CHAPTER 22

Electric Circuits

22.1 INTRODUCTION

Electrical energy is very important in our lives, as evidenced by the great inconvenience when it is not available — for instance, trying to cope without refrigeration when camping, or trying to cope without cooking appliances during electrical blackouts caused by industrial strikes or storm damage. The great explosion in technology in the twentieth century has been almost solely due to applications of electrical energy. The information age to which we belong would not be possible without methods of distributing large quantities of electrical energy for operating appliances or being able to store and transmit information across telephone, television and computer networks.

The electrical age began around 200 years ago when it was discovered how to store electrical energy and thus control it, rather than just deal with its electrostatic effects. The Italian scientists **Luigi Galvani** (1737–98) and Count **Alessandro Volta** (1745–1827) experimented with electrical effects in animal tissues, showing that the nervous system is electrically operated. Volta was able to produce the first example of an electric battery, which he called a 'pile', constructed from a series of pairs of dissimilar metal electrodes separated by moist cloth layers. Today we call this apparatus a voltaic battery or just a battery.

In this chapter we will examine the various effects of electric current, together with a model for its behaviour and the laws under which it flows in circuits. By the end of the chapter questions such as:

- what causes electric current to flow?
- what controls the direction of electric current flow?
- how is electric current measured?
- which is the more dangerous, voltage or current?
- how can we use electrical energy safely?
- how will electrical energy affect me in the future?

which you may have asked in the past, will be able to be answered satisfactorily.

Although electrical energy is widely used in modern society, it should never be treated lightly as it can become extremely dangerous when used inappropriately.

NEI Activity 22.1 ELECTRICITY AROUND THE HOME

1. Examine the following electrical devices found around the home and find the voltage marked on each: torch battery, car battery, calculator battery, watch battery.
2. Look at several light bulbs and determine the wattage rating marked on each.
3. Determine how many electric cable wires are coming into your house from the distribution pole in your street.

ELECTRIC CHARGES IN MOTION 22.2

In Chapter 21 we saw that an electric potential difference applied across a set of parallel plates causes an electric field with a resulting force acting on any electric charges within the field. In this chapter this idea will be taken further to define the nature of electric current in various types of conductors.

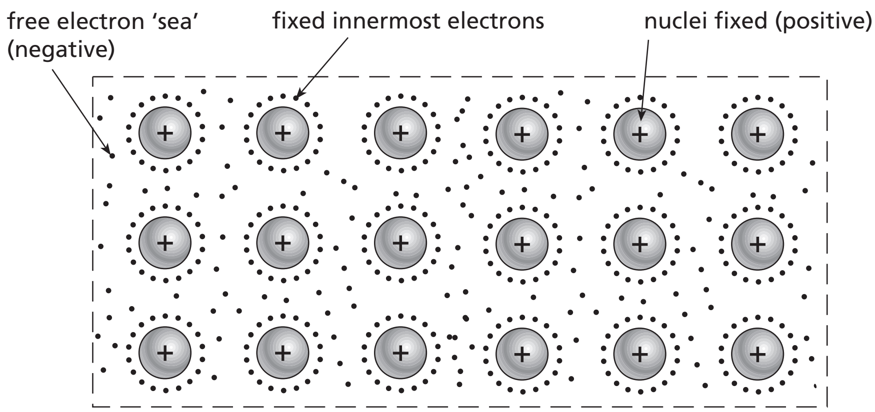


Figure 22.1
Metallic lattice. Positive nuclei in a sea of mobile electrons.

Generally metals are very good conductors of electric current. (Refer to Section 21.3.) This is because metal elements contain loosely bonded **valence electrons** in their outermost atomic electron shells. These are available for shared bonds with other nuclei. This atomic bonding pattern within blocks of metals creates a virtual 'sea of electrons' within the metal, allowing very easy motion of the electron particles under the influence of an applied electric field (Figure 22.1). The non-metal graphite is also a good conductor because of a similar pattern of loosely bound electrons within its solid crystalline lattice structure. Within metals it is therefore the negative electron particles that are free to move through a fixed nuclei lattice of positive charges.

Consider crystalline solids such as sodium chloride (common salt — NaCl). If this substance is dissolved in water, it dissociates into positive sodium **ions** (neutral atoms that have lost electrons) and negative chloride ions (neutral atoms that have gained electrons). Salt solution is referred to as an **electrolyte**. If an electric field is placed across this type of material, then charge movement of both positive and negative ions will occur. This is referred to as electrolyte conduction. A typical voltaic or electrolytic cell is shown in Figure 22.2, involving both electrolyte conduction and metallic conduction.

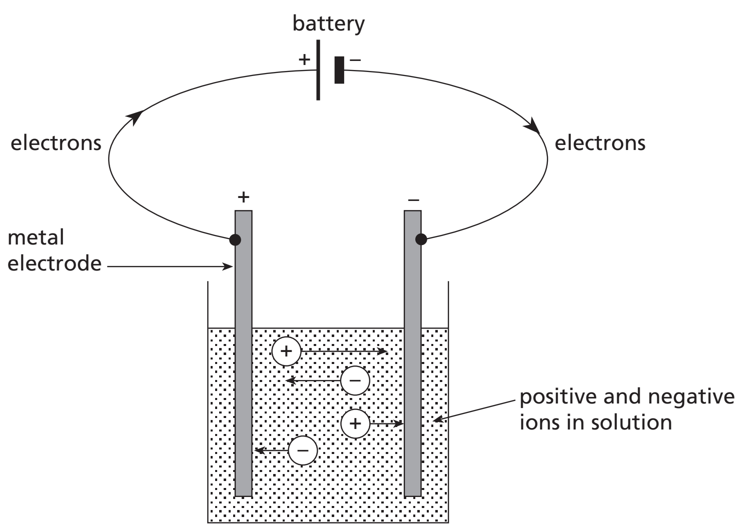


Figure 22.2
Electrolyte conduction.

Gaseous substances are normally insulators and will not conduct electricity due mainly to the wide spacing between nuclei and possible charge carriers. Gases can be made to conduct if the atoms are given enough energy by either heating or high voltage, or by irradiating with ultraviolet light or X-rays. Under these conditions the atoms of the gas are stripped of some of their electrons, the atoms become ionised, and charge motion due to both ions and free electrons can occur (Figure 22.3).

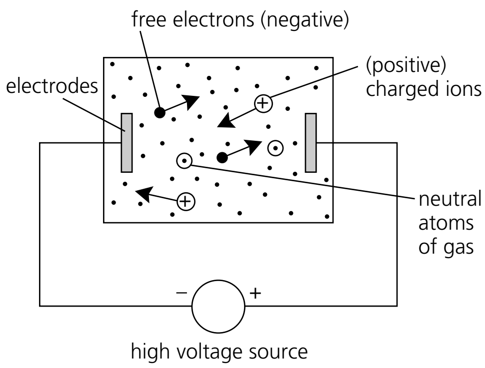


Figure 22.3
Gaseous conduction.

Let us return to conduction within typical metals. Consider a piece of copper conductor that has been drawn out into a fine wire owing to its very good **ductility**. The valence electrons within the metallic lattice are moving about at very high speed in random directions. If an external electric field is applied through the copper wire by means of a potential difference across its ends, then the free electrons will move under the influence of electric forces towards the higher potential. Remember, any one particular electron will experience a force $\boldsymbol{F} = q\boldsymbol{E}$ (Figure 22.4).

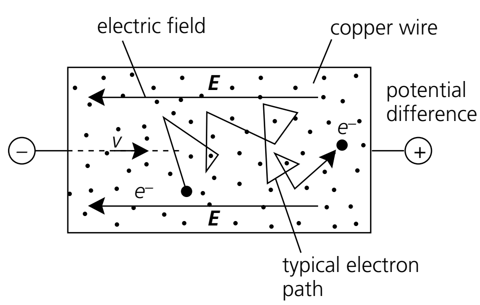


Figure 22.4
Drift velocity in metals.

Because the metallic lattice contains large numbers of nuclei, the electrons in motion undergo collisions that slow their progress. In general, the electrons drift at a particular terminal velocity characteristic of the conductor, which is known as the **electron drift velocity**, v. Typical metals have values for drift velocities of about 1×10^{-4} m s^{-1}. The flow of electric current along the wire occurs much more rapidly because an electrostatic repulsive pulse between neighbouring electrons occurs as soon as the electrons begin to move under the influence of the applied electric field. We would imagine an electron entering one end of the wire and, almost instantaneously, another electron being repelled from the opposite end of the wire. The actual electric current, I, flowing along the wire is the total number of electrons, q, passing any given point in the wire every second, t. If the rate of flow is constant then:

$$I = \frac{\text{charge}}{\text{time}} = \frac{q}{t}$$

The unit of electric current is the ampere or amp (A). One **ampere** of electric current is thus a flow of charge of 1 coulomb per second. 1 A = 6.25×10^{18} electrons per second. One ampere of current is quite large. In most electric circuits currents of microamps (μA) or milliamps (mA) are more common. Electric current is measured with an ammeter. (Refer to Section 22.5.)

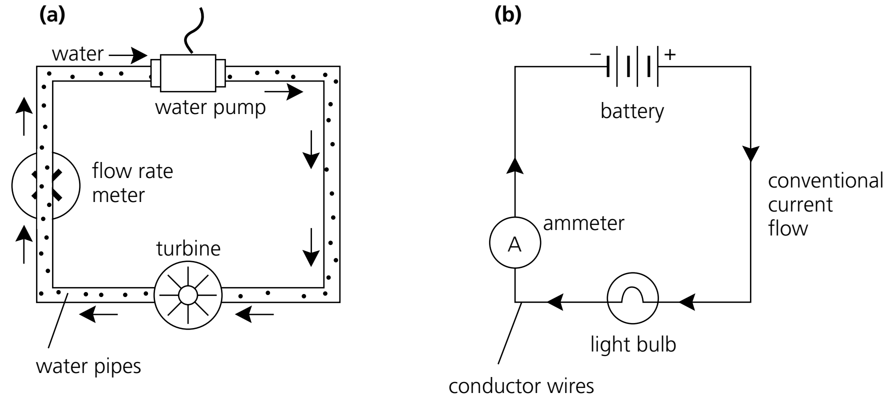


Figure 22.5
The water model.

It is very useful to consider an analogy such as a water model when considering the flow of electric charge. (See Figure 22.5.) The water mechanical pump is the equivalent of the electric battery. The water pipes are the equivalent of the electrical conductors and the water itself is analogous to the electric charges in motion, that is, the current. Note that as the water flows around the pipe circuit it can provide energy to run a water wheel, just as charge flowing around an electric circuit can provide energy to operate a light bulb. It is important to realise that in the water pipes water never gets used up, it just keeps getting recycled. The same thing occurs with electric charge. The electric charge doesn't get used up; it will keep flowing until the battery potential difference is reduced to zero as a result of energy transferred to the light bulb.

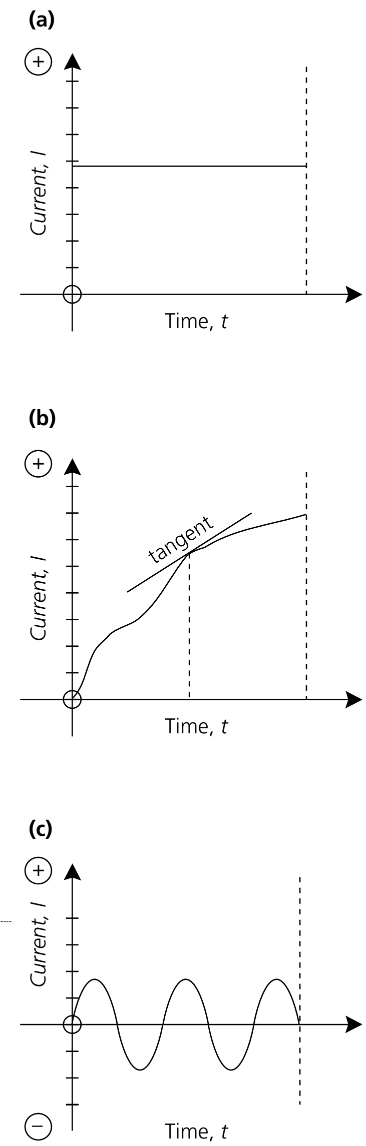
An electric **circuit** must be a complete closed loop path. In this case, the charges flow from the battery through the conductors to the light bulb and deliver the energy given to them by the battery. If the path is not complete, charge will not flow and the current stops. This is called an **open circuit**. If the battery terminals are connected directly together without the circuit containing a device such as a light bulb to restrict the amount of charge flowing, then a **short circuit** occurs. This is a very dangerous situation as the very large current that may flow can cause heating of the conductors, and subsequent fires. In fact, it is possible to cause sparking and welding of the metal conductors when very large batteries are short-circuited.

It is a historical fact that experiments were carried out with electricity and electrostatic charge long before the nature of atomic electrons was discovered. Benjamin Franklin had originally used the term 'positive charge' in electrostatics and early experimental work on electric current assumed that the charges in motion in conductors were positive charges and that they flowed along conductors from the higher positive potential to the lower negative potential (a little like water naturally flowing downhill). It is still common in physics and electric circuit analysis to refer to **conventional current** as the motion of positive charges from positive to negative. This is the convention used in this textbook. **Electron flow** is the direction of actual electron particle motion in a conductor from negative to positive. One amp of conventional current in one direction is the same as one amp of electron flow in the opposite direction. Recall that the convention for E, electric field direction, is that in which a positive test charge will move.

When electric charge flows from the source of charge around a circuit in the one direction, as in Figure 22.5, the type of current is called **direct current** (DC). Batteries and voltaic cells provide DC. The magnitude and direction of the flow is constant over time.

Figure 22.6**(a)** illustrates this I,t relationship graphically. If the magnitude of the rate of flow of charge changes without the direction of flow changing in a circuit, then the instantaneous electric current can be found from the slope of the I,t graph as in Figure 22.6**(b)**. An electric generator device involving rotating coils of wire in a magnetic field (refer to Chapter 26) will produce electric currents that vary in both magnitude and direction many times per second. This oscillating type of current flow in a conductor is called **alternating current** (AC) and is represented graphically in Figure 22.6**(c)**. Industrial and household electricity is distributed via this type of current flow. (Refer to Sections 22.6 and 22.7.)

Figure 22.6
AC and DC waveforms.



Example

A particular type of metal has an estimated 1×10^{23} free electrons per metre of its length. If this metal carries an electric current of 1.4 amps, estimate the drift velocity of the electrons through the metal.

Solution

- Let the conductor contain n electrons per metre.
- Let the electron drift velocity be v m s^{-1}.
- In a time of t seconds, a total number of electrons = nvt will pass a given point.
- This represents a total charge $Q = nqvt$, if the charge on one electron is q coulombs.

But electric current is calculated:

$$I = \frac{Q}{t} \qquad I = \frac{nqvt}{t} = nqv$$

thus:

$$v = \frac{I}{nq} = \frac{1.4}{1.0 \times 10^{23} \times 1.6 \times 10^{-19}}$$

$$v = 8.7 \times 10^{-5} \text{ m s}^{-1}$$

which represents the drift velocity in the metal.

22.3 ELECTROMOTIVE FORCE AND VOLTAGE

Recall that in the previous section it was stated that a battery can supply direct current (DC). Let us take this idea further to see why this is possible. A **simple cell** consists of two dissimilar metals separated by a conducting solution. If several simple cells are joined together the combined arrangement is called a **battery**. For example, the normal 12 volt car battery usually has six individual cells connected together. The simple cell allows two dissimilar metals to be separated by a conducting electrolyte solution or paste. In a copper-zinc cell such as in Figure 22.7, chemical reactions cause the copper electrode to become positively charged and the zinc electrode to become negatively charged with a potential difference of about 1.0 V. The familiar carbon-zinc dry cell (carbon-positive, zinc case-negative) produces a potential difference of about 1.5 V.

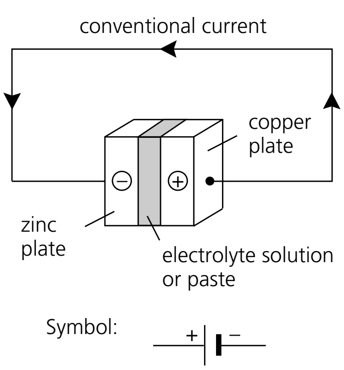


Figure 22.7
A simple cell.

NOVEL CHALLENGE

In the 1950s, car manufacturers changed from 6 V to 12 V batteries. Why do you suppose they did this? Are motorcycle batteries 12 V as well? Is the positive or negative of the battery connected to the car's body?

When a simple cell is constructed, the metal plates are separated by a salt solution, a weak acid solution or a conducting paste. The electric potential difference still exists between the positive and negative metal electrodes of the cell. This potential difference is measured in volts (V) and is usually referred to as the **electromotive force** (EMF) of the cell or simply its **voltage**. The term electromotive force is a historical reference to the original idea that a simple cell might force charges to flow in an external conductor. Experimentation with different combinations of metals in simple cell arrangements has identified a list, in order of the effectiveness in producing an EMF. This list is given in Table 22.1 and is known as the **electrochemical series**. Generally, the further apart two metals are located on the electrochemical series, the greater is the voltage (EMF) produced. Note the positions of familiar metals used in modern battery technology, such as lithium, manganese and nickel–cadmium.

Table 22.1 ELECTROCHEMICAL SERIES OF METALS

METAL		BEHAVIOUR
Lithium		metals
Caesium		donate
Barium		electrons
Calcium		
Magnesium		
Aluminium		
Manganese		
Zinc		
Iron		Potential difference
Cadmium		
Cobalt		
Nickel	e^-	
Tin		
Lead		
Copper		metals
Silver		accept
Gold		electrons

Photo 22.1
The battery in a car.

Once several cells are connected together and a battery is produced, the device can be used to provide electric current or a flow of charges in an external circuit connecting the positive and negative terminals, as shown in Figure 22.8. The battery itself is the energy pump that raises the charge to a higher electric potential at the positive terminal. Positive conventional current will flow from the positive terminal of the battery through the external circuit conductors and back to the negative battery terminal. Along this pathway the charge loses potential energy as it does work in various circuit elements. Potential energy is converted to other forms such as thermal, kinetic or light energy. Remember that in this process of energy conversion, the charge is not destroyed or used up, but its electric potential energy is reduced back to zero as it reaches the negative battery terminal. The battery will restore the electric potential energy of the charges back again to a high value. Figure 22.8 also illustrates this changing electric potential energy state of the charge carriers in the circuit. Remember, actual electron flow in the circuit is opposite to conventional current. In an electric circuit, electric potential is a measure of the electric potential energy per unit charge. More often than not, the most important feature in an electric circuit is the electric potential difference, which is commonly referred to as either a **potential rise** or a **potential drop**. The battery is a device that produces potential rises, whereas load elements such as light bulbs, resistive elements or motors can cause potential drop.

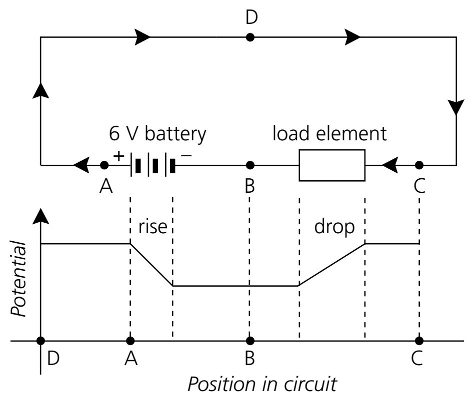


Figure 22.8
A simple circuit and potentials.

$$\text{Potential difference} = \frac{\text{work done to move charge}}{\text{amount of charge moved}}$$

$$V = \frac{\Delta W}{q}$$

where V is measured in volts (V); ΔW is measured in joules (J); q is measured in coulombs (C).

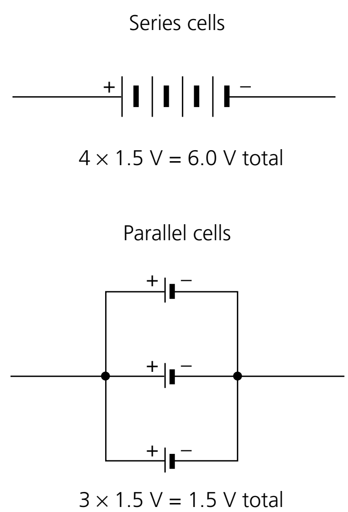
A potential rise of 1 volt means that a source of electric energy will give 1 joule of energy to each coulomb of charge that passes through it. A potential drop of 1 volt means that a load element such as a light bulb or resistor will remove 1 joule of energy from each coulomb of charge that passes through it. Recall from the electric current discussion in Section 22.2 that the current $I = \frac{q}{t}$, hence it is easy to show algebraically that $\Delta W = VIt$, which has the units of energy change.

Notice that the battery symbol, illustrated in Figure 22.8, actually consists of three separate cells connected together so that positive electrodes are directly connected to negative electrodes. This type of connection is called a **series connection** of the cells and the total EMF is the sum of the EMFs of each cell.

Series connection total EMF = sum of individual cell EMFs

Individual cells may also be connected together so that all positive electrodes are connected together and all negative electrodes are also connected together. This is called a **parallel connection** and the total EMF is then the same as each individual cell. In this connection a battery cannot supply more energy to each electron, but can in fact supply a greater quantity of electrons per unit time or a greater current flow in any external circuit. (See Figure 22.9.) Note that only equal values of EMF should be paralleled.

Figure 22.9
Cells in series and parallel.



Parallel connection total EMF = individual cell EMF

Example

A battery is known to contain four individual cells connected in series and is able to supply 3.6 J of energy to every 0.6 C of charge passing through it. What is the potential rise (EMF) produced by each cell?

Solution

Work done is equal to energy gained, hence $V = \frac{\Delta W}{q} = \frac{3.6\text{ J}}{0.6\text{ C}} = 6$ V. If the total EMF of the battery is 6 V, then each cell will produce EMF = 1.5 V.

Activity 22.2

NEI

A Big cells

Use a library, Internet searching or even the *Guinness Book of Records* to establish what is the largest existing lead–acid cell in the world, and what its electrical power output is.

SR

B The human nervous system

Read the following text information and answer the questions that follow.

The human nervous system contains important nerve-conducting pathways called neurons. Each neuron consists of a cell body containing a nucleus, and outgrowths called processes. The main one of these processes is the **axon**, which is responsible for carrying outgoing messages from the cell. This axon can originate in the central nervous system (CNS) and extend all the way to the body's extremities, effectively providing a highway along which messages travel to and from the CNS.

Dendrites are smaller, secondary processes that grow from the cell body and axon. On the end of these dendrites lie the axon terminals, which 'plug in' to a cell where the electrical signal from a nerve cell to the target cell can be made. This 'plug' (the axon terminal) connects into a receptor on the target cell and can transmit information between cells. The 'all-or-none law' applies to nerve cell communication; they use an ON/OFF signal (like a digital signal) so that the message can remain clear and effective throughout its travel from the CNS to the target cell or vice versa. This is a factor because, just like electricity signals, the signal fades out and must be boosted along its journey; if the message is either 1 or 0 (i.e. ON or OFF) the messages are absolute.

Nervous cells are classified into **inter-neurons** (neurons lying entirely within the CNS); **afferent neurons** (also known as sensory neurons — specialised to send impulses *towards* the CNS and *away from* the peripheral system); and **efferent neurons** (carrying signals *from* the CNS *to* the cells in the peripheral system).

When it was discovered over a century ago that nerve-impulses involved electric charges, it was assumed that a nerve impulse was simply an electric current flowing through a nerve, just as electric currents flow through conducting wires. Measurements of actual electric currents in nerves proved that the conduction process could not solely be due to conduction along the nerve fibre as its resistance was far too high and the speed of conduction was far too slow. It was proposed by Julius Bernstein in Germany in 1902 that nerve conduction primarily involved an electrochemical process. Bernstein suggested that the permeability of the nerve cell membrane varies for different ions in solution, especially sodium and potassium ions, and that the selectivity of the nerve membrane maintains the separation of ions and thus the electric potential. With subsequent modifications to the original Bernstein theory, the transmission of nerve impulses through neurons following stimulation is thought to occur as follows.

NOVEL CHALLENGE

Make up five questions that would test a person's understanding of electric current. Think about whether your questions are just about recall of facts or are really testing the person's understanding.

The membrane of a resting neuron is polarised; that is, the inside is negative relative to the outside. The concentration of sodium ions is greater outside, while the concentration of potassium ions is greater inside the neuron. Any stimulation causes the membrane to undergo a change allowing sodium ions to rush into the cell, which causes the inside to become positively charged relative to the outside. Very quickly, the membrane becomes permeable to potassium ions and they now rush out of the cell, which restores the inside of the cell again to a negative state. It is this rapid reverse polarisation of the membrane at successive points along the cell that constitutes a transmitted nerve impulse. Following the passing of the electrical impulse the ionic balance of the cell is restored back to its usual resting state by a biological ion exchange pump. It can be seen that the separation of charge and the subsequent electric potentials are vitally important in biological systems and not just in non-living systems. Within these biological systems the electric potential differences are of the order of 50–90 mV and are known as **action potentials**.

When multiple cells depolarise, either simultaneously or sequentially, they generate an electrical waveform which can be detected by external electrical circuits. For example, the depolarisation of cardiac cells produces the ECG (electrocardiogram). These millivolt signals can be detected electronically by either bipotential or instrumentation amplifiers.

Questions

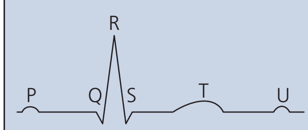
1 Why is the human nervous system like an electrical circuit? Do you think Ohm's law might apply to the circuitry? Refer to Section 22.4 to help you answer this.

2 Draw a diagram of what a typical human neuron might look like from the description above. Compare this with one you will find in any good Biology textbook. Oxford texts are best!

3 If nervous transmission is an 'all-or-none' system, what are the voltage amplitudes of the electrical switch signals that are travelling the body?

PHYSICS FACT

To obtain a standard ECG (as shown in the figure below), a patient is connected to the machine with three electrical leads (one to each wrist and another to the left ankle) that continuously monitor heart electrical activity using an instrumentation amplifier.



Each peak in the ECG is identified with a letter from P to U that corresponds to a specific electrical activity of the heart: The P-wave represents the electrical excitation (or depolarisation) of the atria, which leads to the contraction of both atria. The QRS complex represents the depolarisation of the ventricles, which initiates the ventricular contraction. The contraction starts shortly after Q and marks the beginning of the systole. Voltage peaks are of the order of 1.0 millivolts. The T-wave represents the return of the ventricles from excited to normal state (repolarisation). The end of the T-wave marks the end of the systole. The U-wave is usually very small and represents the repolarisation of a collection of specialised muscle fibres that make up the pacemaker system, which is responsible for spreading the electrical signal throughout the ventricle. Obviously, by counting the number of QRS complexes that occur in a given time period, one can determine the heart rate of an individual, but an ECG can give a lot more information. For example, since the ECGs obtained from different individuals have roughly the same shape for a given lead configuration, any deviation from this shape indicates a possible abnormality or disease.

For you to investigate

Draw the waveform for a person with: tachycardia, atrial fibrillation and ventricular fibrillation. Explain what each of these conditions means.

22.4 RESISTANCE AND RESISTIVITY

When a potential difference is applied across a metallic conductor, the electrons do not move very rapidly along the conductor. The electrons are accelerated by the applied electric force field due to their small mass; however, they very quickly collide with the positive metallic lattice ions in the conductor and lose energy. This rapid acceleration and subsequent collision leads to the average electron drift velocity, as discussed in Section 22.2. The magnitude of current through a conductor is proportional to the drift velocity of electrons through it. The effect of the collisions within the lattice is to reduce the current. This is the same as occurs in a stream that contains a lot of rocks, trees and other debris that reduce the rate of flow of water along it. Every time an electron collides with one of the metallic lattice ions, it loses energy, which is transferred to the lattice as heat and vibrational energy. This means that the temperature of the conductor increases. This opposition to the flow of electric current that any conductor produces is called its **electrical resistance**. The smaller the value of current that flows as a result of any given applied voltage, the larger the resistance.

Several factors determine the resistance of a conductor. Firstly, the longer the length L of a conductor, the greater the number of collisions occurring, while the likelihood of a collision is decreased if the conductor's cross-sectional area A is increased. Different conductors will have varying lattice types. For example, if the atomic lattice is tightly packed, more collisions are likely. The type of material from which any conductor is made controls the property called the resistivity, rho (ρ). Thus the overall electric resistance R is given by

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

where ρ = resistivity measured in Ω m; L = length measured in m; A = cross-sectional area measured in m^2.

The measurement unit for resistance is the **ohm**, named after **Georg Simon Ohm** (1787–1854), a German physicist. Its symbol is the Greek letter omega (Ω). Electric meters known as ohmmeters, as well as multimeters, can be used to measure any resistance value for a particular conductor; however, a simple experimental circuit can also be used, as shown in Figure 22.10.

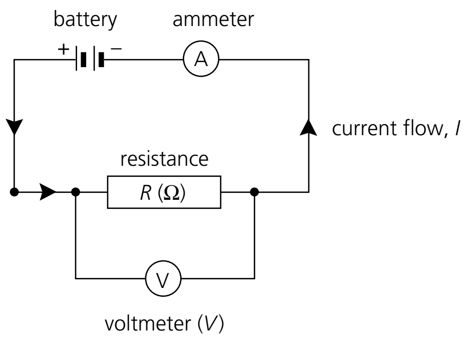


Figure 22.10
Measuring resistance.

This circuit measurement depends on the relationship between applied voltage and subsequent electric current through the resistance, which is known as **Ohm's law** and which is discussed more fully in Section 22.5, but is stated as:

The current flowing through a conductor is directly proportional to the potential difference applied across its ends, provided temperature and all physical conditions remain constant.

The ratio of V to I is defined as the electrical resistance, R. Thus, mathematically, I is proportional to V:

$$\frac{V}{I} = R \quad \text{or} \quad V = IR \quad \text{or} \quad R = \frac{V}{I}$$

A conductor would have a resistance of 1 ohm (1 Ω) if a potential difference of 1 volt (1 V) across its ends produces a current of 1 amp (1 A) flowing through it.

Table 22.2 ELECTRIC RESISTIVITY AND TEMPERATURE

MATERIAL	RESISTIVITY, ρ (Ω m)	TEMPERATURE COEFFICIENT, α (°C^{-1})
Silver	1.5×10^{-8}	4.1×10^{-3}
Copper	1.7×10^{-8}	4.1×10^{-3}
Aluminium	2.6×10^{-8}	3.9×10^{-3}
Iron	8.9×10^{-8}	6.2×10^{-3}
Platinum	9.8×10^{-8}	3.7×10^{-3}
Mercury	94×10^{-8}	0.88×10^{-3}
Nichrome	100×10^{-8}	0.4×10^{-3}
Carbon	5×10^{-5}	-5×10^{-4}
Silicon	600	-700×10^{-4}
Fused quartz	$\approx 10^{17}$	

Like many physical properties, resistivity not only depends on the material involved but also on the temperature. Table 22.2 lists the electric resistivity, ρ, properties of various materials as well as their temperature coefficient of resistivity, α, values. The resistivity of pure metals increases linearly with temperature because a temperature increase causes the lattice ions to vibrate with greater amplitude. This increases the likelihood of electron collisions and decreases the current through the conductor. The expression for the increase in resistivity with temperature for any conductor is:

$$\rho_T = \rho_0 \ (1 + \alpha \Delta T)$$

and since resistivity is proportional to the resistance, R, then we can also write:

$$R_T = R_0 \ (1 + \alpha \Delta T)$$

where R_T = conductor resistance at a temperature of T°C; R_0 = conductor resistance at a temperature of 0°C; α = temperature coefficient of resistivity °C^{-1}; ΔT = temperature change in °C.

A practical application of the resistance change with temperature is a **resistance thermometer**.

NOVEL CHALLENGE

A A wire is stretched to twice its length. What happens to its resistance? Justify your answer mathematically.

B Can a copper wire and an aluminium wire of the same length (say 1.0 m) have the same resistance? There are at least two answers and you should justify these mathematically.

Activity 22.3 NOT YOUR NORMAL THERMOMETER!

Platinum is a metal with a very high melting point and reasonably high resistivity value. Using the library, or encyclopaedia, research the construction and method of operation of a platinum resistance thermometer. Describe how its variable resistance characteristic could be measured in a practical situation where it might be used to determine the operating temperature of a furnace.

Example

What is the electrical resistance at 0°C of a piece of copper wire whose length is 1.2 m and whose cross-sectional area is 17.2 mm^2? How would the electrical resistance change if the copper wire temperature was raised to 25°C?

Solution

From Table 22.2, the resistivity for copper is 1.7×10^{-8} Ω m at 0°C. Using:

$$R_0 = \rho \frac{L}{A} = \frac{1.7 \times 10^{-8} \times 1.2}{17.2 \times 10^{-6}}$$

$$R_0 = 1.18 \times 10^{-3} \ \Omega$$

and using the value of the coefficient from Table 22.2 for copper:

$$R_T = R_0 \ (1 + \alpha \Delta T)$$
$$R_T = 1.18 \times 10^{-3} \ (1 + 4.1 \times 10^{-3} \times 25)$$
$$R_T = 1.3 \times 10^{-3} \ \Omega \text{ at } 25°\text{C}$$

Notice in Table 22.2 that some substances like silicon and carbon actually posses a negative temperature coefficient and thus will decrease their resistance as the temperature increases. This feature can lead to difficult handling methods when trying to control their temperature in working electronic circuits.

Practical resistors vary in design and size and are very common in electronic devices. They will be further discussed in terms of this application in Chapter 23; however, resistive elements are used wherever electrical energy needs to be converted into heat energy, such as in domestic electrical appliances like room heaters, stove elements and hot water systems. The resistive element in these applications is usually made of an alloy containing nickel and

Photo 22.2
Various resistors.

chromium metal called nichrome wire. Notice its very high resistivity value in Table 22.2. Quite often, long lengths of resistive wire are wound on special insulating formers and, in conjunction with a sliding contact, produce a device whose resistance can be varied. It is known as a **rheostat**. This type of device is used to control voltages in electric circuits and to act in conjunction with electric motors and dimmer switches. The common volume control knobs on radio, television and stereo equipment are always simple variable resistor (rheostat or **potentiometer**) components. Tungsten wire forms the filament of modern incandescent light bulbs. The high resistivity of tungsten, especially when allowed to heat up within the controlled environment of a halogen gas inside the glass bulb, causes very bright light to be emitted with good efficiency.

Human skin is a very good insulating material, luckily, but the tissues and fluids just beneath the skin contain a large number of ions and hence conduct electricity very efficiently with low resistance. The variable skin resistance can be measured with sensitive equipment and is often the basis of the American Justice System polygraph or lie-detector test.

Another application is in diagnostic medicine. By producing a small electric current between two points on the body surface it is possible to measure the electric resistance. Usually one electrode is attached to a patient's leg and another is moved over the body surface with a voltage applied between the electrodes. The electrical path resistance varies especially near abnormalities such as nerve damage or tumour tissue locations. This technique is quite useful in the detection of cancer, for instance.

Internal resistance

Finally in this section, let us look at the ideas of **internal resistance** of a battery and connections of resistances in series and parallel. In a battery, chemical energy is continuously being converted into electric energy when the battery is in use. During this process, internal heat is produced and the amount of heating is dependent on the current being drawn from the battery. Thus the battery behaves as if it had an internal resistance, *r*.

Figure 22.11
Battery internal resistance.

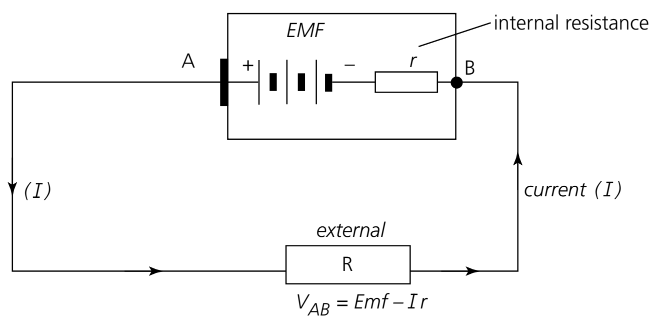


Figure 22.11 shows the circuit diagram for a battery supplying current to an external resistance, *R*, and includes the battery's internal resistance. Because the current, *I*, passes through the battery as well, a potential drop of *Ir* is caused, which subtracts from the battery EMF. Thus the terminal voltage of the battery, as measured by a voltmeter, would be:

$$V_{AB} = EMF - I \times r$$

Notice that, if the battery is not supplying any external circuit current, the terminal voltage equals the EMF. When the car is started, a very large current, in the order of 100 A, must be supplied by the battery for a short period of time. If the car is started with the lights on, the lights will usually dim considerably as the terminal voltage is reduced by *Ir* across the battery itself, producing a much lower voltage across the headlights. All new batteries have an internal resistance that is quite small, say, 0.05 ohm for a typical D cell. As the battery gets older, its internal resistance builds up to such an extent that it is no longer able to deliver any useful current, due to the fact that its terminal voltage reduces to zero. We commonly call this a 'flat' battery.

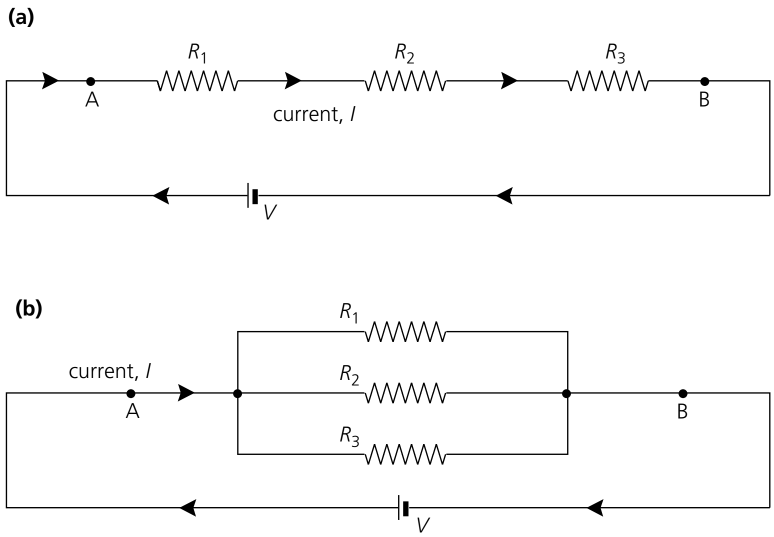


Figure 22.12

Consider Figure 22.12**(a)** which shows three resistors connected in series so that any current flowing from A to B must pass through each in turn. This effect simply adds the individual resistances to create a total of all three. It is the same as increasing the effective length of a single resistor. Thus:

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

Consider Figure 22.12**(b)**, which shows three resistors connected in parallel, like the rungs of a ladder. Current flowing from A to B in this situation has three paths to take. In a sense, the total cross-sectional area of the conductor for current I is being increased and thus the total resistance is reduced. This leads to the addition of the reciprocals of each resistance to give a relationship expressed as:

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

Both of these connection rules will be proved in greater detail using the electrical circuit laws of Ohm and Kirchhoff in the next section.

EI Activity 22.4 CHRISTMAS AND CONDUCTIVITY

1. Inexpensive Christmas tree lights have the individual bulbs connected in series. Predict what would happen if one of the light bulbs blew. Try this out by carefully removing a bulb from a working set. Also try this with more expensive light sets where the individual resistive bulbs are connected in parallel. What is your prediction now?
2. Use the *Guinness Book of Records* to find the highest temperature at which practical applications of the principle of superconductivity (zero effective resistance) will occur.

Example

Calculate the total resistance of a pair of 25 Ω resistors connected in parallel to a battery whose EMF is 12 V. Deduce the current, measured by a DC ammeter, that will flow from the battery.

Solution

Calculate the total effective resistance:

$$\frac{1}{R_{tot}} = \frac{1}{25} + \frac{1}{25} = \frac{2}{25}$$
$$R_{tot} = 12.5\ \Omega$$

Use $V = I \times R_{tot}$ to find current as measured by the ammeter:

$$12 = I \times 12.5$$
$$I = \frac{12}{12.5} = 0.96\text{ A}$$

Questions

1 Describe the difference in behaviour between static electricity, direct current (DC) electricity and alternating current (AC) electricity in terms of flowing charges.

2 What is the voltage necessary to move 15 coulombs of charge through a conductor, if the energy required is 80 joules?

3 A piece of metal conductor is estimated to contain 3×10^{22} electrons per metre of its length. If it carries a current of 1.5 A, determine the average drift velocity of the electrons in the conductor.

4 Calculate the increase in potential produced by a cell if every 2.6 coulombs of charge passing through is supplied with 3.9 joules of energy.

5 A voltage of 120 V is applied to a bulb whose resistance is 200 Ω.
(a) What is the current through the bulb?
(b) How much charge flows through the bulb every hour?

6 A pigeon stands on a 100 kV high-tension wire that carries 50 A. If the line resistance is $2.0 \times 10^{-4}\ \Omega\ m^{-1}$, calculate the voltage across the bird if its feet are 3.0 cm apart. What can you deduce about the likelihood of the pigeon being electrocuted?

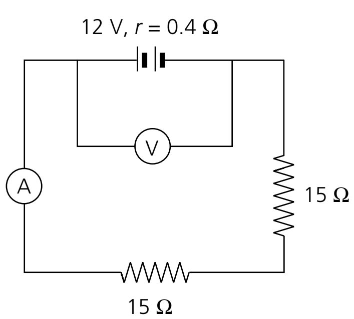
7 You are asked to design the electrical parts of an electric toaster. Describe the nature of the electrical conductors you might use.

8 The resistance of a certain metal conductor, A, is found to be 0.36 Ω at 25°C. If you found another conductor, B, made of the same material but different in characteristics as shown below, calculate in each case the new resistance value of B compared with A.
(a) Conductor B is three times longer than A.
(b) Conductor B is only half the cross-sectional area of A.
(c) Conductor B has just been taken from an oven operating at 350°C.

9 Refer to Figure 22.10. A student set up the experimental apparatus and found the following results as tabulated. Plot a current versus voltage graph and determine the value of the resistance at all points. Describe what you find. Is the resistor 'ohmic' in its characteristics? Explain.

Current (A)	0.0	0.013	0.25	0.04	0.05	0.06	0.08
Voltage (V)	0	2	4	6	8	10	12

Figure 22.13
For question 10.



10 Consider Figure 22.13, showing an EMF source and its internal resistance connected to two series resistors of value 15 Ω. Calculate the readings on the circuit meters shown.

22.5 ELECTRIC MEASUREMENT AND CIRCUITS

In this section we will look at:

- important electric measurement meters
- the laws of DC electric circuits and how to draw them using correct symbols
- methods of analysing the circuits to calculate values of current, voltage and resistance.

Let us first deal with the basic laws of electric circuits. Recall that in the previous section, an experimental circuit was discussed that allowed the measurement of resistance. (Refer to Figure 22.10.) If this circuit has a variable source of EMF, a data table of current flow, I versus applied voltage, V obtained, and a graph of the results drawn, then an important set of conclusions can be drawn (Figure 22.14).

- We find that a linear relationship exists between current, I, and voltage, V, for most types of resistors or resistive elements.
- The graph of current versus voltage is a straight line that passes through the origin.
- The slope of this line is a constant value.
- If a different value of resistance is used, the same type of relationship is found but the graph has a new slope.

These conclusions were first reached by Georg Simon Ohm (1787–1854), a German physicist, and they are summarised as a general property of materials, called Ohm's law:

> The current flowing through a conductor is directly proportional to the potential difference applied across the ends of the conductor, provided temperature and other physical factors are kept constant.

The measured ratio of voltage to current is defined as the conductor resistance, R.

From the definition of resistance, we obtain the equivalent forms $V = IR$ and $I = \frac{V}{R}$. The equation $V = IR$ is often used in circuit calculations to evaluate resistance and link voltage to current. It may represent Ohm's law.

All conductors that obey Ohm's law are called **ohmic conductors** whereas conductors that do not are called **non-ohmic conductors**. The best examples of non-ohmic conductors are modern semiconductor devices such as transistors, diodes and thermistors and these will be discussed in Chapters 23 and 24. A graph of current versus voltage for any non-ohmic conductor will not be a straight line, but the gradient of the tangent at any point can be used to determine the instantaneous dynamic resistance at any specific voltage or current. This is useful in more advanced AC calculations and circuit analysis.

The next two circuit laws were formulated by **Gustav Robert Kirchhoff** (1824–87), also a German physicist, while studying electrical networks. The first of these laws is based on the law of conservation of electric charge and applies to junction points in a circuit; that is, points where three or more wires join together. It is usually referred to as **Kirchhoff's junction law** and is represented in Figure 22.15**(a)**.

This law is expressed as:

> The sum of all currents entering any circuit junction is equal to the sum of all currents leaving that junction point.

or symbolically:

$$I_1 = I_2 + I_3$$

The second is called **Kirchhoff's loop law** and is based on the law of conservation of energy as applied to complete closed circuit paths or loops. (See Figure 22.15**(b)**.) This law is expressed as:

> The algebraic sum of all voltage changes encountered in any complete closed circuit loop is equal to zero.

Figure 22.14
Ohm's law.

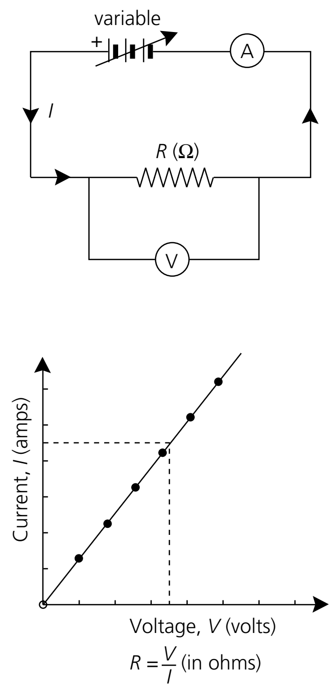
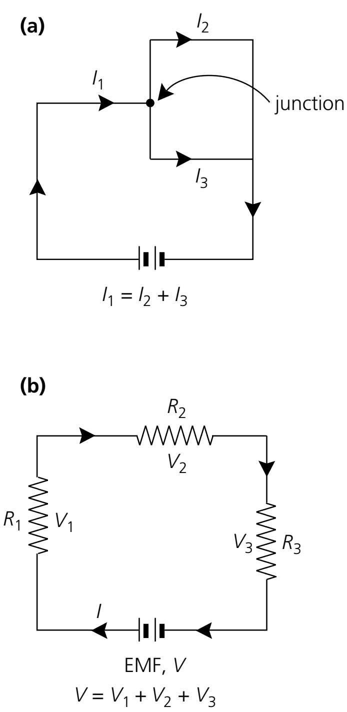


Figure 22.15
Kirchoff's circuit laws. Junction law **(a)**; loop law **(b)**.



or symbolically:

$$V = V_1 + V_2 + V_3$$

Remember that in most simple circuits with constant current flowing, electric charge gains electric potential energy in the battery and loses it within each external load element such as resistors. Hence, this voltage loop law is the same as saying that the voltage rise of the battery is equal to the sum of the potential drops across each load resistor.

At this point it is important to realise that in the analysis of most DC circuits these three laws are always used in combination, as in the next example.

Example

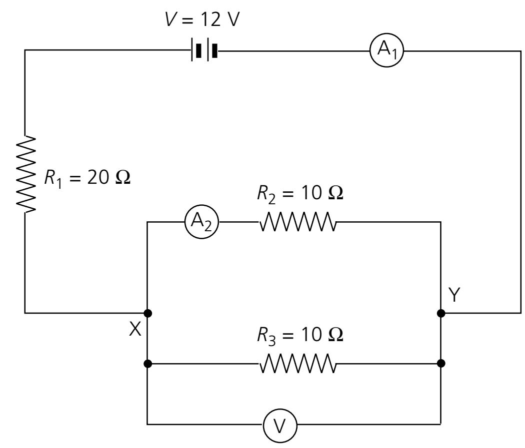


Figure 22.16
A simple network circuit.

Consider the circuit drawn in Figure 22.16 containing a simple network of three resistors connected to a DC battery of 12 V. Use circuit laws to calculate the readings on the electric meters in the circuit.

Solution

Reading the circuit, we need to find:

(a) the equivalent resistance of the parallel pair XY;
(b) the total equivalent resistance in the circuit;
(c) the total current flowing from the battery, A_1;
(d) the voltage drop across the equivalent resistance XY;
(e) the current flowing through resistor R_2 measured by meter A_2.

Thus, for the parallel pair:

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

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

$$R_{XY} = 5 \text{ ohms}$$

Note: the circuit could now be redrawn with only this single equivalent resistor.

Thus, total circuit resistance:

$$R_{tot} = R_1 + R_{XY} = 20 + 5 = 25 \text{ ohms}$$

Hence total current flowing from battery:

$$I_{tot} = \frac{V}{R_{tot}} = \frac{12}{25} = 0.48 \text{ A} = 480 \text{ mA}$$

Because of Kirchhoff's loop law:

$$V = V_{XY} + I_{tot} \times R_1$$
$$V_{XY} = V - (I_{tot} \times R_1)$$
$$V_{XY} = 12 - (480 \times 10^{-3} \times 20)$$
$$V_{XY} = 2.4 \text{ volts}$$

Notice that the sum of voltages around the circuit is 2.4 V + 9.6 V = 12 V.
Thus the current flowing through the resistor R_2 is given by:

$$V_{XY} = I_2 \times R_2$$
$$2.4 = I_2 \times 10$$
$$I_2 = 0.24 \text{ A} = 240 \text{ mA}$$

This is the reading on ammeter A_2.

Electric meters

With the development of the early electricity industry in the 1880s, engineers needed a simple, reliable and, above all, very fast way of measuring electric currents and voltages. The methods of the physics laboratory requiring delicate apparatus, controlled environments, careful calibrations and lengthy calculations were not suitable for the rough conditions of the industrial engineer. William Ayrton and John Perry, engineers from the Finsbury Technical College in London, devised new robust and portable instruments, which they called the ammeter and the voltmeter. It is interesting to note that the British physicists of the day were not at all impressed with these new engineering instruments. It was their opinion that the only quantities that could be measured directly were mass, length and time. They regarded all other quantities as having to be derived from these 'absolutes' by the ingenuity and skill of the experimenter and certainly not able to be read from a 'scaled instrument'. To the physicists of the Victorian era these new instruments were a threat to the moral development of students. How times have changed; today, electric meters are an integral part of any physics laboratory.

When electric measurements are made on a circuit it is obviously important that the electric meters used should only alter the circuit's behaviour in a very minor way. Any electric meter is going to have some internal resistance and this will need to be taken into account in the way in which the meter is used. The two most useful electric meters, as already seen in this chapter, are the **ammeter** and the **voltmeter**, for measuring current and voltage respectively. Both of these meters require current to operate, yet they must have negligible effects on the currents and voltages within the circuit itself. Let us see how. Both ammeters and voltmeters contain a sensitive assembly known as a **galvanometer**. This assembly contains a fine wire coil that has a pointer needle attached to it and is free to rotate within a magnetic field. The galvanometer uses the electromagnetic motor principle in which a current-carrying coil will rotate in a magnetic field. This rotation is balanced by a return spring and the needle deflection will register directly the amount of current flowing through the galvanometer coil. (See Photo 22.3.) The internal resistance of galvanometers can vary but is usually quite low (20–100 Ω) and the maximum current that the fine wire coil can carry is also very low, of the order of microamps or milliamps when producing a **full scale deflection** (FSD) across the measurement pointer scale of the instrument.

Photo 22.3
Galvanometer assembly.

In order to make a galvanometer operate as an ammeter it must be placed in series into the main circuit and also contain a current bypassing **shunt resistor** of sufficient value to prevent internal damage to the galvanometer (Figure 22.17). The parallel shunt resistor allows most of the measured current to bypass the galvanometer and not damage it. The shunt is often a piece of resistance wire.

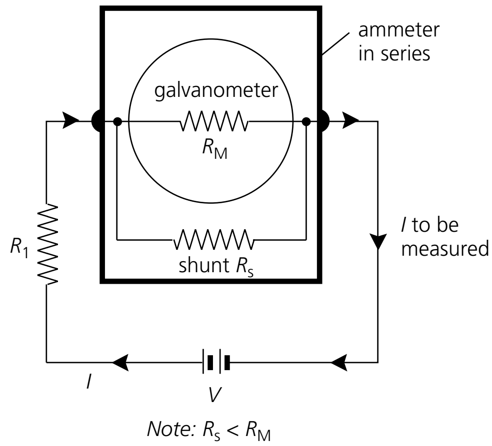


Figure 22.17
A galvanometer used as an ammeter.

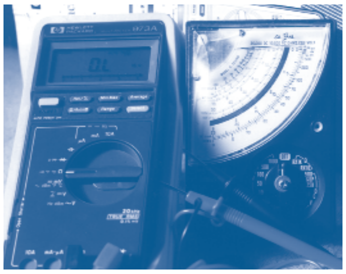


Photo 22.4
Multimeter instruments.

Example

What value of shunt resistor would be required by a galvanometer, whose internal resistance, R_M, is 25 Ω and whose FSD current, I_M, is 1.0 mA, if it is required to form part of an ammeter that will measure up to 6 A in total?

Solution

Let the current to be measured, I_{tot}, be 6 A.
Because the shunt resistor is in parallel with the galvanometer, then $V_{shunt} = V_{meter}$.
Therefore, using Ohm's law:

$$I_S \times R_S = I_M \times R_M$$

But $I_{tot} = I_M + I_S$ by junction law:

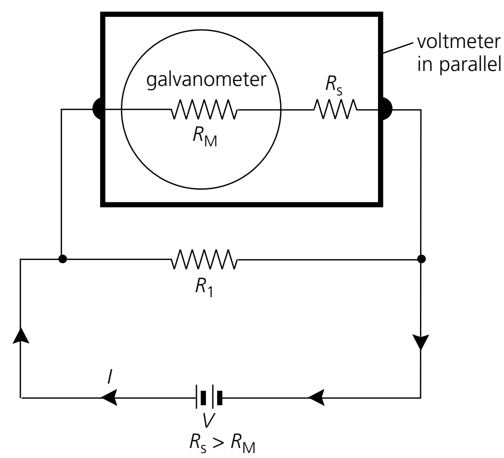
$$R_S = \frac{I_M \times R_M}{I_{tot} - I_M} = \frac{1.0 \times 10^{-3} \times 25}{6.0 - 1.0 \times 10^{-3}}$$

$$\text{shunt resistor } R_S = 4.2 \times 10^{-3}\ \Omega$$

Photo 22.5
CBL2 data-logger and graphics calculator.

A voltmeter is a galvanometer placed in parallel to the circuit component across which the voltage is being measured. Since the galvanometer typically has a low internal resistance, most of the current flowing in the circuit would flow through it and cause damage. To prevent this, a voltmeter always contains a very high value series resistor, so that the resistance of the voltmeter becomes large compared with that of the circuit component being measured and the current flow in the circuit is hardly altered. (See Figure 22.18.)

Figure 22.18
A galvanometer used as a voltmeter.



Example

What value of internal series resistor would be required by a galvanometer whose internal resistance, R_M, is 25 Ω and whose FSD current, I_M, is 1 mA, if it is to form part of a voltmeter that is required to measure up to 12 V in total?

Solution

As the series resistor and R_M are in series and together must only allow a total current flow of 1 mA through the voltmeter, then:

$$V = I_M (R_S + R_M)$$

If $V = 12$ V, then

$$12 = 1.0 \times 10^{-3} (R_S + 25)$$

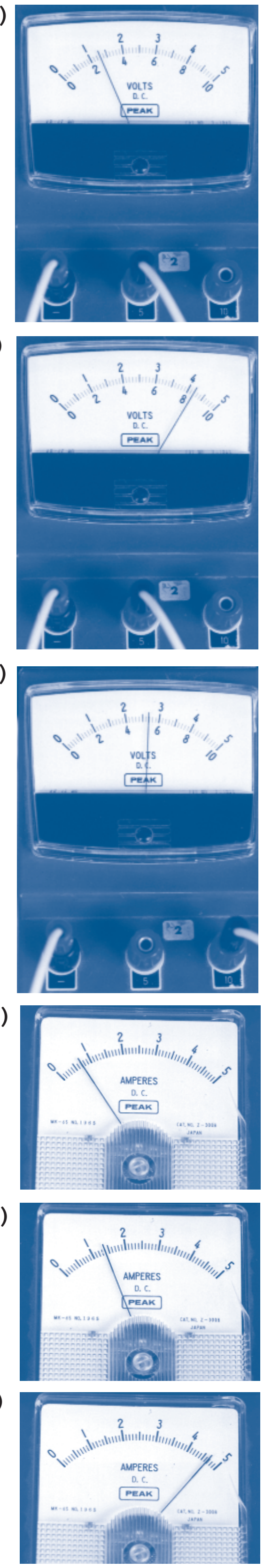
$$R_S = \frac{12}{1.0 \times 10^{-3}} - 25$$

Series resistor $R_S = 12\ 000\ \Omega = 12\ \text{k}\Omega$ would be used.

Often electricians or electronics technicians make use of a combined meter called a **multimeter**. (See photo.) This instrument is a multi-scaled device that is usually capable of measuring resistance, voltage and current in both DC and AC modes. In recent times, the output display is a digital display rather than the analog needle movement type of voltmeter and ammeter described in this section. The use of a multimeter has more importance in electronics and will be further discussed in Chapter 23. Electricians who need to test the effective resistance of insulation around conductors to check safety requirements use an instrument called a 'megohm tester', which is able to measure the resistance at a particular high voltage.

Photo 22.6
Meter scales.

(a) (b) (c) (d) (e) (f)



Activity 22.5

SR

A Read the meter scales

Use the set of photographs (Photo 22.6) showing various electrical instrument scales. Read the measured quantities accurately. List what each instrument is, and its scale reading in correct units.

EI

B Battery discharge project

You are required to test and complete an experimental report on the discharge characteristics of several different types of batteries. To do this you will need to design and set up a discharge circuit that allows the data-logging of the terminal voltage under load of the various battery types. You could, for example, compare such types as normal zinc–carbon batteries with Energizer alkaline MAX, Energizer e2-Titanium, Nickel–cadmium rechargeable and lithium metal hydride batteries. The final choice is up to you.

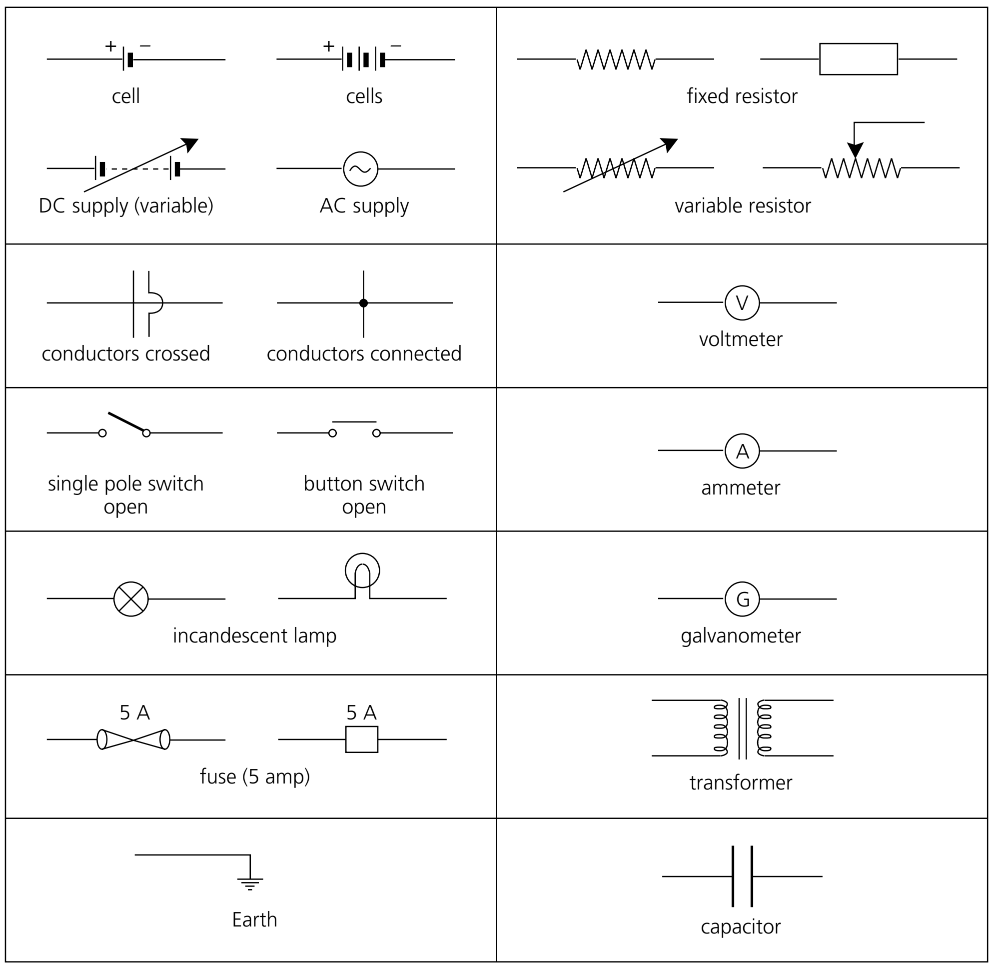
The test rig should be able to allow the connection and slow discharge of the batteries through a normal light bulb circuit and you should program the CBL2 data-logger to take voltage sensor readings as the battery discharges through the light bulb circuit. Your experimental design should include all circuit diagrams and constructional methods. You should display all final results in graphical form for easy comparison by using the features of the data-logger.

If you have both voltage and current sensors for the CBL2 or an equivalent data-logger, then you may be able to directly compare voltage and current discharge characteristics for your battery set. You could also compare your findings with technical data that is available on the Internet sites of companies such as Eveready, Energizer, Panasonic or TDK.

Circuit symbols

We have been using several common electric circuit symbols already. Electric circuit diagrams are the standard method of representing actual circuits in practice. Some standard electric symbols used are shown in Figure 22.19. More will be met in the next chapter. It should be noted that a rectangular style is used when drawing electric circuit diagrams. This is for ease of reading the connections between various components but, in practice, the actual working circuit may not follow this rectangular style, especially if forming part of a printed circuit board in a consumer electronic device such as a television set or computer. Finally in this section, we will analyse a more complex electric circuit, making use of all circuit laws, electric meters and methods of connection discussed so far. This process is very important as you must be able to read unfamiliar electric circuits and carry out the necessary calculations to solve for unknown or required circuit component values. You must also be able to use the laws of circuit behaviour to predict voltages and currents at any point in a circuit. The following example illustrates the general steps that might be followed, but remember that there is usually more than one way to the solution.

Figure 22.19
Circuit component symbols.



Example

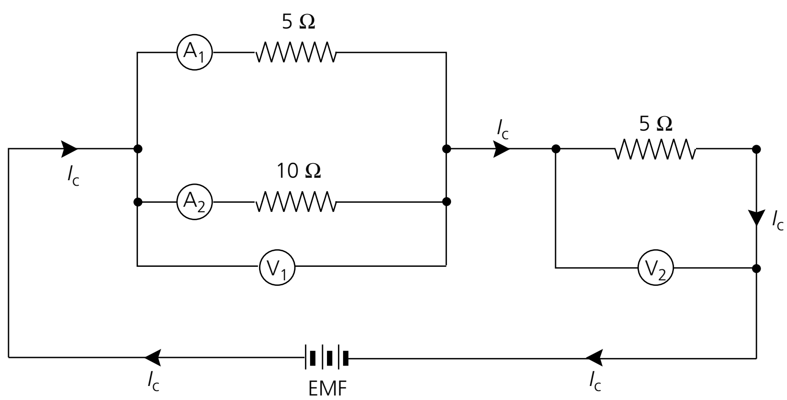


Figure 22.20

Consider the circuit shown in Figure 22.20. Calculate the circuit current, I_c, flowing from the battery, as well as the current reading on ammeters A_1 and A_2 and the voltage reading on V_1 and V_2. What is the battery EMF if it contains three cells each of 1.5 V?

Solution

Note the following points about this circuit:

- Battery has three cells each of 1.5 V, therefore EMF = 4.5 V.
- 10 Ω and 5 Ω resistors are in parallel and this combination is in series with the 5 Ω resistor.
- The current readings $A_1 + A_2$ will equal I_c because of Kirchhoff's junction rule.
- The voltages across the 5 Ω and 10 Ω resistors will both be equal to voltage V_1.
- The sum of voltages $V_1 + V_2$ will equal the EMF, 4.5 V, due to Kirchhoff's loop law.

Step 1 Calculate equivalent resistance of parallel combination:

Use $$\frac{1}{R_P} = \frac{1}{5} + \frac{1}{10} \Rightarrow \frac{1}{R_P} = \frac{3}{10} \Rightarrow R_P = 3.3\ \Omega$$

Step 2 Calculate equivalent circuit total resistance in series with battery:

$$R_{tot} = R_P + 5 = 3.3 + 5 = 8.3\ \Omega$$

Step 3 Calculate total current flow, I_c, using Ohm's law:

$$I_c = \frac{V}{R_{tot}} = \frac{EMF}{R_{tot}} = \frac{4.5}{8.3} = 0.54\ A$$

Step 4 Now consider only the 5 Ω resistor. Apply Ohm's law to find the voltage V_2:

$$V_2 = I_c \times R = 0.54 \times 5 = 2.7\ V$$

Step 5 Calculate the voltage V_1, using the loop law:

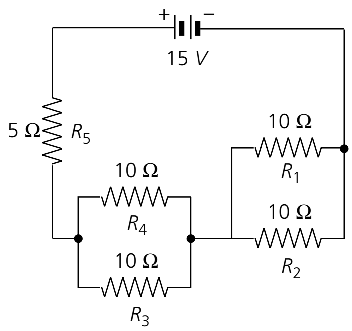
$$V_1 + V_2 = EMF \Rightarrow V_1 + 2.7 = 4.5 \Rightarrow V_1 = 1.8 \text{ volts}$$

Step 6 Voltage V_1 = 1.8 V is the voltage drop across each resistor 5 Ω and 10 Ω in the parallel arm. Hence, calculate currents A_1 and A_2:

$$V_1 = I_1 \times 5 \qquad 1.8 = I_1 \times 5 \qquad I_1 = 0.36\ A$$
$$V_1 = I_2 \times 10 \qquad 1.8 = I_2 \times 10 \qquad I_2 = 0.18\ A$$

Notice finally that the sum of the currents I_1 and I_2 equals the circuit current I_c = 0.54 A as required by Kirchhoff's law. It is also possible to redraw equivalent but simplified circuit diagrams at each step to further aid understanding of the analysis.

Figure 22.21
For question 12.



Questions

11 A student set up an electric circuit with two 25 Ω resistors in parallel, connected to a battery of EMF 12 V. She wishes to calculate total circuit current and the individual currents through each resistor. Draw a circuit diagram she would use and calculate values.

12 Consider the electric circuit shown in Figure 22.21. Calculate the current flowing through each resistor and the voltage drop across each resistor using the laws of circuit analysis. Fully describe your steps and redraw the appropriate equivalent circuits at each step.

ELECTRICAL ENERGY AND POWER 22.6

The most important aspect of electrical energy use in modern society is the ease with which this form of energy can be converted into a whole range of other energy forms, such as heat, light, mechanical energy, electromagnetic energy — radio, television. Electrical energy is generated in several ways, at a simple DC level with devices such as cells and batteries, through to AC generators of different types. Domestic and industrial AC electricity supply is generated often by coal, oil or gas burning power stations or even by thermal, wind power or hydroelectric power stations. The basis of all forms of AC electric generators is the spinning coil induction turbine. Once the electrical energy is produced, AC transformers can change the voltage so that it may be efficiently distributed via conducting cables around the countryside to factories and homes. These devices, techniques and issues will be discussed in detail in Chapter 26.

NOVEL CHALLENGE

A writer in *New Scientist* magazine (July 1998) described how in 1938 he stayed in a country house in England and helped wind up a 1 tonne steel ball suspended on a chain into the roof space. During the evening, the ball was allowed to fall slowly, turning a generator to keep a light glowing all night. He said that this was impossible as there was not enough gravitational potential energy in the ball to do this. Verify his claim by working out how long a 60 W lamp would glow if the ball was raised 5.0 m. Assume the energy conversion was 100% efficient (unlikely!). In actual fact it turns out that the steel ball did not turn a generator but turned an enclosed 44 gallon drum partly submerged in petrol. As the drum turned, petrol evaporated and was burnt in a gas lantern.

NEI Activity 22.6 BIG GENERATORS

1. Use library research or send away to your local electricity authority to find out about the types of power stations that produce electricity for your school and home. If you have a solar or wind-powered electric generator at your house or school, find out how it works and write a short descriptive report.
2. Research from an encyclopaedia, Internet searching or the *Guinness Book of Records* the highest voltage ever produced and where it was accomplished.
3. Try to find out from similar sources the location of the largest electric generator operating in the world and what its output is.

When an electric current flows through a resistor, thermal heat is produced, as was discussed in Section 22.3. Electrical energy is being converted to thermal energy within the resistor and this forms the basis of any electric appliance designed to produce heat, such as radiators, electric stove elements, hot water systems, electric blankets and electric kettles. In an electric light bulb, this resistive heating of the filament wire even begins to produce light energy. Electrical energy is often converted into mechanical energy; for example, in any appliance that contains an electric motor. Whenever electrical energy conversion is occurring, electric charge, Q, is being moved through a potential difference, V. This requires an electric force doing work, W, given by $W = Q \times V$.

The rate of energy transfer or the rate at which electrical work is done is called **electrical power**. Thus:

$$P = \frac{W}{t} = \frac{Q \times V}{t} = V \times I$$

Power is the product of the potential drop or voltage across an appliance times the current flow through the appliance. This formula is appropriate in both DC and AC voltage and current situations. The unit for electrical power is the **watt** (W) with 1 watt being equivalent to a rate of energy transfer of 1 joule per second: 1 W = 1 J s^{-1}.

Using Ohm's law, it can be readily seen that alternative forms of the power formula can be derived, namely:

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

Many domestic and industrial electric appliances state the **power rating** on their compliance plates. For example, a television set that is rated at 110 W will consume electrical energy at the rate of 110 joules per second. It is this energy usage that consumers have to pay for as it is supplied by the electricity authority. (Refer to Section 22.7.)

Example

(a) Calculate the power dissipated by an electric drill operating from the normal 240 V AC supply and drawing an operating current of 1.6 A.
(b) Calculate the monthly energy used by a television set whose power rating is 110 W and is operating daily for 6.5 hours.

Solution

(a) Use $P = V \times I$ = 1.6 A × 240 V = 384 W.
(b) Energy used daily:

$$W = P \times t = 110 \times 6.5 \times 3600 = 2.6 \times 10^6 \text{ J}$$

But if the set is used for one month of, say, 30 days, then total energy used = 7.7×10^7 J.

The common unit for electrical energy usage in domestic and industrial situations is the **kilowatt-hour** (kW h). The electricity authority commonly refers to the kW h as a 'unit' of electricity and it represents the amount of electrical energy used by a device rated at one kilowatt over a period of one hour.

NOVEL CHALLENGE

The formula P = V^2/R implies that if the resistance (R) of a light bulb is decreased, the power consumption (P) will increase and hence it will glow brighter. But the formula $P = I^2 R$ implies that if R is decreased, P is also decreased and the bulb will get dimmer. They can't both be right. What is your answer to this apparent anomaly?

Questions

13 Calculate the power rating of a light bulb operating at 240 V and 0.6 A.

14 What is the resistance at normal operating conditions of the following appliances run from the 240 V AC mains: **(a)** 50 W television set; **(b)** 1 kW hair dryer; **(c)** 100 W light bulb?

15 A heater is connected to the normal mains supply. If the resistance element has a value of 8 ohms, how much electrical energy is supplied to the heater in 5 minutes?

16 It requires 4.2 kJ of energy to raise the temperature of 1.0 kg of water by 1°C. If an electric hot water system is rated at 6.5 kW for 240 V AC and it holds 250 kg of water, calculate **(a)** its coil resistance while operating; **(b)** the energy required, in kW h, to heat the water from 15°C to 80°C.

HOUSEHOLD ELECTRICITY AND ELECTRICAL SAFETY

22.7

NOVEL CHALLENGE

One that most people get wrong: 100 W bulbs glow brighter than 40 W bulbs when connected in parallel across a 240 V source.
If these two bulbs were connected in series, how would their brightness compare?

NEI

Activity 22.7 YOUR METER BOX

Look into the meter box at your house, and (without touching anything!) determine:

1. how many meters it contains;
2. how many fuses, switches or circuit-breakers appear to be used;
3. the descriptions associated with each fuse or switch;
4. which way the spinning discs inside each of the largest meters turn.

Electrical energy produced by power stations is AC or alternating current. The current changes direction in any household AC circuit at a frequency of 50 Hz and in Australia is provided at a voltage of 240 V. (Refer back to Figure 22.6**(c)**.) This 240 V is converted at local street pole transformers from much higher AC voltages on the main high-tension (high-voltage) distribution grid. Our domestic 240 V AC electricity is potentially very dangerous and significant precautions must be taken in any household installation in order to protect consumers from faults that may occur with appliances.

The electrical cabling involved in household electricity usually contains three colour-coded insulated conductor wires. The first is the brown or red covered **active wire**. This is often called the live wire and carries the current to the appliance when it operates. The electric potential of the active wire varies between positive and negative, and is particularly dangerous as it would produce a fatal shock if touched because the potential (voltage) involved would force current to flow through your body to earth. The second wire is covered in blue or black insulation and is called the **neutral wire**. The neutral wire allows return current to flow from the appliance in operation. This neutral wire is at earth potential (zero volts) because it is earthed at the local electricity supply sub-station, and is thus far less potentially dangerous than the active wire. The third wire is covered in green and yellow, or just green, insulation and is called the **earth wire**. This is a safety connection made to a thick metal stake entering the ground at some point around your house.

NOVEL CHALLENGE

In an experiment to measure the efficiency of a microwave oven, 1 L (1000 g) of water was placed in an icecream bucket and its temperature measured. It was then cooked on 'high' for 2 minutes and its temperature measured again. Use the formulas $Q = mc\Delta T$ and $P = W/t$ to prove that the power output of the microwave $(P) = 34.8 \times \Delta T$. *Hint:* let $Q = W$. *If a 750 W microwave raised the temperature of 1 L of water by 20°C, calculate the efficiency of the oven.*

Activity 22.8 YOUR EARTH SYSTEM

Locate and describe the position and type of the main earthing point in the electrical system wiring at your house. Is it located under cover or out in the open? Why is it located at this position? In the past a mains water pipe has often been used as the main earthing point. This is less common today. Explain why this might be the case.

In most household situations both the earth and neutral cables are connected together at the fuse-box to form what is known as the **multiple earth neutral** (MEN) system. If an appliance has a metallic outer surface then it is connected internally to the earth wire. This is because, if the active wire insulation breaks down or an internal fault occurs, causing the outer metallic case to become live at 240 V potential, the current will flow through the earth wire and not through the higher resistance of someone touching it. Earthed appliances are generally much safer for this reason. Electrical power points in the walls are similarly connected with a three-pin socket for active, neutral and earth (Figure 22.22). The electrical switch must be placed in the active line, in order to turn an appliance on or off at the wall socket.

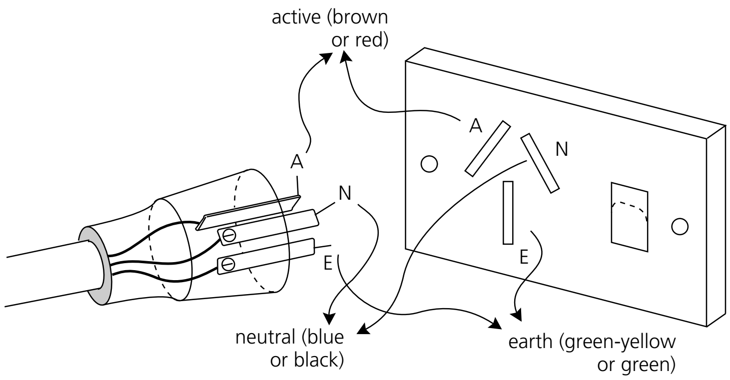


Figure 22.22
Electric plug and socket.

240 VOLT COLOUR STANDARDS	FLEX (POWER LEADS)	WALL CABLE
Active	brown	red
Neutral	blue	black
Earth	green-yellow	green-yellow

NOVEL CHALLENGE

The Australian flat-pin plug (see Figure 22.22) is similar to the plug used in mainland China, but dimensional differences prevent the Chinese plugs from being used in Australia. Argentina uses the same plug as Australia but the Active and Neutral are reversed, and the plugs are banned from use in Australia. What is the problem with having A and N reversed?

You may have noticed that some appliances have a power lead that contains only figure-of-eight twin conductor wire. This type of appliance has a **double insulated** rating, which means that any internal metal parts are not only insulated with the normal protective wire insulation but also the outer case of the appliance is plastic and cannot become live in the event of a fault condition or primary internal insulation breaking down. Compare the diagrams in Figure 22.23, which also shows the commonly used symbol for a double insulated appliance — a concentric pair of squares.

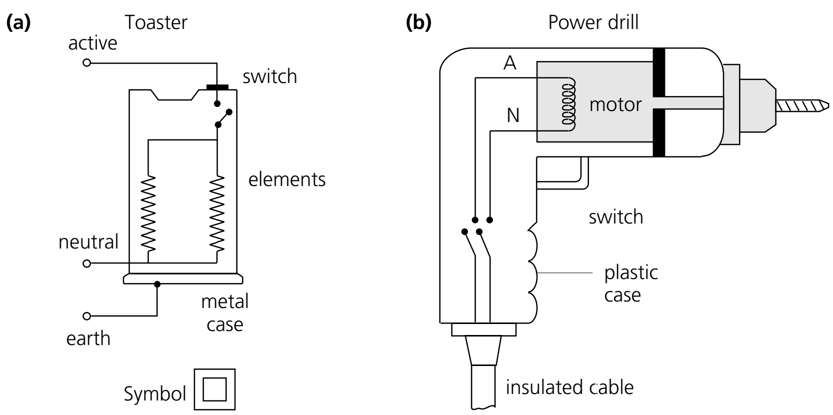
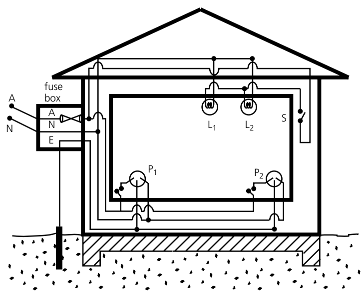


Figure 22.23
Earthing **(a)** and a double insulated appliance **(b).**

If a fault occurs in the electrical wiring of a house, or if an appliance becomes faulty, a short circuit, which allows a high current to flow very easily, may be produced. This subsequently causes rapid heating of the conductors. This heating effect would be high enough to cause melting of insulation and a fire if it were not for fuses placed in the active lines of the household circuits. A **fuse** is a small piece of resistive wire alloy that is designed to melt and

Photo 22.7
Household meter box.

Figure 22.24
Simplified household AC wiring.



break with excessive overheating or at a particular current rating such as 8 or 16 amps. Once the fuse breaks a completed circuit is no longer present and any further current is stopped. Once the fault condition is diagnosed by an electrician or the faulty appliance repaired, the broken fuse can be replaced and the circuit is again complete. Fuses are also important because they prevent a circuit being loaded with too many appliances in parallel and thus causing excessive currents to be drawn.

A modern replacement for the fuse is the **electromagnetic circuit-breaker** (see Photo 22.7), which is a small electromagnetic solenoid switch that will also break the circuit if a fault current develops. The advantage is that it can be quickly manually reset. Figure 22.24 gives some idea of how a typical household room might be wired with two power points and two lights with switches. Notice that the room lights are not usually earthed and that both the power points and the lights are in paralleled connections.

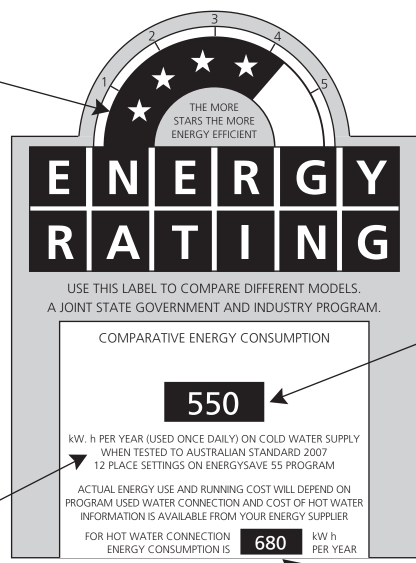
One of the most successful techniques for maintaining electrical safety in the household is to install an **earth leakage circuit-breaker** (ELCB), also called a **residual current device** (RCD) (see Photo 22.7). This device is usually permanently installed in the meter–fuse-box of the house. It will electronically sense the very small differences in the electric current balance between incoming active line and outgoing neutral line that will occur in any wiring or appliance fault condition that allows current flow to earth. These devices are available in different trip current ratings (the most common tripping at 30 mA) and are very sensitive and fast-acting (10–20 ms), so that electrical safety is maintained. In some situations around the house even portable RCD units are becoming popular.

Household appliances should always be chosen and used on the basis of their electrical operating efficiency. Many larger appliances in homes and industry, such as refrigerators, washing machines, dryers, dishwashers and range stoves, carry an **Australian energy rating** system label, which contains vital testing information relating to a national standard for electrical efficiency. See Figure 22.25 for an example of this label from a dishwasher.

Figure 22.25
The dishwasher energy rating label explained.

How do I choose the most energy efficient dishwasher?
• The simplest way to compare the energy efficiency of dishwashers is look for the stars. The more stars on the Energy Rating Label the more energy efficient the dishwasher. More stars means the dishwasher uses less electricity to achieve the same level of performance.

How does a dishwasher get an Energy Rating?
• To determine the Energy Rating manufacturers must have their appliances tested to an Australian Standard. The program setting used in the tests is stated on the label and this program will satisfy the needs of an average wash.



What do the figures on the label mean?
• The dishwasher Energy Rating Label shows two energy consumption figures in red boxes. They will tell you how much energy the dishwasher will use per year, if it is operated once a day.

• The figure in the large box is based on the manufacturer's recommended water connection.

• The figure in the small box is based on an alternative water connection. (Usually hot water only or a dual hot/cold connection). Here the operating costs will vary depending on your hot water system.

Appliances usually fall into two broad categories: the high power devices that mostly generate heat and the low power devices that include lighting and consumer electronic items such as radios, TVs and computers. Table 22.3 lists the electrical ratings of some appliances, showing the typical operating range.

Table 22.3 ELECTRICAL POWER AND ENERGY CONSUMPTION

APPLIANCE	TYPICAL POWER (W)		AVERAGE USE (h day^{-1})		ENERGY USE (AVE) (W h day^{-1})	
	MIN.	MAX.	MIN.	MAX.	MIN.	MAX.
Kitchen:						
• Lights	11	100	1.00	3.00	11	300
• Refrigerator	100	260	6.00	12.00	600	3 120
• Microwave	650	1 200	0.17	0.25	111	300
• Toaster	600	600	0.03	0.08	18	48
Laundry:						
• Lights	11	100	0.25	1.00	3	100
• Iron	500	1 000	0.17	0.42	85	420
• Washing machine	500	900	0.22	0.33	110	300
• Clothes dryer	1 800	2 400	0.20	0.54	360	1 300
• Water pumps	300	500	0.25	1.00	75	500
Lounge:						
• Lights	15	100	1.00	4.00	15	400
• Television	25	200	0.50	5.00	13	1 000
• Video recorder	100	100	0.5	5.0	50	500
• Stereo	60	80	0.5	3.00	30	240
• Vacuum cleaner	100	1 000	0.13	0.25	13	250
• Oil radiator heater	1 000	3 000	8.00	14.0	8 000	42 000
• Strip heater	500	1500	0.5	1.00	250	1 500
Bedroom:						
• Lights	11	100	0.5	2.00	6	200
• Radio	10	40	0.33	3.00	3	120
Garage:						
• Lights	11	100	0.17	2.00	2	200
• Power tools	200	800	0.17	0.17	34	136
• Hot water (storage)	3 000	20 000	5.00	8.00	10 000	24 000

Example

If the tariff cost from the local electricity supplier for domestic light and power is 9.18 cents per kilowatt-hour, use the information in Table 22.3 to calculate the total monthly cost of operating a television set of 120 W at maximum average daily use.

Solution

From the table, average daily use in 5 hours, at power rating P, = 120 W for the set:

$$\text{Energy} = P \times t = 5 \times 120 = 600 \text{ W h per day}$$

For one month of 30 days = 18 000 W h = 18 kW h, at cost of 9.18c = $1.65 total.

NOVEL CHALLENGE

Have you seen the new compact fluorescent bulbs designed to replace the normal incandescent ones? They cost about $20 but last 8000 hours and produce light equivalent to a 75 W incandescent bulb but only consume 20 W of power. Incandescent bulbs cost 75 c and last about 1200 hours. Which is better value?

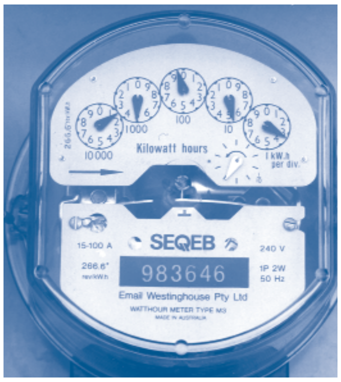
NOVEL CHALLENGE

Consider the statement: 'Electricity from a battery is 100 times more expensive than the electricity from your power point'. Is this true? Design an experiment to find out how much electricity you can get out of a 1.5 V AA battery and compare it to the 240 V mains supply (10 cents per 'unit').

NOVEL CHALLENGE

Incandescent light bulbs have a life proportional to $1/V^{14}$ seconds (where V is the applied voltage). Hence, if you run a 240 V bulb at 80% of its rated voltage you will increase its lifetime. By how many times will its life be increased? We think 23 times; but how did we get that?

Photo 22.8
Kilowatt hour meter ENERGEX.



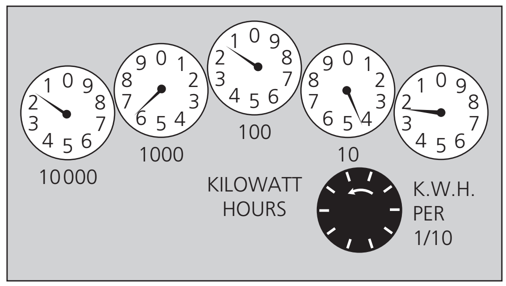
Activity 22.9 APPLIANCES

1. Try to find out if the larger appliances in your house have an energy rating label. From it calculate the average cost of operating them as normal for one year.
2. Figure 22.26 gives a diagram of a typical set of dials on the meter box electrical kilowatt–hour meter. Refer also to Photo 22.8. Can you work out how to read the dials? Try reading your own household meters and keep a weekly record of the power consumption in order to compare the readings with your electricity bill.
3. RCD- or ELCB-type devices only protect against certain types of electrical faults. How do these devices actually work and what specific types of hazards do they protect us against?

Figure 22.26
How to read a meter.

How to read a meter
Some customers like to check their meter readings from time to time.

- The dial type meter is the most common type installed. Stand directly in front of the meter so that you can see the exact position of the pointer. Start at the right-hand dial and record the number the pointer has just passed on each dial.
- If you wish to check your average daily consumption, take readings at the same time of day, several days apart and divide the difference in readings by the number of days.



The reading from the dials above is 16142

Also, remember that meters belong to ENERGEX (or other authorities in other States). Interfering with them is illegal and staff are trained to spot any evidence of tampering.

Electric shock

NOVEL CHALLENGE

A 240 V jug rated at 2000 W takes 1 min 45 s to heat 2 cups (500 g) of water from 23°C to boiling (100°C). Calculate its percentage efficiency. If 1 L of water was being boiled from the same temperature, propose whether the time would be exactly twice or more, or less, than twice. Hmmm — think of the energy losses. Check our web page for some real data!

Finally in this chapter we will take a look at some of the effects of DC and AC electricity on the human body, including **electrocution**. The severity of an **electric shock**, that is, bringing the body into contact with an EMF source, depends on the current flow, duration, frequency, skin moisture, surface area of contact, pressure exerted, temperature and the path taken by current through the body. A current passing through vital organs such as the brain or heart is the most dangerous. The biological effects of electricity result from both the DC electrical resistance of the body and the AC electrical impedance (frequency-dependent resistance).

Table 22.4 EFFECTS ON THE HUMAN BODY OF 240 V, 50 Hz AC FOR 0.5 s

CURRENT (mA)	EFFECT ON THE BODY
0.5	threshold of perception
1.0	able to be felt; tingling sensation
4.0	pain felt; rarely causes damage
10.0	threshold of 'let-go'; just able to release
20.0	muscles paralysed; unable to release
50.0	severe electric shock; burns; ventricular fibrillation threshold
150.0	breathing difficult; major damage
200.0	death likely
500.0	serious burning; breathing stops; death inevitable

Voltages as low as 32 V AC or 115 V DC can be dangerous. Table 22.4 lists several identifiable levels of electric shock. In general, it is true that an AC voltage is more dangerous than an equal DC voltage because it will trigger stronger muscular contractions. Fortunately the human skin is a fairly good insulator, which provides a barrier against dangerous electric currents. The effective resistance between two points on opposite sides of the body, when the skin is dry, is in the range 10 000 to one million ohms; however, if the skin is wet, the resistance may be less than 1000 ohms. For voltages greater than about 50 V, the human skin begins to break down as an effective barrier and the body's internal resistance becomes more important in determining the current flow through the body.

INVESTIGATING

During times of heavy power demand, the voltage of the electricity from the power station drops by up to 2%.
Is this to save money, to save power or for some other reason?

Table 22.5 AVERAGE TOTAL BODY RESISTANCE FOR 95% OF POPULATION

TOUCH VOLTAGE (V)	AC RESISTANCE (Ω)
25	6100
50	4400
75	3500
100	3200
110	3000
240	2100
500	1600
1000	1500

Table 22.5 lists the total average body resistance for 95% of the population at various touch voltages. From these tables it can easily be seen that at 240 V the body current typically is about 100 mA and, depending on the contact time, can be fatal most of the time. The most dangerous path for current is from one limb to another, across the chest, as this is most likely to affect the heart. Exposure to electric shock, especially via this pathway, can bring about **cardiac fibrillation**, or rapid and uncontrolled beating of the heart, which can starve the brain of oxygen, quite quickly causing permanent damage or even death.

If fibrillation of the heart begins, ambulance officers at the scene of an electrical accident will begin a procedure known as **defibrillation**, which involves usually two steps. Firstly, the rapid fibrillation must be stopped. This is done by placing the plates of a defibrillator on the chest on either side of the heart. A 5 kV DC pulse lasting about 1–50 ms passes through the heart causing it to stop temporarily. The defibrillator recovers within 2–3 s and is ready then to deliver a second pulse. The second step involves a second pulse identical to the first, applied again through the heart, if it hasn't restarted its normal sinus rhythm naturally. If this is unsuccessful, a third, even stronger, pulse is applied. In the event that a defibrillator is not available, cardiopulmonary resuscitation (CPR) should be administered until hospitalisation.

SR

ACTIVITY 22.10 CARDIAC DEFIBRILLATION

You are required to examine the following information, provided on the Biomedical Electronics pages of the website of the Australasian Society of Cardio-Vascular Perfusionists Inc. Read and interpret the material carefully, also using assistance from Chapters 21 and 22, and complete the questions that follow.

Principles of operation of DC defibrillator

A Energy used for cardioversion and defibrillation

Electrical output of defibrillators is expressed in terms of energy. Joules (J) or watt-seconds (W s) describe the power (watts) and the length of time for which it is applied (s).

Thus energy (joules) = power (watts) × duration (seconds)

Note: watt = current (amps) × voltage (volts)

1 watt = 1 J s^{-1}

Defibrillators are set according to the amount of energy stored; this depends on both the charge and the potential. Capacitance is the measure of the ability of an object to hold an electrical charge; SI unit is coulomb (C).

$$\text{coulombs} = \text{amperes (A) x seconds (s)}$$

$$\text{potential (V)} = \frac{\text{power (W)}}{\text{current (A)}}$$

$$\text{power } (W) = \text{energy (J) per second}$$

$$\text{current (A)} = \text{charge (C) per second}$$

$$\mathrm{V} = \frac{\mathrm{Js^{-1}}}{\mathrm{Cs^{-1}}} = \frac{\mathrm{J}}{\mathrm{C}}$$

$$\mathrm{J} = \mathrm{C.V}$$

Stored energy (J) $= \frac{1}{2} \times$ capacitance (C) $\times$ potential (V) $= \frac{1}{2} \times \mathrm{C} \times V^2$

Example: with paddles potential of 5000 V applied across two plates of a capacitor, produces a store of electrons of 160 mC of charge.

B Operation and circuit

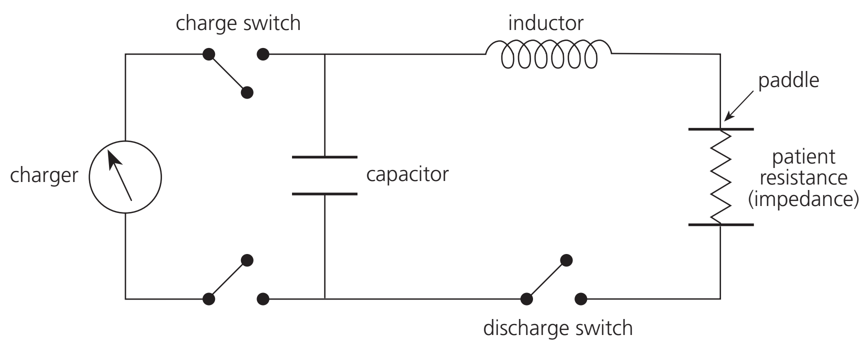
Defibrillation energy is temporarily stored in a capacitor. The large capacitor is charged to the selected energy and then discharged through the paddles applied to the chest. The energy stored in the capacitor is released as a current pulse (e.g. 35 A for 3 ms) resulting in a synchronous contraction of the heart after which a refractory period and normal beats may follow.

An inductor is included in circuit to ensure that the electric pulse has an optimal shape and duration.

During discharge, the inductor absorbs some of the energy so that not all is discharged to the patient.

Defibrillators are calibrated in terms of delivered energy, not stored energy.

Figure 22.27
For Activity 22.10B.



C DC defibrillator pulse shapes (waveforms)

The defibrillation waveform is a major factor in determining efficacy of defibrillation.

A damped sine wave defibrillator consists of a capacitor, inductor and electrodes.

Placing of an inductance coil in series with the capacitor, the resultant waveform is half sinusoidal in configuration; a slight variation is the underdamped sine wave, in which the sine wave reverses slightly, and which may reduce the defibrillation threshold.

The duration of the current for adult is 5–10 ms. Current intensity depends on the set stored energy on the defibrillator.

Patient impedance, or the resistance to current that is offered by the chest, is called chest impedance; an average figure is 75 Ω.

Variations in the patient's impedance cause the delivered dose of current to vary widely.

Factors that influence impedance between the defibrillator paddles (resistance) are:

- delivered energy
- paddle (electrode) size and composition
- interface between paddle and skin (gel used to reduce this)
- paddle pressure (increased pressure decreases impedance)
- time interval between discharges
- number of discharges (increased number decreases impedance)
- phase of patient ventilation
- distance between paddles.

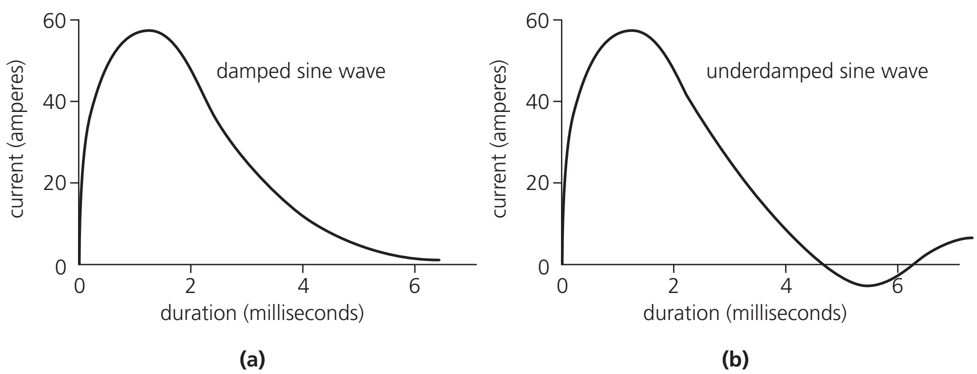


Figure 22.28
For Activity 22.10C.

D Energy levels required for internal and external defibrillation

1 External — transthoracic defibrillation

(a) Children (weighing 2.5–50 kg) = 1–5 J/kg
(b) Adults (body weight in adults does not seem to be a major factor determining energy requirements)

Initial setting 200 J followed rapidly by 300 J and 360 J if needed; animal studies suggest that these doses are also valid during hypothermia.

2 Internal — direct open chest defibrillation
Adults: initial setting 5 J with increments up to 20 J.

Questions

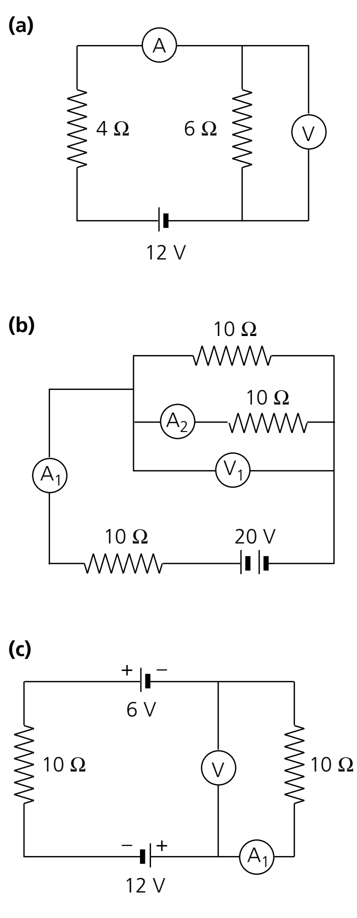
1 Calculate the energy (in joules) delivered by the paddles in the example in section A above.
2 Why does the inductor in the circuit change the shape of the waveform?
3 What are the factors that cause current delivery to the patient to change?
4 Why do you think body weight in adults is not so important as in children?
5 Why is the energy for external defibrillation much higher than for internal defibrillation?

Australian farmers make use of electric fences. A typical **electric fence** produces 7500 V DC pulses, lasting 0.2 ms at intervals of about one second. These voltage spikes are usually produced from a 12 V battery. Electricity authorities specify a 10 000 V maximum and the unit must be able to deliver at least 5000 V under a typical load of 500 Ω. A good electric fence unit connected to a clean fence should be able to maintain 7500 V over 20 km of fencing. Farmers check the fence voltage with a voltmeter and can usually tell from specified points, such as open gates, if the system is working properly. Animals that occasionally get caught in the fence will die of stress, not from the electric shock given. Usually, after the first shock onto a cold wet nose, the cattle or other stock learn very quickly not to approach the electrified fence.

Probably the most dramatic effect of electricity on the body is the use of an **electric chair** in the American criminal justice system. It was in 1890, in New York, that William Kemmler became the first criminal in history to be put to death by electrocution. Apart from a period in the 1970s, several hundred people a year have been executed in the 'chair', between 1890 and the present in the USA. Traditionally the prisoner is securely fastened to a solid chair by straps holding the chest, groin, arms and legs. The electrodes are moistened copper plates attached to each calf and a band around the head. Jolts of 4–8 A at between 500 and 2000 V AC are applied for a half-minute at a time. A doctor inspects the body to see if death has occurred or if another jolt should be administered. At Sing Sing prison in New York, an initial voltage of 2200 V at 7–12 A is used at half-minute intervals over a period of two minutes. Current flow in each leg and the head is monitored. Body temperatures rise to above 50°C. The use of the electric chair has dropped in recent years as lethal injection is being adopted by more US States. The use of capital punishment in all forms is currently banned in Australia.

It is important to realise the biological effects of even small voltages on our bodies. Electrical safety must always be utmost on our minds when we work at home or in the laboratory. Electrical energy, while vitally important in modern society, deserves our utmost respect. It is far too dangerous for anyone to be complacent about its potential.

Figure 22.29
For question 23.



Practice questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

Review — applying principles and problem solving

***17** What is the electric current in the following cases?
- **(a)** A 20 C charge passes an ammeter in 5 s.
- **(b)** A 5 C charge passes an ammeter in 20 s.
- **(c)** A 200 C charge passes an ammeter in 3 minutes.

***18** What is the energy gained by a charge of 18 C when it passes through a source of EMF of 12 V?

***19** If a 1.5 m length of resistance wire has a resistance of 1.9 Ω and the wire has a diameter of 0.9 mm, calculate the resistivity of the wire.

***20** With the aid of a circuit diagram, show how you might measure the operating resistance of a single light bulb. You have a battery, ammeter and voltmeter.

***21** The accumulator of a car produces 12 V. If the car lights at the sides and rear are each rated for 12 V, but the two interior lights are only rated at 6 V, how should the lights be connected — in series or in parallel?

***22** How does the resistance of a 60 W, 240 V light bulb compare with that of a 25 W, 240 V light bulb? Which has the thicker bulb filament?

***23** In each circuit of Figure 22.29, find the readings on all voltmeters and ammeters, as well as the total circuit equivalent resistance.

***24** Explain why birds can safely touch overhead power cables but humans standing on the ground cannot.

**25 In the circuit of Figure 22.30, calculate the following:
(a) The battery voltage.
(b) The circuit current at the points labelled X, Y and Z.
(c) The reading on the voltmeter, V.

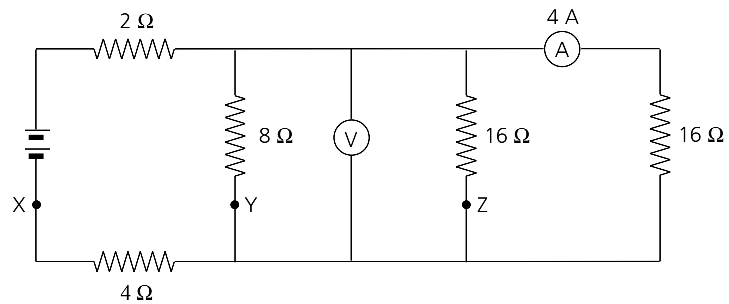


Figure 22.30
For question 25.

26 An automatic washing machine is labelled 240 V, 960 W. Calculate **(a) the operating current in normal use; **(b)** the operating resistance in normal use.

**27 A set of decorative Christmas lights consists of bulbs labelled 12 V, 1 W. If the set is designed to operate from the AC mains, determine:
(a) how many bulbs are in the set;
(b) what the total power consumed by the set of lights is;
(c) what the average voltage drop across each bulb is;
(d) what the current in each bulb is and the resistance of each.

*28 Explain the physical and operational differences between a fuse and a circuit-breaker as safety devices in household circuits.

*29 Explain the precautions that are required if any metal-framed appliance is to be connected to the household mains supply of electricity. Complete a circuit diagram.

**30 Figure 22.31 shows a graph of potential difference versus current for two different electrical devices A and B.
(a) Which device is an ohmic resistor?
(b) If A and B are connected in series and a current of 200 mA passes through them, what is the total potential difference across A and B?
(c) If A and B are joined in parallel, what PD across them would produce a current in A equal to half the current in B?
(d) What is the resistance of device A and how does this compare with the resistance of B with a voltage of 15 V applied?

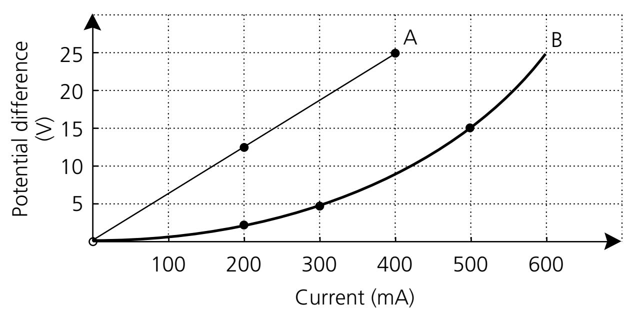


Figure 22.31
For question 30.

**31 The resistance of a 1.5 m length of conductor was measured as a function of temperature and the following data values obtained:

Temp (°C)	−50	0	50	150	250
Resistance × 10^{-2} Ω	2.6	3.35	3.9	5.3	6.6

(a) Plot a graph, resistance versus temperature. Use a line of best fit.
(b) From the line gradient, find the value of (α).
(c) Develop a conversion formula from resistance to temperature.

***32** Draw the circuit diagram that represents the following description. Two paralleled 50 Ω resistors are connected in series with three larger resistors of 100, 200 and 250 Ω. This assembly is connected to a 20 V battery and an ammeter to measure total circuit current. A voltmeter and an ammeter must be used to measure current flow through and voltage drop across one of the 50 Ω resistors, when a main circuit switch is closed.

****33** Design and draw the diagram for a two-way model circuit that will operate a lamp from two different locations in a house, say, from upstairs or downstairs.

****34** Electric kettles range in power from 1000 W to 2500 W. The rating is usually stamped underneath. Table 22.6 has been taken from *Choice* magazine and compares the performance of 10 different cordless kettles.

Table 22.6 CORDLESS KETTLES

BRAND: MODEL	MASS (kg)	CAPACITY (mL)	BOILING TIME (1 L WATER)	POWER CONSUMPTION (W)
Kambrook KU300	0.64	1500	3 min 15 s	1890
Kambrook KU400	0.64	1430	3 min 15 s	1910
Kenwood JK800	0.73	1640	2 min 50 s	2190
Linda Superboil LJ6	0.60	1500	3 min 5 s	2040
Moulinex A94	0.70	1760	3 min 10 s	2010
Ronson 8523	0.71	1680	2 min 55 s	2210
Russel Hobbs 3110	0.92	1620	2 min 50 s	2240
Sunbeam KE019	0.71	2050	2 min 40 s	2290
Tefal Freeline	0.72	1660	3 min 0 s	2120

(a) Plot a graph to determine if there is any relationship between power consumption and the boiling time for 1 L of water. Describe the relationship.
(b) Estimate the boiling times of a 1600 W kettle and a 2400 W kettle.
(c) The efficiency of a kettle can be calculated by the formula:

$$\text{efficiency} = \frac{\text{power out}}{\text{power in}} \times 100\%.$$

The power in is shown in the table as 'Power consumption'. The power out can be calculated from data about heating up the water. Assume that the water started at a temperature of 25°C. Calculate the efficiency of each kettle and make a rank order of them. Are the high powered kettles the most efficient?
(*Hint:* the efficiency of the Linda superboil is 84%.)

Extension — complex, challenging and novel

*****35** The headlights on a car operate typically at 60 W and the parking lights typically at 5 W. Assuming there are two main headlights and four parking lights, what length of time will it take to discharge a 60 Ah battery, if the lights are left on?

*****36** In the circuit of Figure 22.32, CD is a 2.0 m length of nichrome wire of value 1.8 Ω. The galvanometer connected between A and B registers no current. Calculate the value of the unknown resistor *R*.

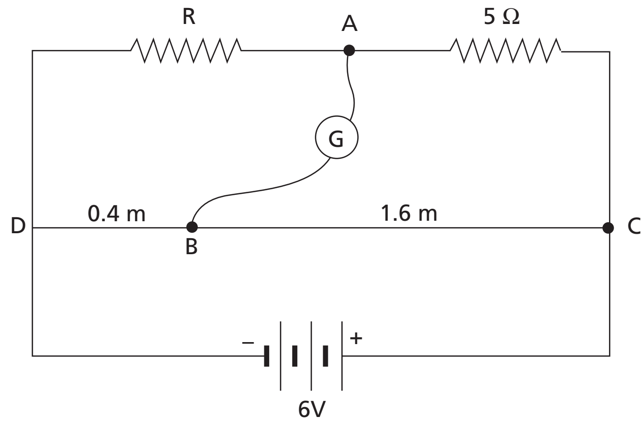


Figure 22.32
For question 36.

*****37** The diagram of Figure 22.33 is known as a Wheatstone bridge and is used to measure unknown resistances. An unknown resistance R_x is placed into the circuit and resistor R_3 is varied until the galvanometer reads zero current. This is called a null balance.

(a) Explain what occurs when a null balance is attained in the circuit, in terms of voltage.

(b) Prove that the formula for the unknown resistor is $R_x = \frac{R_2}{R_1} \times R_3$.

(c) Calculate the value of an unknown resistor when $R_1 = 710\ \Omega$, $R_2 = 317\ \Omega$, $R_3 = 2.24\ \text{k}\Omega$.

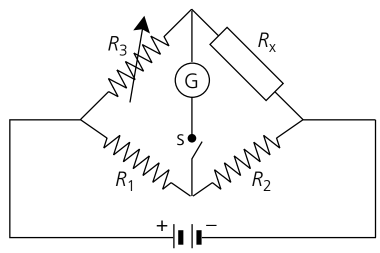


Figure 22.33
Wheatstone bridge circuit.

*****38** Figure 22.34 shows a complex circuit. Calculate the following values:

(a) total circuit resistance;

(b) voltage drop across the 60 Ω resistor.

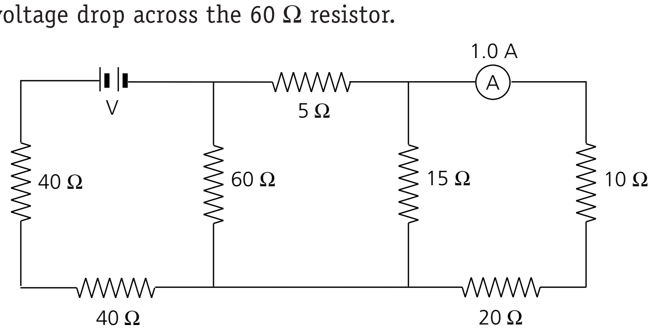


Figure 22.34
For question 38.

*****39** A 100 Ω resistor is connected in series with a second, unknown, resistor, R_2, and a 120 V battery, as shown in Figure 22.35. If the battery has negligible internal resistance and the unknown resistor dissipates 30 W of power, calculate its resistance value.
(*Hint:* there are actually two values that are possible in this case!)

Figure 22.35
For question 39.