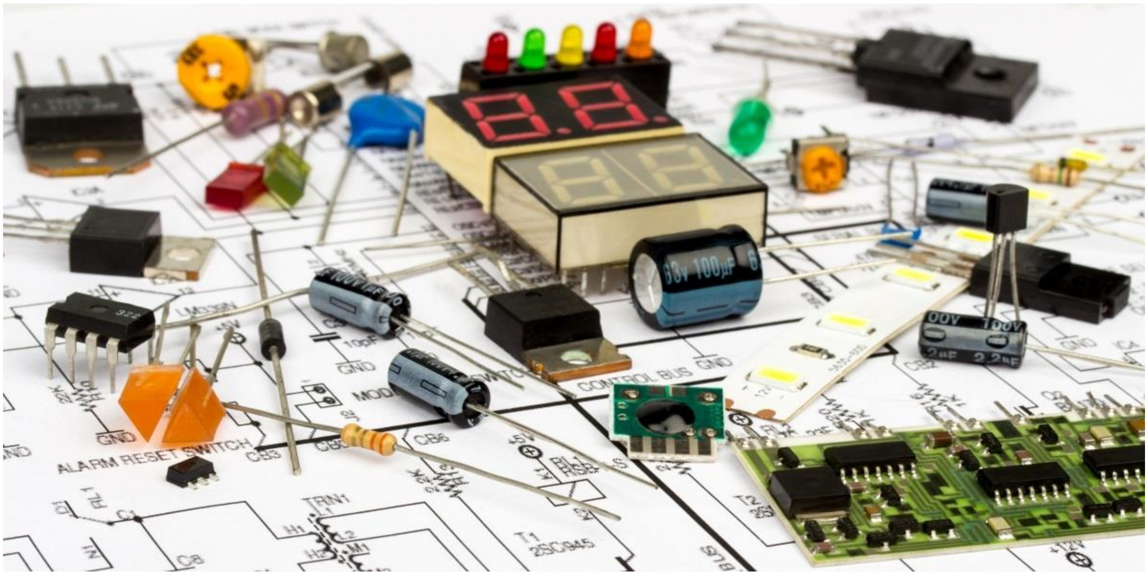
Systems Control in Engineering

Electronic Principles

Candidate Support Booklet



INTRODUCTION

This support booklet is written for candidates preparing for the examination in Systems Control in Engineering (Electronics) and should be used alongside the specification criteria. It is not intended to be a rigorous academic text, but rather that it should provide candidates with a working knowledge of the electronics covered by this subject specification.

In the examinations, candidates will be expected to draw appropriate circuit diagrams and perform calculations using equations. It is essential that candidates are able to identify units of measure for Voltage (Volts), Resistance (Ohms) and Current (Amps) with the additional expectation that values are often required to be converted from Mega (x10 6), Kilo (x10 3), milli (x10 -3), micro (x10 -6) and nano (x 10 -9) in order to multiply them together.

Time is always measured in seconds (s)

Capacitance is measured in Farads, a typical capacitor has a value in micro farads (x10 -6)

Prototyping of circuits can be completed using circuit simulation (Circuit Wizard), Breadboarding and finally a dedicated PCB can be designed and manufactured.

It is essential that candidates have a good knowledge of components and circuits. This includes common Integrated circuits (I.C's) and microcontrollers (PIC /GENIE / ARDUINO).

Programming of microcontrollers can be achieved by using the flowchart method, basic or Arduino depending on the type.

It is important that candidates are able to communicate the correct terminology for electronic components. Fault finding, testing and combining of circuits to achieve a solution are part of the learning and must be seen as times when both success and failure must be seen as part of the learning process. Real world electronic devices are designed and manufactured by teams of highly experienced engineers with considerable budgets that allow for purchasing of electronic components of considerable value. Candidates are expected to be able to learn the principles of systems design so that they can appreciate complex systems and make a prototype of a solution. This does not always have to include specific final components but may substitute componets which represent a stage of the solution.

Mr Hodgson.

CONTENTS

SAFETY

3.1 Electrical Safety

Candidates must be able to work safely and prevent accidents in the laboratory, workshop or home.
Candidates must know what to do if an accident happens.

All practical work with electronic circuits and equipment has the possibility that someone may be hurt or injured. In most cases the Risk (chance of an accident) is very small, but not zero and so it is the responsibility of everyone to ensure that the risks are minimised. Some of the risks are obvious - a hot soldering iron is likely to burn, and mains electricity can cause electrocution. Other risks are less obvious. For example, wire cutters. There is a very small risk of someone cutting their finger with wire cutters, but there is a much larger risk of someone cutting a piece of wire and the cut piece flying into someone's eye and injuring the eye. As a second example, consider a 9V battery. No danger of electrocution from that. But what about a burn? A small value resistor connected across a 9V battery could become as hot as a soldering iron and give a nasty burn to anyone touching it. It is therefore very important to always carry out a Risk Assessment before carrying out any practical work.
To carry out a Risk Assessment you should make a list of the things that could cause an accident and then you should state how you are going to eliminate the Risk.
If the Risk cannot be eliminated then you should aim to minimise the Risk.

A Risk Assessment should also include possible Risks to others working with you since you have a responsibility under the Health and Safety at Work Act (1974) to minimise the Risk to others.
This should also be applied to equipment, for while a multimeter falling from a bench onto the floor may not injure anyone directly, it may injure your pocket if you have to replace it!

Some of the equipment that you use will be mains operated and as part of the Electricity at Work Act (1989) all users are required to carry out a visual inspection of the equipment prior to use, to check for such faults as a broken case, damaged mains cable or damaged plug.
If any such fault is identified the equipment should not be used until it has been repaired.
The Electricity at Work Act (1989) also limits the maximum voltage which students use to 30V, and so you will not be able to use mains electricity within your project or build a high voltage "Stun Gun" even if it is powered by a 9V battery!

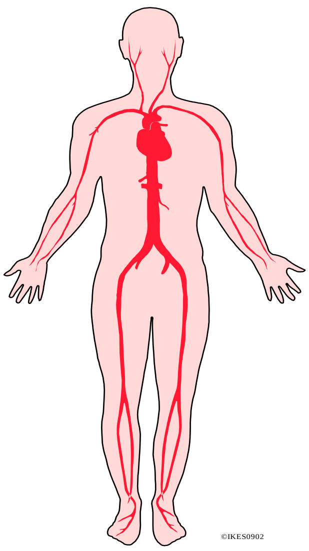
3.1.1 Dangers of Electricity

Candidates should know the effects on the human body of an electric current.

The passage of an electrical current through the body may stun the casualty, cause breathing problems and even stop the heart. The electric current may cause burns both where it enters the body and where it leaves. Alternating current additionally causes muscle spasms that often prevent the casualty from "letting go" of a live electrical cable.

Contact with high voltage cables as used by the electrical supply industry are usually immediately fatal. Severe burns always result, and the sudden muscular spasm produced by the shock may propel the casualty some distance away so causing other injuries such as fractures. High voltage electricity may "jump" a considerable distance in damp conditions.

Even though the domestic electrical supply is at a much lower voltage, it can also cause serious injury and even death. Many injuries result from faulty switches, frayed cables or defects within the appliance itself. Young children are especially at risk.
It is essential to be aware of the hazards of water, which is a surprisingly good conductor of electricity. Handling an otherwise safe appliance with wet hands, or when standing on a wet floor, substantially increases the risk of shock.
The way in which the electrical shock is received will affect considerably the damage caused to the casualty. If there is a passage of current from hand to hand or from hand to foot then the arteries and veins will carry the current through the heart and will probably disrupt the normal operation of the heart. It can also cause the heart to stop completely. It is imperative that such electrical shocks are prevented. A shock from hand to arm, though unpleasant, will not be so serious since it will not pass through the heart.
The diagram below shows the location of the main veins and arteries in the body.



3.1.2 First Aid

Candidates need to be able to outline the procedures for dealing with a casualty who has suffered an electric shock or burn.

When encountering a casualty who has suffered an electrical shock it is vitally important to ensure that he/she is no longer in contact with the source of electricity **before** touching him/her. Failure to do so will result in you also suffering an electrical shock. If possible, disconnect the electrical supply by either unplugging the appliance or tripping the circuit breaker.
If the casualty is unconscious, check breathing and pulse and, if you have been trained, be prepared to resuscitate if necessary. Any burns should be cooled with water and an ambulance should be called as soon as possible.
If the casualty seems to be unharmed, he/she may still be badly shaken and should be advised to rest. The casualty should be checked by a doctor.

When the body receives an electrical shock, the function of the circulatory system may well be disturbed. When this happens, insufficient oxygen reaches the body tissues and the medical condition known as **shock** will develop. If shock is not treated swiftly, the vital organs can fail, leading ultimately to death.

Very soon after receiving an electrical shock, the casualty is likely to have a rapid pulse and cold clammy skin, followed by weakness and giddiness, sickness, thirst, rapid shallow breathing and a fast irregular pulse. If the oxygen supply to the brain weakens then the casualty may become restless and anxious, may yawn and gasp for air and then become unconscious.

To treat shock, the casualty should be laid on the floor with the legs raised slightly by resting them on a low object (pile of books). Tight clothing should be loosened and he/she should be covered with a blanket or coat to prevent loss of body heat.
Medical assistance **must** be obtained.

3.1.3 Prevention of Accidents with Electricity

Candidates should be able to:

- explain why an individual should not work without proper supervision and explain why all persons should know how to summon help in an emergency
- carry out a risk assessment of their planned activity while considering how the environment affects the dangers of electricity
- explain why portable appliances should be regularly tested
- explain why components may become hot
- explain why capacitors may hold a lethal charge even though the equipment is isolated.

The vast majority of all accidents are preventable. Accident prevention is largely common sense, but unfortunately when you are tired or in a hurry, or both, common sense is not always applied and mistakes can be made. If you do have an accident you will rely on someone else coming to your rescue. It is for this reason that you should **never** work alone or without proper supervision.
If an accident does occur the first step is to prevent further injury to the casualty by removing the source of danger. Assistance should then be summoned by dialling 999 on a telephone and asking for the ambulance service. (On internal telephone systems it is often necessary to dial 9 first to obtain an outside line.) When you are connected to the ambulance service you should speak clearly and as calmly as possible. You will be asked for your location and telephone number and details of the state of the casualty. Some ambulance services will remain on the phone to you until the ambulance arrives and will advise you of any First Aid that you should give the casualty.

It is common sense to undertake a simple Risk Assessment of any task that you are going to do. This need not be an involved process but should involve you identifying any possible dangers. You should then aim to eliminate the dangers. If they cannot be totally eliminated then they should be minimised to a safe, acceptable level.

If this is not possible then the task should not be undertaken.

Whenever you use a piece of electrical equipment you should inspect it visually for signs of damage or wear that would make it unsafe to use. Equipment with damaged mains cables or broken plugs must not be used until they have been replaced. Soldering irons and other portable electrical tools are particularly vulnerable to this type of problem. All equipment that is fitted with a plug should be regularly tested (Portable Appliance Test, PAT) by a qualified electrician.

When a current passes through any resistive component, electrical power will be dissipated (given out), which will make the component become warm. How hot the component becomes will depend on the current passing and the physical size and properties of the component. Care should be taken to ensure that all components within a circuit are given adequate time to cool down, after being switched off, before carrying out any work on the circuit.

Even when an appliance is disconnected from the mains electricity supply there is still a possibility of a serious electrical shock. Electronic equipment requires a low voltage, direct current supply, whereas the mains supply is at a high voltage and is alternating. To achieve this change, much modern equipment uses a *switched mode power supply* which involves changing the mains electricity into a direct supply at approximately 320V. This is smoothed by a capacitor which charges to this high voltage. If the equipment fails then it is possible for the capacitor to be left charged to this high voltage for a long time, although all responsible manufacturers include a 'bleed resistor' across the capacitor to discharge it in such an event. Such a high voltage could cause sufficient current to pass through the body to cause a lethal shock. Televisions and computers use this type of power supply.

If there is any risk of an electrical shock then it is vitally important to take precautions to prevent the electrical current passing from hand to hand or from hand to foot as this could well be fatal. Ensure that you are isolated from the ground and that you are only using one hand (the other hand kept well out of the way, e.g. by putting it in your pocket.)

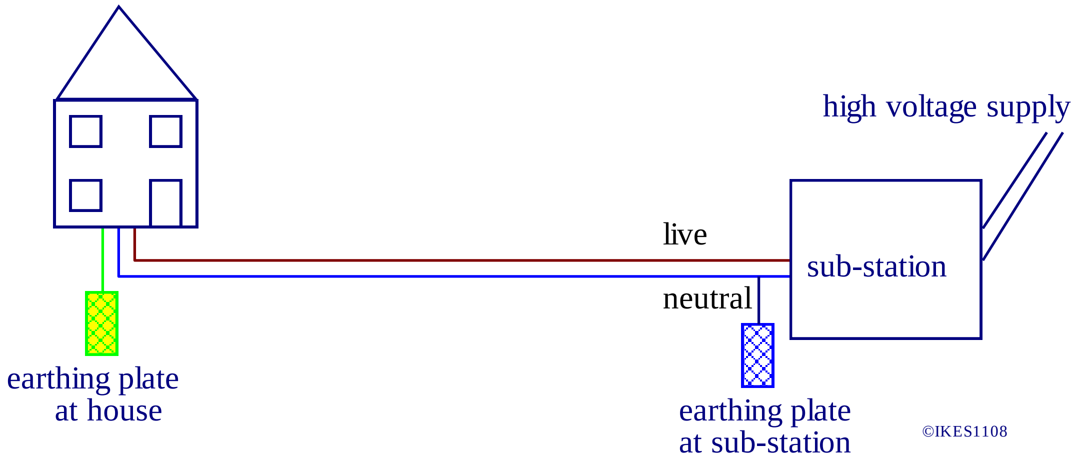
3.1.4 Electrical Safety Devices

Candidates should know:

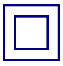
- the purpose and limitations of circuit breakers (thermal, fuse, magnetic)
- how to calculate the appropriate value for the circuit breaker
- how to wire a three-pin mains plug
- that a transformer can be used to obtain a safe low voltage from the mains supply.

In order to understand the electrical safety devices necessary when using the domestic electrical supply it is necessary to know a little about how the supply originates.
Electricity is transmitted around the country at very high voltages by the National Grid, which is a series of overhead and underground cables. These high voltages are converted to the 230V of the domestic supply at a sub-station which is essentially a large transformer with associated switch gear and circuit breakers.

After the transformer has changed the high voltage to 230V, there would be two wires to go to each house, each of which would be capable of giving a severe electric shock. To reduce the risk, one of the wires is connected to a large metal plate buried in the earth at the substation. This wire then becomes the NEUTRAL wire while the other remains the LIVE wire. In theory the neutral wire will be at 0V, but in practice it can rise as high as 50V when a very large current passes along it. The neutral wire will therefore not give a severe electric shock if touched whereas the LIVE wire most certainly will.

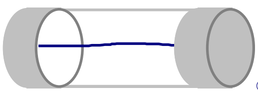


Any piece of electrical equipment that has any exposed metal parts must be either 'double insulated' or earthed.
Double insulation is achieved by making the equipment in such a way that it is physically impossible for the metal parts to ever make contact with the live wire of the electricity supply. Such equipment is subjected to very careful testing and is marked with a



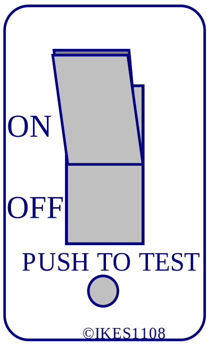
Earthing is achieved by connecting the exposed metal parts to a metal plate or pipe buried in the ground at the site of the user, via a wire in the mains cable. Often the cold water supply pipe is used for the main earth for a house but in these days of plastic water pipes many electricians prefer to use a 1 metre length of copper pipe hammered into the ground. If a fault develops with the appliance so that the exposed metal parts become 'live' then a large current flows to earth, making the fuse or circuit breaker fail and so switching off the electrical supply. **It is for this reason that the fuse is included in the live side of the electrical supply.**

In order to limit the damage caused to the wiring by a very large current flowing, an **Over Current Circuit Breaker** must be included in every circuit.
The simplest circuit breaker is a **fuse**, as shown in the diagram below. This is nothing more than a thin piece of wire that melts if too much current passes through it.



While fuses have the disadvantage that they are not resettable and can take several milliseconds to operate, they are very cheap and reliable.

Resettable circuit breakers (those that can be used again) are usually of one of two types. A typical example is shown in the diagram opposite.



A **thermal circuit breaker** relies on a piece of metal becoming hot as a result of the current passing through it. As the metal becomes hot it bends and releases a spring loaded switch which disconnects the electrical supply. These, like fuses, have the disadvantage that they can take several milliseconds to operate. However, this can sometimes be an advantage when using equipment which takes a large current when it is first switched on, e.g. audio amplifiers, computers etc.

A **magnetic circuit breaker** relies on the magnetic field produced by the current flowing through a small coil to release a spring loaded switch which disconnects the electrical supply. These respond much faster than thermal circuit breakers, but this can be a disadvantage when using equipment which takes a large current when it is first switched on, e.g. audio amplifiers, computers etc.

While these circuit breakers protect against large current flow, they provide no protection from an electric shock. A current of as little as 50mA is capable of producing a severe electric shock, which could be fatal. Devices that protect users from electric shocks are available under the general name of **Residual Current Devices**, or **RCDs**. There are several variants, e.g. Residual Current Circuit Breaker, RCCB, Earth Leakage Circuit Breaker, ELCB, or Ground Fault Detector, GFD.

These devices have two specific purposes:

- to prevent fatal electric shock by reducing to a 'safe' level (not eliminating) the length of time the current flows through the body,
- to help protect equipment from fires started by low fault currents passing from live to earth, that a fuse or circuit breaker might not detect.

An RCD does not detect excessive or 'over' currents or short circuits and must be used together with conventional circuit breakers. Some manufacturers now combine an over current circuit breaker and RCD in the same physical package. These are known as Residual Circuit Breaker with Over current protection or RCBOs.

Although the actual method of how a RCD works varies from manufacturer to manufacturer, the basic theory is straightforward. All of the current flowing from the supply along the live wire must return to the supply along the neutral wire. An RCD monitors these currents and detects any imbalance between these two currents. If this imbalance exceeds a pre-determined level then the supply is disconnected within a few milliseconds. An imbalance will be caused by current flowing back to the supply via the earth, possibly through the body of the person using the appliance. The pre-set trip level of imbalance is typically 30mA but can range from 5mA to 100mA depending upon the location and application.

To calculate the correct value for a circuit breaker it is necessary to find out the power rating of the appliance or circuit. This will usually be stamped onto a plate attached to the appliance.

Consider an electric kettle that is rated at 2.2kW or 2200W.
The voltage and current are related to the electrical power by the formula

$$\textbf{power} = \textbf{voltage} \times \textbf{current}$$

Therefore,

$$\textbf{current (amps)} = \frac{\textbf{power (watts)}}{\textbf{voltage (volts)}}$$

The voltage of the domestic electrical supply is nominally 230V.
So for the kettle,

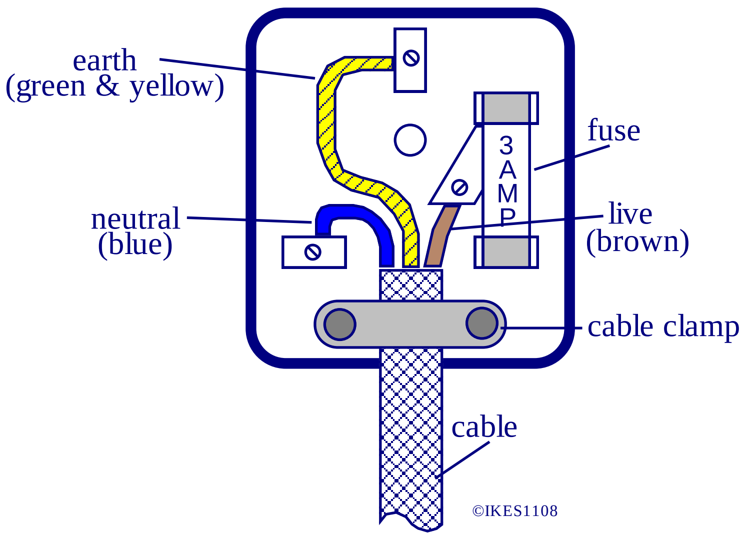
$$\textbf{current} = \frac{\textbf{power}}{\textbf{voltage}} = \frac{\textbf{2200}}{\textbf{230}} = \textbf{9.6A}$$

Although 10 amp fuses are available, a 13 amp fuse/circuit breaker should be fitted to the plug to allow for the larger current that flows when the element is cold.

As a general rule, if the appliance has a power rating of less than 750W then it should be fitted with a 3 amp fuse. If the power rating is more than 750W then a 13 amp fuse should be fitted.

The only exception to this is for appliances that contain an electric motor, e.g. freezers.
These will often have a power rating of only about 200W, but each time that the motor starts it will draw a substantial current which will cause a 3 amp fuse to fail.
A 13 amp fuse should therefore be fitted.

A correctly wired mains plug is shown below. The figure shows the view of the top of the plug with the cover removed.

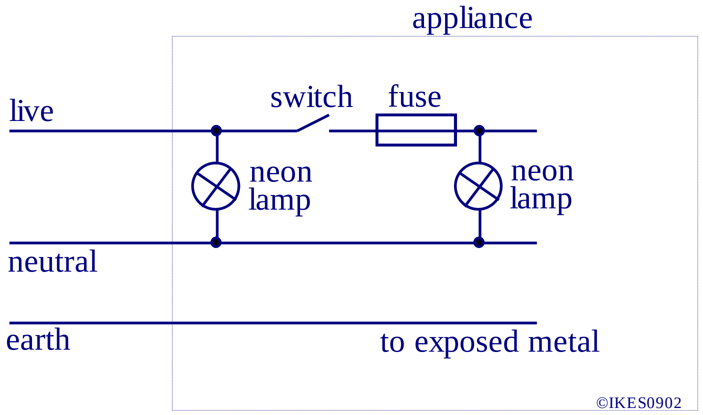


The following are essential points to note when wiring a plug:-

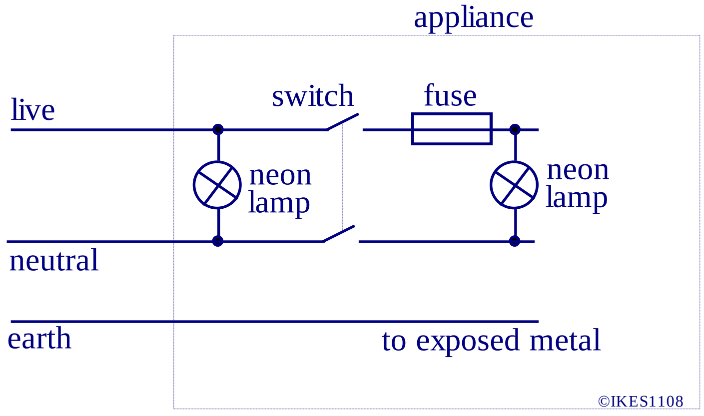
- the cable must be held securely by the cable clamp,
- the neutral (blue) must be connected to the left hand terminal,
- the live (brown) wire must be connected to the right hand terminal,
- the earth (green and yellow striped) wire must be connected to the top terminal,
- the insulation of each wire must extend to the correct terminal, with the bare wire passing into the terminal but **not** extending beyond the terminal,
- the fuse must be connected to the **live** side of the plug.

All equipment that is fitted with a plug should have a regularly test (Portable Appliance Test, PAT). If a plug is not wired as shown above, then it is dangerous and will not pass the test.

In order to isolate any piece of electrical equipment from the domestic mains supply it is essential to disconnect the **live** wire. If the **neutral** wire is disconnected instead, then the equipment will still be live and will still be able to give an electric shock. It is for this reason that fuses are **always** put in **series** with the **live** wire and that an On/Off switch must also be connected in **series** with the **live** wire, as shown in the diagram below.



However, it should be noted that a double pole isolating switch that disconnects both the live and neutral wires is to be preferred as shown below.



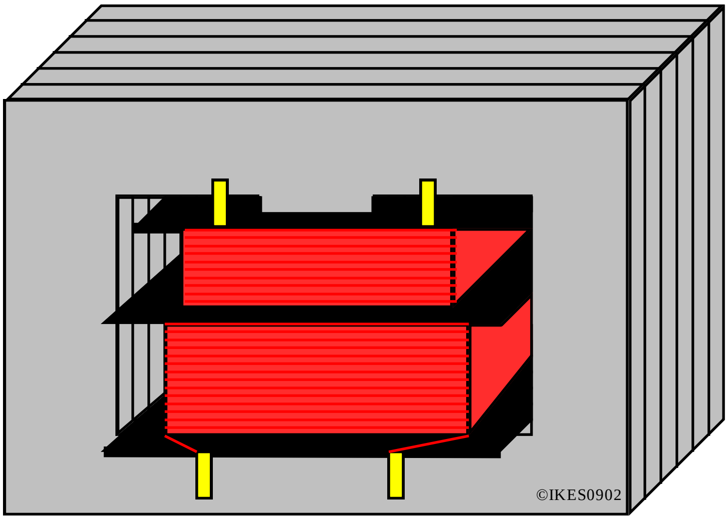
All pieces of electrical equipment that operate from the mains supply should have two indicators:

(i) to show that the mains supply is connected and
(ii) to show when the equipment is switched on.

It is normal to use 'neon' lamps for this purpose. (Normal filament lamps are not suitable for this application since they have a short lifetime.)

A neon lamp is a small glass enclosure filled with neon gas and containing two electrodes. When a voltage (usually more than 60V) is applied across the electrodes the neon gas glows. To prevent excessive current flow, a resistor is connected in series with the neon lamp, though this may be incorporated into the 'indicator lamp body'. Neon lamps have the advantage that they consume very little power and have an exceptionally long life. This makes them ideal as indicator lamps.
Some equipment manufacturers are now starting to use LEDs, but these use more power and are not yet as reliable as neon lamps.

A transformer is used to change the high voltage of the domestic electricity supply to a low voltage suitable for electronic circuits. A transformer only works with alternating electrical supplies. It consists of two coils, called the primary and the secondary, which are not electrically connected. The coils are wound either one on top of the other or side by side on a soft iron, or iron dust core, as shown below.



An alternating voltage is applied to the primary coil and this produces a changing magnetic field in the core. This changing magnetic field passes through the secondary coil and induces an alternating voltage. If the number of turns on the primary coil is much larger than the number of turns on the secondary, then the secondary voltage will be much smaller than the primary voltage. As a result of the two coils being electrically isolated from each other, the secondary voltage is isolated from the primary supply.

SYSTEMS

3.2 System Design

Electronic systems are composed of one or more subsystems.
Electronics engineers design complex systems composed of combinations of subsystems in order to solve problems.

3.2.1 System Diagrams

Candidates should know:

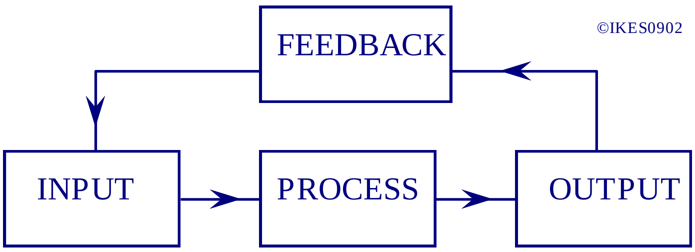
- that a simple system has an input, a process and an output
- that using arrows between subsystems represents the flow of information rather than wiring.

Candidates should be able to analyse and design system diagrams as an aid to the understanding and representation of complex systems.

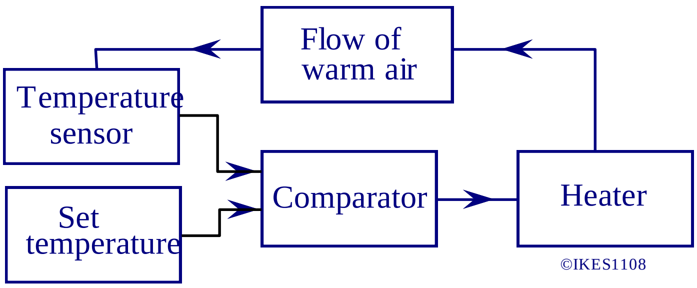
All electronic systems can be considered to consist of the following sections:-

- an input,
- a processor,
- an output,
- (and feedback).

(The feedback section on simple systems may not be needed.)
Using this concept, complex electronic systems can be broken up into smaller and simpler sub-systems, where each section is represented by a labelled box and the lines between the sections represent the flow of information. A typical example is shown below.
The arrows indicate the flow of information through the system.

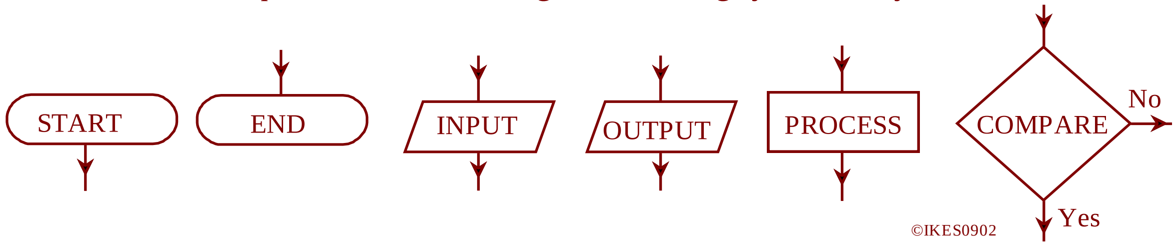


For example, consider a system to maintain a constant temperature in a room. The input could be from a temperature sensor and the processor a comparator. The output could be a heater and the feedback would be the heat received by the temperature sensor.

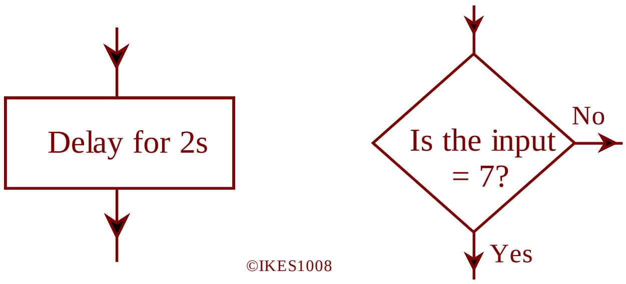


3.2.2 System Sequence

Candidates should be able to construct and interpret flowchart diagrams which describe a sequence of events, using the following symbols only.

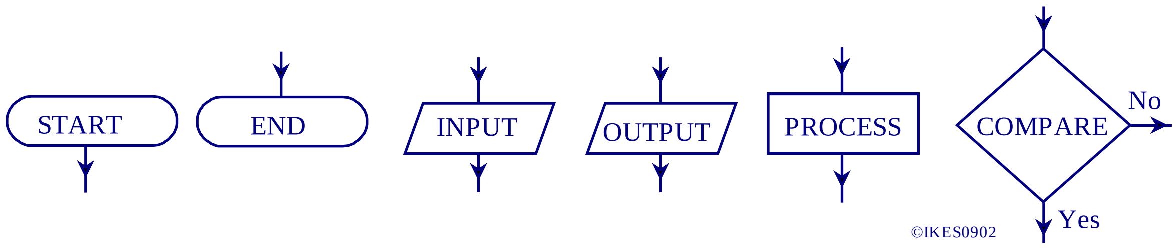


The content of each 'box' may be the result of a subroutine or group of instructions, e.g.

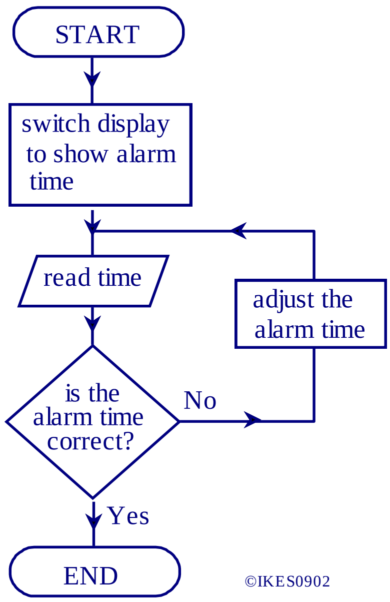


In order to be able to use sequential and programmable systems it is necessary to be able to think logically through the sequence of events that the system is required to do. Flow chart diagrams are one of several graphical methods that can be employed to help determine the sequence of operations required.

The symbols below are those used both in this booklet and in the subject specification.



The START and END symbols are often known as TERMINAL boxes.
The best way to learn how to construct and interpret flow diagrams is by studying examples such as the one below for setting the alarm on an alarm clock.
The flow diagram is self explanatory and shows the correct use of the various symbols.



It is good practice to try to analyse tasks into the separate steps that could be put into a flow chart. Remember that most programmable systems are very simple and can only operate on one instruction at a time.

A useful exercise would be to design a flow chart to produce a soft-boiled egg.

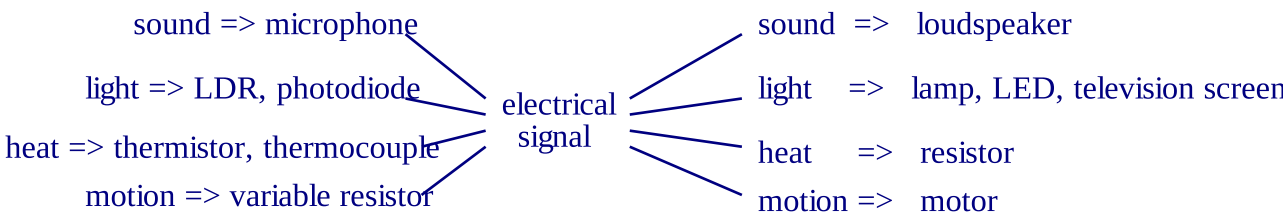
3.2.3 System Inputs and Outputs

Candidates should be able to:

- describe the functions and uses of common input and output transducers
- recall that a signal is an electrical current or voltage representing information
- explain that electrical noise is an unwanted signal
- describe how electrical noise may be reduced.

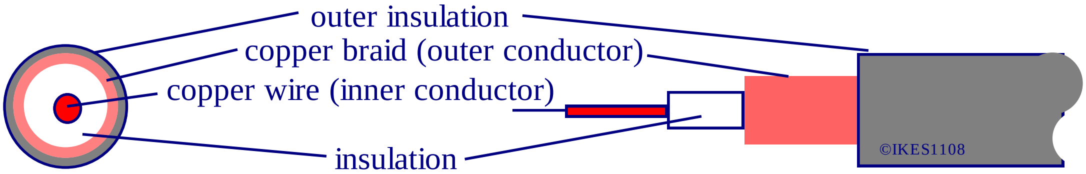
Electronic systems are only able to process information if the information is first changed into electrical signals representing that information. This is the function of the input device or *transducer*. There are many different types of input device. Some will actually generate an electrical signal, e.g. a dynamic microphone and a photodiode. Others rely on a change of their properties (e.g. resistance) to cause a change in an electrical circuit, e.g. an LDR (Light Dependent Resistor) or a thermistor. With both of these, their resistance changes with light intensity and temperature respectively.

Once the electronic system has processed the information, the electrical signals need to be changed back into a form that is usable by the outside world. This is the purpose of the output device or transducer. A summary of input and output transducers is given below.



Electrical signals are variations in an electrical current or voltage which represents information. Unfortunately any electronic system will not only process the electrical signals that it is intended to process, but also any others that happen to be present at the same time. These *other* electrical signals can arise in a variety of ways ranging from the random motion of the electrons moving through the electrical components to *'mains hum'*. Such unwanted electrical signals are often called **noise** and need to be kept to a minimum. (Technically it is only *random unwanted signals* that are classified as noise.)
The most serious problems with unwanted signals arise when the noise is produced in the input device, e.g. background noise in a microphone. If the input signal is amplified then the noise signal will also be amplified by the same amount and so the 'quality' of the information signal will be poor. Think of how much more noticeable background noise is when replayed at high volume!

Digital processing almost eliminates any additional noise being added to a signal, but it is very important to ensure that noise is kept to a minimum before the signal is converted into a digital signal.
Reducing random noise is very difficult. Reducing other types of noise is much more straightforward and usually involves shielding the electrical signals and processors from stray electric and magnetic fields. The processing parts of the system should be enclosed in earthed metal boxes to protect them from stray electric fields. Input devices should be connected to the processing sections by *screened cables*. A diagram of a screened cable is shown below. The outer part of the cable, consisting of many copper wires woven to form a conducting tube, is connected to earth. The electrical signal is carried along the centre conductor.



Interference from magnetic fields is reduced by ensuring that there are no loops of wire or copper circuit track since these would result in an electrical signal being produced by a changing magnetic field e.g. from a transformer.

3.2.4 System Processors

Candidates should be aware of the following basic processes:

- counting
- timing
- amplifying
- logic
- memory
- ADC and DAC.

There are many different types of basic processing that can be carried out by the processor in an electronic system. A brief description of each of the main types is given below.
(Many of these are described in more detail elsewhere.)

COUNTING

This is a digital process and relies on a digital circuit to increase the binary value it stores by one each time that a signal is received. The processing components will often be D-type flip-flops or 4017 counter ICs in this specification. (See section 3.3.3)

TIMING

This process will be initiated by the signal from the input transducer and will result in the output transducer operating for a certain period of time. The processing section of a timer will often be a monostable circuit made from a 555 timer IC. (See section 3.3.4.)

AMPLIFYING

This process will result in the input signal being increased (or occasionally decreased) in size. The processing section of an amplifier will often be an op-amp, although if a large increase in current or power is required, then the amplifier will usually be constructed from transistors and MOSFETs. (See section 3.3.7.)

LOGICAL OPERATIONS

There are many different logical operations that can be incorporated into a processor, resulting in the output transducer responding in a defined way to the state of the various input signals. All logical operations, however, consist of the three basic logical operations of AND, OR and NOT. The actual function of a logic processor is defined by a truth table which will summarise ALL of the possible output states for ALL of the possible input states. (See section 3.3.2.)

MEMORISING SIGNALS

This process stores the state of the input signal for future use. The complexity of this processor will vary considerably depending upon the application, but could be as simple as a circuit to remember if there has been a signal from the input transducer. In such an application the processor would be called a *latch*. (See section 3.3.3.)

ADC & DAC (analogue to digital and digital to analogue conversion)

Analogue to digital conversion is the process whereby the voltage of an analogue signal is sampled (measured) and then converted into a binary number. The speed with which this occurs and hence the number of samples per second depends on the type of analogue signal. E.g. a telephone signal is sampled 8000 times per second while a video signal is effectively sampled 27 million times per second.

Digital to analogue conversion is the reverse process, whereby an output voltage is produced which is proportional to the binary number at the input.

Information System Processing

3.3 Information System Processing

Candidates need to be aware that many input devices produce analogue signals and that audio systems usually contain audio amplifiers which are analogue systems requiring an analogue input and producing an analogue output.
Candidates should investigate these subsystems in a practical context and there is the opportunity for them to use protoboard in preparation for their controlled assessment (practical project).
Candidates should be aware that analogue and digital information need to be processed in different systems and that analogue information can be converted to digital information and vice versa.

3.3.1 Digital Subsystems

Candidates should be able to explain the use of logic gates, flip-flops, counters and timers.

3.3.2 Combinational Logic

Candidates should be able to recall that:

- in a digital system a voltage signal is either at a high level or low level and that these states are represented by 1 or 0 respectively
- a logic gate is a device with one output and several inputs and the output is either at a high level or a low level depending on the combination of input signals.

Digital electronics is concerned with switching-type circuits in which the inputs and outputs involve only two levels of voltage (or current). Digital information (signals) therefore consists of a series of voltage pulses, with a **HIGH** voltage being represented by a **1** and a **LOW** voltage being represented by a **0**.

Digital circuits consist of logic gates which control the flow of digital information. A logic gate is a device which has one output and one or more inputs. The output will either be a logic 1 (high) or a logic 0 (low) depending on the input signals. The logic gates covered in the syllabus are assumed to have a very high input resistance, and a low output resistance. Logic 0 is assumed to be less than half of the supply voltage and logic 1 is assumed to be more than half of the supply voltage. These are the characteristics of the CMOS, 74HC and 74HCT logic families.

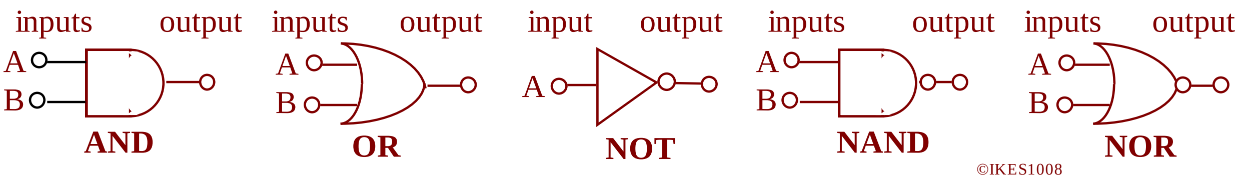
All of these logic circuits will operate from a well regulated +5V supply and it is assumed in circuit diagrams that a power supply is connected even though the connections will not be shown.

Analogue electronics uses continuously varying voltages and so it is not possible to produce tables showing the relationship between every possible input and output, the tables would be infinitely long.
Digital electronics, however, having only two states for each input, does not have this problem. Tables showing the relationship between inputs and output can be readily constructed for digital circuits. These are known as **TRUTH TABLES**.

Truth Tables

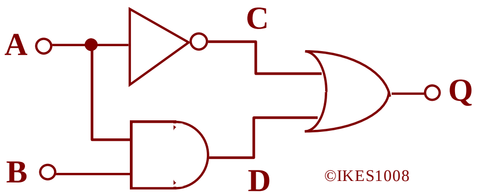
Candidates should be able to:

- demonstrate knowledge of AND, OR, NOT, NAND and NOR gates using the following symbols only



- construct and interpret truth tables for each of the gates above
- use truth tables to determine the output of a combination of up to four of the above gates

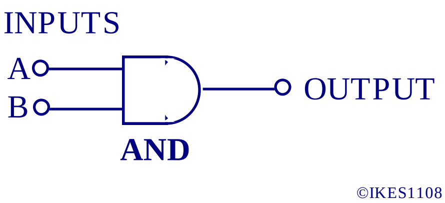
e.g.



A	B	C	D	Q
0	0	1	0	1
0	1	1	0	1
1	0	0	0	0
1	1	0	1	1

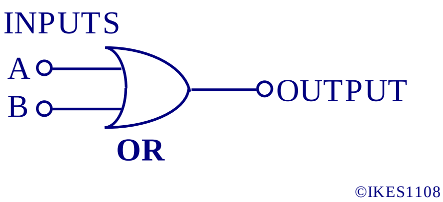
- solve system problems, stated in words, using combinations of logic gates
- solve system problems which may have up to three separate inputs.

There are three basic logic functions or gates: **AND**, **OR**, and **NOT**.
All digital electronic circuits are built from combinations of these basic gates.
The truth table and logic symbol for a two input AND gate is shown below.



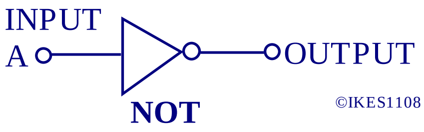
A	B	OUT
0	0	0
0	1	0
1	0	0
1	1	1

The truth table and logic symbol for a two input OR gate is shown below.



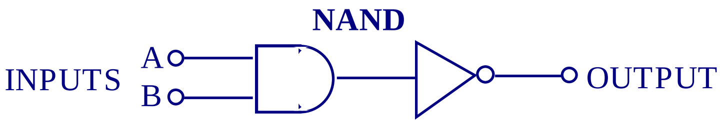
A	B	OUT
0	0	0
0	1	1
1	0	1
1	1	1

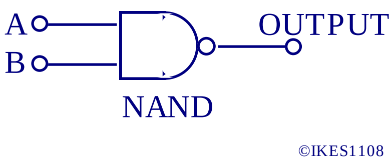
The truth table and logic symbol for a NOT gate is shown below.



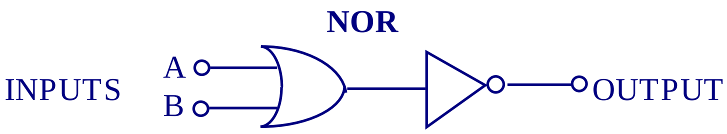
A	OUT
0	1
1	0

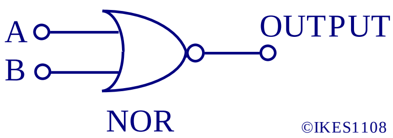
From these basic gates more complex ones can be constructed, the most common of these being the **NAND** and **NOR** gates. The logic symbols and truth tables for these gates are shown below.





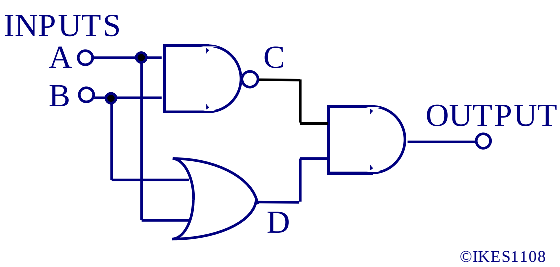
A	B	OUT
0	0	1
0	1	1
1	0	1
1	1	0





A	B	OUT
0	0	1
0	1	0
1	0	0
1	1	0

The method for analysing complex digital circuits is shown in the example below.
The output of each gate is recorded as a separate column in the truth table. In this way, inputs A and B give the intermediate outputs C and D, which in turn, form the inputs for the final AND gate.



A	B	C	D	OUT
0	0	1	0	0
0	1	1	1	1
1	0	1	1	1
1	1	0	1	0

When designing logic circuits to solve system problems it is necessary to be able to take a description of a logical process and translate it into a circuit, using logic gates, that will perform the required task.
The easiest way of understanding the process is by way of an example, e.g.,

> *A car manufacturer wants to incorporate a seat belt alarm to warn the driver when his seat belt is not fastened. The alarm must sound when the ignition is switched on, the driver is sitting in the driver's seat and the seat belt is not fastened. The manufacturer fits switches into the seat and seat belt. The seat switch gives a logic 0 when the seat is occupied and a logic 1 when it is unoccupied. The seat belt switch gives a logic 0 if it is fastened and a logic 1 if it is unfastened. If the ignition switch is on then it gives a logic 1. The alarm needs a logic 1 to sound.*

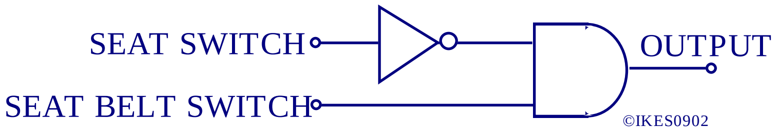
As a description, the problem appears to be very complex, but it becomes easier once the information is put into a truth table. The problem also becomes easier if two of the inputs are dealt with first. As with all truth tables, every possible input combination must be listed.
Consider first the seat switch and the seat belt switch. The alarm must sound if the seat is occupied but the seat belt is not fastened.

SEAT SWITCH	SEAT BELT SWITCH	REQUIRED ALARM
0	0	0
0	1	1
1	0	0
1	1	0

Looking at the truth tables for the basic logic gates it can be seen that the truth table above is similar to that for an AND gate in that there is only one input combination that gives a logic 1 output. The next task is to consider how this could therefore be made using an AND gate.
A little thought will show that if the SEAT SWITCH output is inverted by passing it into a NOT gate, then an AND gate can be used to combine the two inputs.
This is shown in the truth table below.

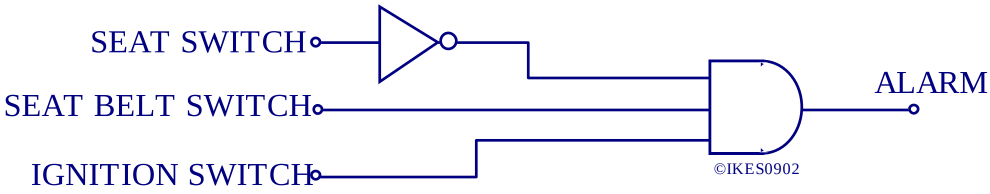
SEAT SWITCH	**NOT** (SEAT SWITCH)	SEAT BELT SWITCH	ALARM
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	0

The seat switch and seat belt switch can therefore be combined using the circuit shown below.



Also the alarm must sound only when the ignition switch is on, i.e. at logic 1, **AND** when the output from the previous circuit is also a logic 1.
These two signals can therefore be combined using an AND gate.

The complete circuit is shown below.



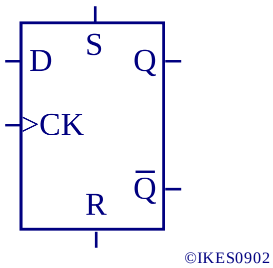
3.3.3 Sequential Logic

Candidates should be able to:

- describe the operation and use of a 4013 type D-type flip-flop
- explain the function of a D-type flip-flop as a data latch and as a frequency divider
- recognise and draw simple timing diagrams for frequency dividers
- describe the operation and use of a 4017 type counter IC
- recognise and draw simple timing diagrams for 4017 type counters.

All the logic circuits and gates considered so far reflect a change in output within a very short time of the inputs changing. (The delay is approximately 10ns per gate.) This can lead to erratic changes in output as the different inputs settle to new logic levels. In large logic systems, like microprocessors, this can cause very serious problems. It is overcome by using a CLOCK signal to ensure that any change in output occurs at a specific time. The clock signal is used to control flip-flops and one of the most common types is the Data flip-flop which is usually known as a D-type flip-flop.

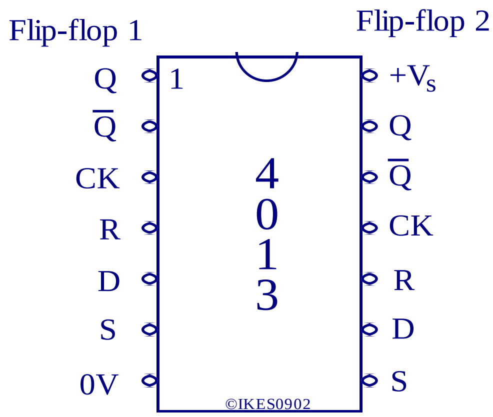
The symbol for a D-type flip-flop is shown below, together with its truth table.



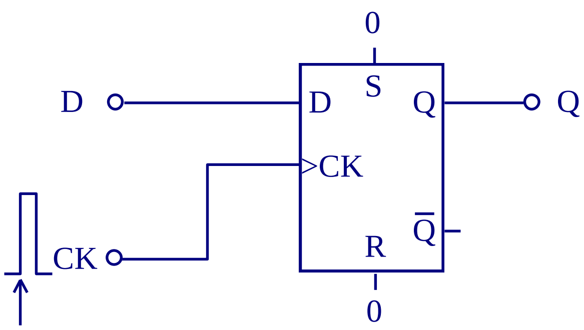
CK	D	Q	$\overline{Q}$
0	0	Q	$\overline{Q}$
0	1	Q	$\overline{Q}$
↑	0	0	1
↑	1	1	0

D is the **Data** input and it is the information on this input that is stored in the flip-flop.
CK is the **Clock** input and it is the state of this input that determines when the information on the Data input is stored in the flip-flop.
Q is the output and $\overline{\mathbf{Q}}$ is the inverse of **Q**.
S is the **SET** input and makes the output **Q** logic 1 when **S** is a logic 1, irrespective of the state of **D** and **CK**.
R is the **RESET** input and makes the output **Q** logic 0 when **R** is a logic 1, irrespective of the state of **D** and **CK**.
The > symbol in front of the **CK** shows that the information on **D** is stored in the flip-flop when the clock input goes from 0 to 1.
This type of D-type flip-flop is said to be rising edge triggered.

An example of such a device is the 4013 IC. The pin diagram for the 4013 is shown below. From the diagram it can be seen that there are actually two D-type flip-flops in each IC. The flip-flops are completely separate and can be used independently.



To use a D type flip-flop as a Data Latch, **S**, **R** and **CK** are connected to 0V. The data to be stored (one bit per D-type flip-flop) is connected to the **D** input and the clock input **CK** is taken from logic 0 to logic 1 and back again to logic 0. The data is stored and appears at **Q** when the clock input goes from logic 0 to logic 1.
A typical circuit diagram for a 1 bit latch is shown below.



Data transfer takes place on the rising edge of the clock pulse

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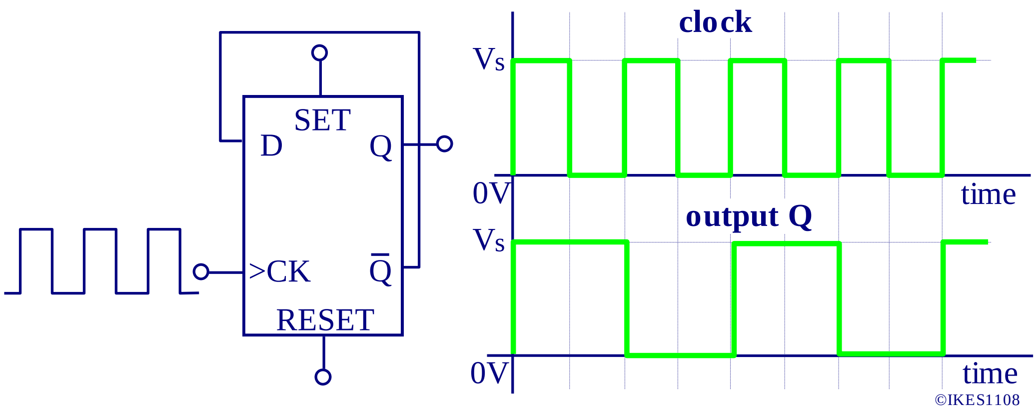
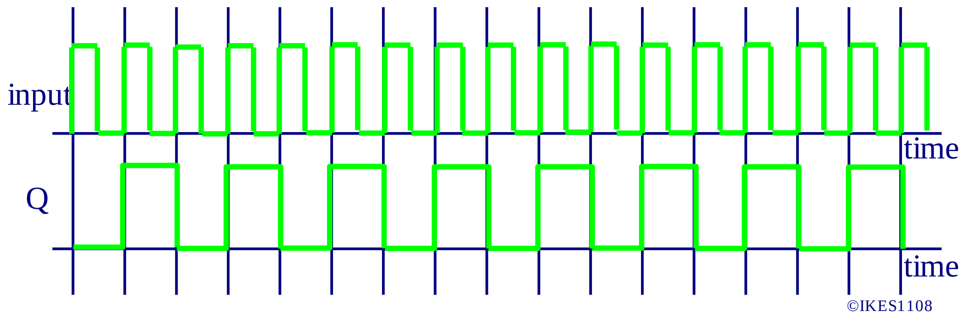
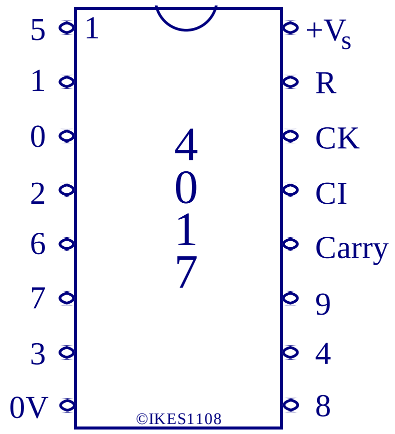
As well as being used for storing data, D-type flip-flops can also be used as frequency dividers. Since **Q̄** is always opposite to **Q**, if **D** is connected to **Q̄** and the clock input is connected to a pulse generator, **Q** will change at half the rate of the clock pulses.
To enable a D-type flip-flop to toggle, i.e. change state on each successive clock pulse, the **D** input should be connected to the **Q̄** output. The **D** input is then always opposite to **Q** and so toggling occurs on each successive clock pulse. The arrangement is shown below, where the D-type flip-flop is shown with its normal logic symbol.



Both the **SET** and **RESET** inputs are connected to logic **0**.
This circuit has many applications since it effectively has an output frequency that is half the input frequency as shown in the diagram below.



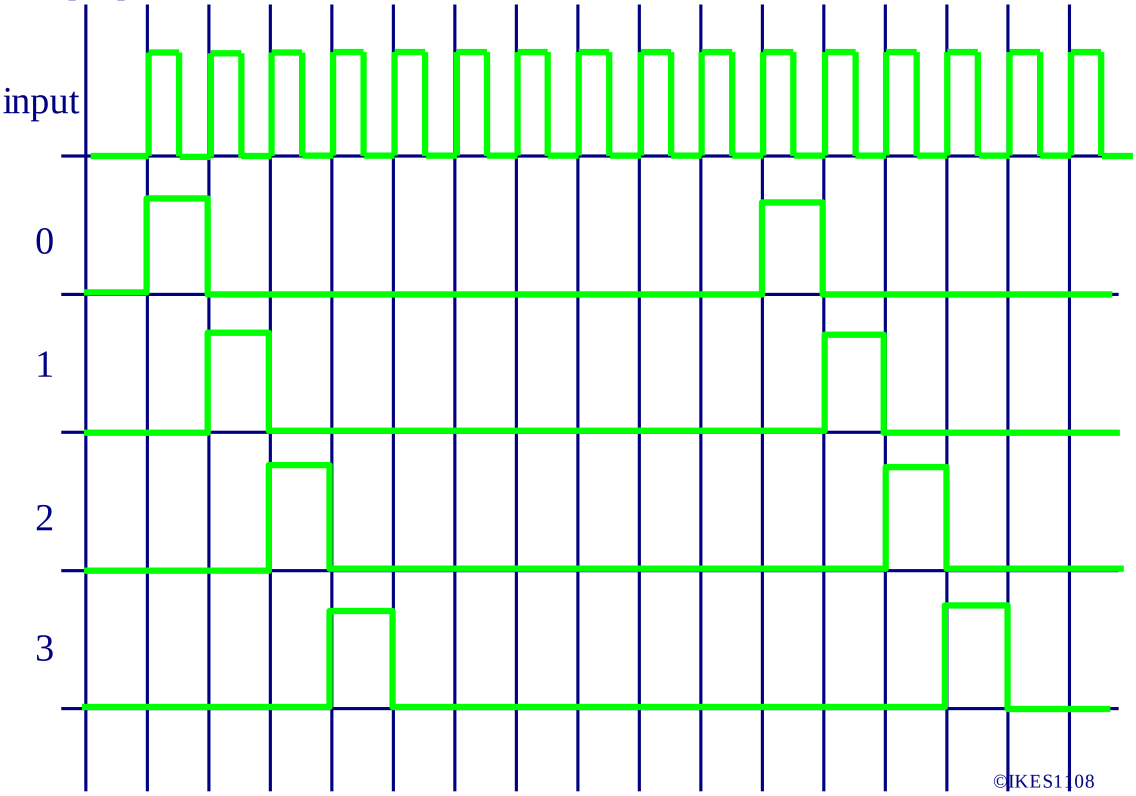
D-type flip-flops can be connected together to form counter circuits. A particularly useful form of counter circuit is the 4017 integrated circuit. This gives 10 decoded outputs.
The pin-out diagram of the 4017 is shown below.



In the diagram above, the outputs are represented by the numbers **0** to **9**. Each output can provide sufficient current (sink and source) to light a LED. Since each output is current limited, a series resistor with each LED is not required when the IC is operated from a 5V or 9V power supply.
R is the **RESET** input and is normally a logic 0. When it is logic 1, the outputs **1** to **9** are set to logic 0 and the output **0** is set to logic 1.
CK is the **CLOCK** input and the outputs change state on the rising edge of the clock pulse.
CI is the **CLOCK INHIBIT** input. Normally it is logic 0, but when it is logic 1, the outputs do not change even if the clock does.
Carry is the output that can be linked to the clock input of a second 4017 to provide a cascaded output. The **Carry** output is logic 1 for outputs from **0** to **4** and logic 0 for outputs **5** to **9**.

The 4017 counter IC is sensitive to pulses on the power supply and so it is advisable to connect a 10μF capacitor across the power supply close to the IC.

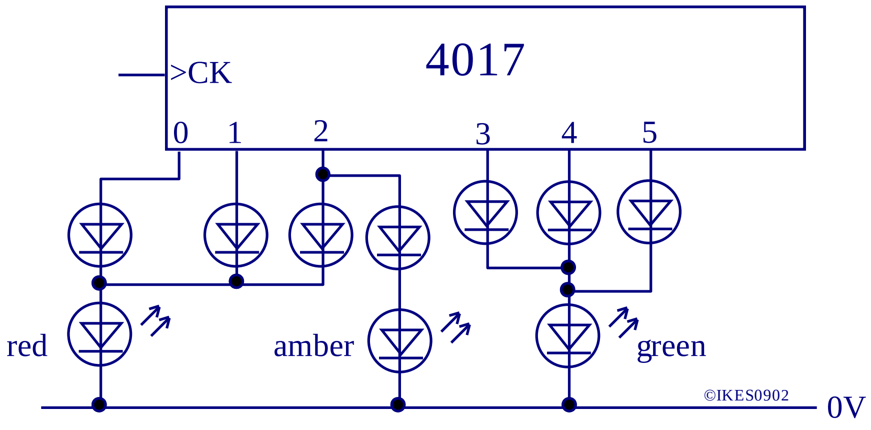
A timing diagram showing the first three outputs of a 4017 counter is shown below for 16 clock input pulses.



The 4017 counter is a very versatile IC and can be used in a wide variety of applications. These include:

counters, when the output is displayed on a series of LEDs
electronic dice,
random number generators,
reaction timers
games, e.g. shoot the LED,
traffic light controller,
rhythm unit for electronic drum machines,
sequencer for electronic music,
general industrial process controller.

To use a 4017 counter IC as a Sequence controller it is necessary to use diodes to isolate the outputs from each other when they are connected together. An example of a Sequence control application is shown below for the initial sequence of a traffic light controller.
Note how each output is isolated by the use of diodes.
When the 4017 is reset, the RED LED is lit. After the first clock pulse, output 0 is set to logic 0 and output 1 is set to logic 1. Current will still pass through the RED LED and so it will still be lit. On the next clock pulse, the logic 1 output moves to output 2. This causes current to pass through both the RED and AMBER LEDs, lighting both of them. On the next clock pulse, the logic 1 output moves to output 3 so turning off both the RED and AMBER LEDs and lighting the GREEN LED. The GREEN LED will then stay lit for the next two clock pulses. It is a useful exercise to complete the traffic light sequence by using and adapting the remaining outputs of the 4017 counter IC.



3.3.4 Astable and Monostable Generators

Candidates should be able to:

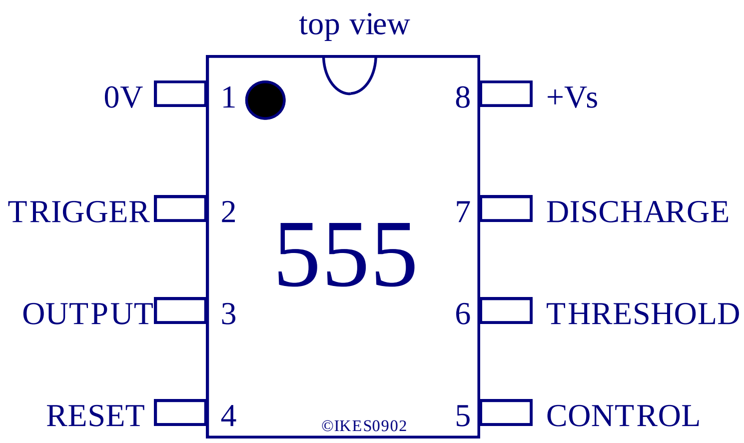
- use and explain the application of a 555 integrated circuit in monostable and astable mode
- use the formulae for the 555 integrated circuit which relates time period to circuit values in both monostable and astable modes.

Candidates need to be able to use and manipulate the formula for time period.

This very versatile integrated circuit was first produced in 1973. The circuit and its derivatives are still used in large quantities. While it is not necessary to know the internal structure of this device, it does aid understanding if the main internal features are known. These are as follows.

- three precision resistors are connected across the power supply as a voltage divider and so give voltages of $^{1}/_{3}$$\mathbf{V_S}$ and $^{2}/_{3}$$\mathbf{V_S}$, where $\mathbf{V_S}$ is the supply voltage;
- two comparators, one switching at $^{1}/_{3}$$\mathbf{V_S}$ via the **TRIGGER** input and the other switching at $^{2}/_{3}$$\mathbf{V_S}$ via the **THRESHOLD** input;
- a latch, SET by the output of the **TRIGGER** comparator and RESET by the output of the **THRESHOLD** comparator;
- a high current output capable of sinking or sourcing 200mA;
- an open collector transistor switch, which connects the **DISCHARGE** terminal to 0V when the output terminal is at 0V.

The pin diagram for a 555 timer IC is shown below.

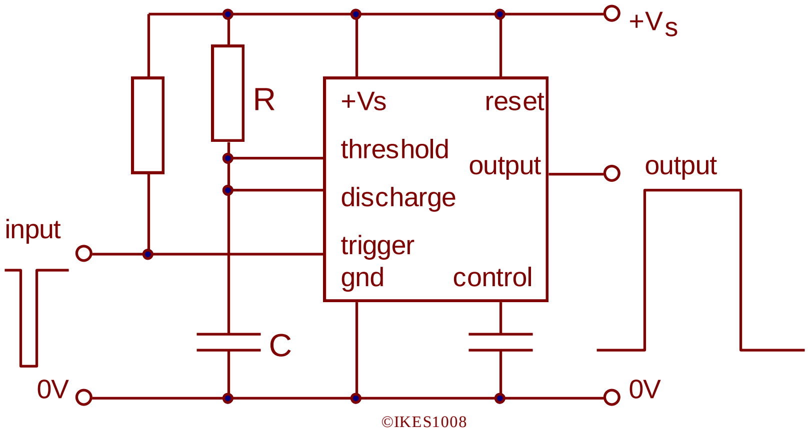


The operation of a 555 can be summarised as follows.

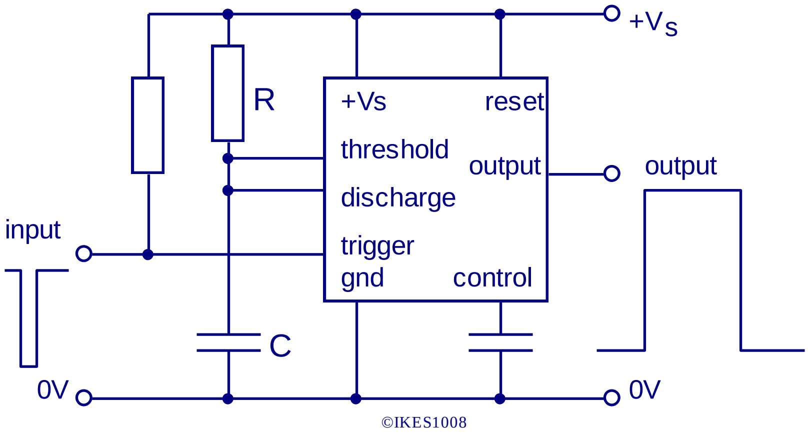
- If the voltage at the **TRIGGER** input is less than $^{1}/_{3}\mathbf{V_s}$, the output goes to $\mathbf{V_s}$ and remains there until the voltage at the **THRESHOLD** input rises above $^{2}/_{3}\mathbf{V_s}$, at which value the output is set to **0V**.
- The **RESET** terminal can be used to set the output to 0V at any time by being connected momentarily to 0V. Normally, the **RESET** terminal is connected to $\mathbf{V_s}$ to prevent any spurious resetting of the output.
- The **CONTROL** terminal is connected to the $^{2}/_{3}\mathbf{V_s}$ point of the voltage divider and can be used to alter the voltage switching levels of the comparators. Normally it is decoupled by a 10nF capacitor connected to 0V.

In monostable mode

time period T = 1.1 R × C



The circuit diagram for a 555 monostable is shown below.



The resistor connected to the **TRIGGER** input ensures that it is held above $^{1}/_{3}\mathbf{V_s}$ in the absence of an input signal. Typically the value of this resistor would be 10kΩ or greater; its value is not critical. Before being triggered, the output of the monostable is at 0V, and the **DISCHARGE** terminal of the 555 is also at 0V, ensuring that the timing capacitor is discharged.

When $\mathbf{V_{in}}$ goes below $^{1}/_{3}\mathbf{V_s}$, the output voltage, $\mathbf{V_{out}}$, becomes $\mathbf{V_s}$ and the **DISCHARGE** terminal becomes open circuit, so allowing the capacitor, **C**, to charge through resistor **R**. The output will stay at $\mathbf{V_s}$ until the voltage across **C** becomes greater than the threshold switching voltage, $^{2}/_{3}\mathbf{V_s}$. When this happens, the output voltage will return to 0V and the **DISCHARGE** terminal will again connect to 0V, so discharging **C** very quickly. This state is STABLE and the circuit will remain like this until $\mathbf{V_{in}}$ becomes less than $^{1}/_{3}\mathbf{V_s}$.

In theory any combination of R and C is possible to achieve a required time period.
In practice, however, there are several things to remember.

- The transistor connected to the **DISCHARGE** terminal, as well as having to conduct the short-circuit current of the timing capacitor when the monostable resets, also has to carry the current flowing through the timing resistor. To prevent destruction of this transistor the minimum value of **R** should be **1kΩ**.
- The minimum value of **C** should be considered as **100pF**, since any smaller value will be similar to the input capacitance of the timer circuit and so the time periods will be inaccurate.
- There are two factors to consider when looking at the maximum value of **C**. The first is that any large value capacitors will be electrolytic and so have a leakage current which must pass through **R**. If the leakage current is too large for the value of **R** then the time period will be inaccurate. It could well happen, if there is a large leakage current, that the voltage across **C** never reaches $^{2}/_{3}\mathbf{V_s}$ and so the threshold switching voltage level is *never* reached!
- The second factor is the current that will pass through the discharge transistor at the end of the timing period. If the short circuit current is too large then the transistor will be destroyed. The maximum value of **C** should therefore be limited to **1000μF**.
- All electrolytic capacitors are inaccurate and their values change with time, so accurate time periods cannot be produced by monostable circuits with electrolytic capacitors. Tantalum bead capacitors will give a little more accuracy and stability than normal electrolytic capacitors.
- The **THRESHOLD** input requires a current of a few μA, so this, combined with the leakage current of the capacitor **C**, needs to be taken into account when using very large values for R. In practice it is worth limiting the maximum value of **R** to **1MΩ**.

Taking all these factors into account, the minimum time period of a 555 monostable is about 0.1μs and the maximum time period is approximately 1000s.

For the **monostable** the time that the output voltage is at $\mathbf{V_s}$ is calculated by using the formula.

$$\mathbf{T = 1.1 \times R \times C}$$

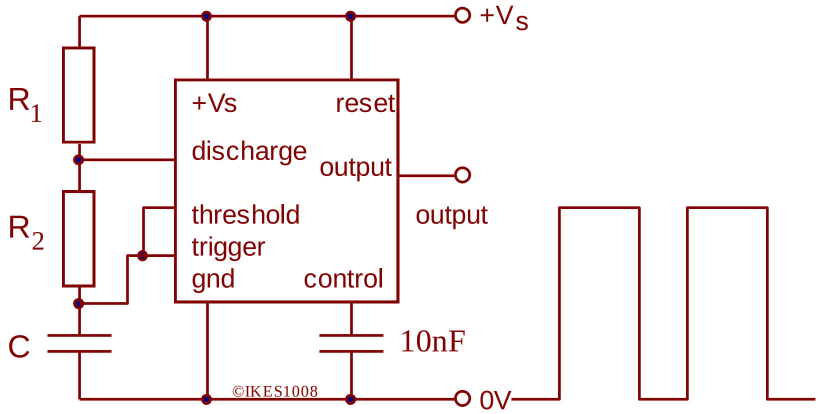
where T is in seconds, R is in ohms and C is in farads.

For example, if R has a value of 100kΩ and C has a value of 100μF then the time for which the output will be at the supply voltage is

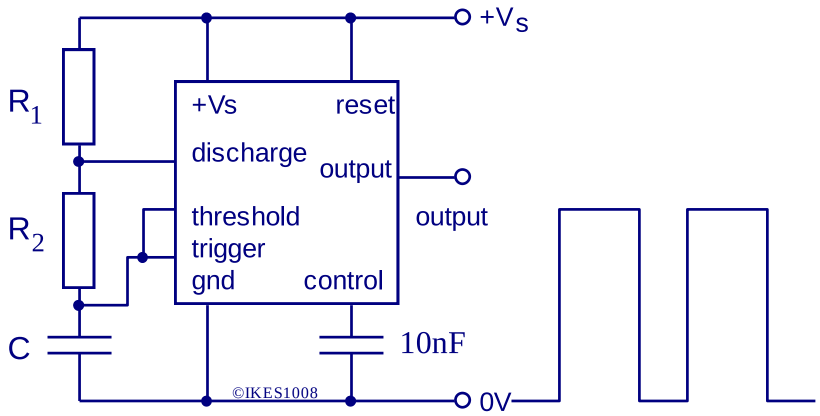
$$\mathbf{T = 1.1 \times 100000 \times 0.0001 = 11\,seconds.}$$

In astable mode,

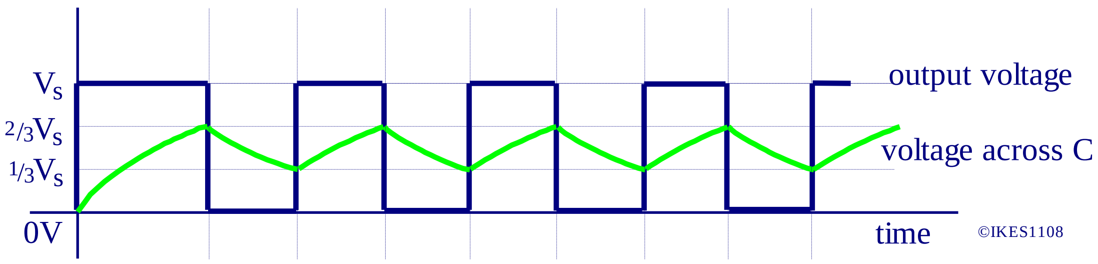
$$\text{time period, } T = \frac{(R_1 + 2R_2)C}{1.44}$$



The common circuit for a 555 astable is shown below.



When first switched on the capacitor, **C**, is discharged and so the voltage across this capacitor is less than the **TRIGGER** voltage and so the output goes to $\mathbf{V_s}$. The capacitor, **C**, charges through $\mathbf{R_1}$ and $\mathbf{R_2}$ until the voltage across **C** is greater than the **THRESHOLD** switching level, at which point the output voltage becomes 0V and the **DISCHARGE** terminal becomes connected to 0V.
The capacitor now discharges through $\mathbf{R_2}$ until the voltage across **C** becomes less than the **TRIGGER** switching voltage. When this happens, the output voltage becomes $\mathbf{V_s}$ and the process repeats. It should be noted that the first pulse is longer than the remainder, since **C** has to charge from 0V and not $\mathbf{{}^1/_3V_s}$. The same restrictions apply to the values of **C** and **R** ($\mathbf{R_1}$ and $\mathbf{R_2}$) as for the monostable.
The timing diagram for the astable is shown below.



For the **astable** the timing period is given by

$$\mathbf{T = \frac{(R_1 + 2R_2) \times C}{1.44}}$$

For example, if $\mathbf{R_1}$ has a value of 100kΩ, $\mathbf{R_2}$ has a value of 47kΩ and **C** has a value of 100µF then the time period is

$$\mathbf{T = \frac{(100000 + 2 \times 47000) \times 0.0001}{1.44}}$$

$$\mathbf{\Rightarrow T = \frac{194000 \times 0.0001}{1.44} = 13.5s.}$$

With the usual circuit for a 555 astable it is not possible to obtain a square waveform, i.e. when the output is at the supply voltage for as long as it is at 0V.

It might be thought that this could be achieved by making $\mathbf{R_1}$ equal to zero. If this is attempted, then as soon as the output goes low the **DISCHARGE** terminal is connected to 0V, so short circuiting the power supply and damaging the **DISCHARGE** transistor. The minimum value for $\mathbf{R_1}$ should be considered to be 1kΩ. If, however, $\mathbf{R_1}$ has a value of 1kΩ and $\mathbf{R_2}$ has a value of 1MΩ then the error in the ratio of the time for which the output is high to that for which the output is low (mark to space ratio) will be about 0.1%, which may well be adequate.

The only way to obtain a mark to space ratio of exactly 1:1 is by the use of frequency division.

There is a self marking assessment exercise on the 555 IC on the *IKES* website in the 'IKES Online', Homework section, which should be used to provide practice.

3.3.5 Analogue Signal Processors

Candidates should be able to:

- recall that analogue signals are those that vary with time, taking on all values between a maximum and a minimum
- recall that analogue circuits are those which handle analogue signals.

3.3.6 Analogue Subsystems

Candidate should be aware of:

- the use of the low power audio amplifier ICs
- the use of the op-amp comparators with various sensors.

An analogue signal is one in which the information is represented by the value of a voltage or a current. The value of the voltage (or current) can be any value with in a specified range, i.e. there are an infinite number of possible values. Usually the analogue signal varies with time and this is represented as a voltage variation with time.

Analogue signals are readily produced. For example, a microphone converts sound waves into a time varying voltage. However, since the information is related directly to the value of the voltage, any change to that voltage will cause distortion to the information. Noise is also a problem since the noise voltage is added to that of the information and so degrades the quality of the information signal.

Amplifiers will change the value of the voltage of an analogue signal without causing distortion so long as all of the different voltages are amplified by the same amount.
If this does not happen then the signal becomes distorted (e.g. if the amplifier clips the top and bottom voltages of the analogue signal).

3.3.7 The Audio Amplifier

Candidates should be able to:

- use the relationship

$$\textbf{voltage gain, } G_V = \frac{V_{out}}{V_{in}}$$

- know that bandwidth is the range of frequencies over which the amplifier produces at least half of its rated output power
- describe the operation and use of an audio amplifier IC (low power types only such as LM380, LM386 or TBA820).

Three of the parameters that determine the effectiveness of an amplifier are as follows.

The **voltage gain** is the number of times that the voltage signal from the output is larger than the input voltage signal. It is a ratio and so does not have any units. It is given by the formula

$$\text{Voltage gain } (G_V) = \frac{V_{out}}{V_{in}}$$

e.g. If the output voltage from an amplifier is 8V and the input voltage is 0.2V then

$$\text{Voltage gain } (G_V) = \frac{8}{0.2} = 40$$

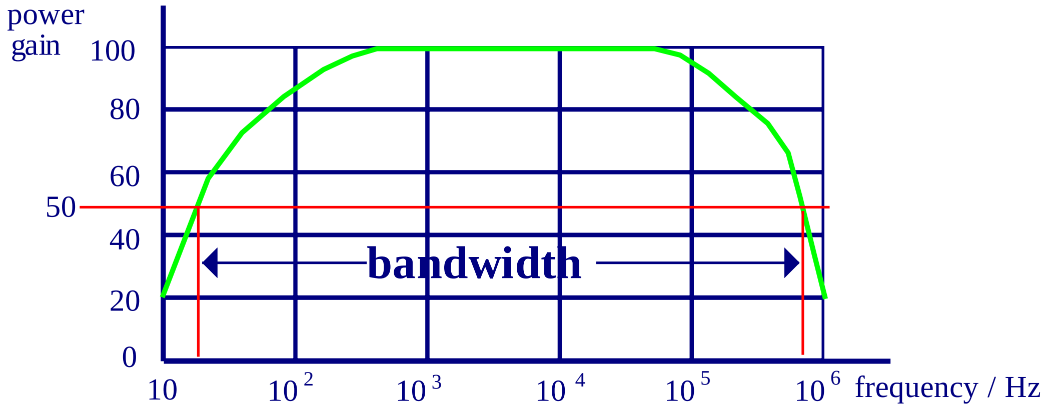
The **power gain** is the number of times that the output power from an amplifier is larger than the input power. It is a ratio and so does not have any units. It is given by the formula

$$\text{Power gain } (G_P) = \frac{P_{out}}{P_{in}}$$

e.g. If the output power from an amplifier is 20W and the input power is 1mW then

$$\text{Power gain} (GP) = \frac{20}{0.001} = 20000$$

As a result of stray capacitance and inductance in circuits, amplifiers are not able to amplify all frequencies equally. High and low frequencies are often amplified less than those frequencies in-between.
The graph below shows how the voltage gain of a typical amplifier varies with frequency. The frequency is plotted on a non-linear scale to accommodate the large range.



The **bandwidth** of an amplifier is defined as the range of frequencies within which the **Power Gain** does not fall below **HALF** of its maximum value. So for the graph above, the bandwidth would be from approximately 20Hz to 800kHz.

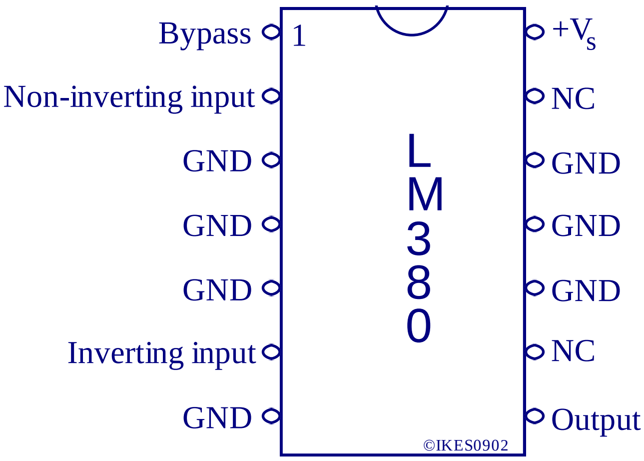
There are many sophisticated audio amplifier integrated circuits available ranging from ultra miniature devices that will only power earphones up to those that will provide several hundred watts of sound into large loudspeakers. All function in a similar way and provide both voltage and power amplification (gain), i.e. they have a small signal as their input and produce a large signal output. This specification focuses on low power audio amplifiers that will produce a watt or so of power and so can drive a loudspeaker. Such amplifier ICs can be used in a variety of applications including:

an intercom,
loudspeaker output from a portable CD, minidisk, MP3 player,
loudspeaker output from a simple radio,
an oscillator which will drive a loudspeaker as an alarm,
a signal tracer,
a loud-hailer etc.

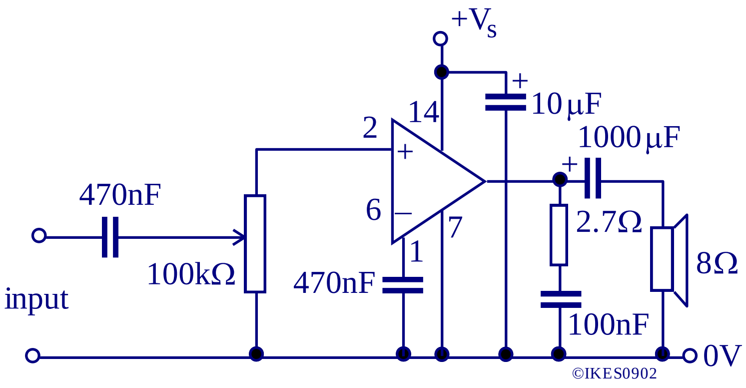
Three examples of such audio amplifiers are the LM380, LM386, and TBA820M

LM380

Supply Voltage	8 to 22V
Voltage gain	50
Output power	2W
Input resistance	150kΩ
Bandwidth	100kHz

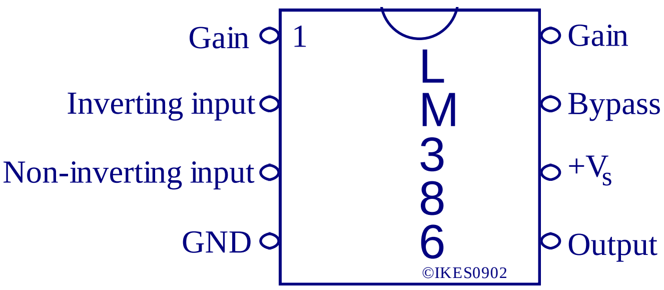


There are many different ways in which this IC can be connected to function as an audio amplifier and a typical arrangement is shown below. As can be seen from the pin-out diagram above, pins 3, 4, 5, 10, 11, 12 are all marked as Ground (GND) connections and should all be connected to 0V along with pin 7. These pins act as a heat sink for the amplifier to prevent it from over heating and failing. If this IC is used to provide its maximum power output then these pins should be soldered onto a suitably sized piece of copper on a printed circuit board. This IC, along with the others, can become unstable (i.e. oscillate) if the input circuit is not kept well away from the output circuit. The circuit should also have a 10μF capacitor connected directly from the **+V$_s$** input to 0V.



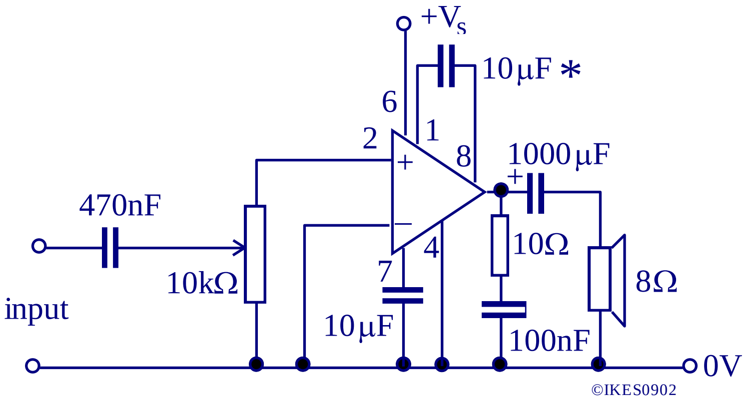
LM386

Low voltage applications	4 - 12V
Low quiescent current	4mA
Variable voltage gain	20 - 200
Output power	300 - 500mW
Bandwidth	up to 300kHz
Input resistance	50kΩ



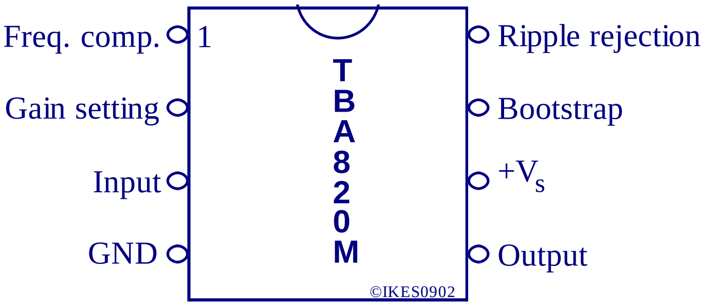
This IC provides a smaller power output than the LM380 and so does not need the heat sink connection pins. The voltage gain is internally set to 20, but this can be increased to 200 by connecting a capacitor between pins 1 and 8 as in the circuit diagram below

Typical circuit



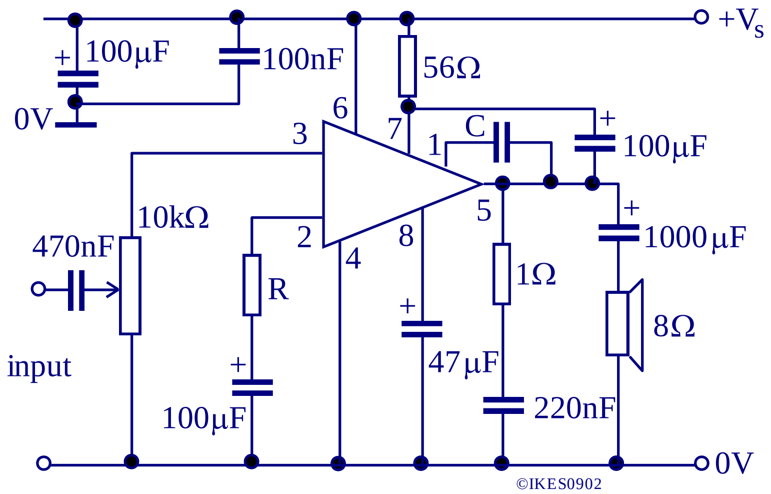
TBA 820M

Low voltage applications	3 - 15V
Low quiescent current	4mA
Variable voltage gain	up to 200
Output power	2W
Bandwidth	up to 22kHz
Input resistance	5MΩ



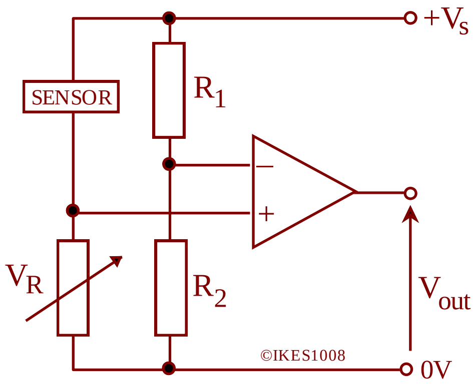
This IC amplifier has a very low quiescent current consumption and yet is able to provide up to 2W of power to a loudspeaker. The voltage gain is adjustable with a value of R of 100Ω giving a gain of 50. The voltage gain can be increased by reducing the value of R. The frequency response of the amplifier is controlled by C, with a value of 220pF giving a frequency response of 25 to 20kHz.

Typical circuit

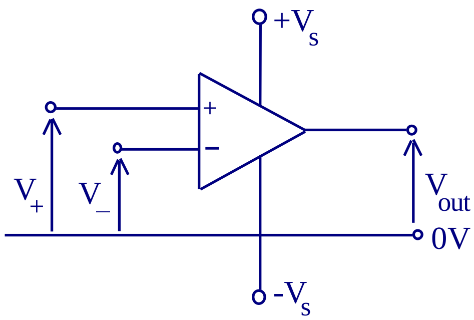


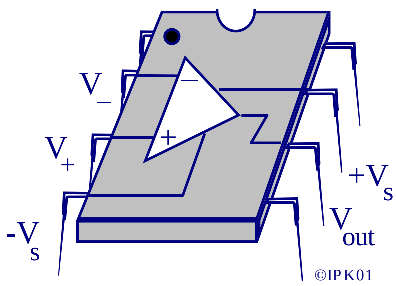
3.3.8 The Op-amp Comparator

Candidates should know that an operational amplifier has a very large input resistance, a low output resistance, a very large voltage gain and saturates at the supply voltages.
Candidates should be able to explain the function and use of the circuit below as a voltage comparator using a single rail supply.
A voltage comparator can be used as a one-bit analogue to digital converter.



An operational amplifier (op-amp) is a voltage amplifier which amplifies the difference between the voltages on its two input terminals.
Op-amps are often require a dual balanced d.c. power supply, e.g. ± 15V.
The power supply connections are often omitted from circuit diagrams for simplicity.
The diagram below shows the typical connections for an op-amp.





The '+' input terminal is known as the non-inverting input and the '–' input terminal is known as the inverting input terminal.
The output voltage is given by

$$V_{out} = A\ (V_{+} - V_{-})$$

A is the open loop voltage gain, i.e. when there is no feedback.

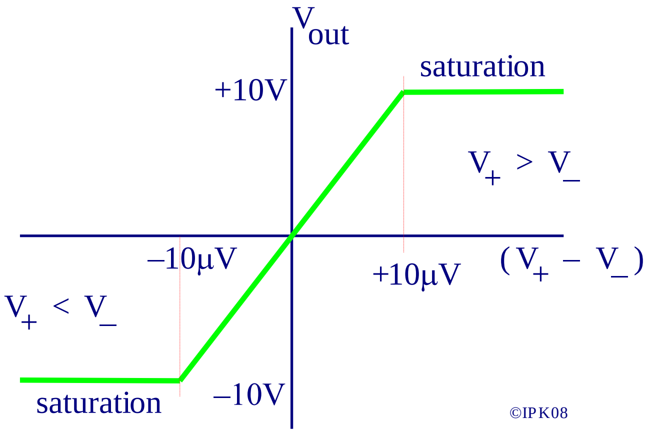
For the purposes of the written test, the op-amp is assumed to behave ideally i.e.

- the open loop gain is very large (in practice it is only very large at low frequencies),
- the maximum output voltage is equal to the power supply voltage, (in practice it is about 2V less),
- it has infinite input impedance so no current passes into the input terminals, (in practice the input impedance is not infinite so there is a current of a few nano-amps),
- the output impedance is zero so it can supply any required current, (in practice the op-amp is designed to limit the current to a few milliamps),
- the output voltage is zero when the two inputs are equal, (in practice there is a small offset voltage which needs a variable resistor to balance out).

The output voltage of an op-amp is given by

$$V_{out} = A\ (V_+ - V_-)$$

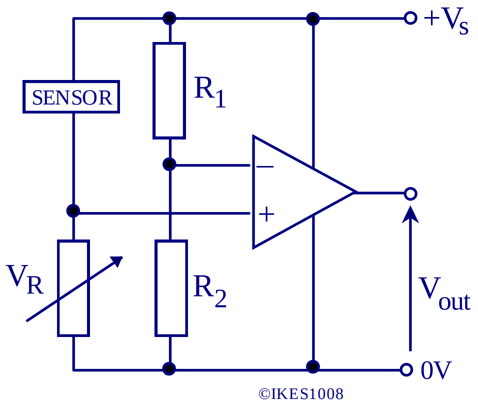
Since the op-amp has a very large open loop gain, A, only a very small difference between V_+ and V_- is needed for the output to be saturated i.e as positive or negative as the output can be. The transfer characteristic for an op-amp is shown below, which has an open loop gain of 10^6 and power supply voltages of ±10V.



As can be seen from the diagram above, the op-amp is saturated except for a difference in input voltages of ±10μV.
This characteristic enables the op-amp to compare the two voltages on its input terminals.
If V_+ is greater than V_-, the output saturates at the positive supply voltage.
If V_- is greater than V_+, the output saturates at the negative supply voltage.
This principle can be used to compare two voltages, a reference voltage and a varying input voltage.

$$V_+ > V_- \Rightarrow V_{out} = +V_s$$
$$V_- > V_+ \Rightarrow V_{out} = -V_s$$

An op-amp can be used as a comparator either with a dual power supply or with a single power supply, but this specification only requires a single power supply to be considered.



In this circuit, the comparator compares the voltages at the junctions of the two voltage dividers with results as summarised below.

If $\mathbf{V_+} > \mathbf{V_-}$ then $\mathbf{V_{out}}$ saturates at the positive supply voltage, $\mathbf{+V_S}$.

If $\mathbf{V_-} > \mathbf{V_+}$ then $\mathbf{V_{out}}$ saturates at the negative supply voltage, **0V**

In practice the op-amp output only usually gets to within 2 volts of its power supply.

The sensor shown in the circuit above could be a thermistor or LDR.
These sensors are covered in detail in section 3.4.2.
For an LDR, as the light intensity increases the resistance of the LDR decreases.
So therefore $\mathbf{V_+}$ becomes larger as the light intensity increases.
When the light is dim, $\mathbf{V_+}$ is less than $\mathbf{V_-}$ and so the output saturates at **0V**.
When the light is bright, $\mathbf{V_+}$ is greater than $\mathbf{V_-}$, and so the output saturates at $\mathbf{+V_s}$.
The value of the light intensity at which this change occurs is set by the value of the variable resistor $\mathbf{V_R}$.
The output voltages can be reversed (i.e. $\mathbf{+V_s}$ in dim light) in two ways.

(a) the input connections to the op-amp can be swapped over, or
(b) the variable resistor and sensor can be swapped.

An Analogue to Digital Converter produces a digital output from an analogue input. Since a comparator produces an output which only has two states it can be thought of as a one-bit analogue to digital converter. This makes the comparator ideal for connecting analogue sensors to logic circuits.

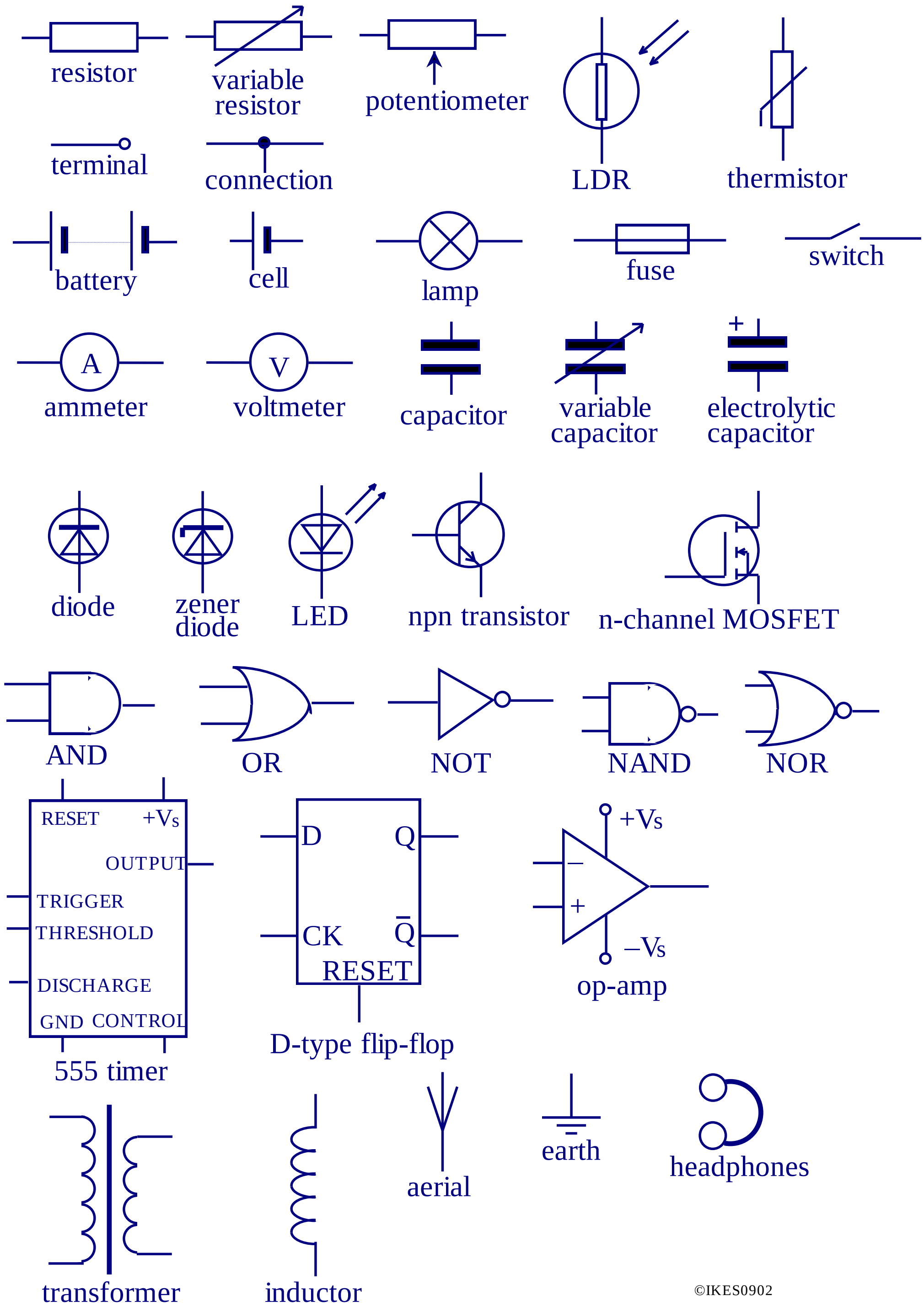
There is a self marking assessment exercise on the Comparator on the *IKES* website in the 'IKES Online', Homework section, which should be used to provide practice.

The Science of Components

3.4 The Science of Components

This unit considers the components that candidates are likely to encounter in their course and examines the underlying scientific concepts.

If circuits were to be drawn as pictures, producing them would be very time consuming and cumbersome. All electronic components are therefore represented as symbols and those used in this specification are given below.



3.4.1 Basic Principles

Candidates should be able to draw and interpret circuits using standard symbols for components (see Appendix G) in this specification.

Candidates should know that:

- the unit of voltage is the volt, (V)
- the unit of current is the amp, (A)
- The unit of resistance is the ohm, (Ω).

Candidates should be able to use the facts that:

- the sum of the voltages in a series circuit is equal to the voltage across the whole circuit
- there is the same voltage across each component in a parallel circuit
- the current in a series circuit is the same everywhere in the circuit
- the sum of the currents entering a junction is the same as the sum of currents leaving the junction
- there may be a current passing through a component only when there is a voltage across it
- the resistance of a component or circuit is given by

$$\text{resistance} = \frac{\text{voltage}}{\text{current}} = \frac{V}{I}$$

Candidates should be able to:

- calculate the effective resistance of up to four resistors in series
- calculate the effective resistance of two resistors in parallel
- explain the use and applications of a voltage divider
- calculate the output voltage of a voltage divider assuming a negligible load current
- explain the use and application of a pull up/pull down resistor.

Candidates should be able to:

- use the following formula to calculate power

$$P = I\,V$$

and know that the unit of power is the watt, (W).

Candidates should know, and be able to use the fact that:

- the unit of frequency is hertz, (Hz)
- the unit of capacitance is the farad, (F).

Candidates should be able to:

- use the relationship peak value = 1.4 × rms value for a sine wave
- sketch a voltage-time or current-time graph for a sine wave, indicating peak and period values
- use the relationship

$$\text{frequency} = \frac{1}{\text{time period}}$$

Electricity is the effect of the movement of electric charge. The smallest quantity of electric charge possible is called an *electron*. The amount of electric charge each electron carries is very small and so very many electrons are involved in electric and electronic circuits.

Voltage can be thought of as being a measure of the *amount of energy* that the electrons have when moving in a circuit. An electric current can be thought of as a *measure of the number* of electrons passing through a conductor per second.

If electrons are to move then they must have energy and so there can only be a current (flow of electrons) in a component when there is a voltage across it. If there is no voltage across a component, then there can be no current flow. However, it should also be remembered that if there is no path for electrons to pass through, then there will not be any current even though there may be a voltage difference.

It is important that all quantities used in electronics have appropriate units associated with them. The common units and their symbols are listed below.

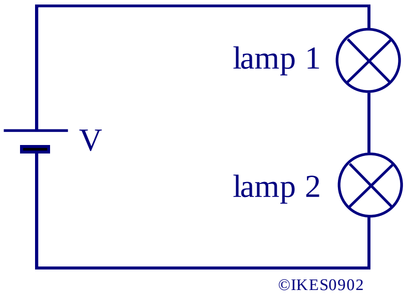
Quantity	Unit	Symbol
voltage	volt	V
current	ampere	A
resistance	ohm	Ω
power	watt	W
frequency	hertz	Hz
capacitance	farad	F

These units are often too large or too small for given measurements. The farad is a very large unit; the capacitance of the Earth, when treated as a capacitor, is only a small fraction of a farad. On the other hand the ohm, when used in electronic circuits is very small and usually components with resistance of many thousands of ohms are used. To simplify the use of these standard units, prefixes are used in front of them, just as they are with distance measurements, e.g. millimetre, kilometre etc.

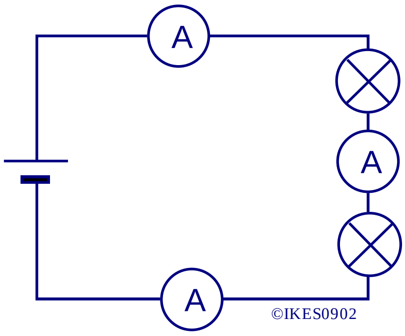
Each of the common prefixes is shown below, together with one or more examples of units of magnitudes typically encountered in electronics.

giga	×1,000,000,000	(G)	GHz
mega	×1,000,000	(M)	MHz, MΩ
kilo	×1,000	(k)	kHz, kΩ, kV
milli	×0.001	(m)	mV, mA, mW
micro	×0.000 001	(μ)	μV, μA, μW, μF
nano	×0.000 000 001	(n)	nF
pico	×0.000 000 000 001	(p)	pF

There are essentially two ways in which electronic components can be arranged in a circuit, in **series** or **parallel**.
A simple series circuit is shown below, consisting of a cell (battery) and two lamps.



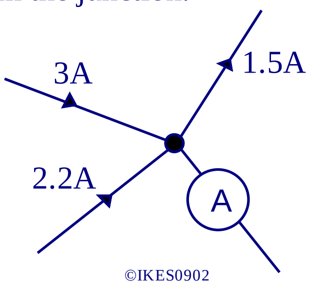
As electrons pass around a circuit, they lose energy. (Electrons are **not** *"used up"* in any way. Indeed, if they were, then the whole circuit would become radioactive!!)
This means that in a series circuit the current will be the same where ever it is measured.
If three ammeters were placed in the series circuit as shown below, they would all have the same reading.



The same argument can also be applied to currents entering and leaving a junction in a circuit. The diagram below shows a junction in a circuit. Since electrons cannot suddenly appear or disappear, the current shown on the ammeter must equal the sum of the other currents.
The ammeter therefore reads

3A + 2.2A – 1.5A = 3.7A

with the current flowing away from the junction.



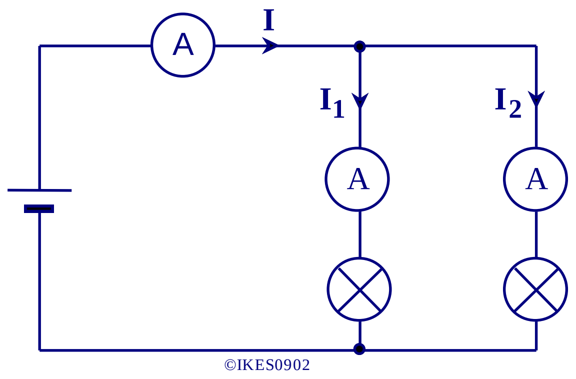
Electrons cannot give out any more energy in a circuit than they are supplied with initially by the power supply or battery. In a simple series circuit this means that the sum of the voltages across all of the components is equal to the voltage of the power supply. Therefore in the series lamp circuit at the top of this page;

voltage across lamp 1 + voltage across lamp 2 = voltage of battery, V.

The only common circuit in which lamps are arranged in series is Christmas tree lights. There are usually twenty lamps connected together in series. Each lamp is rated at 12V and so the whole series circuit can be connected to the mains electricity supply of 240V (230V).

A simple parallel circuit is shown below. As can be seen, each lamp is connected directly (through an ammeter) to the battery, and so the voltage across each lamp is the same as the battery voltage.
The current, however, is split at each junction. This means that:

$$\mathbf{I = I_1 + I_2}$$



Ohm's Law

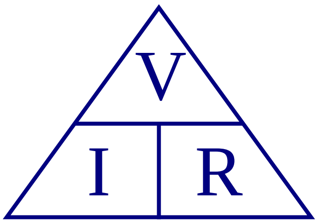
Electrons move more easily through some materials than others when a voltage is applied across the material. The opposition to current flow is called **resistance** and is measured in **ohms, (Ω)**. Larger units are *kilohm*, (kΩ = 10^3 Ω) and *megaohm*, (MΩ = 10^6 Ω.)

Resistance is defined as follows.

$$\mathbf{resistance = \frac{voltage}{current} = \frac{V}{I}}$$

The resistance will be measured in ohms when the voltage is in volts and the current is in amps.

This formula is often known as Ohm's Law and is probably the most important formula in electronics.
Ohm's law can be placed into a *Magic Triangle* to help with its re-arrangement.
The magic triangle is shown on the right.
To find a formula, cover up the letter that you require and the formula can be read from the triangle.



e.g., to find I, cover the letter I and then I = V/R.

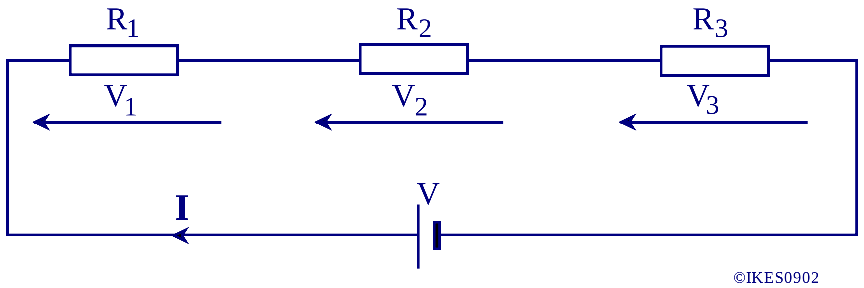
EXAMPLE.

A resistor has a voltage of 25V across it and a current passing through it of 0.5A. What is the resistance of the resistor?

$$\text{resistance} = \frac{\text{voltage}}{\text{current}} = \frac{25}{0.5} = 50\Omega$$

There is a self marking assessment exercise on Ohm's Law on the *IKES* website in the 'IKES Online', Homework section, which should be used to provide practice.

Resistors in Series



When several resistors, e.g. $\mathbf{R_1}$, $\mathbf{R_2}$, and $\mathbf{R_3}$ are connected in series, as in the diagram above,

- the same current, **I,** passes through each resistor,
- the applied voltage, **V,** is equal to the sum of the voltages across the separate resistors :

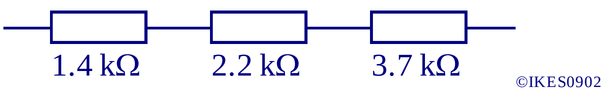
$$\Rightarrow \mathbf{V = V_1 + V_2 + V_3}$$

- the total resistance, **R,** is the sum of the separate resistors.

$$\Rightarrow \mathbf{R = R_1 + R_2 + R_3}$$

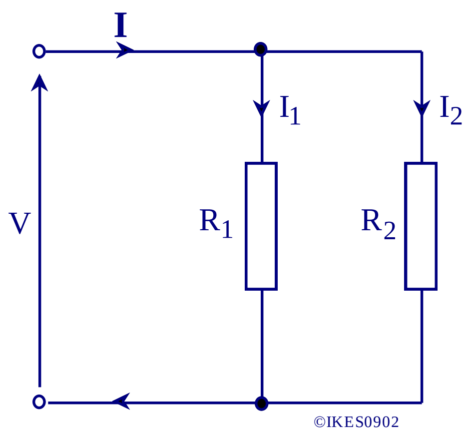
EXAMPLE

What single resistor could replace the three resistors shown in the diagram below?



$$\Rightarrow \mathbf{R = R_1 + R_2 + R_3 = 1.4 + 2.2 + 3.7 = 7.3k\Omega}$$

Resistors in Parallel



When two resistors, e.g. R_1 and R_2, are connected in parallel, as in the diagram above,

- the voltage across each resistor is the same, **V**,
- the total current, **I**, is equal to the sum of the currents in the separate resistors,

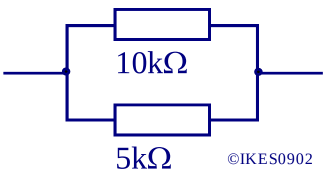
$$\mathbf{I = I_1 + I_2}$$

- the resulting resistance, **R**, is given by:-

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

EXAMPLE

What single resistor could replace the two resistors shown in the diagram below?

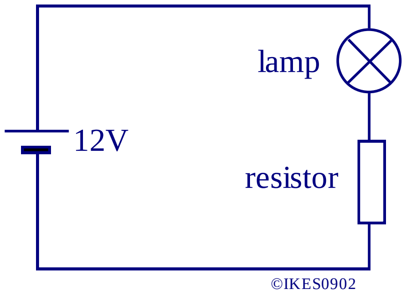


$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{10} + \frac{1}{5} = \frac{1+2}{10} = \frac{3}{10}$$

$$\Rightarrow R = {}^{10}\!/_{3} = 3.3\text{k}\Omega$$

There is a self marking assessment exercise on resistor combinations on the *IKES* website in the ‘IKES Online’, Homework section, which should be used to provide practice.

Since a resistor opposes the flow of electricity, it can be used to limit the current passing into a component. If a 6V, 60mA lamp was to be used in a circuit operating from 12V, too much current would pass through the lamp and it would be destroyed. If a suitable resistor is connected is series with the lamp, then the resistor can limit the current flowing to a safe level for the lamp. The arrangement is shown below.



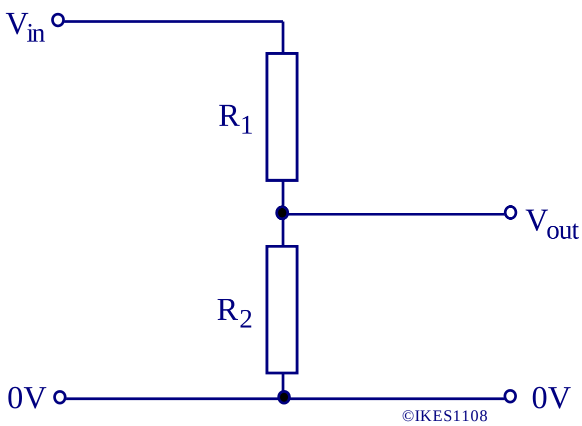
The value of the resistor is calculated using Ohm's Law.

The current passing through the resistor is the same as through the lamp, i.e. 60mA.
The lamp only requires 6V, and so there must be (12 - 6)V across the resistor, i.e. 6V.
Using Ohm's law,

$$\mathbf{R = \frac{V}{I} = \frac{6}{0.06} = 100\Omega}$$

Therefore the value of the resistor should be 100Ω.
This technique has many applications in electronics especially with LEDs.

Voltage Dividers



Two fixed resistors can be used to obtain a lower voltage from a fixed voltage supply. The circuit diagram of a voltage divider is shown above. The voltage across each resistor is in the same ratio as their resistances.
The output voltage, $\mathbf{V_{out}}$, is given by the formula below.

$$\mathbf{V_{out} = \frac{V_{in} \times R_2}{R_1 + R_2}}$$

This formula is only valid if there is no current passing from the output of the voltage divider.

EXAMPLE 1
Calculate the output voltage, V_{out}, from a voltage divider if R_1 is 10kΩ, R_2 is 20kΩ and the input voltage, V_{in}, is 12V.
Substituting into the formula above gives

$$V_{out} = \frac{12 \times 30}{10 + 30} = 9V$$

EXAMPLE 2

The output voltage from a CD player is 0.5V and an amplifier only requires an input signal of 0.05V to give maximum power. The CD player needs to operate into a resistance of at least 47kΩ. Design a suitable voltage divider to enable the CD player to be connected to the amplifier.

Problems of this type often cause difficulties because the circuit designer has to make a decision as to one of the component values. In this case the information about the CD player is helpful and since the minimum resistance for the CD player is 47kΩ, $\mathbf{R_1}$ can be set at this value. The voltage divider formula needs rearranging so that $\mathbf{R_2}$ can be found with the formula below.

$$R_2 = \frac{R_1 V_{out}}{V_{in} - V_{out}}$$

The values can now be substituted and $\mathbf{R_2}$ calculated.

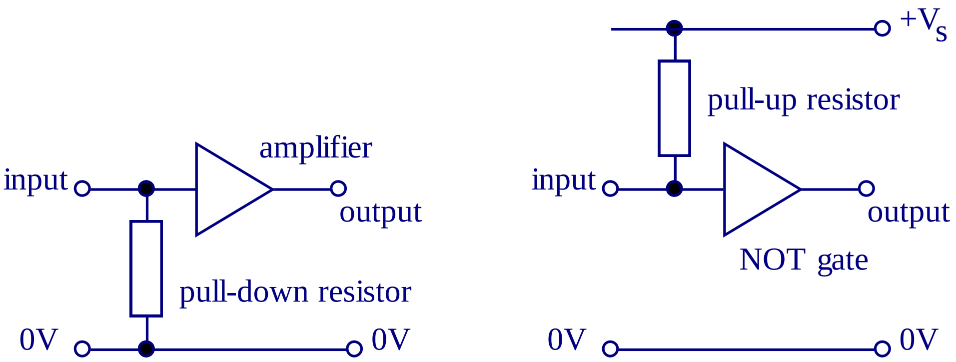
$$R_2 = \frac{47 \times 0.05}{0.5 - 0.05} = 5.22k\Omega$$

The nearest preferred value to this is **5.1kΩ**.

A variable resistor provides a convenient method of changing the resistor ratio. The output voltage is varied as the wiper is moved along the track. There are two types of variable resistor, with either a linear or a logarithmic track. A logarithmic variable resistor should be used for volume controls since its adjustment matches the change in volume as perceived by the ear.

Pull-up / Pull-down Resistors.

Electronic circuits often require inputs to be help either at 0V or at a specific voltage, often the supply voltage, until an input signal is applied. This is accomplished by using a resistor connected between the input and either 0V or the supply voltage. Two examples are shown below.
In the first example, the input of an amplifier is connected to 0V via a resistor to ensure that it does not pick up noise or interference in the absence of a signal. When a signal voltage is applied, a current passes through the pull-down resistor, causing a voltage at the input of the amplifier.
In the second example, the input of the NOT gate is held at $+V_S$ by the pull up resistor in the absence of a digital signal. If a logic 0 is applied to the input, by joining the input to 0V, then the pull-up resistor limits the current that passes.



There is a self marking assessment exercise on the Voltage Divider on the *IKES* website in the 'IKES Online', Homework section, which should be used to provide practice.

The Effects of an Electric Current

When electrons pass through a material, they 'collide' with the atoms that make up the material. With each collision they lose a small amount of energy, which is transformed into heat within the material. So when a current passes through a material, the material is heated.

The amount of heat produced depends on the following.

- the current flowing,
- the resistance of the material.

Each electron has associated with it a very small magnetic field. When electrons are moving around randomly with in a conductor the overall magnetic field created is zero because the random fields of each electron cancel. When electrons are forced to move in the same direction, i.e. when there is an electric current, then the magnetic fields of each electron are no longer random and a net magnetic field is created. The strength of the magnetic field is determined by how many electrons are forced to pass in the same direction i.e. on the strength of the electric current.

So an electric current produces both a **heating effect** and a **magnetic effect**.

Electric Power

It can be shown quite simply that the electric power given out (dissipated) by a component is the product of the voltage across the component and the current through the component, i.e.

$$\mathbf{P = V \times I}$$

But Ohm's law states that $\mathbf{V = I \times R}$

Combining these formulae together gives two more equations for power

$$\mathbf{P = I^2 \times R \text{ and } P = \frac{V^2}{R}}$$

Examples.

e.g. A current of 0.5A passes through a component when there is 6V across it. What power is dissipated in the component?

$$P = V \times I = 6 \times 0.5 = 3W$$

e.g. A 60W lamp operates from a 230V supply. What is the resistance of the lamp?

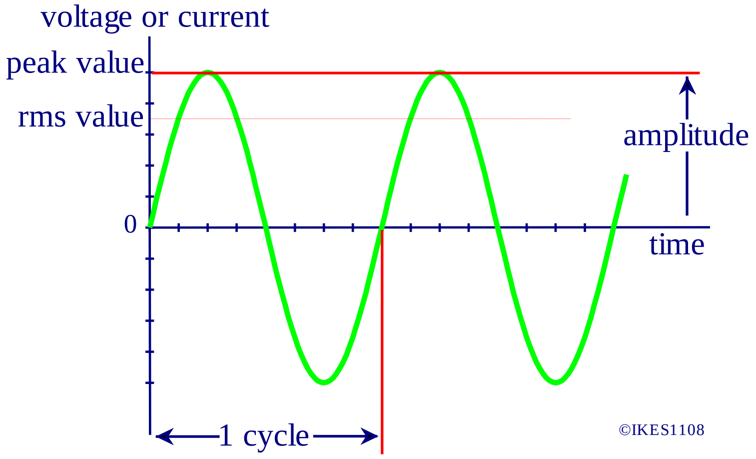
$$P = \frac{V^2}{R}$$

$$\Rightarrow R = \frac{V^2}{P} = \frac{230^2}{60} = 882\Omega$$

Students will need to be able to perform power calculations.

Alternating Current

While most electronic circuits require an electric current that flows in only one direction it is not economic or efficient to have a mains supply that is direct current (dc). All mains electricity is generated and distributed as **alternating current (ac)**. In Europe the direction of the current changes 100 times per second resulting in the alternating current having a frequency of 50Hz. In America the frequency of the mains supply is 60Hz.
For an alternating current (ac) the electrons flow first in one direction and then in the other at a regular rate producing a sine waveform as shown below.



The **amplitude** is the maximum positive or negative value of the current or voltage.
It is also known as the **peak** value.

The value of an alternating current or voltage changes continuously, which causes a problem for measurement. The average value of the current or voltage over one cycle is zero!
In order to do calculations for ac which are similar to those for dc, the *effective value* of the ac is used.

This effective value is called the **root mean square (rms) value** and is defined as the equivalent steady direct current or voltage which would give the **same heating effect** as the alternating current or voltage.

e.g. A lamp, designed to be fully lit by a direct current of 0.5A from a 6V battery, will be fully lit by an alternating current of $0.5A_{rms}$ from an alternating $6V_{rms}$ supply.

It can be shown that for sine waveforms,

$$\textbf{rms value} = \frac{\textbf{peak value}}{\sqrt{2}}.$$

This is usually approximated to

rms value = 0.7 × peak value
peak value = 1.4 × rms value

e.g. A mains transformer gives an output of $12V_{rms}$. What is the peak voltage?

peak value = 1.4 × rms value = 1.4 × 12 = 16.8V.

The time for one cycle is called the **PERIOD**.
The **frequency**, **f**, is measured in **Hertz** (Hz) and is the number of cycles per second;

$$\textbf{frequency} = \frac{\textbf{1}}{\textbf{time period}}.$$

when the period is measured in seconds.

e.g. If the alternating mains supply in the British Isles has a frequency of 50Hz, what is the time period?

$$T = \frac{1}{f} = \frac{1}{50} = 0.02\text{s or } 20\text{ms}.$$

3.4.2 Passive Components

Candidates should be able to:

- select components with appropriate power or current or voltage ratings for a given application
  (Constructional details of the components specified in the specification will not be examined.)
- interpret the markings on a resistor using the colour code and BS1852 code to determine its value and tolerance
- select an appropriate preferred value from the E24 series of resistors
- interpret the markings on a capacitor (excluding colour code), to determine the capacitance, voltage rating, tolerance and polarity (where necessary)
- interpret the markings on a surface mounted resistor or a capacitor using the BS code
- select an appropriate component from a given list of alternatives
- explain the differences in application and use of polarised and non-polarised capacitors
- select and describe the use of an appropriate switch, e.g. reed switch, microswitch, toggle switch, tilt switch etc
- recognise and recall circuits which make use of the components given above.

Candidates should be able to state and use the fact that:

- a diode conducts in one direction only
- the forward voltage drop of a silicon diode is 0.7V.

Candidates should be able to:

- explain the meaning of the terms forward-bias and reverse-bias
- explain the use of diodes in rectification as half-wave and bridge full-wave rectifiers
- explain the use of a diode connected across a relay coil or motor as a device to protect the semiconductor driver from damage
- use a light emitting diode (LED) and calculate the value of an appropriate series resistor for the LED
- use the fact that a light-dependent resistor (LDR) has a very high resistance in the dark and that its resistance decreases as the illumination increases
- use the fact that a thermistor (ntc type) has a resistance that decreases as the temperature increases
- recognise and recall circuits which make use of the components given above.

Although knowledge of the details of the construction of components is not required for this specification, there are occasions when such knowledge will help with an understanding of how the component works. When this is felt to be the case, details of construction are included just for information.

Apart from the actual value of a component, there are four other factors to consider when selecting a component for a circuit.

1). The **physical size** of the component. Some applications demand miniature components, e.g. mobile phones. The use of Surface Mounted Devices (SMDs) is essential in such applications, while the use of leaded components is often more useful in circuits like washing machine controllers, where space is not important.

2). The **cost** of the components. Very cheap components should not be used if it is likely to affect the reliability of the electronic system, especially in critical applications e.g. the Engine Management Units in cars!

3). The **power rating** of the component. Whenever a current passes through a component that has resistance, power is dissipated and the component will become hot. It is important when selecting components to ensure that the component is able to withstand **more** than the maximum power that it is likely to be subjected to in the worst possible case. This means that when selecting a component with a suitable power rating, the maximum power to be dissipated in the worst case should be calculated and then a component with a slightly higher power rating should be selected.

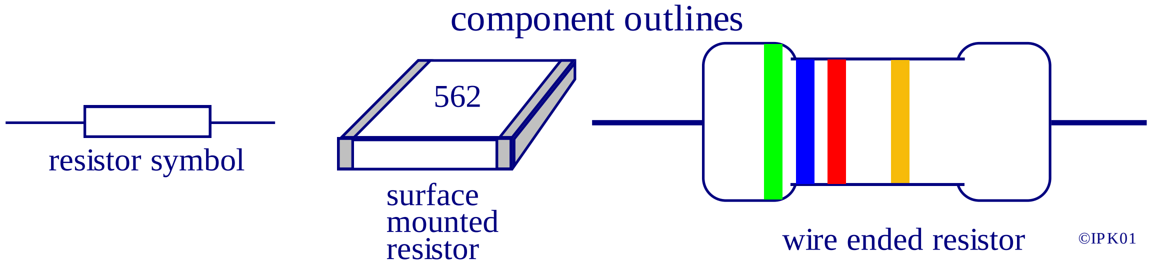
4). The **voltage rating** of the component. This is of primary importance with capacitors and semiconductors. If the voltage rating of a component is exceeded in the circuit then the electrons will have enough energy to make an excessive current flow, causing the component to dissipate power and so fail. As with the power rating of a component, the maximum voltage to be encountered by the component should be calculated and then a component with a higher voltage rating should be selected.

Components are said to be Passive if they are unable to provide any *broad-band amplification*. This means that components such as resistors, capacitors, normal diodes, LEDs etc. are described as passive. Section 3.4.3 deals with **active** components which are able to provide broad-band gain. These include such devices as transistors and MOSFETs.

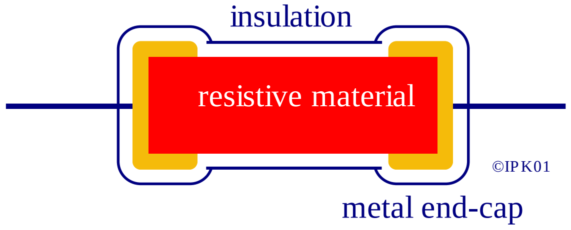
Resistors

A resistor is a component that restricts the electric current passing through a circuit.
It is therefore useful for limiting the amount of current passing through a component.
A resistor is also useful for providing a voltage across it when a current is passed through it.

Resistors are either shaped like a tube with a wire coming from each end or, if it is a *surface mounted* resistor, as a tiny square with two solder connections. Both types have the symbol shown below.



A resistor consists of two metal end caps with a resistive material placed in between as shown in the cross-sectional diagram below



There are three common substances used for the resistive material.
These are Carbon, Metal Oxide and Thin Wire.

Carbon resistors are cheap but they tend to be unstable (their resistance changes with temperature and time) and can produce unwanted noise in circuits.
Metal oxide resistors are more expensive but are more accurate (smaller tolerance), more stable and produce much less electrical noise.
Wire wound resistors are the most expensive but can be very stable and accurate. They can often be designed to dissipate large amounts of power. However, because they are made from a coil of fine wire they are of little use in radio circuits since they have appreciable inductance.

Resistance is measured in units called **ohms**, in memory of Georg Simon Ohm who did much work on resistance during the nineteenth century.
The symbol for the ohm is the capital Greek letter Omega, drawn as **Ω.**

Resistor Tolerance

Although manufacturing techniques have improved significantly during the last few years, the value of a resistor is unlikely to be exactly the same as the value marked on it. The tolerance of a resistor shows how close its actual value was to its marked value when it was made.
e.g. a 100Ω resistor with a tolerance of ±10% could have a value between 90Ω (100 - 10) and 110Ω (100 + 10).

Typical tolerances are ±1%, ±2%, ±5% and ±10% and individual resistors are marked accordingly.

Printed Code

This code, BS1852, is printed on resistors, variable resistors and is also sometimes used on circuit diagrams. It consists of letters and numbers.

$$\mathbf{R \equiv \times 1 \qquad K \equiv \times 1000 \qquad M \equiv \times 1000000}$$

The position of the letter indicates the position of the decimal point,

e.g. 4R7 ≡ 4.7Ω, 4K7 ≡ 4.7kΩ 4M7 ≡ 4.7MΩ

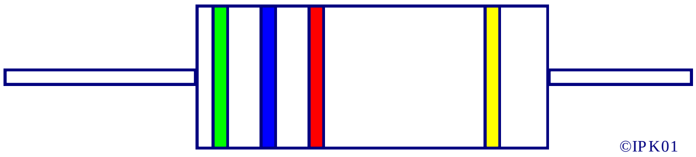
The tolerance of the resistor is given by the letter at the end of the code.
The letters used are:-

F = ±1%, G =± 2%, J = ± 5%, K = ± 10%, M = ± 20%

e.g. 270RG = 270Ω ± 2% , 47KJ = 47kΩ ± 5% , 1M5K = 1.5MΩ ± 10%.

Resistor Band Colour Coding

A resistor has either four or five coloured bands painted on it, although this specification only considers resistors with four bands as shown below.



The first two bands give the value in significant figures, the third gives the multiplier and the fourth the tolerance.

Colour.	First	Second	Third	Fourth
Black	0	0	—	—
Brown	1	1	0	±1%
Red	2	2	00	±2%
Orange	3	3	000	—
Yellow	4	4	0000	—
Green	5	5	00000	—
Blue	6	6	000000	—
Violet	7	7	—	—
Grey	8	8	—	—
White	9	9	—	—
Silver	—	—	0.01	±10%
Gold	—	—	0.1	±5%

e.g. a resistor with bands of green, blue, red, gold
has a value of 5 - 6 - 00 - ±5%
i.e. 5.6kΩ ± 5%.

e.g. a resistor with bands of yellow, violet, brown and gold
has a value of 4 - 7 - 0 - ±5%
i.e. 470Ω ±5%.

Students will need to be able to calculate resistor values from their colour codes.

There is a self marking assessment exercise on the *IKES* website in the IKES ‘Online’, Homework section, which should be used to provide practice.

Preferred Values

Since exact values of fixed resistors are unnecessary in most circuits, only certain *preferred* values are made. The values chosen for the E24 series (with ± 5% tolerance) are as follows.

1.0, 1.1, 1.2, 1.3, 1.5, 1.6, 1.8, 2.0, 2.2, 2.4, 2.7, 3.0, 3.3, 3.6, 3.9, 4.3, 4.7, 5.1, 5.6, 6.2, 6.8, 7.5, 8.2, 9.1, and multiples that are powers of ten greater.

These values give maximum coverage with minimum overlap with the ± 5% tolerance.

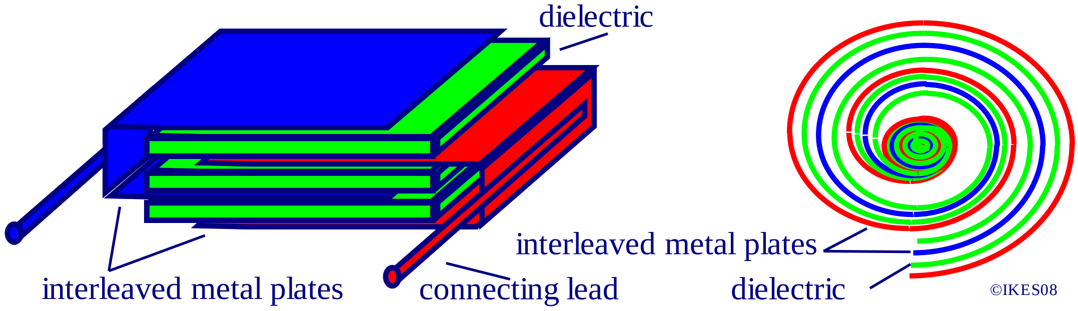
When a resistor value has been calculated it will often fall in between two of the preferred values. The one that is chosen will depend on the application within the circuit. If the absolute maximum value for current flow has been used in the calculation then it will usually mean that the preferred value that is the next largest to the calculated value will be selected. This will ensure that the maximum current is not exceeded. This is an important consideration when working with LEDs.

Uses of resistors

- limiting the current flow through a device e.g. LED, zener diode, base of a transistor,
- converting a current flow into a voltage,
- converting a voltage into a current,
- voltage divider circuits,
- with capacitors as charging and discharging circuits.

Capacitors

The diagram below shows the construction of capacitors.



A capacitor consists of two overlapping conducting plates separated by an insulator called the dielectric. The separation of the two plates is often very small. When a voltage, V, is applied across the two conducting plates they store electrical charge, Q (+Q on one plate and –Q on the other). The charge stored per volt is called the capacitance, C.

$$\Rightarrow \quad \mathbf{C} = \frac{\mathbf{Q}}{\mathbf{V}}$$

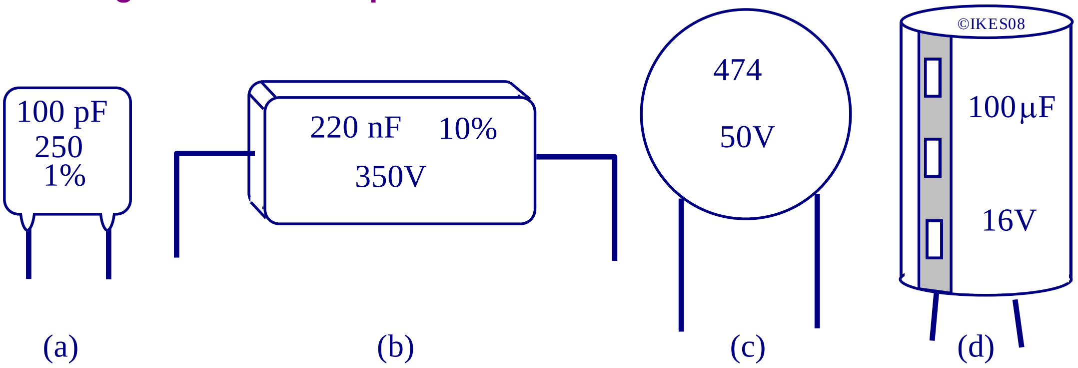
The unit of capacitance is the farad (F). This is the capacitance required to store a charge of 1 coulomb when there is a voltage of 1 volt across the plates.
This is a very large unit and so sub-units are usually used:-

1 microfarad	(1 μF)	$= 1 \times 10^{-6}$F
1 nanofarad	(1 nF)	$= 1 \times 10^{-9}$F
1 picofarad	(1 pF)	$= 1 \times 10^{-12}$F

The capacitance increases when:
- the area of overlap of the plates is increased,
- the distance between the plates is decreased,
- an insulator (dielectric) with a higher dielectric constant is used.

When selecting capacitors for a particular use, the factors to be considered are as follows:
- the capacitance,
- the tolerance,
- the working voltage, (This is the largest voltage which can be applied across the plate before the dielectric breaks down and conducts.)
- the leakage current, (No dielectric is a perfect insulator but the loss of charge through it should be small.)

The Markings on a Fixed Capacitor



The diagram above shows some typical component outlines of capacitors and the typical markings found on them.

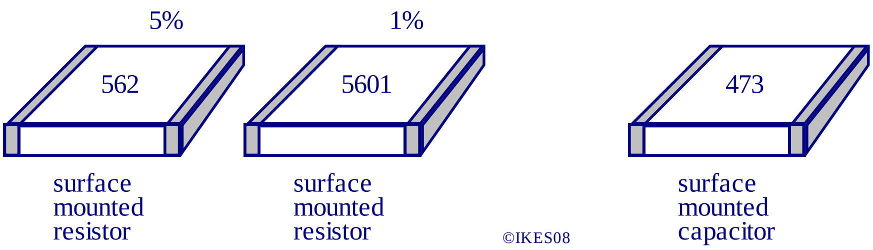
Types (a) and (b) are typical of close tolerance capacitors which have their value, working voltage and tolerance marked.

Type (c) represents a ceramic capacitor with its value (474 ≡ 470000pF ≡ 0.47µF) and working voltage marked.

Type (d) represents an electrolytic capacitor and has its value, maximum working voltage and polarity marked.

Electrolytic capacitors are made by electrolysis; the two plates are coated with liquid and a current passed between them. This forms a very thin layer of dielectric on one plate. Electrolytic and tantulum capacitors are polarised and must be connected the correct way round.

As a result of the small size of surface mounted resistors and capacitors, their values are identified by a number, as shown in the diagram below.



The code used for the value consists of three numbers for a 5% (or greater) tolerance or four numbers for a 1% tolerance. The first two (or three) numbers give the significant figures of the value and the third (or fourth) figure gives the multiplier.

e.g. for the surface mounted resistors in the diagram the value of the 5% device is 5600 ohms i.e. 5.6kΩ
The 1% resistor has the same value 5600 ohms
i.e. 5.60kΩ
For capacitors the value is given in picofarads (pF), so the value is 47 000pF
i.e. 47nF or 0.047µF

Direct current does not pass through an ideal capacitor since there is an insulator separating the metal plates that form the capacitor. However, if a voltage larger than the insulator will withstand (the working voltage) is applied, then the electrons will have enough energy to break through the insulator and cause a current to pass. Any passage of current will cause energy to be dissipated and so the capacitor will be rapidly destroyed. It is very important therefore, to ensure that the maximum working voltage of a capacitor is greater than the voltage that the capacitor will actually experience.

Large valued capacitors using separate metal plates and insulators will be physically large. In order to produce large valued capacitors with a small physical size it is necessary to use a different technique. This consists of using thin aluminium foil for the plates. This foil has a chemical coating which causes a layer of aluminium oxide to form between the plates which acts as the dielectric. This oxide layer is produced by electrolysis, which means that there must be a small current passing between the plates. In other words, the capacitor must have a leakage current to maintain the dielectric and the capacitor is therefore polarised, i.e. it must be connected the correct way round in the circuit.
Such capacitors are known as ELECTROLYTIC capacitors.
Usually the negative terminal is marked with 

Electrolytic capacitors have the following weaknesses:

- poor tolerance (often ±50%) of their stated value,
- poor stability (the value changes with time),
- poor high frequency response as a result of the tightly coiled aluminium plates,
- noise which is introduced by the leakage current and
- a leakage current can interfere with critical timing circuits.

They are, however, the only way to obtain large value capacitors that are physically small. Capacitors made from Tantalum have better characteristics than normal electrolytic capacitors but are considerably more expensive.

Electrolytic capacitors are mainly used for smoothing and decoupling (removal of low frequency signals) from power supplies. Wherever possible, their use in the signal path of circuits should be avoided so as to minimise signal distortion. Non-polarised capacitors should be used instead.

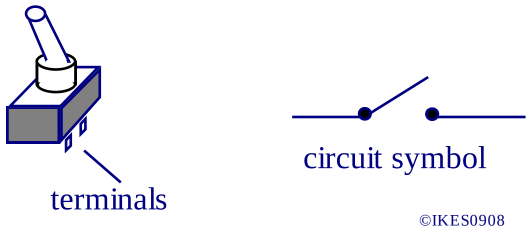
Uses of capacitors

- smoothing out variations in power supplies,
- removing alternating signals,
- blocking the passage of direct current while allowing the passage of alternating current,
- combination with inductors for resonant tuned circuits,
- combination with resistors as charging and discharging circuits.

Switches

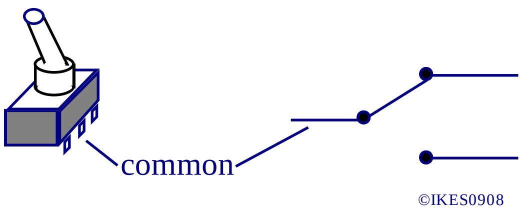
There are many different types of switch available but they all have a single feature in common - they all rely on the mechanical movement of pieces of metal to come into contact and so close an electrical circuit, or separate, to break a circuit.
Switches with contacts that close to make a circuit are known as **Normally Open** or **NO**.
Switches with contacts that are normally closed and open to break a circuit are known as **Normally Closed** or **NC**.
With switches, the change in resistance is dramatic, from almost zero ohms when the contacts are closed to almost infinite resistance when the contacts are open.

The most readily identifiable switch is the "Toggle Switch" which is often used as an On/Off switch in electrical equipment. It is also used to operate most lighting circuits both in the home and in the work / educational place. A diagram of a toggle switch is shown below.



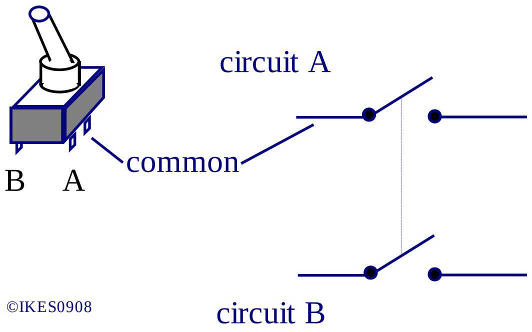
The switch is operated by moving the lever. The lever is spring loaded so that as soon as the switch starts to operate, the spring helps complete the operation quickly to minimise any sparks between the contacts that may form as the circuit is made or broken.

The switch shown above can only control one circuit and so is known as a Single Pole, Single Throw (SPST) switch. Toggle switches are also available that can switch between two circuits as shown in the diagram below



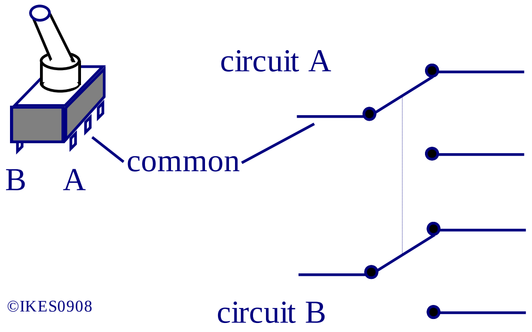
Such a switch is known as a Single Pole, Double Throw (SPDT) switch and, as can be seen in the diagram above, it can be used to switch power between two different circuits.

Although a SPST switch can be used as a mains On/Off switch for an appliance so long as it is wired into the Live wire, it is safer if both the Live and Neutral wires are switched (in case someone wires the plug incorrectly!). Such a switch would have to contain two separate switches but both controlled by the one lever. Such a switch and its use is shown in the diagram below.

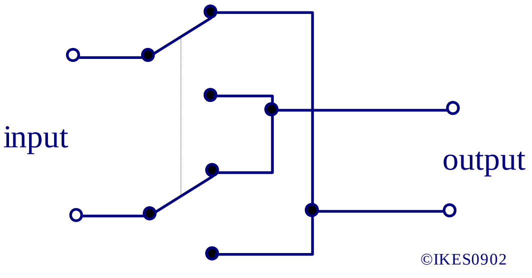


The switch above is a Double Pole, Single Throw (DPST) switch, the "Pole" referring to the fact that there are two separate switches, both controlled by the same lever.

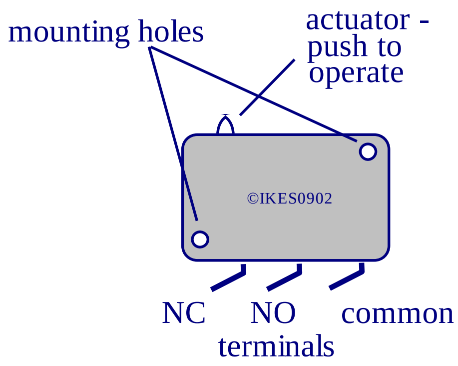
It is also possible to combine all of these features together and produce a Double Pole, Double Throw (DPDT) switch, which is effectively two completely separate change over switches operated by the same lever, as in the diagram below.



Such switches can be used to reverse the direction of current flow in a circuit and so can be used to switch from "forwards" to "reverse" on a model train set.
The circuit diagram of such a reversing switch is shown below.

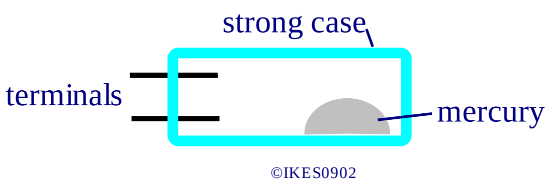


Sometimes a switch is required that operates with a much smaller movement than a toggle switch e.g. the safety switch on a microwave cooker, which switches off the power if the door is opened. Such switches are known as microswitches, the ‘micro’ referring to the movement needed to operate the switch, not to its physical dimensions or its current carrying capacity, which can often be as high as 15A. A diagram of a microswitch is shown below.



Most microswitches are SPDT types. They can also be used on remote control buggies and robots as ‘collision’ detectors.

A ‘tilt switch’, as its name implies, will operate when tilted, and so can be used in anti theft devices. The original tilt switches consisted of two metal electrodes encapsulated in plastic along with a small amount of mercury, as shown in the diagram below.



When the switch is tilted in one direction, the mercury flows to the end with the electrodes and so completes the circuit between the electrodes. When tilted in the opposite direction, the mercury flows to the opposite end and so breaks the circuit.
For safety reasons, most tilt switches now have a small metal ball instead of the mercury.

Another useful switch is one that operates in the presence of a magnetic field. Such switches are known as ‘Reed Switches’ and are often used in burglar alarm systems to detect when a door is open or closed. A reed switch is shown in the diagram below.

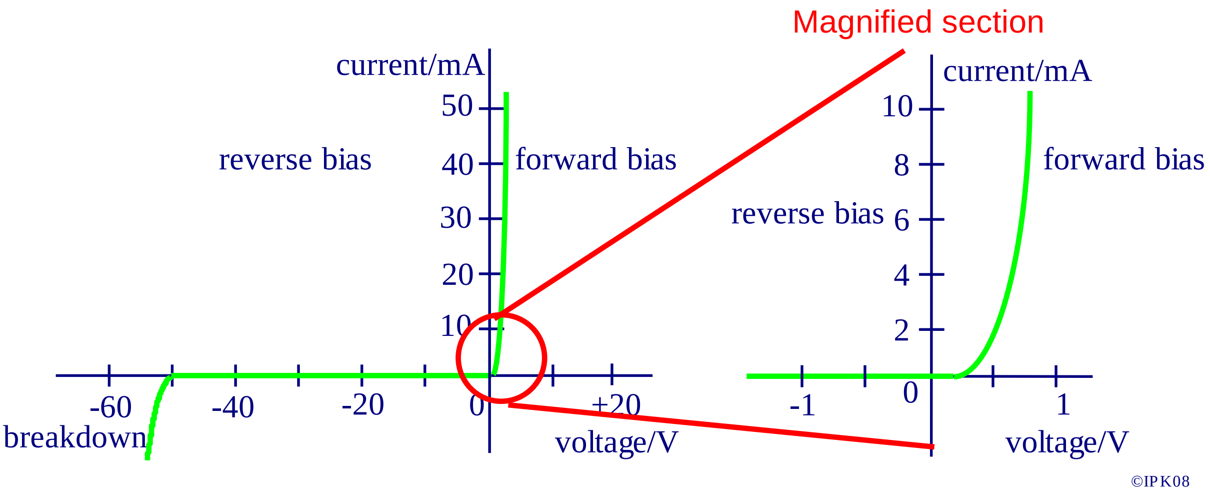
It consists of two thin pieces of steel with gold plated contacts.
The pieces of steel are magnetised so that they repel each other and so keeping the contacts apart.
When a strong magnetic field is placed near to the reed switch, this external magnetic field induces an opposite magnetic field which causes the contacts to close.
As soon as the external field is removed, the contacts open again.
Although most reed switches are SPST types, it is possible to obtain SPDT types.
Reed switches are only suitable for switching small currents (<200mA) but because of the small movement of the contacts they can switch quickly (a few hundred Hertz).

Diodes

A diode is a semiconductor device that only allows current to pass one way. The symbol for a diode is shown below, the direction of the arrow indicating the direction of the conventional current flow from anode to cathode.

When the current passes from the anode to the cathode of the diode, the anode is positive with respect to the cathode and the diode is said to be *forward biased*.
When the cathode of a diode is positive with respect to the anode then no current will flow and the diode is said to be *reverse biased*.

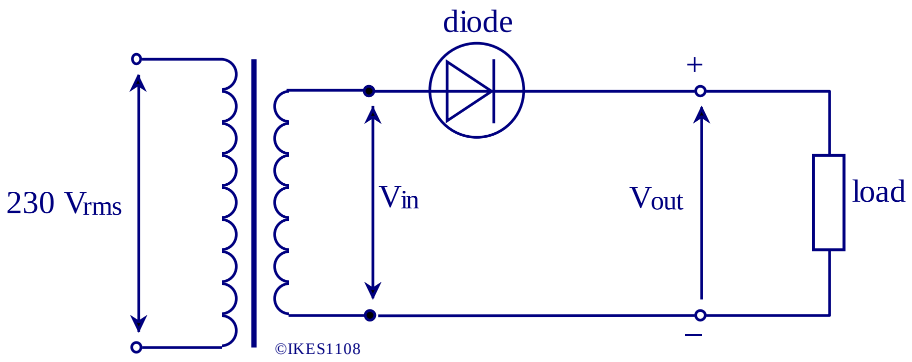
When a silicon diode is forward biased, conduction does not start until the voltage across it is about 0.7V. Once conduction has started, a very small increase in voltage produces a large increase in the current as shown in the diode characteristics below.



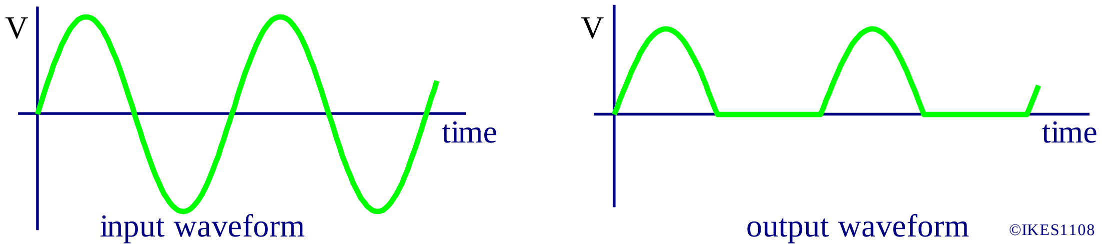
Rectification

In many power supply units a transformer steps down the alternating mains from 230Vrms to 6, 9, or 12Vrms. This is then converted to direct current using a rectifier consisting of one or more silicon diodes. A diode is a semiconductor device which is made so that it has a low resistance in the forward direction (forward bias) and a very high resistance in the reverse direction (reverse bias).

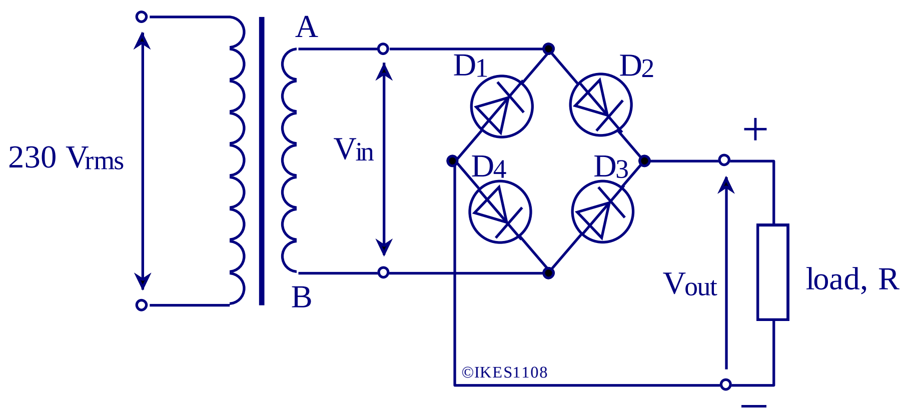
A half -wave rectifier consists of a single diode as shown below.



On each positive half cycle of the ac input from the transformer the diode conducts, so producing a voltage across the load resistor. The peak voltage is about 0.7V less than the input peak voltage. On each negative half cycle the diode does not conduct so there is no voltage across the load. The graphs below show the input and output waveforms. The output voltage is unidirectional but is not smooth.



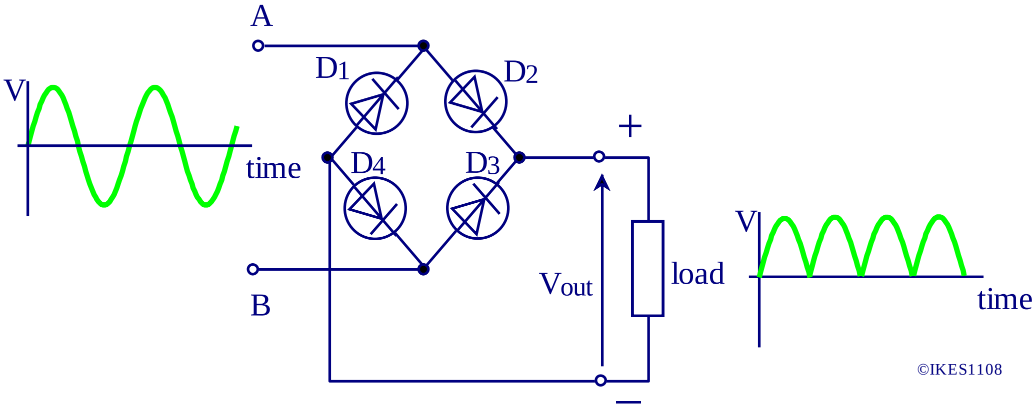
A full wave rectifier uses four diodes in a bridge network as shown below.



In each half cycle when A is positive with respect to B, diodes D_2 and D_4 conduct and the current takes the path A $\rightarrow D_2 \rightarrow$ R $\rightarrow D_4 \rightarrow$ B.

In each half cycle when B is positive with respect to A, diodes D_1 and D_3 conduct and the current takes the path B $\rightarrow D_3 \rightarrow$ R $\rightarrow D_1 \rightarrow$ A.

Therefore the current through R is unidirectional, but the output waveform is a varying dc as shown below.



The two important parameters for a rectifying diode are as follows.

1). The **maximum forward current**, $\mathbf{I_F}$, which, if exceeded, causes overheating leading to the destruction of the diode,

2). The **maximum peak inverse voltage**, P.I.V., which, if exceeded, causes permanent damage because of the large reverse currents that flow.

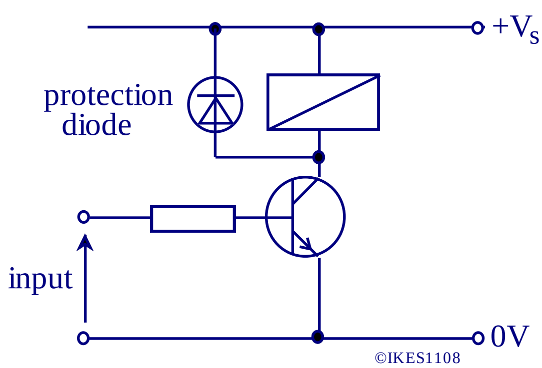
The diode chosen must be able to carry the required output current of the power supply. In a bridge rectifier, two diodes are always conducting and since their resistances may not be equal, it is necessary to choose diodes having a P.I.V. equal to *at least twice* the peak input voltage.

The full-wave rectifier is generally preferred to the half-wave rectifier since an output voltage is produced on each half cycle rather than just the positive half cycle. This makes the output easier to smooth.

The choice of suitable diodes for use in a rectifier depends on their characteristics and the specification for the power supply, but each diode should have a P.I.V. of at least twice the output voltage of the power supply.

A full wave rectifier consisting of four diodes is available in a single package with two ac input terminals and two dc output terminals.

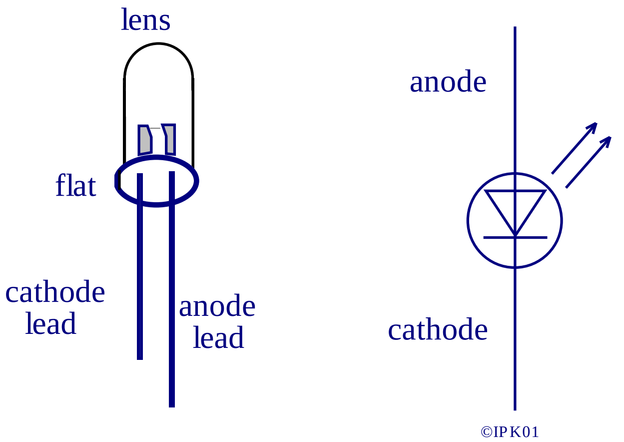
A diode can also be used to protect semiconductor devices against high voltages.



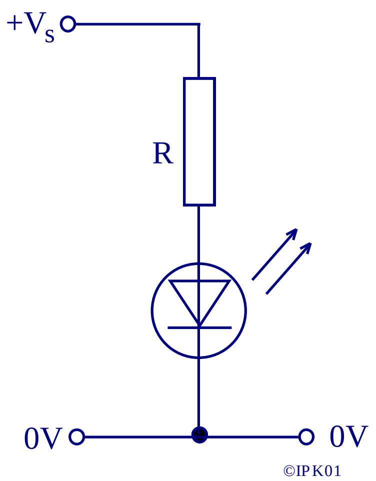
When the current in the coil of a relay or a reed switch falls to zero, a large 'reverse' voltage is induced in the coil due to its inductance. This induced voltage would damage the transistor used to drive the relay. A diode is connected in parallel with the relay so that it is in reverse bias with the voltage supply. The diode offers an easy path to the induced voltage and so prevents it damaging the transistor, as in the diagram above.

Light Emitting Diode (LED)

LEDs provide a very convenient way of obtaining an output from the processor of an electronic system, since they can be interfaced directly to logic gates and op-amps.



An LED is a diode made from the semi-conductor gallium arsenide phosphide. Its component outline and symbol are shown opposite.
When forward biased it conducts and emits light of a certain colour depending on its composition.
No light emission occurs in reverse bias and if the reverse voltage exceeds approximately 5V then the LED may be damaged.



A LED requires a series resistor to ensure the current does not exceed its maximum rating. If in doubt this should be taken as 20mA.
The forward voltage drop across a LED is about 2V, though it does depend upon the colour of the LED.
(A blue LED can have a forward voltage drop across it of 4.5V.)
The data sheet for an LED will show its maximum current and the forward voltage drop.
To calculate the value of the series resistor follow these steps:-
1). Calculate the voltage across the series resistor. This will equal the supply voltage minus the forward LED voltage.
2). The LED current will also pass through this resistor and so, using Ohm’s law, the resistor will equal the voltage across it divided by the current passing though it.
3). The **minimum** value used for R should be the next **largest** preferred value.

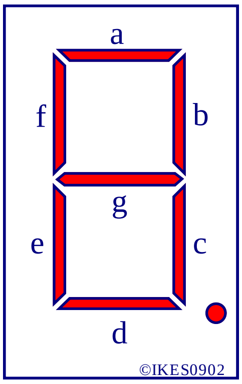
Example

A green LED has a forward voltage of 2.5V at a maximum current of 25mA.
The LED is to be powered from a 9V battery, calculate a suitable series resistor.
STEP 1. The voltage across the LED is 9 – 2.5V = 6.5V.
STEP 2. R = 6.5 / 0.025 = 260Ω
STEP 3. The next largest preferred value is 270Ω.

LEDs are used as indicator lamps and in seven-segment displays. They have the advantages of small size, long life, a small operating current and high operating speed. There is now a large range of different LEDs readily available with outputs ranging from infra-red to ultra-violet wavelengths and sizes ranging from 1mm to 50mm.

Students will need to be able to calculate the series resistor for LEDs.
There is a self marking assessment exercise on the *IKES* website in the IKES ‘Online’, Homework section, which should be used to provide practice.

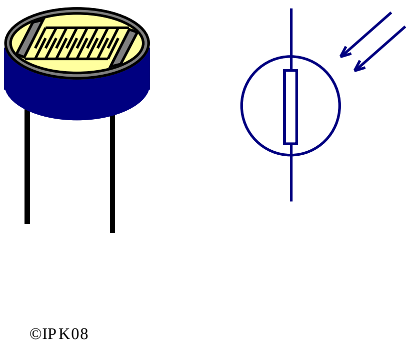
Seven Segment Array

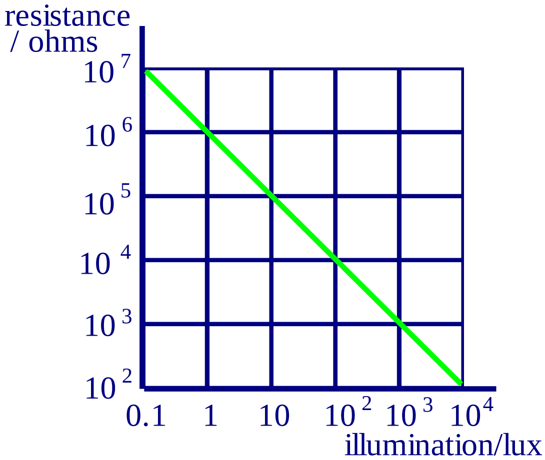


Electronic calculators, clocks, cash registers and measuring instruments often have seven-segment LED displays as numerical indicators. Each segment is an LED and by lighting up different segments all numbers from 0 to 9 can be displayed. Each segment needs a separate current limiting resistor to prevent damage to the segment by excess power dissipation.
All the cathodes (common cathode type) or all the anodes (common anode type) are joined to form a common connection. If the driving circuit is made from transistors, so that the seven-segment display segments are connected in the collector circuits, then a common anode display will be required.

The Light Dependent Resistor (LDR)

The resistance of a light dependent resistor decreases as the illumination on it increases.
It can therefore convert changes in light intensity into changes in electric current.
The LDR consists of metal electrodes embedded into the surface of a film of cadmium sulphide.
Its component outline, symbol and a typical characteristic are shown below.



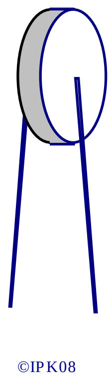


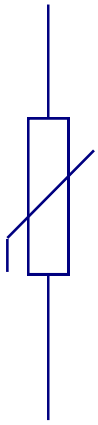
There is only one type of LDR readily available and it has the code number of ORP12.

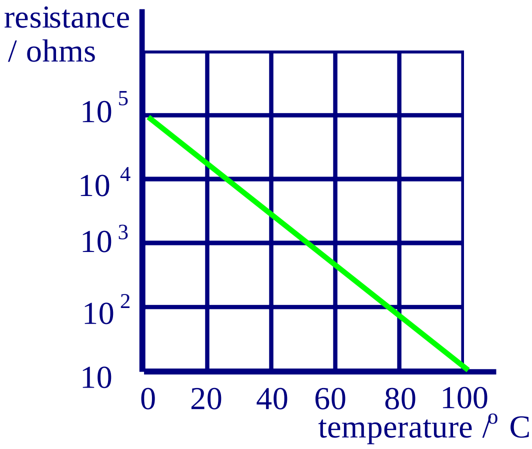
As light level increases, the LDR resistance decreases.

Thermistors (negative temperature coefficient, n.t.c.)

This is a resistor whose resistance decreases considerably when its temperature rises.
It can therefore convert changes in temperature into changes in electric current.
Its component outline, symbol and a typical characteristic are shown below.





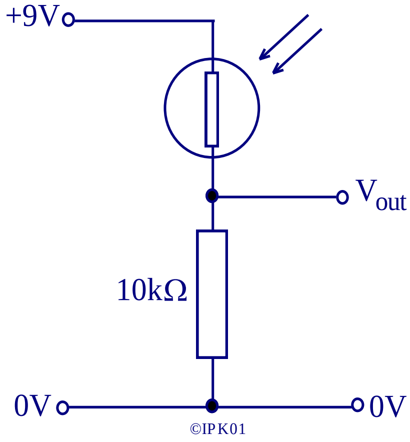


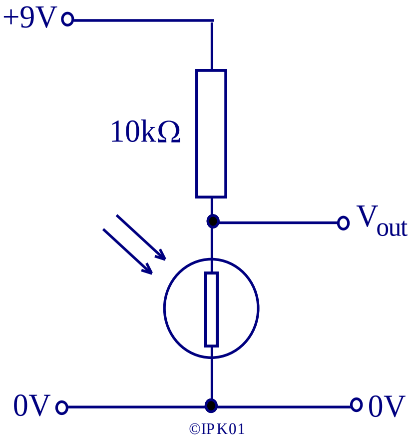
There are many different types of thermistor available varying in both physical size and the change of resistance with temperature.

As temperature increases, the thermistor resistance decreases.

Using Resistive Input Transducers with a Voltage Divider

Consider the circuit opposite.
Resistor R_1 of a voltage divider has been replaced with a LDR which has a resistance of 1MΩ in the dark and 100Ω in bright light.
It is a worthwhile exercise to verify that in the dark, V_{out} is 0.089V and in the light, V_{out} is 8.9V.
This circuit, therefore, gives a logic 0 output in the dark and a logic 1 output in the light.





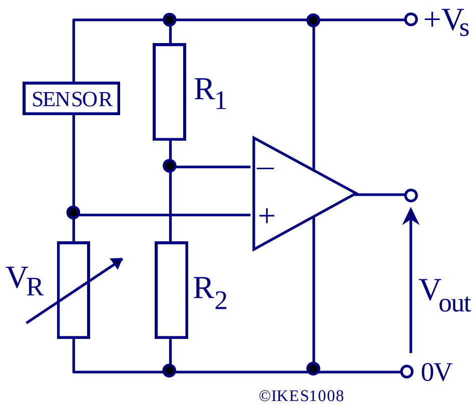
Consider the circuit opposite.
Resistor R_2 of the voltage divider has been replaced with a LDR which has a resistance of 1MΩ in the dark and 100Ω in bright light.
It is a worthwhile exercise to verify that in the dark, V_{out} is 8.9V and in the light,
V_{out} is 0.089V.
This circuit, therefore, gives a logic 1 output in the dark and a logic 0 output in the light.

In both of these circuits the LDR could be replaced with a thermistor, so that the output voltage was dependent upon temperature rather than on light intensity.

These circuits can be connected directly to CMOS type logic gates, since the gates have a very high input resistance and take almost no current from the output of the voltage divider. They can also be connected directly to op-amp comparators because the input resistance of the op-amp is very large.

Example

Consider the circuit diagram below.



The sensor shown in the circuit above could be a thermistor or LDR.. For an LDR, as the light intensity increases the resistance of the LDR decreases. So therefore $\mathbf{V_+}$ becomes larger as the light intensity increases. When the light is dim, $\mathbf{V_+}$ is less than $\mathbf{V_-}$ and so the output saturates at **0V**. When the light is bright, $\mathbf{V_+}$ is greater than $\mathbf{V_-}$, and so the output saturates at $\mathbf{+V_s}$. The value of the light intensity at which this change occurs is set by the value of the variable resistor $\mathbf{V_R}$.
The output voltages can be reversed (i.e. $\mathbf{+V_s}$ in dim light) in two ways.

(a) the input connections to the op-amp can be swapped over, or
(b) the variable resistor and sensor can be swapped.

3.4.3 Active Components

Candidates should know that:

- a bipolar transistor is a 3-lead device, the lead names being emitter, collector and base. (Examination questions will be restricted to npn silicon transistors.)
- a MOSFET (Metal Oxide Semiconductor Field Effect Transistor) is a 3-lead device, the lead names being source, drain and gate.
  (Examinations questions will be restricted to n-channel type devices.)

Candidates should be able to:

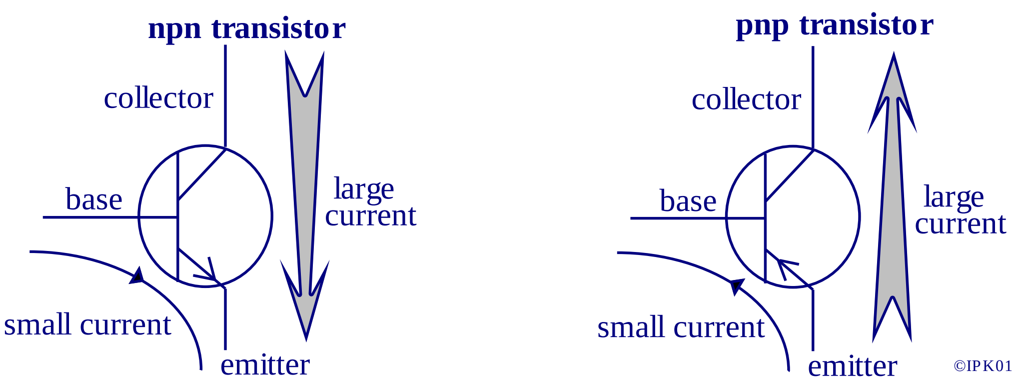
- explain how an npn transistor and an n-channel MOSFET can be used as switches after gates, counters etc., as drivers to deliver power to an output device, and put this into practice
- explain why a base resistor is needed for an npn transistor
- compare the advantages and disadvantages of a MOSFET with a bipolar transistor
- recognise and recall circuits which make use of the components given above.

Bipolar Transistors

A bipolar transistor has three terminals and amplifies currents.
There are two types of junction transistor:-

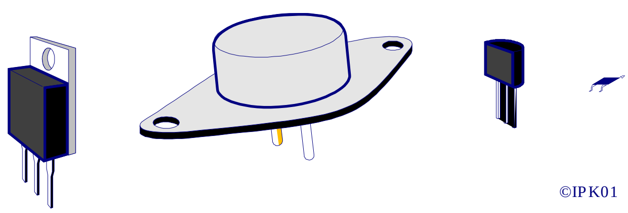
npn transistors which amplify a positive current,
pnp transistors which amplify a negative current.

Their symbols and current flow diagrams are shown in the diagram below.



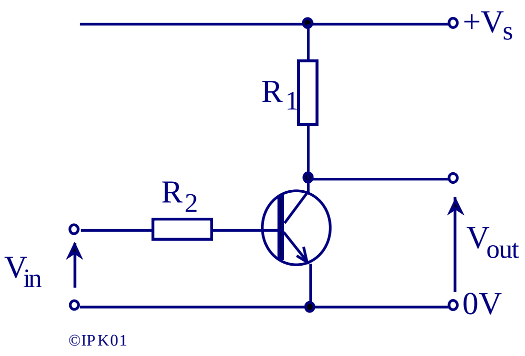
This specification only requires a knowledge of npn transistors.

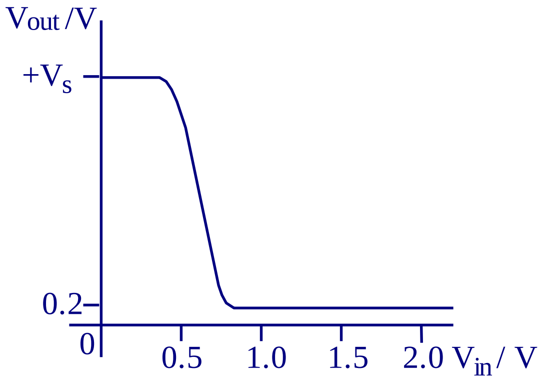
Transistors come in several shapes and sizes as shown below.



In normal operation, the base-emitter junction of a transistor behaves like a forward biased diode. When a small current passes through the base emitter junction a much larger current is made to pass through the collect and emitter. Since the base emitter behaves as a forward biased diode, for a silicon transistor there will be a voltage of 0.7V between the base and emitter when a collector current passes.

The diagram below shows an npn transistor arranged as a switch.
The graph shows how V_{out} varies with V_{in}.

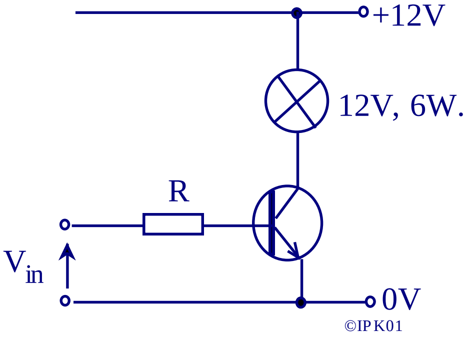




As can be seen from the graph, the output voltage remains at the supply voltage, $+V_s$, until V_{in} approaches 0.5V.
At this voltage a small collector current flows and V_{out} begins to fall.
When V_{in} reaches about 0.7V, the maximum collector current is flowing (limited by R_1) and the transistor saturates with a collector-emitter voltage of about 0.2V.
Any further increase in V_{in} has no effect on V_{out}.
The transistor is therefore operating as a switch.

When V_{in} is less than 0.5V, V_{out} is equal to the supply voltage.
When V_{in} is greater than 0.7V, V_{out} is 0.2V.

The resistor in the collector circuit, R_1, can be replaced with any form of load,
e.g. a 12V, 6W lamp that needs to be switched by a small current, e.g. from a logic gate.



In this case the current needed to pass through the lamp, and therefore the collector current, is 0.5A.
To ensure that as little power as possible is dissipated in the transistor, it is essential that the transistor is saturated when conducting. Since the range of current gains for transistors of the same type can be wide, it is normal to use a resistor, possibly even as low as 470Ω to ensure saturation.

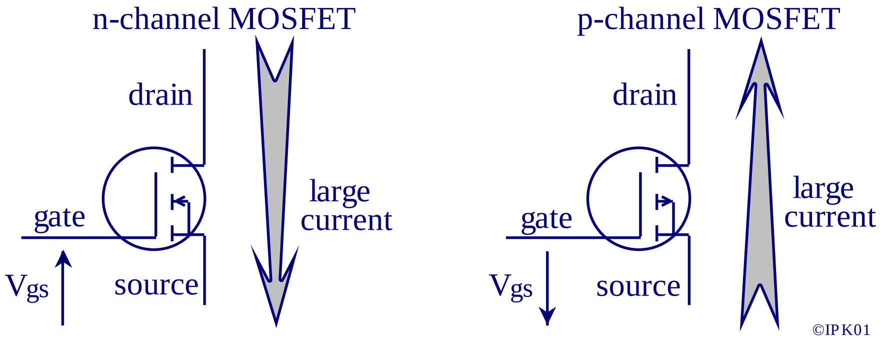
The power dissipated in the transistor when switched **'on'** equals the collector current multiplied by the collector-emitter voltage. In this case

$$\textbf{Power} = I_c \times V_{ce} = 0.5 \times 0.2 = 0.1\text{W}$$

The input resistance of a transistor switch circuit is low, of the order of 1kΩ.
This can provide an unacceptable drain on some circuits.
A better alternative to junction transistors are enhancement mode MOSFETs.

Enhancement Mode MOSFETs

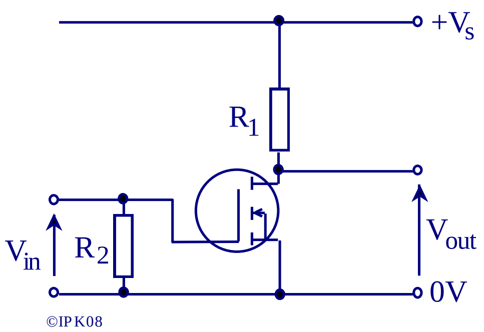
Enhancement mode MOSFETS are voltage operated, three terminal devices.
They have a very large input resistance, (>50MΩ), and a correspondingly large current gain.
Their electrical symbols and current flows are shown below.

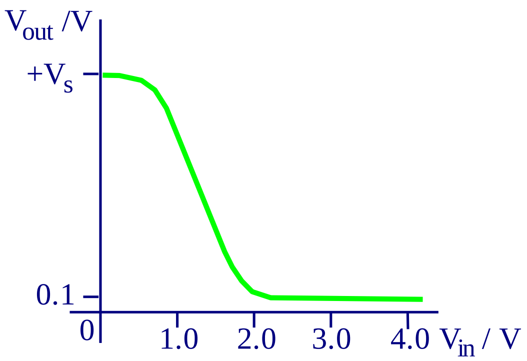


This specification requires only a knowledge of the n-channel MOSFET.

To obtain a drain current, $\mathbf{I_d}$, a voltage, $\mathbf{V_{gs}}$, is applied between the gate and source.

The diagram below shows an n-channel MOSFET arranged as a switch.





As can be seen from the graph of V_{out} against V_{in}, the output voltage does not change much until V_{gs} is greater than approximately 1V.
Drain current passes and the MOSFET saturates at about 0.1V, when V_{gs} is about 2V.
The actual values depend on the type of MOSFET and the drain current passing.
Any further increase in V_{in} has no effect on V_{out}.
The MOSFET is therefore operating as a switch in the same way as the transistor.

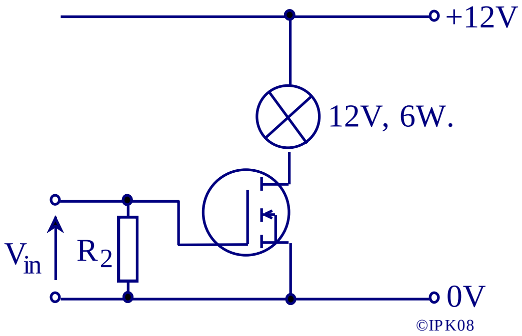
There are many different MOSFETs available and the one selected should be able to:-

- operate at the supply voltage (V_{ds}),
- pass sufficient drain current (I_d),
- dissipate sufficient power (P_d),
- give a very low drain to source resistance (r_{ds}).

For this example, V_{ds} (voltage across the drain and source) must be greater than 12V.

I_d (the drain current) must be greater than 0.5A.

R_{ds} (the drain to source resistance) must be low, preferably less than 0.1Ω.



With a value of $R_{DS} = 0.1\Omega$, the power dissipated is

$$\mathbf{P_D = I_D^2 \times R_{DS} = 0.5^2 \times 0.1 = 0.025W}$$

The resistor R_2 is not strictly necessary but it will prevent any damage to the MOSFET by static electricity.
A typical value for R_2 would be 1MΩ.
Again, using components that are operating at the limit of their specification leads to poor reliability.
A suitable MOSFET for carrying out the circuit above would be an IRF630 and it is a useful exercise to verify that the specification well exceeds the requirements in this application, though the device is relatively inexpensive.

The main advantages of a MOSFET over a junction transistor are:

- the very large input resistance, (although its impedance at high frequencies can be very low),
- the very large current gain,
- it has a positive thermal coefficient, i.e. if its temperature increases, the resistance from drain to source increases and so decreases the drain current flowing.

The main disadvantage of MOSFETs is that they are currently more expensive than junction transistors.

3.4.4 Microcontrollers

Candidates should be able to:

- describe the use and application of microcontrollers
- know that a microcontroller is a programmable integrated circuit into which software can be loaded to carry out a range of different tasks
- describe and explain the effect of microcontrollers on society.

Microcontrollers are complete microcomputers (processor, RAM and ROM) fabricated onto a single chip (System on a Chip, SoC). It was realised that such device would enable the simplification of much of the circuitry required for electronic control of commercial, industrial and domestic equipment.and two companies in America independently began work on such SoCs in the late 1980s. In England, the company ARM also began work on microcontrollers but instead of releasing their controllers as separate ICs, they sell their designs to incorporate into other companies ICs.
(Many mobile phones have ARM microcontrollers.)

Microchip Technologies produced the PIC (Programmable Interface Controller) in the early 1990s and Atmel released the AVR soon after. The success of these devices is largely due to their cost and processing ability. Since they are programmable devices they can be used in many diverse applications ranging from cars, washing machines, phones through to hand held games and talking dolls. As a result of their very wide application they can be mass produced which ensures low cost.

Both PICs and AVRs are based on the Harvard architecture and early versions used an 8-bit Reduced Instruction Set Computer (RISC) processor having only a few tens of instructions. This small number of instructions also improved the take up and use of these devices as they did not require the high degree of training needed to program them when compared to processors having Complex Instruction Sets Computer (CISC) e.g. Pentiums. The latest versions of these microcontrollers are now available with 32 bit processing.

Since there are separate buses for the program instructions and data information, the instructions do not have to be restricted to being 8-bits wide like the data. In fact the early PICs used a 12-bit instruction set, later moving to 16-bits for some of the more complex devices. The AVRs use as standard a 16-bit word format for their instructions. The use of separate data and program buses enables 'pipe-lining' to be implemented so that while one instruction is being executed, the next instruction is pre-fetched from the program memory. This enables instructions to be executed in every clock cycle.

The early success of these devices prompted the manufacturers to add more facilities onto the chip including real time clocks, counter / timers, power on reset circuitry, Input and Output ports, Analogue to Digital Converters, Serial Input and Output ports etc. The whole chip is implemented in Complementary Metal Oxide Semiconductor (CMOS) and so has an inherently low power consumption. This coupled with a sleep mode makes them suitable for battery operated equipment as well. The clock speed of PICs and AVRs is wide ranging and many will operate at clock frequencies as high as 200MHz. While this may seem slow compared to Pentium 4 processors operating at 3GHz, the specially optimised instruction set and programs written in machine code instructions ensures that they are able to carry out many operations and processes quickly and efficiently.

Social and Economic Implications of Microcontrollers

The effect of single IC programmable control systems on modern life has been significant. They have permeated all areas of modern appliances and machines and their effect will continue to increase as more powerful devices are developed. They are already used extensively in modern domestic appliances, e.g. washing machines, microwave cookers, DVD players/recorders, CD players etc. with the result that complex features can be incorporated into them as standard features. Most modern road vehicles have Engine Management Systems (EMS) controlling the operation of the engine. The heart of the EMS is a PIC or AVR which not only is able to maintain the efficient operation of the engine but is also able to monitor the operation of the engine and determine when servicing is required as well as help diagnose faults. Vehicles are just beginning to appear which have many programmable controllers incorporated which are able to monitor every aspect of the car, not just the engine. As a result, if it rains the windscreen wipers are switched on; if it goes dark the lights are turned on etc. without the driver having to take any action. Such cars obviously have Anti-lock Braking Systems (ABS) as standard fittings which is controlled by a programmable controller. With so many electronic systems on board, the repair and maintenance of such vehicles becomes a specialised business.

The availability of many cheap computer peripherals e.g., printers, digital cameras, scanners etc. is also largely due to the use of control SoCs. They are able to monitor precisely the

mechanical operation of these items and correct for imperfections in the mechanics of the peripheral. The result is that less precise mechanisms can be used, so reducing cost, but the controller is able to maintain the overall quality.
Each mobile phone has its own programmable control system on board to take care of the frequency management as the phone moves from one cell to another. Since this is a vital role but one that does not use a significant amount of processing power, it leaves the processor free for other tasks, like managing an address/phone number data base, generating ever complex (and annoying) ring tones, running games on the phone screen etc. However, since a mobile phone has to communicate with the local base station regularly when it is switched on so that the mobile phone system knows that it is available to receive calls it means that the location of the phone is also known to within a few hundred metres. So you cannot hide if you have a mobile phone switched on!
The next major development with SoCs will be in their use in Smart cards. These will be the next version of credit and bank cards which will be able to store information about the owner as well as be used for intelligent information exchange in shops etc. The potential growth in this market is very large.

With the increasing complexity of the software used in microprocessor control systems, it becomes very difficult to ensure that the software is reliable under all of the operating conditions that may be encountered. While it may be an inconvenience if a fault in the software causes the front door on a microprocessor controlled washing machine to suddenly open while the machine is full of water, software faults in engine management systems could be fatal. Consider the theoretical situation in which a car with a microprocessor controlled (EMS), pulls out to overtake a vehicle. The driver sees an oncoming vehicle in the distance and in order to ensure a completely safe overtake, changes into a lower gear. However, if an undetected software fault in the EMS causes the engine to falter and a crash results, no evidence of the software fault would be found in the subsequent enquiry, and the driver would be blamed for the accident.

There is still controversy surrounding the crash of the Mk2 Chinook helicopter ZD576 on the Mull of Kintyre in 1994, in which 29 people died including the two pilots, Flight lieutenants Trapper and Cook. In the subsequent Ministry of Defence enquiry, the pilots were found guilty of gross negligence. However, subsequent enquiries and press interest (mainly Computer Weekly) have raised questions about the reliability of the software used in the engine control system on the aircraft.

It is therefore vital that all software is fully and exhaustively tested to ensure that all operating conditions are covered reliably.

APPLICATIONS OF ELECTRONICS SYSTEMS

3.5. Applications of Electronic Systems

Candidates should be aware of the use of electronics in audio entertainment systems.

Introduction

A major application of electronic systems is in the processing and transmission of information by electronic signals. The amount of information to be transmitted at any one time determines the frequency range or *bandwidth* of the electronic signal.

The human ear can detect sounds in the range of 20Hz to 20kHz. This is considered to be the range of frequencies that need to be transmitted for a hi-fi music system, although it should be noted that radio programs, MP3 players and CDs only have a bandwidth that extends to 15kHz. If it is not intended to transmit music but only speech, then the bandwidth required can be reduced to extend from 300Hz to 4kHz. This reduced bandwidth is the range that normal telephones use.

So long as the overall rate of transmission of information is slow, pictures can also be transmitted with a small bandwidth signal. A fax machine is able to send pictures along a telephone line. However, as soon as a moving picture is required to be transmitted then the bandwidth of the signal has to increase considerably to accommodate all of the additional information. A typical analogue colour television picture signal occupies a bandwidth from 50Hz to approximately 6MHz, or 300 times the bandwidth of a hi-fi music signal.

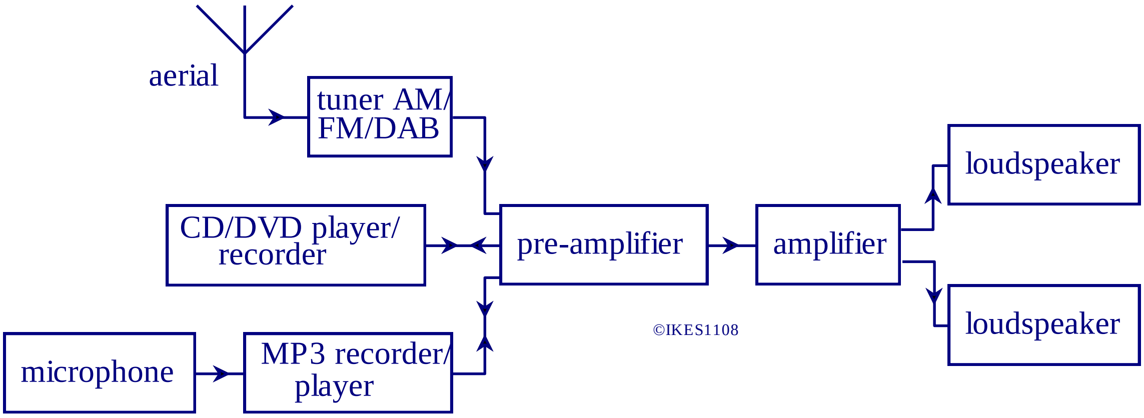
To transmit information requires either the various signals to be passed along cables (metal or optical fibre) or to be *modulated* onto a radio frequency carrier signal. Most commercial radio stations have a carrier frequency that is greater than 150kHz and can extend well into the GHz region of the radio spectrum. Although high frequencies are used for the radio carrier signals, the actual bandwidth of the transmitted signal is much smaller. A television signal transmitted at a frequency of 487.25MHz will occupy a bandwidth that extends to 493.25MHz, while an AM signal in the medium wave band will only occupy a bandwidth of approximately 10kHz.

3.5.1 Audio Systems

Candidates should be able to describe the function of each of the following subsystems of an audio entertainment system:

- tuner
- amplifier
- microphone
- loudspeakers
- MP3, CD and DVD players and recorders.

A block diagram of a typical audio entertainment system is shown below.



Each sub-system of the audio entertainment system has a specific function which is detailed below.

The **tuner** receives the radio signals from the aerial and translates them into audio electrical signals. A strong radio station will produce an output from the aerial of approximately 50µV across the tuner input impedance of 75Ω and this will result in an audio signal at the output of the tuner of approximately 300mV. The use of Digital Audio Broadcasting (DAB) is continuing to grow and it is expected that many AM and FM radio stations will cease to operate over the next few years.

The **CD/DVD player/recorder** reads the digital information stored on a compact disc and translates it into an audio electrical signal of approximately 300mV. As well as being able to read the digital information, many are now able to also write audio electrical signals back onto writable CDs and DVDs.

The **MP3 recorder/player** uses solid state memory cards to store digital information, which it can both translate into audio electrical signals like a CD/DVD player. but also record audio information and store in a digital format.

The **microphone** changes sounds into electrical signals which can be recorded by the MP3 recorder. There are several different types of microphone available but a typical microphone will have an output of approximately 10 - 100mV.

The **pre-amplifier** has two main functions. It contains the signal source selector so that the tuner, CD player etc. can be selected. It also provides extra amplification of the signals and boosts them to the level required by the amplifier (approximately 2V). The pre-amplifier will also contain the other controls, e.g. volume, treble, bass, balance, graphic equaliser, etc.

The **amplifier** boosts the level of the signal from the pre-amplifier to the level required by the loudspeakers without distorting the signal. A typical amplifier is capable of delivering 30 - 100 watts of electrical power to each loudspeaker.

The **loudspeakers** change the electrical audio signals into sound. Many domestic speakers nominally have an impedance of 8Ω, while car speakers have an impedance of 4Ω. Most loudspeakers are very inefficient and often more than 95% of the power delivered to the speaker by the amplifier just heats up the loudspeaker without being converted into sound.

3.5.2 Radio Systems

Candidates should be able to:

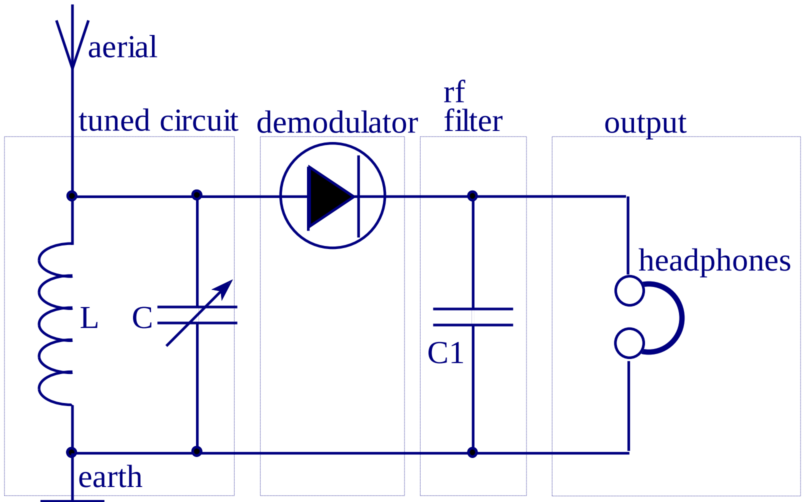
- draw and label the following block diagram of a simple radio receiver and explain how it works in terms of the functions of the subsystems

- explain the meaning of the terms amplitude modulation (AM) and frequency modulation (FM)
- sketch a voltage-time graph for an amplitude modulated wave with relation to its carrier wave and the modulating signal
- sketch a voltage-time graph for a frequency modulated carrier wave with relation to its carrier wave and the modulating signal
- compare the relative merits of FM and AM systems
- explain the meaning of the terms sensitivity and selectivity.

The basic block diagram of a simple radio receiver is shown below.

The aerial receives radio waves from transmitting stations, and other sources of radio waves, which induce alternating currents and voltages in the aerial.
These small voltages and currents then pass to the radio frequency (rf) tuned circuit which filter out the required radio station.
The demodulator removes the radio frequency carrier component and restores the original audio signal.
The audio frequency (af) signal is then amplified to power a loudspeaker or earphones.

The circuit diagram of part of such a simple receiver is shown below.
The audio amplifier section can be made using an audio amplifier e.g. TBA820M.



This type of receiver is often known as a *crystal set* and will provide a signal to sensitive earphones or a crystal earpiece without the need for any batteries. The tuned circuit selects the desired range of radio frequencies. The demodulator or detector consists of a signal diode (a diode designed to have a very small junction area to reduce capacitance). For crystal sets these are often made from **germanium** rather than silicon because only 0.2V is needed to make a germanium diode conduct. Demodulation is achieved by the diode blocking the negative going half of the amplitude modulated (AM) signal. The rf component of the demodulated signal is removed by capacitor C_1, which shunts the rf component to ground. The low frequency af signal is passed to the output.

Two important parameters for a radio receiver are its sensitivity and selectivity. The sensitivity is a measurement of how weak a signal can be for it to still be received accurately. The selectivity is a measure of how near in frequency two radio signals can be for them to be received separately.

The sensitivity and selectivity of a simple receiver are both poor. The energy to drive the output is derived from the aerial and so a large aerial consisting of a good length of wire strung from a tree or pole will be required to produce a reasonable output, particularly in weak signal areas. A suitable earth connection can be made by driving a length (0.5 to 1m) of copper pipe into moist ground.

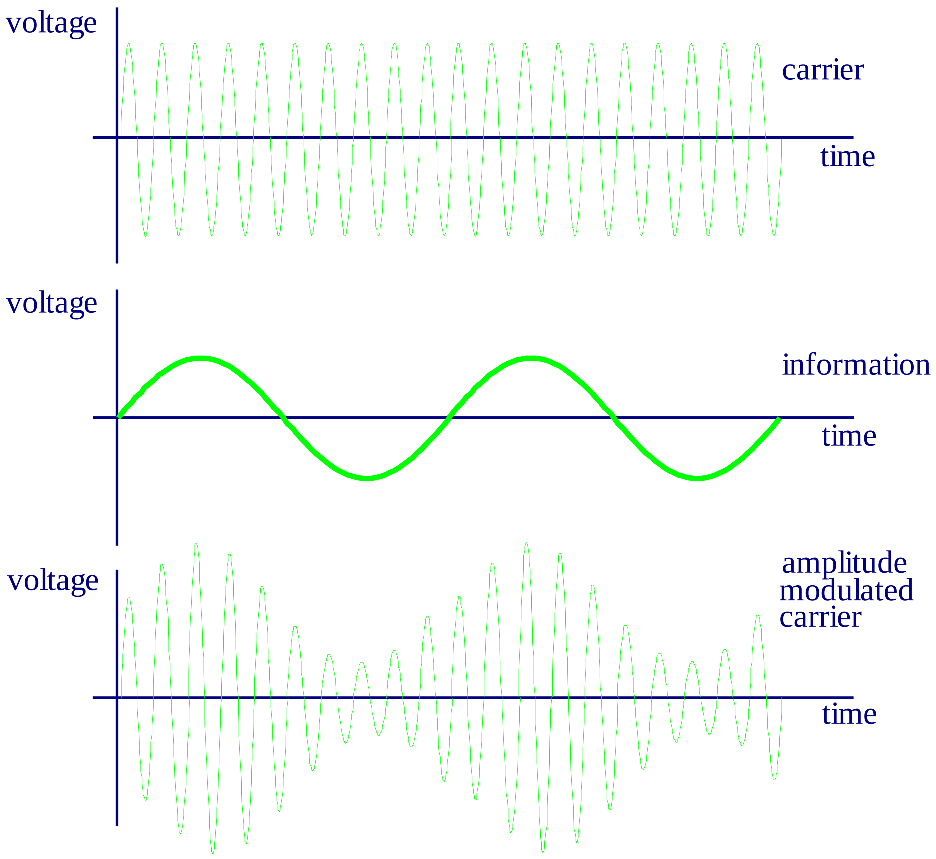
Modulation

There are two main ways in which information can be put onto a carrier wave for radio transmission. Either the amplitude of the carrier is varied by the information signal, forming amplitude modulation (AM), or the frequency of the carrier is varied by the information signal, forming frequency modulation (FM).

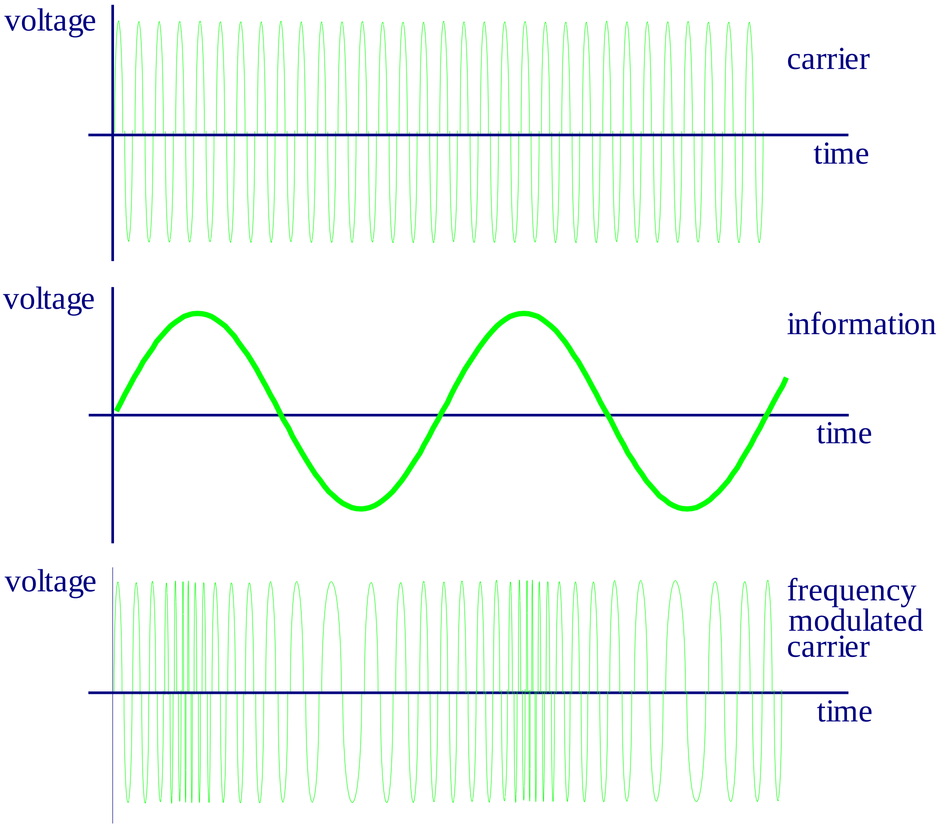
The diagram below shows an amplitude modulated wave. The amplitude of the carrier is varied in proportion to the information signal. With a 100% amplitude modulated carrier the amplitude of the radio signal varies from zero to twice the amplitude of the carrier wave.

If the carrier is given any further modulation then the signal becomes distorted and interference to adjacent radio stations will be produced.

Most broadcast stations limit their modulation to 80%.



The next diagram shows an frequency modulated wave. In frequency modulation the carrier frequency varies or deviates according to the amplitude of the AF signal. A typical FM carrier frequency (for radio transmission) is 100MHz and the maximum frequency deviation is limited, by international agreement, to ±75kHz. The bandwidth of an FM signal is, theoretically, very broad, but in practice the outer extremities of the frequency spectrum of an FM signal can be omitted without causing audible distortion.



A principal advantage of FM transmission over AM is its improved immunity to impulsive noise and static interference. Impulsive noise produces momentary variations in the amplitude of the signal which are suppressed in an FM receiver by a limiter circuit. The limiter circuit is simply an amplifier in saturation so the output is not capable of rising as a result of impulsive noise. FM transmission is used for high quality signal transmission, but at the cost of a much wider bandwidth and a more complex receiver. Most commercial FM stations use the VHF waveband since it enables the larger bandwidth to be accommodated, but such high frequencies can make circuit design more difficult.

PRACTICAL WORK

3.6 Practical Skills and Processes

Practical work is an integral part of any course in electronics. Candidates should have a range of practical experiences, the skills from which will be required in their controlled assessment. Examiners are at liberty to deal with aspects of practical work in the written examination.

Candidates should be able to:

- recognise a component from its physical appearance
- use a catalogue or data sheet to select required components
- draw a layout of a given circuit containing no more than 10 components using prototype board and showing all connections clearly
- assemble a circuit following a circuit diagram
- select and use a range of test instruments (e.g. multimeter, oscilloscope and signal generator)
- identify simple faults in circuit diagrams and component layout.

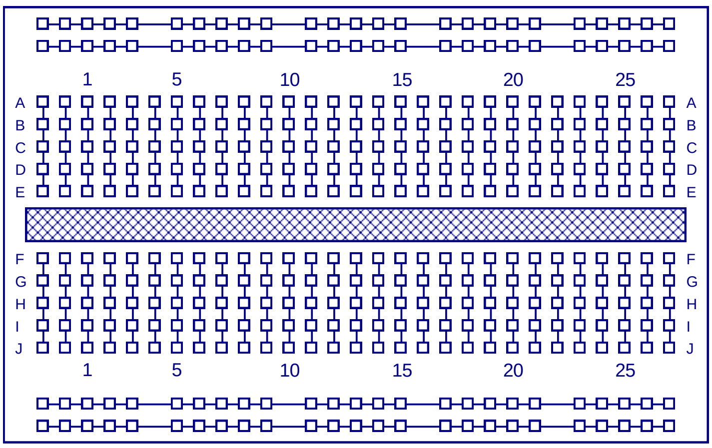
Electronics is a practical subject. Electronic circuits have to be constructed and evaluated for them to be of any use. The first step in constructing any electronic circuit is to decide on the method that is to be used. There are three main methods available to the amateur;

SOLDERLESS BREADBOARDS OR PROTOBOARDS,
STRIP BOARD,
PRINTED CIRCUIT BOARD.

This subject specification requires candidates to only use solderless breadboards or protoboards. Which ever method is used it is essential that the circuits are constructed in a neat, tidy and logical manner. Remember you may have to repair or modify the circuit you have built and so it is in your own interest to keep your circuits tidy!

To enable circuits to be built quickly, push-in or SOLDERLESS BREADBOARDS have been developed. These often have many different commercial names and shapes but they all work on the same principle, that of the wires of the components being pushed through holes in a plastic case and held tightly by a metal spring.
The general name used for all of these boards is **protoboards**.

The layout of a typical protoboard is shown in the diagram below.



Each hole on the board will accommodate **one** wire. The lines show which holes are joined together by the metal springs. The holes in the main body of the protoboard are joined vertically, with a gap in the middle to accommodate integrated circuits. The holes at the top and bottom of the board are joined horizontally and can be used as power supply lines.

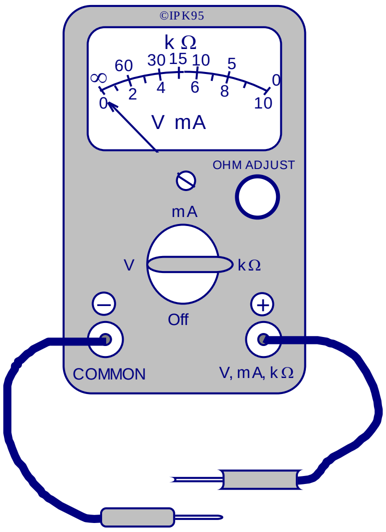
Protoboards are ideal for developing circuits since changes can be made very rapidly. They are not, however, suitable for all types of circuit because of the capacitance between the adjacent metal connecting strips. High gain audio amplifiers and radio frequency circuits built on protoboards are often unstable or subject to interference and noise.

They are also not suitable for any permanent circuits as they are unlikely to be able to withstand the knocks and bumps experienced by electronic circuits in everyday use.

Using Multimeters

Analogue Multimeter

An analogue multimeter consists of a sensitive moving coil meter (often 50μA full scale deflection, FSD). The deflection of the pointer over a scale represents the value of the quantity being measured.

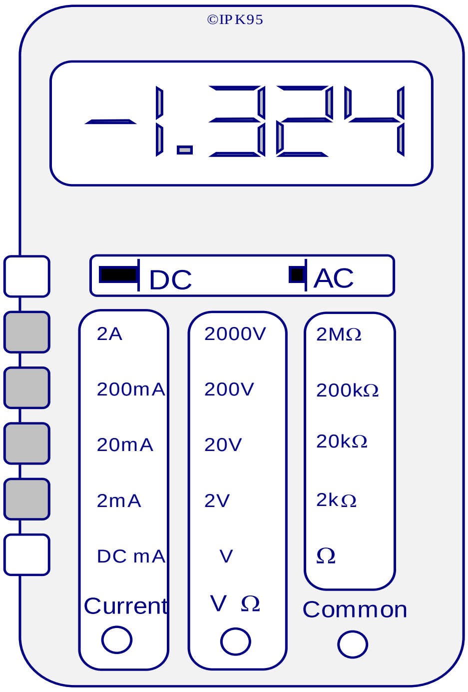


To allow the meter to measure larger currents, low value resistors are connected in parallel with the meter by the range switch. To allow the meter to measure voltages, high value resistors are connected in series with the meter, again by the range switch. As a result of the current that passes through the meter when it is measuring voltages, the meter affects the circuit being tested and so can alter the quantity being measured.

A voltmeter should have a very large resistance so that only a very small current passes. The sensitivity of a voltmeter is expressed in ohms per volt, i.e. the resistance that the meter must have when reading 1 V full scale deflection. So a 50 μA meter will need to have a total resistance of 20 kΩ when it has a FSD of 1V. The sensitivity of such a meter is then 20,000 Ω /V.

On the 10 V range its resistance is therefore 200 kΩ, the increase in resistance being due to extra resistors connected in series by the range switch. For a given sensitivity the higher the voltage range the less the disturbance to the circuit.

Digital multimeter



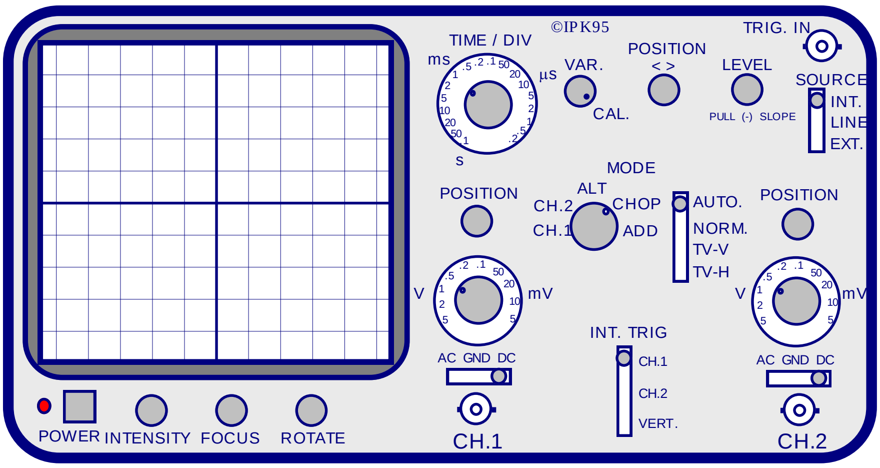
The reading on the decimal display is produced by a voltage measuring analogue to digital converter. The binary output from the A to D converter is applied to a decoder which controls the display. Very small input voltages (a few millivolts) are amplified before being measured. For varying voltages a latch system is used to hold the display steady at the latest value while a further sampling occurs. With extra internal circuitry brought in by various range switches, currents and resistances can be measured.

The advantages of the digital over the analogue multimeter include:-

- The input resistance on voltage ranges is high (11MΩ) and is the same on all ranges so the disturbance effect on the circuit under test is reduced.
- Errors are less likely to occur from reading the wrong scale or from estimating the reading when the pointer is not exactly over a marking on the scale.
- It has a much higher operating frequency on its ac ranges.

Using An Oscilloscope

The oscilloscope is a very useful test instrument in electronics. It is essentially a voltmeter with a very rapid response to changing input voltages. A diagram of a typical modern analogue oscilloscope is shown below.



An oscilloscope can be used for measuring the following quantities:-

the peak voltage of a signal,

the peak current of a signal by measuring the peak voltage across a known resistor,

the time period of a signal, from which the frequency can be calculated,

Measurement of Peak Voltage and Frequency

a) Set up the oscilloscope according to the manufacturer's instructions.
b) Connect the voltage signal to the input terminals.
c) Adjust the y gain control so the trace covers at least half the height of the screen.
d) Adjust the trigger control so that the trace is stable.
e) Adjust the time base control to give between three and six cycles.
f) Measure the vertical peak to peak displacement of the signal on the screen in cm and divide by two to find the amplitude. Use the **y gain sensitivity** setting in V/div to calculate the amplitude.

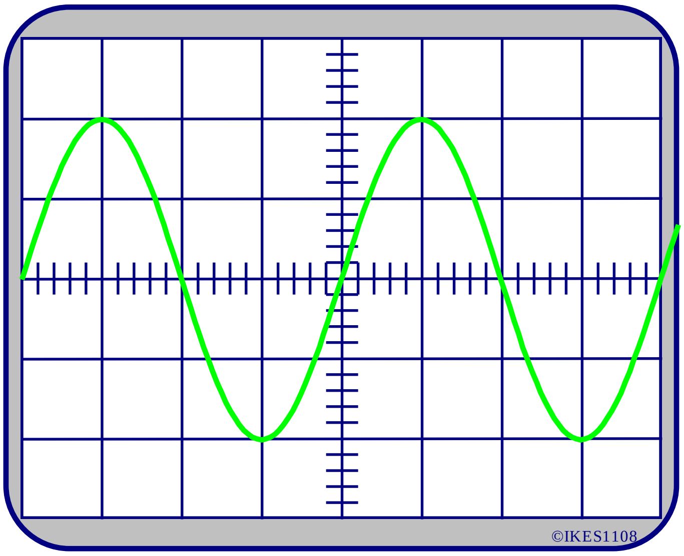
Peak voltage (V) = amplitude (div) x y gain sensitivity (V/div)

g) Measure the horizontal distance occupied by one cycle on the screen and use the time base setting to calculate the time period.

Time period, T(ms) = distance of one cycle in cm x time base (ms/div)

To calculate the frequency use $f = \frac{1}{T}$

e.g. Consider the diagram below.



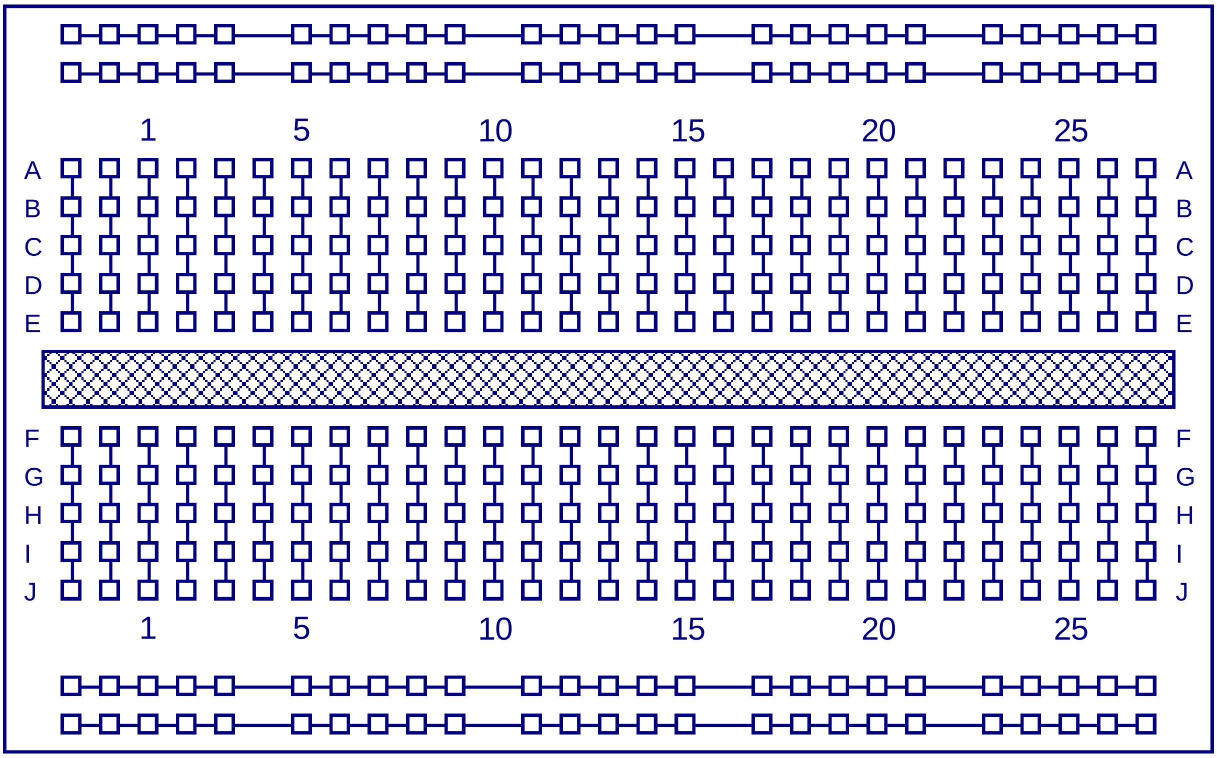
Y sensitivity = 2V/div. and the time base setting = 5ms/div

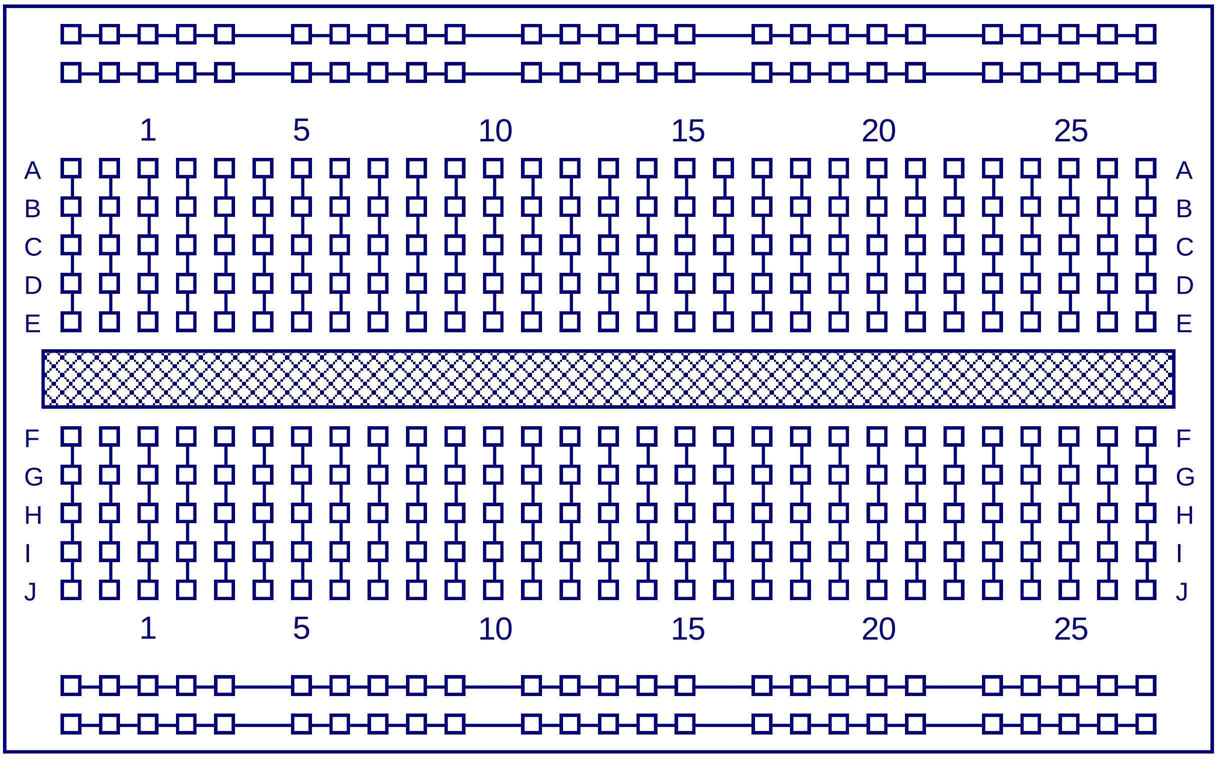
From the diagram, the peak to peak value is 4div.
So the amplitude of the signal = 2.0div.
Voltage amplitude = 2div x 2V/div = **4.0V**

From the diagram the period distance of the signal = 4.0div
Time period, T = 4.0div x 5ms/div = **20ms**

Frequency $f = \frac{1}{T} = \frac{1}{20ms}$ **= 50Hz**

APPENDIX A.


1 5 10 15 20 25
A B C D E
F G H I J
1 5 10 15 20 25


1 5 10 15 20 25
A B C D E
F G H I J
1 5 10 15 20 25

APPENDIX B.