10.1.1 Internal resistance and the V-I graph

Name: _____ Class: _____ Date: _____ **Total: 27 marks**

KEY WORDS internal resistance • terminal potential difference • electromotive force • gradient • intercept

Objective

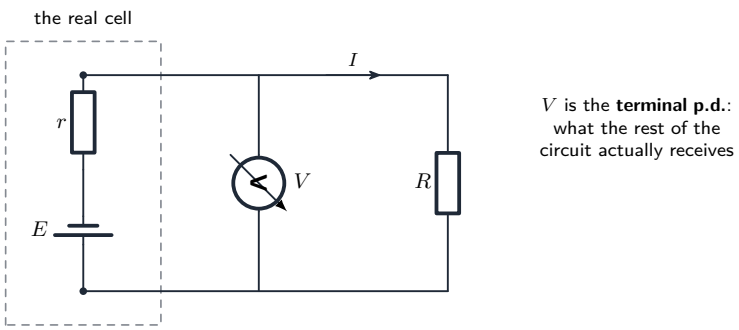
Answer exam questions on **internal resistance** : why the **terminal potential difference** of a real source is less than its e.m.f., the equation $E = V + Ir$, the limiting cases, and the V–I graph that measures E and r. Syllabus 10.1, learning outcome 5.

You must be able to:

- explain the effect of internal resistance on the terminal p.d., in terms of energy
- use $E = V + Ir = I(R + r)$ to find a current, a terminal p.d. or an internal resistance
- state what happens when no current is drawn and when the terminals are shorted
- find E and r from the intercept and gradient of a graph of V against I, and the power wasted inside the source

1 Key knowledge and worked examples

Key knowledge: internal resistance



Each coulomb is given E joules by the source, gives up Ir joules inside the cell and V joules outside it, so $E = V + Ir$, or $V = E - Ir$. Nothing is lost – the missing energy is dissipated *inside* the cell, which is why a battery gets warm.

Follow one coulomb round the circuit:

$$E = V + Ir \qquad \Longleftrightarrow \qquad V = E - Ir \qquad \Longleftrightarrow \qquad E = I(R + r)$$

- It is given E joules by the source.
- It gives up Ir joules **inside** the cell, warming it – these are sometimes called the "lost volts".
- It gives up V joules **outside**, in the rest of the circuit. V is the **terminal p.d.**: what the circuit actually receives.

Two limiting cases the exam likes:

situation	**what happens**
no current drawn ($I = 0$)	$V = E$: the terminal p.d. **equals** the e.m.f., because nothing is lost inside
terminals shorted ($R = 0$)	$I = \dfrac{E}{r}$, the **largest current** the cell can deliver, and all of the energy is wasted inside it

■ **Worked example: current and terminal p.d.**

A cell of e.m.f. 1.5 V and internal resistance 0.50 Ω is connected to a 2.5 Ω resistor.

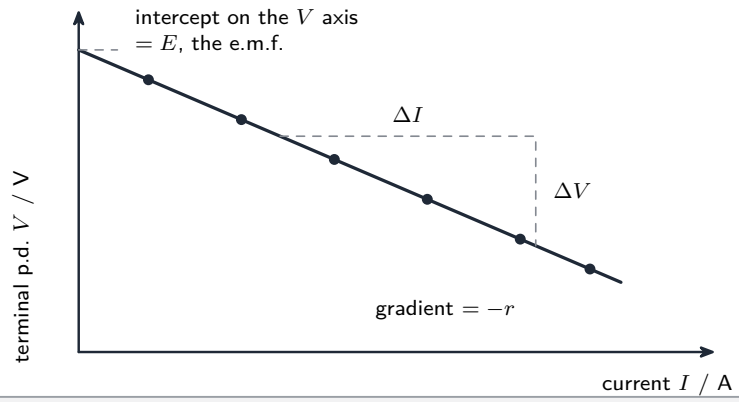
- the e.m.f. drives the current through **both** resistances

$$I = \frac{E}{R + r} = \frac{1.5\ \text{V}}{2.5\ \Omega + 0.50\ \Omega} = 0.50\ \text{A}$$

- then the terminal p.d. is what is left after the internal drop

$$V = E - Ir = 1.5\ \text{V} - (0.50\ \text{A})(0.50\ \Omega) = \mathbf{1.25}\ \text{V}$$

■ Worked example: the experiment, one graph, two answers



Vary the external resistance, plot V against I, and $V = E - Ir$ gives a straight line: the **intercept** is the e.m.f. and the **gradient** is minus the internal resistance. Extrapolating back to $I = 0$ is how you measure an e.m.f. you can never read directly, because any real voltmeter draws some current.

Vary the external resistance, record V and I each time, and plot V against I. Since

$$V = E - rI$$

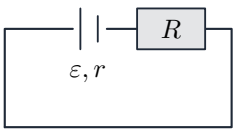
is $y = c + mx$:

- the **intercept** on the V axis is the **e.m.f.** E;
- the **gradient** is $-r$, so the internal resistance is **minus** the gradient, and it is positive.
- This is how an e.m.f. is measured, because a real voltmeter always draws a **small current**, so the reading straight across the cell is always slightly **less** than E. The graph extrapolates to the $I = 0$ case that cannot quite be reached.
- **Power:** the source supplies EI in total, of which I^2r is wasted inside and VI is delivered outside.

2 Practice

Now use the methods above.

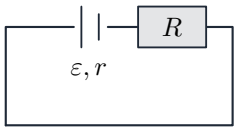
2.1 A cell of e.m.f. 1.5 V and internal resistance 0.40 Ω delivers a current of 0.60 A. Calculate the terminal p.d. [2]



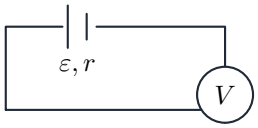
1.5 V

0.40 Ω

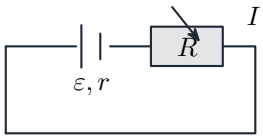
2.2 Explain why the terminal p.d. of a cell falls as the current drawn from it increases. [2]



2.3 State the terminal p.d. of a cell when **no** current is drawn from it, and explain your answer. [2]



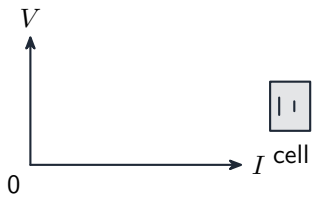
2.4 Calculate the largest current the cell in **2.3** could deliver, and state the condition under which this happens. [2]



3 Exam-style questions

3.1 As the current drawn from a cell increases, the terminal potential difference [1]

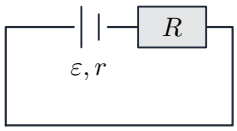
- [ ] **A** increases, because more energy is transferred each second.
- [ ] **B** stays the same, because the e.m.f. of the cell is fixed.
- [ ] **C** decreases, because more energy is dissipated in the internal resistance.
- [ ] **D** decreases, because the e.m.f. of the cell falls.



3.2 A battery of e.m.f. 6.0 V and internal resistance 0.80 Ω is connected to a lamp of resistance 4.0 Ω.

(a) Explain why the p.d. across the terminals of the battery is less than its e.m.f. when the lamp is lit. [2]

(b) Calculate the current in the lamp. [2]



6.0 V

0.80 Ω

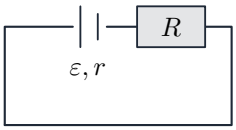
(c) Calculate the terminal p.d. [1]

(d) Calculate the power wasted inside the battery. [2]

3.3 A student varied the resistance of the external circuit and recorded the terminal p.d. V and the current I.

I / **A**	**0.20**	**0.45**	**0.70**	**0.95**	**1.20**
V / V	5.72	5.45	5.18	4.91	4.64

(a) State the equation relating V and I for this circuit, and state what the gradient and the intercept of a graph of V against I represent. [3]



1.20 A

(b) Use the first and last pairs of readings to calculate the internal resistance of the source. [3]

(c) Calculate the e.m.f. of the source. [2]

(d) Calculate the power dissipated inside the source when the current is 1.20 A. [2]

(e) Explain why connecting a voltmeter directly across the terminals of the source does not give exactly its e.m.f. [1]