Note that the voltmeter measures the voltage at the mid point of the potential divider and it is this junction which feeds through to the base of the transistor.


## Step 4

A simple piece of wire can be very effective at testing some components in a circuit. With the piece of wire in the position as shown then the LED should light, irrespective what is happening in the rest of the circuit. If not then there is a problem with the LED or resistor. Remember the wire is only a temporary connection and should be removed as soon as possible.


## Step 5

If all the other tests have been carried out then use a link of wire to make a connection as shown. With this link in place the LED should light, especially if Step 4 has been carried out. If the LED does not light then the transistor is probably faulty. Remove the wire as quickly as possible.


Note that this is a fairly extensive test on this circuit. Electronics is a fairly exact science and if we follow a particular sequence of tests we will find the problem with many of our circuits. It is also good practice not to solder a full circuit but to build one section and test it thoroughly before moving on. This is especially true if the circuit is complex,

## Input Devices

## Switches



Switches are probably the most common input devices used in many circuits. They may perform a very simple function such as push-to-make or motor reversal which requires the use of a double pole double throw arrangement.

Electronic circuits are designed to carry out a particular function, for example to automatically switch on street lighting when it becomes dark. Circuits can be designed to detect changes in ambient conditions, process the signal and switch on an output device in reaction to the input conditions. In a refrigeration system a detector may pick up the condition of an increase in temperature and switch on a fan to counteract the increase of temperature and maintain a steady temperature.

## Types of sensors

(a) Simple alarm circuit


The circuit illustrates the principle of an alarm circuit. The reed switch which is controlled by a magnet, i.e. when magnet is close to the reed switch then the switch is closed and when the magnet is removed from the reed switch the switch is "broken" i.e. we have an open circuit.

With the switch in the closed position (B) the voltage on the base of the transistor is 0 V , the transistor is switched off and the buzzer is in quiescent state. When the magnet is moved to position A the switch will open. Voltage on the base of the transistor is now greater than 0.7 V , the transistor is switched on and the buzzer is now in an active state.
(Note some buzzers contain a coil of wire which generates very high voltage when a rapid change of current occurs, it is therefore good policy to fit a diode as shown across the buzzer to prevent damage to the transistor)
(b) The light dependent resistor (LDR)

As the name suggests this device changes its resistance according to the amount of light falling on it. In bright sunlight it has a resistance of about $100 \Omega$. In total darkness its resistance is more than $1 \mathrm{M} \Omega$. The main disadvantage is that their response time is low. An LDR takes about 75 milliseconds to respond to a fall in light intensity and may take many hundreds of milliseconds to respond to a rise in light level.

Remember the resistance value is not linear with change in light conditions, in other words if we know the resistance at say 100 lux we cannot assume that at 200 lux the resistance will be halved. In fact if we plot a graph of light $v$ resistance we find it is similar in shape to a capacitor discharging, it is logarithmic.


This circuit illustrates the action of an LDR in a simple transistor switching circuit. The LDR and the $47 \mathrm{~K} \Omega$ resistor form a voltage divider circuit.

With the LDR in bright conditions (Resistance $=$ $400 \Omega$ ), the voltage on the base of the transistor is 75 mV which is not sufficient to switch on the transistor so the bulb is switched off.

Note the voltmeter is simply put in the circuit to record the voltage at the junction of the voltage divider circuit and take care when deciding if the units are V or mV .


The circuit opposite illustrates the circuit operating in dark conditions. Notice the resistance of the LDR has now been increased to over $300 \mathrm{~K} \Omega$.

Correspondingly the voltage at the junction of the voltage divider circuit has risen to 0.9 V . As this is greater than the 0.7 V required to switch the on the transistor, the bulb is lit.

## (c) Moisture Sensor

For best results probes should be in the region of 50 mm in length, 6 mm in diameter and not more than 3 mm apart when used to check the moisture content in soil or similar. When used to monitor wet external conditions the above mentioned probes can be placed on a piece of blotting paper.

Resistance under wet conditions is very low in the region of a few ohms, so a sensor is used as a switch to activate a transistor under wet conditions.


Under wet conditions the contacts of the moisture circuit are effectively a short circuit. A base current can flow as the voltage on the base is now 0.7 V . The transistor is now switched on and the bulb is lit.

Under dry conditions the contacts of the moisture sensor are an open circuit with an extremely high resistance across the probes. No voltage appears on the base so the transistor is switched off, and the lamp is now unlit.
(d) Thermistors

Thermistors are devices which react to changes in temperature by
 changing their resistance. There are two types although only one is commonly used.

The most commonly used type is referred to as NTC (negative temperature coefficient) which means that the resistance of the thermistor decreases with an increase in temperature.


The general sequence of operation is shown in the circuit opposite. As the temperature falls the resistance increases and hence increases the voltage to the base of the transistor.

## Output Devices

LEDs, buzzers and motors are all examples of electrical output devices.
Buzzers are commonly used to give an audible warning. Note that while the type shown below is often listed as a 6 V type, it will in fact work from a 9 V supply.


Symbol for a buzzer

Motors are used to cause rotation as in a fan, they convert electrical energy into motion.


Another useful output device is a relay. Relays are essential devices as they allow us to use small voltages to control much larger ones.


If we consider the circuit opposite we can see that the vertical line divides the 5 V supply from the 10 V on the right hand side. The switch is open and contact 1 touches contact 2 . There is a gap in the circuit and hence the bulb is unlit.


If the switch is now closed a magnetic effect causes the pole of the switch to move across and touch contact 3. This creates a complete circuit and the bulb will light.

A 5 V supply is being used to control a 10 V circuit. Equally a 5 V circuit could be used to control a 220 V or even 1000 V circuit, assuming a suitable relay.

## Logic gates

Logic systems are constructed so that all inputs and outputs can only have either one of two states (on/off, high/low) and are termed logic systems or logic circuits. Consider the circuit shown below, the procedure is to operate the switches in all possible configurations and record the output voltages.

## Operation of an AND Gate



A table has been drawn giving output voltages for all possible condition of the switches.

| Switch A | Switch B | OUTPUT (V) |
| :---: | :---: | :---: |
| OPEN | OPEN | 0 V |
| OPEN | CLOSED | 0 V |
| CLOSED | OPEN | 0 V |
| CLOSED | CLOSED | 5 V |

Note that the starting condition is with both switches open and proceeding through all conditions until reaching the condition of both switches being closed. The output condition (measured in volts) is given for each condition. The table is referred to as a truth table and the following statement can now be made:

If switch A AND switch B are closed the output is 5 V otherwise the output is always 0 V .
The circuit above can be called an AND gate as switch A and switch B must both be closed to give an output of 5 V (often referred to as 'high'). This information is often presented in a shorthand format using letters and symbols which are a universally accepted notation.

- Instead of saying switch A and switch B drop the word switch and simply talk in terms of A and B
- When a switch is open the integer 0 is used.
- When the switch is closed the integer 1 is used.
- When the output voltage $=0 \mathrm{~V}$ the integer 0 is used.
- When the output voltage $=5 \mathrm{~V}$ the integer 1 is used.

By applying these rules the truth table can now be redrawn in standard notation. The revisions are shown on the truth table.

| A | B | Output |
| :---: | :---: | :---: |
| 0 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 1 |

Truth table for an AND gate

The expression now reads if A AND B $=1$ then OUTPUT $=1$
If the Output $=1$, the output of the AND gate is 5 volts in this case.

- The Output $=0$ is often termed as the output being LOW
- The Output $=1$ is often termed as the output being HIGH

Symbol for an AND gate
$\begin{array}{ll}A & \square \text { OUTPUT } \\ B & \square\end{array}$

Note that this is a 2 -input AND gate and normally comes in an IC format with four AND gates on a 16 pin IC.

## A practical use of logic gates (AND)

Please note that in some software packages the logic gates only operate correctly at 10 V or ay some other set level.

To start a motor when both the start switch
 has been pressed and the safety guard is in place switch A and switch B must be closed to give a "high" output from the AND gate.

With both switches closed the output from the AND gate will be high (close to 10 V ) and will switch on the transistor and activate the relay. The motor is wired through the relay.

The diode is included to protect the motor from Back EMF generated in the coil of the relay.


The same procedure will be carried out as before, all conditions of the switches will be recorded, with relevant outputs (note if either of the switches are closed an output will be recorded as 'high')

| Switch A | Switch B | OUTPUT (V) |
| :---: | :---: | :---: |
| OPEN | OPEN | 0 V |
| OPEN | CLOSED | 5 V |
| CLOSED | OPEN | 5 V |
| CLOSED | CLOSED | 5 V |

If switch A OR switch B OR both are closed then the output is high or at 5 V .
Using the shorthand notation a new truth table is drawn up as shown be
Truth table for an OR gate.

| A | B | Output |
| :---: | :---: | :---: |
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 1 |

Symbol for OR GATE


If $\mathrm{A} \mathbf{O R B}=1$ then the Output $=1$.

## Practical circuit for an OR gate.



If switch A or switch B or both are closed then the LED will light.

## The NOT gate, sometimes called an Inverter



First it is important to note that a NOT gate only has one input.

If the voltage at A is measured and found to be 10 V then the voltage at B is 0 v . Likewise if the voltage at $\mathrm{A}=0 \mathrm{~V}$ then the voltage at $\mathrm{B}=$ 10 V .

The output is always the opposite of the input, the signal has been inverted.

Truth table for NOT gate

| V IN | V OUT |
| :---: | :---: |
| 0 VOLTS | 10 VOLTS |
| 10 VOLTS | 0 VOLTS |

Again reverting to the shorthand method, as there is only one input (VIN) it will be designated the term A.

Truth table for NOT gate

| A | Output |
| :---: | :---: |
| 0 | 1 |
| 1 | 0 |

Thus when $\mathrm{A}=0$ the output $=1$ and when $\mathrm{A}=1$ the Output $=0$

SYMBOL for NOT gate


