Please check the examination details below before entering your candidate information

Candidate surname	Other names
StemUp Model Solution	

Centre Number | Candidate Number

Pearson Edexcel Level 3 GCE

Thursday 15 June 2023

Morning (Time: 2 hours 30 minutes)

Paper reference **9PH0/03**

Physics

Advanced

PAPER 3: General and Practical Principles in Physics

You must have:
Scientific calculator, ruler

Total Marks

Instructions

- Use **black** ink or ball-point pen.
- If pencil is used for diagrams/sketches/graphs it must be dark (HB or B).
- **Fill in the boxes** at the top of this page with your name, centre number and candidate number.
- Answer **all** questions.
- Answer the questions in the spaces provided – *there may be more space than you need.*

Information

- The total mark for this paper is 120.
- The marks for **each** question are shown in brackets – *use this as a guide as to how much time to spend on each question.*
- In questions marked with an **asterisk** (*), marks will be awarded for your ability to structure your answer logically, showing how the points that you make are related or follow on from each other where appropriate.
- The list of data, formulae and relationships is printed at the end of this booklet.

Advice

- Read each question carefully before you start to answer it.
- Try to answer every question.
- Check your answers if you have time at the end.
- You are advised to show your working in calculations including units where appropriate.

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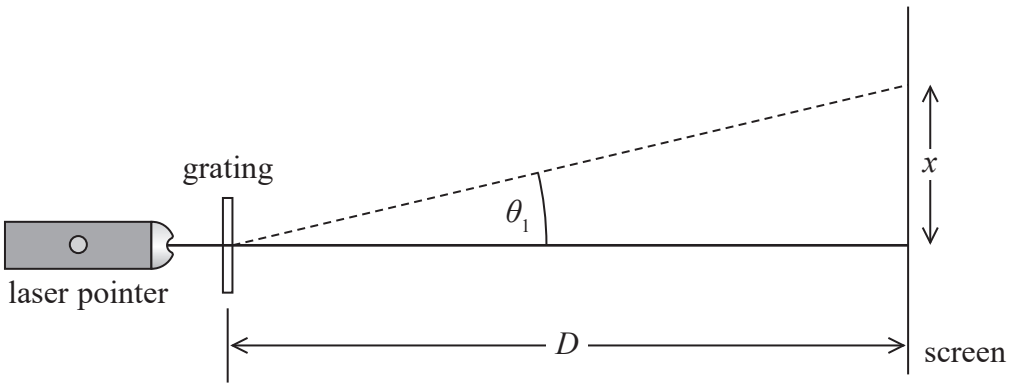
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Answer ALL questions in the spaces provided.

1 A student used a laser pointer to direct monochromatic light normal to the plane of a diffraction grating as shown.



A diffraction pattern was produced on the screen. The distance between the first order maximum and the central maximum of the diffraction pattern was x. The distance between the diffraction grating and the screen was D.

(a) The diffraction grating had 300 lines per mm.
The laser pen was marked with $\lambda = 520\,\text{nm}$.

Determine whether the spacing of the diffraction pattern was consistent with these values.

$x = 43.5\,\text{cm}$
$D = 2.75\,\text{m}$

(4)

tan θ = x/D = 0.435 m ÷ 2.75 m = 0.158, so θ = 8.99°

d = 1 ÷ number of lines per metre = 1 ÷ (300 × 10^3 m^{-1}) = 3.33 × 10^{-6} m

nλ = d sin θ with n = 1: λ = 3.33 × 10^{-6} m × sin 8.99° = 5.21 × 10^{-7} m ≈ 520 nm

This agrees with the marked wavelength λ = 520 nm, so the spacing of the diffraction pattern was consistent with these values.

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(b) The student wrote the following conclusion:

"The value of x was measured with a metre rule. A metre rule has a precision of 0.1 cm, so this value was determined with a high degree of accuracy."

Comment on this conclusion.

(3)

The metre rule has a resolution of 0.1 cm, not a precision of 0.1 cm.

Precision is how closely grouped repeated readings are, so one reading cannot show precision.

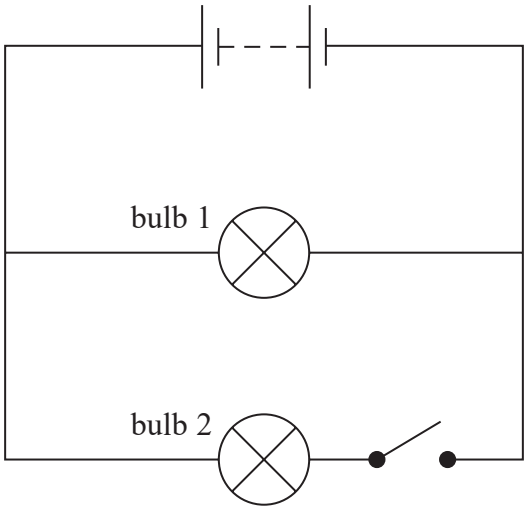
Accuracy is how close the measured value is to the true value.

A systematic error, such as a zero error or parallax error, may shift the measured value away from the true value, and it is difficult to judge the positions of the maxima, so the conclusion is not valid.

(Total for Question 1 = 7 marks)

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2 A battery has an e.m.f. of 12 V and an internal resistance of 0.50 Ω. The battery is connected into a circuit, as shown.



Each bulb has a normal working power of 40 W when a potential difference (p.d.) of 12 V is applied.

(a) Initially the switch is open.

Calculate the terminal p.d. of the battery when bulb 1 is lit. Assume that the resistance of the bulb has its normal working value.

(4)

$P = V^2/R$ so $R = V^2/P = (12\ V)^2 \div 40\ W = 3.6\ \Omega$

Sum of e.m.fs = sum of p.d.s: $12\ V = I \times (3.6\ \Omega + 0.50\ \Omega)$

$I = 12\ V \div 4.1\ \Omega = 2.93\ A$

Terminal p.d. $V = IR = 2.93\ A \times 3.6\ \Omega = 10.5\ V$

Terminal p.d. of battery = 10.5 V

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(b) Explain how the brightness of bulb 1 changes when the switch is closed. No further calculations are necessary.

(3)

When the switch is closed, bulb 2 is in parallel with bulb 1, so the resistance of the external circuit decreases.

So the current from the battery increases, and the lost volts (Ir) across the internal resistance increase.

Therefore the terminal p.d. decreases, so the p.d. across bulb 1 decreases and the brightness of bulb 1 decreases.

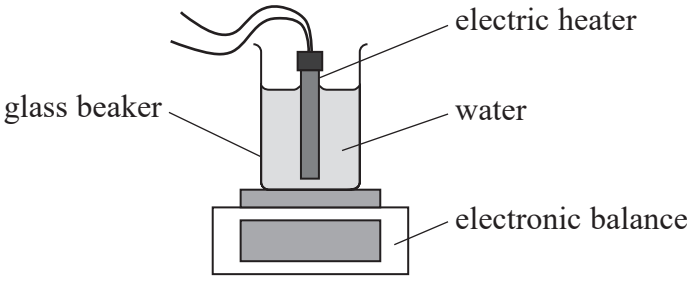
(Total for Question 2 = 7 marks)

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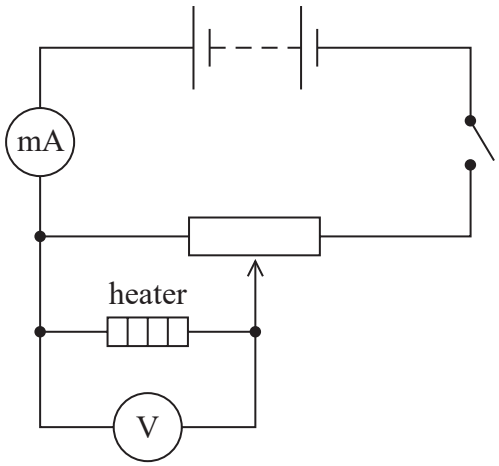
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3 The specific latent heat of vaporisation of water can be determined using the apparatus shown.



(a) A student planned to vary the current in the heater from 0 A to 5 A. The student connected the following circuit to measure the current in the heater.



Criticise the student's circuit.

(2)

The ammeter is not measuring the current through the heater: it should be connected in series with the heater.

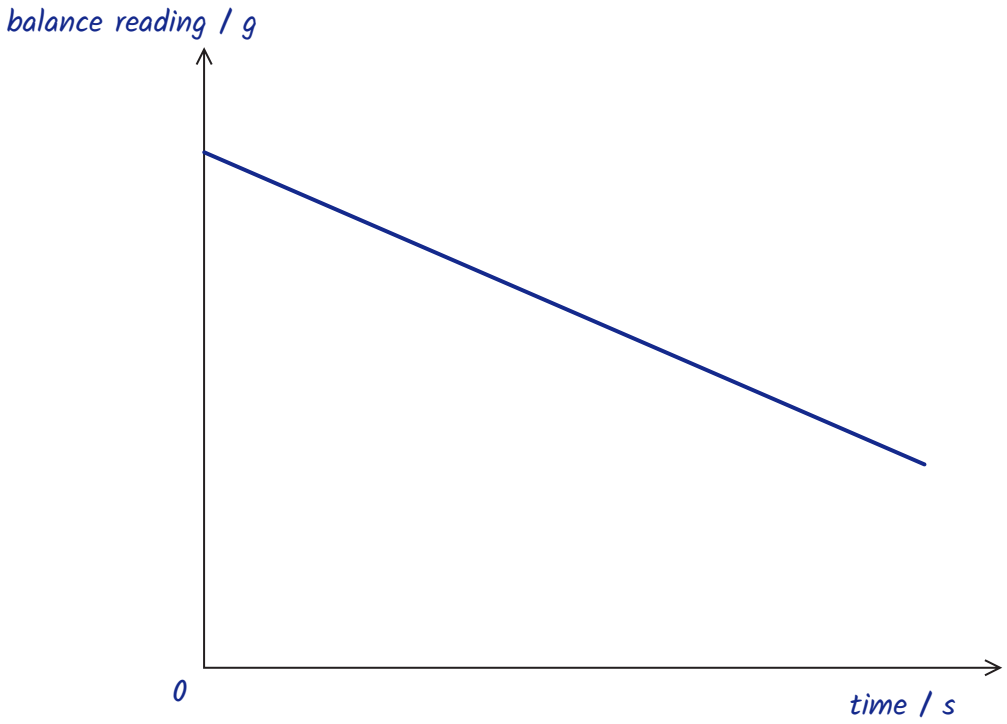
The range of the milliammeter (mA) is too small for currents up to 5 A; a 0 to 5 A (or 10 A) ammeter is needed.

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(b) (i) The student corrected the circuit and closed the switch. He waited until the water started boiling. He started a stopwatch and recorded the readings on the balance at regular time intervals.

Sketch a graph, on the axes below, of how the readings on the balance would vary with time.

(3)



(ii) The heater was switched on for 6.0 minutes and the change in mass of water in the beaker was 7.5 g.

Calculate the specific latent heat of vaporisation of water, L.

$V = 12\,V$
$I = 4.2\,A$

(3)

$W = VIt = 12\ V \times 4.2\ A \times (6.0 \times 60)\ s = 1.81 \times 10^4\ J$

$\Delta E = mL$ so $L = 1.81 \times 10^4\ J \div 7.5 \times 10^{-3}\ kg = 2.42 \times 10^6\ J\ kg^{-1}$

$L = 2.4 \times 10^6\ J\ kg^{-1}$

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(iii) The errors in the experiment include uncertainty in the mass reading and uncertainty in reading the stopwatch, as the water boils.

Explain how another significant source of error affects the value of L obtained from the experiment.

(2)

Energy is transferred from the heater, beaker and water to the surroundings, so not all of the energy supplied vaporises water.

So less mass is vaporised for the energy calculated, and the calculated value of L will be larger than the true value.

(Total for Question 3 = 10 marks)

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*4 Alpha particle scattering experiments led Rutherford to propose the nuclear model of the atom. Alpha particles were directed towards a thin gold foil.

Describe how evidence from these experiments supports the nuclear model of the atom.

Most of the alpha particles passed straight through the gold foil without being deflected.

This indicates that the atom is mostly empty space.

Some alpha particles were deflected from their path through small angles.

This indicates that there is a charged centre in the atom, which repels and deflects the positive alpha particles that pass close to it.

A very small proportion of the alpha particles were deflected through more than 90°, back towards the source.

This indicates that most of the mass of the atom (and the positive charge) is concentrated in a very small nucleus at the centre of the atom.

(Total for Question 4 = 6 marks)

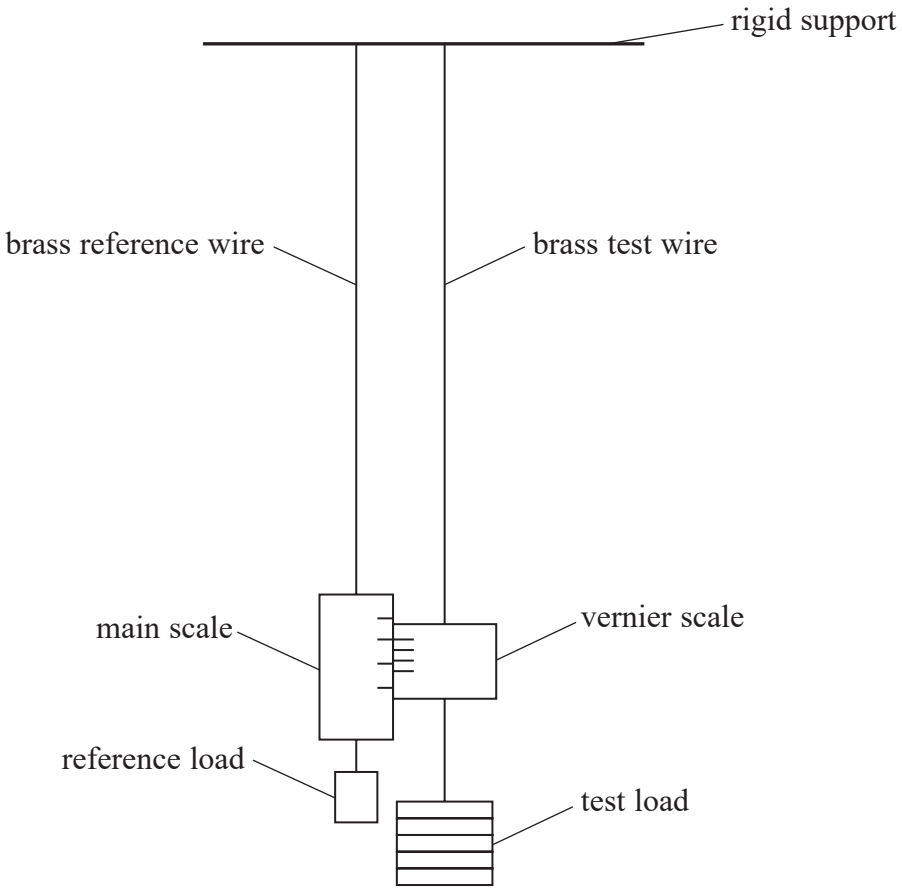
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5 A student used the apparatus shown to determine the Young modulus of brass. Loads were added to the test wire and corresponding readings taken from the vernier scale. The test wire and the reference wire were identical.



(a) (i) Give one advantage of using a reference wire as well as a test wire.

(1)

Changes in the recorded length due to temperature changes (or due to the support bending) are minimised, as both wires are affected equally.

(ii) State why a reference load was applied to the reference wire.

(1)

To keep the reference wire taut and straight (under tension).

(b) Explain why the test wire should be both long and thin.

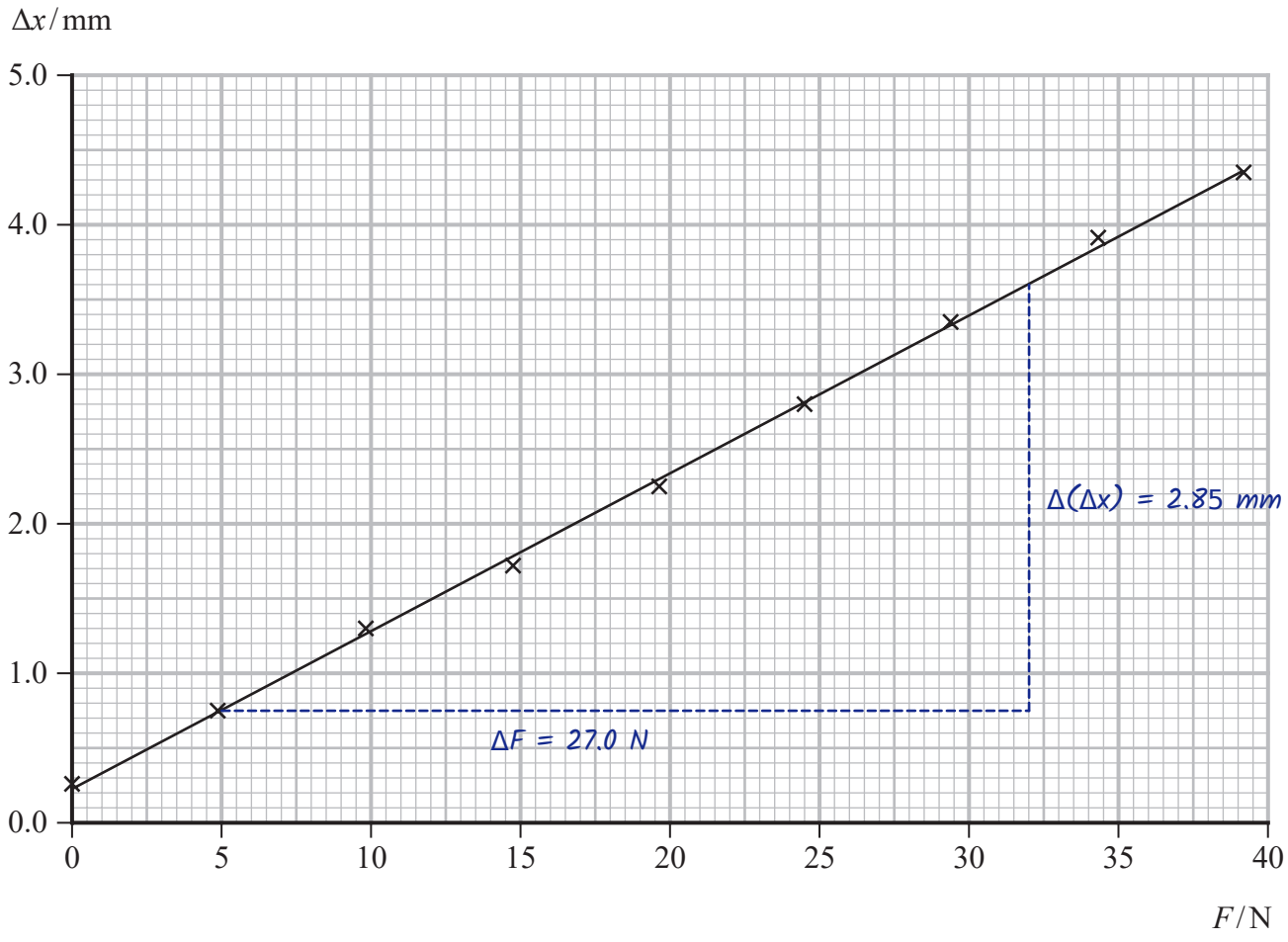
(3)

A thin wire has a small cross-sectional area, so there is a large stress for a given load.

A long, thin wire has a large extension for a given stress ($\Delta x = \sigma x/E$).

Hence the percentage uncertainty in the measured extension is reduced.

(c) The student varied the load F on the test wire and recorded the corresponding change in length Δx from the vernier scale. The results are shown on the graph.



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Determine a value for the Young modulus of brass.

length of wire = 2.75 m
diameter of wire = 5.60×10^{-4} m

(5)

$A = \pi d^2/4 = \pi \times (5.60 \times 10^{-4}\ m)^2 \div 4 = 2.46 \times 10^{-7}\ m^2$

$Gradient = \Delta x/F = (3.60 - 0.75) \times 10^{-3}\ m \div (32.0 - 5.0)\ N = 1.06 \times 10^{-4}\ m\ N^{-1}$

$E = \sigma/\varepsilon = (F/A) \div (\Delta x/x) = (F/\Delta x) \times (x/A)$

$So\ E = (1/gradient) \times (x/A) = (1 \div 1.06 \times 10^{-4}\ m\ N^{-1}) \times (2.75\ m \div 2.46 \times 10^{-7}\ m^2)$

$E = 1.06 \times 10^{11}\ N\ m^{-2}$

Young modulus of brass = $1.1 \times 10^{11}\ N\ m^{-2}$

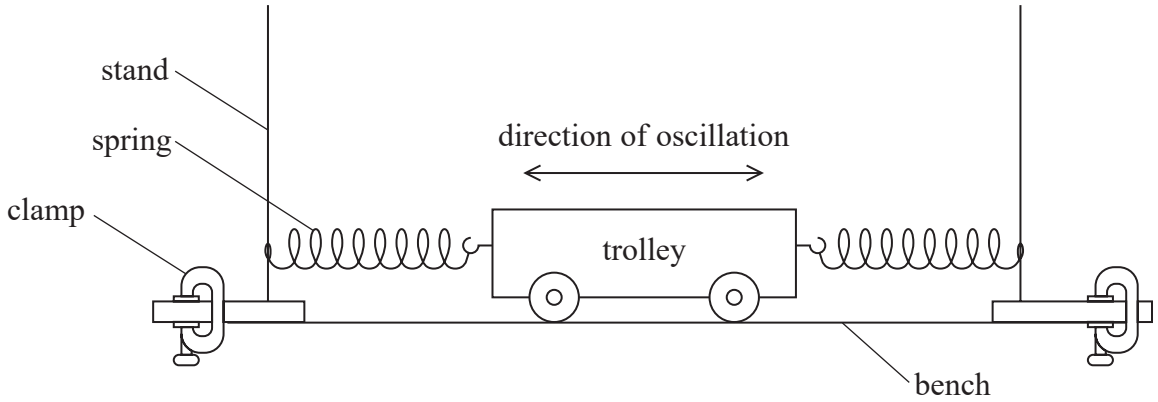
(Total for Question 5 = 10 marks)

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6 A student investigated the horizontal oscillations of a trolley between two springs, using the apparatus shown.



The student displaced the trolley from its equilibrium position. She then released the trolley and started a stopwatch. She stopped the stopwatch when the trolley had completed one oscillation.

(a) Describe how the method used by the student could be improved to determine a more accurate value of the time period.

(4)

Time a number of complete oscillations (e.g. 10) and divide the total time by the number of oscillations.

Repeat the timing several times and calculate a mean value.

Use a fiducial marker at the equilibrium position, so it is easier to see when the trolley passes a particular point.

Time from the mid-point (equilibrium position) of the oscillation, and wait for the oscillation to settle before starting to time.

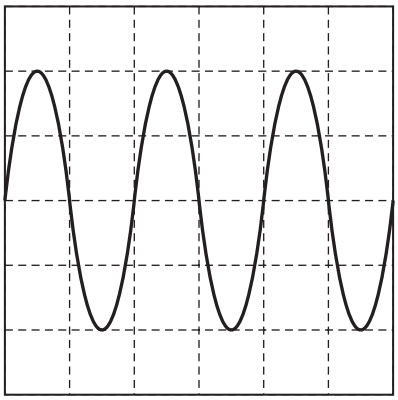
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(b) The student displaced the trolley 6.0 cm from the equilibrium position.
She recorded the velocity of the oscillating trolley using a sensor connected to a data logger.

The output from the data logger is shown below.



The time-base of the data logger output was set to 250 ms div^{-1}.

Determine the maximum velocity of the trolley.

(5)

From the trace, one complete cycle occupies 2 divisions.

$T = 2\ div \times 250\ ms\ div^{-1} = 500\ ms = 0.50\ s$

$\omega = 2\pi/T = 2\pi \div 0.50\ s = 12.6\ rad\ s^{-1}$

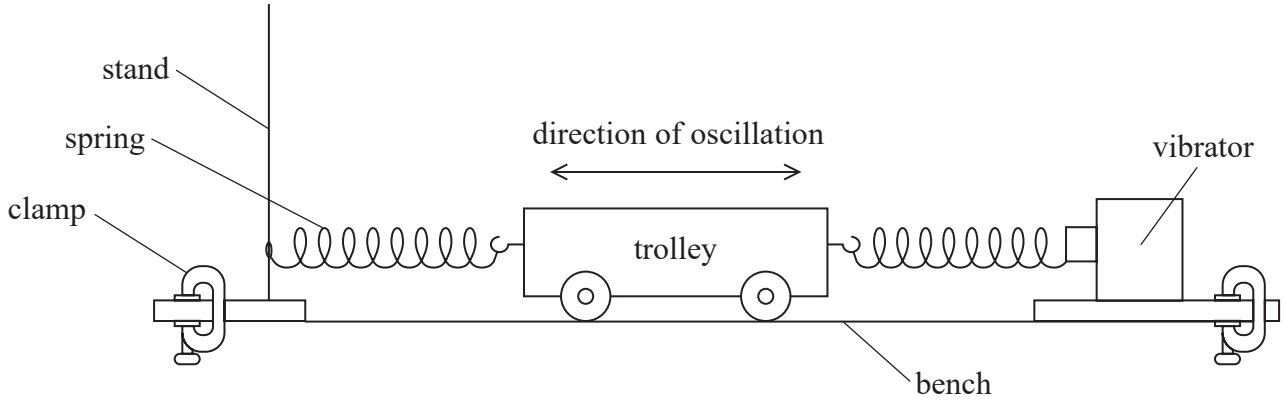
$v = -A\omega \sin \omega t$ so $v_{max} = A\omega = 6.0 \times 10^{-2}\ m \times 12.6\ rad\ s^{-1} = 0.754\ m\ s^{-1}$

Maximum velocity of trolley = *$0.75\ m\ s^{-1}$*

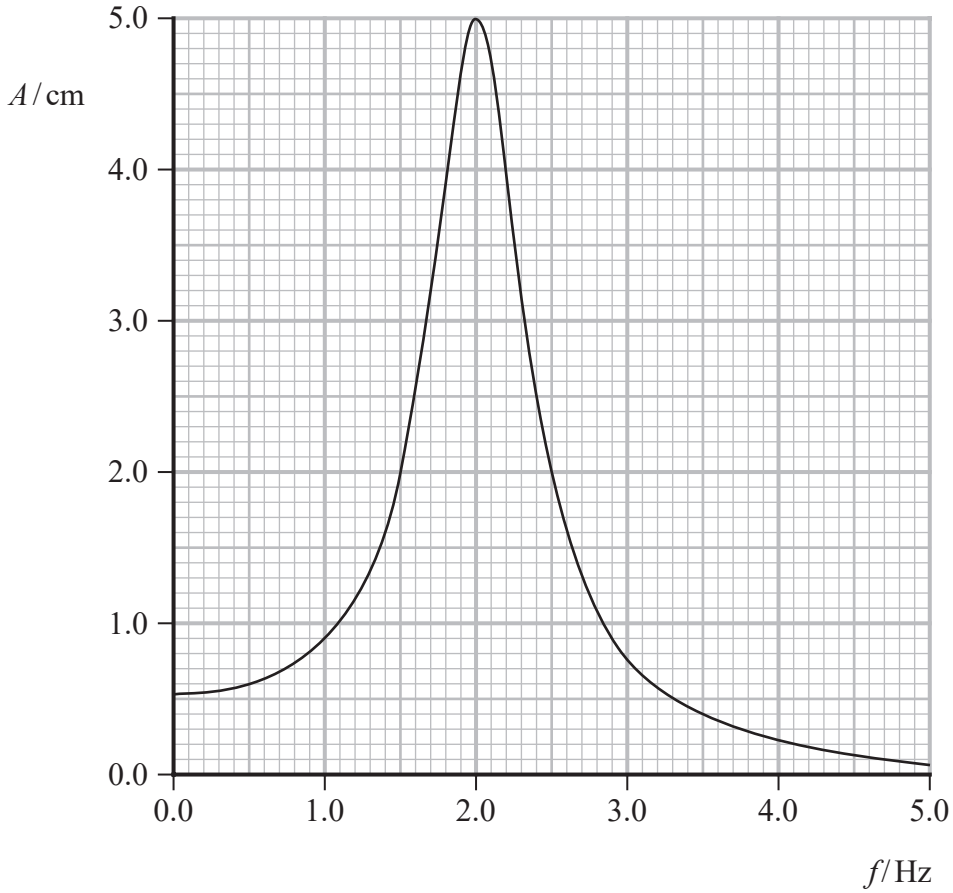
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(c) The student modified the apparatus so that the trolley was driven into oscillation by a vibrator, as shown.

A sensor connected to a data logger recorded the amplitude A of the oscillations.



The graph shows how A varied as the student increased the frequency f of the oscillations.



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(i) Explain the shape of the graph.

(4)

As the frequency is increased, the amplitude increases to a maximum at a frequency of 2.0 Hz, and then decreases.

2.0 Hz is the natural frequency of oscillation of the trolley.

When the vibrator drives the trolley at its natural frequency, there is a maximum transfer of energy from the vibrator to the trolley.

This is resonance.

(ii) Determine the effective spring constant k of the oscillating trolley system.

mass of trolley = 0.87 kg

(2)

At resonance $f = 2.0$ Hz, so $T = 1/f = 0.50$ s

$T = 2\pi\sqrt{(m/k)}$ so $k = 4\pi^2 m/T^2 = 4\pi^2 \times 0.87\ kg \div (0.50\ s)^2 = 137\ N\ m^{-1}$

$k =$ 140 N m^{-1}

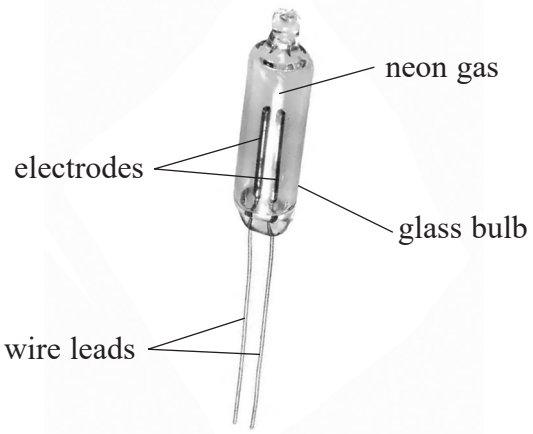
(Total for Question 6 = 15 marks)

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7 The neon lamp shown is a glass bulb filled with neon gas at low pressure.



(Source: https://media.digikey.com/Photos/Visual%20Communications%20Company%20VCC/A1A.JPG)

*(a) When in use, the neon gas between the electrodes emits electromagnetic radiation.

Explain why this happens when there is an electric current between the electrodes.

(6)

The electric current is a movement of electrons (charge carriers) between the electrodes, accelerated by the p.d.

The moving electrons collide with the neon atoms.

In the collisions, energy is transferred from the electrons to the neon atoms.

This causes electrons in the neon atoms to be promoted to higher energy levels, so the neon atoms are excited.

After a short time, the electrons in the neon atoms return to lower energy levels (the ground state), so the atoms de-excite.

When an electron returns to a lower energy level it emits a photon of electromagnetic radiation, with energy equal to the difference between the energy levels ($E = hf$).

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(b) When light from the neon lamp is incident upon a metal surface, electrons with a maximum speed of $2.68 \times 10^5\,m\,s^{-1}$ are emitted from the surface.

The table shows the work functions of some metals.

Metal	Caesium	Potassium	Sodium
Work function / 10^{-19} J	3.36	3.68	3.84

Deduce which metal the light is incident upon.

frequency of light from the neon lamp = 5.56×10^{14} Hz

(4)

Photon energy $E = hf = 6.63 \times 10^{-34}\ J\ s \times 5.56 \times 10^{14}\ Hz = 3.69 \times 10^{-19}\ J$

Max kinetic energy $= \frac{1}{2}mv^2 = 0.5 \times 9.11 \times 10^{-31}\ kg \times (2.68 \times 10^5\ m\ s^{-1})^2 = 3.27 \times 10^{-20}\ J$

$hf = \phi + \frac{1}{2}mv_{max}^2$ so $\phi = 3.69 \times 10^{-19}\ J - 3.27 \times 10^{-20}\ J = 3.36 \times 10^{-19}\ J$

This equals the work function of caesium, so the metal is caesium.

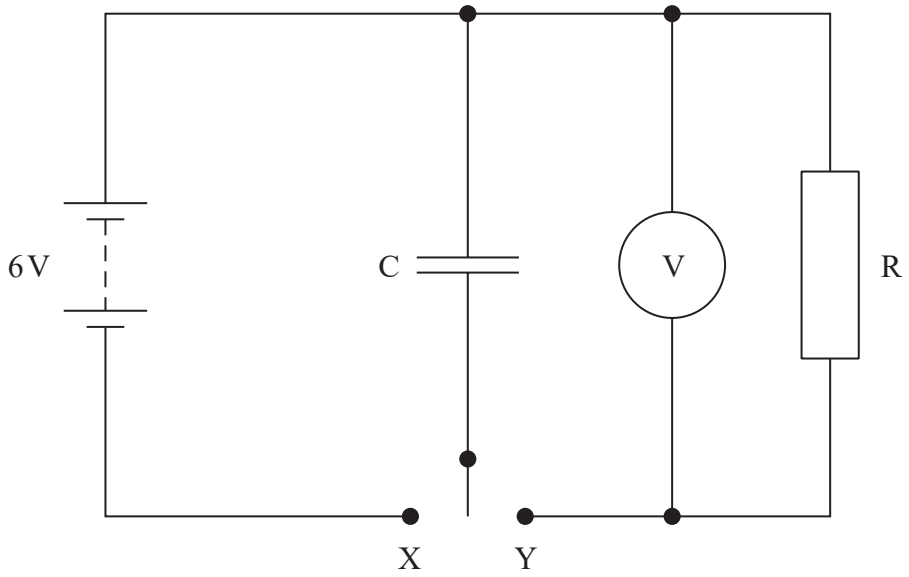
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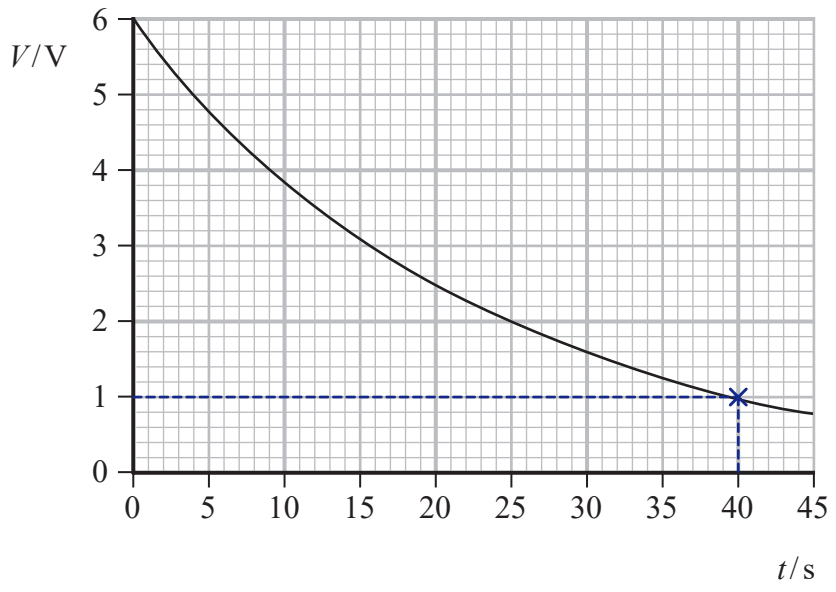
8 A student investigated the discharge of a capacitor C through a resistor R using the circuit shown.



The student used the switch to connect C to X to charge the capacitor. She then connected C to Y to discharge the capacitor through R.

As the capacitor discharged, she recorded values of the potential difference V across C and corresponding values of time t. She used a stopwatch to measure t.

The student used her results to plot the following graph.



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(a) The capacitor was marked 220 μF ± 20%.

Deduce whether the student's data give a value of capacitance within the stated range.

$R = 82\,\text{k}\Omega$

(5)

From the graph, at $t = 40$ s, $V = 1.0$ V, and $V_0 = 6.0$ V

$V = V_0e^{-t/RC}$ so $\ln(V/V_0) = -t/RC$

$\ln(1.0\text{ V} \div 6.0\text{ V}) = -40\text{ s} \div (82 \times 10^3\ \Omega \times C)$

$C = 40\text{ s} \div (1.79 \times 82 \times 10^3\ \Omega) = 2.72 \times 10^{-4}$ F $= 270$ μF

220 μF ± 20 % gives a range of 176 μF to 264 μF

270 μF is greater than the largest value, 264 μF, so the student's data do not give a value of capacitance within the stated range.

(b) The student suggested that her results would have been more accurate if she had used a data logger to record the data.

Assess the student's suggestion.

(3)

The data have to be collected in a short time (under a minute); a data logger has a high sampling rate, so it can take many more readings in the time for the capacitor to discharge.

It would be difficult to read the voltmeter and the stopwatch simultaneously, but a data logger records V and t at the same instant.

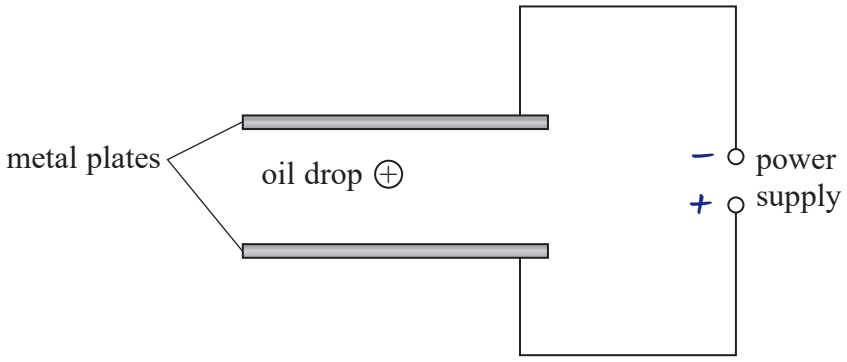
So the student's suggestion is correct.

(Total for Question 8 = 8 marks)

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9 A student investigated the behaviour of small, positively charged oil drops in an electric field.

He introduced an oil drop between two horizontal metal plates. A potential difference V was applied to bring the oil drop to rest as shown.



(a) (i) Add to the diagram to show the polarity of the power supply when the oil drop is at rest.

(1)

(ii) The oil drop was at rest when $V = 4870\,\text{V}$.

The student expected the charge on the oil drop to be a whole number multiple of the charge on an electron.

Deduce whether this is confirmed by the experimental data.

distance between top plate and bottom plate = 1.55 cm
density of oil = $920\,\text{kg m}^{-3}$
radius of the oil drop = $1.78 \times 10^{-6}\,\text{m}$

(6)

Volume = $4/3\ \pi r^3 = 4/3 \times \pi \times (1.78 \times 10^{-6}\ m)^3 = 2.36 \times 10^{-17}\ m^3$

$m = \rho V = 920\ kg\ m^{-3} \times 2.36 \times 10^{-17}\ m^3 = 2.17 \times 10^{-14}\ kg$

$E = V/d = 4870\ V \div 1.55 \times 10^{-2}\ m = 3.14 \times 10^{5}\ V\ m^{-1}$

At rest $EQ = mg$, so $Q = mg/E = (2.17 \times 10^{-14}\ kg \times 9.81\ N\ kg^{-1}) \div 3.14 \times 10^{5}\ N$

$C^{-1} = 6.78 \times 10^{-19}\ C$

Number of electron charges $N = Q/e = 6.78 \times 10^{-19}\ C \div 1.60 \times 10^{-19}\ C = 4.2$

4.2 is not a whole number, so the student's expectation is not confirmed by the experimental data.

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(b) The student determined the terminal velocity of the oil drop in order to obtain a value for the weight of the oil drop.

He disconnected the power supply and the oil drop fell downwards. He viewed the oil drop through a microscope.

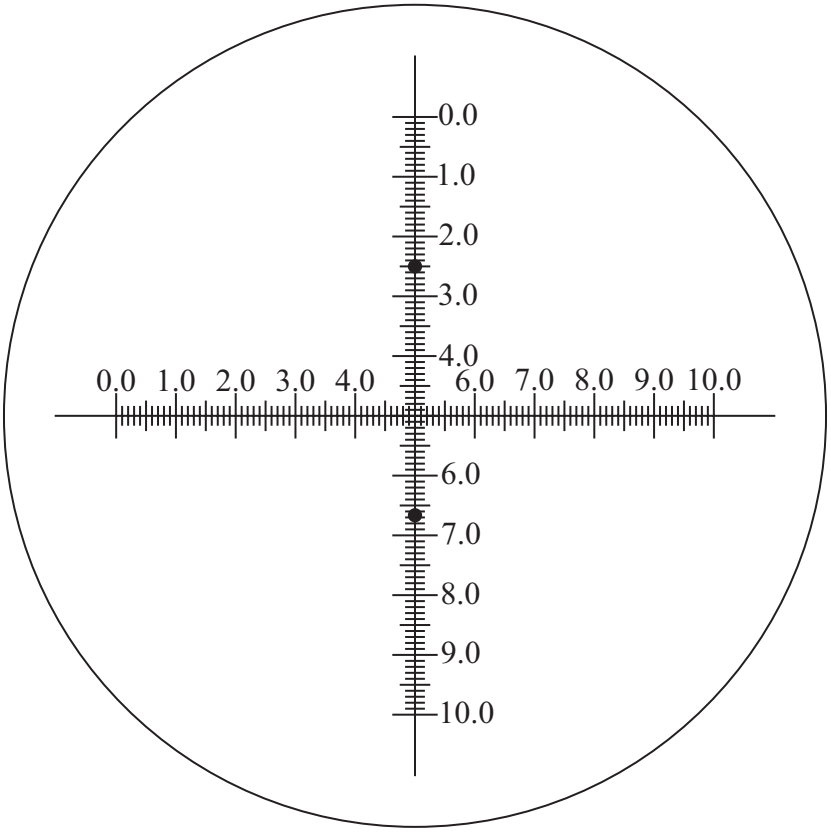
(i) Explain why the student should wait a short while before starting to take measurements.

(2)

The drop initially accelerates, as its weight is not yet balanced by the drag force (and upthrust), so it takes time to reach terminal velocity; measuring at once gives a velocity less than the terminal velocity.

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(ii) The view through the microscope is shown below. The scale is in millimetres.



The position of the oil drop at the start and end of a 120 s time interval is indicated by the black dots.

Determine the terminal velocity of the oil drop.

(3)

Start position = 2.50 mm, end position = 6.65 mm

Displacement = 6.65 mm − 2.50 mm = 4.15 mm

$v = s/t = 4.15 \times 10^{-3}\ m \div 120\ s = 3.46 \times 10^{-5}\ m\ s^{-1}$

Terminal velocity = $3.5 \times 10^{-5}\ m\ s^{-1}$

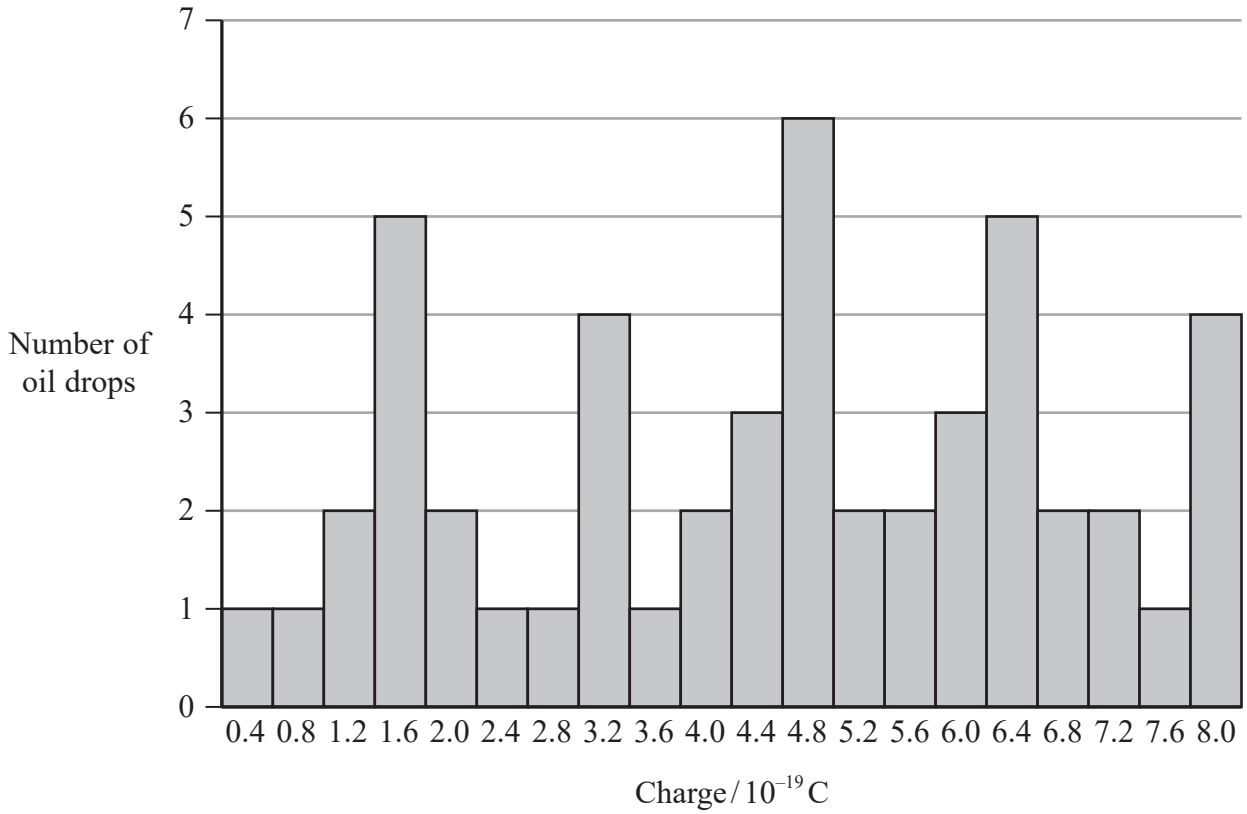
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(c) The student repeated the measurements on fifty oil drops. For each drop the student calculated the charge on the oil drop.

His results are shown in the bar chart.



The student predicted that the charge on each oil drop would be a whole number multiple of the charge on an electron.

Comment on the extent to which the bar chart supports the student's prediction.

(3)

The maxima are at charges of 1.6, 3.2, 4.8 and 6.4 × 10^{-19} C, i.e. e, 2e, 3e and 4e, so 24 drops had a charge that was a whole number multiple of e.

But only 24 out of 50 (48 %) had an integer value: a significant number of drops had non-integer charges.

So the evidence from the bar chart is inconclusive; the spread may be due to experimental uncertainties.

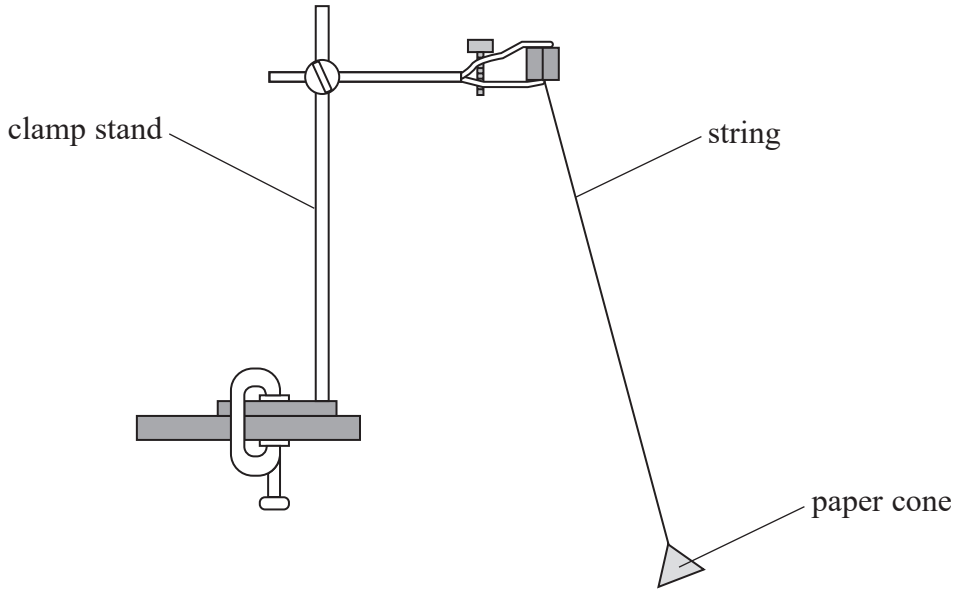
(Total for Question 9 = 15 marks)

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10 A student made a simple pendulum by connecting a paper cone to a piece of string.
She attached the pendulum to a clamp as shown.



(a) (i) The student displaced the pendulum through a small angle so that it oscillated.
She determined the time period T as 2.50 s.

Calculate the length of the pendulum.

(2)

$T = 2\pi\sqrt{(l/g)}$ so $l = gT^2/4\pi^2$

$l = 9.81\ m\ s^{-2} \times (2.50\ s)^2 \div 4\pi^2 = 1.55\ m$

Length of pendulum = 1.55 m

(ii) Explain why the amplitude of oscillation of the pendulum did not stay constant.

(3)

Resistive forces (air resistance on the paper cone) act on the pendulum, so the oscillation is damped.

Work is done against the resistive forces, so energy is transferred from the pendulum to the surroundings.

So the energy of the oscillation decreases and the amplitude decreases.

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(b) The student recorded how the amplitude of oscillation varied over time.

(i) It is suggested that the relationship between amplitude A and time t is

$$A = A_0 e^{-\frac{kt}{T}}$$

where A_0 is the initial amplitude of the oscillation and k is a constant.

Explain why a graph of $\ln A$ against t would give a straight line.

(2)

Taking natural logs: $\ln A = \ln A_0 - (k/T)t$

Compare with $y = c + mx$: the gradient is $-k/T$, which is constant, so the graph is a straight line (intercept $\ln A_0$).

(ii) The table shows the student's data.

t/s	A/cm	ln (A / cm)
2.5	17.6	2.868
5.0	14.3	2.660
7.5	11.6	2.451
10.0	9.4	2.241
12.5	7.6	2.028

Plot a graph of $\ln A$ against t on the grid opposite. Use the additional column to show your processed data.

(5)

(iii) Determine values for A_0 and k.

(4)

Intercept = $\ln A_0 = 3.08$, so $A_0 = e^{3.08} = 21.8$ cm

Gradient (large triangle) = $(2.07 - 3.08) \div (12.0 - 0)$ s = $-0.0842\ s^{-1}$

Gradient = $-k/T$, so $k = 0.0842\ s^{-1} \times 2.50$ s = 0.210

$A_0 =$ 22 cm

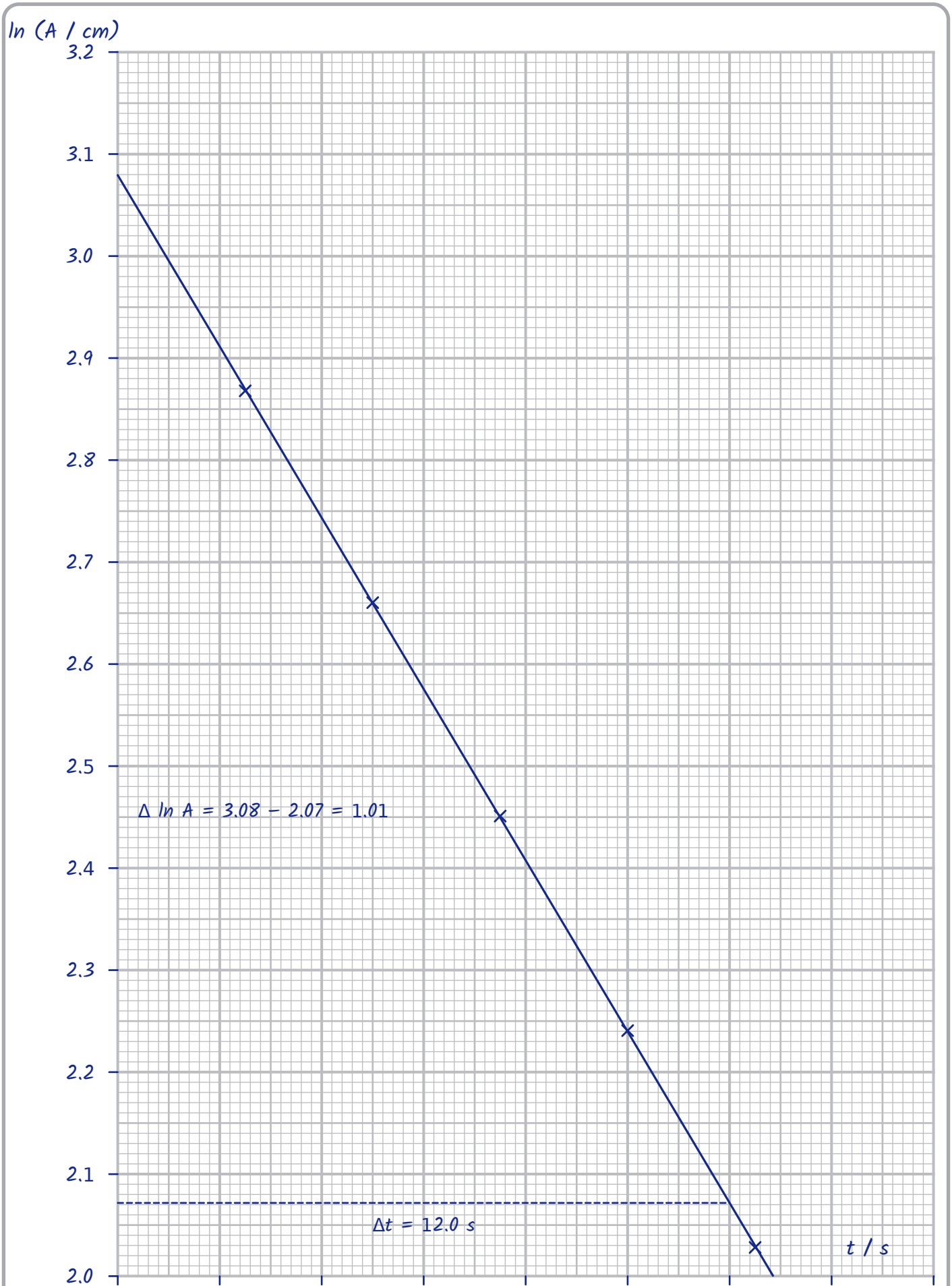
$k =$ 0.21

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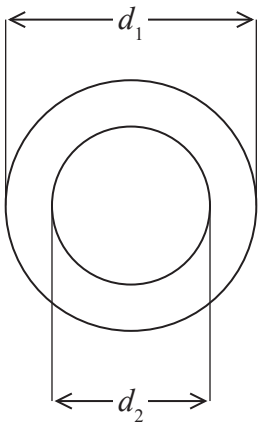
(Total for Question 10 = 16 marks)

11 The photograph shows some metal washers. A student carried out an experiment to determine the density of the metal the washers are made from.



(Source: © NJH Photography/Shutterstock)

Each washer has a diameter d_1 of about 4.5 cm. The internal diameter d_2 of each washer is about 2.5 cm. Each washer has a thickness t of about 4 mm.



(a) The student used a half metre rule to make measurements of a washer.

Comment on the student's choice of measuring instrument.

(3)

The half metre rule has a resolution of 1 mm.

It is not suitable to measure t (about 4 mm), as the percentage uncertainty would be too large (about 25 %).

She should use vernier calipers, which have a resolution of 0.1 mm (or digital calipers, resolution 0.01 mm).

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(b) The student measured t for each of the five washers and then calculated a mean value.

Explain how the student could modify her method to obtain a more accurate mean value for t.

(3)

Stack the five washers together, measure the total thickness of the stack and divide by 5.

This increases the distance being measured.

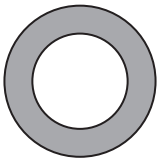
So the percentage uncertainty in t is reduced.

(c) The student obtained the following mean values.

$d_1 = 4.52\,\text{cm} \pm 0.02\,\text{cm}$

$d_2 = 2.53\,\text{cm} \pm 0.02\,\text{cm}$

She calculated the area A of a washer indicated by the shaded section below.



She used the formula $A = \frac{\pi}{4}(d_1 + d_2)(d_1 - d_2)$

(i) Show that the percentage uncertainty in her value for the area of a washer is about 3%.

(4)

Uncertainties add for a sum and a difference: uncertainty in $(d_1 + d_2)$ and in $(d_1 - d_2) = 0.02 + 0.02 = 0.04$ cm

% uncertainty in $(d_1 + d_2) = 0.04$ cm ÷ 7.05 cm × 100 % = 0.57 %

% uncertainty in $(d_1 - d_2) = 0.04$ cm ÷ 1.99 cm × 100 % = 2.0 %

% uncertainties add for a product: % uncertainty in A = 0.57 % + 2.0 % = 2.6 %, which is about 3 %

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(ii) The student obtained the following values of t for each of the five washers.

t/mm	4.3	4.2	4.1	3.9	4.0

The table shows the density of iron and steel.

Metal	Iron	Steel
Density/g cm^{-3}	6.9	7.9

Deduce whether the washers are made from iron or steel.

mean mass of a washer = 32.0 g

The uncertainty in the mass is negligible.

(6)

Mean t = (4.3 + 4.2 + 4.1 + 3.9 + 4.0) mm ÷ 5 = 4.1 mm

Uncertainty in t = half range = (4.3 − 3.9) mm ÷ 2 = 0.2 mm, so % uncertainty in t = 0.2 ÷ 4.1 × 100 % = 4.9 %

$V = A \times t = \pi/4 \times 7.05$ cm × 1.99 cm × 0.41 cm = 4.52 cm^3

$\rho = m/V$ = 32.0 g ÷ 4.52 cm^3 = 7.08 g cm^{-3}

% uncertainty in ρ = 2.6 % + 4.9 % = 7.5 %

Maximum ρ = 1.075 × 7.08 = 7.61 g cm^{-3}; minimum ρ = 0.925 × 7.08 = 6.55 g cm^{-3}

The range 6.6 to 7.6 g cm^{-3} includes iron (6.9 g cm^{-3}) but not steel (7.9 g cm^{-3}), so the washers are made of iron.

(Total for Question 11 = 16 marks)

TOTAL FOR PAPER = 120 MARKS

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List of data, formulae and relationships

Acceleration of free fall	$g = 9.81 \text{ m s}^{-2}$	(close to Earth's surface)
Boltzmann constant	$k = 1.38 \times 10^{-23} \text{ J K}^{-1}$	
Coulomb law constant	$k = \frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^{9} \text{ N m}^2 \text{ C}^{-2}$	
Electron charge	$e = -1.60 \times 10^{-19} \text{ C}$	
Electron mass	$m_e = 9.11 \times 10^{-31} \text{ kg}$	
Electronvolt	$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$	
Gravitational constant	$G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$	
Gravitational field strength	$g = 9.81 \text{ N kg}^{-1}$	(close to Earth's surface)
Permittivity of free space	$\varepsilon_0 = 8.85 \times 10^{-12} \text{ F m}^{-1}$	
Planck constant	$h = 6.63 \times 10^{-34} \text{ J s}$	
Proton mass	$m_p = 1.67 \times 10^{-27} \text{ kg}$	
Speed of light in a vacuum	$c = 3.00 \times 10^{8} \text{ m s}^{-1}$	
Stefan-Boltzmann constant	$\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$	
Unified atomic mass unit	$u = 1.66 \times 10^{-27} \text{ kg}$	

Mechanics

Kinematic equations of motion

$$s = \frac{(u + v)t}{2}$$

$$v = u + at$$

$$s = ut + \tfrac{1}{2}at^2$$

$$v^2 = u^2 + 2as$$

Forces

$$\Sigma F = ma$$

$$g = \frac{F}{m}$$

$$W = mg$$

moment of force $= Fx$

Momentum

$$p = mv$$

Work, energy and power

$$\Delta W = F\Delta s$$

$$E_k = \tfrac{1}{2}mv^2$$

$$\Delta E_{grav} = mg\Delta h$$

$$P = \frac{E}{t}$$

$$P = \frac{W}{t}$$

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

$$\text{efficiency} = \frac{\text{useful power output}}{\text{total power input}}$$

Electric circuits

Potential difference

$$V = \frac{W}{Q}$$

Resistance

$$R = \frac{V}{I}$$

Electrical power and energy

$$P = VI$$

$$P = I^2R$$

$$P = \frac{V^2}{R}$$

$$W = VIt$$

Resistivity

$$R = \frac{\rho l}{A}$$

Current

$$I = \frac{\Delta Q}{\Delta t}$$

$$I = nqvA$$

Materials

Density

$$\rho = \frac{m}{V}$$

Stokes' law

$$F = 6\pi\eta rv$$

Hooke's law

$$\Delta F = k\Delta x$$

Young modulus

$$\text{Stress } \sigma = \frac{F}{A}$$

$$\text{Strain } \varepsilon = \frac{\Delta x}{x}$$

$$E = \frac{\sigma}{\varepsilon}$$

Elastic strain energy

$$\Delta E_{\text{el}} = \tfrac{1}{2}F\Delta x$$

Waves and particle nature of light

Wave speed

$$v = f\lambda$$

Speed of a transverse wave on a string

$$v = \sqrt{\frac{T}{\mu}}$$

Intensity of radiation

$$I = \frac{P}{A}$$

Power of a lens

$$P = \frac{1}{f}$$

$$P = P_1 + P_2 + P_3 + \ldots$$

Thin lens equation

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

Magnification for a lens

$$m = \frac{\text{image height}}{\text{object height}} = \frac{v}{u}$$

Diffraction grating

$$n\lambda = d \sin\theta$$

Refractive index

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$n = \frac{c}{v}$$

Critical angle

$$\sin C = \frac{1}{n}$$

Photon model

$$E = hf$$

Einstein's photoelectric equation

$$hf = \phi + \tfrac{1}{2}mv^2_{\text{max}}$$

de Broglie wavelength

$$\lambda = \frac{h}{p}$$

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Further mechanics

Impulse

$$F\Delta t = \Delta p$$

Kinetic energy of a non-relativistic particle

$$E_k = \frac{p^2}{2m}$$

Motion in a circle

$$v = \omega r$$

$$T = \frac{2\pi}{\omega}$$

$$F = ma = \frac{mv^2}{r}$$

$$a = \frac{v^2}{r}$$

$$a = r\omega^2$$

$$F = mr\omega^2$$

Fields

Coulomb's law

$$F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$$

Electric field strength

$$E = \frac{F}{Q}$$

$$E = \frac{Q}{4\pi\varepsilon_0 r^2}$$

$$E = \frac{V}{d}$$

Electric potential

$$V = \frac{Q}{4\pi\varepsilon_0 r}$$

Capacitance

$$C = \frac{Q}{V}$$

Energy stored in a capacitor

$$W = \tfrac{1}{2}QV$$

$$W = \tfrac{1}{2}CV^2$$

$$W = \tfrac{1}{2}\frac{Q^2}{C}$$

Capacitor discharge

$$Q = Q_0 e^{-t/RC}$$

$$I = I_0 e^{-t/RC}$$

$$V = V_0 e^{-t/RC}$$

$$\ln Q = \ln Q_0 - \frac{t}{RC}$$

$$\ln I = \ln I_0 - \frac{t}{RC}$$

$$\ln V = \ln V_0 - \frac{t}{RC}$$

In a magnetic field

$$F = BIl \sin\theta$$

$$F = Bqv \sin\theta$$

Faraday's and Lenz's laws

$$\mathscr{E} = \frac{-\mathrm{d}(N\phi)}{\mathrm{d}t}$$

Root-mean-square values

$$V_{rms} = \frac{V_0}{\sqrt{2}}$$

$$I_{rms} = \frac{I_0}{\sqrt{2}}$$

Nuclear and particle physics

In a magnetic field

$$r = \frac{p}{BQ}$$

Thermodynamics

Heating

$$\Delta E = mc\Delta\theta$$

$$\Delta E = L\Delta m$$

Molecular kinetic theory

$$\frac{1}{2}m\langle c^2\rangle = \frac{3}{2}kT$$

$$pV = \frac{1}{3}Nm\langle c^2\rangle$$

Ideal gas equation

$$pV = NkT$$

Stefan-Boltzmann law

$$L = \sigma AT^4$$

$$L = 4\pi r^2\sigma T^4$$

Wien's law

$$\lambda_{max}T = 2.898 \times 10^{-3}\ \text{m K}$$

Space

Intensity

$$I = \frac{L}{4\pi d^2}$$

Redshift of electromagnetic radiation

$$z = \frac{\Delta\lambda}{\lambda} \approx \frac{\Delta f}{f} \approx \frac{v}{c}$$

Cosmological expansion

$$v = H_0 d$$

Nuclear radiation

Mass-energy

$$\Delta E = c^2\Delta m$$

Radioactive decay

$$A = \lambda N$$

$$\frac{dN}{dt} = -\lambda N$$

$$\lambda = \frac{\ln 2}{t_{½}}$$

$$N = N_0\, e^{-\lambda t}$$

$$A = A_0\, e^{-\lambda t}$$

Gravitational fields

Gravitational force

$$F = \frac{Gm_1m_2}{r^2}$$

Gravitational field strength

$$g = \frac{Gm}{r^2}$$

Gravitational potential

$$V_{grav} = \frac{-Gm}{r}$$

Oscillations

Simple harmonic motion

$$F = -kx$$

$$a = -\omega^2 x$$

$$x = A\cos\omega t$$

$$v = -A\omega\sin\omega t$$

$$a = -A\omega^2\cos\omega t$$

$$T = \frac{1}{f} = \frac{2\pi}{\omega}$$

$$\omega = 2\pi f$$

Simple harmonic oscillator

$$T = 2\pi\sqrt{\frac{m}{k}}$$

$$T = 2\pi\sqrt{\frac{l}{g}}$$

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