SUPERVISOR'S USE ONLY

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Draw a cross through the box (☒) if you have NOT written in this booklet

Mana Tohu Mātauranga o Aotearoa
New Zealand Qualifications Authority

Scholarship 2024
Physics

Time allowed: Three hours
Total score: 32

Check that the National Student Number (NSN) on your admission slip is the same as the number at the top of this page.

You should answer ALL the questions in this booklet.

For all 'describe' or 'explain' questions, the answers should be written or drawn clearly with all logic fully explained.

For all numerical answers, full working must be shown and the answer must be rounded to the correct number of significant figures and given with the correct SI unit.

Formulae you may find useful are given on page 3.

If you need more room for any answer, use the extra space provided at the back of this booklet.

Check that this booklet has pages 2–24 in the correct order and that none of these pages is blank.

Do not write in any cross-hatched area. This area will be cut off when the booklet is marked.

YOU MUST HAND THIS BOOKLET TO THE SUPERVISOR AT THE END OF THE EXAMINATION.

Question	Score
ONE	
TWO	
THREE	
FOUR	
TOTAL	

ASSESSOR'S USE ONLY

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The assessment starts on page 4.

The formulae below may be of use to you.

$v_f = v_i + at$

$d = v_i t + \frac{1}{2}at^2$

$d = \frac{v_i + v_f}{2}t$

$v_f^{\,2} = v_i^{\,2} + 2ad$

$F_g = \frac{GMm}{r^2}$

$F_c = \frac{mv^2}{r}$

$\Delta p = F\Delta t$

$\omega = 2\pi f$

$d = r\theta$

$v = r\omega$

$a = r\alpha$

$W = Fd$

$F_{net} = ma$

$p = mv$

$x_{COM} = \frac{m_1x_1 + m_2x_2}{m_1 + m_2}$

$\omega = \frac{\Delta\theta}{\Delta t}$

$\alpha = \frac{\Delta\omega}{\Delta t}$

$L = I\omega$

$L = mvr$

$\tau = I\alpha$

$\tau = Fr$

$E_{K(ROT)} = \frac{1}{2}I\omega^2$

$E_{K(LIN)} = \frac{1}{2}mv^2$

$\Delta E_p = mg\Delta h$

$\omega_f = \omega_i + \alpha t$

$\omega_f^2 = \omega_i^2 + 2\alpha\theta$

$\theta = \frac{(\omega_i + \omega_f)}{2}t$

$\theta = \omega_i t + \frac{1}{2}\alpha t^2$

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

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

$E_p = \frac{1}{2}ky^2$

$F = -ky$

$a = -\omega^2 y$

$y = A\sin\omega t$ $\quad y = A\cos\omega t$

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

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

$\Delta E = Vq$

$P = VI$

$V = Ed$

$Q = CV$

$C_T = C_1 + C_2$

$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2}$

$E = \frac{1}{2}QV$

$C = \frac{\varepsilon_o\varepsilon_r A}{d}$

$\tau = RC$

$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$

$R_T = R_1 + R_2$

$V = IR$

$F = BIL$

$V = BvL$

$F = Bqv$

$F = Eq$

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

$\phi = BA$

$\varepsilon = -\frac{\Delta\phi}{\Delta t}$

$\varepsilon = -L\frac{\Delta I}{\Delta t}$

$\frac{N_p}{N_s} = \frac{V_p}{V_s}$

$E = \frac{1}{2}LI^2$

$\tau = \frac{L}{R}$

$I = I_{MAX}\sin\omega t$

$V = V_{MAX}\sin\omega t$

$I_{MAX} = \sqrt{2}\,I_{rms}$

$V_{MAX} = \sqrt{2}\,V_{rms}$

$X_C = \frac{1}{\omega C}$

$X_L = \omega L$

$V = IZ$

$f_0 = \frac{1}{2\pi\sqrt{LC}}$

$v = f\lambda$

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

$n\lambda = \frac{dx}{L}$

$n\lambda = d\sin\theta$

$f' = f\frac{V_W}{V_W \pm V_S}$

$E = hf$

$hf = \phi + E_K$

$E = \Delta mc^2$

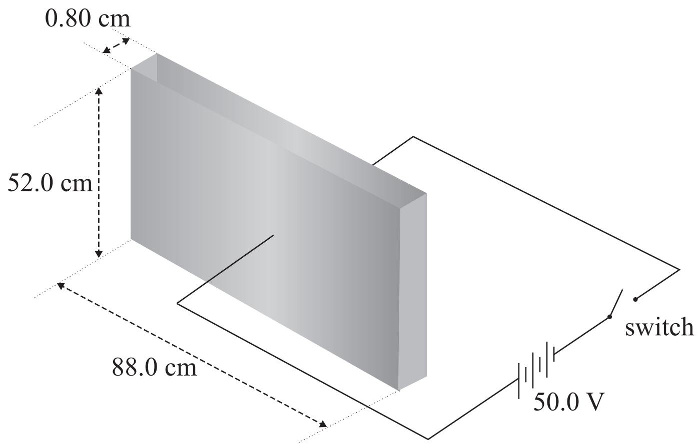
$\frac{1}{\lambda} = R\left(\frac{1}{S^2} - \frac{1}{L^2}\right)$

$E_n = -\frac{hcR}{n^2}$

QUESTION ONE: CAPACITOR TANK

Permittivity of free space = 8.85×10^{-12} F m^{-1}
Relative permittivity of air = 1.0

Hannah uses a rectangular tank, as shown in the diagram, to carry out a series of experiments investigating the behaviour of a parallel plate capacitor. The front and back of the tank are made of conducting metal plates 88.0 cm wide and 52.0 cm high. The sides and bottom of the tank are 0.80 cm wide, and are made of thin, non-conducting plastic.



(a) (i) For her first experiment, Hannah closes the switch to connect the plates to the 50.0 V power supply.

Show that the charge stored on the plates is 2.5×10^{-8} C.

Explain why this value should be stated to two significant figures.

(ii) Explain why the amount of energy stored in the charged capacitor is only half of the total energy provided by the power supply.

(b) The tank can be filled with a non-conducting oil with a relative permittivity of 2.1. No charge is transferred from the plates to the oil. There is a valve in the bottom of the tank that can be opened to drain the oil from the tank.

For her second experiment, Hannah starts with the tank empty, the plates uncharged, and the switch open. She then carries out the following steps in sequence to achieve a potential difference between the plates that is greater than 50.0 V:

Step 1: Close the switch.

Step 2: Fill the tank with oil.

Step 3: Open the switch.

Step 4: Drain the oil from the tank.

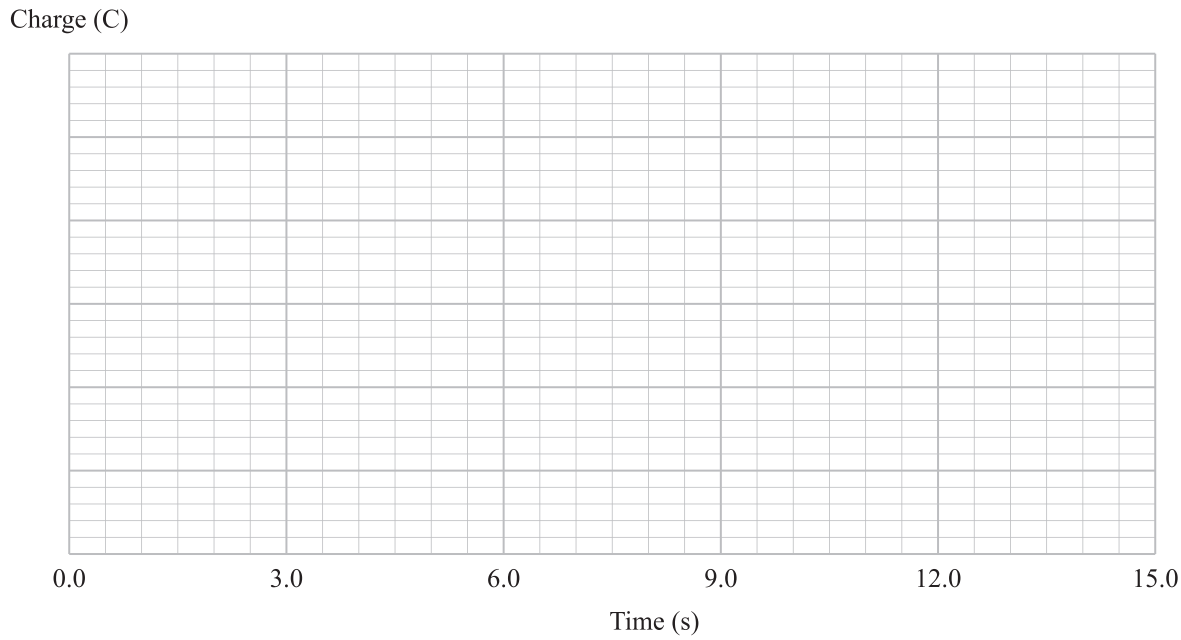
(i) Explain the effect of each of these steps, and how this sequence results in a potential difference that is greater than 50.0 V between the plates.

(ii) Calculate the value of the potential difference between the plates that results from following the sequence of steps described on page 5.

(c) For her third experiment, Hannah fills the tank with oil and closes the switch so that the potential difference across the plates is 50.0 V. At time $t = 0.0$ s, she opens the valve and oil drains from the tank while the switch remains closed. The tank is completely empty after 12.0 s. Assume the oil flows from the tank at a constant rate.

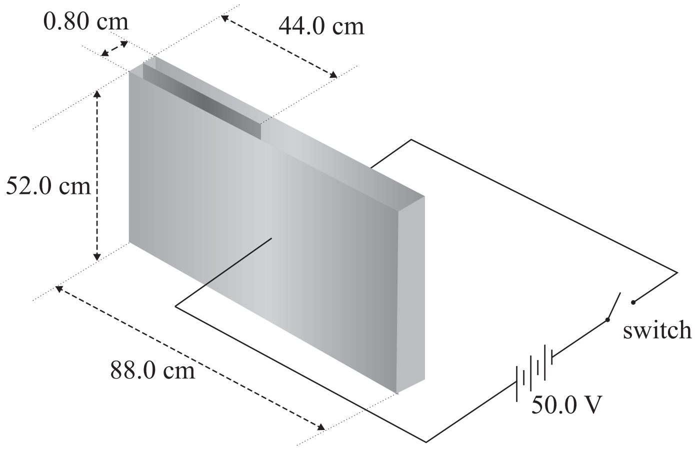
Sketch a graph on the axes below to show how the charge stored on the plates changes over the first 15.0 s.

Indicate key values on the charge axis.

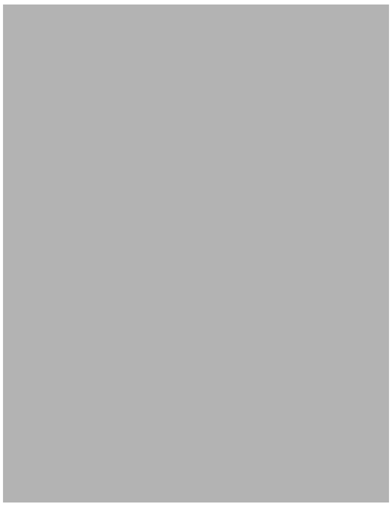


(d) For her last experiment, Hannah now adds a third parallel thin metal plate between the two original plates. The new plate is the same height as the two original plates, but is only half the width, and has negligible thickness.

Using appropriate physics concepts, explain the effect that adding the third plate will have on the total capacitance of the tank.



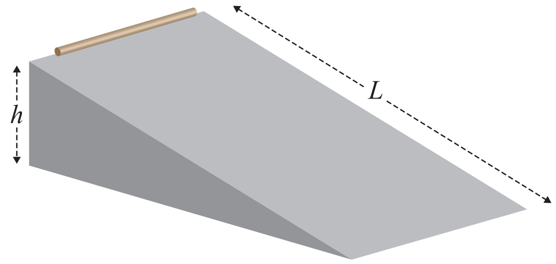
QUESTION TWO: MARTIAL ARTS



Source: www.festival.nz/article/a-window-into-te-ao-m%C4%81ori-the-taiaha/

Several cultures around the world have a history of martial arts using a staff. Some examples include Japanese Bōjutsu, Portuguese Jogo Do Pau, and Māori Mau Rākau.

Ben is practising using a cylindrical staff with mass m and radius r. Ben places the staff on its side at the top of a slope with length L and vertical height h, and releases it from rest. The cylindrical staff rolls freely down the slope without sliding. The rotational inertia I of a solid cylinder about a central axis along its length is $I = \frac{1}{2}mr^2$.



(a) Show that the time, t, taken for the staff to reach the bottom of the slope is given by:

$$t = L\sqrt{\frac{3}{gh}}$$

where g = the acceleration due to gravity.

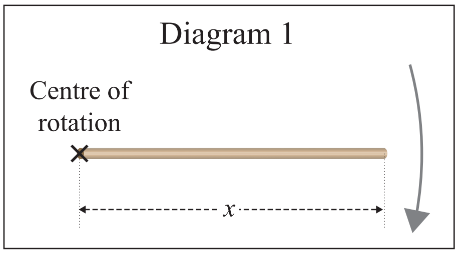
(b) By referring to relevant physics principles, discuss the validity of these two statements:

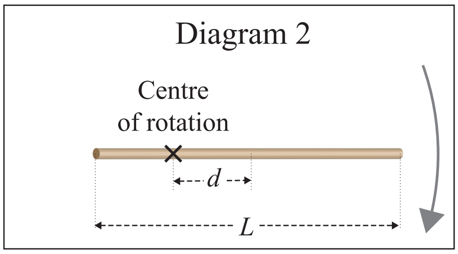
(i) **Statement 1**: For an object with fixed mass to have linear acceleration, it must experience a non-zero net force.

(ii) **Statement 2**: For an object with fixed mass to have angular acceleration, it must experience a non-zero net torque.

(c) For a uniform thin rod with total length x and mass m rotating about one end, as shown in Diagram 1, the rotational inertia I is given by $I = \frac{1}{3}mx^2$.

While performing a sideways strike, a staff can be modelled as a thin, uniform rod rotating about a vertical axis through the centre of rotation, which is in a fixed position. The centre of rotation is closer to one end of the rod than the other, as shown in Diagram 2. The rotational inertia of a thin, uniform rod rotating about an axis part way along the rod can be found by adding the rotational inertias of the sections of the rod either side of the centre of rotation.

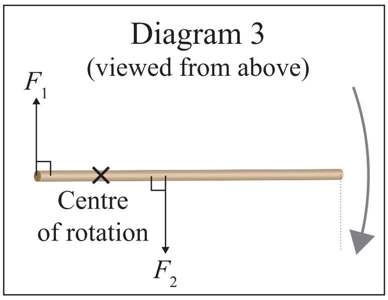




Show that the rotational inertia of a thin, uniform rod of length L and mass m rotating about a point a distance d from the centre of mass is given by:

$$I = m\left(\frac{L^2}{12} + d^2\right)$$

(d) Ben makes the staff rotate around a vertical axis by applying two horizontal forces F_1 and F_2, one with each hand. These forces push the ends of the staff in opposite directions, as shown in Diagram 3 (viewed from above). The forces F_1 and F_2 produce a net torque that gives the staff an angular acceleration about the centre of rotation. The forces F_1 and F_2 are spaced equally from the centre of rotation and are applied perpendicular to the staff's length. The centre of rotation stays in the same position.



(i) Discuss the relative sizes of the forces F_1 and F_2 needed to cause the staff to have an angular acceleration while the centre of rotation does not move.

(ii) A sideways strike can be blocked by holding a second staff vertically in front of the rotating staff.

Explain the position and direction that the blocking force should be applied to stop the rotating staff most effectively.

Explain the effect this blocking force has on the motion of the rotating staff.

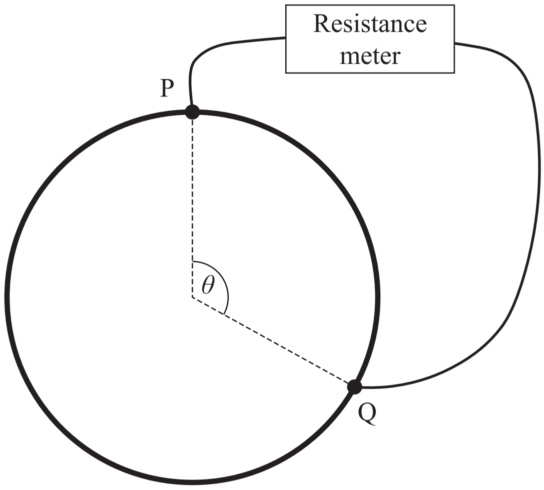
Source: www.reddit.com/r/martialarts/comments/13cdmpy/mau_rakau_and_wharetutaua/?rdt=43199

QUESTION THREE: LOOPS AND RINGS

Acceleration due to gravity = 9.81 m s^{-2}

A long, straight piece of thin resistive wire has a total resistance R between one end and the other. The piece of wire is now bent into a circular shape and the ends are connected together to make a single circular loop.

A resistance meter is connected between two points on the loop, P and Q, which are separated by an angle θ around the loop as shown.



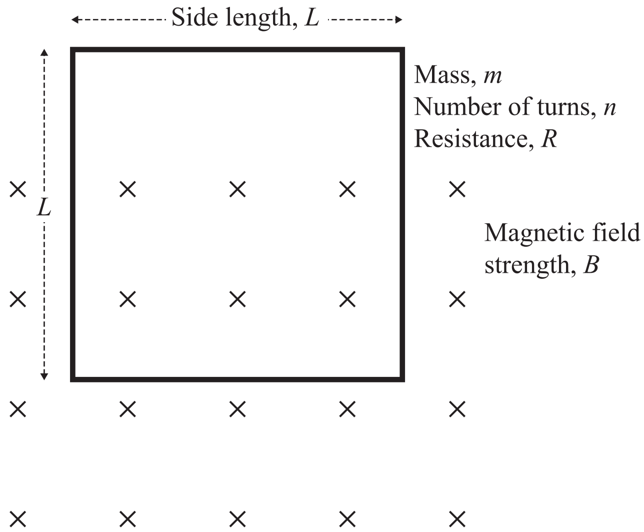
Point P remains fixed at the top of the loop, but point Q can be moved to any point around the edge of the loop.

(a) By considering the resistance of the two sections of the circular loop (clockwise from P to Q, and anticlockwise from P to Q), show that R_{PQ}, the total resistance of the loop between the points P and Q, is given by the expression:

$$R_{PQ} = \frac{R\theta}{2\pi}\left(1 - \frac{\theta}{2\pi}\right)$$

(b) Explain, using physics concepts, where point Q should be placed to give the largest value of R_{PQ}, and determine the maximum value of R_{PQ} for a length of wire with resistance $R = 10\ \Omega$.

(c) A square coil of wire with mass, m, resistance, R, and number of turns, n, falls freely into a uniform magnetic field as shown. The effects of air resistance can be ignored.



(i) By considering the forces acting on the coil, show that the terminal velocity of the coil as it falls into the field is given by:

$$v = \frac{mgR}{B^2 L^2 n^2}$$

(ii) By choosing realistic values for m, n, and L, estimate the terminal velocity of a small coil with resistance $R = 1.0\ \Omega$ as it falls into a magnetic field of strength $B = 1.0 \times 10^{-3}$ T.

Discuss the motion of your coil as it enters the field.

(d) A square coil is unwound, and the same piece of wire is used to make a second square coil with sides twice as long as the original coil.

Use physics concepts to explain how the terminal velocity of the new coil compares to that of the initial coil when dropped into the same magnetic field.

QUESTION FOUR: LASER COOLING

Planck's constant = 6.63×10^{-34} J s
Mass of a sodium atom = 3.82×10^{-26} kg
Speed of light = 3.00×10^{8} m s^{-1}

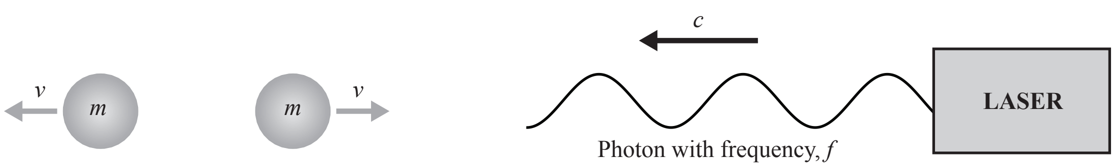
Physicists use lasers to transfer momentum and slow down gaseous atoms. This can cool a gas down to temperatures close to absolute zero.

The momentum of a photon is related to its wavelength by the relationship:

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

A laser of frequency, f, is shone into a container holding gaseous sodium atoms. The energy of each photon is slightly less than the difference in energy between two electron energy levels in a sodium atom.

Gaseous sodium atoms can be moving in any direction, but for the purposes of Question Four, we will only consider one-dimensional motion – either towards or away from the laser.



(a) Explain which sodium atom, the one moving towards the laser or the one moving away from the laser, can absorb a photon from the laser.

(b) Explain how the momentum of each of the sodium atoms, the one moving towards the laser and the one moving away from the laser, may be affected by the photon.

(c) For an observer moving at speed v, where v is much less than the speed of light, the apparent change in frequency Δf of an electromagnetic wave of frequency f, due to the Doppler effect, can be approximated by:

$$\Delta f = \frac{fv}{c}$$

A transition between energy levels in a sodium atom occurs when a photon with wavelength 5.89×10^{-7} m is absorbed. The average speed of a gaseous sodium atom at room temperature is 5.70×10^{2} m s^{-1}.

Calculate the percentage change in momentum of a sodium atom caused by the absorption of a photon with wavelength 5.89×10^{-7} m.

Question Four continues on the following page.

(d) Despite being used for slowing atoms down, this process can sometimes result in an atom moving faster than it was originally. After absorbing a photon, the sodium atom can then emit a photon when the electron drops back down to its original energy level. The emitted photon can be emitted in any direction.

Explain how this process can result in the atom moving faster than its original speed if the photon is emitted in the same direction the original photon was travelling (away from the laser).

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