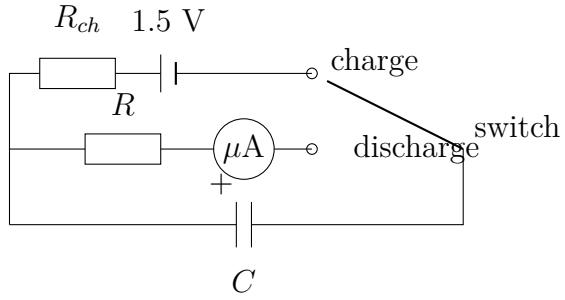
Capacitor discharge and stored charge

Name: _____ Class: _____ Date: _____

Aim Test exponential decay and estimate the initial stored charge. Allow 70–90 minutes.

Model During discharge, $I = I_0 e^{-t/(RC)}$. The **time constant** is $\tau = RC$. Plot $\ln(I/I_*)$ against t, with the fixed reference $I_* = 1\,\mu\text{A}$, so the logarithm has no unit. Its gradient is $s = -1/\tau$.

Apparatus 1.5 V cell, labelled 1000 μF capacitor, 100 kΩ discharge resistor, 1 kΩ charging resistor, break-before-make changeover switch, sensitive microammeter, leads and stopwatch; shared capacitance/resistance meter if available.



Safety Match capacitor polarity and voltage rating. Use low voltage only. Change connections with the supply disconnected. Discharge through the resistor; never short the capacitor directly. Have the circuit checked.

1 Plan, then measure

1. Record nominal R, C, their tolerances and instrument resolutions. Measure R, C if suitable meters are available. Estimate RC to choose a time interval.
2. Charge through R_{ch} for at least $5R_{ch}C$ (about 5 s for 1 kΩ and 1000 μF). Keep the charging voltage the same in each run.
3. Change to discharge and start timing together. A pilot should establish a visible, positive current and at least eight useful readings before the current approaches meter resolution.
4. Use fixed intervals (about 10–20 s for nominal $RC = 100$ s). Repeat a full discharge after recharging. Record raw currents; stop logarithmic analysis before readings are zero or dominated by resolution.

Processing check (synthetic data) A log-current gradient is $s = -0.0100 \pm 0.0010\,\text{s}^{-1}$. Calculate τ and its approximate uncertainty. Then invert both endpoint gradients: is the exact interval symmetric?

2 Record and process

$R =$ _____ kΩ $C =$ _____ μF $V_0 =$ _____ V.

Current resolution: _____ Timing uncertainty: _____.

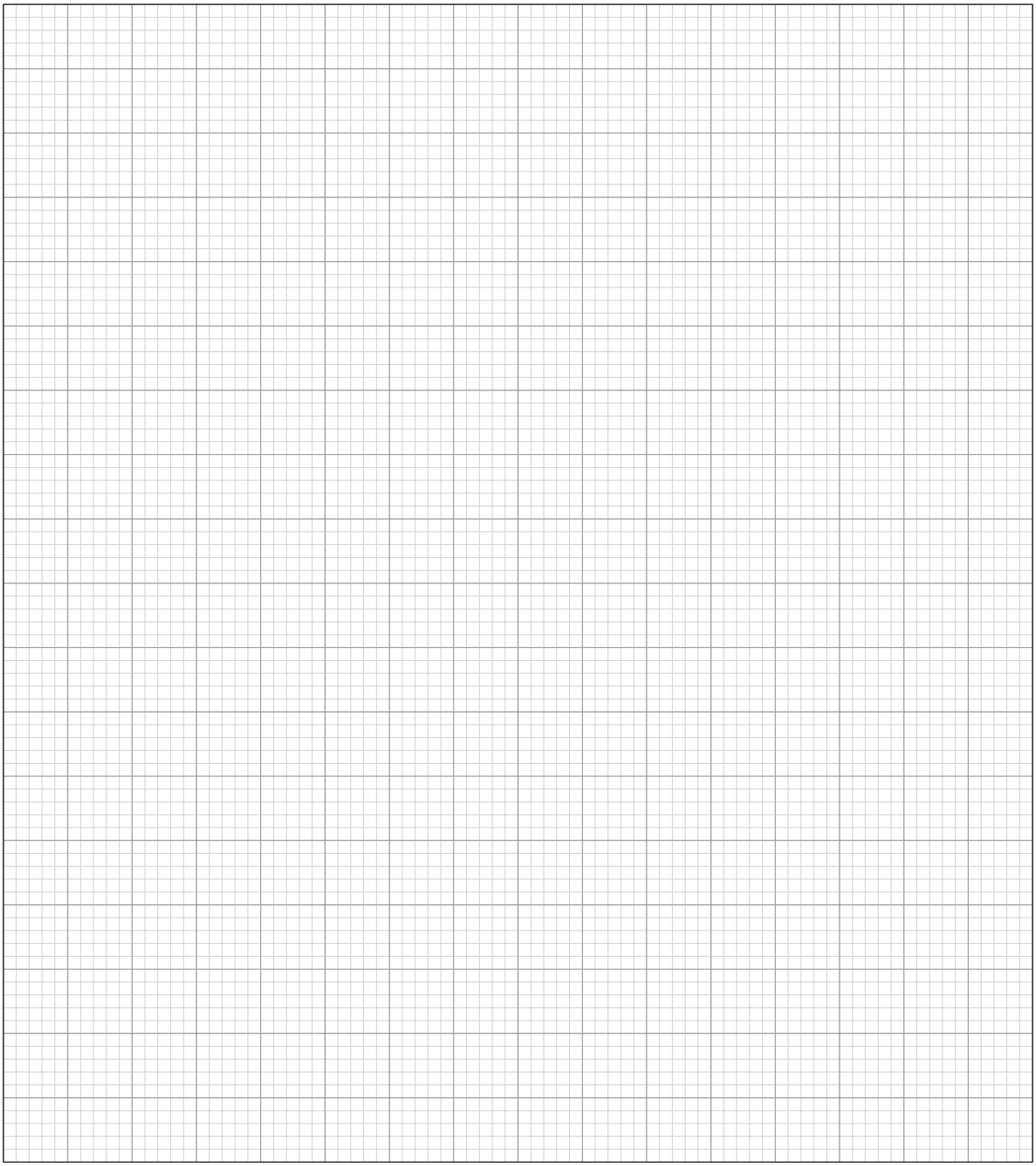
t/s	I_1/μA	I_2/μA	$\bar{I}/\mu$A	$\ln(\bar{I}/I_*)$

Planning record Justify your time interval and stopping current. State how you kept the starting charge consistent.

Uncertainty For positive current, $\Delta \ln I \simeq \Delta I / I$. Why do the last readings have larger logarithmic uncertainty?

3 Graph

Plot $\ln(\bar{I}/I_*)$ against t. Add justified vertical error bars. Draw the best-fit line and the steepest or shallowest acceptable line.



Choose scales and label both axes with quantities and units. Mark a large gradient triangle on the best-fit line where appropriate.

4 Analyse and evaluate

1. Find s, its unit and Δs from an extreme acceptable line. Calculate $\tau = -1/s$ and $\Delta\tau/\tau \simeq \Delta s/|s|$. Compare with measured or nominal RC, including component tolerances.

2. Find the intercept b, then $I_0 = I_* e^b$. Convert I_0 to amperes and calculate $Q_\infty = I_0\tau$. Compare with CV_0, giving charge in coulombs.

3. Use the table to estimate charge by the trapezoidal sum $Q_{\text{measured}} = \sum \frac{1}{2}(I_j + I_{j+1})(t_{j+1} - t_j)$, with currents in A. Estimate the unmeasured tail as $I(t_{\text{last}})\tau$. Explain any early-time gap.

4. Predict how replacing 100 kΩ by 47 kΩ changes I_0, τ and total charge at fixed C, V_0. Identify two limitations and matched improvements; consider switching delay, leakage and meter loading.

Before you leave Return the apparatus, clear the bench and submit your recorded data.

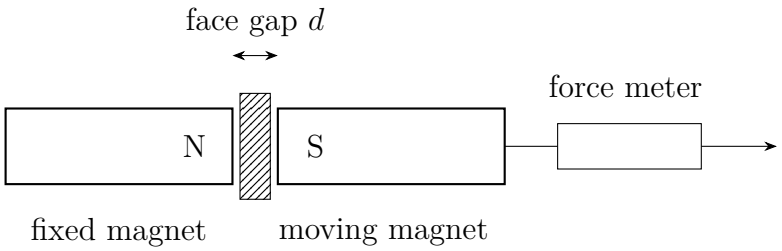
Magnetic force and separation

Name: _____ Class: _____ Date: _____

Aim Test an empirical power law over a measured distance range. Allow 60–75 minutes.

Model $F = K(d/d_*)^n$, with $d_* = 1$ m. Then $\log_{10}(F/F_*) = n\log_{10}(d/d_*) + b$, where $F_* = 1$ N and $K = F_* 10^b$. A log–log gradient gives the exponent n. Real bar magnets do not behave as two isolated point poles.

Apparatus Two bar magnets, force meter, clamp, tape/string, six card spacers, micrometer and ruler.



Safety Clamp firmly and pull slowly along the magnet axis. Keep fingers clear of snapping magnets. Keep magnets away from sensitive equipment and follow the school's guidance for medical implants.

1 Set up and measure

1. Zero the force meter. Align opposite poles face-to-face so they attract. Attach the moving magnet securely; keep the pulling direction along the axis.
2. Measure each spacer stack with the micrometer, using the ratchet gently. The gap d is the actual stack thickness between the facing surfaces, not magnet-centre distance.
3. Insert one stack. Increase the pull slowly and record the peak force just before separation. Do not jerk the meter or exceed its range.
4. Repeat three times with the same stack, reseating the magnets each time. Change to at least six different gaps, retaining orientation and alignment.
5. Pilot the largest gap: its force must remain clearly above resolution. Do not assume the exponent will be -2.

Processing check (synthetic data) Mean forces are 1.00 N at 2.00 mm and 0.250 N at 4.00 mm. Calculate the two-point exponent n. Explain why these two points alone cannot establish a power law over other distances.

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2 Record and process

Micrometer zero error: _____ Force resolution: _____.

d/mm	F_1/N	F_2/N	F_3/N	$\bar{F}$/N

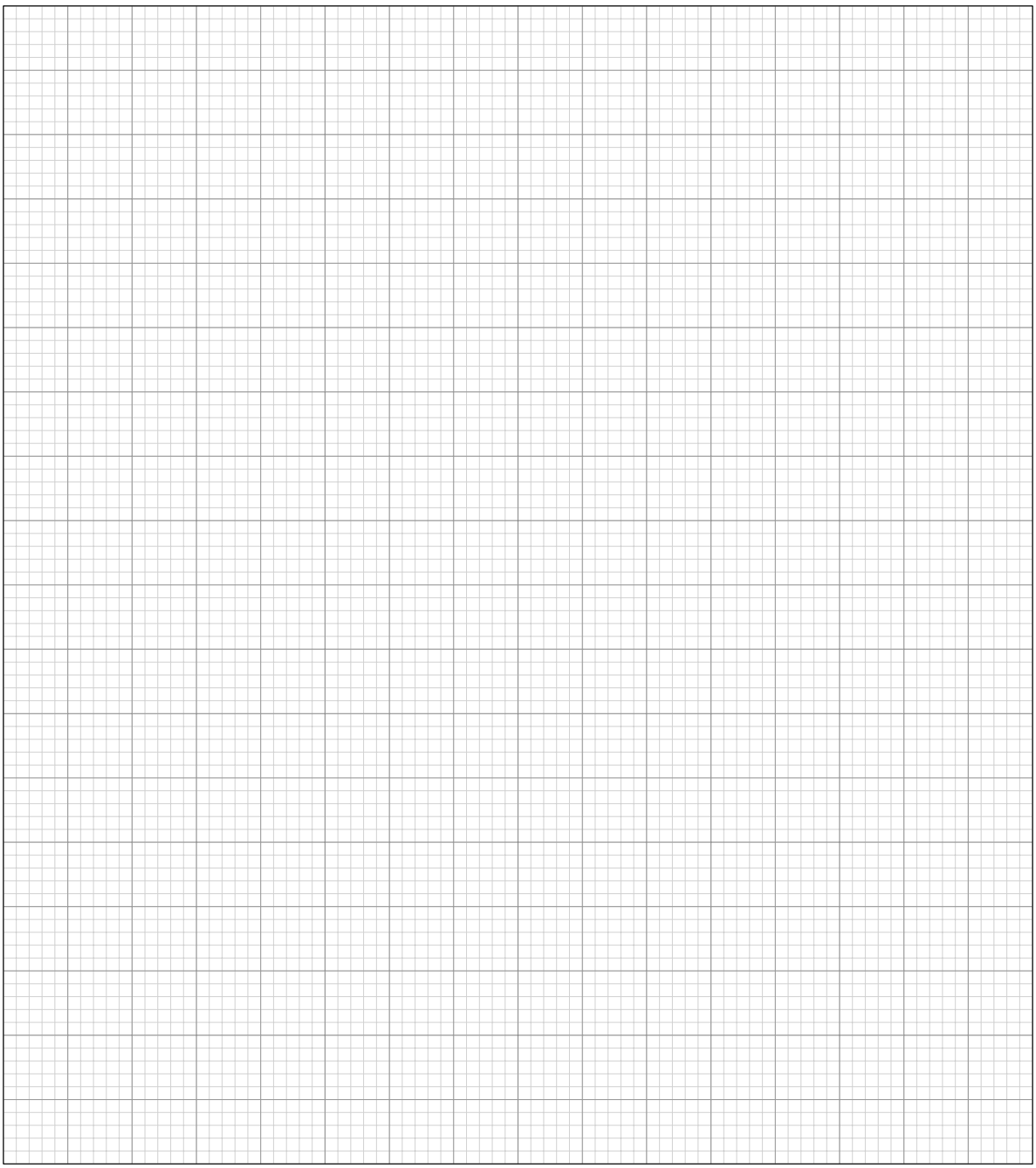
d/m	$\log_{10}(d/d_*)$	$\log_{10}(\bar{F}/F_*)$	ΔF/N

Controls Explain how you maintained alignment and a consistent separation method.

Uncertainty Combine the repeat spread and meter resolution into a justified ΔF. Record Δd.

3 Graph

Plot $\log_{10}(\bar{F}/F_*)$ against $\log_{10}(d/d_*)$. Use $\Delta \log_{10} F \simeq \Delta F/(F \ln 10)$ for vertical bars and $\Delta \log_{10} d \simeq \Delta d/(d \ln 10)$ for horizontal bars. Look for curvature.



Choose scales and label both axes with quantities and units. Mark a large gradient triangle on the best-fit line where appropriate.

4 Analyse and evaluate

1. Find n and its uncertainty using an extreme acceptable line. Does one straight line describe the full measured range? Refer to points, error bars and any pattern in the deviations.

2. Find b and K. Use your model to predict force at a distance within your measured range. Show the distance in metres and use the correct log base.

3. The source suggests predicting force at $d = 0.20$ m. Calculate the formal prediction, then explain why this long extrapolation may be unreliable. Would agreement with $n = -2$ prove an inverse-square law for all distances?

4. Plan a more sensitive repulsion experiment using a digital balance. State the zero reading, measured separation and conversion $F = \Delta mg$ with mass in kg. Give two controls and two limitations of the original method.

Before you leave Return the apparatus, clear the bench and submit your recorded data.

Spring stiffness from rotational oscillations

Name: _____ Class: _____ Date: _____

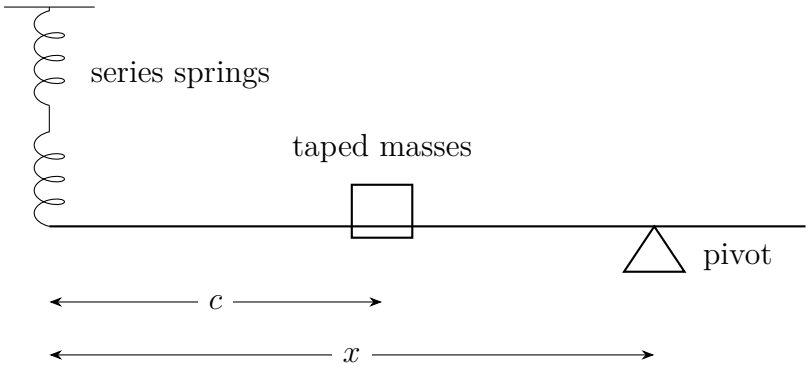
Aim Estimate spring stiffness using a physically explicit oscillation model. Allow 75–90 minutes.

Model A loaded rule rotates through a small angle about a fixed pivot. If two springs in series have effective stiffness k_e, then

$$T^2x^2 = \frac{4\pi^2 M}{k_e}(x-c)^2 + \frac{4\pi^2 J_c}{k_e}.$$

M is total mass; c is its centre-of-mass distance from the spring line; J_c is its rotational inertia about its centre. This supplied model accounts for the rule's extended mass.

Apparatus Metre rule, two springs in series, secure low-friction pivot, stand/clamp, string, two taped 100 g masses, stopwatch, balance and ruler.



Safety Weight the stand, secure the masses and retain the pivot position during motion. Keep oscillations small and springs within their elastic range. Stop if the rule slips or lifts from the pivot.

1 Set up and time

1. Secure the two masses near the rule's balance point. Measure the combined M and balance again to find c, from the spring attachment point.
2. Choose $x > c$. Set the rule horizontal and springs vertical. Use a pivot approved by the teacher that allows rotation without sliding.
3. Displace the spring end only a few millimetres. Time 10 full oscillations through a fixed reference, starting and ending in the same direction. Take a second timing after resetting the displacement.
4. Use at least six well-spread safe x values. Keep the masses, springs and amplitude unchanged. Record if motion is not a clean single oscillation.

Processing check (synthetic data) An identical-spring pair has $k_e = 10.0 \pm 0.8\,\mathrm{N\,m^{-1}}$. Calculate each spring stiffness and its uncertainty. Does multiplying by two double the percentage uncertainty?

2 Record and process

$M =$ _____ kg $c =$ _____ m $\Delta x =$ _____ m.

x/m	t_1/s	t_2/s	$\bar{t}$/s	$T = \bar{t}/10$/s

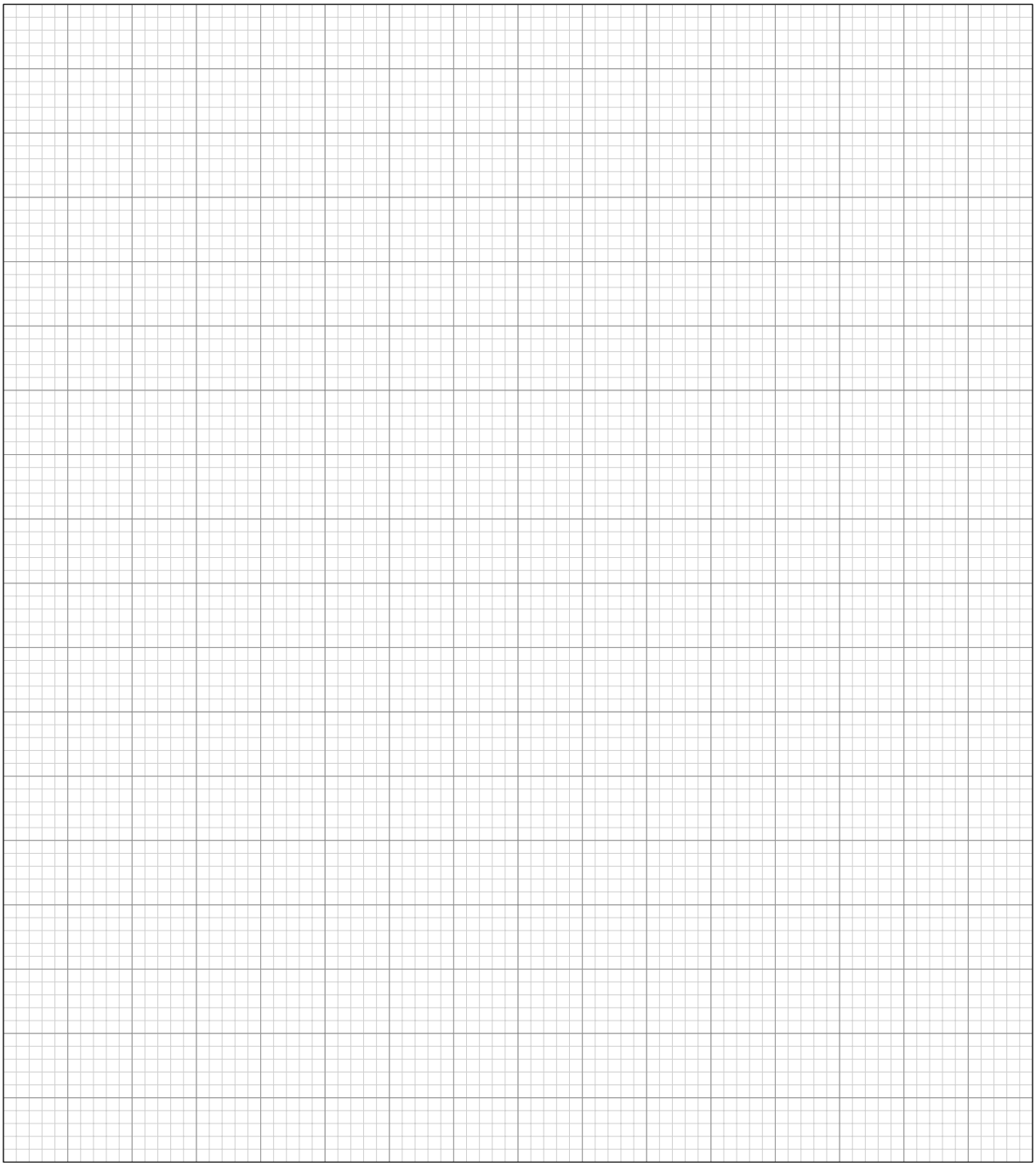
$X = (x-c)^2/\mathrm{m}^2$	$Y = T^2x^2/\mathrm{s}^2\mathrm{m}^2$	$\Delta Y/\mathrm{s}^2\mathrm{m}^2$

Uncertainty Estimate ΔT from timing resolution and repeat spread. Use $\Delta Y/Y \simeq 2\Delta T/T + 2\Delta x/x$ as a conservative estimate.

Model check Why must you measure the balance point after adding masses? What observation would invalidate the fixed-pivot assumption?

3 Graph

Plot $Y = T^2x^2$ against $X = (x-c)^2$. Include ΔY bars and horizontal bars $\Delta X \simeq 2|x-c|(\Delta x+\Delta c)$. Draw best and extreme acceptable lines; do not force a zero intercept.



Choose scales and label both axes with quantities and units. Mark a large gradient triangle on the best-fit line where appropriate.

4 Analyse and evaluate

1. Find gradient s and intercept b, with units. Calculate $k_e = 4\pi^2 M/s$. For identical series springs, each has $k = 2k_e$. Explain why the individual stiffness is larger.

2. Estimate Δs from the extreme line, then $\Delta k_e/k_e \simeq \Delta M/M + \Delta s/|s|$. Explain why small $x - c$ makes the uncertainty in X important.

3. Use $J_c = bk_e/(4\pi^2)$ to estimate rotational inertia. Is a positive intercept expected? Compare your dynamic k_e with a separately measured static force–extension stiffness, if available.

4. Explain two limitations and matched improvements. Consider sliding pivots, damping, spring mass and correlated distance errors. State whether the data support this model over your measured range.

Before you leave Return the apparatus, clear the bench and submit your recorded data.

Specific heat capacity with a cooling correction

Name: _____ Class: _____ Date: _____

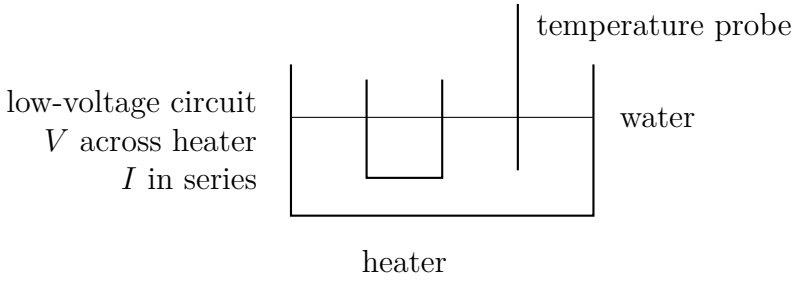
Aim Use heating and cooling rates to correct for heat loss. Allow 80–100 minutes, including cooling.

Model At the same water temperature, let $S_H = d\theta/dt > 0$ during heating and $S_C = -d\theta/dt > 0$ during cooling. If heat loss is the same in both stages,

$$VI = (m_w c_w + m_g c_g)(S_H + S_C), \quad c_g = 840\,\mathrm{J\,kg^{-1}K^{-1}}.$$

The **specific heat capacity** c_w is the target; this model neglects the heater and probe heat capacities.

Apparatus Teacher-approved immersion heater or suitably rated 15 Ω resistor, current-limited low-voltage d.c. supply, ammeter, voltmeter, switch, glass beaker, about 75 $\mathrm{cm^3}$ water, thermometer/probe, stirrer, balance and stopwatch.



Safety Switch off before touching the heater or changing connections. Keep it submerged when powered. Keep plugs and supply dry. Hot water can scald; use a stable beaker and no mains heater. Never exceed component power ratings.

1 Measure a continuous temperature record

1. Weigh dry beaker m_g, then beaker plus water m_t; $m_w = m_t - m_g$. Record room temperature. Position heater and probe without contact with glass.
2. Start heating and timing together. Record V, I and temperature every 30–60 s, chosen by a pilot. Stir gently and consistently throughout.
3. At about 15 °C above the start, switch off. Mark the exact switching time. Keep the same clock, stirring, water and apparatus positions.
4. Continue recording until at least 6 °C below the peak. Do not remove the heater. Record power readings during heating to test whether power stayed constant.

Processing check (synthetic data) For $P = 9.60$ W, $S_H = 0.0200$, $S_C = 0.00400\,\mathrm{K\,s^{-1}}$, $m_w = 0.0750$ kg and $m_g = 0.100$ kg, calculate corrected c_w. Recalculate ignoring cooling and compare.

2 Record measurements

$m_g =$ _____ kg $m_t =$ _____ kg $m_w =$ _____ kg.

Room temperature: _____ Temperature resolution: _____.

t/s	θ/ °C	V/V	I/A	Heating/cooling

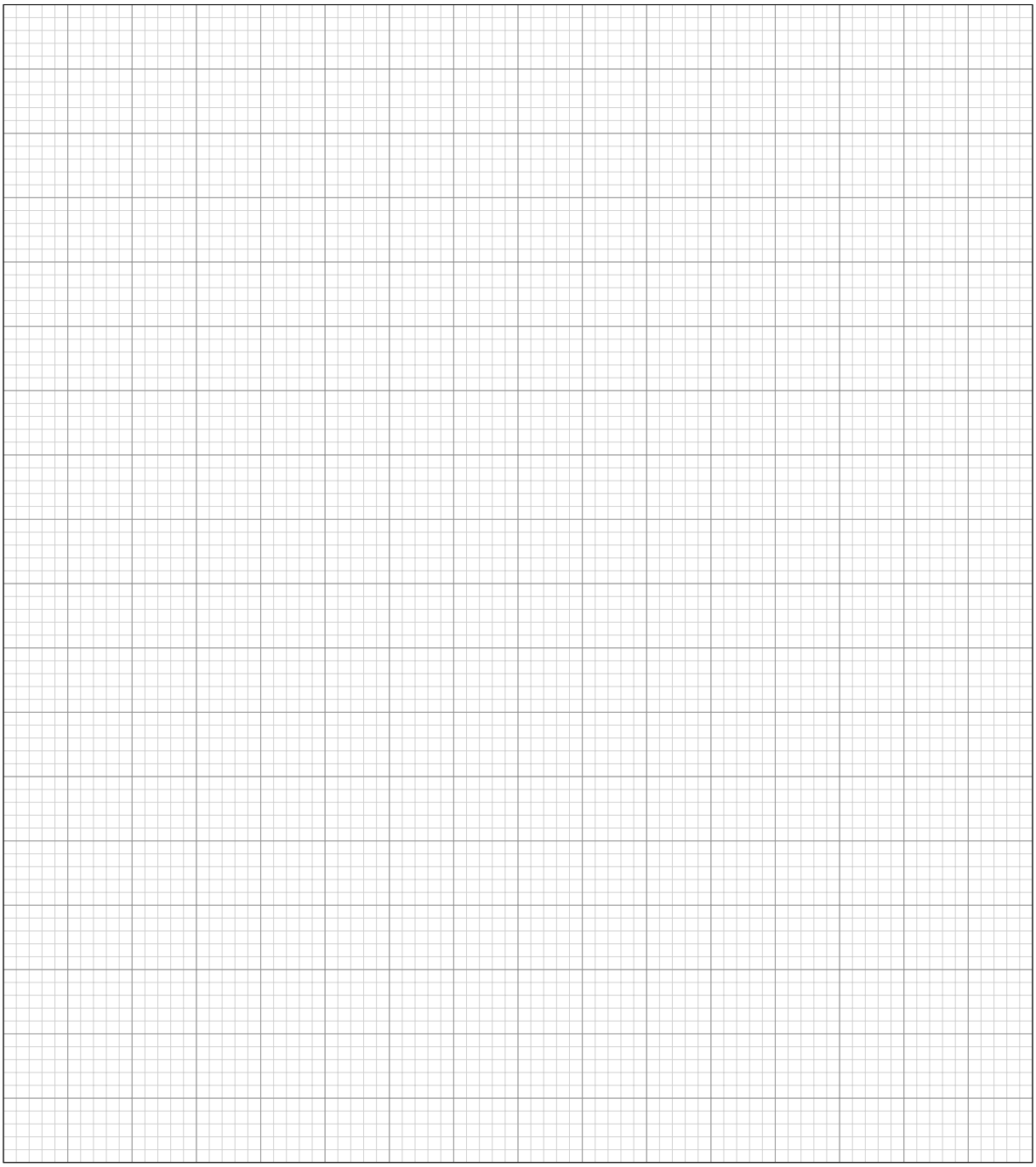
Record Switching time: _____ s. Peak temperature: _____ °C.

Selected common temperature θ_1 (about 4 °C below peak): _____ °C.

Note any evaporation, power variation or temperature lag.

3 Graph

Plot θ against the continuous time t. Draw smooth heating and cooling curves. At the same θ_1, draw a tangent to each curve and large triangles for their gradients.



Choose scales and label both axes with quantities and units. Mark a large gradient triangle on the best-fit line where appropriate.

4 Analyse, evaluate and plan

1. Calculate S_H and the positive magnitude S_C in K s^{-1}. Rearrange to $c_w = [VI/(S_H + S_C) - m_g c_g]/m_w$. Show substitutions. Compare with 4.18×10^3 J kg^{-1} K^{-1}, allowing for limitations.

2. Explain why the two tangents must be taken at the same temperature. Predict the direction of error if cooling losses are ignored. Explain the likely effect of neglected heater heat capacity.

3. Estimate uncertainty by drawing plausible alternative tangents. Identify two limitations with matched improvements; consider lag, uneven water temperature, evaporation and changing power.

4. Plan a separate test of $\theta - \theta_R = (\theta_0 - \theta_R)e^{-\alpha t}$. Specify readings, controls, safety and a graph whose gradient determines α. State why room temperature must be measured and small temperature differences are unreliable.

Before you leave Return the apparatus, clear the bench and submit your recorded data.

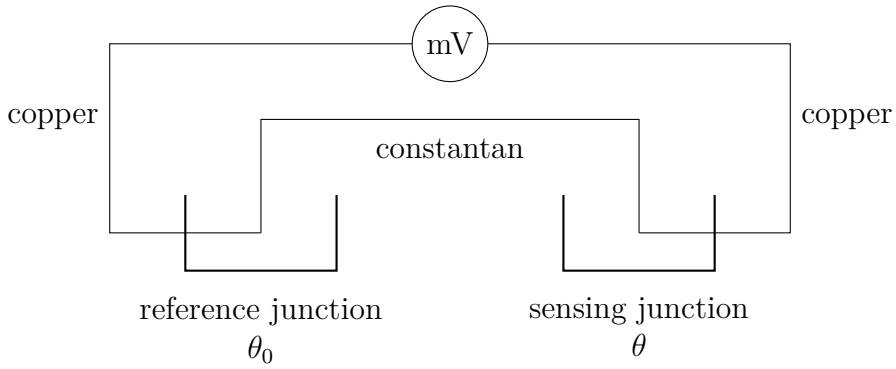
Planning and calibrating a thermocouple

Name: _____ Class: _____ Date: _____

Aim Plan and carry out a calibration, then assess an unknown temperature. Allow 70–90 minutes.

Model A **thermocouple** uses two different metals. Over a limited range, $V = a(\theta - \theta_0) + b$. θ is the sensing-junction temperature and θ_0 is the reference-junction temperature. Determine a and b without forcing the graph through zero.

Apparatus Two copper wires and one constantan wire, sensitive millivoltmeter, digital or non-mercury thermometer, two water baths/beakers, warm water, stirrer and clamp. Teacher supplies the unknown warm-water bath.



Safety Use teacher-provided warm water and stable containers. Keep the meter dry. Do not heat a wire in a flame: extrapolating a water calibration to a flame temperature is unreliable and unnecessary.

1 Plan before handling apparatus

Write a method to obtain at least six well-spread temperature differences and repeat readings. Explain how you will form secure junctions, keep θ_0 stable, measure both bath temperatures and wait for thermal equilibrium. Include a zero-difference check and meter polarity.

State two controls, a usable temperature range and precautions for hot water and sharp wire ends.

Teacher method/safety check: _____ Date: _____.

2 Carry out and record

After approval, form secure copper–constantan junctions. Keep both copper-to-meter connections together at the same room temperature. Place the reference junction in a stable room-temperature bath. Stir each bath gently; let the junction and thermometer settle before reading.

Meter resolution: _____ mV Thermometer resolution: _____ °C.

θ/°C	θ_0/°C	$\Delta\theta$/K	V_1/mV	V_2/mV	$\bar{V}$/mV

Zero check With both junctions at the same temperature, measured $V =$ _____ mV.

Unknown bath $V_u =$ _____ mV $\theta_{0,u} =$ _____ °C.

Record the unknown thermometer reading only after predicting its temperature: _____ °C.

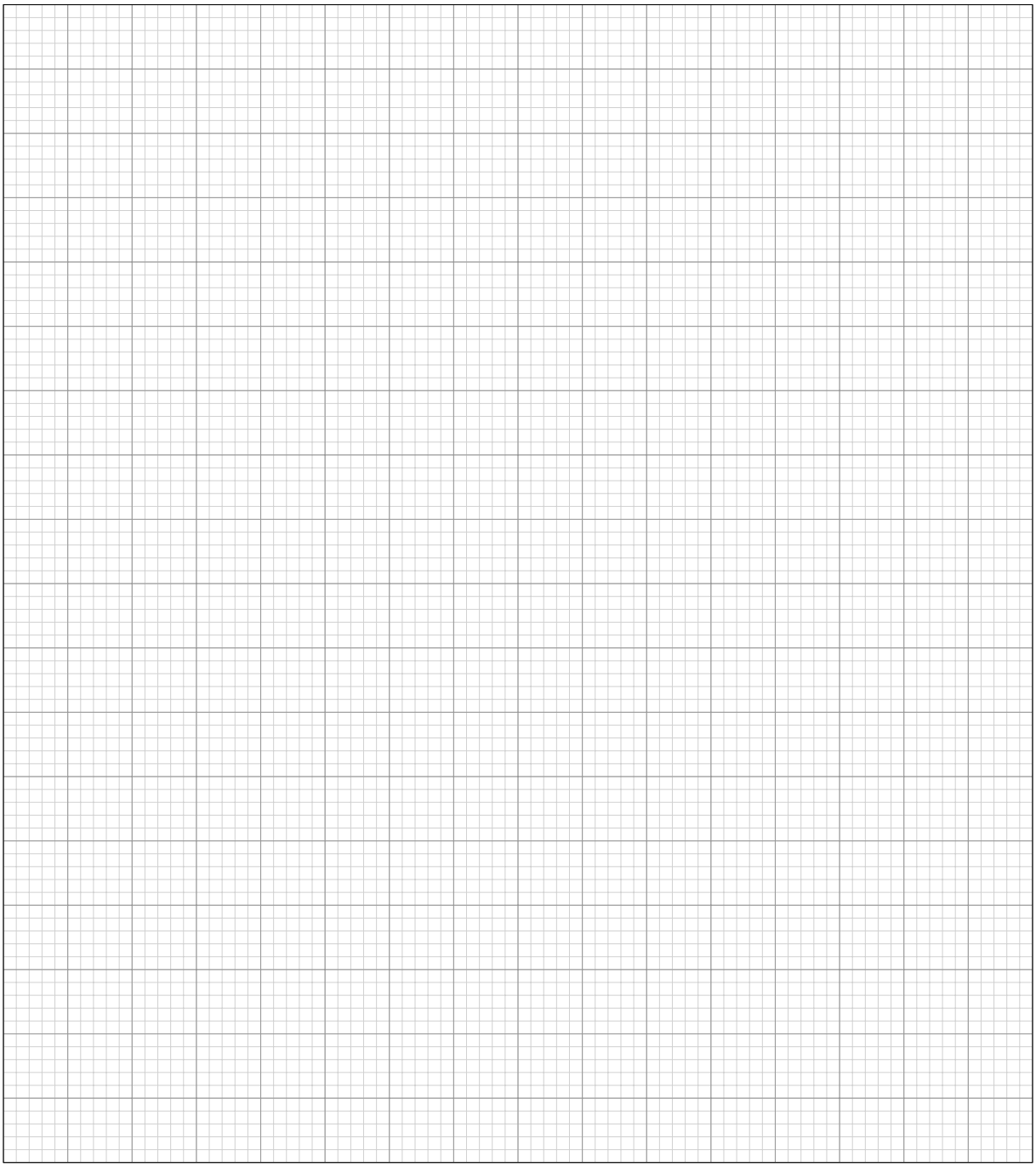
Uncertainty Estimate ΔV and $\Delta(\Delta\theta)$. A temperature difference includes uncertainty in both temperatures.

Method changes Describe any revision to your plan and why it was needed.

Processing check (synthetic data) For $V_u = 1.220$ mV and $\theta_{0,u} = 20.0\,°\text{C}$, two acceptable fits are $(a, b) = (0.0390, 0.0300)$ and $(0.0410, 0.0100)$ in mV K^{-1} and mV. Calculate both predicted temperatures, keeping each slope with its own intercept.

3 Calibration graph

Plot $\bar{V}$ against $\Delta\theta = \theta - \theta_0$. Include uncertainty bars. Fit a line without forcing zero; use extreme acceptable lines to estimate the range of possible calibrations.



Choose scales and label both axes with quantities and units. Mark a large gradient triangle on the best-fit line where appropriate.

4 Analyse and evaluate

1. Find a and b, with units. Does your zero-difference check agree with the fitted intercept? Explain whether a non-zero b is likely to be a physical thermocouple e.m.f. or an offset in the measurement.

2. Calculate $\theta_u = \theta_{0,u} + (V_u - b)/a$. Use extreme acceptable calibrations to estimate a temperature interval. Compare with the independent thermometer reading and its uncertainty.

3. Explain why θ_0 must be recorded during calibration and unknown measurement. Identify two limitations, such as changing reference temperature, poor junction contact or thermal lag, and give matched improvements.

4. Why would extrapolating this calibration to a flame be weak evidence? Consider non-linearity, range, wire oxidation and equilibrium. State the temperature range over which your calibration is supported.

Before you leave Return the apparatus, clear the bench and submit your recorded data.

Free fall acceleration from a V-shaped pendulum

Name: _____ Class: _____ Date: _____

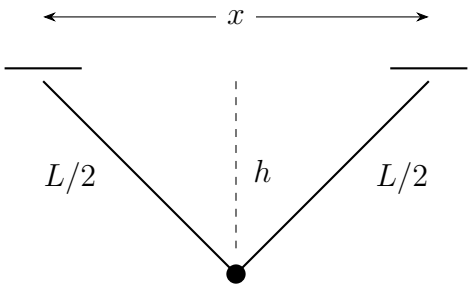
Aim Plan a linearised experiment to estimate g. Allow 70–90 minutes.

Model A bob is fixed at the midpoint of a string of total effective length L, whose ends are fixed at equal height, separation x. Swing it perpendicular to the plane of the V through a small angle. With vertical drop h, $T = 2\pi\sqrt{h/g}$ and $h^2 = (L^2 - x^2)/4$. Hence

$$T^4 = \frac{4\pi^4 L^2}{g^2} - \frac{4\pi^4}{g^2}x^2.$$

Both equal arms have length $L/2$, measured from support to the bob's centre.

Apparatus Two weighted stands with clamps, secure bob and fixed-length string, stopwatch, metre rule and set square; protractor if needed.



small swing perpendicular
to the plane of this page

Safety Weight the stands, secure the bob and keep its path clear. Do not make the arms almost horizontal: tension increases sharply. Stop if a support shifts, a string slips or the bob hits anything.

1 Plan and obtain approval

Describe how to fix equal arms, measure effective L, keep supports at equal height and vary x without changing arm lengths. Choose at least six well-spread safe separations $0 < x < L$. Explain your small-amplitude and repeat timing method.

Predict the sign of the graph gradient. State which quantities you will hold constant and how you will test that the intended swing is stable.

Teacher method/safety check: _____ Date: _____.

2 Record and process

$L =$ _____ m $\Delta L =$ _____ m Length resolution: _____.

Time 10 complete cycles in the same direction. Reset and repeat. $T = \bar{t}/10$.

x/m	t_1/s	t_2/s	$\bar{t}$/s	T/s

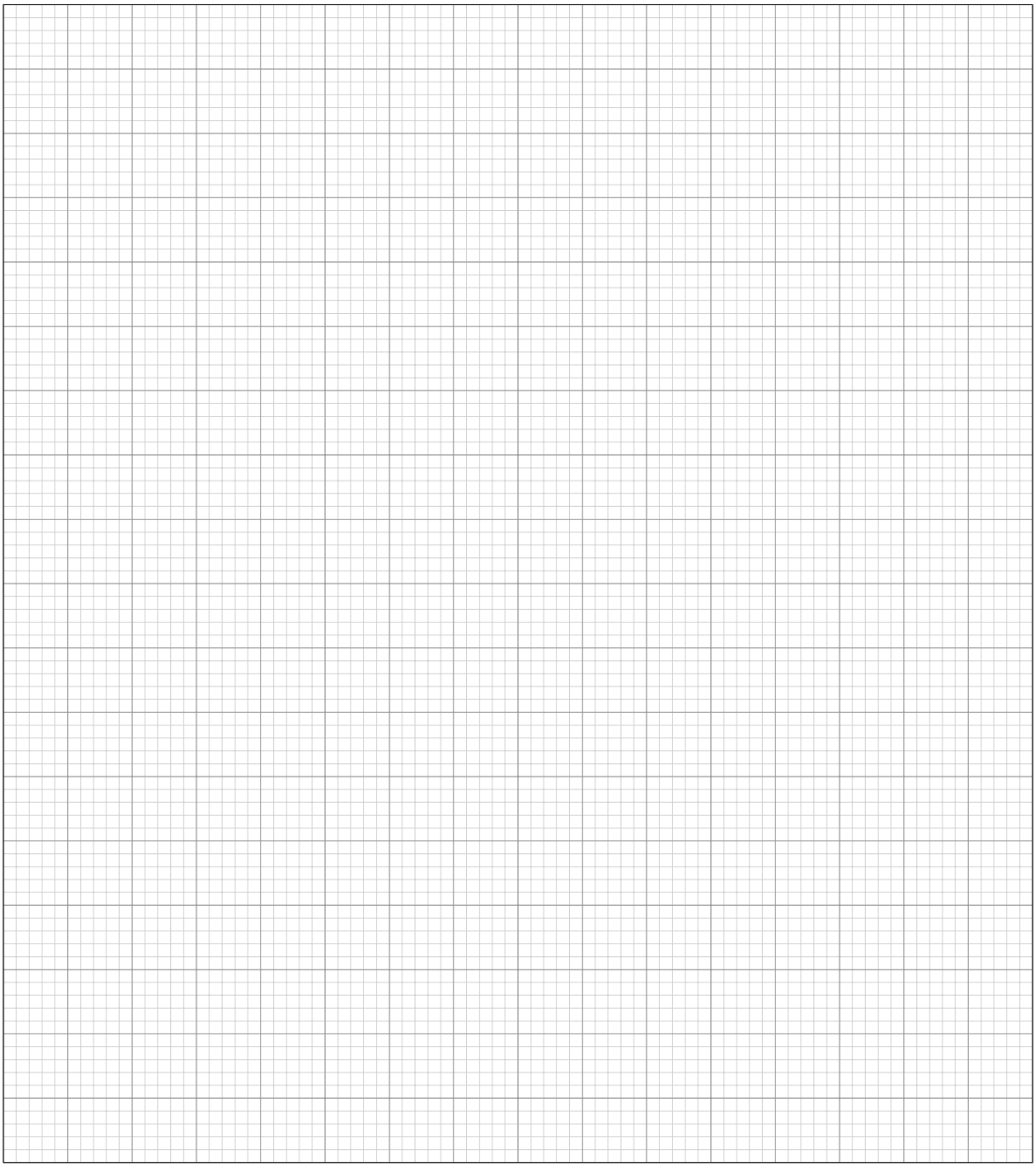
x^2/m^2	T^4/s^4	$\Delta(T^4)$/s^4

Uncertainty Estimate ΔT from repeat spread and timing limits. Use $\Delta(T^4)/T^4 \simeq 4\Delta T/T$ and $\Delta(x^2) \simeq 2x\Delta x$.

Validity check Record evidence that the bob swung perpendicular to the support plane and that L did not change.

3 Graph

Plot T^4 against x^2. Include uncertainty bars, the best-fit straight line and an extreme acceptable line. A negative gradient and positive intercept are expected.



Choose scales and label both axes with quantities and units. Mark a large gradient triangle on the best-fit line where appropriate. **Processing check (synthetic data)** A gradient is $s = -4.05 \pm 0.20\,\mathrm{s^4\,m^{-2}}$. Calculate g and its approximate percentage uncertainty. Would $9.81\,\mathrm{m\,s^{-2}}$ be consistent?

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4 Analyse and evaluate

1. Find gradient s and intercept b, with units. Calculate $g = \sqrt{-4\pi^4/s}$. Show substitutions and quote a justified precision.

2. Estimate Δs and use $\Delta g/g \simeq \frac{1}{2}\Delta s/|s|$. Compare with 9.81 m s^{-2}. Judge agreement using your uncertainty, not a fixed percentage rule.

3. Use $L_{\text{graph}} = \sqrt{-b/s}$ as a second geometry check. Compare it with measured L. Explain why slope and intercept estimates are linked rather than independent measurements.

4. Identify two limitations and matched improvements. Consider finite bob size, unequal arms, knot slipping, mixed swing directions and timing. Plan an alternative graph using measured h and T^2, including its gradient and controls.

Before you leave Return the apparatus, clear the bench and submit your recorded data.