Index

The big picture

? Guiding question(s)

- How do charged particles flow through materials?
- How are the electrical properties of materials quantified?
- What are the consequences of resistance in conductors?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

Electric eels can generate up to 600 volts to stun their prey (**Figure 1**). Would you get an electric shock as well if you were nearby? Can electric eels stun big creatures like sharks and whales?

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Figure 1. An electric eel.

Credit: Wangel, Getty Images

A typical AA cell (battery) is rated at 1.5 volts. An electric eel giving an electric shock of 600 volts means that it is acting as a giant battery – the equivalent of $\frac{600}{1.5} = 400$ AA batteries. This creates electric potential difference, which moves the charged particles in the water and through the body of the eel's prey. This interferes with the nervous system of the fish and paralyses it. **Figure 2** shows how an electric eel gives an electric shock to its prey.

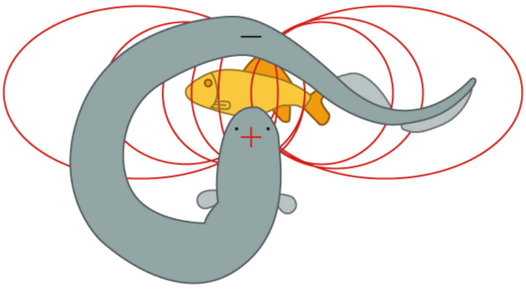

Figure 2. How an electric eel stuns its prey.

More information for figure 2

The diagram illustrates an electric eel in the center, depicted in gray, curving around a yellow fish. Red lines emanate from the eel, representing electric fields. These lines form loops that encircle the fish, symbolizing how the eel's electric discharge affects its prey. The eel's head has a plus and minus sign, indicating different electric charges, while the fish appears stunned, implying it is being paralyzed by the eel's electric current. The overall image demonstrates how an electric eel can generate and direct electricity towards its prey.

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Watch **Video 1** to see how electric eels can attack horses, crocodiles and even humans.

Video 1. Electric eels can attack large prey.

How can the same knowledge which aids our understanding of the electric eel enhance our lives, from charging our smartphones to harvesting energy for satellites in deep space?

Prior learning

Before you study this subtopic, make sure that you understand the following:

- Energy and power (subtopic A.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43083/)).
- Particle theory (subtopic B.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43777/)).
- Circuit symbols (pre-IB study).

Practical skills

Once you have completed this subtopic, apply you knowledge of circuits by going to Practical 7: Investigating the resistivity of a conducting wire (/study/app/math-aa-hl/sid-423-cid-762593/book/investigating-the-resistivity-of-a-conducting-wire-id-

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46511/) and Practical 8: Measuring the internal resistance of a cell (/study/app/math-aa-hl/sid-423-cid-762593/book/measuring-the-internal-resistance-of-a-cell-id-46512/).

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Conductors, electric potential difference and current

B.5.1: Cells as a source of emf B.5.2: Chemical cells and solar cells B.5.4: Direct current B.5.5: Electric potential difference B.5.6: Electrical conductors and insulators

Learning outcomes

At the end of this section you should be able to:

- Explain the properties of electrical conductors and insulators.
- Describe cells as the source of emf in a circuit.
- Describe electric potential difference as the work done per unit charge in moving a positive charge between two points along the path of the current, and electric current as a flow of charge.
- State the advantages and disadvantages of different sources of electrical energy.

Look at **Video 1**. It shows a high electric potential difference being applied between two ends of a piece of wood. Wood is an electrical insulator. This means that it does not conduct electricity well. Does the pattern remind you of anything?

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Video 1. Wood can conduct electricity when a high electric potential difference is applied.

The pattern is similar to that made by lightning (**Figure 1**). Air is an electrical insulator too. So how are these patterns created?

Figure 1. Lightning.

Electrical conductors and insulators

Student view

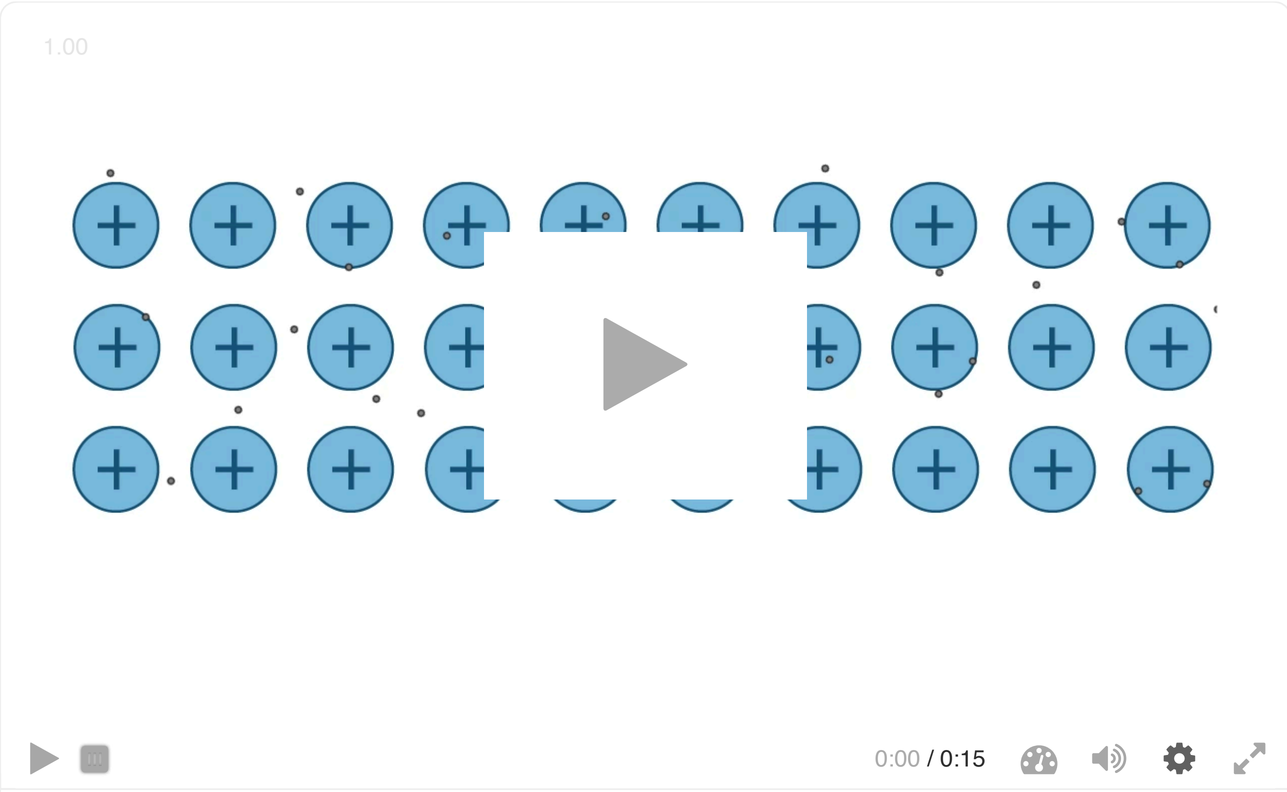
Conduction of electricity depends on the physical properties of the substance. The arrangement of the particles in the substance gives rise to specific properties.

Electricity is the movement (or flow) of mobile charge carriers through a material. Usually, the charge carrier (the charged particle that moves through a material) is the electron.

Materials with lots of mobile charge carriers conduct electricity better. They are known as electrical conductors. Metals are electrical conductors. Electrical circuits are usually made from metals to take advantage of the mobility of the electrons.

Electrical insulators are materials, such as wood, that have fewer mobile charge carriers, and therefore electricity does not flow through them easily.

Interactive 1 shows the movement of electrons in metal.



Interactive 1. Metal Is a Good Conductor.

More information for interactive 1

A simple animation video of moving electrons in a metal conductor. It includes a regular arrangement of positively charged ions, represented by blue circles with plus signs, forming a fixed lattice structure. Small black dots, representing free electrons, move randomly between the ions while generally drifting in a specific direction. The animation explains the concept of electrical conduction by illustrating how mobile charge carriers flow through a material. The video demonstrates how metals allow the movement of electrons due to their high number of free charge carriers.

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However, **Video 1** shows that wood and air can act as conductors when there is a high enough electric potential difference.

Cells and electromotive force

An AA battery is also known as a chemical cell. **Figure 2** shows the circuit symbol for a cell. The cell has a positive terminal and a negative terminal.

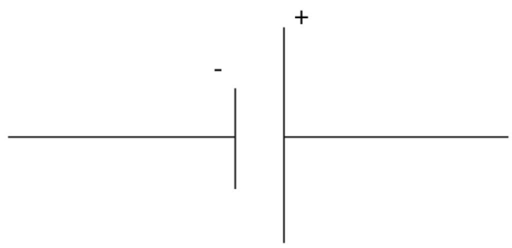

Figure 2. The circuit symbol for a cell.

More information for figure 2

The image depicts a standard circuit symbol used to represent a battery cell. There is a vertical line on the left side, which is shorter, indicating the negative terminal. Adjacent to it, a longer vertical line represents the positive terminal. These two lines are parallel and positioned horizontally in the center of the image, indicating the flow of current from the positive to the negative terminal in an electric circuit. Additionally, horizontal lines extend outward from both terminals, symbolizing the connection points in a circuit.

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A chemical cell is a source of energy for an electric circuit, in which chemical energy is converted to electrical energy. Another type of cell is a solar cell, which converts radiation energy to electrical energy.

Creativity, activity, service

Strand: Creativity
Learning outcome: Demonstrate engagement with issues of global significance

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It is becoming more common for vehicles to be powered by cells instead of liquid fuels.

Solar Impulse 2 travelled 25 000 miles around the world using the energy from 17 248 solar cells. Other vehicles, such as electric cars, are powered by chemical cells.

Design a poster to show the advantages and disadvantages of using solar cells compared to chemical cells to power vehicles.

Figure 3. Solar Impulse 2.

Source: "Solar_Impulse_SI2_pilote_Bertrand_Piccard_Payerne_November_2014 (https://commons.wikimedia.org/wiki/File:Solar_Impulse_SI2_pilote_Bertrand_Piccard_Payerne_November_2
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The amount of energy that a cell transfers to each unit of charge is known as the electromotive force (emf). It is measured in volts (V).

Concept

Electromotive force is defined as the work done per unit charge in moving charge across the terminals of a cell. It is the amount of energy that a source of energy, such as a cell, transfers to each unit of charge.

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Study skills

An electron has a negative charge, but in a macroscopic circuit, there are so many electrons that it would be difficult to count them. Instead, we use a unit of charge called the coulomb. One coulomb is the amount of charge on 6.25×10^{18} electrons.

Note that although electromotive force is called a force, it is not actually a force (subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)).

Nature of Science

Aspect: Theories

The term ‘force motrice électrique’ (electromotive force) was introduced by the Italian physicist Alessandro Volta in 1801. He is credited as being the inventor of the battery.

Why do you think the term force is still used in electromotive force?

Figure 4. Alessandro Volta’s battery.

Source: “VoltaBattery (https://en.wikipedia.org/wiki/File:VoltaBattery.JPG)” by GuidoB is licensed under CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0/deed.en)

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Electric potential difference

Electric potential difference, V, is defined as the work done per unit charge in moving a unit positive charge between two points. It can be calculated using the equation in **Table 1**.

Table 1. Equation for electric potential difference.

Equation	Symbols	Units
$V = \frac{W}{q}$	V = electric potential difference	volts (V)
	W = work done	joules (J)
	q = charge	coulombs (C)

Worked example 1

6.4 μJ of energy is used to transfer 12 nC of charge between two points on a circuit. Determine the electric potential difference that is required.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required by the equation.	$W = 6.4\ \mu\text{J}$ $= 6.4\times10^{-6}\ \text{J}$ $q = 12\ \text{nC}$ $= 12\times10^{-9}\ \text{C}$
Step 2: Write out the equation.	$V = \frac{W}{q}$
Step 3: Substitute the values given.	$= \frac{6.4\times10^{-6}}{12\times10^{-9}}$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 533.333\ \text{V} = 530\ \text{V}\ (2\ \text{s.f.}$

You may see electric potential difference being referred to as voltage.

Student view

International Mindedness

Mains voltage is the electric potential difference supplied by electricity companies via the power grid to customers. The electric potential difference of Japan's mains voltage is 100 V, the USA's is 120 V, while Spain's is 230 V. Why do countries' electrical supplies differ?

Current

Electric current is the rate of flow of charge. In other words, it is a measure of how much charge flows past a point per second. Current is measured in amperes (amps) (A).

Direct current (dc) flows in one direction only. It can be calculated using the equation in **Table 2.**

Table 2. Equation for direct current.

Equation	Symbols	Units
$I=\frac{\Delta q}{\Delta t}$	I = current	amperes (A)
	q = charge	coulombs (C)
	t = time	seconds (s)

Current can flow in an electric circuit only if the circuit is closed. Without a complete loop to flow around, the current is zero.

Study skills

Electric current is the rate of flow of charge. The phrase 'rate of' means how a certain quantity changes per unit time. Mathematically, it is:

$$\frac{\Delta q}{\Delta t}$$

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Worked example 2

18 C of electrons pass through a cell in 1 minute and gain 90 J of energy. Calculate the current flowing through the cell and the electric potential difference across the cell.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert to the values required by the question.	$q = 18\text{ C}$ $t = 1\text{ minute}$ $= 60\text{ s}$ $W = 90\text{ J}$
Step 2: Write out the equation for current.	$I = \frac{\Delta q}{\Delta t}$
Step 3: Substitute the values given.	$= \frac{18}{60}$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 0.30\text{ A (2 s.f.)}$
Step 5: Write out the equation for electric potential difference.	$V = \frac{W}{q}$
Step 6: Substitute the values given.	$= \frac{90}{18}$
Step 7: State the answer with appropriate units and the number of significant figures used in rounding.	$= 5.0\text{ V (2 s.f.)}$

Aspect: Hypotheses

In 1752, Benjamin Franklin made the assumption that the charge carriers are positive in a circuit. This led to electric current being defined as the rate of flow of *positive* charge. We now call this conventional current.

It was not until 1897 that J.J. Thomson discovered that the charge carriers in electric circuits are electrons.

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When we talk about current, we still refer to conventional current and say that current ‘flows’ from positive to negative. Why do we use conventional current even when we know it is often factually incorrect?

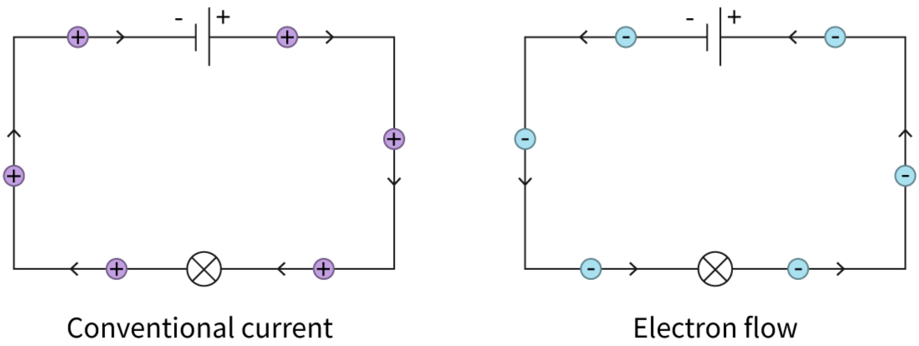

Figure 5. Conventional current and electron flow.

More information for figure 5

The image consists of two circuit diagrams. On the left, the circuit illustrates conventional current flow. It features a circuit path with a battery on the right side, indicating positive charges moving in a clockwise direction. This path loops through a light bulb represented by a circle with an "X" inside, located at the bottom of the diagram. The top side is connected to the positive terminal of the battery. Arrows are drawn in the clockwise direction, following the positive charge flow.

On the right, the second circuit diagram shows electron flow. Here, negative signs represent electrons moving in a counter-clockwise direction. Like the left diagram, this one includes a battery on the left side with its positive terminal connecting to the top of the path. The light bulb is positioned similarly at the bottom of the loop, and arrows are drawn counterclockwise, in the direction of electron movement.

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Carry out the activity to check your understanding of electric potential difference and current.

Activity

- **IB learner profile attribute:**
  - Inquirer
  - Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity**: 15 minutes
- **Activity type**: Pair activity

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Instructions

The interactive shows two electric circuits, with identical light bulbs. Discuss the following questions with a partner then click the 'Show or hide solution' buttons to see the answers:

- What does the 'height' that the charge carriers gain represent?

The 'height' represents the energy supplied to the charge carriers. A 3 V cell supplies twice as much energy to each energy carrier as a 1.5 V cell.

- Look at how fast the charge carriers are moving in each circuit. Why is the speed different?

The charge carriers in the 3 V circuit have more energy, so they are moving faster — the current is greater.

- Look at the brightness of the bulbs in each circuit. Why are they different?

The charge carriers transfer energy to the light bulb (shown by the drop in height). The charge carriers in the 3 V circuit have more energy, and there are more charge carriers per unit time, so the light bulb emits more energy and is brighter.

Interactive 2. A 3 V and 1.5 V Circuit.

More information for interactive 2

This interactive features two side-by-side videos displaying two electric circuits with identical light bulbs. The first circuit operates with a voltage of 3 Volt, while the second uses 1.5 Volt. The layout of the interactive includes controls to navigate between the two videos, allowing a comparison of the

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effects of different voltage levels on the circuit.

In the first video (3 Volt circuit), charge carriers are seen moving faster due to the higher voltage. The greater potential difference results in increased energy gain per charge carrier, which leads to a higher speed of movement.

The second video (1.5 Volt circuit) shows charge carriers moving slower, as the lower potential difference provides less energy per charge carrier, reducing their speed.

Additionally, the brightness of the light bulbs in both circuits differs. In the 3 Volt circuit, the bulb shines brighter because the higher voltage causes a higher current, which provides more energy to the bulb. In contrast, the 1.5 Volt circuit results in a dimmer bulb due to the lower current flow.

In conclusion, this interactive highlights the relationship between the electric potential difference (voltage), current, and the behavior of components like light bulbs in a circuit. The voltage difference directly affects the speed of charge carriers and the brightness of the bulbs, clearly illustrating how these elements are interrelated in an electrical circuit.

5 section questions

Question 1

SL HL Difficulty:

True or false?

Insulators cannot conduct electric current because they have no charge carriers.

False ✓

Accepted answers

False, F, false, f

Explanation

It is not true that insulators have no charge carriers. They have many billions of charge carriers, but they are unable to move through the material without a large amount of energy being applied. Conductors have mobile charge carriers that can flow through the material under the influence of an applied electric potential difference.

Question 2

SL HL Difficulty:

Electric potential difference is the 1 work ✓ done per unit 2 charge ✓ in moving a 3 positive ✓ charge between two points along the path of the current.

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Accepted answers and explanation

#1 work

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#2 charge

#3 positive

+

+ve

General explanation

This is the definition of electric potential difference.

Question 3

SL HL Difficulty:

The current through a light bulb is 0.4 A. Calculate the time it takes for 85 C of charge to pass through the light bulb. Give your answer to an appropriate number of significant figures.

The time taken is 1 200 ✓ s.

Accepted answers and explanation

#1 200

General explanation

$$I = 0.4 \text{ A}$$

$$q = 85 \text{ C}$$

$$I = \frac{\Delta q}{\Delta t}$$

$$\begin{aligned}\Delta t &= \frac{\Delta q}{I} \\ &= \frac{85}{0.4} \\ &= 212.5 \text{ s} \\ &= 200 \text{ s (1 s.f.)}\end{aligned}$$

Question 4

SL HL Difficulty:

A 3 V cell transfers 15 J of energy in 2.0 s. Calculate the current leaving the cell.

1 2.5 A ✓

2 2.0 A

3 1.0 A

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4 5.0 A

Explanation

$V = 3.0 \text{ V}$

$W = 15 \text{ J}$

$t = 2.0 \text{ s}$

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

$$\begin{aligned} q &= \frac{W}{V} \\ &= \frac{15}{3.0} \\ &= 5.0 \text{ C} \end{aligned}$$

$$\begin{aligned} I &= \frac{\Delta q}{\Delta t} \\ &= \frac{5.0}{2.0} \\ &= 2.5 \text{ A (2 s.f.)} \end{aligned}$$

Question 5

SL HL Difficulty:

Circuit A has a cell with twice the emf of circuit B. If the amount of charge passing through circuit A per second is twice that of circuit B, what is the ratio, for a given time, of:

$$\frac{\text{work done by circuit A}}{\text{work done by circuit B}}$$

1 4 ✓

2 2

3 1

4 $\frac{1}{4}$

Explanation

$$\begin{aligned} \text{emf} &= V \\ &= \frac{W}{q} \end{aligned}$$

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$$I = \frac{\Delta q}{\Delta t}$$

$$V_A = 2V_B$$

$$\frac{W_A}{q_A} = \frac{2W_B}{q_B}$$

$$\frac{W_A}{W_B} = \frac{2q_A}{q_B}$$

$$I_A = 2I_B \qquad q_A = 2q_B$$

$$\frac{W_A}{W_B} = \frac{2 \times 2q_B}{q_B} \qquad \frac{W_A}{W_B} = 4$$

B. The particulate nature of matter / B.5 Current and circuits

Resistance, resistivity and Ohm's law

B.5.7: Electric resistance B.5.8: Resistance, potential difference and current B.5.9: Resistivity B.5.10: Ohm's law B.5.11: Ohmic and non-ohmic behaviour B.5.15: Variable resistance

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/resistance-resistivity-and-ohms-law-id-44363/print/) Assign

Learning outcomes

At the end of this section you should be able to:

- Define resistance as $R = \frac{V}{I}$ and define resistivity as $\rho = \frac{RA}{L}$.
- Understand Ohm's law and identify the ohmic and non-ohmic behaviour of electrical conductors.
- Understand that resistors can have variable resistance.

How do security lamps (**Figure 1**) detect movement and know when to turn on? How does your heating or air conditioning system know when your home is the right temperature? How does your fridge make things cold, but not frozen?

The answer to all of these things lies in resistance, and how we can use resistance to control devices.

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Figure 1. How do security lamps detect movement?

Credit: Nickbeer, Getty Images

Resistance

Electrical resistance is a measure of the opposition to the flow of current through a component. The unit of resistance is the **ohm** (Ω), which is named after the 19th century German physicist Georg Simon Ohm.

Resistance is defined as the potential difference across a component per unit current passing through it. It can be calculated using the following equation in **Table 1**.

Table 1. Equation for Ohm's law.

Equation	Symbols	Units
$R = \frac{V}{I}$	R = resistance	ohms (Ω)
	V = electric potential difference	volts (V)
	I = current	amperes (A)

Interactive 1 shows two circuits. Look at the rate of current flowing for each light bulb. Why are they different? How do you think this will affect the brightness of each bulb? Click on 'Show or hide solution' for the answer.

Student view

Interactive 1. Two Circuits with Different Light Bulbs.

More information for interactive 1

The interactive consists of two video panels placed side by side, each with its own playback controls at the bottom — including a play/pause button, progress bar, timestamp, fullscreen toggle, and an option to adjust playback speed accessible via the vertical three-dot menu. Users can play each video independently to compare current flow under different resistance conditions.

Both videos depict a simple series of electric circuits powered by a 3V source. In the first video, the circuit includes a resistor $R1 = 1.0\Omega$, while the second features a higher resistor $R2 = 2.0\Omega$. Purple '+' icons represent positive charge carriers and move clockwise, indicating the direction of conventional current.

The difference in resistance affects the speed of these charge carriers. In the first video, the lower resistance allows for faster movement of '+' icons, indicating a higher current. In contrast, the higher resistance in the second circuit slows the movement of the icons, reflecting reduced current flow.

The 2.0 Ω light bulb has a greater resistance than the 1.0 Ω light bulb. Each light bulb has an electric potential difference of 3.0 V across it. Electric potential difference is the energy per unit charge. A higher resistance means that charge flows more slowly around the circuit (you can see this by looking at the speed of the charge carriers in the animations above), so with a fixed potential difference and a lower charge flow, there must be less energy supplied to the 2.0 Ω bulb, so it is dimmer.

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Worked example 1

Look at the two circuits in **Interactive 1.** Calculate the current through the 1.0 Ω light bulb and the 2.0 Ω light bulb.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert to the values required by the question.	$V = 3.0\ \text{V}$ $R_1 = 1.0\ \Omega$ $R_2 = 2.0\ \Omega$
Step 2: Write out the equation and rearrange to make I the subject.	$R = \frac{V}{I}$ $I = \frac{V}{R}$
Step 3: Substitute the values given.	$I_1 = \frac{3.0}{1.0}$ $I_2 = \frac{3.0}{2.0}$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding	$I_1 = 3.0\ \text{A}\ (2\ \text{s}$ $I_2 = 1.5\ \text{A}\ (2\ \text{s}$

For a particular electric potential difference, if the resistance of a component increases, the current flowing through it decreases.

Resistivity

Resistivity is an intrinsic property of a material. Different materials have different resistivities. The resistance of an electrical component (such as a wire) depends on its resistivity, length and cross-sectional area.

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Resistivity can be calculated using the following equation:

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Table 2. Equation for resistivity.

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Equation	Symbols	Units
$\rho = \frac{RA}{L}$	ρ = resistivity	ohm metres (Ω m)
	R = resistance	ohms (Ω)
	A = cross-sectional area	metres squared (m^2)
	L = length	metres (m)

Figure 2 shows how the resistance of a wire depends on the length and width of the wire.

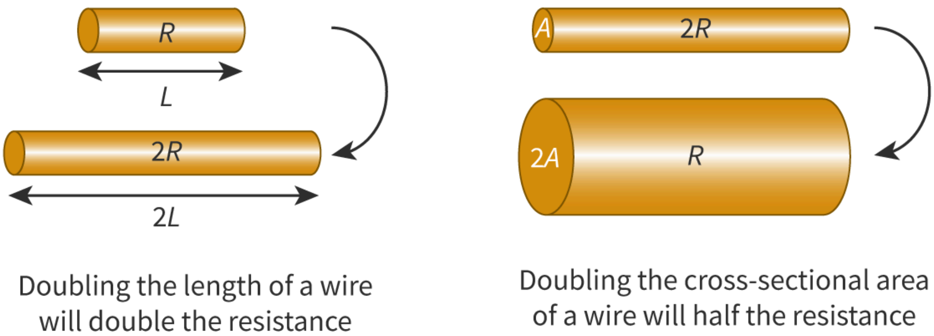

Figure 2. Resistance varies with dimensions of wire.

More information for figure 2

The diagram illustrates the relationship between the resistance of a wire and its dimensions. On the left side, it shows a wire with length 'L' and resistance 'R'. An arrow below it indicates that doubling the length to '2L' results in doubling the resistance to '2R'. Underneath, text reads: "Doubling the length of a wire will double the resistance."

On the right side, another wire is depicted with cross-sectional area 'A' and resistance 'R'. An arrow above indicates that doubling the cross-sectional area to '2A' halves the resistance, now 'R' is shown as '2R' for comparison. Text underneath states: "Doubling the cross-sectional area of a wire will half the resistance."

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Use **Interactive 2** to check your understanding of the factors affecting resistance.

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Interactive 2. Factors That Affect Resistance.

A long wire with a small cross-sectional area has higher resistance than a short wire with a large cross-sectional area. Resistance is a measure of how much a material prevents the charge carriers from flowing.

It might help you to understand this concept if you use a simplified visualisation of what is happening in a wire when it is conducting electricity. Electrical conductors, such as wires, consist of a lattice of positive ions surrounded by negative electrons (section B.5.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/conductors-electric-potential-difference-and-id-44362/)). Electrons colliding with the lattice lose energy. Resistance is representative of this energy loss. The longer the wire, the more ions the electrons must travel past, and so more collisions happen. The thinner the wire, the less ‘space’ the electrons have to get past the ions, so more collisions happen.

Worked example 2

A copper wire, with a resistivity of $1.68 \times 10^{-8}\ \Omega\ \text{m}$, has a total length of 1.5 m and a radius of 3.0 mm. Determine its resistance.

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Solution steps	Calculations
Step 1: Write out the values given in the question and convert to the values required by the question.	$\rho = 1.68 \times 10^{-8}\ \Omega\ \text{m}$ $L = 1.5\ \text{m}$ $\text{radius} = 3.0\ \text{mm} = 3.0 \times 10^{-3}\ \text{m}$
Step 2: Calculate the cross-sectional area.	$A = \pi r^2 = \pi \times (3.0 \times 10^{-3})^2 = 2.83 \times 10^{-5}\ \text{m}^2$
Step 3: Write out the equation and rearrange to make R the subject.	$\rho = \frac{RA}{L}$ $R = \frac{\rho L}{A}$
Step 4: Substitute the values given.	$= \frac{(1.68 \times 10^{-8} \times 1.5)}{2.83 \times 10^{-5}}$
Step 5: State the answer with appropriate units and the number of significant figures used in rounding.	$= 8.9 \times 10^{-4}\ \Omega\ (2\ \text{s.f.})$

Ohm’s law and ohmic and non-ohmic conductors

Ohm's law relates electric potential difference to current and resistance:

$$V = IR$$

It states that the electric potential difference across a conductor is directly proportional to the current flowing through it, at constant temperature.

- Electrical conductors that obey Ohm’s law are called ohmic conductors.
- Electrical conductors that do not obey Ohm’s law are called non-ohmic conductors.

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view

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Making connections

Ohm's law is an example of a linear relationship. Another example of a linear relationship is the spring constant (subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)), which describes the ratio between tension force and extension.

Why are linear relationships useful in science? What are the advantages of a linear relationship between variables instead of a non-linear relationship?

We can use an electric potential difference versus current (V–I) graph to see whether an electrical conductor is ohmic or non-ohmic.

- A V–I graph for an ohmic conductor shows a straight line through the origin.
- A V–I graph for a non-ohmic conductor does not show a straight line.

Figure 3 shows the V–I graphs for an ohmic conductor and a non-ohmic conductor.

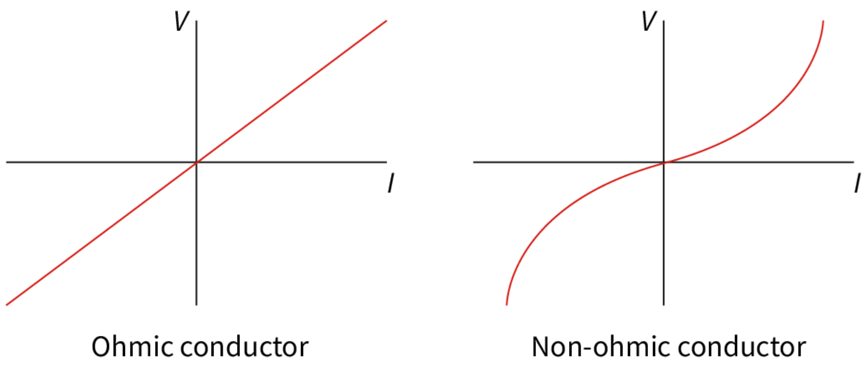

Figure 3. V—I graphs for an ohmic conductor and a non-ohmic conductor.

More information for figure 3

The image displays two graphs, each plotting voltage (V) against current (I). The graph on the left represents an ohmic conductor, characterized by a straight line indicating a linear relationship between voltage and current. The line passes through the origin, demonstrating constant resistance as described by Ohm's law. The graph on the right shows a non-ohmic conductor with a curved line, suggesting a non-linear relationship between voltage and current. This curve indicates that resistance varies as voltage and current change. Both graphs have labeled axes with voltage on the vertical axis and current on the horizontal axis. The scale of the axes is not specified but is uniform in increments.

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The resistance at a particular potential difference can be found by calculating $\frac{V}{I}$ using values from the graph.

- For an ohmic conductor, the resistance is constant.
- For a non-ohmic conductor, the resistance changes.

Figure 4 shows a V–I graph for two resistors, R_1 and R_2. State which resistor is ohmic and which resistor is non-ohmic, and determine the resistance at which R_2 has the same electric potential difference as R_1.

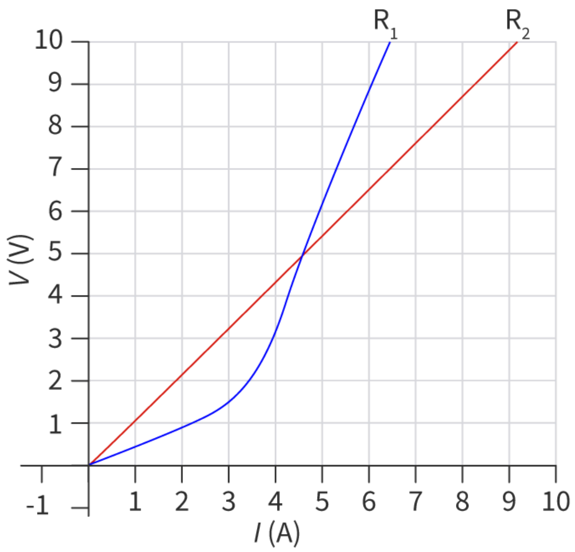

Figure 4. V—I graph for two resistors, R_1 and R_2.

More information for figure 4

The image displays a voltage-current (V-I) graph for two resistors, R1 and R2. The X-axis represents current (I) in amperes ranging from -1 to 10 A, and the Y-axis represents voltage (V) ranging from -1 to 10 V. There are two distinct curves: a red straight line for resistor R2 and a blue curve for resistor R1. The red line of R2 indicates that it is linear, suggesting it behaves as an ohmic resistor with a constant slope. In contrast, the blue curve for R1 deviates from linearity, indicating it is a non-ohmic resistor. The lines intersect, and to find the resistance at which R2 has the same electric potential difference as R1, one should look for the point of intersection.

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Student view

An ohmic conductor gives a straight line while a non-ohmic conductor gives a curve.

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R_2 is ohmic and R_1 is non-ohmic.

The two graphs cross at a potential difference of 5 V. Each resistor has 4.5 A passing through it. Hence, the resistance of each resistor is:

$$\frac{V}{I} = \frac{5}{4.5}$$
$$= 1.1\ \Omega\ (2.\text{s.f.})$$

Study skills

You cannot determine the resistance from the instantaneous gradient of a V–I graph (section A.1.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/describing-motion-id-44298/)). The resistance is defined as $R = \frac{V}{I}$, not $R = \frac{\Delta V}{\Delta I}$.

The correct approach is to read the quantities from the axes and calculate $\frac{V}{I}$.

Resistance and temperature

Wires in circuits contain both positive ions arranged in a fixed lattice and free electrons. The free electrons flow through the lattice, forming an electric current. This structure allows current to flow and electrical energy to be transferred (**Figure 5**).

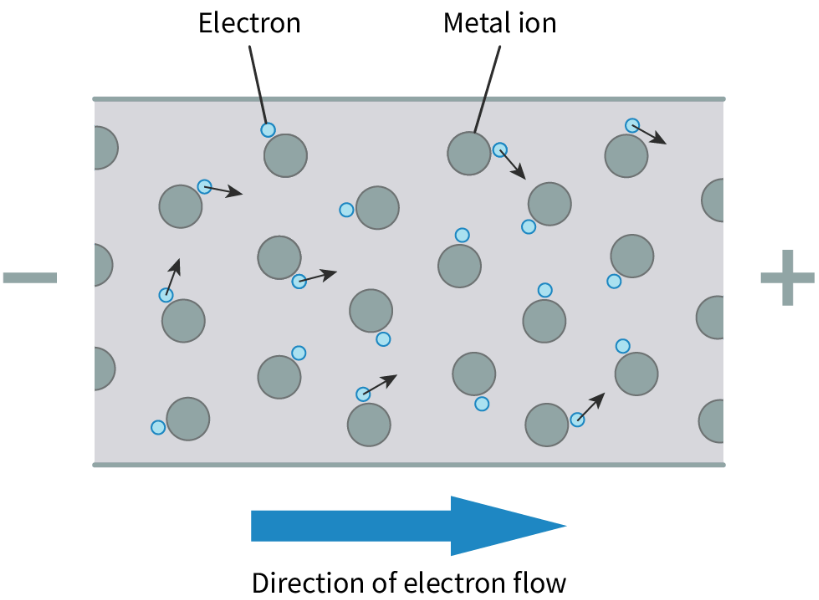

Figure 5. Metal ions form the structure of a wire, whilst electrons are free to move. The net direction of the electrons is towards the more positive terminal, and that flow of charge is the current.

Student view

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Think about the following questions before reading further into this section:

- What is happening to the ions and electrons in the wire?
- What interaction happens between the electrons and the ions?
- What effect does this have?
- How does the temperature of the wire affect these interactions?

As current flows through an electrical conductor, such as a wire, some of the electrons collide with the lattice of metal ions. Some of the kinetic energy of the electrons is transferred to the ions as thermal energy via inelastic collisions (subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)). This raises the temperature of the wire.

As the temperature increases, the ions in the lattice vibrate faster, increasing the chance of collisions between the electrons and the lattice. This impedes the flow of the electrons, which means the resistance increases.

If the resistance of an electrical conductor changes with temperature, then it is a non-ohmic conductor. A filament light bulb is an example of a non-ohmic conductor. It consists of a wire enclosed in a partial vacuum by glass.

As current flows through the wire, it heats up. The heat cannot be effectively conducted away and it increases the temperature of the filament, making the resistance higher. The increase in temperature of the wire causes it to glow, emitting light (**Figure 6**).

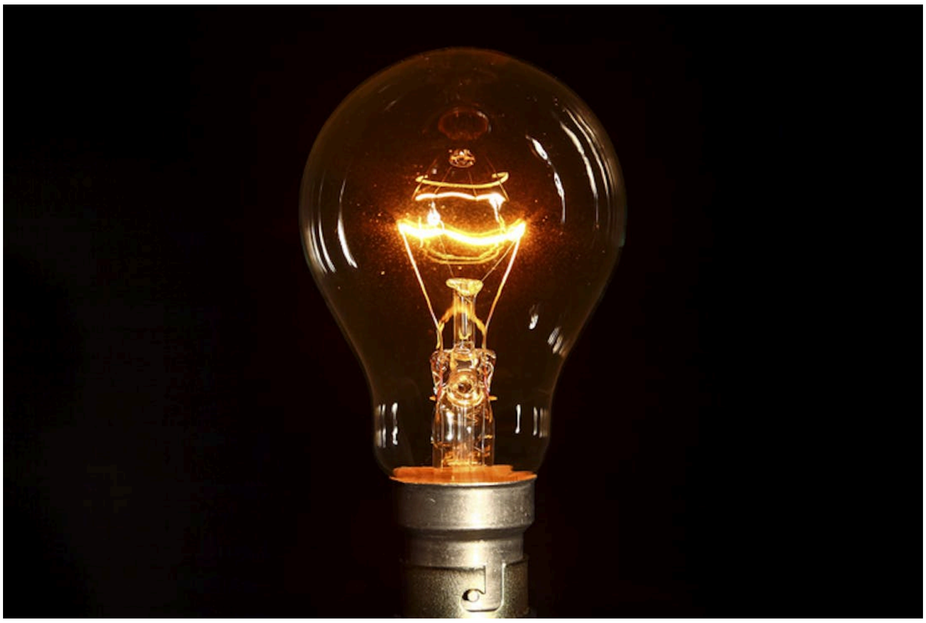

Figure 6. A filament light bulb.

Credit: Andrew Gardner / EyeEm, Getty Images

Student view

Figure 7 shows a V–I graph for a filament light bulb.

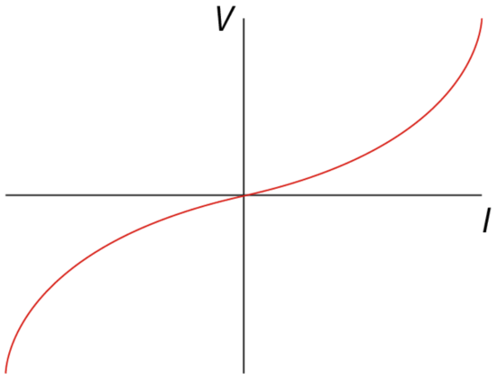

Figure 7. A V—I graph for a filament light bulb.

More information for figure 7

The graph depicts the relationship between voltage (V) and current (I) for a filament light bulb. The X-axis represents current (I) and the Y-axis represents voltage (V). The red curve illustrates a nonlinear increase in voltage with respect to current. Initially, as the current increases, the voltage rises slowly and then accelerates, showing a curvature typical of a filament bulb's resistance increasing as it heats up. This behavior is different from an ideal resistor, which would show a linear V-I relationship.

[Generated by AI]

Resistors with variable resistance

A **thermistor** is a type of resistor. When the temperature of the thermistor increases, its resistance decreases. When the temperature decreases, its resistance increases, as shown in **Figure 8**.

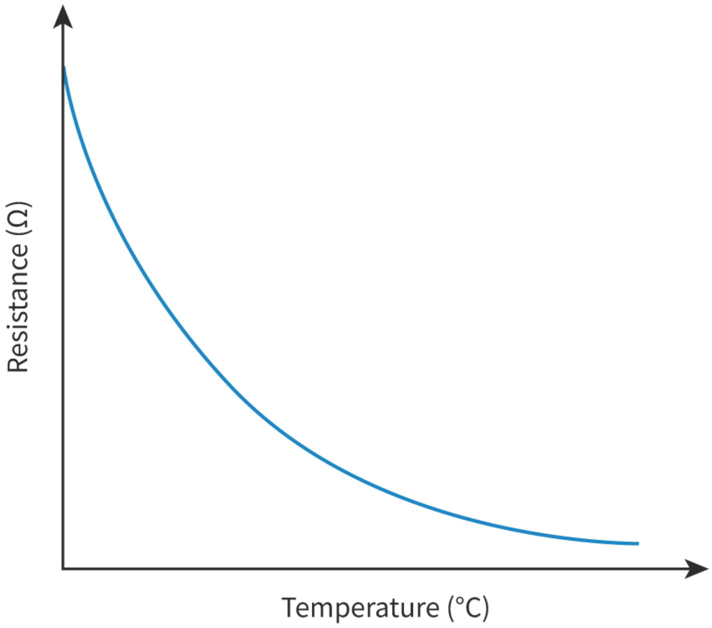

Figure 8. Resistance—temperature graph of a thermistor.

More information for figure 8

The graph displays the relationship between resistance and temperature for a thermistor. The X-axis represents temperature in degrees Celsius (°C), while the Y-axis represents resistance in Ohms (Ω). The curve is downward sloping, indicating that as temperature increases, the resistance of the thermistor decreases. This demonstrates the negative temperature coefficient characteristic of the thermistor, where higher temperatures result in lower resistance, and vice versa.

[Generated by AI]

Figure 9 shows how the current through a thermistor varies with voltage across it.

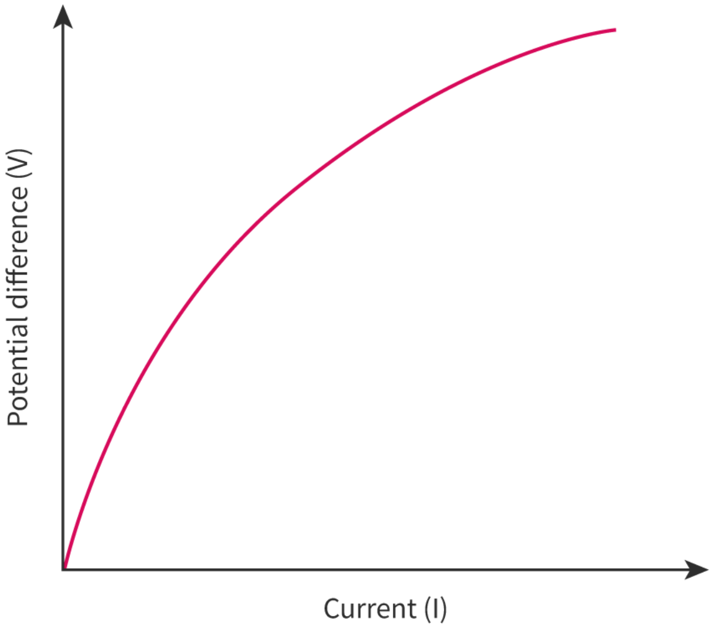

Figure 9. A V—I graph for a thermistor.

More information for figure 9

The graph depicts a V—I curve for a thermistor. The horizontal axis represents current (I), while the vertical axis represents potential difference (V). The curve shows a nonlinear relationship where voltage increases with current, indicating a typical thermistor behavior. The curve starts near the origin and gradually becomes steeper, representing an increase in potential difference as current increases. This reflects the non-ohmic behavior of a thermistor as it does not follow Ohm's law linearly, demonstrating that the resistance of the thermistor changes with temperature, affecting the current flow.

[Generated by AI]

Figure 10 shows a thermistor in a thermometer.

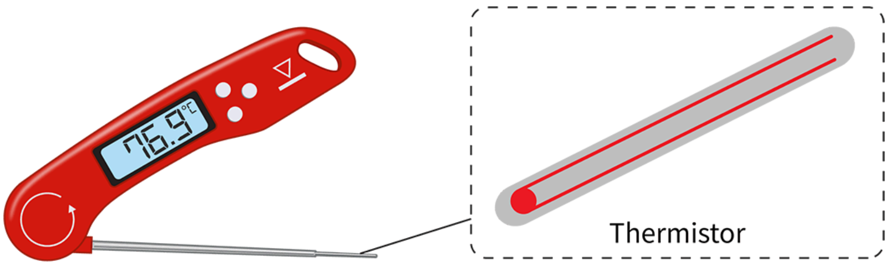

Figure 10. A thermistor in a thermometer.

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Nature of Science

Aspect: Theories

In 1833, an English scientist, Michael Faraday, discovered the fundamental concept of a thermistor while working on the semiconducting behaviour of silver sulfide. Faraday noticed that the resistance of silver sulfide decreased as the temperature increased.

Scientists are constantly testing their theories to find exceptions or to refine their theories. Why is a questioning attitude and a critical analysis of knowledge important traits for scientists?

Figure 11 shows how a thermistor is used as a sensor for controlling the heating element in an oven.

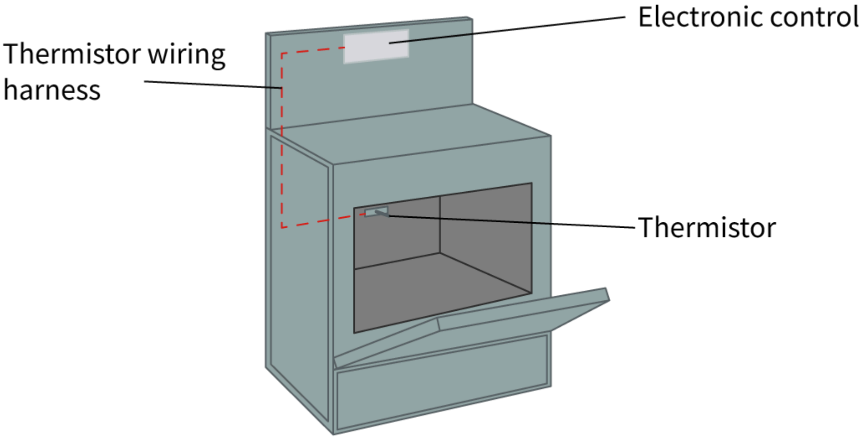

Figure 11. A thermistor is used as a sensor in an oven.

More information for figure 11

The image is a diagram showing an oven with a thermistor sensor. The oven is illustrated as a rectangular appliance with a compartment for heating. Inside the oven, near the center of its interior, a thermistor is depicted, connected with lines that likely represent circuitry or pathways for the sensor's input/output. The diagram may use labels or arrows to indicate the position and connection of the thermistor, highlighting its role in temperature sensing and regulation within the oven appliance.

[Generated by AI]

Student view

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A light-dependent resistor (LDR) is another type of resistor. When light intensity increases, its resistance decreases. When light intensity decreases, its resistance increases. This is how your mobile phone auto-adjusts its screen brightness according to the light level (**Figure 12**).

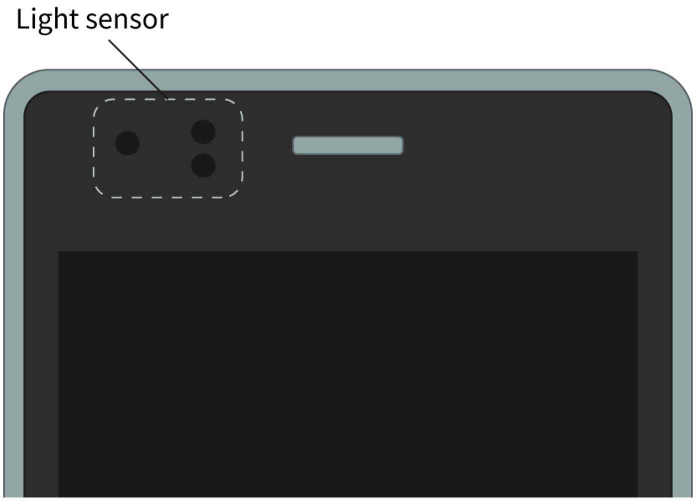

Figure 12. A mobile phone light sensor.

Source: "iPhone ambient light sensor" by Jojhnjoy is in the public domain

Drag and drop the names of the components to label each line in the V–I graph in **Interactive 3**. Then click 'Show or hide solution' to see an explanation.

Student view

Interactive 3. Label the Graph.

More information for interactive 3

This is a drag and drop interactive designed to help learners understand and identify different types of electrical components based on their current-voltage (I-V) characteristics. The graph plots voltage (V) on the y-axis against current (I) on the x-axis and shows four distinct curves, each representing a different type of component. Learners are required to drag and drop the correct labels into the blank boxes adjacent to each curve. The labels provided at the bottom of the screen include “Ohmic resistor with low resistance,” “Ohmic resistor with high resistance,” “Thermistor,” and “Filament light bulb.”

In the graph, there are four distinct lines, each representing the voltage-current (V-I) relationship for a different electrical component. These lines vary in shape and steepness, showing how each component behaves as current increases. The red line is a straight diagonal line through the origin with a steep slope. This indicates a constant resistance and follows Ohm’s Law, where voltage increases proportionally with current. The orange line is also straight and diagonal through the origin but has a shallow slope, representing an Ohmic resistor with low resistance. The green curve starts steep and gradually becomes flatter as current increases. This indicates decreasing resistance with increasing temperature or current, which is characteristic of a thermistor. The blue curve starts shallow and curves more steeply as current

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increases. This behavior indicates increasing resistance with current, typical of a filament light bulb due to heating effects.

The learner needs to carefully examine the characteristics of each curve and match them to the correct component by dragging and dropping the labels into the corresponding boxes on the graph. Once all the labels are placed correctly, the user can press the Check button to confirm their answers.

Solution:

Here are the correct labels for each line in the V-I graph:

Red line: Ohmic resistor with high resistance (steep straight line, constant resistance, high voltage per amp)

Orange line: Ohmic resistor with low resistance (shallow straight line, constant resistance, low voltage per amp)

Green line: Thermistor (curved, resistance decreases with increasing current)

Blue line: Filament light bulb (curved upward, resistance increases with increasing current)

So, drag the labels as follows:

Top-left box (red line): Ohmic resistor with high resistance

Top-center box (blue line): Filament light bulb

Middle-right box (green line): Thermistor

Bottom-right box (orange line): Ohmic resistor with low resistance

This interactive reinforces understanding of how different electrical components behave under varying current conditions and how their resistance properties can be visualized through V—I graphs.

Two graphs are straight lines, which means the resistance is constant and they are ohmic devices. The slope of the red graph is steeper than the yellow graph, so the red graph is an ohmic resistor with high resistance and the yellow graph is an ohmic resistor with low resistance.

For the blue graph, the potential difference changes as the current increases. This means it is a non-ohmic device so it is the filament light bulb.

Practical skills

Tool 3: Mathematics — Graphing

Data presented graphically gives us insights into the data and shows us general trends. Think about:

- What is on each axis
- What the gradient of the graph is and what it equates to

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- What the scales of the graph are
- What the outliers of the data are.

Work through the activity to investigate the resistances of different types of wire and deduce appropriate uses for them.

Activity

- **IB learner profile attribute:**
  - Inquirer
  - Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity**: 30 minutes
- **Activity type:** Pair (or group of three) activity

Open the Physics Aviary simulation (https://www.thephysicsaviary.com/Physics/Programs/Labs/ResistanceOfWireLab/) and follow the instructions below.

Instructions

1. Rearrange the resistivity equation $\rho = \frac{RA}{L}$, so you can plot a graph of length against resistance, where resistivity is the gradient.
2. Choose a type of wire by clicking on its name and choose a cross-sectional area by clicking on the circle.
3. Vary the length of the wire and record the values for length and resistance in a suitable table.
4. Plot your graph and calculate a value for the resistivity. You can plot the graph using a spreadsheet program or on paper.
5. Repeat steps 2 to 4 for the six different materials. Each person should choose three (or two) materials.
6. Repeat the process, this time keeping the length the same for each wire and varying the cross-sectional area.
7. Once you have calculated the resistivities of each material, compare them.

   - Which material would be best to use to minimise resistance? Is it commonly used? Why or why not?
   - Which material would be best to use in the filaments of hairdryers or heaters?

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Is it commonly used? Why or why not?

8. Research the uses of the other materials in an electrical context. Why are they used? Does the resistivity matter? What other properties of the materials might be important?

5 section questions

Question 1

SL HL Difficulty:

Resistance is defined as the 1 electric poten... ✓ across a component per unit of 2 current ✓ passing through it.

Accepted answers and explanation

#1 electric potential difference
potential difference

#2 current

General explanation

This is the definition of resistance.

Question 2

SL HL Difficulty:

A current of 2.6 A flows through a 5.0 Ω resistor. Determine the electric potential difference across the resistor. Give your answer to an appropriate number of significant figures.

The electric potential difference = 1 13 ✓ V

Accepted answers and explanation

#1 13

General explanation

$I = 2.6\ \text{A}$

$R = 5.0\ \Omega$

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

$$\begin{aligned}V&=IR\\&=2.6\times5.0\\&=13.0\text{ V}\\&=13\text{ V (2 s.f.)}\end{aligned}$$

Question 3

SL HL Difficulty:

An iron wire, with resistivity 9.71 × 10^{-8} Ω m, has a total length of 2.5 m and a resistance of 6.0 mΩ.

The radius of the wire is 1 3.6 ✓ mm. Give your answer to an appropriate number of significant figures.

Accepted answers and explanation

#1 3.6

3.6 mm

3,6

3,6 mm

General explanation

$$\rho=9.71\times10^{-8}\ \Omega\text{ m}$$

$$L=2.5\text{ m}$$

$$\begin{aligned}R&=6.0\text{ m}\Omega\\&=6.0\times10^{-3}\ \Omega\end{aligned}$$

$$\rho=\frac{RA}{L}$$

$$\begin{aligned}A&=\frac{\rho L}{R}\\&=\frac{(9.71\times10^{-8}\times2.5)}{6.0\times10^{-3}}\\&=4.0458\times10^{-5}\text{ m}^2\end{aligned}$$

$$A=\pi r^2$$

$$\begin{aligned}r&=\sqrt{\left(\frac{A}{\pi}\right)}\\&=\sqrt{\left(\frac{4.0458\times10^{-5}}{\pi}\right)}\\&=3.59\times10^{-3}\text{ m}\\&=3.6\text{ mm (2 s.f.)}\end{aligned}$$

Student view

Question 4

SL HL Difficulty:

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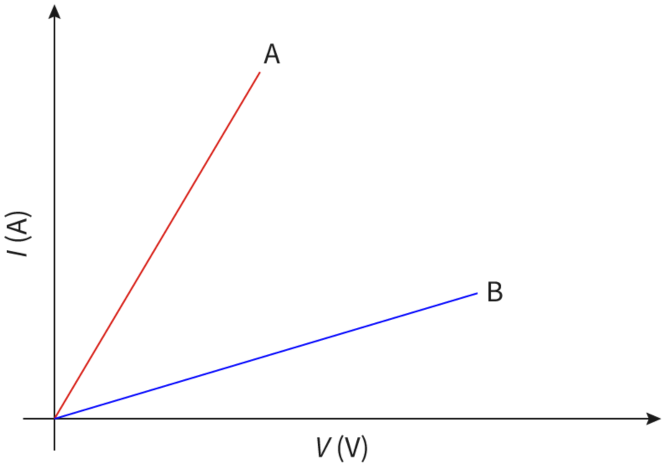
The diagram shows the I—V graph of two resistors, A and B. Identify which resistor has the greater resistance.



More information

B

Accepted answers

B, resistor B, graph B

Explanation

The graph is an I—V graph so it has electric potential difference on the x-axis and current on the y-axis.

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

$$\frac{I}{V} = \frac{1}{R}$$

The gradient of the lines is the inverse of the resistance R.

Resistor B has a less steep gradient so its resistance is greater.

Question 5

SL HL Difficulty:

Wire X has length L and radius r. Wire Y is made of the same metal but has length $2L$ and radius $\frac{1}{2}r$. If the resistance of wire X is R, what is the resistance of wire Y?

1 $8R$

2 $2R$

3 $4R$

Student view

4 0.5R

Explanation

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

For X:

$$R_{\mathrm{X}} = \frac{\rho L_{\mathrm{X}}}{A_{\mathrm{X}}}$$
$$R_X = \frac{\rho L_{\mathrm{X}}}{\pi r_{\mathrm{X}}^2}$$

For Y:

$$\begin{aligned} R_Y &= \frac{\rho L_{\mathrm{Y}}}{A_{\mathrm{Y}}} \\ &= \frac{\rho L_{\mathrm{Y}}}{(\pi r_{\mathrm{Y}}^2)} \\ &= \frac{\rho\, 2L_{\mathrm{X}}}{\pi(0.5r_{\mathrm{X}})^2} \\ &= \frac{2}{0.5^2} \cdot \frac{\rho\, L_{\mathrm{X}}}{\pi {r_{\mathrm{X}}}^2} \\ R_Y &= 8R_X \end{aligned}$$

B. The particulate nature of matter / B.5 Current and circuits

Series and parallel circuits

B.5.3: Circuit diagrams and components B.5.13: Resistors in series and parallel circuits

Learning outcomes

At the end of this section you should be able to:

- Identify series and parallel circuits along with the circuit symbols of electrical components.
- Explain electric potential difference, current and resistance in series and parallel circuits.

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Imagine you have a string of decorative lights that you turn on and off regularly. What happens when one of the bulbs breaks (**Figure 1**)? You do not want all the lights to turn off just because one bulb is broken. It would be hard to work out which one was broken.

Figure 1. What happens when one bulb breaks?

Credit: JJ Goiun, Getty Images

This applies in your home too. If you switch off one light, you do not want all the lights in the whole building to switch off. How should we connect the lights to stop this from happening?

Series and parallel circuits

Before you start looking at circuits, you should familiarise yourself with the electrical components and their circuit symbols shown in **Figure 2**. These are also given in section 1.6.6 (/study/app/math-aa-hl/sid-423-cid-762593/book/electrical-circuit-symbols-id-45158/) of the DP *Physics data booklet*.

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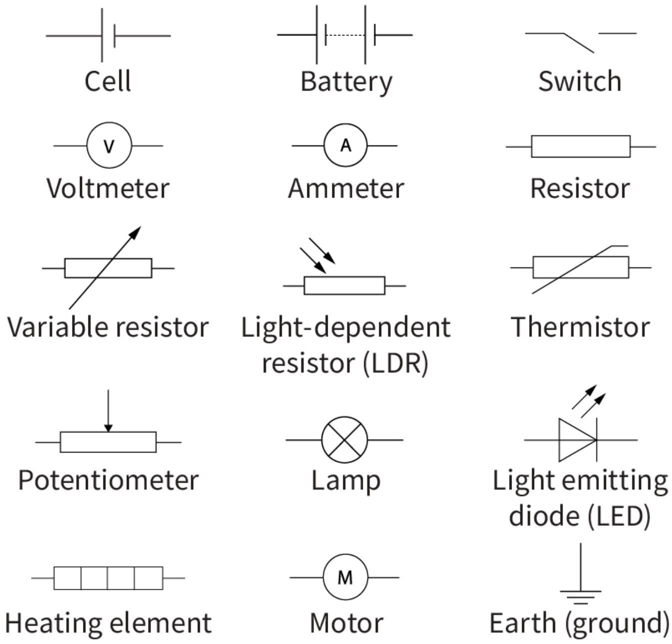

Figure 2. Electrical circuit symbols.

More information for figure 2

The image shows a diagram of electrical circuit symbols for various components. These include symbols for a cell, battery, switch, voltmeter, ammeter, resistor, variable resistor, light-dependent resistor (LDR), thermistor, potentiometer, lamp, light-emitting diode (LED), heating element, motor, and earth (ground). Each symbol is labeled with its corresponding component name. The components are arranged in three rows with four symbols in the first two rows and three symbols in the last row, consistently spaced.

[Generated by AI]

Electrical components can be arranged in circuits. There are two ways to arrange components in circuits – series and parallel. **Figure 3** shows the circuit diagrams with two identical cells and two identical lamps for a series circuit and a parallel circuit. How are the components in series and parallel circuits arranged?

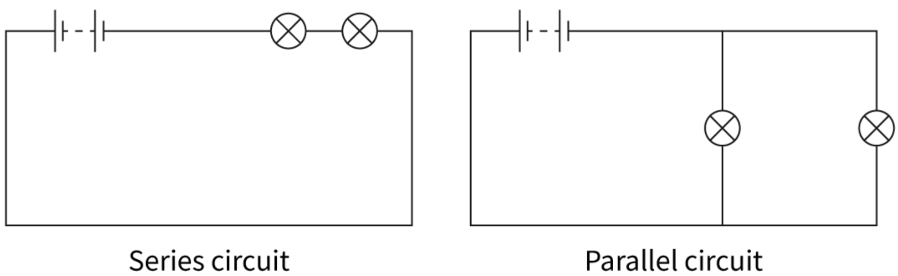

Figure 3. A series circuit and a parallel circuit.

Student view

More information for figure 3

The image consists of two circuit diagrams: one for a series circuit and one for a parallel circuit.

1. **Series Circuit Diagram**:
2. Two cells are placed in series on the left side of the diagram.
3. The circuit is a single loop, connecting two identical lamps one after the other.
4. Current flows from the positive terminal of the cell to the first lamp, then to the second lamp, and back to the negative terminal of the cell.

5. **Parallel Circuit Diagram**:

6. The two cells are again placed in series on the left side, forming the power source for both branches of the parallel circuit.
7. Two lamps are connected in parallel, each having its own loop with the cells.
8. Current divides into two paths here: one path passes through the first lamp, and the other path passes through the second lamp.
9. After passing through the lamps, the paths converge and return to the negative terminal of the cell.

These diagrams demonstrate the typical arrangements of components in series and parallel circuits, which affect how electricity flows through the circuit and how each component is powered.

[Generated by AI]

Current in series and parallel circuits

Look at **Interactive 1**. Compare the two circuits and answer the following questions. Click on 'Show or hide solution' to see the answer.

- Compare the size of the current passing through the cell in each circuit.

The current is greater in the parallel circuit than in the series circuit.

- For each circuit, how many bulbs does a single charge carrier pass through during one complete loop (between the terminals of the cell)?

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Parallel: one bulb

Series: two bulbs

- Look at the branch in the parallel circuit. What proportion of charge carriers travels down each path?

The charge carriers split 50:50.

Interactive 1. Series Circuit and Parallel Circuit.

More information for interactive 1

The interactive consists of two video panels placed side by side, each with its own playback controls at the bottom — including a play/pause button, progress bar, timestamp, fullscreen toggle, and an option to adjust playback speed accessible via the vertical three-dot menu. Users can play each video independently to compare current flow under different resistance conditions.

Both the video panels are side by side and compare two electric circuits: one is a series circuit and the other is a parallel circuit. Both circuits have the same resistors and power source, allowing for a direct visual comparison.

In the first video (Series Circuit), the circuit contains two 1.0Ω resistors arranged in series with a 3V power source. The video shows the current flowing through the circuit. In this series configuration, the same current flows through all components of the circuit. The current passing through the cell remains the same across the entire series circuit because there is only one path for the current to flow.

In the second video (Parallel Circuit), the circuit contains two 1.0Ω resistors connected in parallel with the same 3V

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power source. Here, the current is divided into two paths, one for each resistor. The current passing through the cell is split, with the current in each branch depending on the resistance of that particular branch. The total current supplied by the power source is the sum of the currents in the parallel branches.

Figure 4 shows a series circuit. The charge carriers (electrons) have only one pathway to travel along. Current is the rate of flow of charge, which is how many charge carriers pass a certain point every second. If the charge carriers only have one path, then the current must be the same everywhere in the circuit.

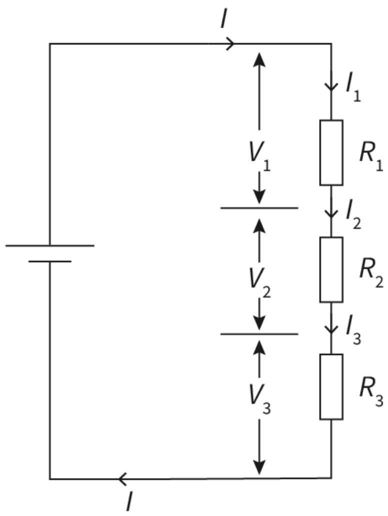

Figure 4. A series circuit.

More information for figure 4

The image is a diagram of a series circuit illustrating the flow of electric current. It features three resistors labeled R1, R2, and R3, connected in a single path. The current (I) flows from a battery on the left side, through the resistors sequentially. Each resistor shows a current label (I1, I2, I3) indicating that the current is the same at all points. Arrows are used to depict the direction of flow through V1, V2, and V3, representing voltage drops across each resistor.

[Generated by AI]

The current in a series circuit is:

$$I = I_1 = I_2 = I_3 = \ldots$$

Student view

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(/study/app/math-aa-hl/sid-423-cid-762593/c

Figure 5 shows a parallel circuit. At each branch in the circuit, there are multiple paths for the charge carriers to take, so the current splits. This means that the current in each branch is less than the current through the cell.

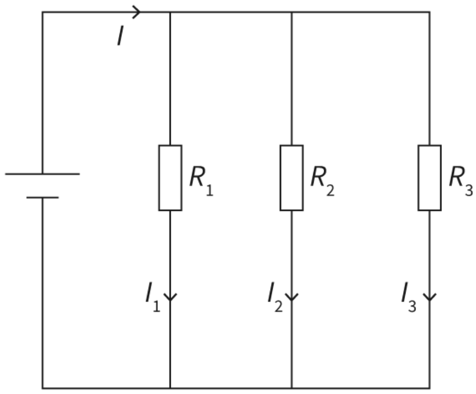


Figure 5. A parallel circuit.

More information for figure 5

The diagram illustrates a parallel circuit containing three resistors labeled R1, R2, and R3. The circuit is connected to a power source that provides a current labeled 'I', which splits at each branch of the circuit. This creates individual currents labeled 'I1', 'I2', and 'I3', each flowing through the corresponding resistors: R1, R2, and R3 respectively. The resistors are arranged in parallel, meaning that each has its own path to conduct current from the power source. This setup ensures that the voltage across each resistor is the same, while the current divides among the different paths. The diagram provides a visual representation of how current distribution works in a parallel circuit.

[Generated by AI]

The current in a parallel circuit is:

$$I = I_1 + I_2 + I_3 + \ldots$$

where I is the current either before the path divides or after it rejoins, and I_n is the current in each path individually.

Worked example 1

The diagram shows a circuit with three identical resistors. The current flowing through the battery is 1.6 A. Deduce the current at the three points in the circuit, marked X, Y and Z. Assume the ammeters have zero resistance.

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

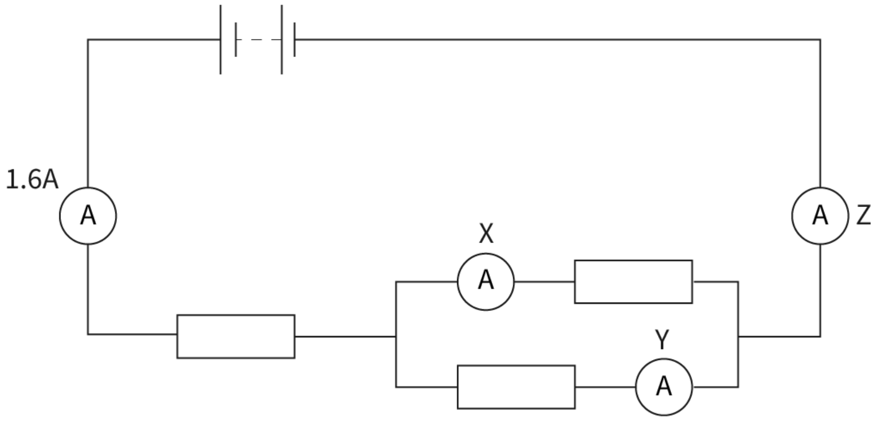


Figure 6. A circuit with three identical resistors.

More information for figure 6

The diagram shows an electrical circuit containing a battery on the top left, labeled with a current of 1.6 A. The circuit branches into three identical resistors arranged in parallel, each connected through different points labeled X, Y, and Z. The point X connects to the first resistor, Y to the second resistor, and Z to the remaining part of the circuit after the third resistor. Each branch loops back, forming a closed circuit. The diagram is labeled such that it helps indicate the flow of current through each resistor and the associated points, assisting with calculating individual currents.

[Generated by AI]

We can break this circuit into its component parts:

- Parallel circuit section, where the current through the cell equals the sum of the currents in each branch: X + Y = 1.6 A
- Series section, where the current is the same throughout: Z = 1.6 A

Because the resistors in parallel are identical, the same current will flow through each one, so:

X = Y

Therefore:

X = 0.8 A

Y = 0.8 A

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

$Z = 1.6 \text{ A}$

Electric potential difference in series and parallel circuits

Figure 7 shows a series circuit.

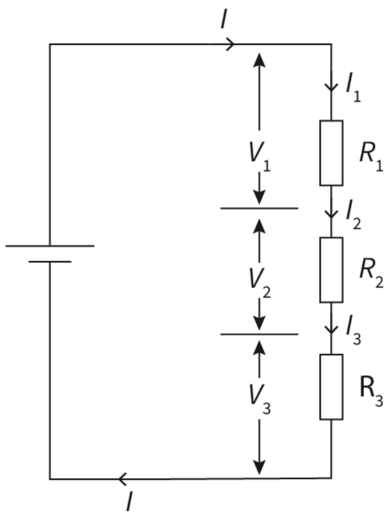


Figure 7. A series circuit.

More information for figure 7

The diagram shows a series circuit with a battery on the left side and three resistors labeled R1, R2, and R3 arranged vertically on the right side. The current I enters the circuit from the positive terminal of the battery and flows through each component in sequence: starting from R1, then R2, and finally R3 before returning to the battery's negative terminal. Each resistor is accompanied by a current and voltage label: I1 and V1 for R1, I2 and V2 for R2, and I3 and V3 for R3. Arrows indicate the direction of current flow and the potential difference across each resistor. The symbols and layout illustrate the flow of electrical current and distribution of voltage in the series circuit configuration.

[Generated by AI]

In a series circuit, the principle of conservation of energy means that the work done, W, by the cell must be equal to the total work done to the resistors:

$$W = W_1 + W_2 + W_3$$

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

There is only one path, so the amount of charges, q, passing through each component must be the same:

$$\frac{W}{q} = \frac{W_1}{q} + \frac{W_2}{q} + \frac{W_3}{q}$$

$V = \frac{W}{q}$ so the electric potential difference in a series circuit is:

$$V = V_1 + V_2 + V_3 + \ldots$$

Figure 8 shows a parallel circuit.

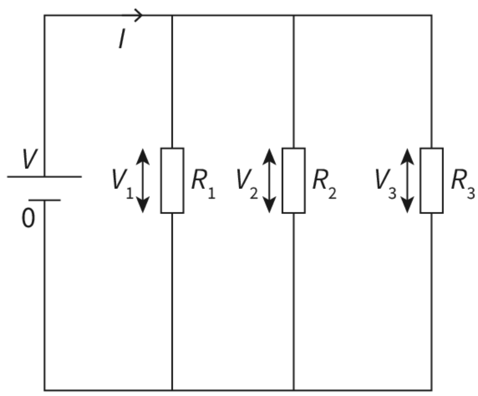


Figure 8. A parallel circuit.

More information for figure 8

The diagram illustrates a parallel circuit with a voltage source at the left side labeled from top to bottom with 'V' and '0'. A line extends to the right from the top labeled 'I'. The circuit features three parallel branches, each including a resistor. The resistors are vertically aligned and labeled from left to right as 'R1', 'R2', and 'R3'. Arrows above each resistor indicate the voltage across each resistor, labeled as 'V1', 'V2', and 'V3' respectively. These branches demonstrate that in a parallel circuit, the voltage is the same across each component, but the current may vary depending on the resistance of each branch. The structure allows the overall circuit to interact with the voltage source and current line at the common junction points, highlighting the essential characteristics of a parallel circuit.

[Generated by AI]

In a parallel circuit, each charge carrier only passes through a single branch. The electric potential on each side of the parallel section is the same (in this case, V and 0), so the electric potential difference across each branch must be the same.

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

The electric potential difference in a parallel circuit is:

$$V = V_1 = V_2 = V_3 = \ldots$$

Worked example 2

The diagram shows three identical bulbs, A, B and C, connected to a cell. The electric potential difference across the cell, V, is 6.0 V.

Determine the electric potential difference across each bulb.

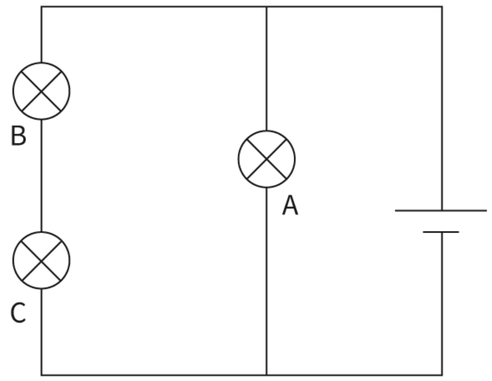


Figure 9. Determine the electric potential difference.

More information for figure 9

The image is a schematic diagram of an electric circuit. It consists of three bulbs labeled A, B, and C. Bulb A is in parallel with bulbs B and C, which are in series. The circuit includes a power source on the right side, connected to the circuit with lines indicating the flow of current. The bulbs are typically illustrated with symbols resembling circles with an X inside to represent the filament. This diagram is likely used to help determine the electric potential difference across each bulb as mentioned in the context outside the image.

[Generated by AI]

The electric potential difference across each branch is the same, so:

$$V_A = V = 6.0\text{ V}$$

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

The electric potential difference across bulbs B and C is also 6.0 V, but bulbs B and C are in series so the electric potential difference is split between them. They are identical bulbs so they each take an identical share. So:

$$V_B + V_C = 6.0 \text{ V}$$

$$V_B = V_C = 3.0 \text{ V}$$

Resistance in series and parallel circuits

Figure 10 shows a series circuit with four resistors. How can you derive an equation for the total resistance, R_s, of a series circuit?

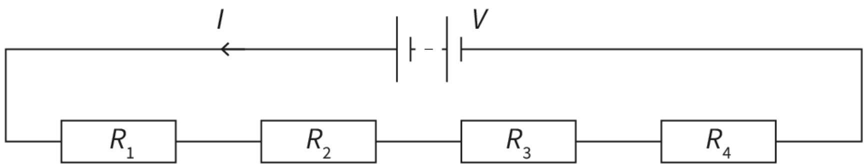


Figure 10. A series circuit with four resistors.

More information for figure 10

The image is a diagram depicting a series circuit. At the top center lies a power source labeled 'V' connected in series with four resistors labeled R1, R2, R3, and R4 from left to right. An arrow pointing to the left beside the wire indicates the direction of current flow, labeled 'I'. All components are arranged in a single loop, showcasing the simple series circuit configuration.

[Generated by AI]

For a series circuit:

$$I = I_1 = I_2 = I_3 = I_4$$

and

$$V = V_1 + V_2 + V_3 + V_4$$

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

$R = \dfrac{V}{I}$ and $V = IR$ so:

$$V_1 + V_2 + V_3 + V_4 = IR_s$$

$$I_1R_1 + I_2R_2 + I_3R_3 + I_4R_4 = IR_s$$

The current is the same throughout a series circuit, so:

$$IR_1 + IR_2 + IR_3 + IR_4 = IR_s$$

$$R_s = R_1 + R_2 + R_3 + R_4 + \ldots$$

The total resistance is equal to the sum of the individual resistances.

Figure 11 shows a parallel circuit with four resistors. How can you derive an equation for the total resistance, R_p, of a parallel circuit?

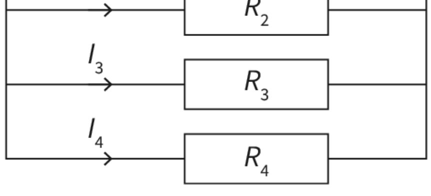


Figure 11. A parallel circuit with four resistors.

More information for figure 11

The diagram illustrates a parallel circuit with a power source at the top, supplying voltage V. There are four resistors labeled R1, R2, R3, and R4 connected in parallel, each with an associated current labeled as I1, I2, I3, and I4 respectively. The overall current from the source is labeled as I. The resistors are aligned horizontally, one above the other, within the circuit paths that branch out from the main supply line at the top and reconvene at the bottom to complete the circuit. The diagram helps in visualizing the flow of electricity in terms of voltage and individual currents through each resistor path in the circuit.

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

[Generated by AI]

For a parallel circuit:

$$I = I_1 + I_2 + I_3 + I_4$$

and

$$V = V_1 = V_2 = V_3 = V_4$$

$R = \frac{V}{I}$ and $I = \frac{V}{R}$ so:

$$I_1 + I_2 + I_3 + I_4 = \frac{V}{R_p}$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \frac{V_4}{R_4} = \frac{V}{R_p}$$

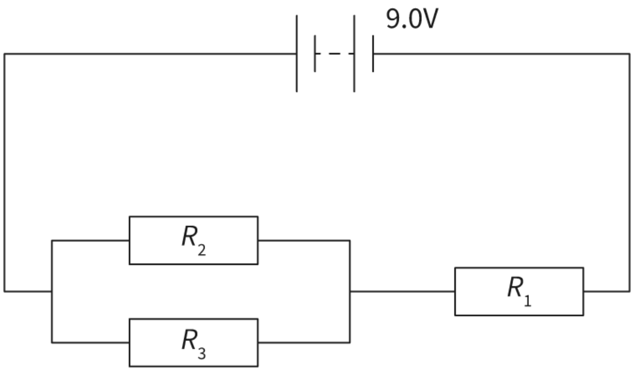
The electric potential difference is the same throughout a parallel circuit, so:

$$\frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} + \frac{V}{R_4} = \frac{V}{R_p}$$

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \ldots$$

Worked example 3

The circuit diagram shows a 9.0 V battery connected to three resistors, $R_1 = 1.0\,\Omega$, $R_2 = 2.0\,\Omega$ and $R_3 = 3.0\,\Omega$. Determine the total resistance of the circuit.



Student view

Figure 12. Determine the total resistance.

More information for figure 12

The image shows a circuit diagram featuring a 9.0V battery connected to three resistors. Resistor R1 is on the right side, while resistors R2 and R3 are arranged in parallel on the left. Specifically, the battery is depicted at the top center, with vertical lines representing its terminals, connected to horizontal lines indicating the wires. The current flows from the battery to R1, marked as 1.0 Ohm, which is in series with the parallel combination of R2 and R3. R2 and R3 are shown as separate components, stacked vertically, each with their own horizontal lines connecting them to the main circuit. R2 is labeled as 2.0 Ohms and placed above R3, which is labeled as 3.0 Ohms. The arrangement suggests calculating the total resistance involves both series and parallel resistance calculations to determine the overall resistance of the circuit.

[Generated by AI]

This circuit has a series and a parallel arrangement.

$$R_1 = 1.0\ \Omega$$

$$R_2 = 2.0\ \Omega$$

$$R_3 = 3.0\ \Omega$$

Parallel circuit (involving R_2 and R_3):

$$\begin{aligned}\frac{1}{R_\text{p}} &= \frac{1}{R_2} + \frac{1}{R_3}\\ &= \frac{1}{2} + \frac{1}{3}\\ &= 0.833\\ R_\text{p} &= 1.2\ \Omega\end{aligned}$$

$$\begin{aligned}\text{Total resistance} &= R_\text{p} + R_1\\ &= 1.2 + 1.0\\ &= 2.2\ \Omega\ (2\text{ s.f.})\end{aligned}$$

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Worked example 4

The diagram shows a parallel circuit. Determine the current through resistor *R* and the electric potential difference across it.

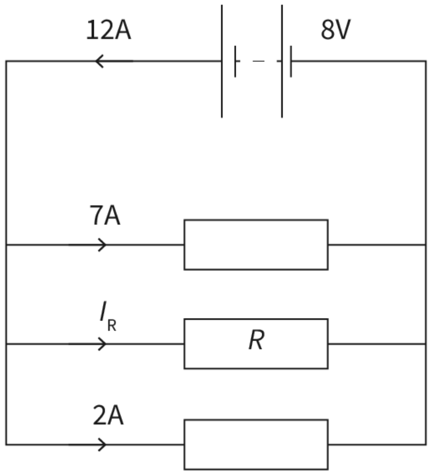


Figure 13. Determine the current and the electric potential difference.

More information for figure 13

The image depicts a parallel circuit diagram with three branches. The top branch shows a current of 7 amperes (A) flowing through it. The middle branch includes a resistor labeled 'R' with a current labeled 'IR'. The bottom branch has a current of 2 amperes (A). The total current entering the circuit is 12 amperes (A), and the voltage across the circuit is 8 volts (V). The goal is to determine the current through the resistor 'R' and the electric potential difference across it.

[Generated by AI]

$$\begin{aligned} I &= I_1 + I_2 + I_3 \\ 12 &= 7 + I_{\mathrm{R}} + 2 \\ I_{\mathrm{R}} &= 12 - (7 + 2) \\ &= 3A \end{aligned}$$

$$V = V_1 = V_2 \ldots$$

So the electric potential difference across resistor R is $8\ \mathrm{V}$.

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

Worked example 5

Three resistors are connected to a 24 V power supply as shown in **Figure 14**.

Calculate the potential difference across the 8.0 Ω resistor.

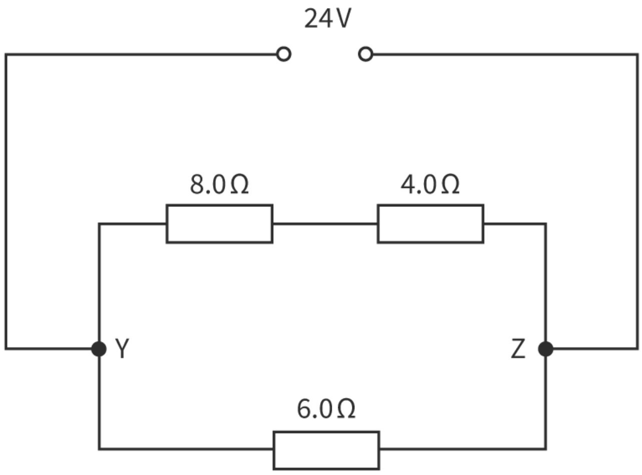


Figure 14. Calculate the potential difference.

More information for figure 14

The image is a circuit diagram depicting three resistors connected to a 24V power supply. At the top center, a straight line represents the power supply with a 24V label. Below this, there are three horizontal resistors arranged in parallel and series. The 8.0 Ω resistor is positioned centrally, followed by the 4.0 Ω resistor in series. Beneath these, a 6.0 Ω resistor is connected in parallel to both. Points Y and Z are marked respectively at the left and right ends of the parallel connection. The diagram illustrates how the resistors are connected within the circuit to distribute the voltage across different paths.

[Generated by AI]

Solution steps	Calculations
Step 1: Calculate the combined resistance of the two resistors in the top branch.	R_{8+4} = 8.0 + 4.0 = 12 Ω

Student view

Overview
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Solution steps	Calculations
Step 2: Calculate the current in the top branch by rearranging Ohm's law for *I*.	Ohm's law → $V = IR_{8+4}$ $$I = \frac{V}{R_{8+4}} = \frac{24}{12} = 2.0\ \text{A}$$
Step 3: Use Ohm's law to calculate the potential difference across the 8.0 Ω resistor.	$V_8 = IR_8$ $= 2 \times 8$ $= 16$ V

Aspect: Models

A common approach in science is to try to simplify a problem to make it easier to solve. Sometimes we do this through assumptions, and sometimes by finding situations where certain variables are negligible. In the case of complex circuits, we can combine resistors together to make a problem simpler. Can you think of other situations where scientists simplify problems in order to reach a solution?

Voltmeters and ammeters

We have established the concepts of electric potential difference and current, but how do we measure them?

Voltmeters measure electric potential difference – in other words, the difference in energy per unit charge before and after a component, so they are connected to either side of a component. They are connected in **parallel** with the component.

Student view

Ammeters measure the rate of flow of charge carriers, so they are connected within the flow of electrons in the circuit. They are connected in **series** with a component.

Overview
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Figure 15 shows a circuit with an ammeter and a voltmeter.

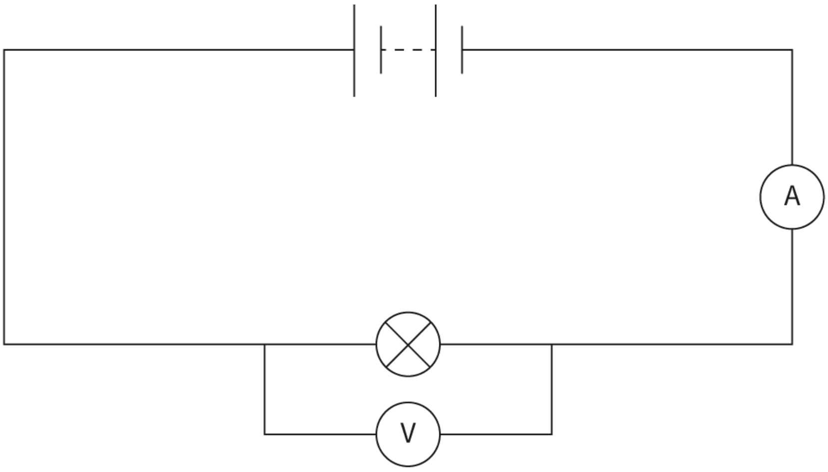

Figure 15. How to connect an ammeter and a voltmeter in a circuit.

More information for figure 15

The image is a circuit diagram showing how to connect an ammeter and a voltmeter. The circuit consists of a battery at the top, symbolized by two parallel lines of different lengths. The ammeter, labeled "A," is incorporated into the circuit path to measure current, and it is shown to the right of the circuit. Below the battery, there is a symbol for an electrical component, possibly a resistor, followed by a circular symbol representing a light bulb. Below the light bulb, a voltmeter, labeled "V," is connected in parallel to measure voltage across the light bulb. The lines connecting these components indicate the flow of electricity through the circuit.

[Generated by AI]

Theory of Knowledge

Before the invention of the ammeter, in the late 1700s, English natural philosopher Henry Cavendish decided to adopt the 'sense perception' approach to measuring current. He measured the strength of the current by literally shocking himself and recording the level of pain.

The ancient world was limited to what people could investigate with their senses. Now, scientists have a range of methods and tools that allow them to detect quantities far beyond our physiological limits. To what extent is the knowledge we produce limited or enhanced by the tools available?

Student view

Overview
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To measure the current passing through a component, an ammeter is placed in series with the component. If the ammeter has a resistance, there is an electric potential difference (because $V = IR$) across the ammeter itself. This decreases the electric potential difference across the component. Therefore, ammeters are manufactured with a minimal resistance.

A voltmeter is placed in parallel with a component to measure the electric potential difference across it. If the voltmeter has a low resistance, a non-negligible current is drawn by the voltmeter. This increases the total current from the power source. Therefore, voltmeters are manufactured with a large resistance.

Study skills

If the resistance of a voltmeter or ammeter is given, then treat it like a normal resistor with a resistance.

An **ideal ammeter** has **zero resistance**, while an **ideal voltmeter** has **infinite resistance**.

Nature of Science

Aspect: Measurement

What are other examples of ideal objects you have encountered in physics? Why do scientists use the concept of ideal objects, which do not exist in reality?

How do we improve reliability of results if the action of measuring affects the measurement? For example, consider the liquid-in-glass thermometer. Imagine you are trying to experimentally estimate the specific heat capacity of water. How might the thermometer affect your result? How can you minimise this effect?

Work through the activity in the next section to check your understanding of series and parallel circuits.

6 section questions

Student
view

Question 1

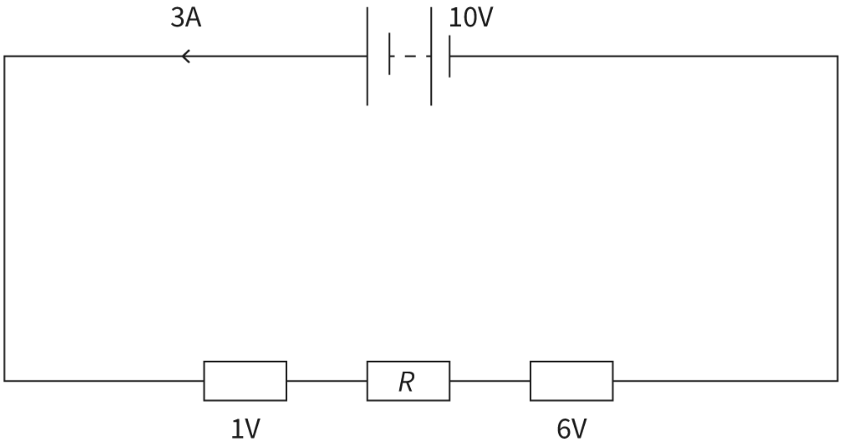
SL HL Difficulty:

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

The diagram shows a circuit. Determine the current through resistor R and the electric potential difference across R. Give your answers to an appropriate number of significant figures.

Current through R is 1 3 A

Electric potential difference across R is 2 3 V



More information

Accepted answers and explanation

#1 3

#2 3

General explanation

The current in a series circuit is the same throughout the circuit, therefore the current through R is 3 A.

Electric potential difference across R:

$$10 = 1 + V_{\text{R}} + 6$$

$$V_{\text{R}} = 10 - (6 + 1)$$
$$= 3\text{ V (1 s.f.)}$$

Question 2

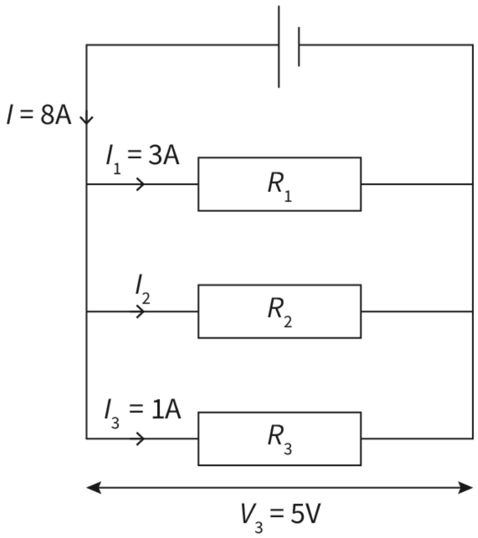
SL HL Difficulty:

The diagram shows a circuit with three resistors . Determine the current through resistor R_2 and the electric potential difference across R_2. Give your answers to an appropriate number of significant figures.

Current through R_2 is 1 4 A

Student view

Potential difference across R_2 is 2 5 V



More information

Accepted answers and explanation

#1 4

4A

4 A

#2 5

5 V

5V

General explanation

$$I = I_1 + I_2 + I_3$$
$$8 = 3 + I_2 + 1$$
$$I_2 = 4 \text{ A } (1 \text{ s.f.})$$

$$V_{\text{cell}} = V_1 = V_2 = V_3$$
$$= 5 \text{ V } (1 \text{ s.f.})$$

Question 3

SL HL Difficulty:

Four identical resistors, each with resistance *R*, are connected together. State which of the following gives the least equivalent (total) resistance.

Overview
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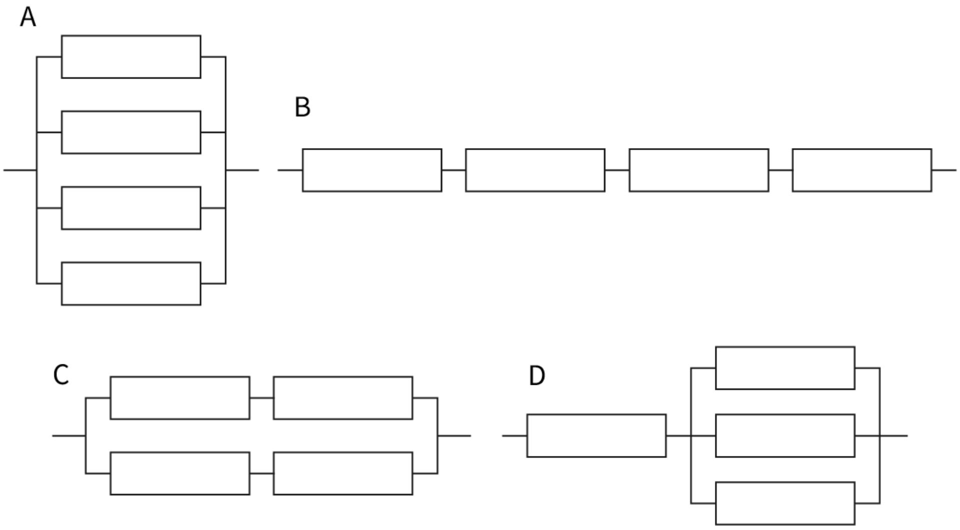


More information

1 A

2 B

3 C

4 D

Explanation

Series: $R_s = R_1 + R_2$

Parallel: $\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2}$

Circuit A is $R_{\text{total}} = \frac{R}{4}$

Circuit B is $R_{\text{total}} = 4R$

Circuit C is:

$$\frac{1}{R_{\text{total}}} = \left(\frac{1}{2R} + \frac{1}{2R}\right) = \frac{2}{2R}$$
$$R_{\text{total}} = R$$

Circuit D is:

$$R_{\text{total}} = \frac{R}{3} + R$$
$$= \frac{4R}{3}$$

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

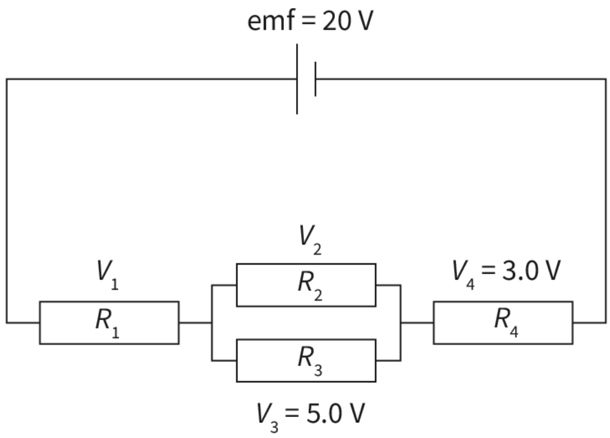
Circuit A has the least equivalent resistance.

Question 4

SL HL Difficulty:

The diagram shows a circuit with resistors in series and in parallel. Determine the value of V_1. Give your answer to an appropriate number of significant figures.

V_1 is 1 12 ✓ V



More information

Accepted answers and explanation

#1 12

12V

12 V

General explanation

R_2 and R_3 have the same electric potential difference so:

$$V_2 = 5.0 \text{ V}$$

The emf of the cell is equal to the sum of the electric potential differences in a series circuit. Consider R_2 and R_3 combined as one resistor with 5.0 V across it:

$$20 = V_1 + 5.0 + 3.0$$

$$V_1 = 12 \text{ V } (2 \text{ s.f.})$$

Student view

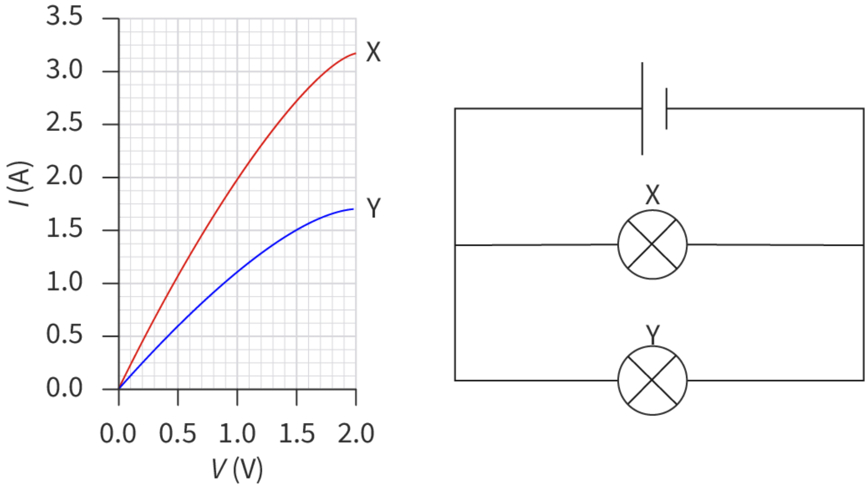
Question 5

SL HL Difficulty:

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

The diagram shows an *I*—*V* graph of two filament light bulbs, X and Y. The emf of the cell is 1.5 V. Determine the total current leaving the cell when X and Y are connected in a parallel circuit. Give your answer to an appropriate number of significant figures.

The total current is 1 4.3 ✓ A



More information

Accepted answers and explanation

#1 4.3

4.3A

4.3 A

General explanation

Since bulbs X and Y are in parallel with the cell, the potential difference across both will be the same = 1.5 V

The currents are 1.5 A and 2.75 A as shown in the I—V graph.

Student view

Overview
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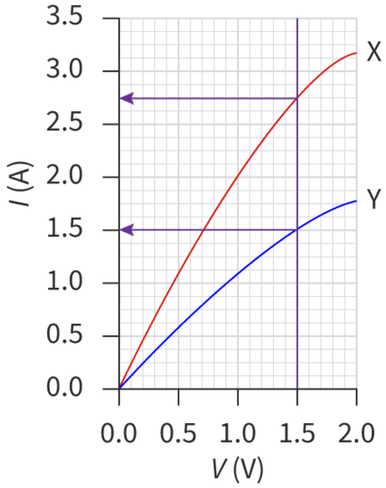


More information

The image is a graph displaying two curves labeled X and Y. The horizontal axis represents voltage (V) and ranges from 0.0 to 2.0 volts, while the vertical axis represents current (I) in amperes, ranging from 0.0 to 3.5 amperes.

Curve X is red and follows a steeper upward trend, starting from the origin (0,0), and the curve reaches approximately 3.0 amps when the voltage is 2.0 volts. Curve Y is blue, also starting at the origin, but increases more gradually than curve X, reaching about 1.5 amps at 2.0 volts.

The graph also includes grid lines and two horizontal markers indicating specific current levels, approximately at 1.5 amps and 3.0 amps. The vertical marker indicates the voltage at approximately 2.0 volts.

[Generated by AI]

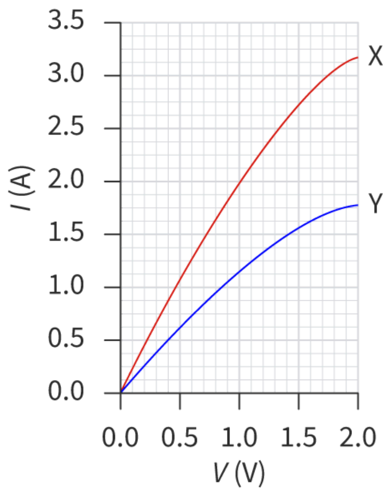
$$\begin{aligned}\text{total current} &= 1.5 + 2.75\\ &= 4.25\ \text{A}\\ &= 4.3\ \text{A}\ (2\ \text{s.f.})\end{aligned}$$

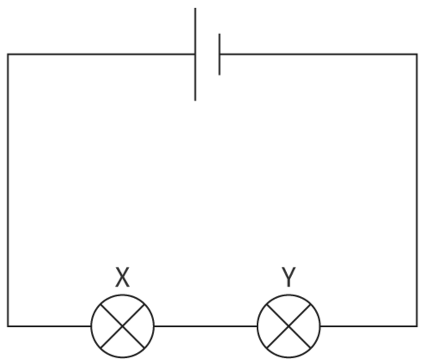
Question 6

SL HL Difficulty:

The diagram shows an *I*—*V* graph of two filament light bulbs, X and Y. The emf of the cell is 1.5 V. Determine the total current leaving the cell when X and Y are connected in a series circuit. Give your answer to an appropriate number of significant figures.

The total current is 1 1.1 ✓ A





Student
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More information

Overview
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Accepted answers and explanation

#1 1.1

1.1A

1.1 A

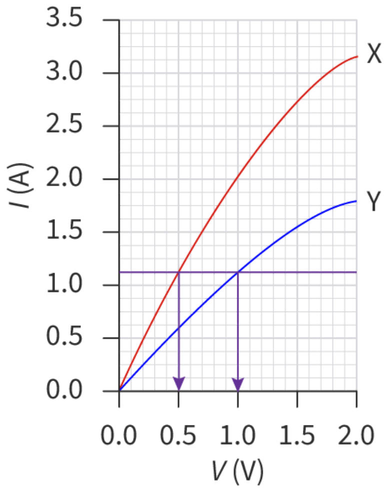
General explanation

I_X and I_Y are the same as the light bulbs are in series.

$V_X + V_Y$ = emf of cell = 1.5 V

Place a ruler horizontally to 'scan' values of V_X and V_Y so that the current is the same and the sum is 1.5 V.

The values are 0.5 V and 1.0 V as shown in the diagram. So the current is 1.1 A (2 s.f.)



More information

The graph displays current (I) in amperes on the Y-axis ranging from 0 to 3.5 A, and voltage (V) in volts on the X-axis ranging from 0 to 2 V. There are two curves labeled X (red) and Y (blue). Curve X starts at the origin and rises steeply to reach a current of 3 A at 1.5 V. Curve Y also starts at the origin but rises more gradually, reaching just above 2 A at 1.5 V. The horizontal purple line at 1 A on the Y-axis indicates a reference level, with two downward arrows pointing at approximately 0.5 V and 1 V on the X-axis, potentially indicating points of interest or critical values.

[Generated by AI]

B. The particulate nature of matter / B.5 Current and circuits

Activity: Series and parallel circuits

B.5.3: Circuit diagrams and components B.5.13: Resistors in series and parallel circuits

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/activity-series-and-parallel-circuits-id-44365/print/) Assign

Student view

Activity

- **IB learner profile attribute:**
  - Inquirer
  - Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 25 minutes
- **Activity type:** Group activity

Instructions

1. Work as a group. Use the simulation to build the circuits shown below. You can adjust the emf values of the batteries and the resistance of the resistors.
2. Measure the electric potential difference across all the components and the current in all branches. (Remember to set up the voltmeters and ammeters correctly.)
3. For the two circuits, how do the current and electric potential difference readings change when you change the resistance of a resistor?
4. What would you expect to see if you built these circuits in the lab?

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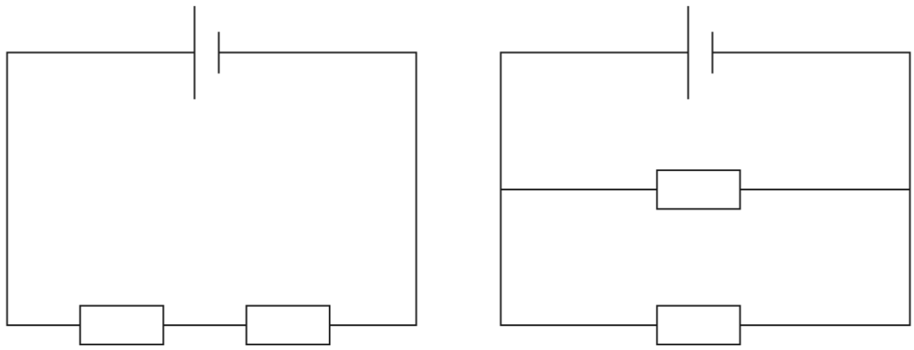

Figure 1. Series circuit and parallel circuit.

More information for figure 1

The diagram consists of two sections, each illustrating a different type of electrical circuit. The left section shows a series circuit where components are arranged in a single loop. It has a power source connected to two resistors in sequence. The right section shows a parallel circuit where components have multiple paths for electricity to flow. It features a power source connected to two resistors, each in separate branches of the circuit. Labels specify 'Series Circuit' and 'Parallel Circuit' above the respective sections.

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Extension

If you would like to challenge yourself further, build the two circuits below using the simulation.

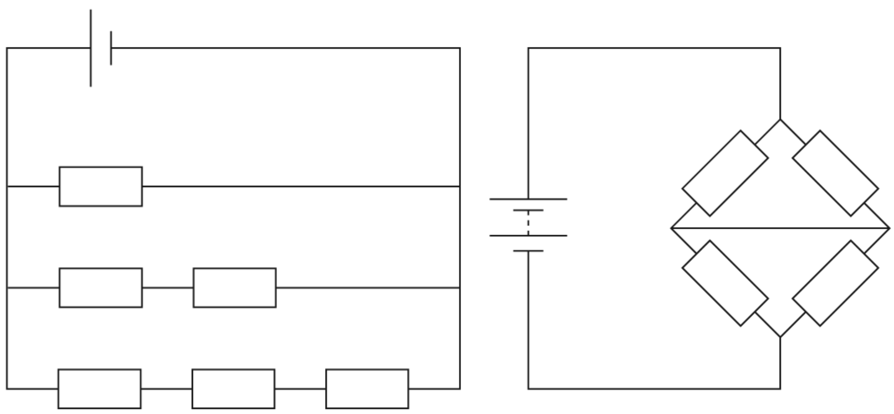

Figure 2. Parallel circuit and Wheatstone bridge circuit.

More information for figure 2

The image displays two diagrams. On the left is a parallel circuit diagram with three horizontal lines representing wires connected to resistors in parallel alignment. Each resistor is represented by a rectangle with lines connected at the top and bottom, indicating current flow. This circuit also includes a battery symbol at the top to denote power source.

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On the right is a Wheatstone bridge circuit diagram, which is more complex. The Wheatstone bridge includes a combination of four resistors forming a diamond shape, with two resistors on the left and two on the right. Each resistor is connected to the adjacent resistor by lines depicting electrical connections. There is a galvanometer symbol in the middle horizontal path and a battery symbol below the diagram to represent the electrical supply. The Wheatstone bridge is used for precise measurement of electrical resistance by balancing two legs of a bridge circuit.

[Generated by AI]

B. The particulate nature of matter / B.5 Current and circuits

Circuits and power

B.5.12: Electrical power

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/circuits-and-power-id-44366/print/) Assign

Learning outcomes

At the end of this section you should be able to determine the electrical power *P* dissipated by a resistor.

Look back at the electric eel in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44361/). Is the electric shock powerful because of the current or the electric potential difference?

A Van de Graaff generator can supply 50 000 V to 150 000 V, which is enough to ionise the air and make a spark (**Figure 1**). How is it safe to use to demonstrate electric charges in science lessons?

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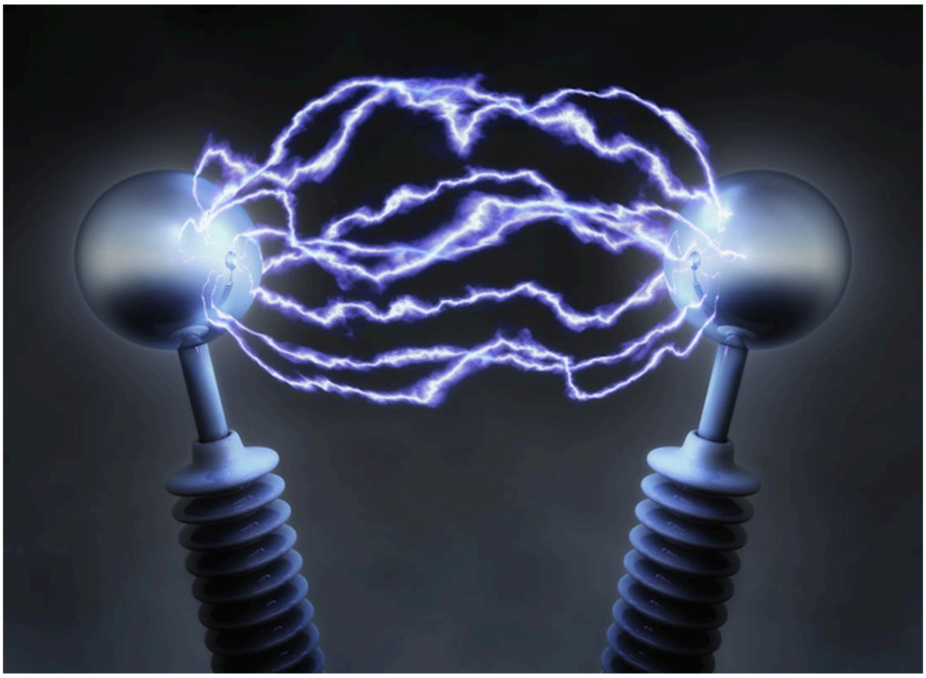

Figure 1. A Van de Graaff generator.

Credit: Matthias Kulka, Getty Images

Power in a circuit

Electrical power is the amount of work done per second, or the amount of electrical energy transferred per second (subtopic A.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43083/)):

$$P = \frac{\Delta W}{\Delta t}$$

The equations for electric potential difference and current are (section B.5.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/conductors-electric-potential-difference-and-id-44362/)):

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

$$I = \frac{\Delta q}{\Delta t}$$

Rearranging the two equations gives:

$$W = Vq$$

$$\Delta t = \frac{\Delta q}{I}$$

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Substituting these expressions into the equation for power:

$$P = \frac{\Delta W}{\Delta t}$$

$$P = \frac{(Vq)}{\left(\frac{\Delta q}{I}\right)}$$

Removing the expression for q and Δq gives:

$$P = IV$$

Using Ohm's law, we can obtain two other expressions for power:

$$\begin{aligned} P &= VI \\ &= (IR)I \\ &= I^2R \end{aligned}$$

and

$$\begin{aligned} P &= VI \\ &= V\left(\frac{V}{R}\right) \\ &= \frac{V^2}{R} \end{aligned}$$

Table 1. Equations for power.

Equation	Symbols	Units
$P = VI$ $P = I^2R$ $P = \frac{V^2}{R}$	P = power	watts (W)
	V = potential difference or emf	volts (V)
	I = current	amperes (A)
	R = resistance	ohms (Ω)

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Worked example 1

A hairdryer has a total resistance of 80 Ω. It is plugged into a power socket with 5.0 A of current passing through it.

Calculate the power dissipated by the hairdryer and determine the thermal energy dissipated in 3.0 minutes.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert to the values required by the question.	$R = 80\ \Omega$ $I = 5.0\ \text{A}$ $t = 3\ \text{minutes}$ $= 3 \times 60$ $= 180\ \text{s}$
Step 2: Write out the appropriate equation for power.	$P = I^2 R$
Step 3: Substitute the values given.	$= (5.0)^2 \times 80$
Step 4: State the answer with appropriate units.	$= 2000\ \text{W}$
Step 5: Write out the equation for power and rearrange the equation to make ΔW the subject.	$P = \dfrac{\Delta W}{\Delta t}$ $\Delta W = P\,\Delta\,t$
Step 6: Substitute the values given.	$= 2000 \times 180$
Step 7: State the answer with appropriate units and the number of significant figures used in rounding.	$= 3.6 \times 10^5\ \text{J}\ (\ 2\ \text{s.f.})$

Theory of Knowledge

Jacob Aron, science writer for the *New Scientist*, wrote in *The Guardian* newspaper that:

“Analogies in science writing are like forklift trucks — when used correctly they do a lot of heavy lifting, but if you don't know what you're doing you'll quickly drive them into a wall of laboured metaphors and cause some major damage.”

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What are the advantages of using analogies to explain scientific phenomena? What analogies do you know in science? What are their potential problems and limitations?

Worked example 2

The diagram shows a circuit with four resistors. Determine the power dissipated by each resistor.

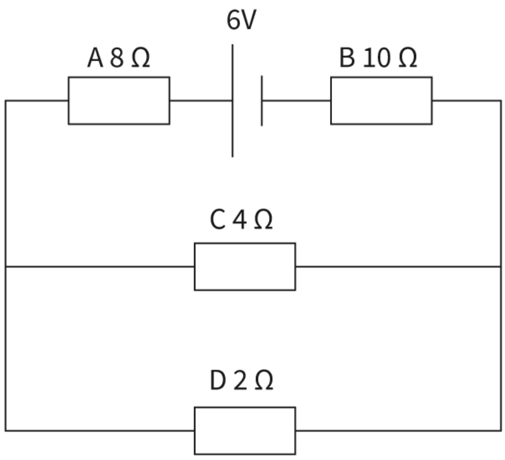

Figure 2. Determine the power dissipated by each resistor.

More information for figure 2

The image is a circuit diagram featuring four resistors labeled A, B, C, and D. Resistor A has a resistance of 8 ohms, B is 10 ohms, C is 4 ohms, and D is 2 ohms. The diagram includes a 6-volt power supply. The resistors A and B are positioned in series on the top path of the circuit. Resistor C is positioned between the branches, forming the midline path in parallel with D, which lies on the bottom path of the circuit. The paths are connected to form a closed circuit, and the flow of current can be determined by examining the arrangement and values of each component.

[Generated by AI]

Solution steps	Calculations
Step 1: Write out the values given in the question and convert to the values required by the question.	$V = 6.0\ \text{V} A = 8.0\ \Omega B = 10\ \Omega C = 4.0\ \Omega D = 2.($

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Solution steps	Calculations
Step 2: Calculate the resistance of C and D.	$\frac{1}{R_{\text{CD}}} = \left(\frac{1}{4} + \frac{1}{2}\right)$ $R_{\text{CD}} = 1.33\ \Omega$
Step 3: Calculate the total resistance.	$R_{\text{s}} = 8 + 10 + 1.33$ $= 19.33\ \Omega$
Step 4: Calculate the total current from the cell.	$V = IR_{\text{s}}$ $I = \frac{V}{R}$ $= \frac{6.0}{19.33}$ $= 0.31\ \text{A}$ This is the current through A and B.
Step 5: Calculate the power dissipated by A and B.	$P = I^2R$ $P_{\text{A}} = 0.31^2 \times 8$ $= 0.77\ \text{W (2 s.f.)}$ $P_{\text{B}} = 0.31^2 \times 10$ $= 0.96\ \text{W (2 s.f.)}$
Step 6: Determine the electric potential difference across A, B, C and D.	$V = IR$ $V_{\text{A}} = 0.31 \times 8$ $= 2.48\ \text{V}$ $V_{\text{B}} = 0.31 \times 10$ $= 3.10\ \text{V}$ $V_{\text{C}} = V_{\text{D}}$ $= V_{\text{x}}$ $6 = 2.48 + 3.10 + V_{\text{x}}$ $V_{\text{x}} = 6 - (2.48 + 3.10)$ $V_{\text{C}} = V_{\text{D}}$ $= 0.42\ \text{V (2 s.f.)}$

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Solution steps	Calculations
Step 7: Calculate the power dissipated by C and D.	$P = \frac{V^2}{R}$ $P_C = \frac{0.42^2}{4} = 0.04 \text{ W (2 s.f.)}$ $P_D = \frac{0.42^2}{2} = 0.09 \text{ W (2 s.f.)}$

Making connections

If you calculate the power dissipated by each component in a circuit, the total power will equal the power supplied by the cell. This agrees with the principle of conservation of energy (subtopic B.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43134/)).

In **Worked example 2**, we can add all the power dissipations from each resistor:

$$\begin{aligned} P_A + P_B + P_C + P_D &= 0.77 + 0.96 + 0.04 + 0.09 \\ &= 1.86 \text{ W} \\ &= P_{\text{cell}} \end{aligned}$$

So what makes an electric eel attack so powerful – electric potential difference or current?

The equation $P = VI$ tells us that both V and I are important. In the case of the Van de Graaff generator, the current is very small and therefore the power dissipated is low enough to be safe in a classroom. In any circuit, including that created by an electric eel, power depends on both current and electric potential difference.

Everything that uses electricity uses electrical energy. The rate at which it uses this electrical energy is its power. Work through the activity to check your understanding of power in electric circuits.

Student view

Activity

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- **IB learner profile attribute:**
    - Inquirer
    - Knowledgeable
    - Caring
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

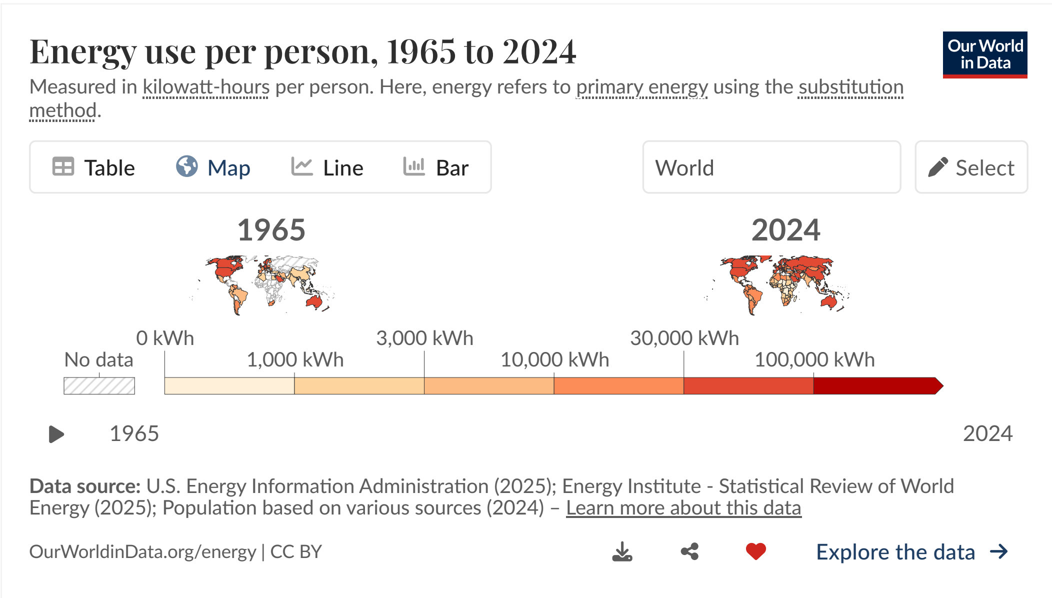
Instructions

Look around your home or school. Find the electrical appliances and look for their power ratings. Some appliances have labels with the power the device uses. Others may be labelled with the voltage (electric potential difference) and current. Some you may have to search the internet for.

Safety note: Turn off each appliance and disconnect it from the mains before looking for the power rating. Appliances like light bulbs or heaters remain hot for a long time after disconnecting.

Try to look at all the electrical appliances in one room, or in one area. Then, find the total power used by this room, or area. Is it more or less than you expected? Estimate the value for the whole building.

If you multiply the power in kilowatts by the amount of time these devices are turned on in hours, you get a unit of energy called the kilowatt hour. Use the interactive map to see the amount of energy the average person in your country used in 2021 (including industry, manufacturing and transport). How do you think you compare?



Interactive 1. Interactive energy map.

More information for interactive 1

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The Energy Use Per Person, 2023 interactive map provides a global comparison of per capita energy consumption, measured in kilowatt-hours. Using a color gradient, the map visually represents energy use across different countries, with darker shades indicating higher energy consumption and lighter shades representing lower energy use. Countries with unavailable data are marked with a striped pattern.

This interactive allows users to:

- Compare energy use across countries and regions, revealing patterns linked to economic development and energy access.
- Switch between data views map, table, or chart to explore energy trends in different formats.
- Use the time-lapse feature to track historical changes in energy consumption from 1965 to 2023.

By exploring this visualization, users can identify disparities in energy consumption between different parts of the world. For example:

- Wealthier nations such as those in North America, Europe, and parts of the Middle East tend to have higher per capita energy consumption due to industrialization, transportation, and household electricity use.
- Developing countries, particularly in Africa and parts of Asia, generally have lower energy use, reflecting differences in infrastructure, access to electricity, and economic activity.

This tool helps users understand global energy consumption trends and reflect on their own energy use in comparison to national and global averages. By connecting personal electricity use to broader energy patterns, users gain insight into how individual, industrial, and transportation energy demands contribute to overall consumption.

4 section questions

Question 1

SL HL Difficulty:

A wire with resistance *R* is connected to a cell of emf *V*. Initially, the power delivered by the cell is *P*. After a while, the temperature of the wire increases.

Which of the following statements is true?

1 *P* decreases because *R* increases ✓

2 *P* increases because *R* increases

3 *P* increases because *R* decreases

4 *P* decreases because *R* decreases

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Explanation

When the temperature of a wire increases, its resistance increases.

V does not change.

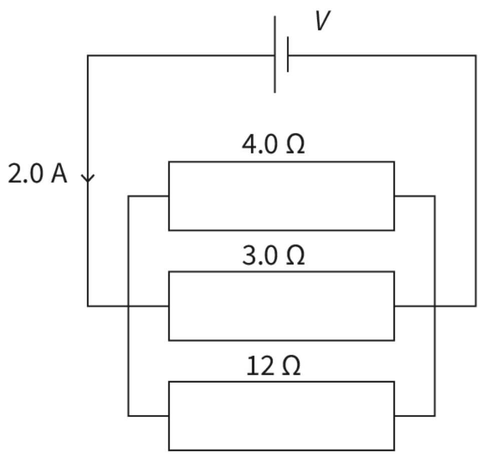
$$P = \frac{V^2}{R}$$

As R increases, P decreases.

Question 2

SL HL Difficulty:

The diagram shows a circuit with three resistors. Determine the power delivered by the cell.



More information

1 6.0 W ✓

2 2.3 W

3 3.0 W

4 0.8 W

Explanation

$$\frac{1}{R_\text{p}} = \left(\frac{1}{4} + \frac{1}{3} + \frac{1}{12}\right)$$

$$R_\text{p} = 1.5\ \Omega$$

Student view

$$P = I^2R$$
$$= 2^2 \times 1.5$$
$$= 6.0\text{ W (2 s.f.)}$$

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Question 3

SL HL Difficulty:

A light bulb is rated at 60 W when connected to a mains voltage of 220 V. Determine its power when it is connected to a mains voltage of 110 V. Give your answer to an appropriate number of significant figures

The power is 1 15 ✓ W.

Accepted answers and explanation

#1 15

15 W

15 watts

General explanation

The light bulb uses 60 W when it is connected to 220 V.

Using the equation $P = \frac{V^2}{R}$

If the mains voltage is reduced to 110 V then the power will be reduced by $2^2 = 4$ times.

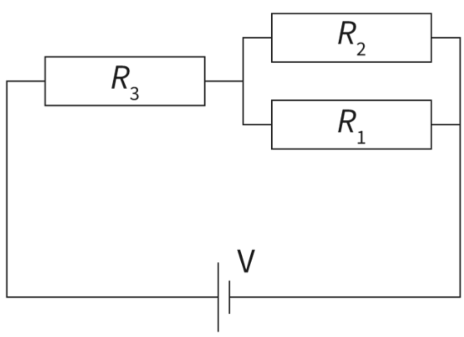
The power will be $\frac{60}{4} = 15\text{ W (2 s.f.)}$

Question 4

SL HL Difficulty:

The diagram shows a circuit with resistors R_1, R_2 and R_3 connected to a cell of emf V. Initially, the resistors have power ratings of P_1, P_2 and P_3, respectively.

R_3 is replaced with a new resistor with nearly zero resistance. Predict the change in P_1 and P_2.



Student view

More information

1 P_1 increases and P_2 increases ✓

2 P_1 decreases and P_2 decreases

3 P_1 increases and P_2 decreases

4 P_1 decreases and P_2 increases

Explanation

At the start, R_1 and R_2 are in parallel, and they are in series with R_3.

R_1 and R_2 each have an electric potential difference smaller than the emf V (since $V_3 > 0$).

When R_3 is changed to nearly 0 Ω, there is no electric potential difference across R_3.

V_1 and V_2 are equal to the emf V.

The electric potential difference across R_1 and R_2 increases.

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

If V increases and R remains constant, P increases.

Cells and internal resistance

B.5.14: Cell emf and internal resistance B.5.15: Variable resistance

Learning outcomes

At the end of this section you should be able to:

- Understand the relationship between emf ε and internal resistance r as given by $\varepsilon = I(R + r)$.
- Understand that resistors can have variable resistance.

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- Determine emf and internal resistance from a graph.

Using the simulation in **Interactive 1**, place one cell on the screen, open the 'advanced' settings box and increase the 'battery resistance' to 1 ohm. Use the voltmeter to measure the electric potential difference across the cell. Now, connect the cell to a resistor. What happens to the potential difference? Why?

Interactive 1. Measuring electric potential difference across a cell.

More information for interactive 1

The interactive simulation, Measuring electric potential difference across a cell, allows users to explore electric circuits by constructing and analyzing them. The interface provides various circuit elements, including wires, a battery, a light bulb, a resistor, and measuring instruments like a voltmeter and an ammeter. Users can assemble circuits by dragging and connecting these elements.

In this scenario, a single battery is placed on the screen, and the voltmeter is used to measure the electric potential difference (voltage) across the battery. The advanced settings panel is open, allowing adjustments to battery resistance and wire resistivity. The battery resistance is set to 1 ohm. The voltmeter, connected across the battery terminals, displays a voltage of 9 V, indicating the potential difference when no external circuit is connected.

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Users can modify parameters to see how different factors influence the circuit. When a resistor is connected across the battery, the potential difference measured by the voltmeter changes. This occurs because the battery, now part of a complete circuit, experiences internal resistance and voltage drop due to current flow. The actual terminal voltage of the battery is affected by the internal resistance. This follows the relationship:

$V = E - I r$, where E is the electromotive force of the battery, I is the current, and r is the internal resistance.

The simulation visually represents current flow, allowing users to switch between electron flow and conventional current representation. By observing these changes, users can develop a deeper understanding of concepts such as internal resistance, voltage drop, and how circuit components interact.

Internal resistance

A cell consists of conductive components and a store of chemical energy. All these materials have resistance. This resistance is known as the internal resistance r.

The internal resistance of a cell can be represented by the circuit diagram in **Figure 1**.

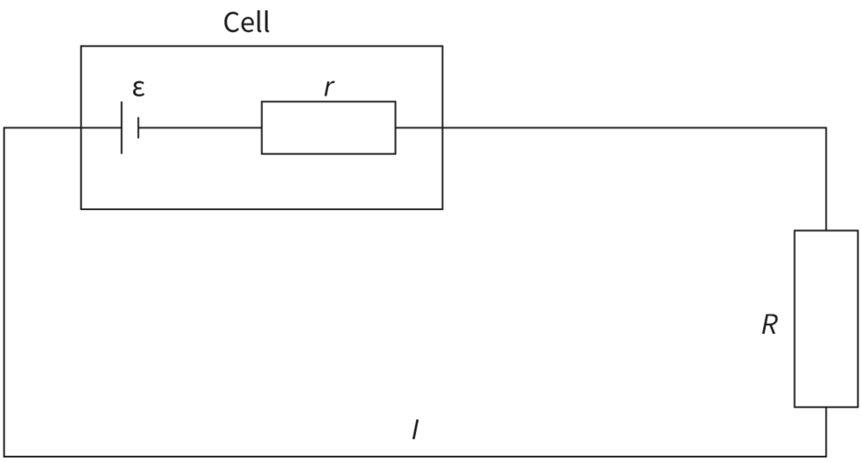

Figure 1. The internal resistance of a cell.

More information for figure 1

The diagram shows a simple electric circuit representing the internal resistance of a cell. It includes a cell (battery) with a voltage symbol denoted by ε. There is a resistor labeled r in series with the cell, which indicates the internal resistance of the cell. An external resistor labeled R is connected in series with the internal components. The total current flowing through the circuit is denoted by I, and this is indicated along the line between the internal resistance r and the external resistor R. The configuration visually represents how the internal and external resistances contribute to the total circuit resistance.

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The total resistance of the circuit is $r + R$.

Using Ohm's law:

$$V = IR$$

$$\varepsilon = I\,(r + R)$$

Table 1. Equation for internal resistance.

Equation	Symbols	Units
$\varepsilon = I(r + R)$	ε = emf of the cell	volts (V)
	R = resistance of the circuit	ohms (Ω)
	I = current flowing through the circuit	amperes (A)
	r = internal resistance	ohms (Ω)

Worked example 1

A cell with an emf of 12 V is connected to a 4.8 kΩ resistor. The current in the circuit is 2.2 mA. Calculate the internal resistance of the cell.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert to the values required by the question.	$\varepsilon = 12\text{ V}$ $I = 2.2\text{ mA} = 0.0022\text{ A}$ $R = 4.8\text{ k}\Omega = 4800\ \Omega$
Step 2: Write out the equation and rearrange the equation to make r the subject.	$\varepsilon = I(r + R)$ $r = \left(\frac{\varepsilon}{I}\right) - R$

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Solution steps	Calculations
Step 3: Substitute the values given.	$= \left(\frac{12}{0.0022}\right) - 4800$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 654.545\ \Omega = 650\ \Omega\ (2\ \text{s.f.}$

Interpreting a V–I graph to find emf and internal resistance

We can set up a circuit with a variable resistor to obtain multiple readings of electric potential difference and current. If we plot a graph of electric potential difference against current, we can use it to determine the emf and internal resistance of a cell.

The circuit set up is shown in **Figure 2**.

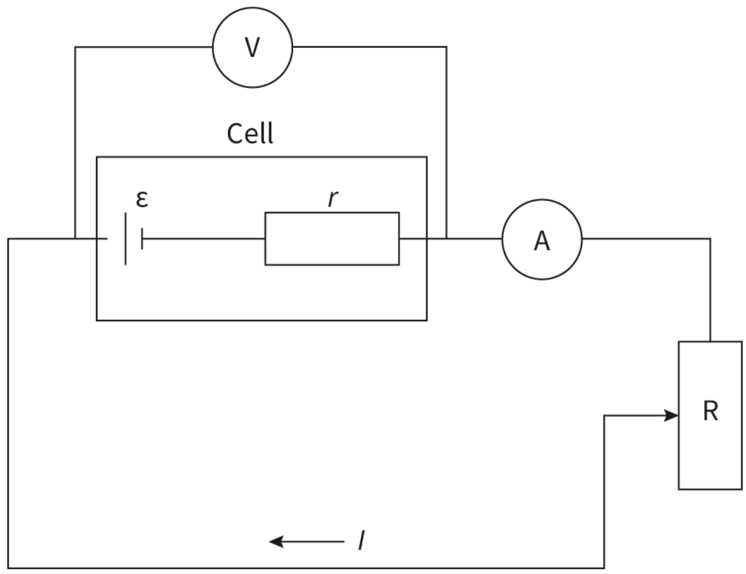

Figure 2. A circuit with a potentiometer.

More information for figure 2

The diagram illustrates an electrical circuit featuring a potentiometer. It depicts a cell with an internal resistance labeled as 'r' and an electromotive force denoted by 'ε'. The cell is connected in series with an ammeter labeled 'A', and a voltmeter labeled 'V' is connected in parallel. The circuit is completed with a potentiometer represented by 'R', which

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acts as a variable resistor. Arrows indicate the direction of current flow. The diagram effectively demonstrates how the resistance 'R' can be adjusted to change the current in the circuit.

[Generated by AI]

Resistor R is a potentiometer. This is an electrical component that can act as a variable resistor. Inside a potentiometer, there is a resistive wire with $R = \frac{\rho L}{A}$ (section B.5.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/resistance-resistivity-and-ohms-law-id-44363/)) so the resistance R is proportional to the length L. The length, L, can be varied in order to change the resistance of the potentiometer.

Figure 3 shows a potentiometer. By connecting the wires to terminals A and W (or W and B), turning the knob increases or decreases the length of the wire, which increases or decreases the resistance.

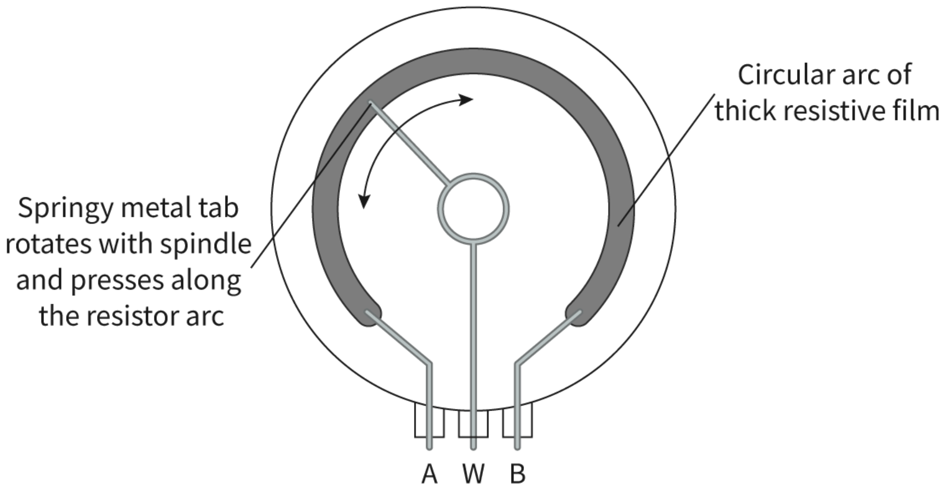

Figure 3. Inside a potentiometer.

More information for figure 3

This is a diagram illustrating the internal structure of a potentiometer. The diagram consists of a circular arc made from a thick resistive film. At the center, there is a spindle with a springy metal tab attached to it. The tab rotates with the spindle and presses along the resistive arc. At the bottom of the diagram, there are three terminals labeled A, W, and B. The path of rotation of the spindle is indicated by arrows, showing how the metal tab moves along the resistive arc. The diagram demonstrates the setup for adjusting resistance in a circuit by changing the position of the tab along the resistive arc. Labels in the diagram indicate the "Springy metal tab rotates with spindle and presses along the resistor arc," and the "Circular arc of thick resistive film."

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Student view

Overview
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If we plot a graph of V against I, what will be the y-intercept and gradient?

$$\varepsilon = I\left(r + R\right)$$
$$\varepsilon = Ir + IR$$
$$\varepsilon = Ir + V$$
$$V = -Ir + \varepsilon$$

By comparing $V = -Ir + \varepsilon$ to the equation for a straight line $y = mx + c$, for a V–I graph:

- y-axis = V
- x-axis = I
- slope = $-r$
- y-intercept = ε

Worked example 2

The graph shows how the electric potential difference across a cell varies with the current leaving the cell. Determine the emf of the cell and its internal resistance.

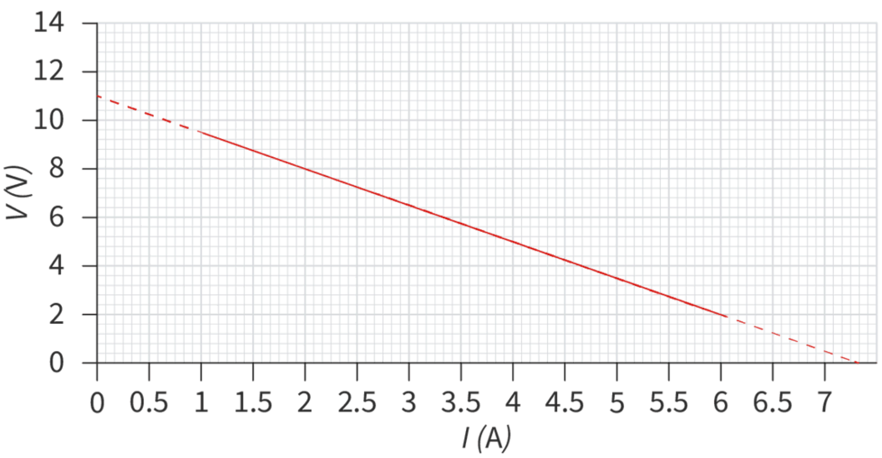

Figure 4. Determine the emf of the cell and its internal resistance.

More information for figure 4

The graph illustrates the relationship between the electric potential difference (V, in volts) and the current (I, in amperes) across a cell. The X-axis represents the current, labeled from 0 to 7 amperes in increments of 0.5 A. The Y-axis represents the voltage, labeled from 0 to 14 volts with increments of 2 V. A red line with a downward trend indicates

Student view

how the voltage decreases as the current increases, suggesting the internal resistance of the cell. The line starts just above 10 V at 0 A and decreases steadily, passing through 5 V at approximately 5 A, showing an approximately linear relationship with a negative slope.

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$$V = -Ir + \varepsilon$$

$$y\text{-intercept} = 11 \text{ V}$$

$$\varepsilon = 11 \text{ V}$$

$$\begin{aligned} \text{gradient} &= -r \\ &= \frac{(9.5 - 2)}{(1 - 6)} \\ -r &= -1.5 \\ r &= 1.5 \ \Omega \ (2 \text{ s.f.}) \end{aligned}$$

Figure 5 shows a V–I graph for a cell. The cell is part of a circuit containing a load resistor R. If the current in the circuit is equal to 1.00 A, calculate the resistance of the load resistor.

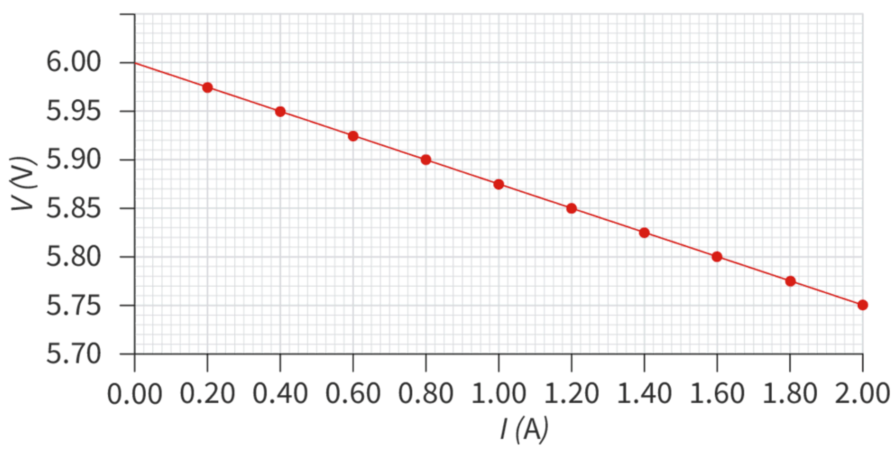

Figure 5. V–I graph for a cell.

More information for figure 5

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The image is a graph plotting voltage (V) against current (I). The X-axis represents the current, measured in amperes (A), and ranges from 0.00 to 2.00 in intervals of 0.20. The Y-axis represents the voltage, measured in volts (V), ranging from 5.70 to 6.00 in intervals of 0.05. The graph shows a downward sloping straight line, indicating that as current increases, the voltage decreases. Data points are plotted along the line, with a smooth decline. This represents the characteristic response of the cell in the circuit as detailed in the text before the image.

[Generated by AI]

Solution steps	Calculations
Step 1: In the data booklet, look for the equation linking electromotive force, current, internal resistance and load resistance.	$\varepsilon = I(R + r)$
Step 2: Rearrange the equation for the load resistance R	$R = \frac{\varepsilon - Ir}{I}$
Step 3: The y-intercept is the electromotive force of the cell	$\varepsilon = 6.00 \text{ V}$
Step 4: The gradient is the internal resistance r of the cell	$\text{Gradient} = \frac{6.00 - 5.75}{0.00 - 2.00}$ $= -0.125 \text{ V A}^{-1}$ $r = 0.125\ \Omega$
Step 5: Substitute the numerical values for electromotive force, current and internal resistance into the equation for R	$R = \frac{6.00 - 1.00 \times 0.125}{1.00}$ $= 5.88\ \Omega \text{ (3 s.f.)}$

Cells and electric potential difference

If we connect a voltmeter across a cell, the electric potential difference reading is equal to the emf ε. There does not appear to be any internal resistance, r. Why is this?

Figure 6 shows two circuits.

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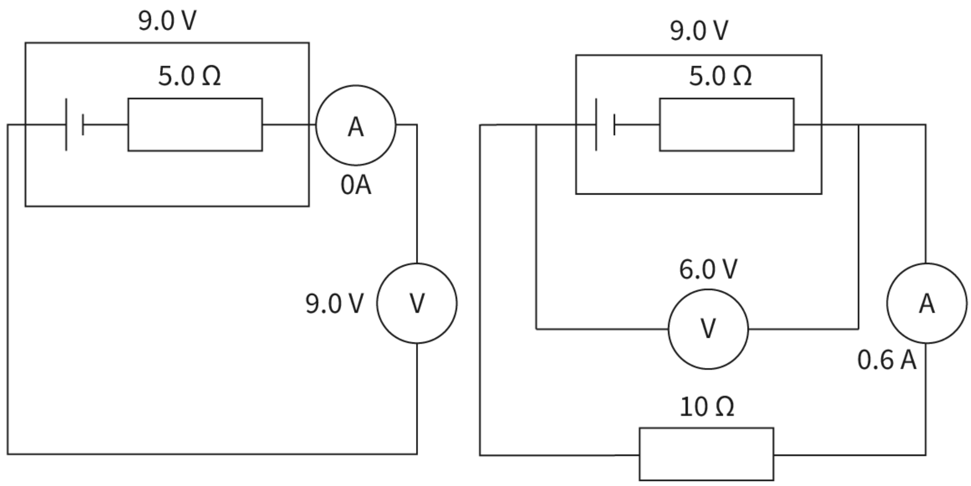

Figure 6. A circuit without a resistor and a circuit with a resistor.

More information for figure 6

The image contains two circuit diagrams side-by-side. The left circuit shows a closed loop with a 9.0V power supply connected to a 5.0Ω resistor. An ammeter is present and reads 0 A, indicating no current flow, and a voltmeter across the battery shows 9.0V. The right circuit also depicts a 9.0V power supply and a 5.0Ω resistor, but includes an additional resistor of 10Ω. Here, the ammeter reads 0.6 A, and a voltmeter shows 6.0V across the original 5.0Ω resistor. This indicates that current is flowing through the circuit.

[Generated by AI]

An ideal voltmeter has infinite resistance. When it is connected across a cell, the current, I, is 0 A.

Rearranging $\varepsilon = I(R + r)$ we can see:

$$\varepsilon = IR + Ir$$

IR is the measured potential difference across the cell, V, so:

$$\varepsilon = V + Ir$$

and

$$V = \varepsilon – Ir$$

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When no current flows in the circuit because the circuit is incomplete, $I = 0$ and so

$$V = \varepsilon$$

When the circuit is connected to a resistor, current flows and so the measured electric potential difference across the cell is again given by:

$$V = \varepsilon – Ir$$

Worked example 3

The diagram shows a circuit with a resistor and an ammeter. The voltmeter is ideal and the cell has zero internal resistance. The ammeter is not ideal. The resistance R of the resistor is 4.8 Ω. Determine the resistance of the ammeter.

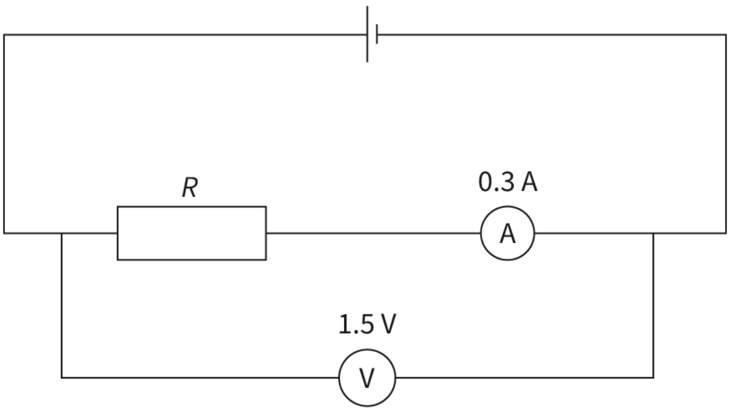

Figure 7. Determine the resistance of the ammeter.

More information for figure 7

The diagram illustrates a simple electrical circuit with the following components: a power source at the top, a resistor labeled "R" with a resistance of 4.8 Ω positioned centrally, an ammeter labeled "0.3 A" to the right of the resistor measuring the current, and a voltmeter at the bottom labeled "1.5 V" measuring the voltage across the circuit. The circuit is complete, demonstrating the flow of current through the resistor. The objective is to determine the resistance of the ammeter within this setup.

[Generated by AI]

Student view

$V = IR$ across resistor R and the ammeter:

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$$1.5 = 0.3 \times (R + \text{resistance of ammeter})$$
$$1.5 = 0.3 \times (4.8 + \text{resistance of ammeter})$$
$$\text{resistance of ammeter} = \frac{1.5}{0.3} - 4.8$$
$$= 0.2\,\Omega\ (2\text{ s.f.})$$

Concept

The emf of a cell is equal to the electric potential difference across the cell when there is no current moving through the electrical circuit.

5 section questions

Question 1

SL HL Difficulty:

State which words complete this statement.

When an ideal voltmeter is directly connected across a cell, the reading of the voltmeter is always ______ the emf of the cell.

1 equal to ✓

2 smaller than

3 larger than

4 none of the above

Explanation

$$\varepsilon = V + Ir$$

When I = 0 A:

$$\varepsilon = V$$

Question 2

SL HL Difficulty:

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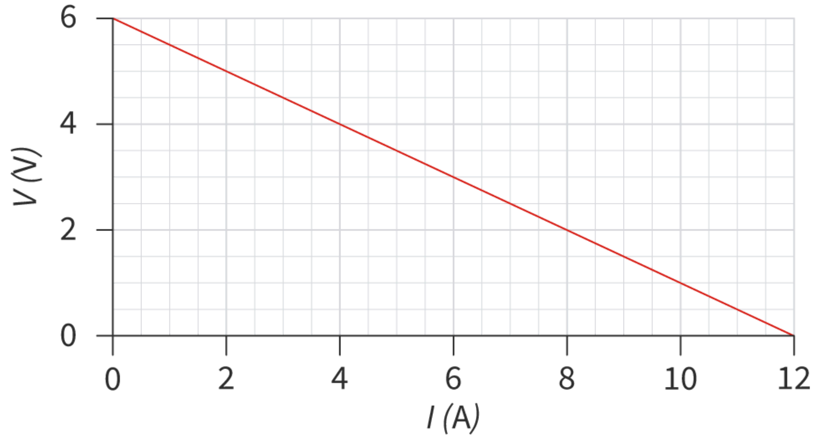
The graph shows how the electric potential difference across a cell varies with the current leaving the cell. Determine the internal resistance of the cell. Give your answer to an appropriate number of significant figures.

The internal resistance is 1 0.5 ✓ Ω



More information

Accepted answers and explanation

#1 0.5

0.5 ohms

0.5ohms

General explanation

$$V = -Ir + \varepsilon$$

$$\begin{aligned} \text{gradient} &= -r \\ &= \frac{(6.0 - 0.0)}{(0.0 - 12.0)} \\ &= -0.5 \end{aligned}$$

$$r = 0.5\ \Omega\ (2\text{ s.f.})$$

Question 3

SL HL Difficulty:

The graph shows how the electric potential difference across a cell varies with the current through the cell. The emf is 1 6.0 ✓ V.

Give your answer to a suitable number of significant figures.

Student view

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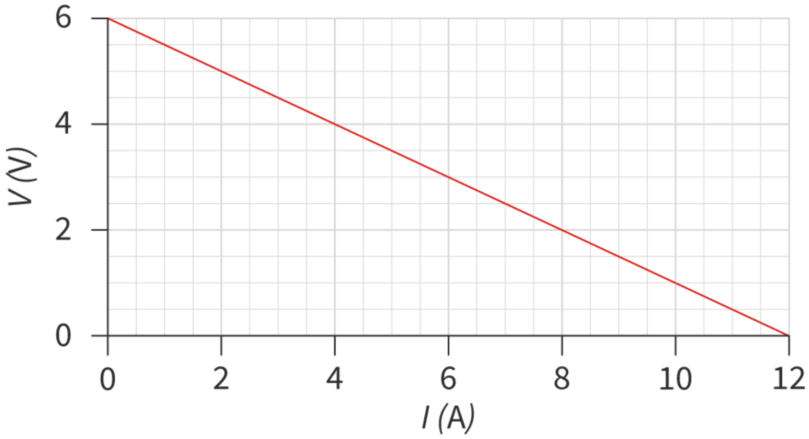


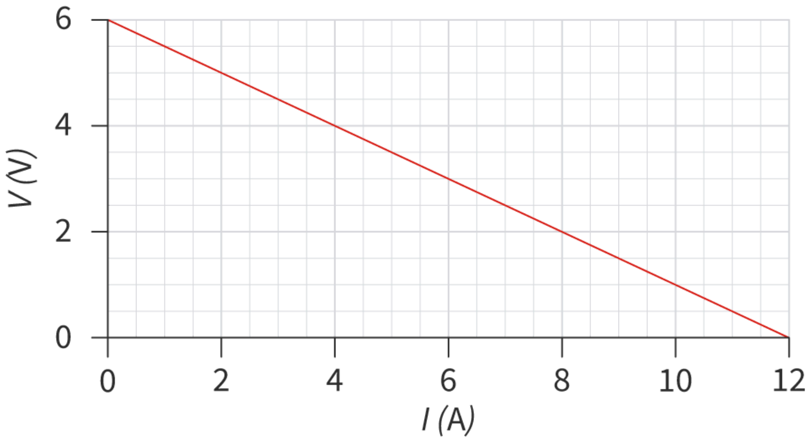
More information

Accepted answers and explanation

#1 6.0

6

General explanation



More information

This graph depicts the relationship between current (I) in amperes on the X-axis, ranging from 0 to 12, and voltage (V) in volts on the Y-axis, ranging from 0 to 6. The plotted red line shows a linear decrease in voltage as the current increases, indicating an inverse relationship. The line starts at the point (0, 6) and declines steadily to the point (12, 0). The graph is marked with grid lines for better readability, allowing for precise interpretation of values along both axes.

[Generated by AI]

$V = -Ir + \varepsilon$

y-intercept = ε

y-intercept is 6.0

$\varepsilon = 6.0$ V

Question 4

SL HL Difficulty:

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The electric potential difference across a cell with internal resistance is 2.4 V when the current is 0.6 A, and 2.2 V when the current is 0.7 A. Determine the emf of the cell. Give your answer to an appropriate number of significant figures.

The emf is 1 3.6 ✓ V

Accepted answers and explanation

#1 3.6

3.6 V

3.6V

General explanation

$$\begin{aligned}\varepsilon &= I(R+r)\\ &= V + Ir\\ &= 2.4 + 0.6r\end{aligned}$$

$$\varepsilon = 2.2 + 0.7r$$

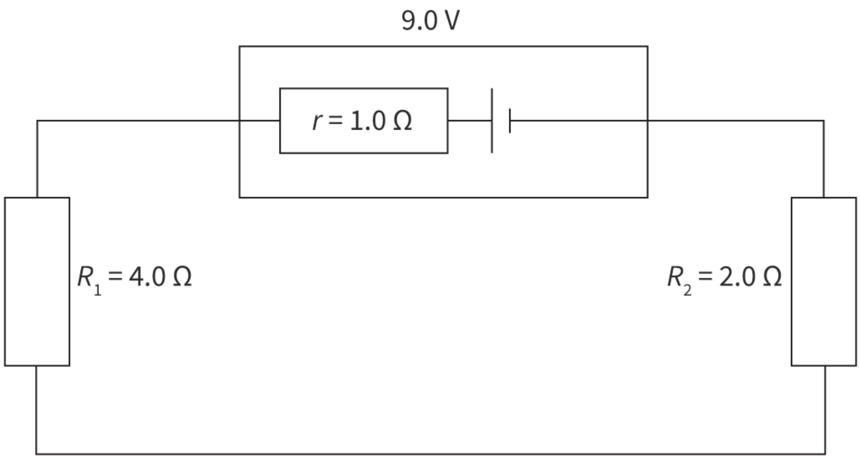
$$\begin{aligned}2.4 + 0.6r &= 2.2 + 0.7r\\ 0.2 &= 0.1r\\ r &= 2.0\ \Omega\end{aligned}$$

$$\begin{aligned}\varepsilon &= V + Ir\\ &= 2.4 + 0.6r\\ &= 2.4 + (0.6\times 2.0)\\ &= 3.6\ \text{V (2 s.f.)}\end{aligned}$$

Question 5

SL HL Difficulty:

The diagram shows a cell with internal resistance connected to two resistors. Determine the power dissipated in the internal resistor.



More information

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1 1.7 W ✓

2 0.0 W

3 3.3 W

4 6.6 W

Explanation

$$R_s = r + R_1 + R_2$$
$$= 1.0 + 4.0 + 2.0$$
$$= 7.0\ \Omega$$

$$V = IR$$
$$I = \frac{V}{R}$$
$$= \frac{9.0}{7.0}$$
$$= 1.286\ \text{A}$$

$$P = I^2R$$
$$= 1.286^2 \times 1$$
$$= 1.65\ \text{W}$$
$$= 1.7\ \text{W (2 s.f.)}$$

B. The particulate nature of matter / B.5 Current and circuits

Activity: emf and internal resistance

B.5.14: Cell emf and internal resistance B.5.15: Variable resistance

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/activity-emf-and-internal-resistance-id-44368/print/) Assign

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Activity

- **IB learner profile attribute:**
  - Inquirer
  - Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Group activity

Instructions

1. Work as a group of four. Divide into two teams: team A and team B.
2. Each team uses the simulation to build a circuit with a battery, a resistor, a voltmeter and an ammeter. Connect the voltmeter and ammeter properly. Make sure ‘Values’ is not enabled.
3. Each team goes to the other team’s simulation and uses the ‘Advanced’ menu to secretly adjust the ‘Battery Resistance’ slider (for example to 5 Ω), then hides the menu before handing back to the other team. Each team now has a simple circuit with a battery of unknown internal resistance.
4. Click on the resistor in your circuit and adjust its resistance using the slider. Record the values of resistance, current and electric potential difference in a table. Repeat for different values of resistance.

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5. Draw a *V*—*I* graph and use it to estimate the internal resistance and emf of your battery.
6. Open the ‘Advanced’ menu to see the actual value for ‘Battery Resistance’. Was your calculation of internal resistance correct?

Summary and key terms

- Electrical conductors have lots of mobile charge carriers, which are usually electrons. Electrical insulators do not have mobile charge carriers.
- A cell is a source of emf, which is the amount of energy that the cell transfers to each unit of charge. Real cells have resistance like any other electrical component; we refer to this as internal resistance.
- Current is the rate of flow of charge, and electric potential difference is the work done per unit charge to move a positive charge between two points along the path of the current.
- Resistance is a measure of how difficult it is for current to pass through an electrical component. Resistivity is the property of a material that measures how strongly it resists the flow of current.
- Ohm’s law states that the electric potential difference across a conductor is directly proportional to the current flowing through it, at constant temperature.
- A conductor that obeys Ohm’s law is an ohmic conductor. For an ohmic conductor, the resistance is constant. A conductor that does not obey Ohm’s law is a non-ohmic conductor. For a non-ohmic conductor, the resistance changes.
- The temperature of an electrical conductor can affect its resistance and resistors can have variable resistance.
- For a series circuit, the current is the same throughout the circuit, the electric potential difference across the cell is equal to the sum of the electric potential differences across each component, and the total resistance is equal to the sum of all the resistances in the circuit.
- For a parallel circuit, the electric potential difference is the same across a branch of the circuit, the total current is equal to the sum of the currents through each branch of the circuit, and the total resistance is less than the smallest resistance of an individual branch.
- The power dissipated by an electrical component is the amount of electrical energy transferred per unit time.

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Key terms

**Review these key terms. Do you know them all? Fill in as
can using the terms in this list.**

1. is the work done per unit charge c
positive charge between two points along the path of the curren
2. is the amount of energy transferre
charge.
3. is the rate of flow of charge.
4. In a circuit, the current is the sam
circuit.
5. In a circuit, the electric potential d
same across all the branches.
6. Ohm's law states that the electric potential difference across
directly proportional to the flowing th
constant .
7. The resistance of a cylindrical resistive wire is directly propor
and length, and inversely proportion
.
8. The resistance of an conductor is
resistance of a conductor is not cons
9. When an electric cell is in series with a resistor, the electric p
across the cell is .

less | series | ohmic | cross-sectional area
Electric potential difference | Electric current | current
non-ohmic | parallel | resistivity | Electromotive force

Check

Interactive 1. Summary and Key Terms.

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B. The particulate nature of matter / B.5 Current and circuits

Checklist

What you should know

After studying this subtopic, you should be able to:

- Explain the properties of electrical conductors and insulators.
- Describe cells as the source of emf in a circuit.
- Describe electric potential difference as the work done per unit charge to move a positive charge between two points along the path of the current, and electric current as a flow of charge.
- State the advantages and disadvantages of different sources of electrical energy.
- Define resistance as $R = \frac{V}{I}$ and define resistivity as $\rho = \frac{RA}{L}$.
- Understand Ohm's law and identify the ohmic and non-ohmic behaviour of electrical conductors.
- Understand that resistors can have variable resistance.
- Identify series and parallel circuits along with the circuit symbols of electrical components.
- Explain electric potential difference, current and resistance in series and parallel circuits.
- Determine the electrical power *P* dissipated by a resistor.
- Understand the relationship between emf ε and internal resistance r as given by $\varepsilon = I(R + r)$.
- Determine emf and internal resistance from a graph.

Practical skills

Once you have completed this subtopic, go to:

- Practical 7: Investigating the resistivity of a conducting wire (/study/app/math-aa-hl/sid-423-cid-762593/book/investigating-the-resistivity-of-a-conducting-wire-id-46511/) in which you will measure and examine resistivity.
- Practical 8: Measuring the internal resistance of a cell (/study/app/math-aa-hl/sid-423-cid-762593/book/measuring-the-internal-resistance-of-a-cell-id-46512/) in which you will plot the relationship between emf and internal resistance for various cells.

Investigation

- **IB learner profile attribute:**
  - Thinker
  - Communicator
- **Approaches to learning:** Thinking skills – Applying key ideas and facts in new contexts
- **Time required to complete activity:** 30 minutes
- **Activity type:** Group/pair activity

Your task

Discuss why imagination and models are useful to explain the concepts in electric circuits.

Are you familiar with the water pump analogy for electrical circuits? If not, do some research on it and then discuss the limitation of the water pipe analogy. Can it explain all the concepts you have learned about circuits so far?

Suggest a new analogy to explain one or more concepts in the circuit. For example:

- how to explain the properties of series and parallel circuits?
- how to explain ohmic and non-ohmic devices?
- how to explain the behaviour of thermistors and LDRs?

The best model should allow us to explain as many concepts as possible within a system.

Concluding and evaluating

Present a 1–2-minute summary to the class.

Analyse the pros and cons of the new analogies suggested by the other groups.

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Theory of Knowledge

How can we decide when one model/explanation/theory is better than another?

A model is usually showing us a closer look at one specific aspect of a phenomenon only. While models often can provide us a better understanding or explanation of an abstract idea, they are always flawed or not applicable to certain situations. Take the water pipe analogy as an example again. How do we explain the effect of temperature on resistance? When a water pipe gets narrow, the water stream often appears to flow more quickly. Does that not go against our understanding of narrow electrical wires?

B. The particulate nature of matter / B.5 Current and circuits

Reflection

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/reflection-id-47876/print/) Assign

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44361/).

- How do charged particles flow through materials?
- How are the electrical properties of materials quantified?
- What are the consequences of resistance in conductors?

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With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

Once you submit your response, you won't be able to edit it.

0/2000

Submit

Rate subtopic B.5 Current and circuits

Help us improve the content and user experience.

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