17. FORCE, ENERGY AND POWER IN ACTION

17.1 FORCE, MASS, ENERGY AND POWER

Before you study this chapter, you need to know all about force (Chapter 10) and energy (Chapter 14). Just to remind you, a force is a push or a pull and the SI unit of force is the newton, symbol N. A newton is the force you need to lift a mass of about 100 grams (a medium sized tomato) and 10N will lift a mass of about 1 kg (a 1 litre bottle of water). The tree on the right has forced its way through the wall, which has been rebuilt many times, and its roots are forcing up the asphalt road. It grows slowly, but it exerts a lot of force.

A machine makes a job easier by changing the magnitude, direction or point of action of a force (Module 10.9). The simplest machine is the lever in which a force called the effort turns the lever around a fixed point or pivot and moves a load. In this chapter we start by looking at the turning effect of a force. This depends not only on the magnitude of the force but also on its distance from the pivot.

In physics we make an important distinction between mass and weight (Module 10.4). Mass is the amount of matter in an object; it depends only on the number and kind of atoms that the object is made of. Mass is measured in kilograms and does not change. Weight is the force that gravity exerts on an object. Scientists measure weight in newtons but most people use kilograms for weight as well as mass. The force of gravity is almost the same everywhere on Earth so the weight of an object does not vary much if it remains on Earth. On Earth, mass and weight are almost the same thing. However on the moon, where gravity is about one sixth of that on Earth, an object weighs only a sixth of what it does on Earth although the mass remains the same. In outer space, where there is no gravity, it weighs nothing at all! But even in space, we cannot move an object without using force, and the more mass an object has, the more force we need. And the more force we use, and the longer we use it, the more energy we need (Chapter 14). In this chapter you will learn how different forces combine, how we measure energy, and how the motion of objects depends on the force and energy applied to them. We also introduce the scientific notion of power as the rate at which energy is transferred from one place to another, or converted from one form to another. If we compare the electric train below with the tree at the top of the page, they are both very strong but the train has much more power because it delivers its energy much faster.

In the second part of the chapter we look briefly at heat energy, then go on to focus in more detail on electrical energy. The technology of electricity has revolutionised the world we live in. Electricity brings light, heat, mechanical power and information (by TV, radio, telephone, DVD and the internet) into homes, offices and factories. In many countries it also powers transport systems like the one illustrated on the left. In the last eight modules, we look at the nature of electricity, at how it is measured, at how it behaves, and at some of the different effects it produces. We also consider what is involved in the safe use of domestic electricity in the home, including how we measure and pay for electrical power.
17.2 TURNING FORCES AND THE PRINCIPLE OF MOMENTS

When a force is applied to a lever, the lever turns about a pivot (or fulcrum). The diagram shows a spanner (type 2 lever) exerting an anticlockwise turn to remove a nut from a bolt. The turning effect of a force is called the moment of the force. The moment (measured in newton metres) is equal to the magnitude of the force (in newtons) multiplied by the perpendicular distance (in metres) from the pivot to the point where the force is applied. If the force applied to the spanner is 200N and the length of the spanner is 25 cm (0.25 m), then the moment applied to the nut is \(200 \times 0.25 = 50 \text{ newton metres}\).

The principle of moments. The pictures below show a simple balance beam (type 1 lever) and illustrate the principle of moments. Study the first two diagrams, then try to work out where to place the blocks to balance the beam in the last two diagrams (answers in Teachers’ Guide).

\[ \text{Moment (Nm)} = \text{force (N)} \times \text{distance (m)} \]

The principle of moments states that, for a lever in equilibrium, the clockwise moment is equal to the anticlockwise moment. Equilibrium means balance. In the diagrams above, the balance beam is in equilibrium when it is horizontal – neither side goes down. There is a clockwise moment that tries to rotate the beam in the same direction as the hands of a clock, and that is balanced by an anticlockwise moment trying to rotate it in the opposite direction. Clockwise and anticlockwise turning forces are labelled in the diagram of the market balance (left).

Look at the diagram of the wheelbarrow. We can use the principle of moments to work out the effort we need to lift a load of 500 N (or 50 kg). When the handle is lifted, the clockwise moment of the load is balanced by the anticlockwise moment of the effort E. The calculation, in the table under the diagram, shows that an effort of 200 N (or 20 kg) will lift the load of 500 N (or 50 kg).

<table>
<thead>
<tr>
<th>Effort (E)</th>
<th>Load (L)</th>
<th>Moment (Nm)</th>
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<tbody>
<tr>
<td>200 N</td>
<td>500 N</td>
<td>E \times 1.0 = 500 \times 0.4</td>
</tr>
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</table>

So \(E = 200 \text{ N (or 20 kg)}\)

- 1. What are (i) a clockwise moment, (ii) equilibrium?
- 2. Explain two ways in which the turning effect of a spanner can be increased.
- 3. A boy weighing 20 kg sits on one end of a seesaw, 2.5 m from the pivot. His sister weighs 22 kg. Where must she sit to balance the seesaw?
Combining forces. When two forces act on the same object their effects are combined. When two people pull on the same rope, in the same direction, the force of one is simply added to the force of the other. However, the forces acting on an object are often pushing or pulling in different directions. Look at the photo and the diagram on the right. They show five tug boats combining forces to move a big ship into its berth. Three of the tugs are pushing the ship sideways and two are pulling the back and the front of the ship in different directions. The experienced seamen cleverly combine these five forces to move the oil tanker gently into its berth.

A quantity like force, which has a direction as well as a magnitude, is called a vector quantity. When two forces act at the same point, we can work out their combined effect using a parallelogram of forces. This is a diagram in which the two forces are shown by arrows. The length of each arrow represents the magnitude of the force to scale, and the direction of the arrow represents the direction of the force. Study the diagram on the left which shows forces $F_1$ and $F_2$ acting at point $P$. $F_1$ has a magnitude of 300 N and is represented by a line 3 cm long (a scale of 1 cm to 100 N) in the true direction of the force. $F_2$ has a magnitude of 200 N and is represented by a line 2 cm long in the true direction of the force. A parallelogram is constructed so that the side $F_1R$ is parallel to the force $F_2$, and the side $F_2R$ is parallel to the force $F_1$. Now a new arrow $PR$ can be drawn to represent the resultant force $R$ in both magnitude and direction. The resultant force is the combined effect of $F_1$ and $F_2$. The arrow $PR$ is 3.9 cm long so the resultant force experienced at point $P$ is 390 N in the direction of $R$.

Resolving forces. Sometimes it is useful to think of a single force as if it was the resultant of two other forces. This is called resolving a force into parts or components. When we want to know the component of a force that acts in a particular direction, we can resolve the force into a component in that direction and a second component at right-angles. Consider the diagram on the right. This shows a truck that has broken down on a steep hill with an angle of 20º. The weight of the truck is 2000 kg and it acts straight down through the centre of gravity of the truck (Module 10.5). We want to work out how much force we need to pull the truck up the hill. We can think of the weight as having two components as shown in the diagram; $F_1$ backwards along the slope of the hill, and $F_2$ at right angles to the hill. This time the parallelogram of forces is a rectangle because $F_1$ and $F_2$ are at right angles; and this time we start with a single force which is the diagonal of the rectangle. We want to find the magnitude of $F_1$ because that is the component we must pull against to pull the truck up the hill. We can find the magnitude of $F_1$ by drawing the rectangle to scale, or we can use trigonometry which tells us that $F_1 = 2000 \times \cos70º = 684$ kg. We can generalise and state that the component of a force in any direction has a magnitude equal to the force times the cosine of the angle between the component and the force.

1. Find the resultant of a force of 250N pulling north and 500N pulling south-east.
2. In the diagram (left), what is the horizontal component of the force dragging the box?
3. When we resolve a force, why do you think we choose components at right angles?
17.4 INERTIA AND NEWTON’S 1st LAW OF MOTION

Inertia. Any mass resists being moved. And if it is already moving, it resists being slowed down, speeded up, or changed in direction. The tendency of mass to keep doing whatever it is — standing still or moving in a straight line — is called inertia. Inertia is almost the same thing as mass — the more the mass the more the inertia. The diagram (right) shows buckets hanging from a rail. The empty bucket has a small mass and a small inertia. If you hit it with your hand it will swing easily. The bucket full of sand has more mass and more inertia. If you hit it with your hand it will resist moving and you may hurt your hand! It will swing much less than the empty bucket. And if the buckets are both swinging, it will take more force to stop the full bucket than the empty one. The trick on the left is a good example of inertia. When you flick the card, it flies away and the coin falls into the glass! The inertia of the coin makes it too slow to move.

Newton’s first law of motion is about inertia. The inertia of an object means that it will not move unless force is used! And if it is moving, force will be needed to slow it down, or speed it up, or make it change direction. Sir Isaac Newton was one of the first and greatest physicists (Module 1.9). Newton’s first law of motion states that an object at rest will stay at rest, and a moving object will continue to move with uniform velocity, unless an external force acts on it. ‘Uniform velocity’ means that the speed and direction of motion do not change.

Experience tells us that a motor boat or a car will slow down if the engine stops, and that a bicycle on a level road will slow down if we stop pedalling. This happens because the force of friction, including water resistance and air resistance, slows them down (see Module 10.3 about friction). The more we reduce friction, the better we maintain speed. The ice skater on the left is moving fast and there is very little friction between her skate and the ice. She must use a sideways force to change direction soon or she will crash into the side of the skating rink! Another example of motion with low friction is a ball rolling on a smooth surface like a billiard table. After the ball has been hit, it does not slow down much until it hits another ball or the side cushions. In outer space there is no friction at all and no gravity. Once a spaceship has reached the required speed, the engines can be switched off and it can continue in a straight line at the same speed for ever.

1. What are (i) weight, (ii) mass, (iii) inertia, (iv) friction, (v) air resistance?
2. Explain the coin and glass trick. What forces act on the coin after the card is flicked?
17.5 ACCELERATION AND NEWTON’S 2ND LAW OF MOTION

Force and acceleration. In science, acceleration refers to any change of velocity – speeding up, slowing down or changing direction. Before you go on, study the text box on the right to find out more about acceleration.

Think about what happens when a force is applied to a stationary object that is free to move. The initial velocity of the object is zero and it accelerates in the direction of the force for as long as the force continues to act on it. And when the force ceases to act, the object continues to move at the same speed, in the same direction, unless another force (for example friction) acts on it.

Now think about what happens when a force is applied to a moving object. If the force is applied in the direction of the motion, the object will speed up (accelerate positively). If the force is applied in the direction opposite to the motion of the object, the object will slow down (accelerate negatively or decelerate). And if the force is applied in any other direction, the object will change direction and accelerate in the new direction.

Newton’s second law of motion states that, when a force causes an object to accelerate, the acceleration increases in proportion to the force and decreases in proportion to the mass of the object. Study the diagrams below: the acceleration doubles when the force is doubled, but halves when the inertia (or mass) of the object is doubled.

Using SI units, acceleration \( a \) (in \( \text{m/s}^2 \)) is equal to force \( F \) (in N) divided by mass \( m \) (in kg), or \( a = \frac{F}{m} \). This equation, which summarises Newton’s second law, is often transposed as \( F = ma \).

Definition of the newton (\( N \)). Scientists use Newton’s second law to define the newton (N) as the SI unit of force: a newton is the force needed to give a mass 1 kg an acceleration of 1 \( \text{m/s}^2 \).

The acceleration due to the Earth’s gravity. Any unsupported object falls towards the ground because it is attracted by the force of Earth’s gravity. People used to think that a heavy object like a large stone falls faster than a light object like a coin. However, about 400 years ago an Italian named Galileo Galilei (1564 – 1642), measured the acceleration and speed of various falling objects. A famous story says that he dropped different objects from the top of the leaning tower of Pisa and found that they all hit the ground at the same time. Galileo’s experiments showed that, (if we ignore air resistance which obviously slows down something like a feather), all objects fall with the same acceleration.

About 100 years later, Newton’s second law explained why. A heavy object experiences a stronger pull from gravity than a light object, but it also has more inertia which makes it harder to get moving! The two effects cancel out, so all objects fall to Earth with the same acceleration.

The acceleration due to Earth’s gravity is usually represented by \( g \) and has a value of 9.8 \( \text{m/s}^2 \). Ignoring air resistance, an object falling from rest will reach a speed of almost 10 metres per second after one second, 20 m/s after two seconds, 30 m/s after three seconds and so on.

- 1. What is (i) a vector quantity, (ii) acceleration, (iii) a newton, (iv) gravity?
- 2. Use Newton’s second law to find the force of gravity pulling on a mass of 1 kg. What is the usual name of this force?
- 3. Ignoring air pressure, and taking \( g \) as 10 \( \text{m/s}^2 \), work out how fast any object will be moving, and how far it will fall, after (i) 1 second, (ii) 2 seconds, (iii) 7 seconds.
17.6 ACTION, REACTION AND NEWTON’S 3rd LAW OF MOTION

Any force always involves one object trying to push or pull or rotate another. Newton’s third law states that: if object A acts to exert a force on object B, then B reacts by exerting an equal force on A in the opposite direction. A popular version of this law states that for every action there is an equal and opposite reaction. In the example on the left, the weight of the jug pushes down on the table (action) and the table pushes up on the jug with equal force (reaction). The two forces are equal and opposite so they cancel out. There is no resultant force so neither object moves. In the example below, the magnet on the right attracts the magnet on the left, and the magnet on the left attracts the magnet on the right. The forces are equal in strength and opposite in direction. In this case the two magnets will move towards each other and stick together unless other forces (such as friction) prevent it.

Friction is a force that opposes motion between any surfaces that try to slide against each other. Friction is caused by the roughness of the surfaces. When we walk or run, we lift one foot forwards while the other pushes backwards against the ground. This backwards force is an action force, and the friction between our foot and the ground is the reaction force. This equal and opposite force holds our foot in place as we step forwards. However if the ground is slippery, there may not be enough reaction force. If this happens our foot will slip backwards and we may fall! In the same way, Newton’s third law helps to explain how a car or truck moves. When the wheel tries to turn, the rubber tyre pushes backwards against the road (action force) and friction between the tyre and the road usually provides an equal and opposite reaction force. This prevents the tyre from slipping so the wheel turns and carries the vehicle forwards. On a wet or muddy road, friction may not provide enough reaction and the wheel may slip.

Rockets and jet engines depend on Newton’s third law. Think about a toy balloon when you inflate it and let go of the neck. The action force of the stretched rubber squeezes the air out through the neck of the balloon and the reaction force of the air makes the balloon fly off in the opposite direction. Rockets and jet engines work in the same way. A fuel such as kerosene is burnt in oxygen or air in a strong combustion chamber with an opening at one end. The rapidly expanding hot gases are forced out through the opening and the reaction force shoots the rocket or the engine in the opposite direction. The picture (below right) shows the launch of the Apollo 15 rocket that carried three men to the moon in July 1971.

A jet engine is started by using an electric motor to rotate the intake turbine. This turbine sucks air into the combustion area where it is mixed with fuel. The mixture is exploded by a spark and the hot expanding gases shoot out at the back of the engine. As the gases shoot back they rotate a second turbine. This is attached to a shaft and makes the intake turbine rotate too. Once started, a jet engine keeps going until the fuel is cut off. The hot gases expand and escape backwards, and the reaction force pushes the engine forwards.

- 1. What are action and reaction?
- 2. Explain why you think that a jet engine keeps going once it has started.
**17.7 MEASURING MECHANICAL ENERGY AND POWER**

Before you continue, review Modules 14.1 to 14.4 and 16.2 which provide information about energy. Energy is defined by scientists as the capacity to do ‘work’. Anything that does work can be called a machine and a machine either transfers energy from one place to another, or converts energy from one form to another (for example, from mechanical energy to electrical or heat energy). In this module we will focus on mechanical energy.

Mechanical energy is the energy associated with the position or movement of anything that has mass. The mechanical energy transferred doing a job, depends on both the force used and the distance moved by the force. Energy is measured in SI units called joules \((J)\), after the English physicist James Prescott Joule (1818 – 1889) who studied mechanical energy and heat. A joule is the energy transferred when a force of 1 newton \((N)\) moves a distance of 1 metre \((m)\):

\[
\text{energy transferred } (J) = \text{force } (N) \times \text{distance moved } (m)
\]

A medium sized tomato weighs about 100 g and gravity pulls down on that with a force about 1N. 1J is therefore the energy required to lift a tomato, against the force of gravity, a vertical distance of 1 metre. For most purposes, the joule is rather a small unit so we often measure energy in kilojoules \((kJ)\); 1 kilojoule = 1000 joules. The Russian weight-lifter on the right has lifted about 150 kg to a height of about 2 m. We can use the equation above to calculate how much energy he has transferred from his muscles to the bar. The force needed to lift 150 kg is 1500 N and the distance moved is 2 m, so:

\[
\text{energy transferred } = 1500 \times 2 = 3000 \text{ J (or 3 kJ)}.
\]

**Kinetic energy** is the energy associated with any moving mass. This energy is transferred to the mass when a force accelerates it from rest to its present velocity. When the mass is slowed down or stopped, for example if it hits something, some or all of its kinetic energy will be transferred to other masses or converted into other forms of energy such as heat and sound. The kinetic energy \(E_k\) joules, of an object with mass \(m\) kg travelling at a velocity of \(v\) metres per second, is given by the formula:

\[
E_k = \frac{1}{2}mv^2
\]

**Potential energy** is the stored energy that an object may have because of its position, usually its height above the ground (see Module 14.2). Because of gravity, energy is transferred to any mass when it is lifted above the ground. If the object falls, its potential energy will be converted into kinetic energy as it accelerates downwards. The potential energy \(E_p\) joules, of an object with a mass of \(m\) kg, at a height of \(h\) metres, where the acceleration due to gravity is \(g\) m/s\(^2\), is given by the formula:

\[
E_p = mgh
\]

**Power** is energy delivered fast! When we say that an electric saw is more powerful than a hand saw we mean that it cuts wood faster. A powerful car will climb a hill faster than a less powerful one. Scientists define power as the amount of energy transferred or converted in a given time. Power is measured in SI units called watts \((W)\) after Scottish engineer James Watt (1736 – 1819) who developed the first efficient steam engine. A watt is the power delivered when 1 joule of energy is transferred or converted in one second:

\[
\text{power } (W) = \frac{\text{energy } (J)}{\text{time } (s)}
\]

- 1. What are energy and power? How are they calculated and what are their SI units?
- 2. An athlete with a mass of 48 kg runs up a long flight of steps in 15 seconds. The top of the steps is 16 m above the ground. (i) What is the main energy conversion involved in climbing the stairs? (ii) How much energy is converted? (iii) What is the potential energy of the athlete at the top of the steps? (iv) What is the power of the athlete?
17.8 MEASURING HEAT ENERGY

The joule is the SI unit of energy and was defined in the last module as the energy needed to move 1 m against a force of 1 N. Joules are used to measure not only mechanical energy, but also every other kind of energy, including heat.

Heat energy from nuclear fusion in the sun reaches Earth as electromagnetic (infra-red) rays. Together with light energy, it is a major driving force for life on Earth. We also generate heat energy ourselves in various ways, mostly from stored chemical energy by burning fuels, especially fossil fuels.

Everything is made of particles (atoms, ions or molecules) and heat is the kinetic energy of these particles. When heat is transferred to anything, the particles move faster and the temperature rises. In a solid the particles vibrate faster, nudging one another and conducting heat throughout the solid. In a liquid the particles jostle and push past one another faster. And in a gas the particles fly off on their own, faster and faster in all directions. Molecules of nitrogen at room temperature travel at more than 1500 kilometres per hour! Faster particles take up more room and this leads to expansion and to the convection currents that spread heat quickly in liquids and gases. Heat can cause solids to melt and liquids to boil; it can also cause some substances to decompose and others to react with their surroundings, for example by burning.

Measuring heat energy. To measure heat energy we can use the fact that 4.2 kJ of heat will raise the temperature of 1 kg of water by 1ºC. This value was obtained by converting other, more easily measured, kinds of energy completely into heat in water-filled containers. One of the first to experiment with this was the English inventor Count Rumford who, in 1798, reported the results of boring out the barrel of cannon with a blunt drill under water. After 2½ hours the heat produced by friction was enough to boil the water! In 1845 Joule published more accurate measurements which established a value very close to the one we use today. So now we can measure heat energy by using it to heat a known mass of water and measuring the rise of temperature. The quantity of heat energy is given by the formula:

heat energy (kJ) = 4.2 \times \text{mass of water (kg)} \times \text{rise of temperature (ºC)}

The specific heat capacity (or specific heat) of any substance is the heat required to raise the temperature of 1 kg of substance by 1ºC. The SI unit of specific heat is joules per kilogram per degree Celsius. Specific heat (J/kgºC) = energy (J) + mass (kg) + rise of temperature (ºC)

We already know that the specific heat of water is 4.2 kJ/kgºC, but most substances need much less heat than water to warm them up. The specific heat of iron is 0.45 kJ/kgºC and of most plastics is about 2.5 kJ/kgºC. Only 0.45 kJ of heat raises the temperature of 1 kg of iron by 1ºC and only about 2.5 kJ does the same for 1 kg of most plastics.

Using heat energy. We use heat at home to keep us warm and cook our food. We also produce huge quantities of heat by burning fuels to power transport, produce electricity and manufacture a range of products such as metals, cement and plastics. The picture above shows iron being heated in a blacksmith’s forge to soften it before he hammers it into shape. The picture on the left shows heat being used in the manufacture of phosphorus in a chemical factory. Unfortunately heat is a very inefficient form of energy to use. In most technological processes 50 - 90% of heat energy is wasted just warming up its surroundings.

- What is (i) convection, (ii) absolute zero, (iii) specific heat?
- What is heat energy? List the effects of heat on matter.
- Why do you think water is effective for cooling hot iron? A blacksmith plunges 1 kg of red hot iron at 1000ºC into 20 kg of water at 25ºC. How hot does the water become?
17.9 STATIC ELECTRICITY

Matter is made of atoms which have positively charged nuclei. The charge on each nucleus is balanced by that of the negatively charged electrons that orbit around it (Modules 13.1 and 13.5). The electrons are held in place by the attraction of the oppositely charged nucleus but, in certain circumstances, some of the outermost electrons can break free of their nuclei. This independent movement of electrons is the basis of electrical energy. In insulators, localised accumulations of electrons can occur and this causes the phenomena of static electricity. In conductors, electrons do not accumulate in one place because they can flow easily throughout the material. A flow of this kind is the basis of current electricity (see Modules 4.2 to 4.8, and 17.10 to 17.16).

Static electricity is often caused by friction between dry surfaces. When a dry piece of polythene is rubbed briskly with a dry cloth, it tends to pick up electrons from the cloth. The polythene becomes negatively charged and the cloth positively charged. Some other insulators, including glass, Perspex, and cellulose acetate, lose electrons so the insulator becomes positive and the cloth negative. Water conducts electricity so any moisture, even in the air, makes static charges leak away quickly.

The diagram on the right shows how a negatively charged polythene strip, suspended by a thread, is repelled by another negatively charged strip. (Both ends are repelled; there are no ‘poles’ as with magnets). But if the negatively charged polythene strip is approached by a positively charged object, for example a charged glass rod, it will be attracted. Like electric charges repel, but opposite electric charges attract.

In 1926, an American physicist, Robert Van de Graaff, invented a machine that uses friction between a roller and a belt to build up a charge of many thousand volts on a metal sphere. The photograph shows a girl touching the positively charged sphere of a Van de Graaff generator. It is safe for her to do this if she is well insulated from the ground because, although the charge spreads all over her, no electric current flows through her. All the strands of her hair now have the same high positive charge so they repel one another! After she removes her hand, the charge leaks away in a few seconds.

Induced charges. When a charged insulator comes close to any other object, it induces an opposite charge in the part of the object nearest to it. The diagram on the right shows what happens when a negatively charged strip of plastic comes close to an uncharged sphere. The negative charge repels electrons from the closest part of the sphere. This induces a positive charge in the closest part of the sphere and a negative charge on the far side. This leads to attraction between the strip and the sphere. Because of induction, a charged insulator attracts any neutral object that it comes close to. The picture on the left shows an old trick! After the rod is rubbed with the ‘magic’ cloth, it attracts and picks up tiny scraps of paper. The rod becomes charged, induces an opposite charge on the sides of the scraps closest to it, and opposite charges attract. This is also why CDs attract dust.

Everyday examples of static electricity include the hair-raising, crackling, sparking, and minor electric shocks that are familiar to people in very dry climates when they pull on or off clothing or bedding. The crackling, sparking and shocks are caused by electrons jumping from negatively to positively charged materials. Lightning is a more dramatic example of the same thing. Because of friction and other effects, the bases of clouds become negatively charged. This induces a positive charge on the ground below them. If the charges become strong enough, vast numbers of electrons jump from the cloud to the ground creating the gigantic electric sparks we call lightning.

- 1. Rub a dry plastic comb or ball-point pen on your clothing and pick up scraps of paper by induction. Try again with scraps of kitchen foil instead of paper. What happens? Why?
- 2. What are (i) static electricity, (ii) current electricity?
- 3. Explain why plastic CD/DVDs often attract dust.
- 4. A book with a cover made of cellulose acetate may be hard to pull out of a polythene sleeve. Explain why.
**17.10 CURRENT ELECTRICITY AND CIRCUITS**

An electric current is a flow of electric charge. Except in a few special cases, the charge is a negative one and is carried by electrons flowing through metal conductors. Metals consist of a lattice of positive ions surrounded by a ‘cloud’ of easily moved electrons from the outer orbits of their atoms (Module 13.5). The diagram on the right shows a model of the lattice for the metal iron.

**Circuits.** In order for an electric current to flow there must be a source of electrical energy and a complete circuit of conductors (Module 4.2). The conductors are usually metal wires. Electrons enter the circuit from a negative terminal or pole, flow around the circuit, and return to a positive terminal or pole. The energy pushing the electrons around the circuit may come from the chemicals in a cell or battery of cells like the one on the right (Module 4.6), or from generators in power stations (Module 14.9) which convert heat or mechanical energy into electrical energy.

A good example of a simple circuit is the torch illustrated below. Two 1.5 volt cells are connected top to bottom so the voltages add together. When the switch is pushed forward, the metal strip touches the metal plate that the bulb screws into. This completes the circuit. Electrons leave the base of the bottom cell and flow through the spring and connecting wire to the switch, the metal strip, the metal plate, and finally through the bulb and back to the top of the top cell.

**Symbols for circuit diagrams**

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A clear way to show circuits using simple symbols. Some common symbols are shown in the table above. The circuit diagram on the right is the circuit for the torch. Follow the electrons from the negative pole of one cell, around the circuit and back to the positive pole of the other. The diagram on the left shows a simple domestic lighting circuit with a fused 230 volt ac supply (Module 17.15) connected to two lights in parallel (Module 17.13). At present lights L1 or L2 are both off, but either one, or both together, can be switched on with switches S1 and S2. When it is on, light L2 can be dimmed using a variable resistance. Use a finger to trace the flow of electricity around both circuits.

- 1. What are (i) conductors, (ii) insulators, (iii) electrons, (iv) electric current, (v) a fuse, (vi) a switch, (vii) ac?
- 2. What is needed before an electric current can flow?
- 3. Describe the basic structure inside a 1.5 volt cell.
17.11 MEASURING ELECTRIC CURRENT AND VOLTAGE

**Electric current** is a flow of electric charge. Except in a few special cases involving fluids, the charge is carried by electrons. The electrons flow from the negative terminal of an energy source, around a complete circuit of conducting material, and return to the positive terminal. The strength of an electric current is measured as the rate of flow of electric charge. The SI unit of electric current is the ampere (A), usually shortened to amp. The ampere is named after the French physicist André-Marie Ampère (1775 – 1836). A current of one amp corresponds to a rate of flow of electrons of only a fraction of a millimetre per second. However, even this apparently slow speed means that approximately $6.24 \times 10^{18}$ electrons leave the negative terminal every second!

An electric current is measured with an ammeter. The photo shows an ammeter on the front of a CD/DVD recorder; it reads 9.6 amps. To measure the current in a circuit, an ammeter must be connected into the circuit so the current flows through it as shown in the circuit diagram (left). The current through a small torch bulb powered by two 1.5 volt cells is less than half an amp and so is the current through a typical 230 volt domestic light bulb. Other domestic appliances use currents from a fraction of an amp for a radio or a small fan, up to 10 amps or more for a large heater or air conditioner. The current needed to start a truck with a 12 volt battery may be about 200 amps! Most ammeters have a positive terminal (+) which may be coloured red and a negative terminal (–) which may be black. The + terminal connects (through the circuit) to the + terminal of the battery or other energy source. In the same way, the – terminal connects (through the circuit) to the – terminal of the energy source. Look at the circuit diagram and use your finger to follow the electrons from the battery. Confirm that the electrons flow through the ammeter from its – to its + terminal.

**Voltage or potential difference** is what pushes a current through a circuit. It is the difference in the potential energy of the electrons between two points, usually the terminals of a cell or other source of electrical energy. The SI unit of voltage (potential difference) is the volt (V), named after the Italian physicist Alessandro Volta (1745 – 1827). The voltage (potential difference) between the carbon rod at the top of a dry cell and the zinc case at the bottom is 1.5 V, and between the + and – terminals of a car battery is 12 V. The voltage of the mains electricity supplied to homes in most countries is 220 – 240 V (110 – 127 V in the North America, Japan and a few other places).

Voltage is measured with a voltmeter. The voltmeter on the left has an adjustable scale and can measure from 0 to 750 volts. To measure the voltage between two points in a circuit, the voltmeter is connected to both points as shown in the circuit diagram (right). Unlike with the ammeter, the current that flows around the main circuit does not flow through the voltmeter. Most voltmeters have + and – terminals that connect to corresponding sides in the circuit to ensure that electrons flow through the voltmeter from the – to the + terminal. The voltage in the circuit diagram on the right is about 3 volts from the addition of two 1.5 volt cells in series.

- 1. What are (i) an amp, (ii) an ammeter, (iii) a volt, (iv) cells connected in series?
- 2. Copy the circuit diagram from the bottom left of module 17.10 and add (i) an ammeter to measure the current passing through the lamp L2, and (ii) a voltmeter to measure the voltage powering lamp L2.

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**Cells in series.** When two or more electric cells are connected top to bottom (+ to –), they are said to be connected in series. When cells are connected in series their voltages add up. For example, two 1.5 volt cells in series in a torch supply 3 volts, and six 2 volt cells in a vehicle battery supply 12 volts.
Metals are good conductors of electricity, however they all offer some resistance to the flow of an electric current. The resistance opposing a current is like the friction that opposes mechanical motion. Energy, in the form of a voltage, must be supplied before an electric current will flow through any conductor. In 1827, a German physicist and high school teacher named Georg Ohm (1789 – 1854) published the results of some experiments which are the basis of what we now call Ohm’s law. Ohm’s law states that, for a metal conductor, at a constant temperature, the current increases in proportion to the voltage. For example, if we double the voltage, the current will double too. You can confirm Ohm’s law using the simple practical activity described in the text box below. The table of typical results confirms that, as the voltage increases from 1.5 to 3.0 to 4.5 to 6.0 volts, the current increases exactly in proportion from 0.2 to 0.4 to 0.6 to 0.8 amps.

The electrical resistance of a conductor is defined as the ratio of the voltage (potential difference) to the current it produces. The SI unit of resistance is ohms (Ω) and one ohm is the resistance of a conductor when a voltage of one volt causes a current of one amp to flow. So:

\[ R = \frac{V}{I} \]

where V is voltage, I is current and R is resistance; (obviously \( V = IR \) and \( I = V/R \)).

Look at the ‘typical results’ of the activity in the text box on the right. The resistance of the resistor, as calculated from the voltage and current, is 7.5 ohms (see the last line of the table). Note that the wires and the ammeter both have very low resistance so they do not affect the voltage applied by the cells to the resistor.

Factors which affect the electrical resistance of a wire are illustrated in the diagram below.

- For wires of the same thickness, made of the same material, the resistance of the wire increases in proportion to its length.
- For wires of the same length and material, the resistance of the wire decreases with thickness in proportion to the cross-sectional area.
- For wires of the same length and thickness, the resistance of the wire depends on the material it is made of.

Copper has a very low resistance so connecting wires are usually made of copper. A metre of copper wire, 1 mm in diameter, has a resistance of only 0.02 ohms. Aluminium also has a low resistance and is used for high voltage power transmission lines because it is cheaper and lighter than copper. A kilometre of a typical power line has a resistance of only 0.03 ohms. Tungsten has about three times the resistance of copper. The tightly coiled half-metre of thin (0.05 mm) tungsten wire in a typical light bulb has a resistance of about 500 ohms. Special alloys called constantan (copper/nickel) and nichrome (nickel/chromium) have about 50 times the resistance of copper and are used to make ‘resistance wires’ for various applications.

- 1. What are (i) potential difference, (ii) electric current, (iii) electrical resistance, (iv) an ohm?
- 2. Which has the higher resistance: (i) a thick nichrome wire or a thin one of the same length? (ii) a long copper wire or a short one of the same thickness? (iii) a tungsten wire or a constantan one of the same length and thickness?
17.13 SERIES AND PARALLEL CIRCUITS

A single source of electrical energy often has to provide power for several different devices. In a house, for example, electricity must be supplied to several lights, a refrigerator, a TV and so on. When we connect two or more devices to a source of electrical energy we can connect them in series or we can connect them in parallel.

The diagrams on the right show how two ordinary torch bulbs can be connected to a single power source in series and in parallel. The power source is two 1.5 volt cells connected in series in a battery clip giving a total voltage of 3 volts. The two torch bulbs L1 and L2 are the same. Each has a filament of coiled tungsten wire with a resistance of 6 ohms. In an ordinary 3 volt torch, the current through a bulb of this resistance is 0.5 amps and this gives a bright light.

When L1 and L2 are connected in series, the current flows through L1, then through L2, before returning to the battery. When L1 and L2 are connected in parallel, each has its own loop in the circuit. The current divides; part of it flows through L1 and part of it flows through L2, then all of it returns to the battery. In the following sections we look at simple series and parallel circuits in more detail.

A series circuit has a single loop and the current flows through several components one after another. The example on the left is the same as the simple series circuit above with the addition of a switch S. Ammeters and voltmeters have also been added to show the current and voltage at different points in the circuit. Study this example and note the following general features of series circuits:

- The current is the same at all points around the circuit; it depends on the combined resistance of the components.
- All components are controlled by the same switch; they are either all on, or all off.
- The voltage is divided between the components (in this case L1 and L2) in proportion to their resistances.

The two bulbs together have a combined resistance of 12 ohms. The formula R = V/I (see Module 17.12) transposes to I = V/R so the current all round the circuit is 3/12 = 0.25 amps. This is half the current needed to give the bulbs their normal brightness so they will be very dim or may not light at all! Series circuits are not used much because of the reduced current in series circuits, and because each component cannot be switched on and off independently. However, a familiar example of a series circuit is the strings of tiny decorative lights that are often used on festive occasions.

A parallel circuit has two or more loops connected to the same power source. Separate currents flow through each loop. The example below is the same as the simple parallel circuit above with the addition of switches S1 and S2. Ammeters and voltmeters have also been added to show the current and voltage at different points. Both loops connect to the battery through X and Y. Study this example and note the following general features of parallel circuits:

- The voltage of the power source is delivered in full to each loop and thus to the component (bulb) it contains.
- Each loop can be controlled by its own switch; switching one loop on or off has no effect on any other loops.
- The total current delivered by, and returned to, the power source is the sum of the currents in all the parallel loops.

Because of the first two features, parallel circuits are widely used, for example when wiring electricity in our homes.

1. What is the difference between a series and a parallel circuit?
2. Describe, with as much detail as you can, the flow of electrons through (i) the series circuit and (ii) the parallel circuit shown above.
3. Copy the series and parallel circuits above replacing L2 with a 12 ohm resistor. Recalculate all the currents and voltages using R = V/I.
The area around a magnet, in which we can detect the force of the magnet, is called a magnetic field. Magnetic fields can be detected with iron filings or with a magnetic compass (Module 4.12). An electric current has a magnetic field and the text box below on the right describes a simple activity to show this. As you will see from diagram 2, the magnetic field is at right angles to the current. The earth’s magnetic field is caused by a stream of charged particles emitted from the sun as they shoot past the earth like a vast electric current in space.

**An electromagnet** is a coil of insulated wire wrapped around a rod or bar of soft iron. When the ends of the wire are connected to a source of electricity, the magnetic field of the electric current is concentrated in the iron and it becomes a strong magnet. When the current is switched off, the electromagnet loses its power, but if the soft iron rod is replaced by a steel one, the steel rod becomes a permanent magnet. You can easily make your own electromagnet with about a metre of insulated wire, coiled around a large iron nail. The diagram shows the direction of the current in the conventional way; that is, flowing from the positive terminal of the power source, around the circuit and back to the negative terminal. When you look at the end of an electromagnet, if the current flows clockwise that is the south pole of the magnet; if it flows anticlockwise that is the north pole. The diagram (above left) shows an easy way to remember this.

Electromagnets have many uses including electric buzzers and bells. Look at the diagram of the bell on the right. Electricity flows from the +, through the spring to the contact point, then through the electromagnet and back to the –. This attracts the soft iron, pulls the spring away from the contact point, and makes the hammer hit the bell. Now the circuit is broken at the contact point so the electromagnet is switched off and the spring springs back. It makes contact with the contact point again. This switches on the current and the process repeats itself many times a second! The same idea is used in devices called *relays* which use electromagnets to operate switches. Huge electromagnets on cranes are used to pick up scrap iron and electromagnetic coils are also used to make permanent magnets from steel and alloys such as *alnico*.

**The motor effect.** When a conductor carries an electric current close to a magnet, it experiences a force called the motor effect. This is caused by attraction and repulsion between the magnetic field of the current and the magnetic field of the magnet. If electricity is passed through a loop or a coil between the poles of a magnet, it experiences a turning force. This is the basis of the electric motor (Module 14.8).

**Electromagnetic induction.** When a conductor moves in a magnetic field, an electric current is induced in the conductor. If a loop or coil of wire is made to rotate between the poles of a magnet, a current will flow through the coil. This is the basis of most electricity generators.

- 2. What are (i) a magnetic field, (ii) a magnetic pole, (iii) an electromagnet, (iv) electromagnetic induction?
- 3. Find out what *alnico* is and what it is used for.
- 4. Design a simple relay to switch on a light.
17.15 MAINS ELECTRICITY

Generation. Mains electricity is the general purpose electricity supplied to all modern homes. It is produced at power stations where various sources of energy are used to drive generators (Module 14.9). The principle of the generator is illustrated in the diagram. Coils of copper wire (represented by the red loop) are attached to an axel and rotate between the poles of powerful magnets. Electromagnetic induction (Module 17.14) causes an electric current to flow through the coils. This is collected by graphite brushes that press against rotating slip rings connected to the coils. Because the coils rotate past north and then south magnetic poles, the current reverses direction twice during each revolution of the axel. The output is an alternating current that, in most countries, reverses its direction at a frequency of 50 hertz; that is, 50 times per second (60 Hz in North America, Japan and a few other countries). The voltage depends on the size and type of generator and varies from 2 500 to 30 000 volts (2.5 - 30 kV).

Transmission and distribution. Electricity is carried from power stations to sub-stations in distant towns and cities by thick aluminium wires. The wires are suspended from steel pylons by insulators made of ceramics or reinforced plastics. Aluminium is used for the wires because of its light weight and low resistance; typically about 0.03 ohms per kilometre. Step-up transformers at the power station raise the voltage to 110 to 500 kV or more before transmission. These very high voltages keep power losses in the wires to a minimum, typically less than 7%. At the sub-stations, step-down transformers reduce the voltage to meet the needs of various industrial and domestic users. From there the electricity is distributed to factories and homes through local networks of wires. The process is summarised in the flow chart. The transformers, which are essential for transmission and distribution, need the alternating current to enable them to function.

The domestic electricity supply in most countries is 220 – 240 V alternating current at 50 Hz (in North America, Japan and a few other places it is 110 – 127 V at 60 Hz). The supply is delivered through a cable that includes two insulated wires, a live wire and a neutral wire. The live wire provides power at a high voltage and can deliver a severe electric shock. The neutral wire completes the circuit and carries the current back to its source. For reasons of safety this wire is connected to the ground by metal stakes at many points between the generator and the user so its voltage is close to zero. The insulation on the wires is coloured coded; in most countries brown for live and blue for neutral. Domestic systems also have an earth wire which is connected directly to a metal stake in the ground. This has a voltage of zero and is coloured green or yellow.

Lighting and power circuits. In most homes there are at least two separate circuits, one for lights, and one for power points. There may be additional circuits for major appliances such as an electric cooker or a large air conditioner. The diagram below shows part of a typical lighting
circuit. The lights are connected in parallel so they all receive the full voltage and they can all be switched on and off independently. The switches are placed in the live wire to minimise the danger of electric shocks when the light is off. The earth wire is not part of the circuit but, for safety reasons, it is connected to the external metal parts of every light fitting.

The power circuit has a similar layout to a lighting circuit but it has to carry bigger currents. Because of this, thicker wires and larger fuses (15 amps or more) are used. Instead of lights, a number of power points are connected in parallel. A typical power point is illustrated (left) with the corresponding plug. Different countries use different designs, but the live wire always connects to the hole on the right and the neutral wire to the hole on the left. Arrangements for the earth wire vary but it is often in the centre.

The diagram (right) shows how the wires are connected inside a typical plug. Plastic grips hold the cable firmly to protect the connections if anything jerks the cable. A plug should never be removed from a power point (socket) by pulling the cable!

**Safety issues** with mains electricity are mostly about electric shocks and short circuits. You will get an electric shock if you touch a live wire or any metal that is touching a live wire. A shock from mains electricity is always painful and may kill, especially if water is present. In some countries it is forbidden to have power points and switches in bathrooms and other wet areas. Short circuits occur when a live wire accidently connects with a neutral or earth wire. Short circuits offer little or no resistance so the current becomes very high. The wires become very hot, melting the insulation and setting fire to their surroundings. Many house fires are started by short circuits when the insulation breaks down on old electrical wiring. We can minimise the risks of shocks and short circuits by good insulation and earthing, and the proper use of fuses and trip switches.

**Good insulation** protects us against both shocks and short circuits. All wires that carry mains electricity should be well insulated by colour-coded plastic coverings. If the insulation is damaged, the wire should be replaced. When wires are connected to plugs and appliances, or to one another, the end of each wire is bared (as shown on the left) and then firmly clamped into a proper terminal so that no bare wire is exposed. The terminals are then isolated by using the correct plastic cover for the plug or appliance, or by a plastic junction box when wires have been connected to one another.

**Fuses and trip switches** (also called circuit breakers) protect circuits that become overloaded. This happens when too many appliances are used on the same circuit at the same time, or if there is a short circuit. A fuse contains a thin wire which melts and breaks the circuit if the current exceeds a safe limit. A trip switch contains an electromagnet that switches off the circuit if the current becomes too big. Every mains circuit must be protected by a fuse or a trip switch in the live wire.

**Earth wires** are connected to the external metal parts of electrical devices to protect us against shocks. If a live wire accidently touches these parts, it is short-circuited to earth. This ‘blows’ the fuse, or trips the trip switch.

- 1. What are (i) slip rings, (ii) transformers, (iii) lighting circuits, (iv) a power point, (v) an earth wire, (vi) a fuse, (vii) a trip switch?
- 2. In your region what colours are the live, neutral and earth wires?
- 3. Select fuse wire for a lighting circuit, a power circuit, a cooker.
- 4. Explain why transformers are used in the transmission and distribution of electricity. What is the efficiency of transmission?
Mains electricity delivers 110 – 240 volts alternating current (ac) to most homes. High voltage alternating current is suitable for most home appliances including lights, heaters and the motors and pumps that drive fans, washing machines, refrigerators and air conditioners. However, some appliances need direct current (dc), and some need smaller voltages too. These include televisions, radios, battery chargers, and computers and associated devices. Some have built-in transformers and rectifiers that adjust the voltage then convert ac to dc; others use external transformer-rectifiers called ac adaptors that plug into the power point.

Every electrical appliance should be marked with a label that gives basic technical information about it, including the voltage it is designed to be used with, and the power it consumes in watts \((W)\). One watt represents the consumption of one joule of energy per second (Module 17.7). If you are not sure where the joules come from, see the text box below! The label on the left is from an electric kettle. The kettle contains a heating element made from a coil of insulated resistance wire which heats up when a current is passed through it. The label indicates that the kettle must be used with a 230 to 240 volt, 50 Hz ac supply (the symbol ‘~’ indicates ac), and that the heating element converts 2200 to 2400 joules of electrical energy to heat energy every second.

The power \((P)\) of any electrical device can also be obtained, from the voltage \((V)\) it uses and the current \((I)\) it carries, by using the formula:

\[
\text{Power (watts)} = \text{Voltage (volts)} \times \text{Current (amps)}
\]

This formula is often written as \(P = VI\) and can transpose to \(I = P/V\). Look again at the label from the Sunbeam electric kettle. If we take the voltage as 230 volts and the power as 2300 watts, the last version of the formula enables us to calculate that the kettle takes a current of 10 amps. This reminds us that the kettle must be used on a power circuit with an adequate fuse or trip switch. A fuse or switch rated at 15 amps would be suitable. If the kettle was connected to a lighting circuit with a typical 5 amp fuse, the fuse would blow and all the lights on that circuit would go out!

Paying for electricity. The picture on the left shows an electricity metre of the kind installed in most homes by your local electricity company. When we pay for electricity, we pay for the power that we use and the time that we use it for. The metre multiplies the power in kilowatts by the time in hours and gives us a reading in units called kilowatt hours \((kWh)\). When the company reads the metre every month, the units \((kWh)\) that you have to pay for are obtained by subtracting the previous metre reading from the present one. The kilowatt hour is not a scientific unit, but we can easily convert it!

\[
1 \text{ kJ/s} = 1 \text{ kJ/s} \quad \text{and} \quad 1 \text{ h} = 60 \times 60 = 3600 \text{ s}
\]

So \(1 \text{ kWh} = 3600 \text{ kJ} = 3.6 \text{ MJ}\)

What we pay for is the amount of electrical energy we have converted, and each unit represents 3.5 MJ.

- 1. What are (i) ~, (ii) an ac adaptor, (iii) a heating element; (iv) a power circuit, (v) an electricity metre, (vi) a kilowatt hour?
- 2. Find the power ratings in watts for as many home electrical devices as you can. List your results starting with the cheapest-to-run devices. For each device, work out the current it takes.
- 3. From the information in the text above, calculate the resistance of the element of the Sunbeam electric kettle.
- 4. To be scientifically correct we should refer to the electrical energy we convert, not the electrical energy we use. Why?

Where do the joules come from?
From the volts! A volt is the potential energy, in joules, of one unit of electric charge. An amp is a current flow of one unit of electric charge per second. If volts are multiplied by amps, the unit of electric charge cancels out and we are left with joules per second - and joules per second are watts, the units of power.