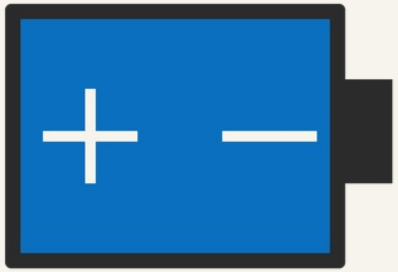
ELECTRICITY 3 · EMF & INTERNAL RESISTANCE

EMF & Internal Resistance

Why a real battery never quite delivers the voltage printed on the label.

Higher Physics



Starter

2007 Higher Physics

Scan the code and answer these:

Q9 **Q28**

Section A · resistors, wavelength

Show your working, not just the letter.

Scan for the paper

Marking scheme

PART 1

EMF and internal resistance

Every real power supply has a little resistance of its own — and that changes everything downstream of it.

By the end of this part...

1. I can define e.m.f., internal resistance, lost volts and terminal p.d.
2. I can explain why the terminal p.d. drops once a current flows.
3. I can state what is meant by an ideal supply, a short circuit and an open circuit.

Voltage is energy per coulomb

- A $6.0\ \mathrm{V}$ cell gives $6.0\ \mathrm{joules}$ of energy to every coulomb of charge it pushes round.
- So $2.0\ \mathrm{coulombs}$ leave the cell carrying $12\ \mathrm{joules}$ between them.
- That is all "voltage" ever means: energy per coulomb of charge.

Why a cell loses some of it

Beyond the examined content — but it is why the lost volts exist at all.

Inside the cell

A chemical reaction between two electrodes supplies the energy.

It warms the cell

Some of that energy heats the cell instead of leaving it.

More current

A bigger current wastes more energy on the way through.

The four terms

- E.m.f. — the energy the cell gives each coulomb. Measured with no current flowing.
- Internal resistance — the resistance of the cell itself.
- Lost volts — the energy per coulomb wasted pushing charge through the cell.
- Terminal p.d. — what is left over for the circuit outside the cell.

JOTTER NOTES

E.m.f. and terminal potential difference

The e.m.f. is the energy the cell gives to every coulomb of charge that passes through it.

You only measure the full e.m.f. when no current is flowing.

Once a current flows, some energy is wasted inside the cell itself.

The voltage left for the rest of the circuit is the terminal potential difference.

JOTTER NOTES

Internal resistance and lost volts

Every real cell has a small resistance of its own inside it, called the internal resistance.

Pushing a current through that internal resistance wastes energy as heat inside the cell.

The voltage wasted inside the cell is called the lost volts.

$$lost\ volts = Ir$$

Ideal, short circuit, open circuit

- An ideal supply has no internal resistance, so nothing is ever lost inside it.
- A short circuit has no external resistance, so the current is as big as the cell can make it.
- An open circuit has a break in it, so no current flows at all.

JOTTER NOTES

Ideal supply, short circuit and open circuit

An ideal supply has no internal resistance, so its terminal potential difference always equals its e.m.f.

A short circuit has no external resistance, so the current is the largest the cell can ever give.

An open circuit has a break in it, so no current flows and a voltmeter reads the full e.m.f.

Watch Out — when the voltmeter reads the e.m.f.

THE MISTAKE

- Reading any voltmeter across a cell as "the e.m.f."
- Forgetting to say why no current means no lost volts

THE CORRECT ANSWER

- It only reads the e.m.f. when no current is flowing.
- No current means nothing is wasted inside the cell.

Show Me: the terms

SHOW ME BOARDS

1. State what is meant by the e.m.f. of a cell.
2. State what is meant by the internal resistance of a cell.
3. A cell is left with nothing connected to it. State what a voltmeter across its terminals would read, and why.
4. State the internal resistance of an ideal supply.
5. Explain why the terminal p.d. of a real cell falls as the current drawn from it rises.

Show Me: the terms

SHOW ME BOARDS

EXTRA PRACTICE

1. State what is meant by the lost volts of a cell.
2. A $1.5\ \mathrm{V}$ cell drives a torch bulb. State whether the voltmeter across the cell reads more than, less than or exactly $1.5\ \mathrm{V}$.
3. Explain, in terms of energy, what a p.d. of $9.0\ \mathrm{V}$ tells you.
4. State what is meant by a short circuit.
5. Two cells have equal e.m.f. but different internal resistance. State and justify which drives the larger current.

Task

Work through the Internal Resistance exercise.
Write down what each symbol stands for before you substitute.

Exercise 3.2.2 (P313/326)
Past papers: 2015 Q10(a), 2016 Q12(a)

Past Paper Finder

Starter

2013 Revised Higher Physics

Scan the code and answer these:

Q3 **Q17**

Section A · uncertainty, circuit reading

Show your working, not just the letter.

Scan for the paper

Marking scheme

PART 2

The e.m.f. equation

One relationship connects everything a real supply does — e.m.f., lost volts and terminal p.d. all in one line.

By the end of this part...

1. I can use $E = V + Ir$ to find e.m.f., lost volts or terminal p.d.
2. I can use $E = I(R + r)$ when I am given the external resistance.
3. I can rearrange either form to find the internal resistance.

$E = V + Ir$

JOTTER NOTES

$$E = V + Ir$$

E	**V**	**I**	**r**
e.m.f. (V)	terminal p.d. (V)	current (A)	internal resistance (Ω)

JOTTER NOTES

Using the e.m.f. equation

The e.m.f. splits in two: the part left for the circuit, and the part wasted inside the cell.

The wasted part is the lost volts, and it grows as the current grows.

With no current at all, nothing is wasted and the terminal potential difference equals the e.m.f.

The other form of the same equation

JOTTER NOTES

$$E = I(R + r)$$

E	I	R	r
e.m.f. (V)	current (A)	external resistance (Ω)	internal resistance (Ω)

JOTTER NOTES

Choosing which form to use

Use the first form when the question gives you the terminal potential difference.

Use the second form when it gives you the resistance of the circuit outside the cell.

Both say the same thing: the e.m.f. is shared between the circuit and the cell itself.

Worked example — terminal p.d.

A battery of e.m.f. $12\ \mathrm{V}$ and internal resistance 0.50 Ω delivers a current of $2.0\ \mathrm{A}$. Calculate the terminal p.d.

$\mathrm{E} = 12\ \mathrm{V}$

$\mathrm{r} = 0.50\ \Omega$

$\mathrm{I} = 2.0\ \mathrm{A}$

$\mathrm{V} = ?$

$E = V + Ir$

$V = E - Ir$

$\mathrm{V} = 12 - (2.0 \times 0.50)$

$\underline{\mathrm{V} = 11\ \mathrm{V}}$

Worked example — internal resistance

A cell of e.m.f. 9.0 V drives a current of 1.5 A through a 5.0 Ω resistor. Calculate the internal resistance of the cell.

$E = 9.0\ \mathrm{V}$

$I = 1.5\ \mathrm{A}$

$R = 5.0\ \Omega$

$r = ?$

$E = I(R + r)$

$9.0 = 1.5 \times (5.0 + r)$

$6.0 = 5.0 + r$

$\underline{r = 1.0\ \Omega}$

Watch Out — $E = V + Ir$

THE MISTAKE

- Putting the external resistance R into the Ir term
- Assuming the terminal p.d. always equals the e.m.f.

THE CORRECT ANSWER

- Ir uses the current and the INTERNAL resistance.
- They are equal only when no current flows.

Show Me: E = V + Ir

SHOW ME BOARDS

1. A cell of e.m.f. $6.0\ \mathrm{V}$ and internal resistance $1.0\ \Omega$ delivers $1.5\ \mathrm{A}$. Calculate the terminal p.d.
2. State the lost volts in the situation above.
3. A $1.5\ \mathrm{V}$ cell with internal resistance $0.50\ \Omega$ delivers $0.20\ \mathrm{A}$. Calculate the terminal p.d.
4. A battery of e.m.f. $12\ \mathrm{V}$ has a terminal p.d. of $11.2\ \mathrm{V}$ when delivering $4.0\ \mathrm{A}$. Calculate its internal resistance.
5. The current drawn from a cell is doubled. State and justify what happens to the lost volts.

Show Me: $E = V + Ir$

SHOW ME BOARDS

EXTRA PRACTICE

1. A cell of e.m.f. $4.5\ \mathrm{V}$ and internal resistance $0.75\ \Omega$ delivers $2.0\ \mathrm{A}$. Calculate the terminal p.d.
2. A battery of e.m.f. $9.0\ \mathrm{V}$ has a terminal p.d. of $8.1\ \mathrm{V}$ at $3.0\ \mathrm{A}$. Calculate its internal resistance.
3. A $1.5\ \mathrm{V}$ cell with internal resistance $0.50\ \Omega$ is connected to a $2.5\ \Omega$ resistor. Calculate the current.
4. The lost volts are $0.60\ \mathrm{V}$ when the current is $1.2\ \mathrm{A}$. Calculate the internal resistance.
5. Explain why a car headlamp dims briefly while the engine is being started.

Task

Work through the e.m.f. equation questions.
Show the relationship, the substitution and the unit every time.

Exercise 3.2.2 (P313/326)
Past papers: 2017 Q12

Past Paper Finder

Starter

2012 Higher Physics

Scan the code and answer these:

Q9

Section A · network resistance

Show your working, not just the letter.

Scan for the paper

Marking scheme

PART 3

Measuring EMF and r

The named experiment: change the load, read the meters, and both e.m.f. and internal resistance fall out of the same circuit.

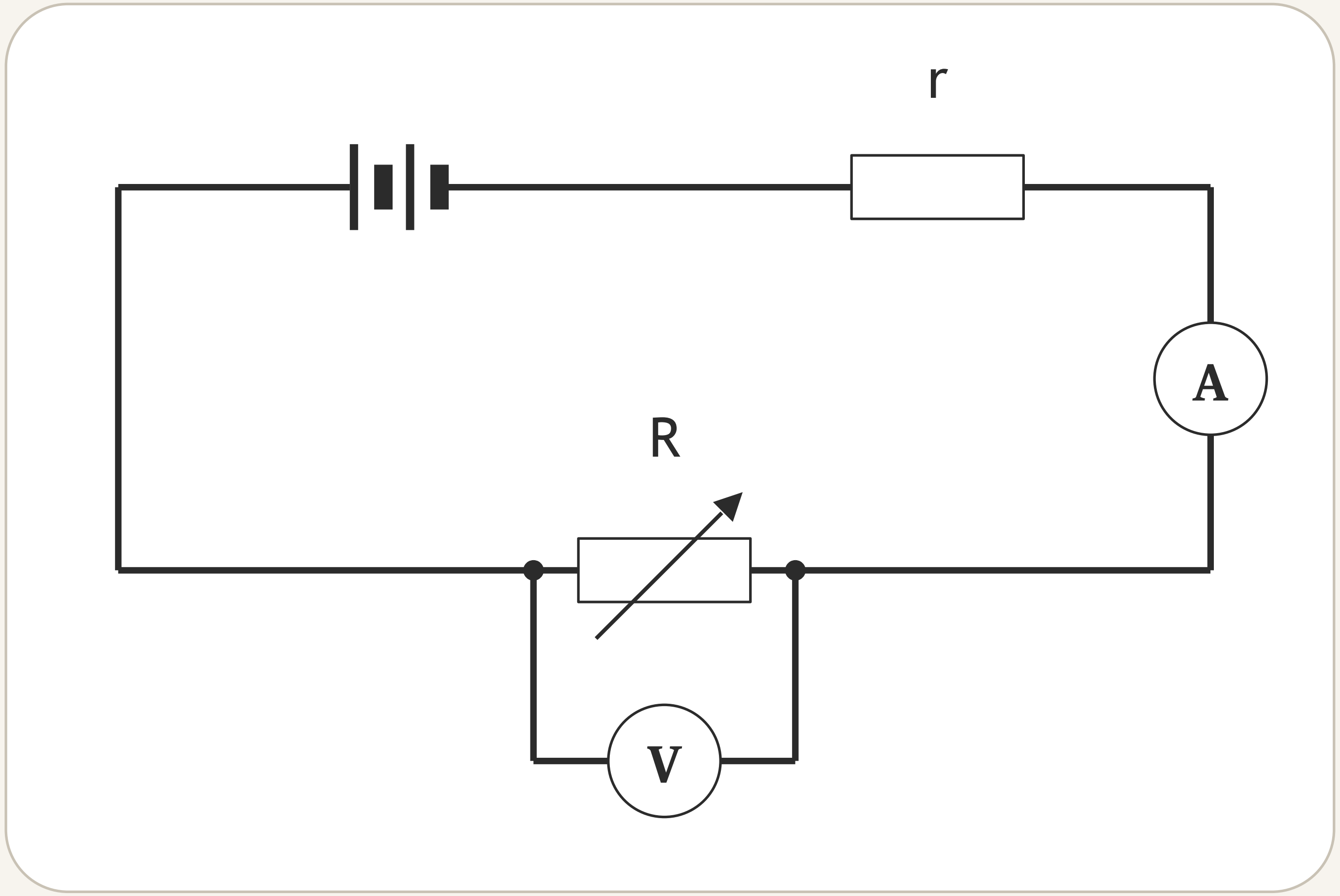
By the end of this part...

1. I can describe an experiment to measure the e.m.f. and internal resistance of a cell.
2. I can state what is varied and what is measured in it.
3. I can explain why the meters are connected where they are.

The experiment circuit

JOTTER NOTES

A voltmeter across the load, an ammeter in series.



JOTTER NOTES

Measuring e.m.f. and internal resistance

Connect the cell in series with a variable resistor and an ammeter.

Connect the voltmeter across the variable resistor.

The variable resistor is the only thing outside the cell, so that reading is the terminal potential difference.

Change the variable resistor and record each pair of voltmeter and ammeter readings.

JOTTER NOTES

Why r is drawn outside the cell

The internal resistance is inside the cell — you cannot reach it or change it.

We draw it as a separate resistor next to the cell only so that it can be labelled.

The cell and that resistor together are what you actually hold in your hand.

JOTTER NOTES

What you do with the readings

Plot the voltmeter readings up the side and the ammeter readings along the bottom.

The points lie on a straight line that slopes downwards.

Draw the best-fit line and continue it until it crosses both axes.

Watch Out — know both methods

THE MISTAKE

- Only being able to describe the graphical method
- Describing the circuit without saying what is varied

THE CORRECT ANSWER

- Know the direct method too: two readings into $E = V + Ir$.
- Say clearly that the variable resistor is changed each time.

Show Me: the experiment

SHOW ME BOARDS

1. State the two meters used in this experiment, and how each is connected.
2. State what is varied during the experiment.
3. State what quantity is plotted on each axis of the resulting graph.
4. Explain why the voltmeter must be connected across the cell rather than across the variable resistor.
5. State how many pairs of readings you would take, and why more than two is better.

Show Me: the experiment

SHOW ME BOARDS

EXTRA PRACTICE

1. Describe how you would find the e.m.f. and internal resistance using only two pairs of readings and no graph.
2. State one reason the graph gives a more reliable answer than two readings.
3. Explain why an ammeter should have a very low resistance in this circuit.
4. Explain why a voltmeter should have a very high resistance in this circuit.
5. The variable resistor is set to its lowest value. State and justify what happens to the voltmeter reading.

Task

Carry out the Graphical Determination experiment.
Record your pairs of readings as you go.
Plot the graph before you leave the lab — the line tells you if a reading is wrong.

Experiment 3.2.3 (P316/329)

Starter

2014 Revised Higher Physics

Scan the code and answer these:

Q16 **Q17** **Q20**

Section A · resistance, uncertainty

Show your working, not just the letter.

Scan for the paper

Marking scheme

PART 4

Finding EMF and r from a graph

The straight line the experiment produces hides both e.m.f. and internal resistance in plain sight.

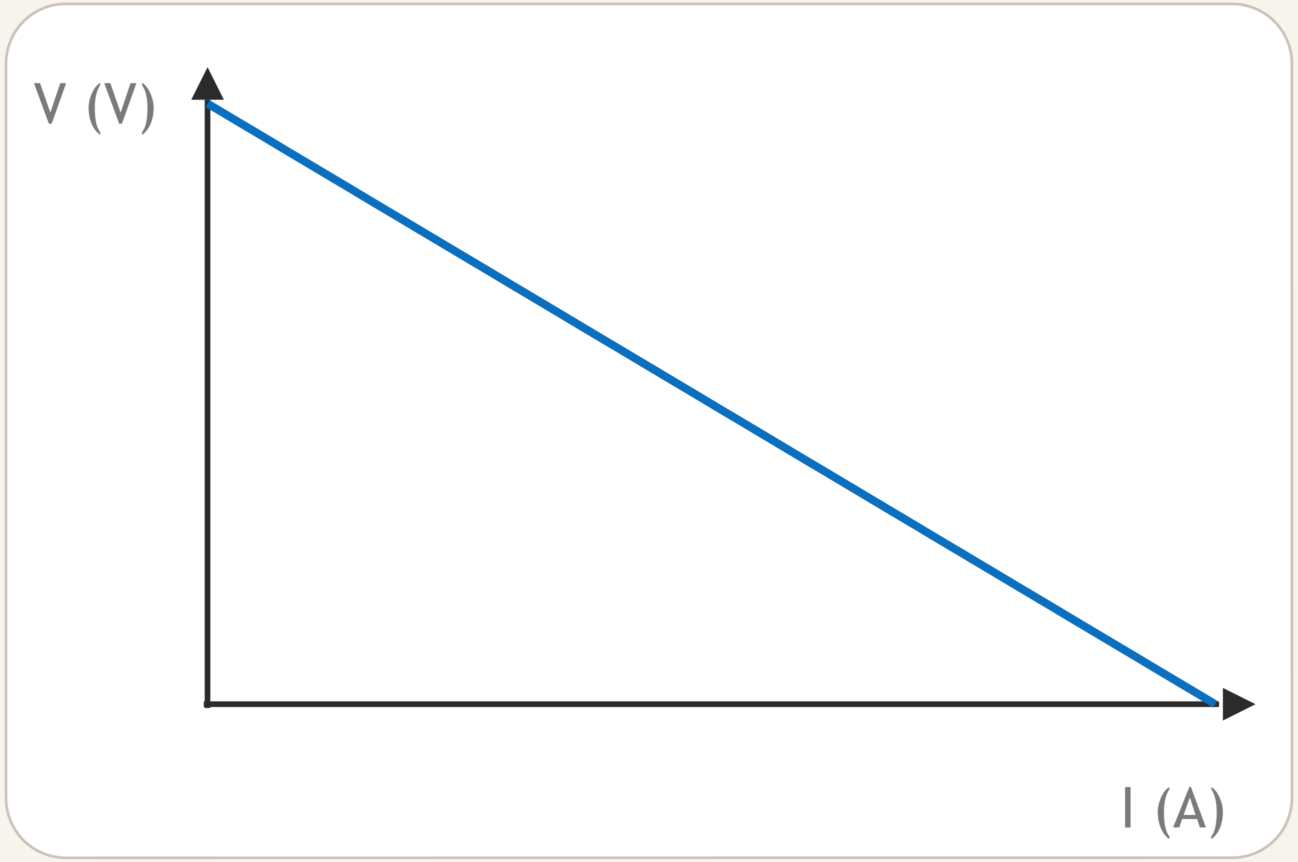
By the end of this part…

1. I can find the e.m.f. from a V-I graph, and justify why.
2. I can find the internal resistance from the gradient.
3. I can find the short-circuit current from the graph.

The graph the experiment gives you

JOTTER NOTES

Terminal p.d. up the side, current along the bottom.



What each feature means

- The y-intercept is where the current is zero — no lost volts, so that reading is the e.m.f.
- The gradient is $-r$. A steeper line means MORE internal resistance, not less.
- The x-intercept is where the terminal p.d. is zero — the short-circuit current.

JOTTER NOTES

Reading the V-I graph

The line slopes down: the more current you draw, the more voltage the cell keeps for itself.

Where the line meets the voltage axis, no current is flowing, so that reading is the e.m.f.

The steepness of the slope is the internal resistance.

JOTTER NOTES

The short-circuit current on the graph

Where the line meets the current axis, the terminal potential difference has fallen to zero.

That reading is the largest current the cell could ever deliver.

$$I_{sc} = E/r$$

Worked example — reading E and r from a graph

A battery's V-I graph is a straight line from (0, 6.0 V) to (12 A, 0 V). Find the e.m.f. and the internal resistance.

V-intercept = 6.0 V

I-intercept = 12 A

E = ?

r = ?

E = y-intercept = 6.0 V

$r = E/I_{sc}$

r = 6.0 / 12

r = 0.50 Ω

Watch Out — justify it, don't assume it

THE MISTAKE

- Writing "gradient = −r" with no reasoning
- Calling the y-intercept the terminal p.d.

THE CORRECT ANSWER

- Say why: at $I = 0$ there are no lost volts, so $V = E$.
- The line slopes down, so the gradient is $-r$, not $+r$.

Show Me: reading the graph

SHOW ME BOARDS

1. A V-I graph runs from $(0, 9.0\ \mathrm{V})$ to $(3.0\ \mathrm{A}, 0\ \mathrm{V})$. State the e.m.f.
2. For the same graph, calculate the internal resistance.
3. State what the x-intercept of a V-I graph represents.
4. A V-I graph runs from $(0, 4.5\ \mathrm{V})$ to $(1.5\ \mathrm{A}, 0\ \mathrm{V})$. Calculate the internal resistance.
5. Explain why the y-intercept gives the e.m.f. and not the terminal p.d.

Show Me: reading the graph

SHOW ME BOARDS

EXTRA PRACTICE

1. A V-I graph runs from $(0, 12\ \mathrm{V})$ to $(24\ \mathrm{A}, 0\ \mathrm{V})$. Calculate the internal resistance.
2. A V-I graph runs from $(0, 1.5\ \mathrm{V})$ to $(0.60\ \mathrm{A}, 0\ \mathrm{V})$. Calculate the internal resistance.
3. Two V-I lines share a y-intercept but differ in gradient. State and justify which cell has the larger internal resistance.
4. Sketch the V-I graph you would expect from an ideal supply.
5. A pupil plots current up the side and p.d. along the bottom by mistake. State what the gradient of their line would give.

Task

Work through the Graphical Determination exercise.
On every graph question, say what the intercept means before you use it.

Exercise 3.2.3 (P317/330)
Past papers: 2024 Q14(a)

Past Paper Finder

Starter

2014 Higher Physics

Scan the code and answer these:

Q8

Section A · resistor network

Show your working, not just the letter.

Scan for the paper

Marking scheme

PART 5

Short circuit and open circuit

The two extremes of the same circuit — no resistance at all, or no path at all.

By the end of this part...

1. I can calculate the short-circuit current of a supply.
2. I can explain what limits the current when a cell is short circuited.
3. I can state and justify the effect of internal resistance on power wasted in the cell.

What a short circuit is

- The two ends of the cell are joined by something with almost no resistance — thick wire, or a spanner across a car battery.
- With no external resistance left, the only thing limiting the current is the cell's own internal resistance.
- The terminal p.d. falls to zero, and all the energy is wasted heating the cell.

JOTTER NOTES

Short circuit current

A short circuit joins the two ends of the cell with almost no resistance between them.

The only thing left limiting the current is the cell's own internal resistance.

This is the largest current the cell can ever deliver.

$$I_{sc} = E/r$$

Worked example — short-circuit current

A battery has e.m.f. $10.0\ \mathrm{V}$ and internal resistance $2.0\ \Omega$.

Calculate the short-circuit current.

$E = 10.0\ \mathrm{V}$

$r = 2.0\ \Omega$

$R = 0\ \Omega$ (short circuit)

$I = ?$

$I_{sc} = E/r$

$I = 10.0 / 2.0$

$\underline{I = 5.0\ \mathrm{A}}$

Watch Out — power wasted inside the cell

THE MISTAKE

- Using R instead of r for power wasted in the cell
- Saying the power "changes" without saying which way

THE CORRECT ANSWER

- Power wasted inside the cell uses r, not R.
- Say which way it changes, and justify it.

Show Me: short circuit

SHOW ME BOARDS

1. A cell of e.m.f. $6.0\ \mathrm{V}$ has internal resistance $0.40\ \Omega$. Calculate the short-circuit current.
2. A cell of e.m.f. $1.5\ \mathrm{V}$ has internal resistance $0.30\ \Omega$. Calculate the short-circuit current.
3. State what limits the current when a cell is short circuited.
4. A cell delivers $2.0\ \mathrm{A}$ and has internal resistance $0.50\ \Omega$. Calculate the power wasted inside the cell.
5. State and justify what happens to the terminal p.d. of a cell as it approaches a short circuit.

Show Me: short circuit

SHOW ME BOARDS

EXTRA PRACTICE

1. A cell of e.m.f. $9.0\ \mathrm{V}$ has internal resistance $0.75\ \Omega$. Calculate the short-circuit current.
2. A cell delivers $3.0\ \mathrm{A}$ and has internal resistance $0.20\ \Omega$. Calculate the power wasted inside the cell.
3. Explain why a car battery is built with a very low internal resistance.
4. Explain why shorting a battery with a spanner is dangerous.
5. A cell is left on an open circuit. State the current, the lost volts and the voltmeter reading.

Task

Sit the Electrical Sources and Internal Resistance test.
Your notes, PhysicsScotland.co.uk and the textbook can all be used to help.

Scholar: end-of-topic test
Past papers: 2023 Q12, 2024 Q14

Past Paper Finder

Checkpoint

1. Define e.m.f. and internal resistance.
2. Explain why the terminal p.d. of a real cell falls as the current rises.
3. Use $E = V + Ir$ to find the lost volts, given E, V and I.
4. Describe the experiment used to measure e.m.f. and internal resistance.
5. State what the gradient and both intercepts of a V-I graph represent, and justify one of them.

Exam Practice

2025 Q14 – changing the setup to increase the current.
2024 Q14 – e.m.f. and r from a V-I graph, and the short-circuit current.
2023 Q12 – terminal p.d., internal resistance and power wasted.

Past papers, Section A

LOOKING AHEAD

Next: Monitoring & Measuring AC

A supply that never stops changing — and the meters built to keep up with it.

Plenary

SHOW ME BOARDS

1. Define e.m.f., internal resistance, lost volts and terminal p.d.
2. State the e.m.f. equation in both of its forms.
3. Describe the named experiment for measuring e.m.f. and internal resistance.
4. State what the gradient and both intercepts of a V-I graph represent.
5. Calculate the short-circuit current of a $6.0\ \mathrm{V}$ cell of internal resistance $0.40\ \Omega$.

Plenary

SHOW ME BOARDS

EXTRA PRACTICE

1. Explain why a car will not start with a battery whose e.m.f. reads normally but whose internal resistance is very high.
2. Explain why an ammeter should have a very low resistance and a voltmeter a very high one in this experiment.
3. State and justify what happens to the lost volts when the external resistance is reduced.
4. Sketch the V-I graph of an ideal supply and explain its shape.
5. Explain, in terms of energy per coulomb, why the terminal p.d. is always less than the e.m.f. when a current flows.

Extension

SHOW ME BOARDS

1. Show that the short-circuit current is E/r, starting from $E = V + Ir$.
2. Two identical cells are connected in series. State and justify the combined e.m.f. and internal resistance.
3. Show that the power wasted inside a cell rises with the square of the current.

Extension

SHOW ME BOARDS

EXTRA PRACTICE

1. Two identical cells are connected in parallel instead. Explain what happens to the combined internal resistance.
2. Show, using $E = I(R + r)$, that a cell delivers maximum power when R is equal to r.
3. Explain why a car battery has a much lower internal resistance than a small torch battery.