

## AQA AS Potential dividers, emf and internal resistance

Matching solutions and teaching prompts for the class review

### Specification points covered

• 3.5.1.5 Potential divider: supplying fixed or adjustable potential differences; applications using variable resistors, thermistors and LDRs; designing and investigating divider circuits.

• 3.5.1.6 Electromotive force and internal resistance:  $\epsilon = E/Q$ ; terminal pd and  $\epsilon = I(R + r)$ . Required practical 6: determine cell/battery emf and internal resistance from terminal-pd and current measurements.

### Teaching focus

Identify the output terminal pair before predicting a sensor response. A divider formula assumes negligible loading; use a parallel equivalent when this assumption fails.

Distinguish emf, terminal pd and the internal drop. Use the practical graph to train correct intercept, gradient and uncertainty language.

### Energy per charge and dividing a supply voltage

#### 1. State what is meant by the electromotive force (emf) of a battery. [1 mark]

**Answer / mark points:** The emf is the energy transferred from a non-electrical form to electrical energy per unit charge by the battery. [1] For this battery, the original form is chemical energy. It is not a force; its unit is  $\text{J C}^{-1} = \text{V}$ .

**Teacher prompt / common error:** Require energy per unit charge and its conversion to electrical form. 'Voltage when no current flows' alone does not define emf.

#### 2. The greenhouse's backup battery has an emf of 12.0 V. Calculate the energy transferred from chemical energy to electrical energy when it supplies 2.50 C of charge. [1 mark]

**Answer / mark points:**  $E = \epsilon Q = 12.0 \times 2.50 = 30.0 \text{ J}$ . [1] This is the total conversion to electrical energy, not necessarily the energy delivered to the external circuit.

**Teacher prompt / common error:** The emf accounts for the internal as well as external energy transfers. Charge is not consumed.

#### 3. A regulated supply of potential difference $V(\text{in})$ powers two resistors $R_1$ and $R_2$ in series. A control input takes negligible current and measures $V(\text{out})$ across $R_2$ . Starting with $V = IR$ , derive $V(\text{out}) = V(\text{in})R_2/(R_1 + R_2)$ . [2 marks]

**Answer / mark points:** The resistors carry the same current,  $I = V(\text{in})/(R_1 + R_2)$ . [1] The output is across  $R_2$ , so  $V(\text{out}) = IR_2 = V(\text{in})R_2/(R_1 + R_2)$ . [1] The derivation assumes negligible output current; a load changes the equivalent lower resistance.

**Teacher prompt / common error:** Identify the output resistor and the no-loading assumption before using the divider formula.

#### 4. During a bench test, a 2.00 k $\Omega$ resistor and a 4.00 k $\Omega$ resistor are in series across the regulated 9.00 V supply. Calculate (a) the series current and (b) the output potential difference across the 4.00 k $\Omega$ resistor. [2 marks]

**Answer / mark points:**  $I = 9.00/(2000 + 4000) = 1.50 \times 10^{-3} \text{ A} = 1.50 \text{ mA}$ . [1]  $V(\text{out}) = IR_2 = 1.50 \times 10^{-3} \times 4000 = 6.00 \text{ V}$ . [1] Resistances may be used as a ratio in k $\Omega$ , but must be converted to  $\Omega$  when calculating current in amperes.

**Teacher prompt / common error:** The larger series resistance receives the larger potential difference; both carry the same current.

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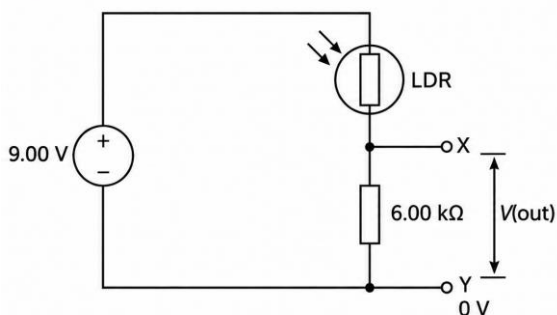
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## Controlling the shading screen

5. Figure 1 controls a greenhouse shading screen. The output is measured between X and Y by a control input of effectively infinite resistance. The LDR resistance is 12.0 k $\Omega$  in overcast conditions and 3.00 k $\Omega$  in bright sunlight. Calculate V(out) for each condition. [2 marks]

Figure 1.



Overcast: 3.00 V

Bright sunlight: 6.00 V

**Answer / mark points:** Overcast:  $V(\text{out}) = 9.00 \times 6.00 / (12.0 + 6.00) = 3.00 \text{ V}$ . [1] Bright sunlight:  $V(\text{out}) = 9.00 \times 6.00 / (3.00 + 6.00) = 6.00 \text{ V}$ . [1] The output is across the fixed resistor, not across the LDR.

**Teacher prompt / common error:** Trace X–Y. A voltage measured across the LDR would change in the opposite direction.

6. The shading screen closes when V(out) is at least 5.40 V. Calculate the greatest LDR resistance that will trigger it in Figure 1. [2 marks]

**Answer / mark points:**  $5.40 / 9.00 = 6.00 / (R(\text{LDR}) + 6.00)$ , with all resistances here in k $\Omega$ . [1 for correct equation/rearrangement]  $R(\text{LDR}) = 6.00(9.00 / 5.40 - 1) = 4.00 \text{ k}\Omega$ . [1] Values at or below 4.00 k $\Omega$  trigger the screen; larger values do not.

**Teacher prompt / common error:** Check the direction of the inequality: lower LDR resistance means higher fixed-resistor output.

7. Explain why V(out) in Figure 1 increases as the light intensity increases. Refer to the LDR resistance, the circuit current and the potential difference across the fixed resistor. [3 marks]

**Answer / mark points:** As light intensity increases, the LDR resistance decreases. [1] Total resistance decreases, so the current through the series circuit increases for the fixed supply voltage. [1] The lower resistance is constant, so  $V(\text{out}) = IR(\text{fixed})$  increases. [1] Do not say that the current increases because the supply voltage increases: the regulated supply remains 9.00 V.

**Teacher prompt / common error:** Use quantity–direction language and a causal chain. The fixed resistor's resistance does not change with the light.

8. The shading threshold must instead occur when the LDR resistance is 3.00 k $\Omega$ , still at V(out) = 5.40 V. Calculate the new value of the fixed resistor. The control input still draws negligible current. [2 marks]

**Answer / mark points:**  $5.40 = 9.00R(\text{fixed}) / (3.00 + R(\text{fixed}))$ , with resistances in k $\Omega$ . [1]  $5.40 \times 3.00 = (9.00 - 5.40)R(\text{fixed})$ , giving  $R(\text{fixed}) = 4.50 \text{ k}\Omega$ . [1] This is a new design; subsequent questions restore the original 6.00 k $\Omega$  value where stated.

**Teacher prompt / common error:** Rearrange with the unknown in both numerator and denominator. Keep units consistent within the resistance ratio.

9. Return to the original 6.00 k $\Omega$  fixed resistor in Figure 1. A replacement control input has resistance 6.00 k $\Omega$  between X and Y. In bright sunlight the LDR resistance is 3.00 k $\Omega$ . Calculate the loaded output voltage and decide whether it reaches the 5.40 V shading threshold. [3 marks]

**Answer / mark points:** The lower effective resistance is 6.00 k $\Omega$  in parallel with 6.00 k $\Omega$ :  $R(\text{lower}) = 3.00 \text{ k}\Omega$ . [1]  $V(\text{out}) = 9.00 \times 3.00 / (3.00 + 3.00) = 4.50 \text{ V}$ . [1] It does not reach the 5.40 V threshold, so the screen is not triggered. [1] An output load is not another resistor in series; it is across the same two output terminals.

**Teacher prompt / common error:** Find the parallel equivalent first. An effectively infinite-resistance input avoids this loading effect.

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## Temperature sensing and adjustable outputs

Table 1 Thermistor calibration

| Temperature / °C | 10   | 20   | 30   | 40   |
|------------------|------|------|------|------|
| Resistance / kΩ  | 18.0 | 12.0 | 8.00 | 5.00 |

10. A second control circuit replaces the LDR in Figure 1 with an NTC thermistor, retaining the 6.00 kΩ fixed resistor and 9.00 V supply. Its calibration is given in Table 1. Explain why the output voltage increases as the temperature increases. The control input draws negligible current. [2 marks]

**Answer / mark points:** The NTC thermistor's resistance decreases as temperature increases. [1] Its share of the supply potential difference decreases, leaving a greater potential difference across the fixed resistor; hence the output increases. [1] Equivalently the total resistance decreases and the current in the fixed resistor increases. Specify which component's voltage is being discussed.

**Teacher prompt / common error:** NTC means resistance decreases with temperature, not that its temperature decreases.

11. The ventilation fan is commanded on when the thermistor circuit's output is at least 4.50 V. Calculate the output at 20 °C and at 40 °C, and decide whether the fan is commanded on at each temperature. [3 marks]

**Answer / mark points:** At 20 °C,  $V(\text{out}) = 9.00 \times 6.00 / (12.0 + 6.00) = 3.00 \text{ V}$ . [1] At 40 °C,  $V(\text{out}) = 9.00 \times 6.00 / (5.00 + 6.00) = 4.91 \text{ V}$ . [1] The fan is not commanded on at 20 °C ( $3.00 < 4.50 \text{ V}$ ), but is commanded on at 40 °C ( $4.91 \geq 4.50 \text{ V}$ ). [1 for both decisions] The divider supplies a control signal, not the fan's operating current.

**Teacher prompt / common error:** Compare each result with the threshold. Distinguish a control signal from the power supplied to the fan.

12. Calculate the thermistor resistance at the 4.50 V switching threshold. Use Table 1 to identify the 10 °C interval containing the switching temperature. Do not assume that the complete resistance–temperature relationship is linear. [3 marks]

**Answer / mark points:**  $4.50 = 9.00 \times 6.00 / (R(T) + 6.00)$ , using kΩ. [1]  $R(T) = 6.00 \text{ kΩ}$ . [1] Table 1 places this between 30 °C (8.00 kΩ) and 40 °C (5.00 kΩ), so  $30 \text{ °C} < \text{threshold temperature} < 40 \text{ °C}$ . [1] No precise interpolation is required or justified without further calibration data.

**Teacher prompt / common error:** A table brackets the threshold; it does not establish linearity over the full temperature range.

13. For a manual test, the upper sensor in Figure 1 is replaced by a variable resistor adjustable from 0 to 12.0 kΩ. The lower resistor remains 6.00 kΩ. Calculate the minimum and maximum output voltages and state which upper-resistor setting produces each. [2 marks]

**Answer / mark points:** At the largest upper resistance, 12.0 kΩ,  $V(\text{minimum}) = 9.00 \times 6.00 / (12.0 + 6.00) = 3.00 \text{ V}$ . [1 for value and setting] At zero upper resistance,  $V(\text{maximum}) = 9.00 \text{ V}$ . [1 for value and setting] This two-resistor arrangement does not provide an output range down to 0 V.

**Teacher prompt / common error:** Zero upper resistance does not short the whole supply: the lower 6.00 kΩ resistor remains in series.

14. Describe a bench method to check the thermistor circuit's switching temperature. Include how to obtain paired temperature and output-voltage readings, how to ensure the thermistor is at the measured temperature, and how to limit self-heating. [3 marks]

**Answer / mark points:** Place the thermistor and a thermometer close together in a suitable water bath, keeping electrical contacts dry/protected. At several bath temperatures read a high-resistance voltmeter across X–Y and the thermometer together, then identify the temperature where the output reaches 4.50 V. [1 for paired measurements and threshold identification]

Stir gently and wait for thermal equilibrium/steady readings so the bath thermometer represents the thermistor temperature. [1]

Use a small measuring current or short powered measurement intervals to limit thermistor self-heating. [1] Repeats improve the calibration, but do not replace thermal equilibrium or a self-heating precaution.

**Teacher prompt / common error:** Use paired, equilibrated readings and limit self-heating. A calibrated thermometer is still required.

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## Can the battery start the ventilation fan?

15. The fan drive is powered directly by the unregulated backup battery, not from the divider output. The battery has emf 12.0 V and internal resistance 1.20  $\Omega$ . During normal operation, the fan drive is modelled by a 4.80  $\Omega$  load resistance. Calculate the battery current and terminal potential difference. [2 marks]

**Answer / mark points:**  $I = \mathcal{E}/(R + r) = 12.0/(4.80 + 1.20) = 2.00$  A. [1]  $V = IR = 2.00 \times 4.80 = 9.60$  V. [1] Equivalently  $V = \mathcal{E} - Ir = 12.0 - 2.00 \times 1.20$ . The external load does not receive the full emf.

**Teacher prompt / common error:** Use total resistance for battery current, then external resistance for terminal pd.

16. For the operating conditions in Question 15, calculate (a) the power dissipated inside the battery and (b) the power delivered to the fan drive. Show that their sum equals the total rate at which the battery transfers energy to electrical form. [3 marks]

**Answer / mark points:** Internal power =  $I^2r = 2.00^2 \times 1.20 = 4.80$  W. [1] Fan-drive power =  $VI = 9.60 \times 2.00 = 19.2$  W. [1] Total =  $4.80 + 19.2 = 24.0$  W =  $\mathcal{E}I = 12.0 \times 2.00$ , satisfying conservation of energy. [1] Do not use terminal V for the battery's total electrical-energy conversion rate.

**Teacher prompt / common error:** Label total conversion, internal dissipation and useful external transfer separately.

17. During start-up, the fan drive is modelled by a load resistance of 1.80  $\Omega$ . It requires at least 8.00 V across its input. The battery's emf and internal resistance are unchanged. Calculate its current and terminal potential difference, then explain whether the battery meets the start-up voltage requirement. [3 marks]

**Answer / mark points:**  $I = 12.0/(1.80 + 1.20) = 4.00$  A. [1]  $V = 12.0 - 4.00 \times 1.20 = 7.20$  V. [1] The requirement is not met because 7.20 V < 8.00 V; the larger current increases the internal voltage drop to 4.80 V, reducing the terminal voltage. [1 for decision linked to the larger internal drop] This conclusion tests the stated effective-resistance model, not detailed motor theory.

**Teacher prompt / common error:** Emf can stay constant while terminal pd falls. 'The battery has lost charge' is not this instantaneous explanation.

18. Two load tests on another battery give  $I = 0.400$  A,  $V = 11.6$  V and  $I = 2.40$  A,  $V = 9.60$  V. Assuming constant emf and internal resistance, determine both values. [2 marks]

**Answer / mark points:**  $r = (11.6 - 9.60)/(2.40 - 0.400) = 2.00/2.00 = 1.00$   $\Omega$ . [1]  $\mathcal{E} = V + Ir = 11.6 + 0.400 \times 1.00 = 12.0$  V. [1] The second pair also gives  $9.60 + 2.40 \times 1.00 = 12.0$  V. The graph's negative gradient is  $-r$ , not  $r$ .

**Teacher prompt / common error:** Find the magnitude of  $\Delta V/\Delta I$ , then recover emf using either paired reading.

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## Required practical 6: Measuring emf and internal resistance

19. Figure 2 is used for Required practical 6 to investigate a replacement battery. The manufacturer specifies a maximum test current of 2.0 A. Describe a method under these headings: connections and readings; varying current and controlling conditions; graphical analysis. Explain how the method gives both emf and internal resistance. Do not exceed the stated current limit. [6 marks]

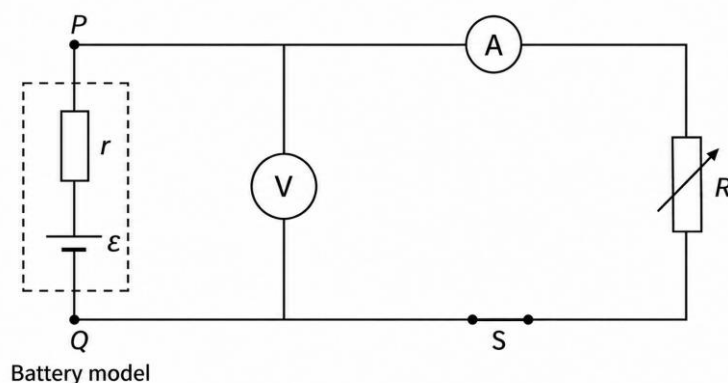


**Figure 2.**

A: series current

V: terminal pd across P–Q

**Answer / mark points:** 1. Use an ammeter in series with the external load and a high-resistance voltmeter across battery terminals P and Q, as in Figure 2. Record current through the battery and terminal pd, not the pd across only its internal resistor. [1]  
 2. Begin with a high external resistance, close S briefly, and take paired stable I and V readings; vary the external resistance to obtain at least six pairs over a useful range. [1]  
 3. Keep I at or below 2.0 A and do not short the battery or connect the ammeter across its terminals. [1]  
 4. Open S between readings to limit warming and depletion; keep battery temperature approximately constant, repeat readings and average consistent results. [1]  
 5. Plot terminal V vertically against I horizontally and draw a straight best-fit line rather than joining individual measurements. [1]  
 6. Use  $V = \varepsilon - Ir$ : the vertical intercept gives  $\varepsilon$  and the magnitude of the negative gradient gives r; use a large gradient triangle, with r in  $\Omega$ . [1]

Accept an equivalent workable method. These six indicative marking points are for this original worksheet, not an official AQA mark scheme. For a non-ideal voltmeter, its own current must be considered; ideal meters are assumed here.

**Teacher prompt / common error:** Require correct meters, a range of paired readings, safe current control, stable conditions and both graphical results.

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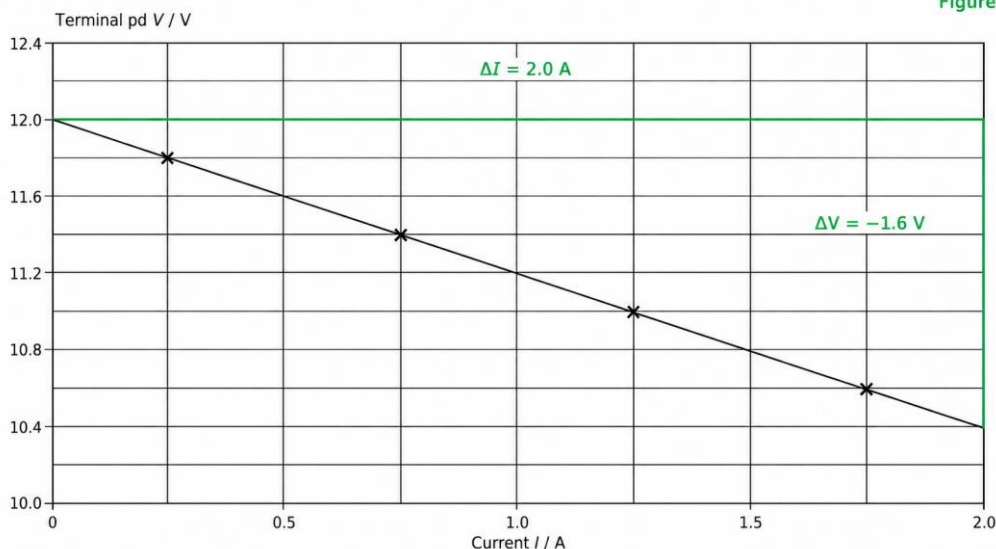
## Analysing the replacement battery

Table 2 Replacement battery readings

| Current $I$ / A     | 0.25 | 0.75 | 1.25 | 1.75 |
|---------------------|------|------|------|------|
| Terminal pd $V$ / V | 11.8 | 11.4 | 11.0 | 10.6 |

20. Table 2 gives four pairs of readings for the replacement battery. Plot all four points on Figure 3 using crosses and draw a straight best-fit line, extending it to the vertical axis. [2 marks]

Figure 3.



**Answer / mark points:** Plot crosses at (0.25,11.8), (0.75,11.4), (1.25,11.0) and (1.75,10.6) to the printed grid precision. [1 for all four] Draw a straight best-fit line through the trend, extended to  $I = 0$ . [1] It meets the vertical axis at  $V = 12.0$  V. The voltage axis starts at 10.0 V, not zero.

**Teacher prompt / common error:** Use crosses and one straight best-fit line. Read the non-zero voltage-axis origin carefully.

21. Using  $V = \epsilon - Ir$ , explain the meaning of the intercept and gradient of your Figure 3 graph. Determine the emf and internal resistance. Show a large gradient triangle or state two widely separated coordinates from your best-fit line. [3 marks]

**Answer / mark points:** At  $I = 0$ ,  $V = \epsilon$ , so the intercept corresponds to emf:  $\epsilon = 12.0$  V. [1]

Using widely separated points, for example (0,12.0) and (2.0,10.4), gradient =  $(10.4 - 12.0)/(2.0 - 0) = -0.80$  V A<sup>-1</sup>. [1]

Since gradient =  $-r$ , internal resistance  $r = 0.80$   $\Omega$ . [1] Accept  $\epsilon = 11.9$ – $12.1$  V and  $r = 0.75$ – $0.85$   $\Omega$  from a reasonable pupil best-fit line; later answers may follow their consistent values. Do not treat the bottom-left grid corner as zero voltage.

**Teacher prompt / common error:** The gradient is negative but internal resistance is positive. The ordinate intercept means  $I = 0$ , not  $V = 0$ .

22. The fan drive must receive at least 9.60 V from the replacement battery. Use your values of  $\epsilon$  and  $r$  to calculate the maximum current allowed by this voltage requirement alone. State the actual maximum permitted test current when the manufacturer's 2.0 A limit is also applied. [2 marks]

**Answer / mark points:** For the voltage criterion,  $I(\text{maximum}) = (\epsilon - V(\text{minimum}))/r = (12.0 - 9.60)/0.80 = 3.00$  A. [1] The actual permitted test current remains at most 2.0 A because the manufacturer's safety limit is more restrictive. [1] Do not test at 3.00 A. The voltage calculation extrapolates the constant- $\epsilon$ , constant- $r$  model beyond the plotted data.

**Teacher prompt / common error:** A voltage-based model limit does not override a safety rating; distinguish calculation from permission to test.

### Language and method check

Award distinct points only, with error-carried-forward for consistent later calculations.

Accept equivalent methods and reasonable graph-reading precision. Never recommend a current above the stated safe test rating.

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