Additional content—Mathematical extension:

Example 3. Moving a crate on a rough floor

Q Figure 1.15 shows an action force of 800 N applied to a crate of mass 80 kg which is resting on a rough floor. As the crate moves, the floor exerts a constant frictional force of 160 N on the crate. Calculate the acceleration of the crate.

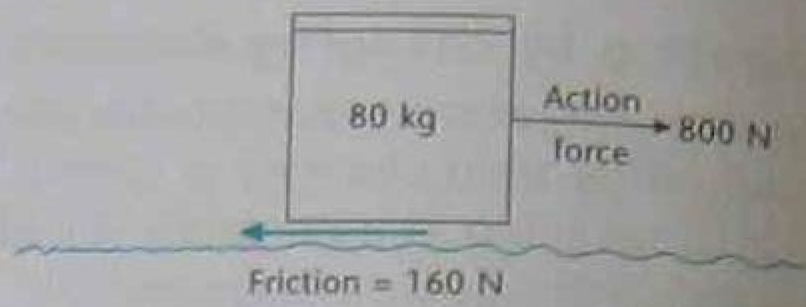


Figure 1.15 Moving a crate on a rough floor

A Net force = action force – frictional force
= 800 – 160 = 640 N.

Using Newton's second law:

$$F = ma$$

$$640 = 80a$$

$$a = 8\ \text{m/s}^2$$

Example 4. Skating on ice

Q A skater is standing still on an ice rink. She is holding a 10 kg bag. She throws the bag out and away in front of her. Use Newton's laws to explain what happens to the skater.

A The skater exerts an action force on the bag in order to throw it away from her. According to Newton's third law the bag will exert an equal and opposite reaction force on the skater. Therefore the skater will move backward as the bag moves forward. This effect is noticeable as the skater is standing on a very low friction surface. A similar observation would be made if an astronaut free-floating in space threw an object away from him. He would be propelled in the opposite direction.

Test yourself

Electrical energy

Electrical energy is an important form of energy in modern society. It is used to power machines, including the majority of large and small household appliances. Electrical energy is transported very rapidly to these appliances via conducting wires in electrical circuits. It is important to remember that the individual free **electrons** in the wire move relatively slowly (a few millimetres per second) but the **electrical energy** is transmitted very rapidly along the conductor. In this way the energy reaches an appliance almost instantaneously when you turn the switch.

There are a number of sources of electrical energy. A **battery** and a **DC transformer** (**'power pack'**) are sources of **direct current** (DC). The mains power points in our homes, however, are connected to a source of **alternating current** (AC) which is generated in power stations by the motion of conductors in magnetic fields. In this topic we consider only DC circuits.

Glossary

Battery—a portable electrical source consisting of a number of electrical cells in series

Current—the flow of electric charge (measured in amps, A)

Electric cell—a device that produces electrical energy by chemical reactions

Resistance—property of a conductor that restricts current flow (measured in ohms, Ω)

Resistor—a device that exhibits resistance to the flow of current

Voltage—the electrical pressure that causes currents to flow (measured in volts, V)

Electrical circuits

An electrical circuit is a complete conducting pathway for the electric current to flow from one terminal of an electric cell or battery (energy source) back to the other terminal. A battery consists of a number of simple electric cells joined in series with one another. The electrical energy is generated inside the electric cell by chemical reactions in each half of the cell. As the electric current flows around the circuit, its energy is transformed into heat and sometimes light. If a motor is connected into the circuit, the electrical energy is partly converted into mechanical energy (a form of kinetic energy).

A simple circuit

A simple electrical circuit consists of:

- **a DC energy source** (eg. battery that stores separate electric charges and gives energy to the charges as they leave it; it also sets up an electric field in the connecting wires)
- **circuit controls**

  —**switches** used to open and close the circuit

  —**branching connecting wires** that allow the current to divide into different parts of the circuit

- **connecting wires**—conductors (such as insulated copper wires) to transfer the current between each components of the circuit
- **resistor(s)**—materials that resist current flow (eg. filaments in light bulbs)
- **measuring devices**
  - —**ammeters** (meters which measure the current flow in the circuit)
  - —**voltmeters** (meters which measure the voltage or potential difference across resistors or other components).

In a household circuit there will also be fuses (or **circuit breakers**) included in the circuit. This is a safety feature in household circuits to prevent overheating and fires from currents that are too high.

Figure 1.19 shows a simple electrical circuit diagram.

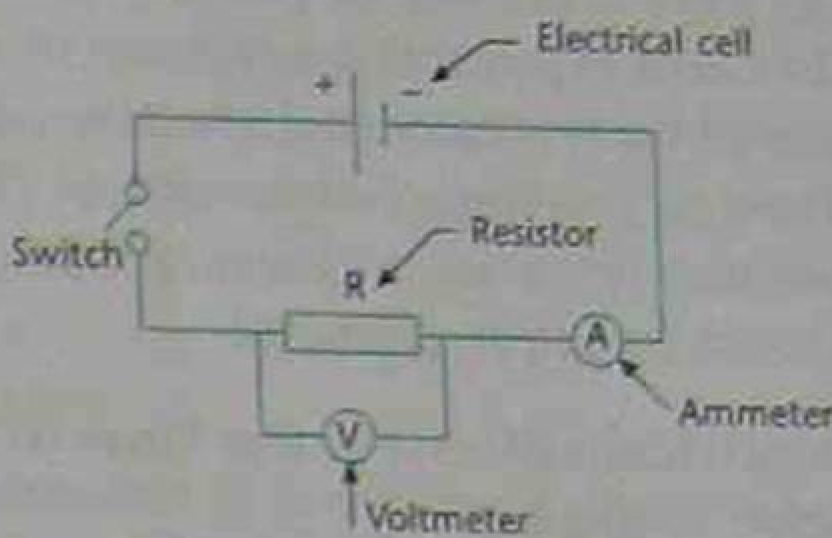


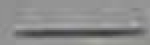
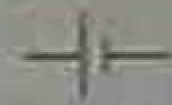
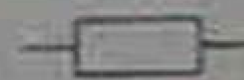
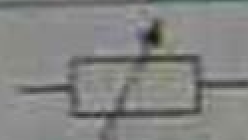
Figure 1.19 Simple electric circuit

The following terminology is used for electrical circuits.

- **Open circuit**—the switch is OFF and no current flows.
- **Closed circuit**—the switch is ON and current flows.

Electrical circuits use circuit symbols which are a type of shorthand. Table 1.6 shows examples of the symbols used in electrical circuit diagrams.

Table 1.6 Electrical circuit symbols

Component	Symbol	Component	Symbol
Conducting wire		Electric cell	
Battery		Resistor	
Lamp		Switch	
Ammeter		Voltmeter	
Fuse		Variable resistor	

Current, voltage and resistance

Current

Before electrons were discovered at the end of the nineteenth century, physicists believed that electrical currents consisted of moving positive charges. Eventually it was discovered that electrical currents were due to the motion of (negatively charged) electrons. Although electrons flow out of the negative terminal of an electric cell and through the circuit to the positive terminal, physicists and electricians continue to use the original convention that electric current is the flow of positive charges out of the cell's positive terminal and around the circuit to its negative terminal.

- An electrical current is the flow of positive charge.

As energised electrical charges flow out of the positive terminal of the battery and into one end of the circuit, energy-depleted charges move back into the battery via the negative terminal.

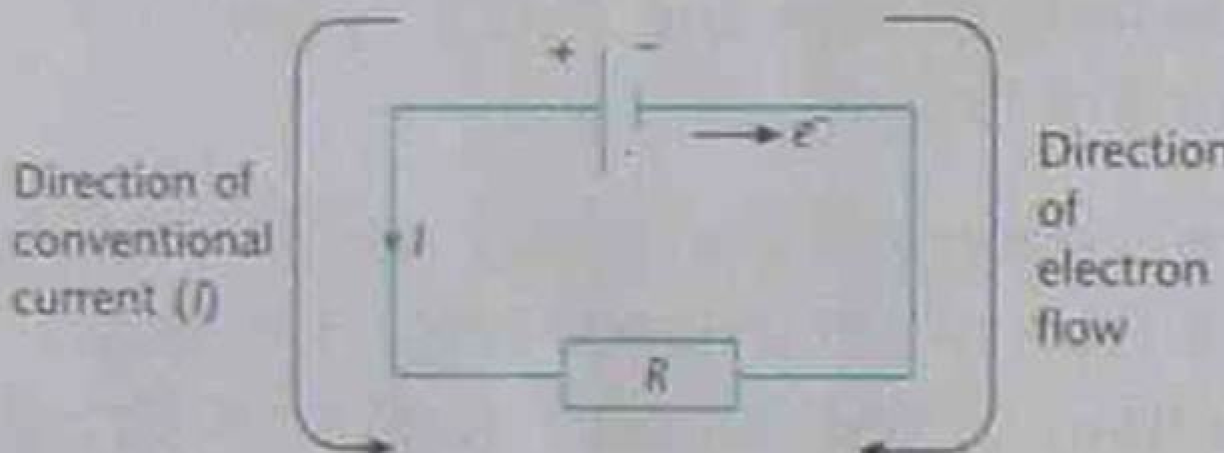


Figure 1.20 Conventional and electron currents

It is often useful to visualise electrical currents in terms of an analogy.

Observation: Current flow is almost instantaneous once the switch is turned on.

Analogy: A long line of marching students is ordered to begin marching along a circular road, starting at the long bridge which links the two ends of the road. They all start together and observers at each side of the bridge and at other points along the road observe immediate movement, even though individual students will take a long time to move around the whole road system and pass a fixed point.

- Electrical currents are measured using ammeters that are placed in the circuit.

These ammeters effectively count the number of electric charges passing any given point in one second. The ammeters themselves have low internal resistances so they do not disrupt the current flow.

- Electrical current is measured in units called 'amperes' or 'amps' (unit symbol = A).

This unit of current is named in honour of the French physicist André Ampère.

Voltage

Electrical charges flow around a circuit in response to an electrical force. The force is caused by the existence of an electric field that is established in the conducting wires when they are connected to the battery terminals. We can think of the charges emerging from the positive terminal of the battery as having a high potential energy. Those charges returning to the negative terminal have zero potential energy. In some parts of the circuit some of this energy is transformed into other forms and the potential energy decreases. This is the potential energy decreases. This is particularly true across a resistor such as the filament in a light bulb. Potential differences therefore exist across various parts of the circuit. These **potential differences** are also called **voltage drops.**

- **Voltage is a measure of the potential energy differences between any two points in a circuit.**

Some people like to think of the voltage of a battery as the electrical pressure it puts on the charges that flow around the circuit.

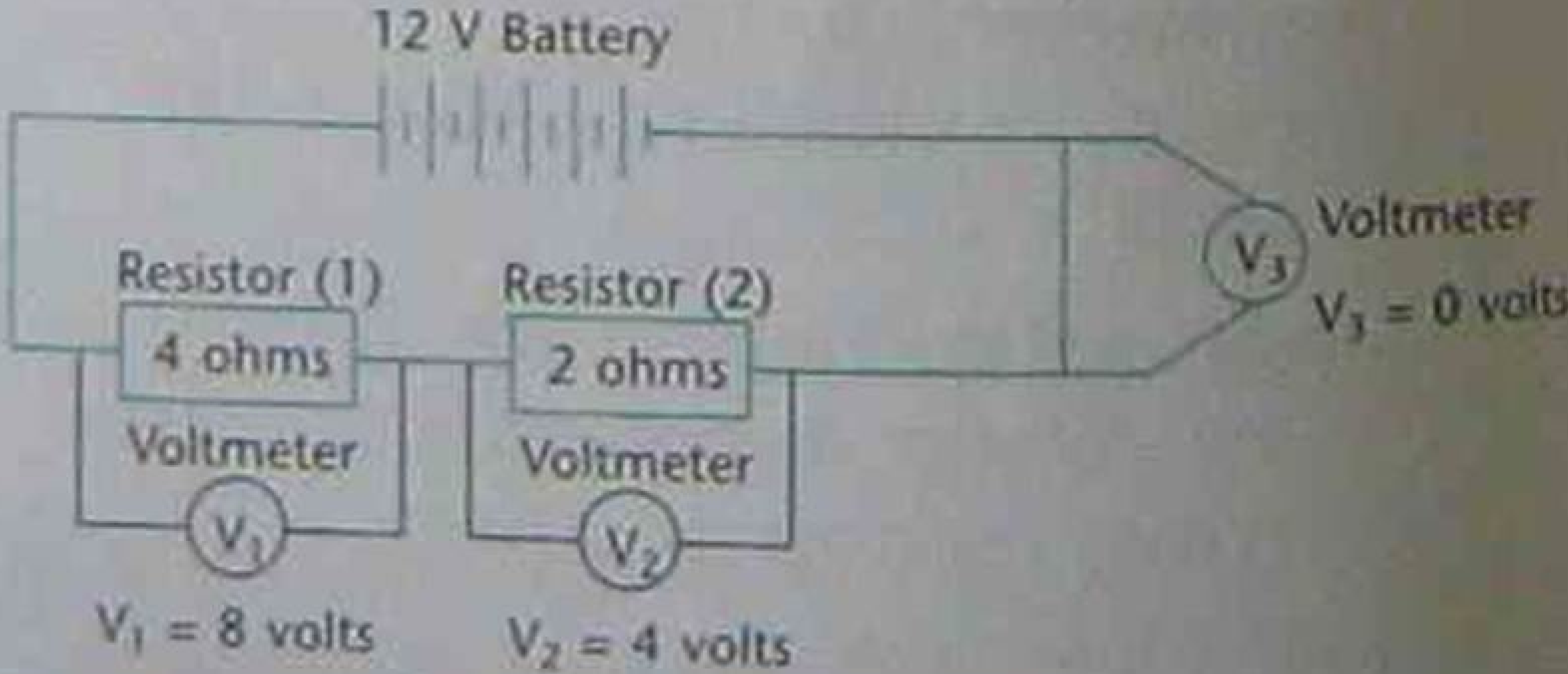


Figure 1.21 Voltage drop around a simple circuit

It is often useful to develop an understanding of the term 'voltage' in terms of an analogy.

Observation: High-voltage batteries make model electric motors spin faster than do batteries with low voltages.

Analogy: Water flows rapidly out of a tap if the water pressure behind the tap is high. If the water is stored in a tank and the tap is opened, the pressure of water flow decreases as the level of water drops in the tank. In this analogy the height of the water column behind the tap creates a pressure (due to the water's gravitational potential energy) which drives the water out when the tap is open. Similarly the high-voltage battery gives the charges a high electric potential energy. When the switch is closed, the charges begin to flow as a response to the electrical pressure.

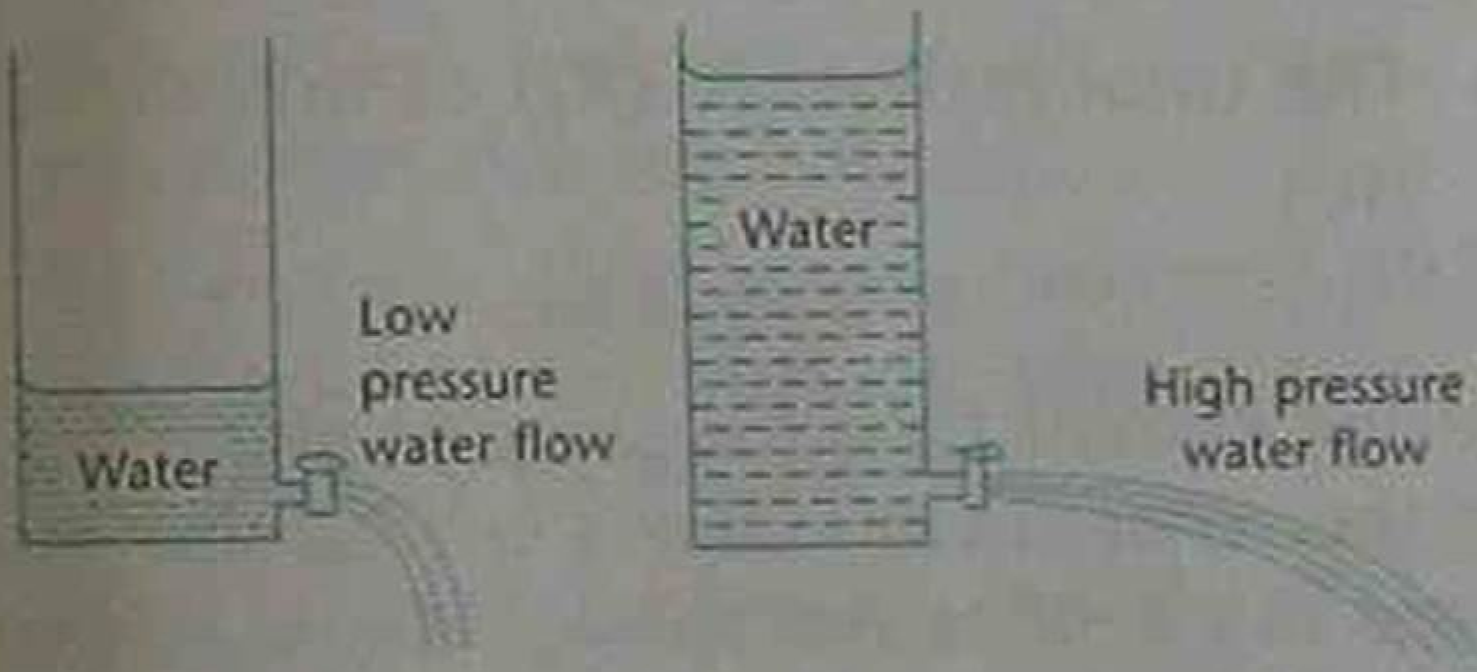


Figure 1.22 Tank of water analogy for voltage

- Voltmeters are used to measure the voltage drop across any two points in a circuit.

Because voltmeters have high internal resistance to current flow, they are placed in parallel to the circuit and so they only sample part of the current flow at the points being measured.

- **Voltage is measured in units called 'volts'. (Unit symbol = V)**

The unit of voltage is named in honour of the Italian physicist Alessandro Volta.

Resistance

Not all materials are excellent electrical conductors like silver and copper. Some materials reduce the flow of electric currents when they are present in a circuit. Nichrome alloy wires, for example, reduce the flow of a current, compared with the flow in similar copper wires. Such materials are said to offer **resistance** to current flow. Materials that completely block current flow, such as plastics and glass, are called **insulators**.

- **Resistance is a measure of the electrical conductivity of the conductor.**

A wire that is a good conductor has a low resistance. A wire that is a poor conductor has a higher resistance. The resistance of any wire also depends upon its length and diameter as well as its temperature.

- **Devices that are manufactured to provide resistance to current flow are called resistors.**

The tungsten filament in a light bulb is a resistor. As current flows though it, considerable energy is transformed into heat energy and light energy. In this case the resistor is designed to emit light. In other appliances, resistors are used to limit current levels in certain parts of a circuit.

- Resistance is measured in units called 'ohms'. (Unit symbol = Ω)

The unit of electrical resistance is named in honour of the German physicist Georg Ohm. Ohm also showed that the voltage, current and resistance are related mathematically. He showed that the resistance (*R*) of a conductor was equal to the voltage drop (*V*) across the conductor divided by the current (*I*) flowing through it.

Additional content—Mathematical extension:

Mathematically, **Ohm's law**, as it is known, is expressed as:

$$R = V/I$$

Example

Q A piece of Nichrome wire is included in a simple electrical circuit. The ammeter registers a current of 2.5 A flowing through the wire and a voltmeter registers a voltage drop of 7.5 V across the wire. Calculate the resistance of the Nichrome wire.

A $I = 2.5$ A

$V = 7.5$ V

$R = V/I = 7.5/2.5 = 3.0\ \Omega$

It is often useful to develop an understanding of the term 'resistance' in terms of an analogy.

Observation: Narrow-diameter wires have greater electrical resistance than wide-diameter wires.

Analogy: Narrow water pipes slow down the flow of water. In a garden hose, the nozzle can be narrowed to restrict the water flow. Water is transported from reservoirs to cities in huge pipes with large diameters to reduce the resistance to flow.

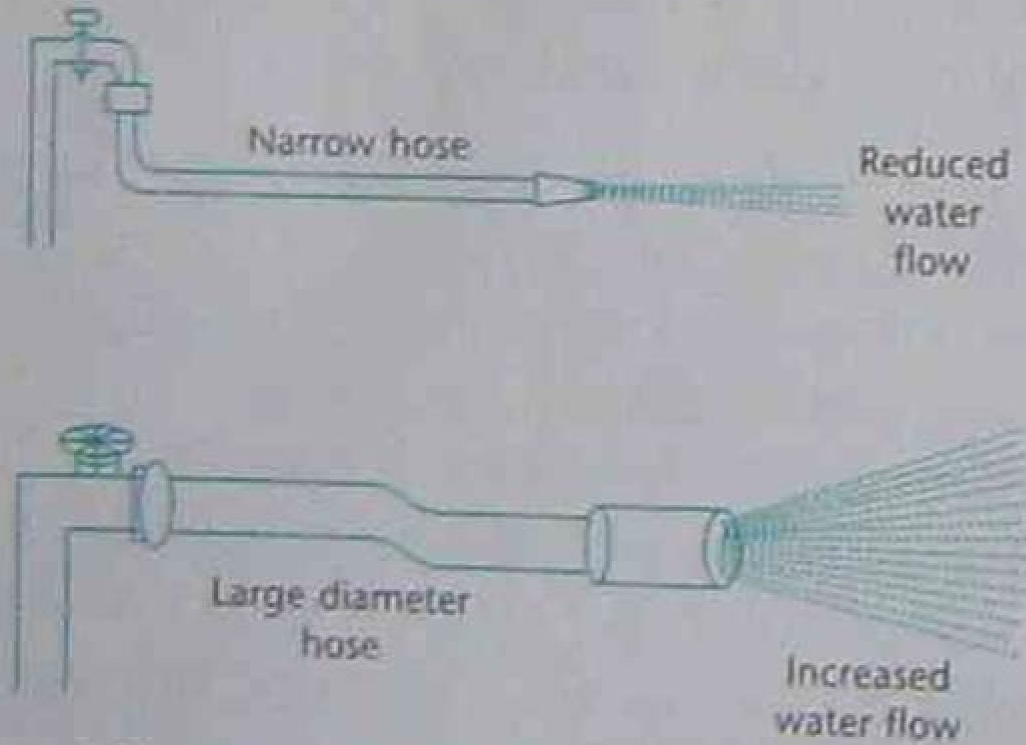


Figure 1.23 Water pipes and resistance analogy

Series and parallel circuits

Resistors can be connected in various arrangements in electrical circuits. They can be connected **in series** or **parallel** or in combinations of the two.

Series circuits

In a series circuit all the resistors are placed one after the other so that the electrical current passes in turn through each resistor as it flows around the circuit.

- At all points in the series circuit the current is the same.
- The voltage drop across the two battery terminals is equal to the sum of the voltage drops across each resistor.
- The greater the number of resistors in series the greater is the total resistance.