# Capacitors 3 solutions

## In graphs charging and equation manipulation

Matching answers and examiner-style commentary

OCR A H556 and AQA 7408 | A-level physics

## Specification and route

OCR A H556: 6.1.1(e)(i), 6.1.2(b), 6.1.3(a)–(c) and (e). Optional modelling: 6.1.3(d).

AQA 7408: 3.7.4.3–3.7.4.4; energy, logarithmic graph skills and RP9 preparation. The separately labelled numerical-model extension is not assumed AQA recall.

A-level only. This is capacitor application; the separate ln and log skills worksheet provides extra preparatory practice.

**21 core parts | 41 marks | Optional extension: 3 marks**

A remote volcano-monitoring station has become unreliable between measurement cycles. Engineers bench-test its sealed capacitor module, infer its capacitance from logged discharge data and set an appropriate recharge interval. Use the switching circuit in Figure 1; the capacitor value is initially unknown.

Original PhysicsUK worked solutions. Use the explanations to check the method, then use the separate marking guidance to award credit.

## The monitoring-station test

The switch is held at A, then moved to B when the logger clock reads 15.0 s. The measured discharge resistance is R = (150 ± 2) kΩ. The logger has input resistance at least 100 MΩ; neglect its loading and capacitor leakage for the initial analysis.

Use $V = V_0 \exp(-t/RC)$ for discharge and $V_C = V_S[1 - \exp(-t/RC)]$ for charging from zero. Here t is elapsed time from switching. In logarithms, divide a voltage by a stated voltage reference so the argument is dimensionless.

## 1 Choose and transform the equation

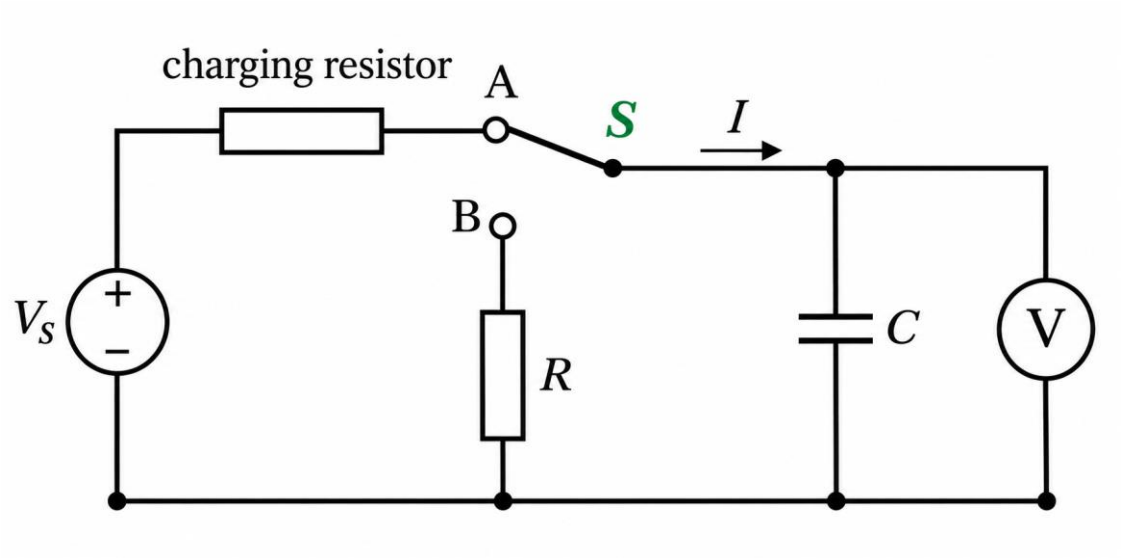



Figure 1 The voltage logger is connected across C. At B the supply is isolated and R determines the nominal discharge path.

**1(a)** For the readings taken after switching to B, identify the appropriate exponential model and explain your choice. **[1 mark]**

Use $V = V_0 \exp(-t/RC)$. The supply is isolated and the charged capacitor is discharging through R, so its p.d. falls from $V_0$ towards zero.

Marking 1: discharge law chosen with the correct switching reason.

**1(b)** Starting from $V/V_0 = \exp(-t/RC)$, take ln of both sides to obtain a linear relationship. **[1 mark]**

Take ln of both sides of the given equation. This is an operation on each whole side, not division by a quantity called ln.

$\ln(V/V_0) = \ln[\exp(-t/RC)]$.

ln and exp are inverse functions, so $\ln(\exp(x)) = x$.

$\ln(V/V_0) = -t/(RC)$.

This is linear in elapsed t: the gradient is $-1/(RC)$ and the intercept is zero.

Marking 1: $\ln(V/V_0) = -t/RC$.

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## 2 Linearise the discharge equation

**2(a)** Show that y = ln(V / 1 V) plotted against elapsed t gives a straight line. State its gradient and intercept. **[2 marks]**

### Step 1 Form the dimensionless quantity on the vertical axis

Start with the discharge law $V = V_0 \exp(-t/RC)$. Divide by the fixed reference voltage 1 V, because a logarithm needs a dimensionless argument.

$V/(1\ \text{V}) = [V_0/(1\ \text{V})] \exp(-t/RC)$.

### Step 2 Take ln and separate the product

Use ln(ab) = ln a + ln b.

$\ln(V / 1\ \text{V}) = \ln(V_0 / 1\ \text{V}) + \ln[\exp(-t/RC)]$.

Since ln(exp(x)) = x, this becomes:

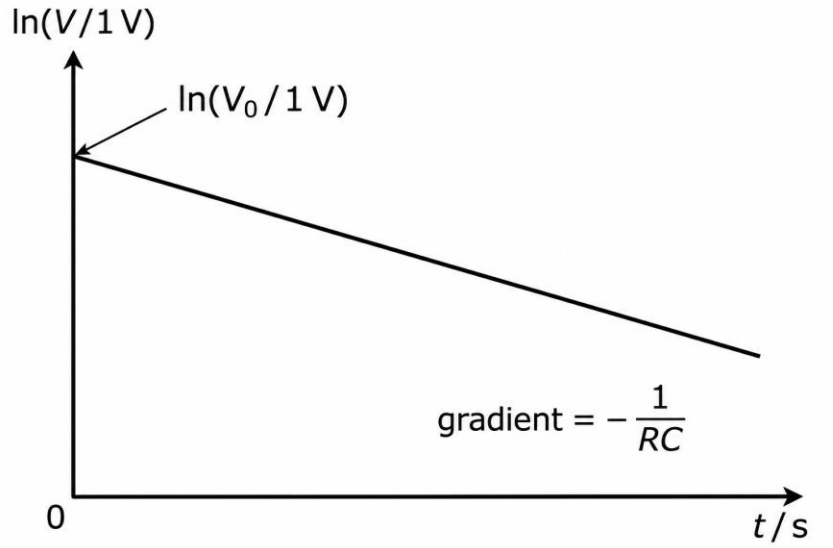
$\ln(V / 1\ \text{V}) = \ln(V_0 / 1\ \text{V}) - t/(RC)$.

### Step 3 Match the equation to y = mt + c

Write it as $y = [-1/(RC)]t + \ln(V_0 / 1\ \text{V})$.

Gradient $m = -1/(RC)$; intercept $c = \ln(V_0 / 1\ \text{V})$.

The gradient is constant, so the graph is a straight line. Its y values are dimensionless; with time in seconds, the gradient has unit $s^{-1}$.




Symbolic model: the intercept and negative gradient correspond to the actual ln(V / 1 V) ordinate. No numerical scale is implied.

Marking 1: correct linear equation; 1: correct gradient/intercept identification.

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## 2 Interpret the intercept and change units

**2(b)** If $\ln(V/V_0)$ is plotted instead, what is its intercept when t is measured from the start of discharge? Explain. **[1 mark]**

The intercept is zero: at elapsed t = 0 the voltage is $V_0$, so $\ln(V/V_0) = \ln(1) = 0$. This transformation is different from ln(V / 1 V), whose intercept contains $V_0$.

Marking 1: zero with correct initial-ratio reasoning.

**2(c)** A fit using t in seconds has gradient $-0.01710\ s^{-1}$. Give the numerical gradient if t is plotted in milliseconds. Also state how the intercept changes if ln(V / 1 mV) replaces ln(V / 1 V). **[2 marks]**

### Step 1 Change the time unit in the gradient

Gradient is change in y divided by change in time. A given time interval has a numerical value 1000 times larger in milliseconds, so divide the numerical gradient by 1000.

$m_{ms} = -0.01710/1000 = -0.00001710\ ms^{-1}$.

For example, the same change in y occurs in 1 s or 1000 ms. It is not a faster or slower physical discharge.

### Step 2 Change the reference used inside the logarithm

Since 1 mV = 0.001 V, V/(1 mV) = 1000 × V/(1 V).

ln(V / 1 mV) = ln(1000) + ln(V / 1 V).

Every y value therefore increases by ln(1000) ≈ 6.908, so the new intercept is the old intercept plus 6.908.

Adding this same constant to every y value shifts the line vertically and leaves its gradient unchanged.

Marking 1: correct millisecond gradient; 1: intercept increases by ln(1000).

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## 3 Construct the ln graph

The table contains measured-style data. Each p.d. reading has uncertainty ±0.02 V. Complete the elapsed-time and ln columns; use t = logger clock − 15.0 s. Give ln values to three decimal places.

| Clock / s | V / V | Elapsed t / s | ln(V / 1 V) |
|---|---|---|---|
| 15 | 6.60 | 0 | 1.887 |
| 27 | 5.37 | 12 | 1.681 |
| 39 | 4.39 | 24 | 1.479 |
| 51 | 3.56 | 36 | 1.270 |
| 63 | 2.91 | 48 | 1.068 |
| 75 | 2.36 | 60 | 0.859 |
| 87 | 1.93 | 72 | 0.658 |

**3(a)** Complete the two missing columns in the table. **[2 marks]**

### Step 1 Change logger clock readings into elapsed times

Discharge begins at clock 15.0 s, so subtract 15.0 s from every clock reading.

For example, clock 27.0 s gives elapsed t = 27.0 − 15.0 = 12.0 s.

The completed elapsed-time column is 0, 12, 24, 36, 48, 60 and 72 s.

### Step 2 Take the natural logarithm of each voltage ratio

Divide by the reference 1 V, then use the calculator's ln function. For the 5.37 V reading:

ln(5.37 V / 1 V) = ln(5.37) = 1.6808279 ≈ 1.681.

The completed ln column is 1.887, 1.681, 1.479, 1.270, 1.068, 0.859 and 0.658. These entries are dimensionless. All given voltages are positive, so their logarithms exist.

Marking 1: elapsed-time column; 1: ln column, allowing one minor rounding slip.

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## 3 Fit the line and calculate its gradient

**3(b)** Plot ln(V / 1 V) against elapsed t and draw a straight line of best fit. Use labelled linear axes and a scale that makes good use of the grid. **[2 marks]**

Put elapsed t in seconds on the horizontal axis and ln(V / 1 V) on the vertical axis. Use evenly spaced linear scales with labelled quantities; ln values have no unit.

Plot (0, 1.887), (12, 1.681), (24, 1.479), (36, 1.270), (48, 1.068), (60, 0.859) and (72, 0.658).

Draw one straight line of best fit through the trend, with points distributed sensibly on either side. Do not join each cross with a separate short segment.

A suitable fit is approximately $y = 1.887 - 0.01710t$ for t in seconds. The intercept is positive and the gradient negative. The line need not pass exactly through every measured point.

Marking 1: labelled scales and accurate plots; 1: appropriate straight fit.

## Extract the model parameters

Use your fitted line, not a gradient between two individual data points.

**3(c)** Use a large triangle on your fitted line to find its gradient and hence determine RC. **[2 marks]**

### Step 1 Select two well-separated points on the fitted line

Use the line of best fit, not two individual measured points. For example, the fitted line is near (0 s, 1.887) and (60 s, 0.861). A large triangle reduces the effect of reading uncertainty.

### Step 2 Calculate the gradient

$\Delta y = 0.861 - 1.887 = -1.026$.

$\Delta t = 60 - 0 = 60$ s.

$m = \Delta y/\Delta t = -1.026/60 = -0.0171\ s^{-1}$.

### Step 3 Rearrange the gradient relationship

From 2(a), $m = -1/(RC)$. Multiply by RC, then divide by m.

$m(RC) = -1$, so $RC = -1/m$.

$RC = -1/(-0.0171) = 58.48\ s \approx 58.5\ s$.

The two negative signs give a positive physical time constant. Accept about 56–61 s from a well-constructed pupil graph.

Marking 1: valid large-triangle gradient near $-0.0171\ s^{-1}$; 1: RC near 58.5 s.

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## 3 Infer capacitance and initial potential difference

**3(d)** Use R = 150 kΩ to find C. Use the graph intercept to recover the initial p.d. $V_0$. **[2 marks]**

### Step 1 Find capacitance from the time constant

The graph gives the product RC, not C alone. Divide the 58.5 s time constant by the measured resistance.

R = 150 kΩ = 150 000 Ω.

C = (RC)/R = 58.5/150 000 = 0.000390 F.

Multiply farads by $10^6$ to convert to microfarads: C = 390 μF.

### Step 2 Undo the logarithm to find the initial p.d.

The intercept c ≈ 1.887 equals $\ln(V_0 / 1\ \text{V})$. Apply exp to both sides.

$\exp(c) = V_0/(1\ \text{V})$.

$V_0 = \exp(1.887) \times 1\ \text{V} \approx 6.60\ \text{V}$.

Do not read 1.887 as a voltage: it is the logarithm of a voltage ratio. Allow follow-through from a sensible fitted line.

Marking 1: C near 390 μF; 1: intercept exponentiated to about 6.6 V.

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## 4 Calculate uncertainty and compare intervals

**4(a)** The label says 470 μF ±10%. For this evaluation use |m| = 0.01710 ± 0.00040 $s^{-1}$ and R = 150 ± 2 kΩ. Add percentage uncertainties to estimate the uncertainty in C, then judge whether the inferred value agrees with the label. **[3 marks]**

### Step 1 Choose the uncertainty rule for C

The graph gives C = 1/(R|m|). The question asks for the conservative first-order estimate found by adding percentage uncertainties for the two factors in the denominator.

### Step 2 Calculate the two percentage uncertainties

Resistance: (2/150) × 100 = 1.333%.

Gradient magnitude: (0.00040/0.01710) × 100 = 2.339%.

Percentage uncertainty in C = 1.333 + 2.339 = 3.672% ≈ 3.7%.

### Step 3 Convert this to an uncertainty in capacitance

Use the inferred C ≈ 390 μF, not the value printed on the component label.

ΔC = 390 × (3.672/100) ≈ 14.3 μF.

The inferred interval is approximately 390 − 14.3 to 390 + 14.3 μF, or 376–404 μF after rounding.

### Step 4 Calculate the labelled tolerance interval

10% of 470 μF is 0.10 × 470 = 47 μF.

Labelled interval = 470 − 47 to 470 + 47 = 423–517 μF.

### Step 5 Make the comparison under the stated model

The upper end of the inferred interval, about 404 μF, is below the lower labelled limit of 423 μF. The intervals do not overlap, so the inferred value does not agree with the label under the assumed discharge model.

This does not by itself prove that the capacitor is faulty; 4(c) examines another explanation. A fit with different supported uncertainty must be assessed using its own interval.

Marking 1: about 3.7%; 1: inferred and label ranges; 1: justified non-agreement under assumptions.

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## 4 Evaluate what the test establishes

**4(b)** Explain why the late, low-voltage readings have a larger relative uncertainty than the early readings, even though every p.d. reading has the same ±0.02 V uncertainty. **[1 mark]**

Relative voltage uncertainty is the absolute uncertainty divided by the reading: $\Delta V/V$.

At 6.60 V: percentage uncertainty = $(0.02/6.60) \times 100 \approx 0.30\%$.

At 1.93 V: percentage uncertainty = $(0.02/1.93) \times 100 \approx 1.04\%$.

The same ±0.02 V is a larger fraction of the smaller late reading, so its relative uncertainty is larger. It also gives a larger uncertainty in the transformed ln value.

Marking 1: same absolute uncertainty divided by a smaller reading gives larger relative uncertainty.

**4(c)** Could the discharge trace alone prove that the capacitor is the faulty component? Explain how an unintended parallel path could affect the inference. **[2 marks]**

No. An extra leakage or instrument path reduces the effective discharge resistance below the measured external 150 kΩ. The capacitor then discharges faster, giving a smaller measured RC.

If the analysis still divides that RC by 150 kΩ, it underestimates C. Check loading/leakage and the resistor before attributing the discrepancy solely to the capacitor. A straight ln plot can still arise from a different constant effective resistance.

Marking 1: reduced effective R/faster decay; 1: smaller apparent C and a conditional diagnosis.

**4(d)** A logger later displays 0.00 V. Explain why this reading cannot simply be included in a ln(V / 1 V) plot. **[1 mark]**

ln(0) is undefined. A displayed zero may mean the signal is below the instrument resolution, rather than that the ideal capacitor has reached exactly zero p.d. Do not replace it by an invented small positive voltage.

Marking 1: logarithm of zero is undefined.

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## 5 Transform the charging curve

For the following charging tests, use a stated design capacitance of 390 μF and a charging resistor of 100 kΩ. The ideal supply has $V_S$ = 6.60 V. This charging resistor replaces the unspecified charging resistor in Figure 1; the discharge resistor R is isolated at A.

For an initially uncharged capacitor, $V_C = V_S[1 - \exp(-t/RC)]$.

**5(a)** Define the remaining voltage gap $U = V_S - V_C$. Show that $\ln(U / 1\ V)$ plotted against t is a straight line, and identify its gradient and intercept. **[2 marks]**

### Step 1 Identify the quantity that decreases exponentially

During charging, $V_C$ rises towards $V_S$. The remaining voltage gap $U = V_S - V_C$ decreases. Substitute the charging model into that definition.

$U = V_S - V_S[1 - \exp(-t/RC)]$.

Expanding the bracket gives $U = V_S - V_S + V_S \exp(-t/RC)$.

The first two terms cancel, leaving $U = V_S \exp(-t/RC)$.

### Step 2 Take ln of the dimensionless voltage gap

Divide by 1 V, then use $\ln(ab) = \ln a + \ln b$ and $\ln(\exp(x)) = x$.

$\ln(U / 1\ V) = \ln(V_S / 1\ V) - t/(RC)$.

### Step 3 Identify the straight-line constants

Comparing with $y = mt + c$ gives $m = -1/(RC)$ and $c = \ln(V_S / 1\ V)$.

Here $V_S$ = 6.60 V, so $c = \ln(6.60) \approx 1.887$. The straight line describes the decreasing gap U, although the capacitor p.d. itself is rising.

Marking 1: correct gap exponential/linear form; 1: gradient/intercept matched.

**5(b)** Explain why $\ln(V_C / 1\ V)$ itself is not the correct straight-line transformation for charging from zero. **[1 mark]**

$V_C$ is proportional to $1 - \exp(-t/RC)$, not simply $\exp(-t/RC)$. Taking its ln does not give a constant-gradient expression in t. It also starts at $V_C = 0$, for which ln is undefined. The remaining gap U is the exponentially decaying quantity.

Marking 1: identifies the non-exponential charging p.d. / the decaying gap as the needed quantity.

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## 5 Find time constant and charging current

**5(c)** A straight-line fit for ln(U / 1 V) against t in seconds has gradient −0.0256 $s^{-1}$. Determine the charging time constant. **[1 mark]**

Use the actual gradient relationship m = −1/(RC). Multiplying by RC and then dividing by m gives RC = −1/m.

RC = −1/(−0.0256) = 39.0625 s ≈ 39.1 s.

The signs cancel to give a positive time constant. As a check, the nominal design gives RC = 100 000 × (390 × $10^{-6}$) = 39.0 s, consistent with the rounded fitted gradient.

Marking 1: 39.1 s.

**5(d)** When $V_C$ = 4.00 V, calculate the charging current. Explain why using $V_C$/R would give the wrong answer. **[2 marks]**

### Step 1 Find the p.d. across the charging resistor

The supply p.d. is shared between the resistor and capacitor. Around the charging loop, $V_S = V_R + V_C$.

$V_R = V_S - V_C = 6.60 - 4.00 = 2.60$ V.

### Step 2 Apply Ohm's law to that resistor

R = 100 kΩ = 100 000 Ω.

$I = V_R/R = 2.60/100\,000 = 0.0000260$ A = 26.0 μA.

### Step 3 Explain the wrong p.d. choice

Using $V_C$/R would put the capacitor's 4.00 V across the resistor. The resistor actually has only 2.60 V across it; the two component p.d.s add to the 6.60 V supply.

Marking 1: 26.0 μA from the resistor p.d.; 1: explains the correct p.d. choice.

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## 6 Solve the timing conditions

Use RC = 58.5 s for the discharge calculations in 6(a) and 6(c). For charging in 6(b), use RC = 39.0 s and $V_S$ = 6.60 V.

**6(a)** Starting at 6.60 V, determine the discharge time needed to reach 1.00 V. Show the logarithmic rearrangement. **[2 marks]**

### Step 1 Isolate the exponential

Start with $V = V_0 \exp(-t/RC)$ and divide both sides by $V_0$.

$V/V_0 = \exp(-t/RC)$.

### Step 2 Take ln, then make t the subject

$\ln(V/V_0) = -t/(RC)$.

Multiply both sides by −RC:

$t = -RC \ln(V/V_0)$.

### Step 3 Substitute the target voltage ratio

$V/V_0 = 1.00/6.60 \approx 0.151515$.

$t = -58.5 \times \ln(1.00/6.60)$.

$t = -58.5 \times (-1.88707) = 110.394$ s ≈ 110 s.

The ratio is below one, so its ln is negative; multiplying by −RC gives a positive elapsed time. The equivalent form $t = RC \ln(V_0/V)$ gives the same answer.

Marking 1: valid logarithmic rearrangement; 1: about 110 s.

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## 6 Solve the two charging conditions

**6(b)** Find the charging time from zero to 80% of $V_S$. In a second test the starting p.d. is $V_i = 1.20$ V: find the time to reach 5.90 V using $V_C = V_S - (V_S - V_i)\exp(-t/RC)$. **[3 marks]**

### First test From zero to 80% of the supply p.d.

### Step 1 Find the fraction of the voltage gap remaining

Starting from zero, $V_C/V_S = 1 - \exp(-t/RC)$. Set $V_C/V_S = 0.80$.

$0.80 = 1 - \exp(-t/RC)$.

Subtract 0.80 from 1: $\exp(-t/RC) = 0.20$.

The exponential represents the remaining 20% gap, not the 80% already reached.

### Step 2 Take ln and calculate the time

$-t/(RC) = \ln(0.20)$, so $t = -RC\ln(0.20)$.

$t = -39.0 \times \ln(0.20) = -39.0 \times (-1.60944) = 62.8$ s.

### Second test From 1.20 V to 5.90 V

### Step 3 Rearrange the supplied non-zero-start model

Start with $V_C = V_S - (V_S - V_i)\exp(-t/RC)$. Moving terms gives:

$V_S - V_C = (V_S - V_i)\exp(-t/RC)$.

Divide by the initial voltage gap $V_S - V_i$:

$(V_S - V_C)/(V_S - V_i) = \exp(-t/RC)$.

### Step 4 Calculate the actual gap ratio

Initial gap = 6.60 − 1.20 = 5.40 V.

Final gap = 6.60 − 5.90 = 0.70 V.

Remaining gap fraction = 0.70/5.40 ≈ 0.129630.

### Step 5 Take ln and calculate the second time

$t = -RC\ln[(V_S - V_C)/(V_S - V_i)]$.

$t = -39.0 \times \ln(0.70/5.40) = -39.0 \times (-2.04307) = 79.7$ s.

This test starts at 1.20 V, so its initial gap is 5.40 V. Substituting $V_i = 0$ would use a different initial condition and give the wrong interval.

Marking 1: 62.8 s from zero; 1: correct non-zero gap ratio/rearrangement; 1: 79.7 s.

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## 6 Derive and compare the energy half-time

**6(c)** Show that the energy remaining during discharge is proportional to exp(−2t/RC). Find its half-time and compare it with the voltage half-time. **[2 marks]**

### Step 1 Relate energy to the voltage ratio

For fixed C, $W = \frac{1}{2}CV^2$ and $W_0 = \frac{1}{2}CV_0^2$. Divide to cancel the common factor ½C.

$W/W_0 = (V/V_0)^2$.

Substitute $V/V_0 = \exp(-t/RC)$. Squaring an exponential doubles its exponent.

$W/W_0 = [\exp(-t/RC)]^2 = \exp(-2t/RC)$.

### Step 2 Solve for the energy half-time

At half energy, $W/W_0 = 0.5$, so $0.5 = \exp(-2t/RC)$.

Taking ln gives $\ln(0.5) = -2t/(RC)$.

Multiply by −RC/2: $t = -(RC/2)\ln(0.5)$.

Since $\ln(0.5) = -\ln 2$, the energy half-time is $(RC \ln 2)/2$.

$t = (58.5 \times 0.693147)/2 = 20.27\ \text{s} \approx 20.3\ \text{s}$.

### Step 3 Compare with the voltage half-time

The voltage reaches half its start when $t = RC \ln 2$.

Voltage half-time $= 58.5 \times 0.693147 = 40.5491\ \text{s} \approx 40.5\ \text{s}$.

The energy halves in half the voltage half-time because energy depends on $V^2$, not V.

Marking 1: squared voltage gives exponent −2t/RC; 1: 20.3 s and correct half-time comparison.

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## 7 Plan an independent investigation

An unknown capacitor is to be tested with a low-voltage dc supply, a suitable two-position switch, a fixed resistor, a resistance meter and a high-input-resistance voltage logger. Use your earlier graph work to organise the method; do not assume that listing apparatus is sufficient.

**7** Describe how to determine the capacitance from a discharge and a ln graph. Include a labelled circuit sketch, the measurements and switching procedure, how the graph leads to C, and one justified point about measurement quality. **[6 marks]**

Measure the discharge resistance R independently. Connect the capacitor so a two-position switch can first charge it from the dc supply and then isolate that supply while connecting the charged capacitor across R. Connect the high-input-resistance logger in parallel with C. A labelled sketch equivalent to Figure 1 is suitable.

Charge to a suitable p.d. below the capacitor rating. Start recording before moving the switch; identify the switching instant and use elapsed discharge time. Record a set of positive capacitor p.d.s at intervals short compared with the expected RC, over a substantial useful range.

Calculate ln(V / 1 V), plot it vertically against elapsed t in seconds, and draw a straight line of best fit. Use a large triangle on the line to find m. Since $m = -1/(RC)$, calculate $C = -1/(Rm)$.

For example, a high-input-resistance logger reduces extra parallel loading, while avoiding voltages close to the resolution limit reduces the large relative uncertainty in late readings. Repeat discharges with the same starting conditions to assess scatter. Accept other specific justified quality choices.

Mark using the levels guidance on the next page. The exemplar is one valid method; alternatives are acceptable.

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## Marking the investigation

Read the whole response and choose the level that best matches the scientific method and the quality of its linked reasoning. Within a level use the upper mark for a secure match and the lower mark for a less complete match.

| Level / marks | Question 7 marking guidance |
|---|---|
| 3 / 5–6 | A workable circuit and switching procedure; useful R, V and elapsed-time measurements; a correct ln graph leading to C; and a justified measurement-quality point. The reasoning is clear and linked. |
| 2 / 3–4 | A partly developed method with some correct measurements and analysis, but the circuit/procedure, graph-to-C link or quality reasoning is incomplete. Some steps are linked. |
| 1 / 1–2 | Some relevant apparatus, measurements or analysis, but the answer does not yet show clearly how a reliable capacitance value would be obtained. |
| 0 | No creditworthy response. |

Do not treat the illustrative method as six compulsory sentences. For a high-level response, the measurements and graph must lead to a capacitance value. A labelled equivalent circuit, another sensible sampling strategy or another specific justified quality point may be accepted.

The method prepares pupils for practical work; it is not evidence that a supervised required practical or PAG has been completed.

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## Optional extension Step modelling

OCR H556 6.1.3(d) / supplied extension for AQA. Allow about 5 extra minutes; this is outside the common timed route.

In a separate ideal model, RC = 60.0 s, $Q_0$ = 3.00 mC and Δt = 10.0 s. Each spreadsheet row uses $Q_{next} = Q_{now} - Q_{now}\,\Delta t/(RC)$.

**E(a)** Calculate Q after the first and second model steps. **[2 marks]**

### Step 1 Apply the first finite time step

Use $Q_{next} = Q_{now} - Q_{now}\Delta t/(RC)$, with $Q_{now}$ = 3.00 mC, Δt = 10.0 s and RC = 60.0 s. Keep charge in mC throughout.

Charge removed in step 1 = 3.00 × (10.0/60.0) = 0.500 mC.

Charge after step 1 = 3.00 − 0.500 = 2.50 mC.

### Step 2 Start the second step with the updated charge

Now $Q_{now}$ = 2.50 mC, so the amount removed is smaller.

Charge removed in step 2 = 2.50 × (10.0/60.0) = 0.416667 mC.

Charge after step 2 = 2.50 − 0.416667 = 2.08333 mC ≈ 2.08 mC.

Subtracting the original 0.500 mC every time would incorrectly make the model linear. The rate estimate must use the charge present at the start of each new step.

Marking 1: 2.50 mC; 1: 2.08 mC using the updated charge.

**E(b)** Explain why using a smaller time step improves the approximation to exponential discharge. **[1 mark]**

Within each finite step the model treats the discharge rate as its value at the start of the step, although the actual rate falls continuously. A smaller step allows less rate change within that step and reduces the accumulated approximation error.

Marking 1: smaller within-step rate change / better tracking of changing rate.

Use consistent signs and retain enough digits during working. Small graph-reading differences and physically equivalent explanations are acceptable where the method is sound.

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