OUTCOME 4

Understand the relationship between resistance, resistivity, voltage, current and power

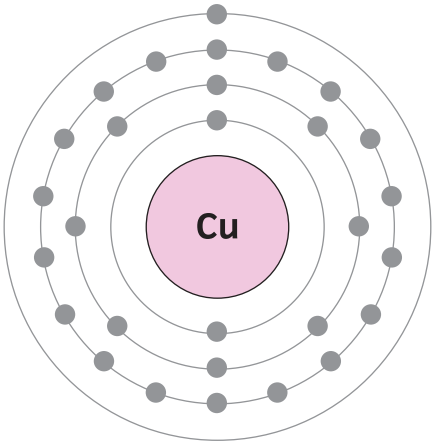
SmartScreen Unit 309

PowerPoint 4 and Handout 4

The basic principles of electricity have been studied for centuries and what is now common electrical theory was once groundbreaking new discovery. You need to understand the basic principles, including atomic composition, in order to work safely with electricity, magnetism and electrochemical reactions, and to progress in the industry.

Assessment criteria

4.1 Describe the basic principles of electron theory



A simplified copper atom structure with electrons

KEY POINT

Atoms are bound by an electrical force, whereas molecules are bound by a chemical force.

ACTIVITY

Copper has 29 electrons and 29 protons. Using textbooks or the internet, find how many there are for:

a) carbon
b) aluminium
c) silicon
d) gold.

ATOMIC THEORY

In order to understand where electricity comes from and what it is, it is necessary to understand a small amount of atomic theory.

Atoms are very small particles that are sometimes arranged as molecules. An atom is not solid but is made up of smaller particles, separated by space. The centre of an atom is the nucleus, which is made up from various particles including protons and neutrons. Protons are positively charged and neutrons have no charge. Orbiting the atom are the electrons, which are negatively charged.

The atoms that make up different materials have different numbers of electrons. In the steady state an atom has equal numbers of protons and electrons, and this leaves the atom electrically neutral.

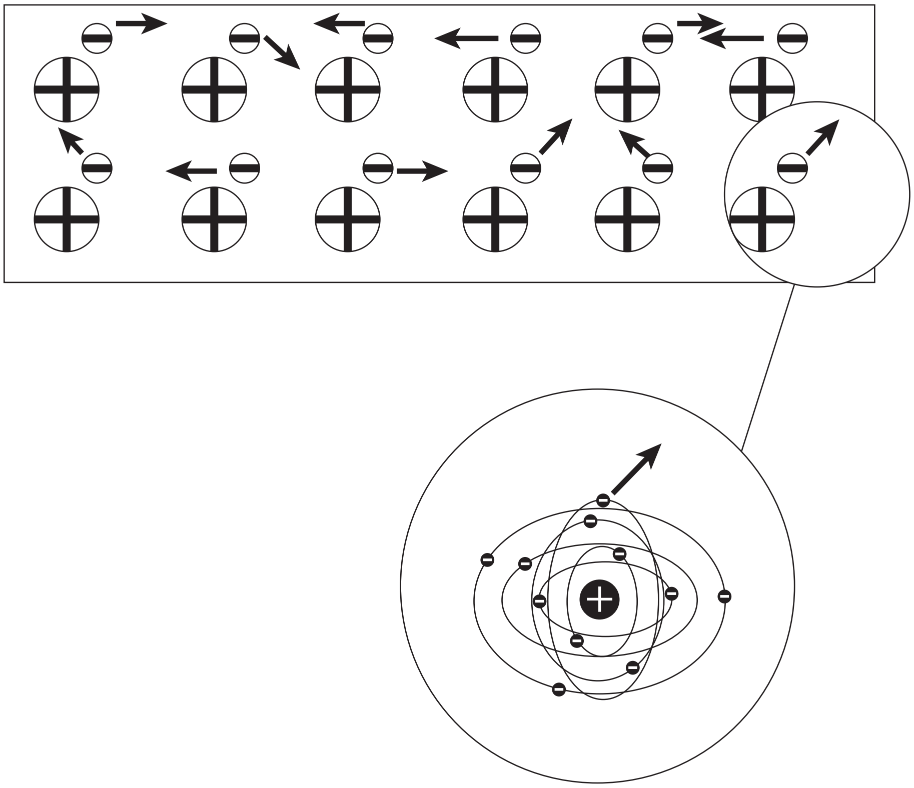
Atoms in solids and liquids are more tightly bound together than those in gases. The diagram (left) shows the simplified structure of copper, which is often used to conduct electricity. The representation is two-dimensional when in fact the actual atom is three-dimensional. Where there are two or more electrons orbiting a nucleus, their orbiting paths are known as shells. The electron paths (shells) form an elliptical orbit.

Reaction of atoms

Different atoms have different numbers of electrons. Copper has 29 electrons and 29 protons. The outer shell is weakly held in orbit and can break free, causing random movement among other copper atoms. The loss of an electron causes an atom to become positively charged. It is known as a positive ion. Positive ions attract electrons, causing electron movement. Negative ions have more electrons orbiting them than protons in the nucleus.

The movement of electrons throughout a material is random but, by the laws of electric charge, like charges repel and unlike charges attract.

The diagram below shows the random movement of electrons in a material. The inset shows the electrons orbiting the proton. Electrons on an outer shell are released, as the force of attraction by the proton is weak, and the electron moves to the next proton.



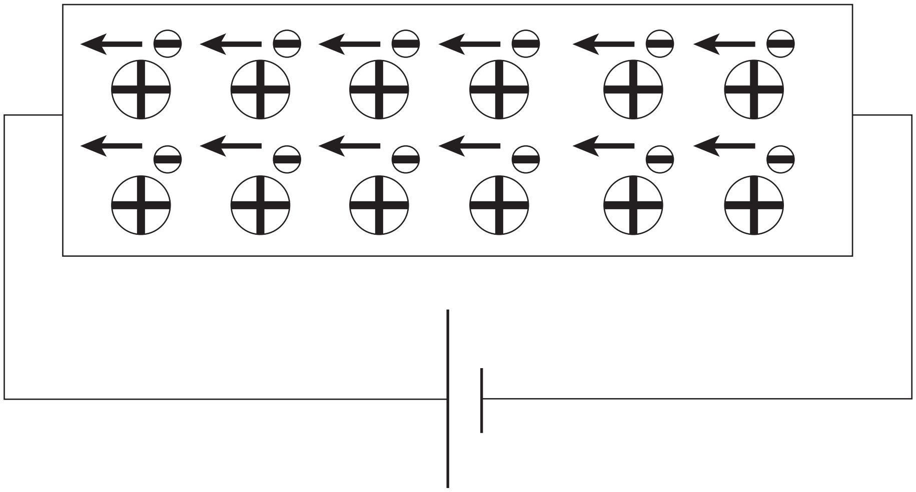
Random movement of electrons in a material

Flow of electrons

Random free electrons can be configured if the conducting material is connected to a battery. The free electrons are attracted to the positive plate and repelled by the negative plate. This causes the electrons to drift, in a conducting material, from the negative terminal of the battery to the positive terminal. As positive ions are unable to drift in solids, every time an electron leaves the negative terminal, one enters the positive terminal. This flow of electrons is electric current.

KEY POINT

Electron is the Greek word for amber. Amber is a material that is easily electrified by static. Rubbing wool on amber can charge the amber, which can then release an electric charge when held against another material or person.



Electrons are attracted in one direction when a source of energy is connected to the material.

Closed circuit

A complete circuit connected to a source of energy. If the circuit contains a switch and the switch is switched off, it becomes an open circuit.

KEY POINT

Conventional current direction is actually opposite to actual current direction. Current flows from negative to positive but, in our industry, we still refer to conventional current flow.

KEY POINT

The flow of current in one direction is called direct current (d.c.), which is the main current form referred to in this unit.

In order for electric current to flow, there must be a **closed circuit**. Once the circuit is opened, the drift of electrons is immediately stopped and the current flow ceases.

Current direction

Electric current flows from a negative terminal to a positive terminal. However, before atoms and electrons were understood, scientists believed that electricity was a fluid and flowed from positive to negative. This is known as conventional current direction and, although it is now understood that electrons flow from negative to positive, we still refer to conventional current direction as being positive to negative.

How many electrons make one ampere?

The flow of electrons in one direction is known as charge, which is measured in coulombs (C).

As electron flow is electrical current and current is measured in amperes (A), how is one converted to the other?

French physicist Charles Coulomb (1736–1806) determined that 1 coulomb of charge is equal to 6.24×10^{18} electrons. That is equal to 6 240 000 000 000 000 000 electrons! So if that many electrons flowed through a material such as copper and past an electron counter, that would be equal to 1 coulomb. He also determined that if the drift of electrons was at a rate of 1 coulomb per second, the resulting current would be 1 ampere.

Therefore a current of 1 ampere flowing indicates a charge of 1 coulomb per second, giving:

$$Q = It \text{ or } I = \frac{Q}{t}$$

where:

Q = charge transferred, in coulombs (C)
I = current, in amperes (A)
t = time, in seconds (s).

Example

If a total charge to be transferred is 750 C in one minute, the current flow is calculated as follows.

Using the formula $Q = It$, calculate the current:

$$I = \frac{Q}{t}$$

Since 1 minute = 60 seconds (s): $\frac{750}{60} = 12.5$ A

The current flow is therefore 12.5 A for 60 seconds to give the total charge of 750 C.

If a current of 25 A was to flow for 2 minutes in the above circuit arrangement, the total charge would be calculated like this.

Since 2 minutes = 120 s and $Q = It$:

$$Q = It = 25 \times 120 = 3000 \text{ C}$$

Therefore the total charge would be 3000 coulombs.

INSULATORS AND CONDUCTORS

As has been described in Assessment criteria 4.1, the movement of free electrons constitutes the flow of electric current and since the atomic structure varies from material to material, some will allow electron movement better than others when an external voltage is applied. Where the freedom of electrons to move is high, the material will act as a good conductor of electricity.

Examples of conductors are:

- aluminium and copper (used in cables and overhead line conductors)
- brass (used in plug pins and terminals)
- carbon (motor brushes)
- mercury (discharge lamps and special contacts)
- sodium (discharge lamps)
- tungsten (lamp filaments).

ASSESSMENT GUIDANCE

These equations may look strange, but do not let them put you off. The letters stand for numbers. Simple calculations are all you will need to do.

KEY POINT

Where a formula shows two symbols together with no mathematical symbol, it means they must be multiplied. So $Q = It$ simply means $Q = I \times t$.

ACTIVITY

Remember that the SI unit of time is the second, not the minute, hour or day. Use the internet to find the definition of the second.

Assessment criteria

4.2 Identify and differentiate between materials which are good conductors and insulators

However, where the material's atomic structure is such that there is minimal electron movement, there will be negligible current flow and the material will act as an insulator.

Examples of insulators are:

- thermoplastics and polyethylene (cable insulation)
- glass and porcelain (overhead line conductor support insulators)
- rubber (mats, gloves and shrouding for live working).

It must be stressed, however, that the level of insulation afforded by an insulator can be severely reduced by:

- damage (cracks, splits, etc)
- deterioration (cracks, splits, etc due to ageing)
- contamination (water, salt spray, chemicals, etc).

Assessment criteria

4.3 State the types and properties of different electrical cables

ASSESSMENT GUIDANCE

The armouring of cables is there to provide mechanical protection to the inner conductors. It is normally made of steel wire in a single or double layer wrapped around the cable bedding and overlaid with PVC sheathing. In older cables steel tape may be found.

SmartScreen Unit 309

Handout 13

CABLE COMPONENTS AND TYPES

Electric cables used for electrical installations in industrial, commercial and domestic situations come in a wide range of sizes, materials and types. Electric cables used for the long-distance transmission of electrical energy (400 kV and 275 kV) are normally buried in the ground or suspended on towers or pylons and the cables used for the more local distribution of electrical energy around the country (132 kV, 66 kV, 33 kV and 11 kV) are buried in the ground or suspended on towers or pylons or on wooden poles.

Cables generally consist of three major components:

- the current-carrying material (conductors)
- electrical insulation (normally colour or number coded for identification)
- a protective outer covering called a sheath (this is not present on some single-core cables).

The makeup of individual cables varies according to the application for which they are to be used. The construction and material are determined by three main factors:

- working voltage, which determines the thickness of the insulation
- current-carrying capacity, which determines the cross-sectional area of the conductor(s)
- environmental conditions – such as requirement for mechanical protection, temperature, water and chemical protection – which ultimately determine the form and composition of the outer protective sheath.

The current-carrying conductors of an electricity cable are normally made of copper or sometimes aluminium, either of stranded or solid construction.

Cable types

There are generally two types of cable:

- single-core cables
- multi-core composite cables.

Single-core cables

Single-core cables are generally un-sheathed cables with only one core or conductor. Insulated single-core cables are required to be installed in containment systems such as conduit or trunking in order to provide mechanical protection. The insulation will usually be colour coded to identify the conductor. Single-core cables may also be bare, for example in the case of supply cables, but these must be suspended from pylons. Single-core cables may also have a further sheath, these are commonly called double-insulated cables.

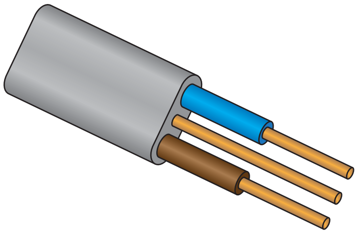
ASSESSMENT GUIDANCE

Single-core cables (singles) must always be installed in a containment system such as conduit or trunking. The only exception is for earthing and bonding conductors.

PVC/PVC cables

In industrial, commercial and domestic wiring installations PVC-insulated and PVC-sheathed cable is the most common form of cable used and is either surface mounted by clipping, embedded in the fabric of the building (plaster), or installed in conduit or trunking.

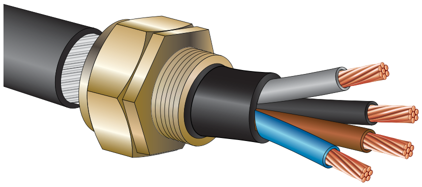
The conductors are covered with colour-coded PVC insulation and then enclosed in a PVC outer sheath.



PVC/PVC cable (also known as twin and earth)

PVC/SWA cable

Cables for direct burial or for exposed installations are constructed of stranded conductors covered with colour-coded PVC insulation and then enclosed in an inner PVC sheath. Steel wire armour (SWA) in the form of steel wires spiralled around the cable provides mechanical protection and an outer sheath of PVC provides corrosion protection. The SWA can provide the circuit protective conductor (CPC) and the cable is terminated by the use of a compression gland. If the SWA does provide the CPC, all strands of the armour must be terminated in the gland and the gland effectively earthed.



SWA with gland assembly

Flexible cable (Flex)

Flexible cable (flexes) connect electrical appliances to the mains, either via plugs or switched spurs. There are many sizes and types of flexible cable but essentially they are all made up of two or three separately insulated cores and in each of these cores the conductor is made up of many thin strands of copper conductors, which give the cord its flexibility.

In three-core flex the cores are colour coded in accordance with European Harmonisation document HD 308: Identification of cores in cables and flexible cords, and to align with BS EN 60445: 2010 Basic and safety principles for man-machine interface, marking and identification – identification of equipment terminals, conductor terminations and conductors. The colours are: brown for live, blue for neutral, green and yellow striped for earth. Three-core flex must be used for equipment that relies upon an earth for safety (class 1).

Two-core flex has only the live and neutral conductors, coloured brown and blue. The outer sheath of a flex can be PVC or rubber or rubber/textile braided. Two-core flex can have a round or flat sheath.

MI cable

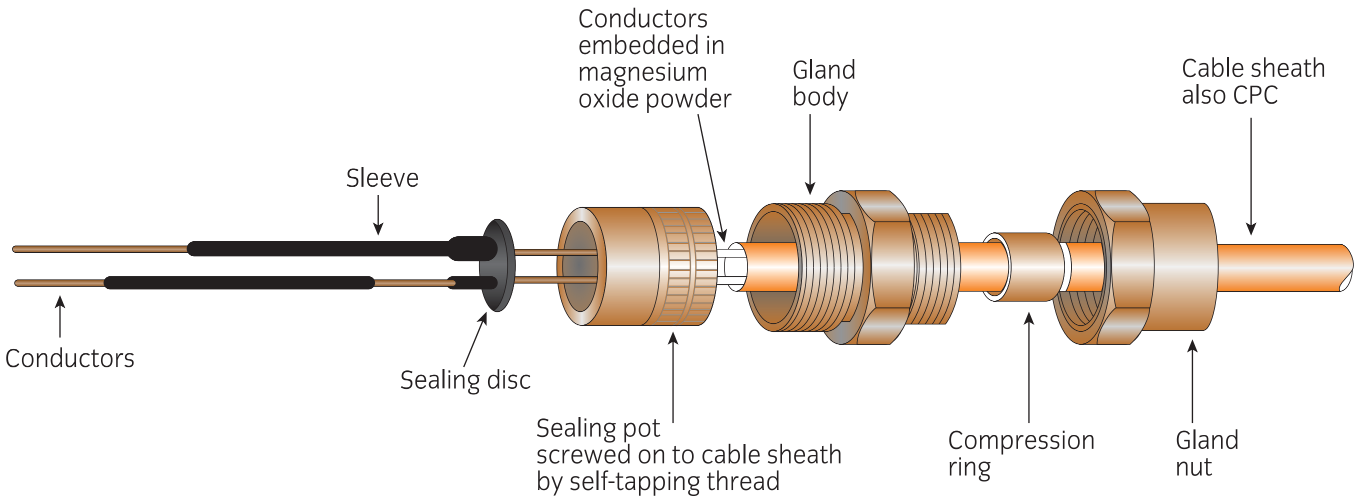
Mineral insulated cable (MI cable) is made by placing copper conductors inside a seamless copper tube filled with dry magnesium oxide powder. The cable has a small overall diameter and, apart from the terminations, does not use organic material as insulation. This makes the cable more resistant to fires than PVC-insulated cables and, as such, they are used in hazardous areas, such as oil refineries and, chemical works, and critical fire protection applications, such as alarm circuits, fire pumps and smoke control systems. MI cable is often known as MICC (mineral insulted copper clad) and pyro after the original manufacturer Pyrotenax.

MI cables may be covered with a plastic sheath, coloured for identification purposes:

- orange for general electrical wiring
- red for fire alarm wiring
- white for emergency lighting.

The plastic sheath also provides additional corrosion protection for the copper sheath.

The copper sheath provides the CPC and the cable is terminated, using a sealing pot filled with sealing compound. The pot is fixed to the sheath, using a self-tapping thread. Terminating MI cable requires quite a high skill level to ensure the termination is electrically sound.



Mineral insulated cable showing the gland and pot assemblies

Fire performance cable

Fire performance cables maintain circuit integrity in a fire and so are suitable for fire detection, alarm and emergency lighting systems. The cable is usually manufactured with solid or stranded conductors that have a fire barrier of a proprietary fire-resistant material such as ‘insudite’ or mica glass tape. This alternative to MI cable does not require special terminations and, as such, is much easier to install than MI cable.

Optical fibre cable

Optical fibre cables are communication cables containing one or more optical fibres and are used for telecommunications and computer networking. The optical fibre elements, made from optical quality plastic, are individually coated with plastic layers and contained in a protective tube. The energy is passed down the cable in the form of a digital pulse of laser light, which always stays within the optical fibre. Each fibre can carry a great number of independent channels, each using a different wavelength of light.

High voltage power cables

The IEC (International Electrotechnical Commission) define a.c. high voltage as above 1000 V. Electric cables used for the long-distance transmission of electrical energy (400 kV and 275 kV) are normally buried in the ground or suspended on towers or pylons and the cables used for the more local distribution of electrical energy around the country (132 kV, 66 kV, 33 kV and 11 kV) are buried in the ground or suspended on towers or pylons or on wooden poles.

ACTIVITY

Using the internet, read about the early battles between Edison and Westinghouse over which supply would win (d.c. or a.c.). It is reckoned that Edison would have needed a power station on each street corner.

SmartScreen Unit 309

Handout 26

Generally, electricity cables are laid directly in the ground and at sufficient depth to avoid undue interference or damage. High voltage power cables operating at 11 kV, which is the common voltage used for underground electricity distribution in urban areas, are required to be placed at a depth of 600 mm. Most power cable sheaths are coloured black, though some high voltage cables are red. If ducts are used and of modern plastic construction, they are normally coloured black.

It was shown in earlier learning outcomes that a given amount of power can be transmitted along a conductor either at a high current and low voltage or at a low current and a high voltage. For economic reasons, the latter is the preferred approach since transmission at low currents means that smaller cross-sectional area conductors can be used as well as the power loss being significantly less.

However, the use of high voltages requires a high level of electrical insulation for the live conductors. High voltage transmission is considerably cheaper by overhead lines rather than underground cables since it is easier to provide the necessary high level of insulation required. For this reason the majority of the National Grid uses overhead transmission (at voltages up to 400 kV).

POWER IN BASIC ELECTRICAL CIRCUITS

Assessment criteria

4.7 Calculate values of power in parallel and series d.c. circuits

It is known that if a potential difference of 1 volt exists between two points, then 1 joule of energy is used in moving 1 coulomb of electricity between the points. Therefore:

$$1 \text{ joule} = 1 \text{ coulomb} \times 1 \text{ volt or } W = QV$$

We also know that power is energy used over a period of time. In electrical circuits we also determine power using the amount of potential difference and current. So:

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PowerPoint 4 and Handout 4

$$P = VI$$

Where:

P is electric power, in watts (W)

I is the current, in amperes (A)

V is the potential difference, in volts (V).

Also, as voltage can be determined using Ohm's law, by multiplying the voltage and resistance, then:

$$P = (IR)I = I^2R$$

Power loss or consumption is proportional to the square of the current flow, ie I^2. Thus, assuming a constant resistance in a circuit, if the current doubles (due to a corresponding increase in voltage) there will be a four-fold increase in power.

Also as:

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

Then:

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

Note that these formulae are not complete for a.c. circuits as a power factor needs to be taken into account. This is covered in Learning outcome 7.

So, using the derived formula, the following calculations are possible.

Example

If a resistor of 10 kΩ is connected to a 100 V d.c. supply, the power dissipated in the resistor is calculated using:

$$P = \frac{V^2}{R} = \frac{100 \times 100}{10\,000}$$

$$= \frac{10\,000}{10\,000} = 1 \text{ W}$$

ACTIVITY

Calculate the resistance of a 3 kW electric fire connected to a 230 V supply.

Calculate the working (hot) resistance of a 60 W 230 V lamp, using:

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

Therefore:

$$R = \frac{V^2}{P} = \frac{230 \times 230}{60}$$

$$= \frac{52\,900}{60} = 881.67\ \Omega$$

Example

To determine the power dissipated in a resistor when a current of 100 A passes through and voltage 100 V is applied to the circuit:

$$P = VI = 100 \times 100 = 10\text{ kW}$$

Calculate the value of the resistance in the same circuit:

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

Therefore:

$$R = \frac{V^2}{P} = \frac{100 \times 100}{10\,000} = \frac{10\,000}{10\,000} = 1\ \Omega$$

Assessment criteria

4.8 State what is meant by the term voltage drop in relation to electrical circuits

VOLTAGE DROP

The flow of electric current through a conductor results in a drop in electrical pressure (voltage), referred to as voltage drop or volt drop, due to the resistance to the current flow presented by the conductor resistance. This loss of voltage represents a loss of energy, which is reflected in the generation of heat.

The voltage drop is determined by the amount of current flowing in a conductor and the resistance of that conductor. It is calculated from the product of the current flowing, measured in amps (A), and the conductor resistance, measured in ohms (Ω), which is simple Ohm's law.

$$\text{Voltage drop} = \text{Current} \times \text{Resistance}$$

$$V = I \times R$$

Example

If a circuit had a total resistance of 0.5 Ω and the load at the end of the circuit had a current demand of 15 A, the voltage drop in the circuit would be:

$$0.5\ \Omega \times 15\text{ A} = 7.5\text{ V}$$

So if the supply voltage at the origin of the circuit was 230 V, the voltage at the load would be:

$$230\text{ V} - 7.5\text{ V} = 222.5\text{ V}$$

If voltage drop is excessive, there may not be enough voltage at the end of the circuit for the load to operate correctly. In order to reduce the amount of voltage drop, the cable resistance must be reduced. This can be done by increasing the cross-sectional area of the circuit conductor.

EFFECTS OF ELECTRIC CURRENT

The three main effects of electrical current (similar to sources of electricity) are:

- thermal (heating)
- chemical
- magnetism.

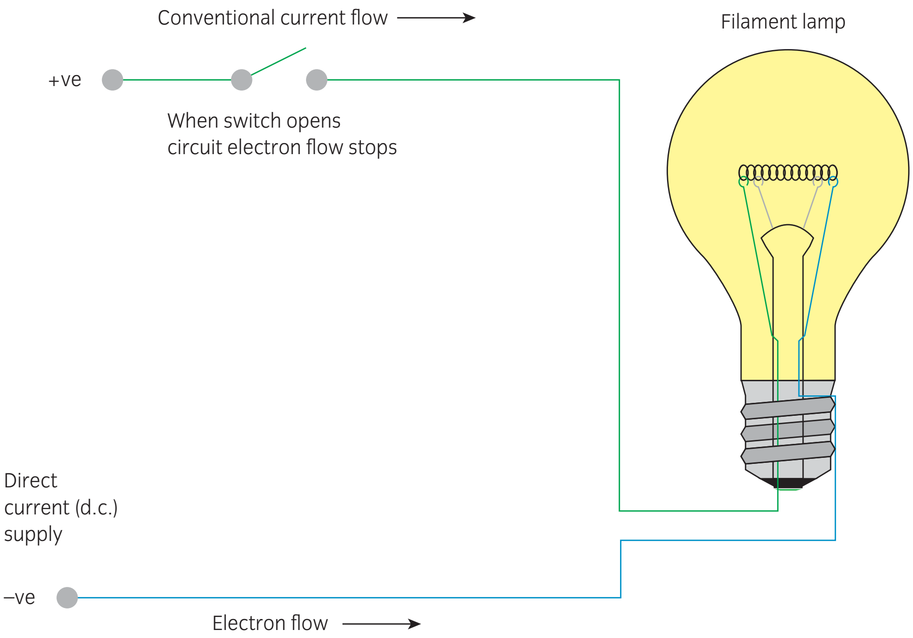
In this section we deal with the thermal and chemical effects. Magnetism is covered in detail in Learning outcome 5 (page 49).

Assessment criteria

4.9 Describe the chemical and thermal effects of electrical currents

Thermal (heating)

When current flows in a wire, apart from the flow of electrons, there is a thermal effect; the wire starts to heat up. The amount it heats up depends on factors such as the cross-sectional area of the wire, the amount of current flowing and the material that the wire is made of. The heating effect of electricity is used in electric fires and other heaters. Variations of this heat effect are used to make light from light-bulb (lamp) filaments, which give off large amounts of light as they glow white hot as a result of the current passing through the thin filament.



An electric light circuit using a d.c. source such as a battery

ACTIVITY

Early incandescent lamps used carbon filaments that were quite fragile. Unfortunately, carbon has a negative coefficient of resistance. This means that, as it gets hotter, the resistance goes down and so it will carry more current and become hotter still. This continues until the filament burns out. For this reason, carbon filaments were limited to small power ratings. What other material has a negative coefficient of resistance?

The effect of current passing through a wire and producing heat is a major consideration when designing electrical installations and will be covered at length during your course. Current that produces heat can be useful in electrical installations, for example in:

- electric heating
- lighting
- cooking
- circuit or equipment protection devices such as fuses or circuit breakers
- monitoring equipment.

ASSESSMENT GUIDANCE

Larger cables have a lower power loss than smaller cables carrying the same current. Although they save on power loss, larger cables cost more to buy and install.

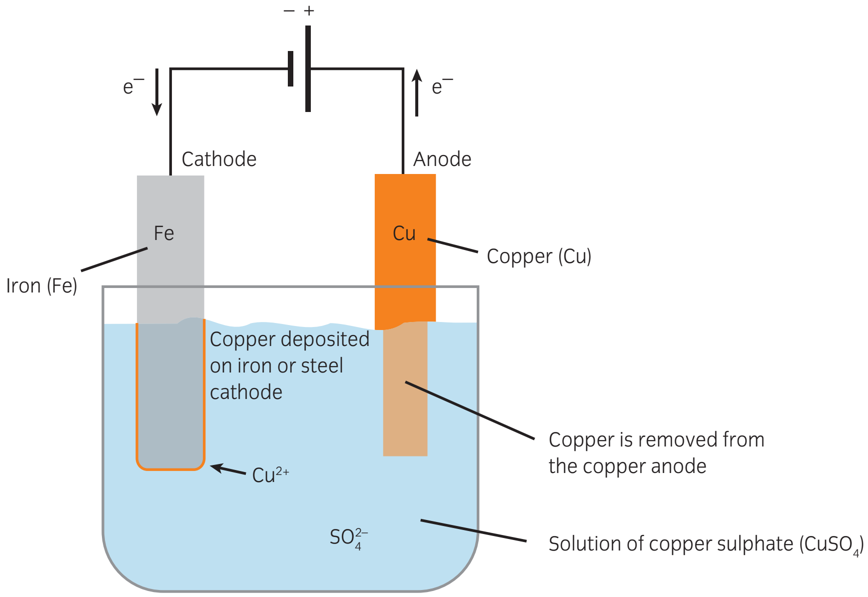
There are also disadvantages, which include:

- circuit cables heating up, causing failure
- equipment getting too hot, causing danger
- energy loss.

A cable is designed to carry electricity from one place to another and is not supposed to heat up by any large amount. If it does heat up, it is using energy to do so which means less energy is available where it is required.

Chemical

When electric current is passed through a chemical solution, this causes basic chemical changes as ions are allowed to move to the positive plate, creating the process of electroplating or electrolysis. This process is used to coat material as, for example, in copper cladding on steel. If a copper-based solution were used, as shown in the diagram, the steel would become coated with copper.



The chemical process of electroplating copper onto an iron or steel object