Past-paper walk-through

Compound DC Circuits ▪ 11.5

eXercise

Questions in this set

- 2024 Q3
- 2023 Q2
- 2018 Q2
- 2015 Q2

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 3

2024 ▪ Q3

[Figure 1: A circuit diagram. An ideal battery of emf $\mathcal{E}$ is connected on the left. From the top of the battery, a wire goes right through resistor R_1 to a node. From that node, resistor R_2 branches down in parallel back to the bottom rail. Also from that same node, a wire continues right to another node, from which resistors R_3 (upper) and R_4 (lower) branch down in parallel, both returning to the bottom rail, which connects back to the battery.]

A circuit consists of an ideal battery of emf $\mathcal{E}$ and four identical resistors R_1, R_2, R_3, and R_4, each of resistance R, as shown in Figure 1.

(a)(i) For parts (a)(i) and (a)(ii), express your answers in terms of numerical values, $\mathcal{E}$, and R only.

Derive an expression for the current I_1 in Resistor R_1.

(a)(ii) Derive an expression for the current I_3 in Resistor R_3.

Question 3

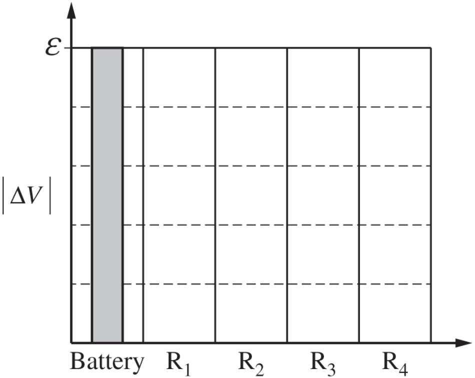


Figure 2

Question 3

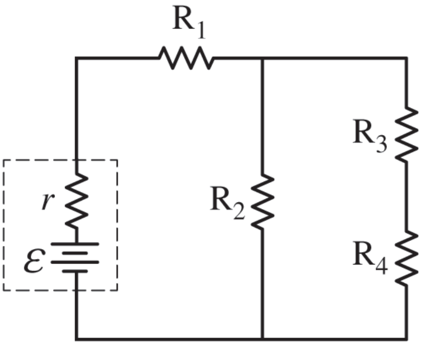


Figure 3

Question 3

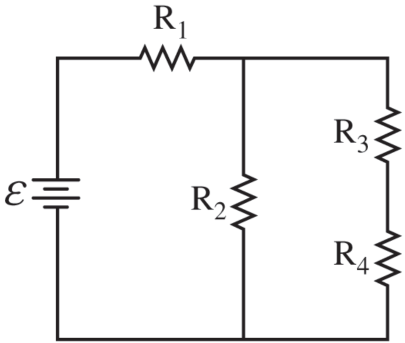


Figure 1

Question 3

2024 ▪ Q3

[Figure 1: A circuit diagram. An ideal battery of emf $\mathcal{E}$ is connected on the left. From the top of the battery, a wire goes right through resistor R_1 to a node. From that node, resistor R_2 branches down in parallel back to the bottom rail. Also from that same node, a wire continues right to another node, from which resistors R_3 (upper) and R_4 (lower) branch down in parallel, both returning to the bottom rail, which connects back to the battery.]

A circuit consists of an ideal battery of emf $\mathcal{E}$ and four identical resistors R_1, R_2, R_3, and R_4, each of resistance R, as shown in Figure 1.

(b) [Figure 2: A partially completed bar chart. The vertical axis is labeled $|\Delta V|$ with a horizontal dashed reference line marked $\mathcal{E}$ near the top. The horizontal axis lists categories "Battery", R_1, R_2, R_3, R_4. A single shaded bar is drawn above "Battery" reaching up to the $\mathcal{E}$ line; the bars for R_1, R_2, R_3, R_4 are blank for the student to draw.]

Question 3

The partially completed bar chart in Figure 2 shows a bar that represents the absolute value $|\Delta V|$ of the potential difference across the ideal battery.
- In Figure 2, **draw** a bar to represent $|\Delta V|$ across **each** resistor, relative to the emf $\mathcal{E}$ of the ideal battery. - The height of each bar should be proportional to the value of $|\Delta V|$ represented by that bar. If $|\Delta V|$ is zero, write a "0" in that column.
A student claims that the rate at which energy is dissipated (power) by the circuit can be expressed as $P = \dfrac{3\mathcal{E}^2}{5R}$.

Question 3

2024 ▪ Q3

[Figure 1: A circuit diagram. An ideal battery of emf $\mathcal{E}$ is connected on the left. From the top of the battery, a wire goes right through resistor R_1 to a node. From that node, resistor R_2 branches down in parallel back to the bottom rail. Also from that same node, a wire continues right to another node, from which resistors R_3 (upper) and R_4 (lower) branch down in parallel, both returning to the bottom rail, which connects back to the battery.]

A circuit consists of an ideal battery of emf $\mathcal{E}$ and four identical resistors R_1, R_2, R_3, and R_4, each of resistance R, as shown in Figure 1.

(c) State whether the expression for P is correct or incorrect. **Justify** your answer by referring to the derivations from part (a) or the bar chart from part (b).

Question 3

2024 ▪ Q3

[Figure 1: A circuit diagram. An ideal battery of emf $\mathcal{E}$ is connected on the left. From the top of the battery, a wire goes right through resistor R_1 to a node. From that node, resistor R_2 branches down in parallel back to the bottom rail. Also from that same node, a wire continues right to another node, from which resistors R_3 (upper) and R_4 (lower) branch down in parallel, both returning to the bottom rail, which connects back to the battery.]

A circuit consists of an ideal battery of emf $\mathcal{E}$ and four identical resistors R_1, R_2, R_3, and R_4, each of resistance R, as shown in Figure 1.

(d) [Figure 3: The same circuit as Figure 1, but the ideal battery is replaced by a nonideal battery, drawn as an emf $\mathcal{E}$ in series with an internal resistance r enclosed in a dashed box. The rest of the circuit (resistors R_1, R_2, R_3, R_4 in the same configuration) is unchanged.]

Question 3

When the ideal battery is connected in the original circuit, the rate at which energy is dissipated by Resistor R_1 is $P_{original}$. The ideal battery is now replaced with a nonideal battery of emf $\mathcal{E}$ and internal resistance r to form the new circuit shown in Figure 3. The rate at which energy is dissipated by Resistor R_1 in the new circuit is P_{new}.
Indicate whether P_{new} is greater than, less than, or equal to $P_{original}$.
_____ $P_{new} > P_{original}$ _____ $P_{new} < P_{original}$ _____ $P_{new} = P_{original}$
Briefly **justify** your answer.

Solution 3

(a)(i) Mark scheme

- Total resistance: the right-most branch (Resistors R_3 and R_4 in series) has $R_s = R + R = 2R$. This branch is in parallel with R_2: $\frac{1}{R_p} = \frac{1}{R} + \frac{1}{2R} = \frac{3}{2R}$, so $R_p = \frac{2R}{3}$. This parallel combination is in series with R_1: $R_{total} = R + \frac{2R}{3} = \frac{5R}{3}$. Applying Ohm's law to the whole circuit with the ideal battery's emf $\mathcal{E}$: $I_1 = \frac{\Delta V}{R_{total}} = \frac{\mathcal{E}}{5R/3} = \frac{3\mathcal{E}}{5R}$. Scoring: 1 pt for correctly determining $R_{total} = 5R/3$; 1 pt for a multi-step derivation with correct substitution of $\mathcal{E}$ and R_{total} into Ohm's law, consistent with the first point (giving $I_1 = 3\mathcal{E}/5R$).

Solution 3

(a)(ii) Mark scheme

- I_3 is the current through the series branch R_3-R_4. Since R_2 and the $(R_3 + R_4)$ branch are in parallel (same potential difference): $I_2 R_2 = I_3(R_3 + R_4) \Rightarrow I_2 R = I_3(2R) \Rightarrow I_2 = 2I_3$. By the junction rule, $I_1 = I_2 + I_3 = 2I_3 + I_3 = 3I_3$, so $I_3 = I_1/3$. Substituting $I_1 = 3\mathcal{E}/5R$ from part (a)(i): $I_3 = \dfrac{3\mathcal{E}/5R}{3} = \dfrac{\mathcal{E}}{5R}$. (Equivalently: one-third of the total current I_1 flows through R_3, since R_2 carries twice the current of the R_3-R_4 branch.) Scoring: 1 pt for applying Kirchhoff's/Ohm's law to relate I_3 to the current in or potential difference across R_1, R_2, or R_3; 1 pt for a correct final expression from a multi-step derivation, consistent with part (a)(i), giving $I_3 = \mathcal{E}/(5R)$.

Solution 3

(b) Mark scheme

- Bar chart of $|\Delta V|$ for each element (Battery bar already shown at $\mathcal{E}$): the R_1 bar is nonzero, at $\Delta V_1 = I_1 R = (3\mathcal{E}/5R)(R) = 3\mathcal{E}/5$. Since R_2 is in parallel with the R_3-R_4 series branch, $\Delta V_2 = \Delta V_3 + \Delta V_4$, and this equals $\mathcal{E} - \Delta V_1 = 2\mathcal{E}/5$. R_3 and R_4 carry the same current and have equal resistance, so $\Delta V_3 = \Delta V_4$, each equal to half of ΔV_2, i.e. $\mathcal{E}/5$. Final bar heights: Battery $= \mathcal{E}$, $R_1 = 3\mathcal{E}/5$, $R_2 = 2\mathcal{E}/5$, $R_3 = \mathcal{E}/5$, $R_4 = \mathcal{E}/5$. Scoring: 1 pt for a bar showing ΔV_3 is nonzero and equal to ΔV_4; 1 pt for a bar showing ΔV_2 is nonzero and equal to $\Delta V_3 + \Delta V_4$; 1 pt for drawing ALL bars correctly (including correct relative heights of Battery, R_1, R_2, R_3, R_4).

Solution 3

(c) Mark scheme

- The equation $P = \dfrac{3\mathcal{E}^2}{5R}$ is CORRECT. Justification: power dissipated can be written $P = (\Delta V)^2/R$. From the bar chart in part (b), the potential difference across the (ideal) battery is $\mathcal{E}$; from part (a)(i), the total resistance is $R_{total} = 5R/3$. Therefore the total power delivered by the battery is $P = \dfrac{(\Delta V)^2}{R_{total}} = \dfrac{\mathcal{E}^2}{5R/3} = \dfrac{3\mathcal{E}^2}{5R}$, matching the given expression, so it is correct. Scoring: 1 pt for stating the equation is correct/incorrect (consistent with the student's own part (a) derivations or part (b) bar chart) with an attempted justification; 1 pt for a justification relating P to at least one of the potential

Solution 3

difference across the battery, the current in the battery, or R_1, R_2, R_3, R_4; 1 pt for a justification that relates the equation $P = 3\mathcal{E}^2/5R$ to the bar chart from (b) or the derivations from (a)(i)/(a)(ii).

Solution 3

(d) Mark scheme

- $P_{new} < P_{original}$. Justification: the emf $\mathcal{E}$ of the battery is the same in the new circuit, but the new circuit has additional internal resistance r, so its total resistance is greater than in the original circuit. A larger total resistance with the same emf means a smaller total (and branch) current, so the current in R_1 is less in the new circuit than in the original — equivalently, the potential difference across R_1 is less. Since the power dissipated in R_1 depends on $I_1^2 R$ (or $(\Delta V_1)^2/R$), a decrease in I_1 (or ΔV_1) means $P_{new} < P_{original}$. Scoring: 1 pt for correctly selecting $P_{new} < P_{original}$ with an attempted justification; 1 pt for a correct justification citing that the current in R_1 (or the potential difference across R_1) is less in the new circuit than in the original.

Question 2

2023 ▪ Q2

(12 points, suggested time 25 minutes)
Students are given an unknown circuit component that is connected in series to a resistor with known resistance $500\ \Omega$.

(a)(i) The students are asked to experimentally determine whether the component is a resistor or an uncharged capacitor.

Complete the following diagram to show how to use standard circuit equipment to determine whether the component is a resistor or an uncharged capacitor.

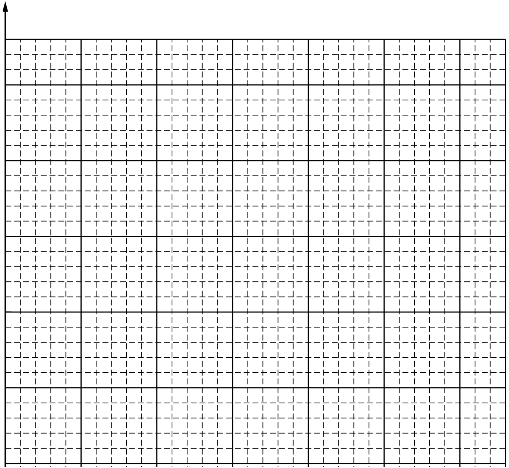
[Diagram: A circuit component box (labeled "Circuit Component") connected in series via a wire to a $500\ \Omega$ resistor, drawn with the standard zigzag resistor symbol. The circuit component is drawn as a rectangle with terminals. The student must complete the diagram with standard circuit equipment (e.g., battery, switch, meters).]

Question 2

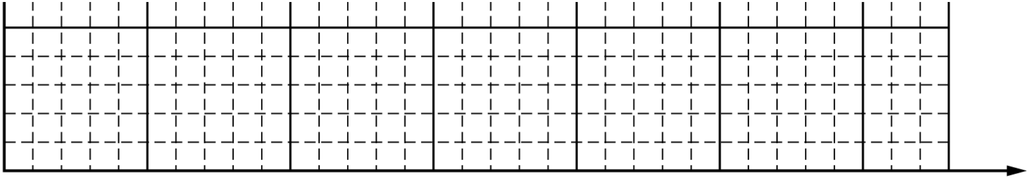
(a)(ii) Describe an experimental procedure to determine whether the component is a resistor or an uncharged capacitor. Refer to the circuit equipment in the diagram drawn in part (a)(i).

(a)(iii) What results would the students expect if the component is an uncharged capacitor? Support your answer in terms of potential difference and charge.

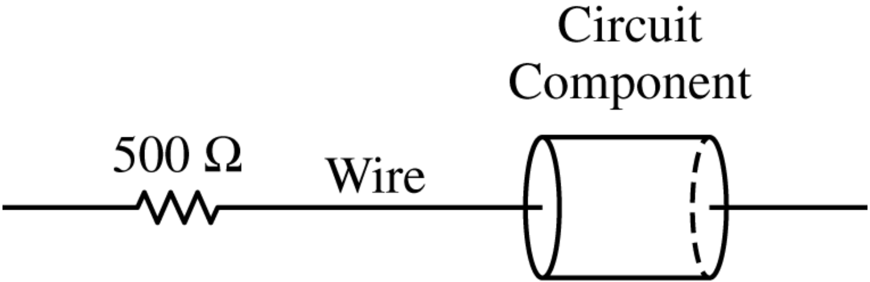
Question 2



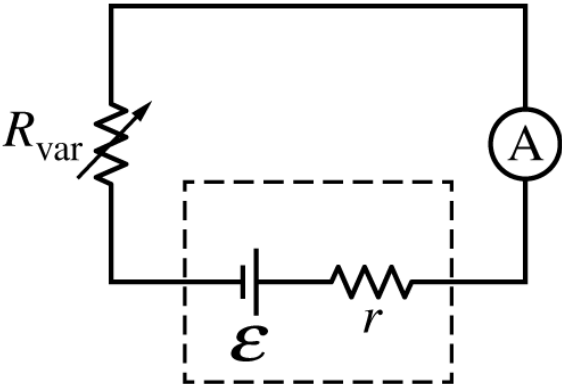
Question 2



Question 2



Question 2



Question 2

2023 ▪ Q2

(12 points, suggested time 25 minutes)

Students are given an unknown circuit component that is connected in series to a resistor with known resistance $500\ \Omega$.

(b)(i) [Figure: A circuit diagram showing a variable resistor R_{var} connected in series with an ammeter (circle with "A"), and a battery with emf $\mathcal{E}$ and internal resistance r (shown as a battery symbol inside a dashed box labeled $\mathcal{E}$, r).]

The students conduct a different experiment to determine the emf $\mathcal{E}$ of a battery that is not ideal and has internal resistance $r = 30\ \Omega$. The battery is connected to a variable resistor in a circuit, as shown. The students measure the current I through the circuit for different values of resistance R_{var} of the variable resistor that is connected to the battery. The following table contains the data collected.

Question 2

I (A)	R_{var} (Ω)
0.087	200
0.060	300
0.042	450
0.027	700
0.016	1200

Write an equation describing the circuit in terms of $\mathcal{E}$, I, r, and R_{var}.

(b)(ii) Which quantities could be graphed to yield a straight line that could be used to calculate a numerical value for the emf $\mathcal{E}$ of the battery?

Horizontal Axis: ____________________ Vertical Axis: ____________________

(b)(iii) Plot the data points for the quantities indicated in part (b)(ii) on the following graph. Clearly scale and label all axes, including units. Draw a straight line that best represents the data. You may use the blank columns in the table for any quantities you graph other than the given data.

[Graph: A blank grid with light dashed gridlines, with an unlabeled vertical axis (arrow pointing up) and unlabeled horizontal axis (arrow pointing right), for the student to plot and scale the chosen quantities.]

Question 2

(b)(iv) Using the graph from part (b)(iii), determine the emf $\mathcal{E}$ of the battery.

Solution 2

(a)(i) Mark scheme

- A correct circuit diagram: the unknown circuit component is connected in series with the $500\,\Omega$ resistor, a wire, and a battery/power supply, forming a complete circuit that produces current through the component (Point 1: source of potential difference in a complete circuit driving current through the component). A voltmeter is connected in parallel across the component (or across the resistor) OR an ammeter is connected in series in the circuit to measure current (a lightbulb in series is an acceptable ammeter substitute) (Point 2: an appropriately connected measurement device, e.g. voltmeter or ammeter).

Solution 2

(a)(ii) Mark scheme

- Procedure: measure one of — the potential difference across the circuit component, the current in the circuit, or the potential difference across the known $500\,\Omega$ resistor (Point 1). Take this measurement at two different times: immediately after the circuit is closed, and again a long time after the circuit is closed (or take a single measurement a long time after closing), consistent with the chosen quantity (Point 2). Example: measure the current in the ammeter immediately after the circuit is closed and a long time after the circuit is closed; or measure the potential difference across the component (or across the $500\,\Omega$ resistor) immediately after closing and a long time after closing.

Solution 2

(a)(iii) Mark scheme

- Expected results if the component is an uncharged capacitor: immediately after the circuit is closed, a nonzero current is measured; a long time after the circuit is closed, the current decreases to zero (equivalently, the charge on the capacitor's plates increases over time until fully charged) (Point 1). The electric potential difference across the capacitor increases from zero (immediately after closing) up to a value equal to the battery's potential difference a long time after closing, since the fully-charged capacitor allows no further current and (by Kirchhoff's loop rule) no potential difference remains across the other circuit elements (Point 2).

Solution 2

(b)(i)

Mark scheme

- Applying Kirchhoff's loop rule around the circuit (battery of emf $\mathcal{E}$ and internal resistance r, in series with variable resistor R_{var}, current I): $0 = +\mathcal{E} - Ir - IR_{var}$.

Solution 2

(b)(ii)

Mark scheme

- Any pair of quantities that linearizes the loop equation to let students find $\mathcal{E}$ from slope or intercept, e.g.: I vs. $\dfrac{1}{r + R_{var}}$ (slope $= \mathcal{E}$); or IR_{var} vs. I (y-intercept $= \mathcal{E}$); or R_{var} vs. $\dfrac{1}{I}$.

Solution 2

(b)(iii)

Mark scheme

- A correctly constructed graph of the chosen linearized quantities: (1) both axes carry numerical values on a linear scale with appropriate labels and units (e.g. I (A) vs. $1/(r + R_{var})$ (Ω^{-1}), or IR_{var} (V) vs. I (A)); (1) the data points are plotted so they span at least half of the grid area; (1) a straight best-fit line is drawn that reasonably approximates the trend of the plotted data points.

Solution 2

(b)(iv) Mark scheme

- Using $I = \mathcal{E}\left(\frac{1}{r + R_{var}}\right) = \mathcal{E}\left(\frac{1}{30\,\Omega + R_{var}}\right)$, the slope of I vs. $1/(r + R_{var})$ equals $\mathcal{E}$: e.g. slope $= \frac{(0.08\text{ A} - 0.04\text{ A})}{(0.004\,\Omega^{-1} - 0.002\,\Omega^{-1})} \approx \mathcal{E} \approx 20$ V. Equivalently, for $IR_{var} = -Ir + \mathcal{E}$, the y-intercept of IR_{var} vs. I equals $\mathcal{E} \approx 20$ V. Full credit for any correct use of the graph (slope or intercept, as appropriate to the chosen axes) giving a value with correct units between 18.0 V and 22.0 V.

Question 2

2018 ▪ Q2

[Circuit diagram: Point A connects to resistor R_1 in series, which connects to a parallel combination of resistor R_2 (top branch, drawn as a zigzag resistor symbol) and a switch S (bottom branch), which then connects to point B.]

Students are given resistor 1 with resistance R_1 connected in series with the parallel combination of a switch S and resistor 2 with resistance R_2, as shown above. The circuit elements cannot be disconnected from each other, and other circuit components can only be connected at points A and B. The students also are given an ammeter and one 9 V battery. The teacher instructs the students to take measurements that can be used to determine R_1 and R_2.

(a) Complete the diagram below to show how the ammeter and the battery should be connected to experimentally determine the resistance of each resistor. Describe the

Question 2

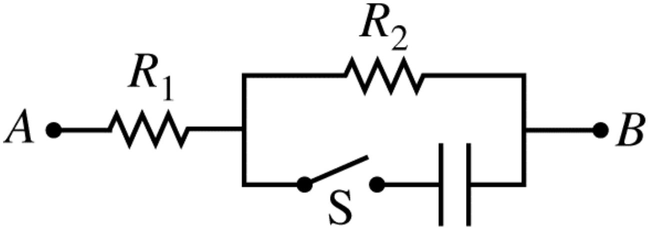
experiment by listing the measurements to be taken and explaining how the measurements would be used to calculate resistances R_1 and R_2.

Complete the Diagram / Describe the Experiment

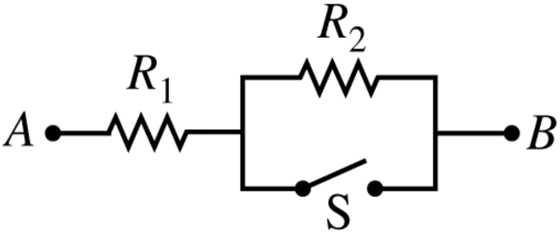
[Diagram: the same circuit (A—R_1—[R_2 parallel with switch S]—B) is shown blank, for the student to add the ammeter and battery connections.]

A second group of students is given a combination of circuit elements that is similar to the previous one but has an initially uncharged capacitor in series with the open switch, as shown above. [Diagram: circuit A—R_1—[R_2 parallel with (switch S in series with a capacitor)]—B.] The combination is placed in a circuit with a power supply so that the potential difference between A and B is maintained at 9 V. The students close the switch and immediately begin to record the current through point B. The initial current is 0.9 A, and after a long time the current is 0.3 A.

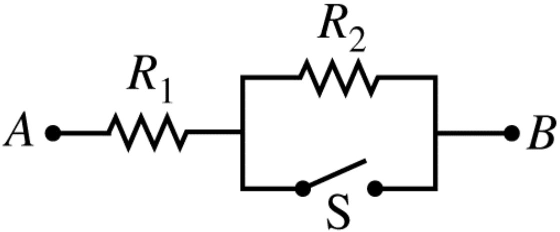
Question 2



Question 2



Question 2



Question 2

2018 ▪ Q2

[Circuit diagram: Point A connects to resistor R_1 in series, which connects to a parallel combination of resistor R_2 (top branch, drawn as a zigzag resistor symbol) and a switch S (bottom branch), which then connects to point B.]

Students are given resistor 1 with resistance R_1 connected in series with the parallel combination of a switch S and resistor 2 with resistance R_2, as shown above. The circuit elements cannot be disconnected from each other, and other circuit components can only be connected at points A and B. The students also are given an ammeter and one 9 V battery. The teacher instructs the students to take measurements that can be used to determine R_1 and R_2.

(b)(i) Compare the currents through resistor 1, resistor 2, and the switch immediately after the switch is closed to the currents a long time after the switch is closed. Specifically state if any current is zero.

Question 2

(b)(ii) Calculate the values of R_1 and R_2.

(b)(iii) Determine the potential difference across the capacitor a long time after the switch is closed.

A third group of students now uses the combination of circuit elements with the capacitor. They connect it to a 9 V battery that they treat as ideal but which is actually not ideal and has internal resistance.

Question 2

2018 ▪ Q2

[Circuit diagram: Point A connects to resistor R_1 in series, which connects to a parallel combination of resistor R_2 (top branch, drawn as a zigzag resistor symbol) and a switch S (bottom branch), which then connects to point B.]

Students are given resistor 1 with resistance R_1 connected in series with the parallel combination of a switch S and resistor 2 with resistance R_2, as shown above. The circuit elements cannot be disconnected from each other, and other circuit components can only be connected at points A and B. The students also are given an ammeter and one 9 V battery. The teacher instructs the students to take measurements that can be used to determine R_1 and R_2.

(c) How does the third group's value of R_1 calculated from the data they collected compare to the second group's value? Explain your reasoning with reference to physics principles and/or mathematical models.

Solution 2

(a) Mark scheme

- Connect the ammeter in series with the 9 V battery, and connect this series combination across points A and B (in series with the R1 / [R2 parallel with switch S] combination). Take two current readings: one with the switch S closed, one with S open. With S closed, R2 is short-circuited by the closed switch, so only R1 carries current: measure that current I_1 and compute $R_1 = V/I_1$ (with $V = 9$ V). With S open, current flows through R1 in series with R2: measure that current I_2 and compute $R_2 = (V/I_2) - R_1$. [Scoring: 1 pt diagram with ammeter+battery in series with the resistor combination; 1 pt indicating current measured with switch both closed and open; 1 pt $R_1 = V/I_1$ with switch closed; 1 pt $R_2 = (V/I_2) - R_1$ with switch open.]

Solution 2

(b)(i) Mark scheme

- Immediately after the switch closes, the initially uncharged capacitor behaves like a short circuit (zero resistance), so current flows through R1 and through the switch branch, bypassing R2 entirely — the current through R2 is zero, while the current through the switch is nonzero. As time passes the capacitor charges up and current into it drops to zero, so a long time after closing, no current flows through the switch branch (blocked by the fully-charged capacitor) — all current instead flows through R1 in series with R2, so R2's current becomes nonzero while the switch's current becomes zero. Because total circuit resistance is smaller immediately after closing (just R1) than a long time after (R1 + R2), the current through R1 immediately after closing is greater than its current a long time after.

Solution 2

Summary: current through R1 is greater immediately after than a long time after; current through R2 is zero immediately after and nonzero a long time after; current through the switch is nonzero immediately after and zero a long time after.

Solution 2

(b)(ii)

Mark scheme

- Immediately after closing (0.9 A flows only through R1, since the capacitor is a momentary short): $9\text{ V} = (0.9\text{ A})R_1 \Rightarrow R_1 = 10\ \Omega$. A long time after closing (0.3 A flows through R1 and R2 in series, since the fully-charged capacitor blocks current, forcing it all through the switch branch's R2): $9\text{ V} = (0.3\text{ A})(R_1 + R_2) = (0.3\text{ A})(10\ \Omega + R_2) \Rightarrow R_2 = 20\ \Omega$.

Solution 2

(b)(iii)

Mark scheme

- A long time after the switch closes, the capacitor voltage equals the battery voltage minus the drop across R1 (which still carries the 0.3 A steady current): $V_C = V_{battery} - V_{R_1} = 9\ \text{V} - (0.3\ \text{A})(10\ \Omega) = 9\ \text{V} - 3\ \text{V} = 6\ \text{V}$.

Solution 2

(c) Mark scheme

- Because the third group's 9 V battery is not ideal, it has internal resistance r, so part of the 9 V is dropped across r rather than across the external circuit — the measured current is smaller than the second group (ideal-battery) case. Since the third group still computes their 'R1' as (battery voltage)/(measured current), assuming an ideal battery, and their measured current is smaller than expected, their calculated value of R1 comes out higher than the second group's true R1 — effectively what they compute is $R_1 + r$, which is larger than the second group's correctly determined R_1.

Question 2

2015 ▪ Q2

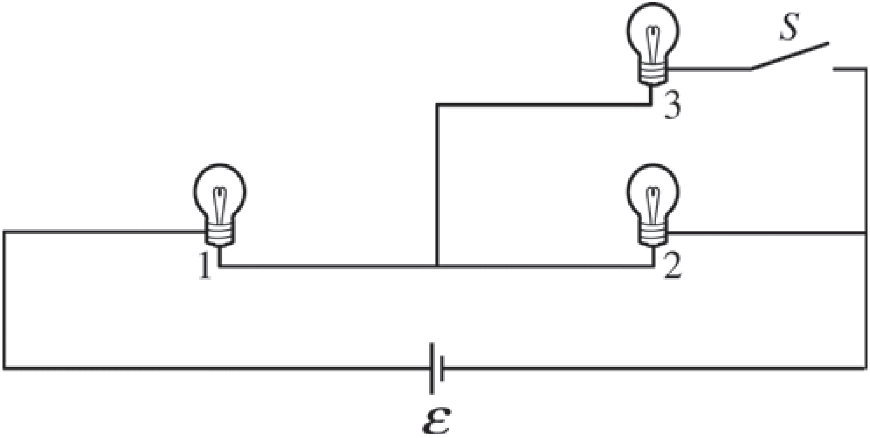
[Circuit diagram: A battery of emf $\mathcal{E}$ is connected at the bottom of the circuit. From the battery, a wire goes up the left side to a node, then splits. Bulb 1 is in the top-left branch. After bulb 1, the wire continues right to a node where the circuit splits into two parallel branches: the upper branch contains bulb 3 in series with switch S (initially open); the lower branch contains bulb 2. Both branches reconnect and return down the right side to the battery. So bulb 1 is in series with the parallel combination of (bulb 3 + switch S) and bulb 2.]

A battery of emf $\mathcal{E}$ and negligible internal resistance, three identical incandescent lightbulbs, and a switch S that is initially open are connected in the circuit shown above. The bulbs each have resistance R. Students make predictions about what happens to the brightness of the bulbs after the switch is closed.

Question 2

(a)(i) A student makes the following prediction about bulb 1: "Bulb 1 will decrease in brightness when the switch is closed."
Do you agree or disagree with the student's prediction about bulb 1? Qualitatively explain your reasoning.
(a)(ii) Before the switch is closed, the power expended by bulb 1 is P_1. Derive an expression for the power P_{new} expended by bulb 1 after the switch is closed, in terms of P_1.
(a)(iii) How does the result of your derivation in part (a)ii relate to your explanation in part (a)i?

Question 2



Question 2

2015 ▪ Q2

[Circuit diagram: A battery of emf $\mathcal{E}$ is connected at the bottom of the circuit. From the battery, a wire goes up the left side to a node, then splits. Bulb 1 is in the top-left branch. After bulb 1, the wire continues right to a node where the circuit splits into two parallel branches: the upper branch contains bulb 3 in series with switch S (initially open); the lower branch contains bulb 2. Both branches reconnect and return down the right side to the battery. So bulb 1 is in series with the parallel combination of (bulb 3 + switch S) and bulb 2.]

A battery of emf $\mathcal{E}$ and negligible internal resistance, three identical incandescent lightbulbs, and a switch S that is initially open are connected in the circuit shown above. The bulbs each have resistance R. Students make predictions about what happens to the brightness of the bulbs after the switch is closed.

(b)(i) A student makes the following prediction about bulb 2: "Bulb 2 will decrease in brightness after the switch is closed."

Question 2

Do you agree or disagree with the student's prediction about bulb 2? Explain your reasoning in words.

(b)(ii) Justify your explanation with a calculation.

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(c)(i) While the switch is open, bulb 3 is replaced with an uncharged capacitor. The switch is then closed.

Question 2

How does the brightness of bulb 1 compare to the brightness of bulb 2 immediately after the switch is closed? Justify your answer.
(c)(ii) How does the brightness of bulb 1 compare to the brightness of bulb 2 a long time after the switch is closed? Justify your answer.

Solution 2

(a)(i) Mark scheme

- Disagree with the student — bulb 1 does not decrease in brightness; it increases. Reasoning chain, each part worth a point: (1) closing the switch puts bulb 3 in parallel with bulb 2, so the resistance of the bulb2+bulb3 combination (and hence the equivalent resistance R_eq of the whole circuit) decreases. (2) By Ohm's law, a decreased R_eq across the fixed EMF increases the total current I_tot, so the current through (and potential difference across) bulb 1 increases, not decreases. (3) Since bulb 1 now carries more current/has a larger potential difference across it, it delivers more power, so its brightness increases — consistent with the current/PD change identified.

Solution 2

(a)(ii) Mark scheme

- Before the switch closes, bulb 1 is in series with bulb 2 only (each resistance R), so $I = \mathcal{E}/2R$ and $P_1 = I^2 R = \frac{1}{4}\left(\frac{\mathcal{E}^2}{R}\right)$ (1 point). When the switch closes, bulb 3 (resistance R) is added in parallel with bulb 2, so the bulb2+3 combination has resistance $R/2$, giving new total equivalent resistance $R_{eq,new} = R + R/2 = \frac{3}{2}R$ (1 point; credit also earned if this was already found in part (a)i and reused here). Manipulating equations: the new current is $I_{new} = \mathcal{E}/R_{eq,new} = \frac{2\mathcal{E}}{3R}$, so the new power in bulb 1 is $P_{new} = I_{new}^2 R = \frac{4\mathcal{E}^2}{9R} = \frac{16}{9}P_1$ (1 point for correctly showing $P_{new} = \frac{16}{9}P_1$).

Solution 2

(a)(iii)

Mark scheme

- Since $\frac{16}{9} > 1$, $P_{new} > P_1$, so bulb 1 expends more power after the switch closes and therefore gets brighter, not dimmer. This confirms part (a)i: a lower circuit resistance raises the current/PD through bulb 1, increasing its power consumption and brightness. Full credit requires explicitly using or referencing the (a)ii expression (e.g. citing $16/9 > 1$) and connecting greater power consumption to greater brightness.

Solution 2

(b)(i)

Mark scheme

- Bulb 2's brightness decreases after the switch is closed. Explanation: once bulb 3 is added in parallel with bulb 2, the current that previously flowed entirely through bulb 2 is now shared between bulb 2 and bulb 3, so the current through (and potential difference across) bulb 2 decreases. Bulb 2 therefore expends less power than before and dims.

Solution 2

(b)(ii)

Mark scheme

- A numeric calculation supporting part (b)i is required, e.g.: before the switch closes, the current through bulb 2 is $I_2 = I_1 = \mathcal{E}/2R$. After closing, $I_{tot} = \mathcal{E}/R_{eq,new} = 2\mathcal{E}/3R$ splits evenly between the two identical parallel bulbs (2 and 3), so $I_2' = I_{tot}/2 = \mathcal{E}/3R$. Since $\mathcal{E}/3R < \mathcal{E}/2R$, bulb 2 carries less current after the switch closes, confirming it is dimmer.

Solution 2

(c)(i) Mark scheme

- (This leaf and 2cii together are worth 3 points on the official scheme: 1 shared point for indicating, in either part, that brightness depends on the potential difference across or current through the bulb, plus 1 point for each part's own justification — allocated here as 2 points to this leaf and 1 to 2cii.) Immediately after the switch closes, bulb 1 is brighter than bulb 2. Reasoning: an uncharged capacitor has zero potential difference across it the instant the switch closes, so it behaves like a short circuit (a wire). Since the capacitor sits in parallel with bulb 2, this diverts current away from bulb 2, so the current through bulb 2 is momentarily zero (or greatly reduced) — less than the current through bulb 1. No

Solution 2

credit for the 'bulb 1 brighter' conclusion without this justification via current/potential difference.

Solution 2

(c)(ii)

Mark scheme

- A long time after the switch closes, bulb 1 has the same brightness as bulb 2. Reasoning: as the capacitor charges, the current through that branch decreases toward zero, and a fully charged capacitor behaves like an open circuit (blocks steady current) after a long time. With (essentially) no current diverted into the capacitor branch, the same current that flows through bulb 1 must also flow through bulb 2, so the two bulbs are equally bright. No credit for the 'same brightness' conclusion without this justification via current/potential difference.