10 Electric Charge and Current

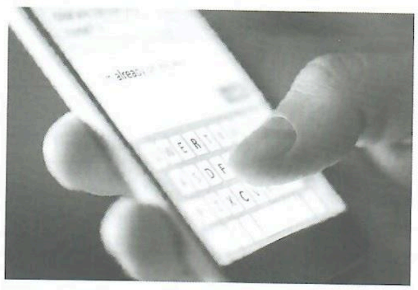
Study Station ▸▸

A Electric Charge and Force

Learning Outcomes

- State that charges are either positive or negative and the unit of charge is coulomb.
- State that unlike charges attract each other and like charges repel each other.

1. The electricity that we use every day involves the movement of electrons, which are *very small particles with* an *electric charge*.
2. For example, when we use our mobile phones to send chat messages, the mobile phones are using electricity to function.



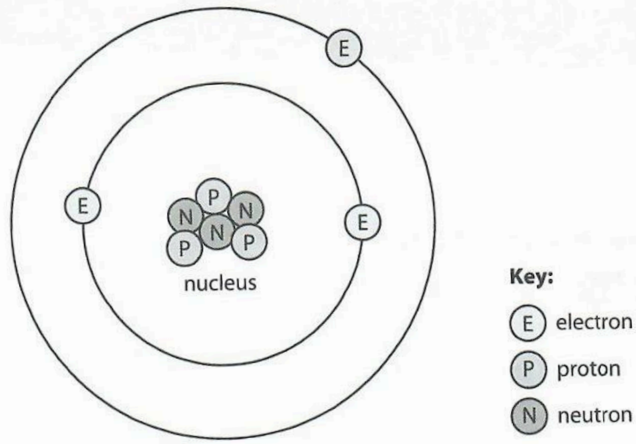
- When we use our phones, electrons move (or flow) through various components in the phones to give us the different functions.
- The electrons have a special property called *electric charge*.

Tip

Here, 'charge' refers to a property of electrons, similar to 'mass'. It does not mean the action of supplying energy, such as in the case of when we 'charge' our phones.

3. **Electric charge** is a basic *property of matter* (recall that mass is also a basic physical property).
   - There are two types of electric charges – positive charge and negative charge.
   - The SI unit of electric charge is coulomb (C).

4. The smallest particle that can have an electric charge is an atom. Generally, atoms consist of protons, neutrons and electrons.



Subatomic Particle	Charge
proton	$+1.60 \times 10^{-19}$ C
electron	-1.60×10^{-19} C
neutron	0 C (a neutron is neutral and has no charge)

5. If an object has more protons (positive charges) than electrons (negative charges), it has an overall positive charge. It the object has more electrons than protons, it has an overall negative charge.
   - For example, an atom with 3 protons and 2 electrons has a net charge of $(3 \times (+1.60 \times 10^{-19}\text{ C})) + (2 \times (-1.6 \times 10^{-19}\text{ C})) = 1.60 \times 10^{-19}$ C.
   - An atom with 3 protons and 3 electrons has a net charge of $(3 \times (+1.60 \times 10^{-19}\text{ C})) + (3 \times (-1.60 \times 10^{-19}\text{ C})) = 0$ C.
   - An atom with **zero charge** is said to be electrically **neutral**.
   - If a neutral atom (0 C) gains two electrons, it will have a final charge of $0\text{ C} + 2 \times (-1.60 \times 10^{-19}\text{ C}) = -3.20 \times 10^{-19}$ C. (A charged atom is also called an ion in Chemistry.)

Tip

The charge of an object always has whole number multiples of 1.60×10^{-19} C. Therefore, when you calculate electric charge, your answer must not be smaller than 1.60×10^{-19} C.

6. When you place two objects with charge near each other, they will experience a force *F* known as **electric force** (also known as electrostatic force).
   - The forces between two *similar charges* (both positive or both negative) are **repulsive** (they push each other).
   - The forces between two *dissimilar charges* (one positive and one negative) are **attractive** (they pull each other).

7. When you rub a balloon against your hair, the balloon becomes capable of attracting your hair.

   - When the balloon is *rubbed* against hair, *electrons are transferred* between the balloon and the hair. Protons do not move and stay in the atoms.
   - The balloon and the hair *become charged with opposite charges and attract each other.*

Common Error

✗ If we look at protons using a powerful microscope, we can see small spheres with '+' symbols.

✓ The '+' and '–' symbols are imaginary symbols to represent the types of charge.

Explanation
A positive charge is not larger than a negative charge even though a positive number is larger than a negative number.

8. A common useful application of electrostatic charging is the **electrostatic precipitator**.
   - The electrostatic precipitator removes smoke and dust particles from the air.
   - It is often used in factories that burn fuels to clean the polluted smoky air due to the burning.
   - It cleans the air to reduce air pollution.

   The diagram describes how the electrostatic precipitator works.

   Firstly, the smoke and dust particles are negatively charged by the metal net as the polluted air passes through it.

   ↓

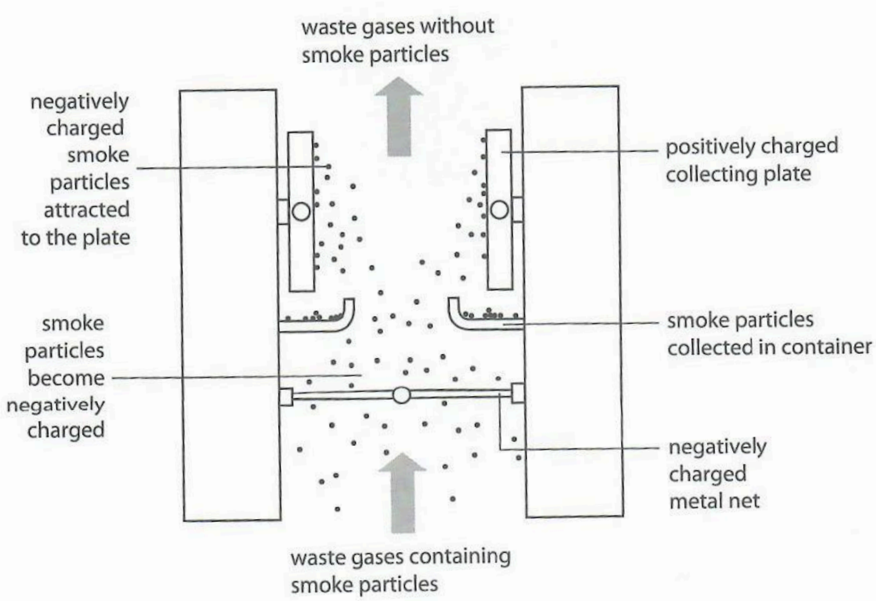
   Then, the negatively charged smoke and dust particles are attracted to the positively charged plates placed higher up in the precipitator.

   ↓

   The smoke and dust particles strike the positively charged plate and become neutralised and fall into a collecting container.

   ↓

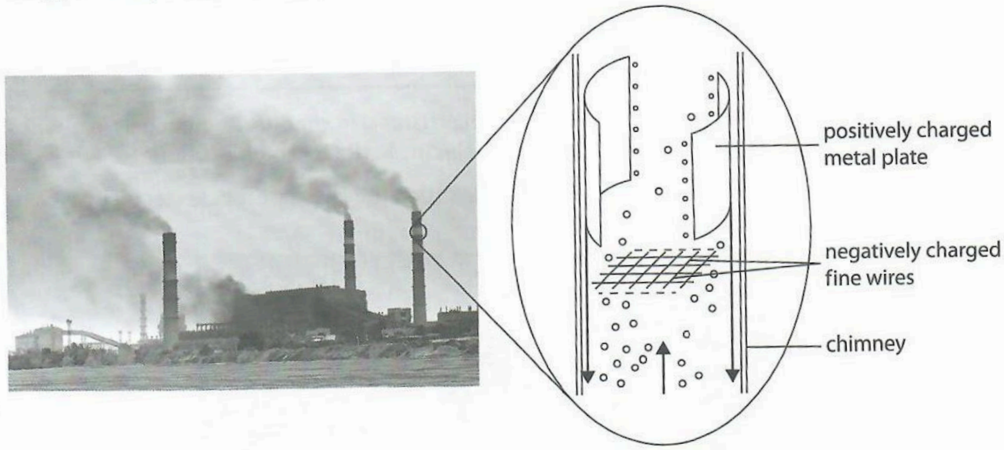
   The air, with fewer smoke and dust particles, has been cleaned and exits the precipitator.



An electrostatic precipitator

Worked Example 10.1

A factory uses an electrostatic precipitator to clean polluted air before releasing them through a tall chimney. The electrostatic precipitator removes smoke and dust particles in the polluted air using positively charged plates.



(a) Why must smoke and dust particles be negatively charged before passing through the precipitator?

(b) Why are electrostatic precipitators often used in power stations?

(c) Explain how a law to encourage power stations to install precipitators can improve the health of the population.

Solution

(a) Unlike charges attract, the particles can be attracted to the positively charged plates only if they are negatively charged. Since smoke and dust particles are electrically neutral, they must be negatively charged first.

(b) Many power stations generate electricity by burning fossil fuels. Electrostatic precipitators can clean the polluted air produced before releasing it into the environment. This helps to reduce air pollution.

(c) Less air pollution will lead to better health of the population.

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Checkpoint 10.1

1. If you increase the positive charge of the metal plates in the electrostatic precipitator, does its ability to clean the air increase or decrease?

Tip

Questions regarding using electric force to clean air have appeared in examinations, e.g., GCE 'O' Level Science Physics Oct/Nov 2020, Paper 2, Q8.

B Electric Current

Learning Outcomes

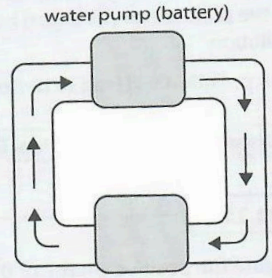
- State that electric current is defined as the rate of flow of charge and its SI unit is ampere (A).
- Recognise that the direction of electron flow is opposite of conventional current.
- Recall and apply the relationship *charge* = *current* × *time* to real-world situations and solve related problems.

1. In electricity, we use the flow of electrons (electric charges) in conducting materials (e.g. wires) to run our electrical and electronic devices (e.g. electric kettle and mobile phone).
2. When you switch on your mobile phone, you are letting the battery provide electricity which enables the phone to function.

- The battery provides energy to electrons and drives the electrons to flow through the phone components (e.g. phone screen and speakers).
- The electrons do work while flowing through the components. The energy of the electrons is transferred out (e.g. by propagation of light waves and sound waves).

Tip

An analogy commonly used to understand electron flow is water flow.
The battery 'pumps' the electrons to move through the electrical component.



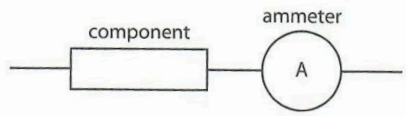
3. Electric current is a measure of how fast electrons move.
4. **Electric current** is defined as the **rate of flow of electric charge**.
   - For constant flow, the current I is the amount of charge Q passing through a point during a time period t.

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

5. We can use an **ammeter** to measure current.

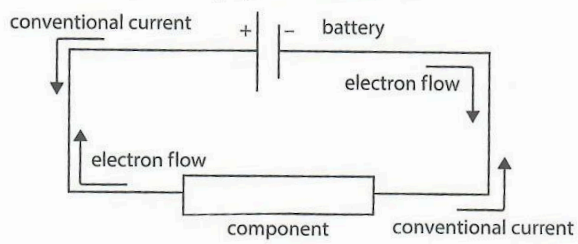
Example of an ammeter and a multimeter with ammeter function

- An ammeter is connected to other electrical components *in series*.



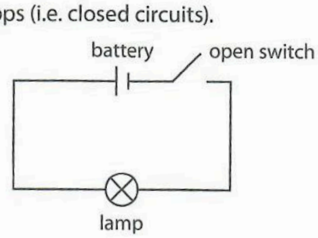
- The ammeter measures the current flowing through itself, which is also the current flowing through the component (rate of flow of electrons is the same in both when connected in series).

6. Current is a concept that was created before the discovery of electrons. By convention (and tradition), the *direction of flow of current* (which is a Physics concept) is the *opposite of the direction of flow of electrons* (which is the actual physical movement).



Conventional current flows from the positive (+) pole to the negative (–) pole of battery

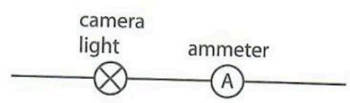
7. Current can only flow in closed loops (i.e. closed circuits).



A lamp in an open circuit does not light up.

Worked Example 10.2

An engineer uses an ammeter to check the current flowing through the flashlight of a phone camera. The reading on the ammeter is 1.2 A.



(a) When the phone camera takes a photo, the camera light flashes for 0.15 s. Calculate the amount of electric charge passing through the camera light during this time period.

(b) Given that the charge of an electron is 1.6×10^{-19} C, calculate the number of electrons passing through the camera light in 0.15 s.

Strategy

(b) Recall that the electric current consists of the flow of electrons.

Solution

(a) $I = \frac{Q}{t}$

$Q = It$

$= 1.2\text{ A} \times 0.15\text{ s}$

$= 0.18\text{ C}$

(b) In 0.15 s, the electric charge passing through the camera light = 0.18 C

Electric charge of one electron = 1.6×10^{-19} C

Therefore, in 0.15 s, the number of electrons passing through the camera light = $\frac{0.18\text{ C}}{1.6 \times 10^{-19}\text{ C}}$
$= 1.1 \times 10^{18}$

Explanation

We normally deal with the flow of very large numbers of electrons in situations involving current of electricity.

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Checkpoint 10.2

1. A fully charged drone can fly for 30 minutes using a battery supplying a constant current of 1.2 A. How much charge flows in the circuit during its flight?

Tip

Questions testing calculations involving current have often appeared in examinations, e.g., O GCE 'O' Level Science Physics Oct/Nov 2021, Paper 2, Q7.

C Electromotive Force and Potential Difference

Learning Outcomes

- State that electromotive force (e.m.f.) of an electrical source of energy is measured in volt (V).
- State that potential difference (p.d.) between two points in a circuit is the work done per unit charge in driving charges between the two points and its unit is volt (V).

1. We use batteries to provide electric current in many devices.
2. There are many types of batteries of different shapes and sizes.
   (a) The AA and AAA batteries are commonly used in small devices such as remote controls and alarm clocks.

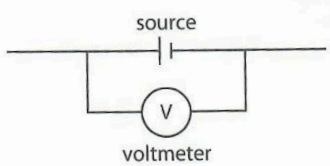
   (b) The lithium-ion batteries are often used in mobile phones.

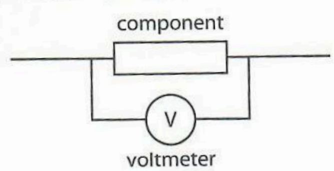
   (c) Car batteries are large and heavy. In older conventional cars, they are used to start the engines in cars that run on petrol. In newer electric cars, they supply electricity to run the car engines directly.

3. The ability of batteries to provide current is described by a quantity called electromotive force.

4. Electromotive force is a measure of energy transferred to each electron while potential difference is a measure of energy transferred from each electron. The table summarises e.m.f. and p.d.

<table>
<tr><th>Electromotive Force (e.m.f.)</th><th>Potential Difference (p.d.)</th></tr>
<tr><td>Electromotive force (e.m.f.) of a source tells us how much energy the source supplies to 1 C of charge in driving them around a complete circuit.
$E = \frac{W}{Q}$</td><td>Potential difference (p.d.) between two points in a circuit is the work done W per unit charge Q in driving the charges between the two points.
$V = \frac{W}{Q}$</td></tr>
<tr><td colspan="2">Both have unit of volt (V) or joule per coulomb (J/C).</td></tr>
<tr><td colspan="2">Both are measured by a voltmeter.

Example of a voltmeter and a multimeter with voltmeter function
(a) A voltmeter is connected to other electrical components in parallel.




(b) The voltmeter measures the difference in potential between its two ends. This reading is either the e.m.f. of a source or the p.d. across components.</td></tr>
</table>

Common Error

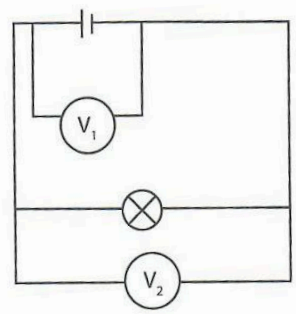
✗ The newton is also a unit of e.m.f.

✓ The newton is not a unit of e.m.f.

Explanation
Despite its name, e.m.f. is not a type of force.

Worked Example 10.3

A portable lamp requires two batteries to function. Put together, the batteries provide an e.m.f. of 3.0 V. The circuit diagram is a simple representation of the electrical connection in the lamp.



(a) State the values shown by V_1 and V_2.

(b) The batteries stop functioning after moving a total of 48 C of charge through the lamp. How much work has been done by the electrons?

Solution

(a) V_1 measures the e.m.f. of the batteries. Thus, V_1 measures 3.0 V. V_2 measures the p.d. across the lamp which is also equal to the e.m.f. of the batteries. Thus, V_2 also measures 3.0 V.

(b) $V = \frac{W}{Q}$

$W = VQ$

$= 3.0 \text{ V} \times 48 \text{ C}$

$= 144 \text{ J}$

Explanation

(b) Note that this is also the amount of energy transferred from the electrons when they move through the lamp, i.e. energy transferred by light wave propagation (light from lamp) and conduction (temperature increase in the lamp).

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Checkpoint 10.3

1. Is there a difference between work done per unit charge and work done per electron in driving the electrons between two points? Which one refers to p.d.?

D Resistance

Learning Outcomes

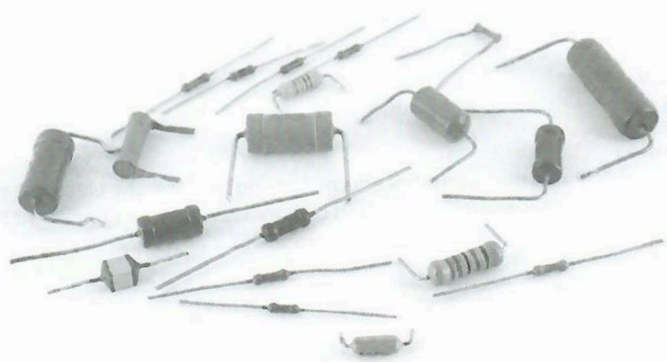
- State that *resistance = p.d. / current*.
- Apply $R = V / I$ to real-world situations and solve related problems.
- Recall and apply the proportionality between resistance and the length and cross-sectional area of a wire $R = \frac{\rho l}{A}$ to real-world situations and solve related problems.

1. Resistance of an electrical component is a measure of how difficult it is for the electrons to flow through the component (recall similar concept of air resistance).
   - **Resistance** R of a component is defined as the *ratio of the potential difference V across it and the current I flowing through it.*

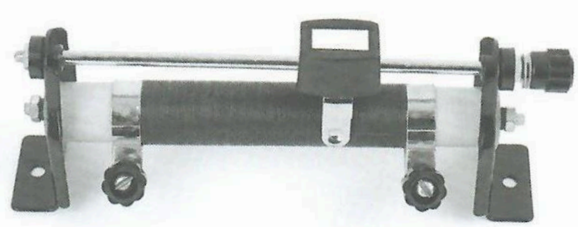
$$R = \frac{V}{I}$$

   - Its SI unit is **ohm (Ω)**.

2. A resistor is a special electrical component that has a known value of resistance.
   - A **fixed resistor** has a *constant* (fixed) value of resistance.
   - A **variable resistor** (or **rheostat**) has resistance that can be changed.



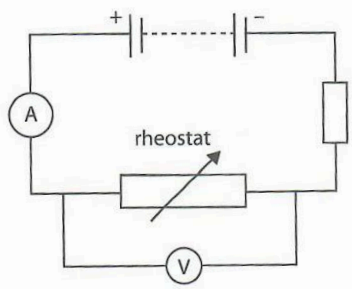
Some common fixed resistors.



A rheostat is a type of variable resistor.

Worked Example 10.4

A phone speaker can be simply represented by a rheostat in an electrical circuit. When the resistance of the rheostat is changed, the loudness of the speaker changes. The battery provides an e.m.f. of 3.8 V.



(a) Calculate the resistance of the rheostat when the ammeter reads 500 mA.

(b) How does current change when the resistance of the rheostat is decreased?

Solution

(a) $R = \frac{V}{I}$

$= \frac{3.8\ V}{0.5\ A}$

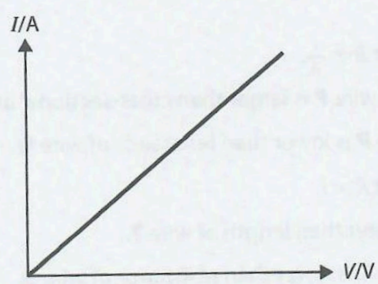
$= 7.6\ \Omega$

(b) $I = \frac{V}{R}$ with V equal to e.m.f. of the battery which does not change. So, as resistance R decreases, current I increases.

Tip

Unlike rheostats (variable resistor), fixed resistors have constant resistances.

The corresponding current I against p.d. V graph is a **linear graph**, with a straight line passing through the origin.



I–V graph for ohmic conductors

3. The resistance of an object is determined by its physical properties. The resistance R of an object is directly proportional to its length l and inversely proportional to its cross-sectional area A.

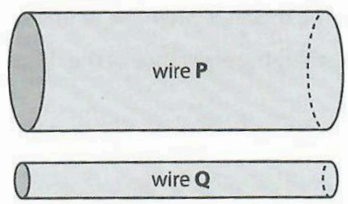
$$R \propto \frac{l}{A} \quad \text{or} \quad R = \frac{\rho l}{A}$$

- The constant of proportionality ρ is also known as the **resistivity**. Its SI unit is **Ω m** as derived from the equation.
- Resistivity is a measure of how difficult it is for the electron to flow through a material that makes up the object. It does not change according to the object's shape (similar to density).

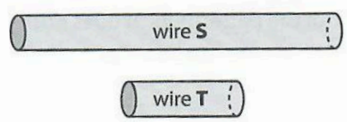
Worked Example

Wires **P**, **Q**, **S** and **T** are made of the same material.

(a) Wires **P** and **Q** are of the same length. Which one has a lower resistance?



(b) Wires **S** and **T** have the same cross-sectional area. Which one has a lower resistance?



Strategy

All wires are of the same material, so they have the same resistivity ρ.

Solution

(a) From $R = \frac{\rho l}{A}$, we can get $R \propto \frac{1}{A}$.

Cross-sectional area of wire **P** is larger than cross-sectional area of wire **Q**.

Thus, resistance of wire **P** is lower than resistance of wire **Q**.

(b) From $R = \frac{\rho l}{A}$, we can get $R \propto l$.

Length of wire **S** is greater than length of wire **T**.

Thus, resistance of wire **T** is lower than resistance of wire **S**.

Worked Example 10.5

Derive the unit of resistivity.

Solution

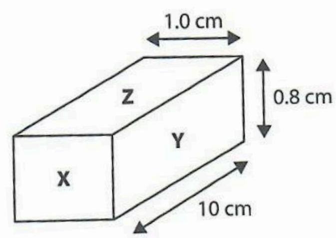
Using $R = \frac{\rho l}{A}$, we get $\rho = \frac{RA}{l}$

So, unit of $\rho = \frac{\Omega\,\text{m}^2}{\text{m}} = \Omega\,\text{m}$

Worked Example 10.6

Different materials have different values of resistivity.

A quality checker passes a current through a block of material through surface **X**. The resistivity of silver is known to be $1.6 \times 10^{-8}\ \Omega$ m. Calculate the resistance of the block if it is made up of pure silver.



Strategy

Recall $R \propto \frac{l}{A}$.

Note that the direction of current determines the values of length l and cross-sectional area A.

Solution

(a) Cross-sectional area $A = 0.8\text{ cm} \times 1.0\text{ cm}$

$= (8.0 \times 10^{-3})\text{ m} \times (1.0 \times 10^{-2})\text{ m}$

$= 8.0 \times 10^{-5}\text{ m}^2$

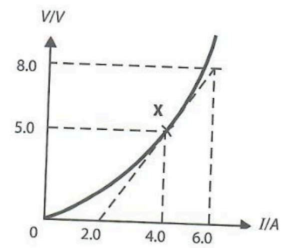
$R = \frac{\rho l}{A}$

$= \frac{(1.6 \times 10^{-8}\ \Omega\text{ m}) \times (0.1\text{ m})}{8.0 \times 10^{-5}\text{ m}^2}$

$= 2.0 \times 10^{-5}\ \Omega$

Common Error

The diagram shows a V–I graph.



✗ Resistance R at point **X** = gradient of tangent at **X**

$$= \frac{V}{I}$$
$$= \frac{(8.0 - 0)\ \text{V}}{(6.0 - 2.0)\ \text{A}}$$
$$= 2.0\ \Omega$$

✓ Resistance R at point X = ratio of V to I

$$= \frac{V}{I}$$
$$= \frac{5.0\ \text{V}}{4.0\ \text{A}}$$
$$= 1.25\ \Omega$$

Explanation

Resistance is simply the ratio of V to I, and not the gradient of V–I graph.

Tip

Summary notes for this chapter:

- Current electricity is actually electrons flowing.
- Protons and electrons have opposite charges and they attract each other.
- Current $I = \frac{Q}{t}$. Its unit is ampere (A).
- *p.d.* $= \frac{V}{Q}$. Its unit is volt (V).
- Resistance, $R = \frac{V}{I}$. Its unit is ohm (Ω).
- Resistance, $R = \frac{\rho l}{A}$, where ρ is resistivity. The unit of resistivity is Ω m.

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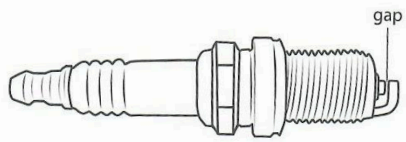
Checkpoint 10.4

1. The resistance of Wire **A** is 10 Ω. Wire **B** is made of the same material as Wire **A** but its length is triple and its diameter is double of Wire **A**. What is the resistance of Wire **B**?

Tip

Questions testing calculations involving resistivity have often appeared in examinations, e.g., GCE 'O' Level Science Physics Oct/Nov 2020, Paper 1, Q18.

4. A spark plug is a device in the chamber of a car engine. When a sufficient amount of electric charge builds up in the device, a sudden discharge occurs across the gap and creates a spark. Before the discharge occurs, a petrol-air mixture flows into the chamber.



When connected to a battery, the potential difference across the gap is 20 000 V. The spark carries a current of 40 A and has a duration of 1 ms.

(a) Calculate the resistance of the air-petrol mixture in the gap. [2]

(b) Calculate the amount of charge carried by the spark. [2]

(c) Calculate the work done to bring the charge across the gap. [2]

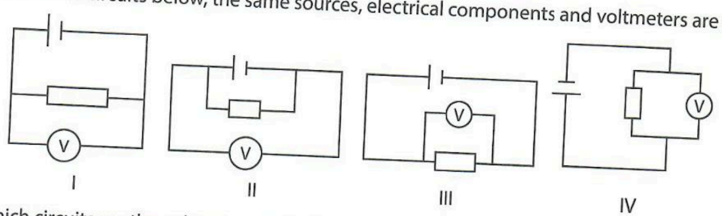
5. The manufacturer of a particular model of electric car claims that a fully charged car battery contains 1.08 MC of charge.

(a) While moving, the electric car engine uses an average current of 100 A. Calculate the time it takes to exhaust the battery in hours. [2]

(b) Researchers have been spending effort to increase the amount of charge that can be supplied by a fully charged battery. Explain why this effort will increase the likelihood that buyers will prefer to buy electric cars over petrol-consuming cars. [3]

Test Station

1. In each of the circuits below, the same sources, electrical components and voltmeters are used.



In which circuits are the voltmeter readings identical?

A I, II and III only

B I, II and IV only

C I, III and IV only

D All of them

2. A variable resistor is connected to an ammeter and a 2 V source in a circuit as shown in Figure 13.1. The resistance of the variable resistor ranges from 100 Ω to 1000 Ω. What is the maximum current flowing through the resistor?

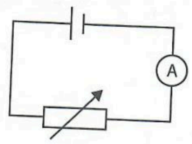


Figure 13.1

A 0.002 A

B 0.02 A

C 0.2 A

D 2 A

3. An electrician examines two pieces of wire made of different materials shown in Figure 13.2.

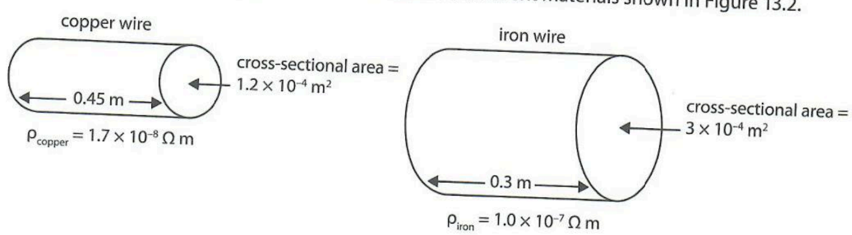


Figure 13.2

Which one has a smaller resistance?

[4]