Past-paper walk-through

Compound Direct Current Circuits ▪ 11.5

eXercise

Questions in this set

- 2023 Set 2 Q2
- 2021 Q1
- 2019 Set 2 Q1
- 2015 Q2
- 2014 Q1

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 2

2023 Set 2 ▪ Q2

[Figure, Perspective View (at time $t = 0$): A sloped section of two parallel conducting rails at height H, with a resistor R at the top of the slope. The rails transition to a horizontal section. A region of magnetic field B_1 (dots, pointing out of the page, +y-direction) covers part of the horizontal rails near the bottom of the slope. Farther along, a separate region of magnetic field B_2 (arrows pointing into the page, +z-direction, shown as downward-slanting field lines with arrowheads) covers another part of the rails. Axes shown: $+x$, $+y$, $+z$ in a right-handed orientation.]
[Figure, Top View (at time t_B): Two horizontal parallel rails separated by distance d, viewed from above. A resistor R is at the left end (position x_0). The bar is shown as a vertical rectangle. Positions marked along the x-axis: x_0, x_1, x_B, x_2, x_3, x_4. The region between x_1 and x_2 is shaded with dots labeled B_1 (field out of the page). The region

Question 2

between x_3 and x_4 has downward arrows labeled B_2 (field into the page). The bar is shown at position x_B, between x_1 and x_2.]
Two parallel conducting rails are separated by distance $d = 0.30$ m. A resistor of resistance $R = 0.20\ \Omega$ connects the rails. A conducting bar is placed on a sloped section of the rails at height H above the horizontal section of the rails. Frictional forces and the resistances of the bar and rails are negligible.
- At time $t = 0$, the bar is released from rest from position x_0 and slides down the sloped section of the rails, as shown in the Perspective View. - At time t_1, the bar reaches position x_1 and smoothly transitions to the horizontal section of the rails and enters a uniform magnetic field of magnitude $B_1 = 0.40$ T that is directed in the $+$y-direction. - At time t_2, the bar reaches position x_2 and enters a region with no magnetic field. - At time t_3, the bar reaches position x_3 and enters a uniform magnetic

Question 2

field of magnitude $B_2 = 0.60$ T that is directed in the +z-direction. - At time t_4, the bar reaches position x_4 and enters a region with no magnetic field.
The bar is at position x_B (shown in Top View) at time t_B such that $t_1 < t_B < t_2$.
(a) [Diagram: a vertical rectangle representing the bar, viewed from the Top View perspective, with no arrows drawn.]
On the following diagram of the bar, as observed from the Top View, draw an arrow indicating the direction of the net force F_{net} exerted on the bar at time t_B. If the net force is zero, write $F_{\text{net}} = 0$.

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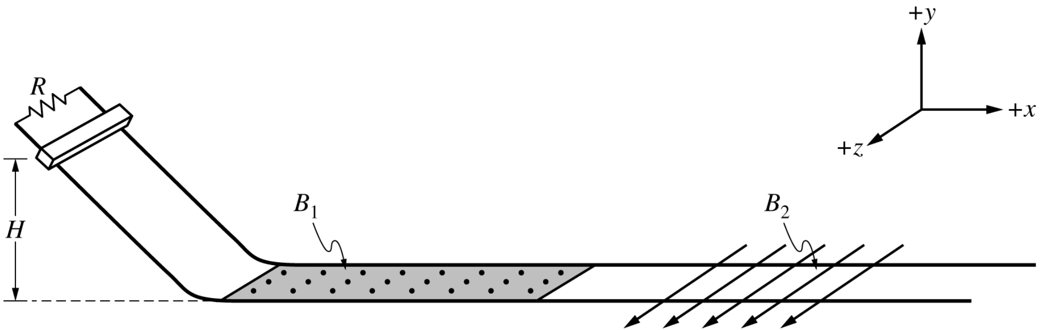
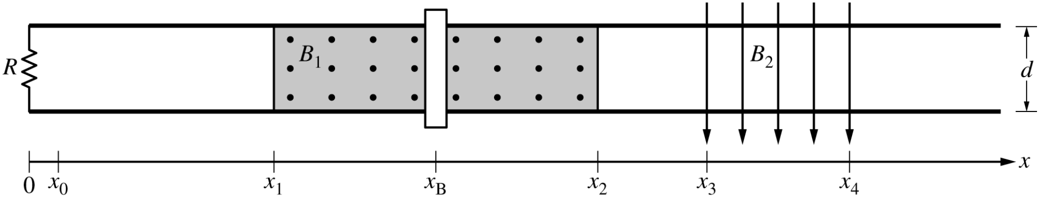


Perspective View (at time $t = 0$)

Question 2



Top View (at time t_B)

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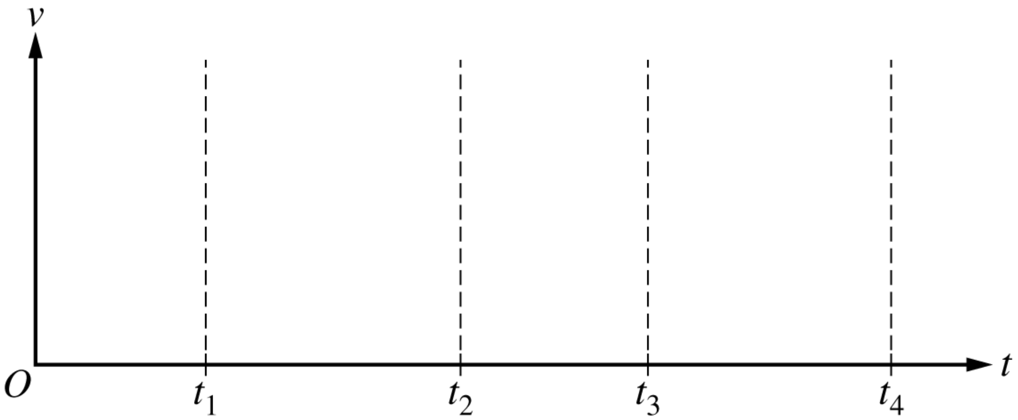

Question 2

2023 Set 2 ▪ Q2

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Question 2

Two parallel conducting rails are separated by distance $d = 0.30$ m. A resistor of resistance $R = 0.20\ \Omega$ connects the rails. A conducting bar is placed on a sloped section of the rails at height H above the horizontal section of the rails. Frictional forces and the resistances of the bar and rails are negligible.
- At time $t = 0$, the bar is released from rest from position x_0 and slides down the sloped section of the rails, as shown in the Perspective View. - At time t_1, the bar reaches position x_1 and smoothly transitions to the horizontal section of the rails and enters a uniform magnetic field of magnitude $B_1 = 0.40$ T that is directed in the $+$y-direction. - At time t_2, the bar reaches position x_2 and enters a region with no magnetic field. - At time t_3, the bar reaches position x_3 and enters a uniform magnetic field of magnitude $B_2 = 0.60$ T that is directed in the $+$z-direction. - At time t_4, the bar reaches position x_4 and enters a region with no magnetic field.

The bar is at position x_B (shown in Top View) at time t_B such that $t_1 < t_B < t_2$.

(b)(i) At time t_B, the speed of the bar is $v = 2.5$ m/s.

Question 2

Calculate the magnitude of the current in the bar at time t_B.

(b)(ii) Calculate the magnitude of the net force F_{net} exerted on the bar at time t_B.

Question 2

2023 Set 2 ▪ Q2

[Figure, Perspective View (at time $t = 0$): A sloped section of two parallel conducting rails at height H, with a resistor R at the top of the slope. The rails transition to a horizontal section. A region of magnetic field B_1 (dots, pointing out of the page, +y-direction) covers part of the horizontal rails near the bottom of the slope. Farther along, a separate region of magnetic field B_2 (arrows pointing into the page, +z-direction, shown as downward-slanting field lines with arrowheads) covers another part of the rails. Axes shown: $+x$, $+y$, $+z$ in a right-handed orientation.]

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Question 2

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The bar is at position x_B (shown in Top View) at time t_B such that $t_1 < t_B < t_2$.

Question 2

(c) On the following axes, sketch a graph of the speed v of the bar as a function of time t between $t = 0$ and t_4.
[Graph: y-axis labeled "v", x-axis labeled "t" with tick marks at t_1, t_2, t_3, t_4 (dashed vertical gridlines at each); axes otherwise unlabeled with numeric values, origin at O.]

Question 2

2023 Set 2 ▪ Q2

[Figure, Perspective View (at time $t = 0$): A sloped section of two parallel conducting rails at height H, with a resistor R at the top of the slope. The rails transition to a horizontal section. A region of magnetic field B_1 (dots, pointing out of the page, +y-direction) covers part of the horizontal rails near the bottom of the slope. Farther along, a separate region of magnetic field B_2 (arrows pointing into the page, +z-direction, shown as downward-slanting field lines with arrowheads) covers another part of the rails. Axes shown: $+x$, $+y$, $+z$ in a right-handed orientation.]

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Question 2

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The bar is at position x_B (shown in Top View) at time t_B such that $t_1 < t_B < t_2$.

Question 2

(d)(i) The original scenario is repeated but with a new bar that has the same mass but with a nonnegligible resistance $R = 0.20\ \Omega$. The new bar is released from rest and smoothly transitions to the horizontal section of the rails and enters the first uniform magnetic field.
Determine the total resistance of the closed circuit.
(d)(ii) In the original scenario, the magnitude of the acceleration of the bar immediately after the bar enters the first uniform magnetic field is a_{original}. In the new scenario, the magnitude of the acceleration of the bar immediately after the bar enters the first uniform magnetic field is a_{new}. Is a_{new} greater than, less than, or equal to a_{original}? Justify your answer.

Question 2

2023 Set 2 ▪ Q2

[Figure, Perspective View (at time $t = 0$): A sloped section of two parallel conducting rails at height H, with a resistor R at the top of the slope. The rails transition to a horizontal section. A region of magnetic field B_1 (dots, pointing out of the page, +y-direction) covers part of the horizontal rails near the bottom of the slope. Farther along, a separate region of magnetic field B_2 (arrows pointing into the page, +z-direction, shown as downward-slanting field lines with arrowheads) covers another part of the rails. Axes shown: $+x$, $+y$, $+z$ in a right-handed orientation.]

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Question 2

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- At time $t = 0$, the bar is released from rest from position x_0 and slides down the sloped section of the rails, as shown in the Perspective View. - At time t_1, the bar reaches position x_1 and smoothly transitions to the horizontal section of the rails and enters a uniform magnetic field of magnitude $B_1 = 0.40$ T that is directed in the $+$y-direction. - At time t_2, the bar reaches position x_2 and enters a region with no magnetic field. - At time t_3, the bar reaches position x_3 and enters a uniform magnetic field of magnitude $B_2 = 0.60$ T that is directed in the $+$z-direction. - At time t_4, the bar reaches position x_4 and enters a region with no magnetic field.

The bar is at position x_B (shown in Top View) at time t_B such that $t_1 < t_B < t_2$.

Question 2

(e) Describe a modification to H, B_1, or d that will result in a larger induced current in the new bar immediately after the bar enters the first magnetic field. Justify your answer.

Solution 2

(a)

Mark scheme

- On the Top View diagram of the bar, draw a single arrow pointing to the LEFT (with no extraneous arrows) representing the direction of the net force F_{net} on the bar at time t_B. This is the magnetic braking force from the induced current interacting with the field, which by Lenz's law opposes the bar's motion; on the horizontal rail section (no gravity component along the rails) it is the only horizontal force, so F_{net} points opposite the bar's velocity, i.e. to the left in the given view.

Solution 2

(b)(i) Mark scheme

- Calculate the magnitude of the current in the bar at t_B, where $v = 2.5$ m/s. (1) Use Faraday's law for the induced emf: $\mathcal{E} = -\frac{d\Phi_B}{dt} = -\frac{d(B_1 dx)}{dt}$ (this point may be earned without the negative sign or a numerical answer). (2) Substitute v for $\frac{dx}{dt}$: $\mathcal{E} = -B_1 d\frac{dx}{dt} = -B_1 dv$ (a student may also earn both of the first two points by starting directly from $\mathcal{E} = B_1 dv$). (3) Substitute the correct resistance into Ohm's law to solve for current. Full solution:
  $\mathcal{E} = -(0.40\,\mathrm{T})(0.30\,\mathrm{m})(2.5\,\mathrm{m/s}) = -0.30$ V; $I = \frac{|\mathcal{E}|}{R} = \frac{0.30\,\mathrm{V}}{0.20\,\Omega} = 1.5$ A.

Solution 2

(b)(ii)

Mark scheme

- Calculate the magnitude of the net force F_{net} on the bar at t_B by substituting the current (or an expression for it) from part (b)(i) into $F = IdB_1$: $F = (1.5\,\mathrm{A})(0.3\,\mathrm{m})(0.4\,\mathrm{T}) = 0.18\ \mathrm{N}$. (Equivalently, deriving symbolically: $F = \dfrac{B_1^2 d^2 v}{R} = \dfrac{(0.4)^2(0.3)^2(2.5)}{0.2} = 0.18\ \mathrm{N}$.)

Solution 2

(c) Mark scheme

- Sketch v vs t from $t = 0$ to t_4 with four required features (1 point each): (1) a straight line with POSITIVE slope starting at the origin from $t = 0$ to t_1 (bar speeding up before/while entering the field region); (2) a curve that is DECREASING and CONCAVE UP from t_1 to t_2 (bar decelerating due to the speed-dependent magnetic braking force, asymptotically slowing its rate of decrease); (3) a NONZERO horizontal line from t_2 to t_3 (constant nonzero speed); (4) a NONZERO horizontal line from t_3 to t_4 (constant nonzero speed continues, possibly at a different level than segment 3). Net shape: rises linearly, then curves down concave-up leveling off, then two flat nonzero segments.

Solution 2

(d)(i)

Mark scheme

- Determine the total resistance of the closed circuit for the new bar ($R = 0.20\ \Omega$) in series with the fixed rail/other resistance of $0.2\ \Omega$: $R_s = \sum_i R_i = (0.2\,\Omega) + (0.2\,\Omega) = 0.4\ \Omega$. Correct answer with units (0.4 Ω) earns the point; it may be earned without supporting calculations.

Solution 2

(d)(ii) Mark scheme

- Determine whether a_{new} is greater than, less than, or equal to $a_{original}$, and justify: the correct answer is $a_{new} < a_{original}$. Full credit requires a chain of correct statements (1 point each, and full credit can be earned with a justification consistent with the resistance calculated in part (d)(i)): (1) inverse relation between resistance and current — as resistance increases, current decreases; (2) direct relation between current and magnetic force — as current decreases, magnetic force $F = IdB$ decreases; (3) direct relation between force and acceleration — by Newton's second law $F = ma$, as force decreases (same mass), acceleration decreases. Example justification: the new bar has greater total

Solution 2

resistance, so it carries less current, so the magnetic force on it is less, so (same mass) its acceleration is less than the original.

Solution 2

(e) Mark scheme

- Describe ONE modification to H, B_1, or d that results in a LARGER induced current in the new bar immediately after entering the first magnetic field, and justify it. (1 point) Correctly identify one of: increasing H, increasing B_1, or increasing d, with an attempted relevant justification. (1 point) Correctly justify why that change increases current. Any one of: Increasing H — a higher release height gives greater potential energy, hence greater kinetic energy/speed entering the field, giving a greater rate of change of flux, so by Faraday's law a greater emf and thus greater current. OR Increasing B_1 — a stronger field increases the flux through the circuit and its rate of change, giving a greater induced emf and thus greater current. OR Increasing d — a larger bar width increases the area enclosed

Solution 2

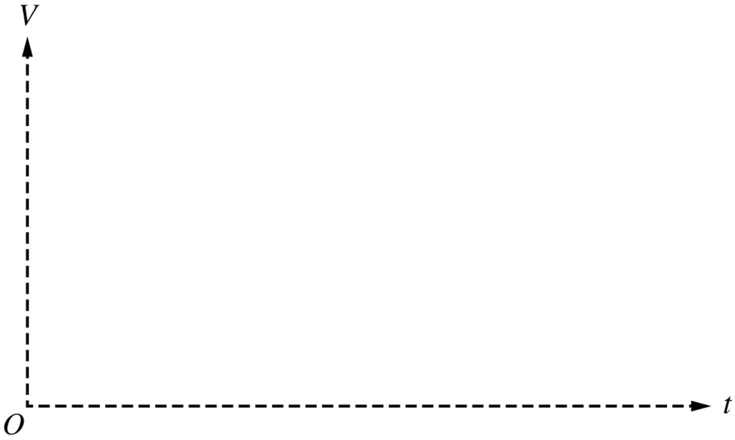
by the circuit, increasing flux and its rate of change, giving a greater induced emf and thus greater current.

Question 1

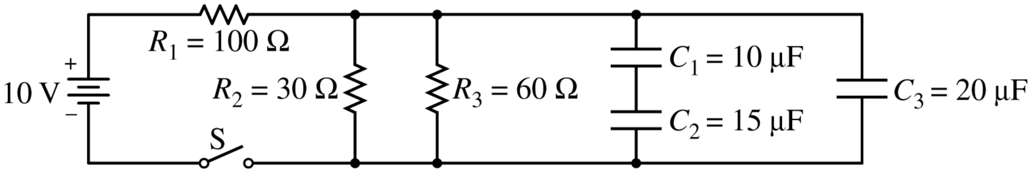
2021 ▪ Q1

[Circuit diagram: An ideal 10 V battery ($+$ terminal on top) connects through a switch S in series with resistor $R_1 = 100\ \Omega$. The circuit then splits into three parallel branches between the top and bottom rails: a branch with resistor $R_2 = 30\ \Omega$ (in series with switch S, both shown on the left branch), a branch with resistor $R_3 = 60\ \Omega$, a branch with two capacitors $C_1 = 10\ \mu$F and $C_2 = 15\ \mu$F stacked in series with each other, and a branch with capacitor $C_3 = 20\ \mu$F.]
The circuit shown above is composed of an ideal 10 V battery, three resistors and three capacitors with the values shown, and an open switch S. The capacitors are initially uncharged. Switch S is now closed.
(a) Calculate the current through R_1 immediately after switch S is closed.

Question 1



Question 1



$R_1 = 100\ \Omega$
+
10 V
−
$R_2 = 30\ \Omega$
S
$R_3 = 60\ \Omega$
$C_1 = 10\ \mu F$
$C_2 = 15\ \mu F$
$C_3 = 20\ \mu F$

Question 1

2021 ▪ Q1

[Circuit diagram: An ideal 10 V battery (+ terminal on top) connects through a switch S in series with resistor $R_1 = 100\ \Omega$. The circuit then splits into three parallel branches between the top and bottom rails: a branch with resistor $R_2 = 30\ \Omega$ (in series with switch S, both shown on the left branch), a branch with resistor $R_3 = 60\ \Omega$, a branch with two capacitors $C_1 = 10\ \mu$F and $C_2 = 15\ \mu$F stacked in series with each other, and a branch with capacitor $C_3 = 20\ \mu$F.]

The circuit shown above is composed of an ideal 10 V battery, three resistors and three capacitors with the values shown, and an open switch S. The capacitors are initially uncharged. Switch S is now closed.

(b) Switch S has been closed for a long time, and the circuit has reached a steady state.

Calculate the potential difference across R_1.

Question 1

2021 ▪ Q1

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The circuit shown above is composed of an ideal 10 V battery, three resistors and three capacitors with the values shown, and an open switch S. The capacitors are initially uncharged. Switch S is now closed.

(c)(i) Calculate the charge stored on the positive plate of capacitor C_2.

(c)(ii) Is the charge stored on capacitor C_3 greater than, less than, or equal to the charge stored on capacitor C_2?

______ Greater than ______ Less than ______ Equal to

Question 1

Justify your answer.

Question 1

2021 ▪ Q1

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The circuit shown above is composed of an ideal 10 V battery, three resistors and three capacitors with the values shown, and an open switch S. The capacitors are initially uncharged. Switch S is now closed.

(d)(i) Switch S is then opened.

Determine the current through R_1 immediately after the switch is opened.

(d)(ii) Calculate the current through R_2 immediately after the switch is opened.

Question 1

2021 ▪ Q1

[Circuit diagram: An ideal 10 V battery (+ terminal on top) connects through a switch S in series with resistor $R_1 = 100\ \Omega$. The circuit then splits into three parallel branches between the top and bottom rails: a branch with resistor $R_2 = 30\ \Omega$ (in series with switch S, both shown on the left branch), a branch with resistor $R_3 = 60\ \Omega$, a branch with two capacitors $C_1 = 10\ \mu$F and $C_2 = 15\ \mu$F stacked in series with each other, and a branch with capacitor $C_3 = 20\ \mu$F.]

The circuit shown above is composed of an ideal 10 V battery, three resistors and three capacitors with the values shown, and an open switch S. The capacitors are initially uncharged. Switch S is now closed.

(e) On the axes below, sketch a graph of the potential difference V across capacitor C_2 as a function of time t if switch S is opened at time $t = 0$. Label the maximum value.

Question 1

[Graph axes: vertical axis V, horizontal axis t; origin labeled O; a dashed vertical guideline is shown near the vertical axis, and a dashed horizontal guideline extends across the plot area; no data plotted, blank axes for the student to sketch on.]

Question 1

2021 ▪ Q1

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The circuit shown above is composed of an ideal 10 V battery, three resistors and three capacitors with the values shown, and an open switch S. The capacitors are initially uncharged. Switch S is now closed.

(f) Capacitor C_3 is replaced by two $10\ \mu$F capacitors connected in series, switch S is closed, and the circuit reaches equilibrium. Switch S is then opened at time $t = 0$. For $t > 0$, would the sketch of a graph of the new voltage across C_2 as a function of time be above, below, or the same as the sketch for part (e)?

Question 1

A^{bove}

B^{elow}

T^{hesame}

Justify your answer.

Solution 1

(a)

Mark scheme

- Immediately after S closes, the initially-uncharged capacitors act as short circuits, so $R_{EQ} = R_1 = 100\ \Omega$ (all current flows through R_1, bypassing R_2 and R_3). By Ohm's law, $I = \Delta V/R = (10\ \text{V})/(100\ \Omega) = 0.10$ A. Points: (1) recognizing capacitors act as short circuits immediately after closing, (2) correct Ohm's-law calculation giving $I = 0.10$ A.

Solution 1

(b)

Mark scheme

- At steady state the capacitors are fully charged (no current into them), so current flows through R_1 in series with the parallel combination of R_2 and R_3: $1/R_P = 1/R_2 + 1/R_3 = 1/30\ \Omega + 1/60\ \Omega \Rightarrow R_P = 20\ \Omega$, so $R_{EQ} = R_1 + R_P = 100 + 20 = 120\ \Omega$. Current through the battery: $I = \Delta V/R = (10\ \text{V})/(120\ \Omega) = 0.083\ \text{A}$. Potential difference across R_1: $\Delta V = (0.083\ \text{A})(100\ \Omega) = 8.3\ \text{V}$. Points: (1) correct steady-state equivalent resistance, (2) correct current/voltage calculation giving $\Delta V_{R_1} = 8.3\ \text{V}$.

Solution 1

(c)(i)

Mark scheme

- The potential difference across C_3 equals that across the parallel branch: $\Delta V_{C_3} = \Delta V_P = IR_P = (0.083\ \text{A})(20\ \Omega) = 1.67\ \text{V}$, which also equals the total p.d. across the series combination of C_1 and C_2 (that series pair is in parallel with C_3). Equivalent capacitance of C_1, C_2 in series: $1/C_S = 1/C_1 + 1/C_2 = 1/10\ \mu\text{F} + 1/15\ \mu\text{F} \Rightarrow C_S = 6.0\ \mu\text{F}$. Charge on C_2 (same as on C_1, series): $Q_2 = Q_S = C_S \Delta V_{C_{12}} = (1.67\ \text{V})(6.0\ \mu\text{F}) = 10\ \mu\text{C}$. Points: (1) correct equation giving $\Delta V_{C_3} = 1.67\ \text{V}$, (2) correct use of the series-equivalent capacitance to get $Q_2 = 10\ \mu\text{C}$.

Solution 1

(c)(ii) Mark scheme

- Greater than. Justification (per the scoring guidelines): The potential difference across the series combination of C_1 and C_2 is the same as the potential difference across C_3 (parallel branches share the same p.d.); thus capacitor C_3 has a greater potential difference across its plates than C_2 individually, and C_3 has a greater capacitance than C_2. Because $Q = C\Delta V$, C_3 stores a greater charge than C_2. (A justification via a full mathematical proof also earns full credit.) Points: (1) selecting 'Greater than' and attempting a relevant justification, (2) a fully correct justification.

Solution 1

(d)(i)

Mark scheme

- Immediately after S is opened, the current through R_1 is zero: $I_1 = 0$. Opening the switch removes R_1's branch from any closed conducting path, so no current flows through it (the capacitors instead discharge through R_2).

Solution 1

(d)(ii)

Mark scheme

- The potential difference across R_2 immediately after opening equals the p.d. across the capacitors just before the switch was opened (capacitor voltage cannot change instantaneously): $\Delta V_{R_2} = \Delta V_{C_{12}} = 1.67$ V. By Ohm's law: $I = \Delta V_{R_2}/R_2 = (1.67\text{ V})/(30\ \Omega) = 0.056$ A. Points: (1) correctly identifying $\Delta V_{R_2} = \Delta V_{C_{12}} = 1.67$ V, (2) correct Ohm's-law calculation giving $I = 0.056$ A.

Solution 1

(e)

Mark scheme

- Sketch an exponential-decay (RC discharge) curve: it must start at $t = 0$ at a nonzero, clearly labeled maximum value ($V = 0.67$ V — the steady-state voltage across C_2 before the switch opened, $Q_2/C_2 = 10\ \mu C/15\ \mu F$), then decrease as a concave-up curve that approaches the horizontal (t) axis asymptotically (never reaching $V = 0$) as $t \to \infty$ (discharge through R_2). Points: (1) curve starts at a nonzero, labeled maximum value, (2) concave-up curve with the horizontal axis as an asymptote.

Solution 1

(f)

Mark scheme

- Below. Justification: Replacing C_3 with two $10\ \mu$F capacitors in series (equivalent capacitance $5\ \mu F$, less than the original C_3) decreases the equivalent capacitance of the circuit; since the discharge time constant $\tau = RC$ decreases, the capacitors discharge more rapidly, so the new V-vs-t curve for C_2 (for $t > 0$) lies below the original curve from part (e). Points: (1) selecting 'Below' and attempting a relevant justification, (2) a fully correct justification.

Question 1

2019 Set 2 ▪ Q1

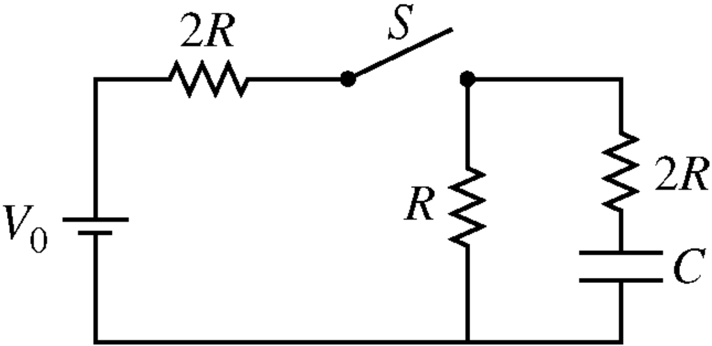
[Circuit diagram: A battery of voltage V_0 on the left, in series with a resistor labeled $2R$ and a switch S. After the switch, the circuit splits into two parallel branches: a resistor labeled R, and a branch containing a resistor labeled $2R$ in series with a capacitor labeled C.]

The circuit represented above is composed of three resistors with the resistances shown, a battery of voltage V_0, a capacitor of capacitance C, and a switch S. The switch is closed, and after a long time, the circuit reaches steady-state conditions. Answer the following questions in terms of V_0, R, C, and fundamental constants, as appropriate.

(a) Derive an expression for the steady-state current supplied by the battery.

Question 1

Question 1



Question 1

2019 Set 2 ▪ Q1

[Circuit diagram: A battery of voltage V_0 on the left, in series with a resistor labeled $2R$ and a switch S. After the switch, the circuit splits into two parallel branches: a resistor labeled R, and a branch containing a resistor labeled $2R$ in series with a capacitor labeled C.]

The circuit represented above is composed of three resistors with the resistances shown, a battery of voltage V_0, a capacitor of capacitance C, and a switch S. The switch is closed, and after a long time, the circuit reaches steady-state conditions. Answer the following questions in terms of V_0, R, C, and fundamental constants, as appropriate.

(b) Derive an expression for the charge on the capacitor.

Question 1

2019 Set 2 ▪ Q1

[Circuit diagram: A battery of voltage V_0 on the left, in series with a resistor labeled $2R$ and a switch S. After the switch, the circuit splits into two parallel branches: a resistor labeled R, and a branch containing a resistor labeled $2R$ in series with a capacitor labeled C.]

The circuit represented above is composed of three resistors with the resistances shown, a battery of voltage V_0, a capacitor of capacitance C, and a switch S. The switch is closed, and after a long time, the circuit reaches steady-state conditions. Answer the following questions in terms of V_0, R, C, and fundamental constants, as appropriate.

(c) Derive an expression for the energy stored in the capacitor.

Question 1

2019 Set 2 ▪ Q1

[Circuit diagram: A battery of voltage V_0 on the left, in series with a resistor labeled $2R$ and a switch S. After the switch, the circuit splits into two parallel branches: a resistor labeled R, and a branch containing a resistor labeled $2R$ in series with a capacitor labeled C.]

The circuit represented above is composed of three resistors with the resistances shown, a battery of voltage V_0, a capacitor of capacitance C, and a switch S. The switch is closed, and after a long time, the circuit reaches steady-state conditions. Answer the following questions in terms of V_0, R, C, and fundamental constants, as appropriate.

(d) Now the switch is opened at time $t = 0$.

Write, but do NOT solve, a differential equation that could be used to solve for the charge $q(t)$ on the capacitor as a function of the time t after the switch is opened.

Question 1

2019 Set 2 ▪ Q1

[Circuit diagram: A battery of voltage V_0 on the left, in series with a resistor labeled $2R$ and a switch S. After the switch, the circuit splits into two parallel branches: a resistor labeled R, and a branch containing a resistor labeled $2R$ in series with a capacitor labeled C.]

The circuit represented above is composed of three resistors with the resistances shown, a battery of voltage V_0, a capacitor of capacitance C, and a switch S. The switch is closed, and after a long time, the circuit reaches steady-state conditions. Answer the following questions in terms of V_0, R, C, and fundamental constants, as appropriate.

(e)(i) Calculate the current in resistor R immediately after the switch is opened.

(e)(ii) On the axes below, sketch the current in the circuit as a function of time from time $t = 0$ to a long time after the switch is opened. Explicitly label the maxima with numerical values or algebraic expressions, as appropriate.

Question 1

[Graph with vertical axis labeled "Current" and horizontal axis labeled "Time"; origin labeled O; axes are blank/unscaled for the student to sketch on.]

Question 1

2019 Set 2 ▪ Q1

[Circuit diagram: A battery of voltage V_0 on the left, in series with a resistor labeled $2R$ and a switch S. After the switch, the circuit splits into two parallel branches: a resistor labeled R, and a branch containing a resistor labeled $2R$ in series with a capacitor labeled C.]

The circuit represented above is composed of three resistors with the resistances shown, a battery of voltage V_0, a capacitor of capacitance C, and a switch S. The switch is closed, and after a long time, the circuit reaches steady-state conditions. Answer the following questions in terms of V_0, R, C, and fundamental constants, as appropriate.

(f) Is the total amount of energy dissipated in the resistors after the switch is opened greater than, less than, or equal to the amount of energy stored in the capacitor calculated in part (c)?

_____ Greater than _____ Less than _____ Equal to

Justify your answer.

Solution 1

(a) Mark scheme

- At steady state the capacitor is fully charged and draws no current, so no current flows through the branch containing the second $2R$ resistor and C. The circuit reduces to the top $2R$ in series with R (effective resistance $3R$). By Ohm's law: $I = \frac{V_0}{R_{eff}} = \frac{V_0}{2R+R}$, so $I = \frac{V_0}{3R}$. (1 pt: using Ohm's law with the correct effective resistance; 1 pt: correct substitution leading to the correct answer.)

Solution 1

(b) Mark scheme

- The stored charge is $q = CV_C$. At steady state no current flows through the $2R$-C branch, so $V_C = V_R$ (the parallel branch's voltage). $V_R = IR = \left(\frac{V_0}{3R}\right) R = \frac{1}{3}V_0$. Therefore $q = CV_R = \frac{1}{3}CV_0$. (1 pt: using the equation relating stored charge to capacitance; 1 pt: correctly determining V_R and substituting.)

Solution 1

(c) Mark scheme

- Energy stored in a capacitor: $U = \dfrac{q^2}{2C}$. Substituting $q = \dfrac{1}{3}CV_0$ from part (b): $U = \dfrac{(CV_0/3)^2}{2C} = \dfrac{1}{18}CV_0^2$. (1 pt: any correct equation for energy stored in a capacitor; 1 pt: correct substitution of charge and/or voltage from part (b).)

Solution 1

(d) Mark scheme

- After the switch opens, current can only flow around the loop containing R, the second $2R$, and C. Voltage loop equation: $V_C - V_R - V_{2R} = 0 \Rightarrow \dfrac{q(t)}{C} = I(R+2R)$. Since the capacitor is discharging, $I = -\dfrac{dq}{dt}$, giving the differential equation $\dfrac{q(t)}{C} = -3R\dfrac{dq}{dt}$ (do not solve it). (1 pt: any correct voltage loop equation for when the switch is open; 1 pt: substituting $-dq/dt$ or dq/dt for the current, consistent with the loop equation.)

Solution 1

(e)(i) Mark scheme

- The capacitor voltage cannot change instantaneously, so immediately after the switch opens $V_C(0^+) = V_R(0^+) = \dfrac{V_0}{3}$ (from part (b)). Current now flows through the total resistance $R + 2R = 3R$: $I = \dfrac{V_0/3}{3R} = \dfrac{V_0}{9R}$. (1 pt: using a voltage consistent with part (b) in $I = V/R$; 1 pt: substituting the correct total resistance $3R$ into Ohm's law.)

Solution 1

(e)(ii) Mark scheme

- The current starts at its maximum value $I_0 = \dfrac{V_0}{9R}$ (from part (e)(i)) at $t = 0$ and decays exponentially toward zero as the capacitor discharges: $I(t) = \dfrac{V_0}{9R}e^{-t/3RC}$. The sketch should show a curve that is concave up throughout, decreasing monotonically toward the horizontal (time) axis as an asymptote, with the initial value explicitly labeled $V_0/9R$ on the vertical axis at $t = 0$. (1 pt: curve concave up throughout the graph; 1 pt: horizontal axis as an asymptote; 1 pt: labeling the maximum current, consistent with part (e)(i).)

Solution 1

(f) Mark scheme

- Equal to. Justification: after the switch opens, the capacitor discharges all of its stored energy and charge; assuming no energy is lost in the connecting wires, the only circuit elements that dissipate this energy are the two resistors (R and 2R) in series with the capacitor, so the total energy dissipated in the resistors equals the energy that was stored in the capacitor (conservation of energy). (1 pt: selecting \"Equal to\"; 1 pt: a correct justification invoking conservation of energy.) [An alternate full-credit path selects \"Less than\" with justification that some energy is additionally lost due to resistance in the connecting wires and/or losses in the capacitor.]

Question 2

2015 ▪ Q2

[Figure: A circuit diagram. At the top, a voltmeter (circle labeled V) is connected across a variable resistor (labeled R, drawn as a resistor symbol with a diagonal arrow through it, indicating it is adjustable). Below, in a dashed box, a battery is shown as an internal resistance r (resistor symbol) in series with an emf source $\mathcal{E}$. The battery (dashed box) is connected in series with the variable resistor R, and the voltmeter is connected across R.]

A student performs an experiment to determine the emf $\mathcal{E}$ and internal resistance r of a given battery. The student connects the battery in series to a variable resistance R, with a voltmeter across the variable resistor, as shown in the figure above, and measures the voltmeter reading V as a function of the resistance R. The data are shown in the table below.

Question 2

Trial	Resistance (Ω)	Voltage (V)	$1/R$ ($1/\Omega$)	$1/V$ (1/V)
1	0.50	5.6	2.00	0.179
2	1.0	7.4	1.00	0.135
3	2.0	9.4	0.50	0.106
4	3.0	10.6	0.33	0.094
5	5.0	10.9	0.20	0.092
6	10	11.4	0.10	0.088

(a)(i) Derive an expression for the measured voltage V. Express your answer in terms of R, $\mathcal{E}$, r, and physical constants, as appropriate.

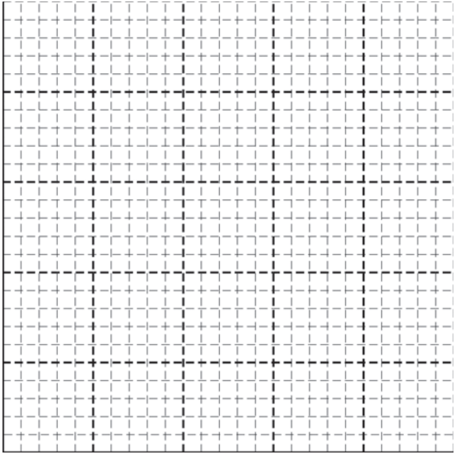
(a)(ii) Rewrite your expression from part (a)-i to express $1/V$ as a function of $1/R$.

Question 2

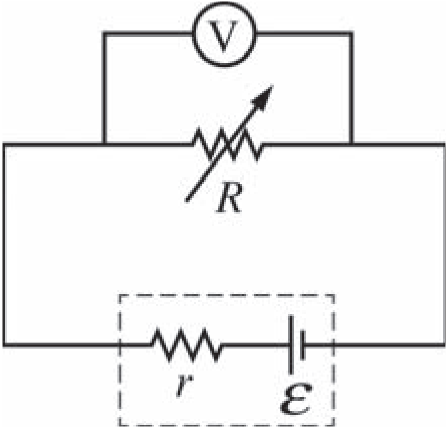
shown in the figure above, and measures the voltmeter reading V as a function of the resistance R. The
shown in the table below.

Trial #	Resistance (Ω)	Voltage (V)	$1/R$ (1/Ω)	$1/V$ (1/V)
1	0.50	5.6	2.00	0.179
2	1.0	7.4	1.00	0.135
3	2.0	9.4	0.50	0.106
4	3.0	10.6	0.33	0.094
5	5.0	10.9	0.20	0.092
6	10	11.4	0.10	0.088

Question 2



Question 2



Question 2

2015 ▪ Q2

[Figure: A circuit diagram. At the top, a voltmeter (circle labeled V) is connected across a variable resistor (labeled R, drawn as a resistor symbol with a diagonal arrow through it, indicating it is adjustable). Below, in a dashed box, a battery is shown as an internal resistance r (resistor symbol) in series with an emf source $\mathcal{E}$. The battery (dashed box) is connected in series with the variable resistor R, and the voltmeter is connected across R.]

A student performs an experiment to determine the emf $\mathcal{E}$ and internal resistance r of a given battery. The student connects the battery in series to a variable resistance R, with a voltmeter across the variable resistor, as shown in the figure above, and measures the voltmeter reading V as a function of the resistance R. The data are shown in the table below.

Trial	Resistance (Ω)	Voltage (V)	$1/R$ ($1/\Omega$)	$1/V$ (1/V)
1	0.50	5.6	2.00	0.179
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4	3.0	10.6	0.33	0.094
5	5.0	10.9	0.20	0.092
6	10	11.4	0.10	0.088

Question 2

(b) On the grid below, plot data points for the graph of $1/V$ as a function of $1/R$. Clearly scale and label all axes, including units as appropriate. Draw a straight line that best represents the data.
[Figure: A blank grid (approximately 30 x 30 gridlines with heavier gridlines every 6 squares) for plotting $1/V$ vs. $1/R$.]

Question 2

2015 ▪ Q2

[Figure: A circuit diagram. At the top, a voltmeter (circle labeled V) is connected across a variable resistor (labeled R, drawn as a resistor symbol with a diagonal arrow through it, indicating it is adjustable). Below, in a dashed box, a battery is shown as an internal resistance r (resistor symbol) in series with an emf source $\mathcal{E}$. The battery (dashed box) is connected in series with the variable resistor R, and the voltmeter is connected across R.]

A student performs an experiment to determine the emf $\mathcal{E}$ and internal resistance r of a given battery. The student connects the battery in series to a variable resistance R, with a voltmeter across the variable resistor, as shown in the figure above, and measures the voltmeter reading V as a function of the resistance R. The data are shown in the table below.

Trial	Resistance (Ω)	Voltage (V)	$1/R$ (1/Ω)	$1/V$ (1/V)
1	0.50	5.6	2.00	0.179
2	1.0	7.4	1.00	0.135
3	2.0	9.4	0.50	0.106
4	3.0	10.6	0.33	0.094
5	5.0	10.9	0.20	0.092
6	10	11.4	0.10	0.088

(c)(i) Use the straight line from part (b) to obtain a value for $\mathcal{E}$.

Question 2

(c)(ii) Use the straight line from part (b) to obtain a value for r.

Question 2

2015 ▪ Q2

[Figure: A circuit diagram. At the top, a voltmeter (circle labeled V) is connected across a variable resistor (labeled R, drawn as a resistor symbol with a diagonal arrow through it, indicating it is adjustable). Below, in a dashed box, a battery is shown as an internal resistance r (resistor symbol) in series with an emf source $\mathcal{E}$. The battery (dashed box) is connected in series with the variable resistor R, and the voltmeter is connected across R.]

A student performs an experiment to determine the emf $\mathcal{E}$ and internal resistance r of a given battery. The student connects the battery in series to a variable resistance R, with a voltmeter across the variable resistor, as shown in the figure above, and measures the voltmeter reading V as a function of the resistance R. The data are shown in the table below.

Trial	Resistance (Ω)	Voltage (V)	$1/R$ $(1/\Omega)$	$1/V$ (1/V)
1	0.50	5.6	2.00	0.179
2	1.0	7.4	1.00	0.135
3	2.0	9.4	0.50	0.106
4	3.0	10.6	0.33	0.094
5	5.0	10.9	0.20	0.092
6	10	11.4	0.10	0.088

Question 2

(d) Using the results of the experiment, calculate the maximum current that the battery can provide.

Question 2

2015 ▪ Q2

[Figure: A circuit diagram. At the top, a voltmeter (circle labeled V) is connected across a variable resistor (labeled R, drawn as a resistor symbol with a diagonal arrow through it, indicating it is adjustable). Below, in a dashed box, a battery is shown as an internal resistance r (resistor symbol) in series with an emf source $\mathcal{E}$. The battery (dashed box) is connected in series with the variable resistor R, and the voltmeter is connected across R.]

A student performs an experiment to determine the emf $\mathcal{E}$ and internal resistance r of a given battery. The student connects the battery in series to a variable resistance R, with a voltmeter across the variable resistor, as shown in the figure above, and measures the voltmeter reading V as a function of the resistance R. The data are shown in the table below.

Trial	Resistance (Ω)	Voltage (V)	$1/R$ (1/Ω)	$1/V$ (1/V)
1	0.50	5.6	2.00	0.179
2	1.0	7.4	1.00	0.135
3	2.0	9.4	0.50	0.106
4	3.0	10.6	0.33	0.094
5	5.0	10.9	0.20	0.092
6	10	11.4	0.10	0.088

Question 2

(e) A voltmeter is to be used to determine the emf of the battery after removing the battery from the circuit. Two voltmeters are available to take this measurement—one with low internal resistance and one with high internal resistance. Indicate which voltmeter will provide the most accurate measurement.

______ The voltmeter with low resistance will provide the most accurate measurement.
______ The voltmeter with high resistance will provide the most accurate measurement.
______ The two voltmeters will provide equal accuracy.

Justify your answer.

Solution 2

(a)(i) Mark scheme

- Apply Kirchhoff's loop rule around the circuit containing the battery (emf $\mathcal{E}$, internal resistance r) and the variable resistor R: $\mathcal{E} = Ir + IR$ (1 point for a correct application of Kirchhoff's loop rule), so $I = \dfrac{\mathcal{E}}{r + R}$. The voltmeter reads the voltage across the variable resistor, so by Ohm's law $V = IR = \dfrac{\mathcal{E}}{r + R}R = \dfrac{\mathcal{E}R}{r + R}$ (1 point for a correct expression for the measured voltage across the variable resistor).

Solution 2

(a)(ii) Mark scheme

- Take the reciprocal of $V = \dfrac{\mathcal{E}R}{r+R}$ from part (a)-i and rearrange into a form linear in $1/R$: $\dfrac{1}{V} = \dfrac{r+R}{\mathcal{E}R} = \left(\dfrac{r}{\mathcal{E}}\right)\dfrac{1}{R} + \dfrac{1}{\mathcal{E}}$ (1 point; the expression must be consistent with the answer from part (a)-i). This is a straight line in $1/R$ with slope $r/\mathcal{E}$ and y-intercept $1/\mathcal{E}$.

Solution 2

(b) Mark scheme

- Plot $1/V$ (vertical axis, units of $1/\text{V}$) versus $1/R$ (horizontal axis, units of $1/\Omega$) using the given data table. Credit: 1 point for correctly labeling both axes with variables and units; 1 point for correctly scaling both axes with an acceptable and appropriate scale (spanning the data, e.g. $1/R$ from 0 to about $2.5\ \Omega^{-1}$ and $1/V$ from 0 to about $0.25\ \text{V}^{-1}$); 1 point for correctly plotting the given data points; 1 point for drawing a single straight best-fit line through the data (not simply connecting the dots). The reference line in the scoring guidelines has a y-intercept near $0.080\ \text{V}^{-1}$ and rises to about $0.20\ \text{V}^{-1}$ near $1/R = 2.3\ \Omega^{-1}$.

Solution 2

(c)(i) Mark scheme

- Read the y-intercept of the best-fit line drawn in part (b): $b \approx 0.080\ \mathrm{V}^{-1}$ (1 point; the value must be consistent with the line drawn in part (b)). From the linear form in part (a)-ii, $\frac{1}{V} = \left(\frac{r}{\mathcal{E}}\right)\frac{1}{R} + \frac{1}{\mathcal{E}}$, the intercept equals $b = 1/\mathcal{E}$ (1 point for correctly substituting into the equation from part (a)-ii), so $\mathcal{E} = \frac{1}{b} = \frac{1}{0.080\ \mathrm{V}^{-1}} = 12.5\ \mathrm{V}$.

Solution 2

(c)(ii)

Mark scheme

- Calculate the slope of the best-fit line from part (b) using two points that lie on the line itself, not the raw data points, e.g. $(0.40, 0.100)$ and $(1.50, 0.151)$: $m = \dfrac{0.151 - 0.100}{1.50 - 0.40} = 0.0463\ \Omega/\mathrm{V}$ (1 point for calculating the slope using the line, not data points). From part (a)-ii, the slope equals $r/\mathcal{E}$, so $r = m\mathcal{E}$ (1 point for correctly substituting into the equation from part (a)-ii); using $\mathcal{E} = 12.5$ V from part (c)-i, $r = (0.0463\ \Omega/\mathrm{V})(12.5\ \mathrm{V}) = 0.58\ \Omega$.

Solution 2

(d)

Mark scheme

- The maximum current the battery can supply occurs when $R = 0$ (short circuit), so Ohm's law applied to the internal resistance alone gives $\mathcal{E} = Ir$ (1 point for using Ohm's law). Substituting the values found in part (c): $(12.5\ \text{V}) = I(0.58\ \Omega)$ (1 point for a correct substitution of the values from part (c)), giving $I = 21.6$ A.

Solution 2

(e) Mark scheme

- Select the voltmeter with high internal resistance (1 point). Justification: a real voltmeter behaves like a resistor placed in the circuit with the battery, and it measures the potential difference across its own internal resistance. The higher that internal resistance, the smaller the current it draws from the battery, and the closer the voltmeter's reading comes to the actual emf of the battery (1 point for a correct justification). Example from the scoring guidelines: 'The voltmeter acts like a resistor in a circuit with the battery. It will measure the potential difference across its own internal resistance. The higher its internal resistance, the closer its potential difference will be to the emf of the battery.'

Question 1

2014 ▪ Q1

[Circuit diagram: A variable DC power supply connects to an ammeter (A) in series, which connects to a node. From that node, resistor $R_2 = 50\ \Omega$ runs across the top back to the power supply, an unknown resistor R_1 runs down the middle in parallel, and resistor $R_3 = 50\ \Omega$ runs across the bottom, also back to the power supply. So R_1, R_2, and R_3 are all in parallel with each other, and this parallel combination is in series with the ammeter and the DC power supply.]

Physics students are analyzing the circuit above. A variable DC power supply is connected to an ammeter and three resistors. The resistances of two of the resistors are known to be $R_2 = R_3 = 50\ \Omega$, but the resistance of the third resistor is unknown. The students collect data on the potential difference across the power supply and the current measured by the ammeter, as follows.

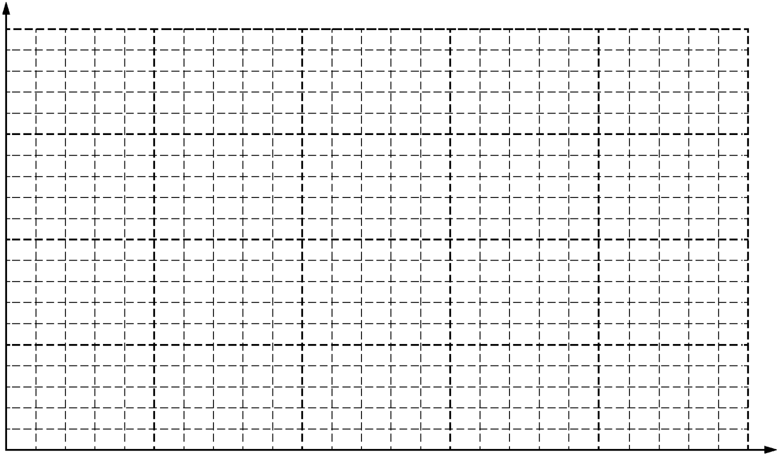
Question 1

Potential Difference (V)	2	4	6	8	10
Current (mA)	40	55	97	138	155

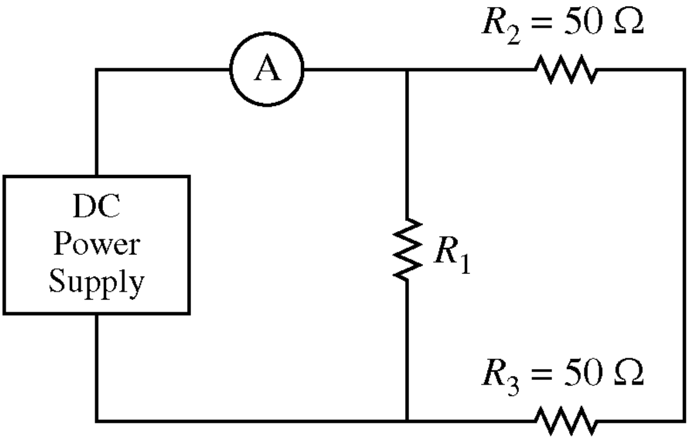
(a) On the grid below, plot the data points for the current as a function of the potential difference. Clearly scale and label all axes, including units if appropriate. Draw a straight line that best represents the data.

[Grid: a blank dashed-gridline graph with a vertical axis (arrow pointing up, unlabeled) and a horizontal axis (arrow pointing right, unlabeled), for the student to plot Current (mA) vs. Potential Difference (V) and draw a best-fit line.]

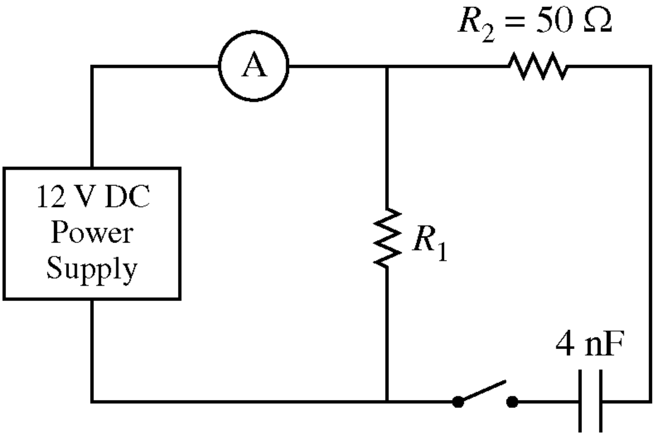
Question 1



Question 1



Question 1



Question 1

2014 ▪ Q1

[Circuit diagram: A variable DC power supply connects to an ammeter (A) in series, which connects to a node. From that node, resistor $R_2 = 50\ \Omega$ runs across the top back to the power supply, an unknown resistor R_1 runs down the middle in parallel, and resistor $R_3 = 50\ \Omega$ runs across the bottom, also back to the power supply. So R_1, R_2, and R_3 are all in parallel with each other, and this parallel combination is in series with the ammeter and the DC power supply.]

Physics students are analyzing the circuit above. A variable DC power supply is connected to an ammeter and three resistors. The resistances of two of the resistors are known to be $R_2 = R_3 = 50\ \Omega$, but the resistance of the third resistor is unknown. The students collect data on the potential difference across the power supply and the current measured by the ammeter, as follows.

Potential Difference (V)	2	4	6	8	10
Current (mA)	40	55	97	138	155

Question 1

(b) Using the straight line from part (a), calculate the total resistance of the three-resistor combination.

Question 1

2014 ▪ Q1

[Circuit diagram: A variable DC power supply connects to an ammeter (A) in series, which connects to a node. From that node, resistor $R_2 = 50\ \Omega$ runs across the top back to the power supply, an unknown resistor R_1 runs down the middle in parallel, and resistor $R_3 = 50\ \Omega$ runs across the bottom, also back to the power supply. So R_1, R_2, and R_3 are all in parallel with each other, and this parallel combination is in series with the ammeter and the DC power supply.]

Physics students are analyzing the circuit above. A variable DC power supply is connected to an ammeter and three resistors. The resistances of two of the resistors are known to be $R_2 = R_3 = 50\ \Omega$, but the resistance of the third resistor is unknown. The students collect data on the potential difference across the power supply and the current measured by the ammeter, as follows.

Potential Difference (V)	2	4	6	8	10
Current (mA)	40	55	97	138	155

Question 1

(c) Calculate the value of R_1.
The power supply is now fixed at 12 V.

Question 1

2014 ▪ Q1

[Circuit diagram: A variable DC power supply connects to an ammeter (A) in series, which connects to a node. From that node, resistor $R_2 = 50\ \Omega$ runs across the top back to the power supply, an unknown resistor R_1 runs down the middle in parallel, and resistor $R_3 = 50\ \Omega$ runs across the bottom, also back to the power supply. So R_1, R_2, and R_3 are all in parallel with each other, and this parallel combination is in series with the ammeter and the DC power supply.]

Physics students are analyzing the circuit above. A variable DC power supply is connected to an ammeter and three resistors. The resistances of two of the resistors are known to be $R_2 = R_3 = 50\ \Omega$, but the resistance of the third resistor is unknown. The students collect data on the potential difference across the power supply and the current measured by the ammeter, as follows.

Potential Difference (V)	2	4	6	8	10
Current (mA)	40	55	97	138	155

Question 1

(d) Calculate the current through R_2.

Question 1

2014 ▪ Q1

[Circuit diagram: A variable DC power supply connects to an ammeter (A) in series, which connects to a node. From that node, resistor $R_2 = 50\ \Omega$ runs across the top back to the power supply, an unknown resistor R_1 runs down the middle in parallel, and resistor $R_3 = 50\ \Omega$ runs across the bottom, also back to the power supply. So R_1, R_2, and R_3 are all in parallel with each other, and this parallel combination is in series with the ammeter and the DC power supply.]

Physics students are analyzing the circuit above. A variable DC power supply is connected to an ammeter and three resistors. The resistances of two of the resistors are known to be $R_2 = R_3 = 50\ \Omega$, but the resistance of the third resistor is unknown. The students collect data on the potential difference across the power supply and the current measured by the ammeter, as follows.

Potential Difference (V)	2	4	6	8	10
Current (mA)	40	55	97	138	155

Question 1

(e)(i) Resistor 3 is now removed and replaced by an open switch in series with an uncharged 4 nF capacitor, as shown below. The power supply is still fixed at 12 V. [Circuit diagram: A 12 V DC power supply connects through an ammeter (A) to a node; from that node $R_2 = 50\ \Omega$ runs across the top back to the supply, R_1 runs down the middle in parallel, and a branch containing an open switch in series with a 4 nF capacitor runs across the bottom back to the supply.]
i. Calculate the current in R_2 immediately after the switch is closed.
(e)(ii) ii. A long time after the switch is closed, will the magnitude of the current in R_2 be greater than, less than, or equal to the current through R_2 found in part (d)?
___ Greater than ___ Less than ___ Equal to
Justify your answer.

Question 1

2014 ▪ Q1

[Circuit diagram: A variable DC power supply connects to an ammeter (A) in series, which connects to a node. From that node, resistor $R_2 = 50\ \Omega$ runs across the top back to the power supply, an unknown resistor R_1 runs down the middle in parallel, and resistor $R_3 = 50\ \Omega$ runs across the bottom, also back to the power supply. So R_1, R_2, and R_3 are all in parallel with each other, and this parallel combination is in series with the ammeter and the DC power supply.]

Physics students are analyzing the circuit above. A variable DC power supply is connected to an ammeter and three resistors. The resistances of two of the resistors are known to be $R_2 = R_3 = 50\ \Omega$, but the resistance of the third resistor is unknown. The students collect data on the potential difference across the power supply and the current measured by the ammeter, as follows.

Potential Difference (V)	2	4	6	8	10
Current (mA)	40	55	97	138	155

Question 1

(f) The 4 nF capacitor is replaced with an uncharged 10 nF capacitor. Will the magnitude of the current in R_2 immediately after the switch is closed be greater than, less than, or equal to the current in part (e)i?

___ Greater than ___ Less than ___ Equal to

Justify your answer.