GIOPHYSICS ORIGINAL EXAMINATION SERIES

AP Physics

Mock examination pack

Two complete original papers with supplied-data graphs, generous working space, and a detailed teacher marking guide.

PAPERS	QUESTIONS	MARKS	TEACHER KEY
2	**20**	**261**	**Included**

INSIDE THIS PACK

PAPER 1

AP Physics · Extended Paper 1

170 minutes | 10 questions | 125 marks

A balanced original practice paper with long-form reasoning, calculations, and supplied-data graphs.

PAPER 2

AP Physics · Extended Paper 2

185 minutes | 10 questions | 136 marks

A balanced original practice paper with long-form reasoning, calculations, and supplied-data graphs.

Original practice - clearly independent

Every question and solution was independently written by GioPhysics. This pack is not an awarding-body document and does not reproduce a released examination question or mark scheme.

AP Physics · Extended Paper 1

A balanced original practice paper with long-form reasoning, calculations, and supplied-data graphs.

CANDIDATE NAME			
CLASS / GROUP		DATE	

PAPER	TIME	QUESTIONS	TOTAL MARKS
1	**170 min**	**10**	**125**

INSTRUCTIONS

- Answer every free-response question in the space provided.
- Show the physics principles and mathematical steps that support each claim.
- Label diagrams and explain how experimental evidence would test a model.
- Answer in the spaces provided and label any additional pages clearly.

INFORMATION

- The total mark for this paper is 125.
- Marks for each task are shown in brackets.
- The detailed marking guide begins after Paper 2.

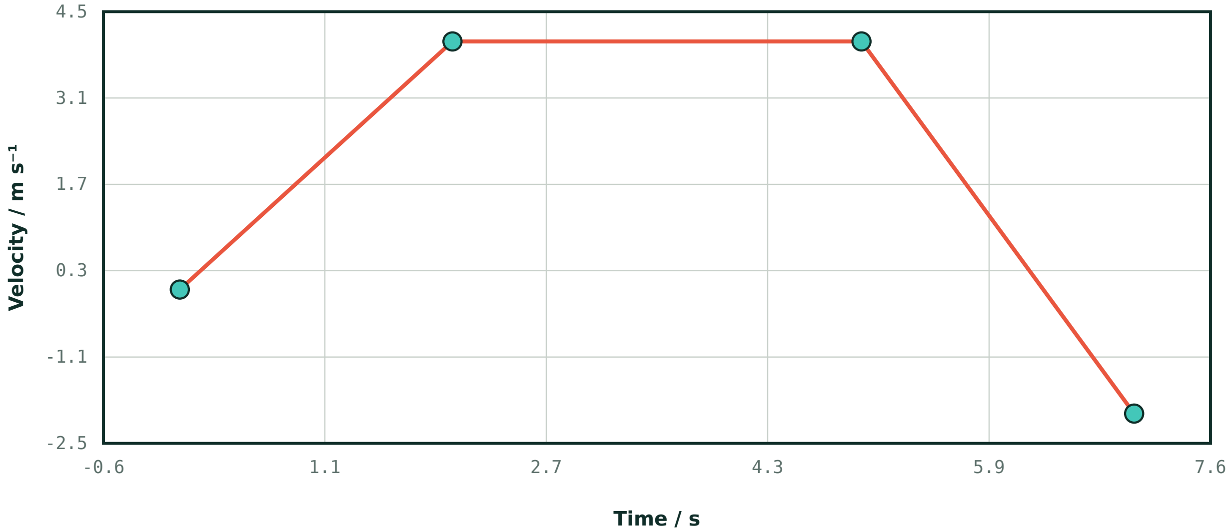
Reconstruct a journey from a velocity graph

[12]

A cart moves along a straight track. Its measured velocity-time coordinates are (0 s, 0 m s⁻¹), (2 s, 4 m s⁻¹), (5 s, 4 m s⁻¹), and (7 s, -2 m s⁻¹); adjacent points are joined by straight lines. Determine the acceleration on each interval, the displacement and total distance from 0 to 7 s, and the time at which the cart reverses. Sketch how the position graph must curve and identify an experimental limitation of estimating velocity by frame-to-frame video differences.

Measured velocity of the cart

Four measured coordinates from the prompt joined by straight segments; the vertical-axis zero crossing is part of the supplied evidence.



ANSWER SPACE

Collision followed by spring compression

[13]

A 0.200 kg clay block moving at 6.00 m s^{-1} strikes and sticks to a stationary 0.800 kg cart on a level low-friction track. The combined object then compresses a spring of constant 180 N m^{-1} until momentarily at rest. Find the speed just after collision, the mechanical energy lost during impact, and the maximum compression. Explain why momentum is used during impact but mechanical energy is used during compression, and propose a measurement that tests the spring model.

ANSWER SPACE

Energy and timing in a spring oscillator

[11]

A 0.400 kg cart attached to a horizontal spring of constant 64.0 N m^{-1} oscillates with amplitude 0.0800 m on a low-friction track. Find the angular frequency, period, total energy, and speed when $x = 0.0500$ m. Starting at $x = +A$ at $t = 0$, determine the first time the cart reaches $x = 0.0500$ m. Describe how modest damping would change the position-time graph without changing the equilibrium position.

ANSWER SPACE

Field, potential and work between two charges

[12]

A +3.00 μC point charge is fixed at x = 0 and a -1.00 μC charge at x = 0.400 m. At the midpoint x = 0.200 m, calculate the net electric field and electric potential. Find the external work required to bring a +2.00 nC test charge slowly from infinity to the midpoint. State the initial direction of its acceleration if released, and explain why zero potential would not necessarily imply zero field.

ANSWER SPACE

Select and bend a proton beam

[12]

Protons travel right through crossed fields: $E = 8.00 \times 10^5$ V m^{-1} upward and $B = 0.200$ T out of the page. The undeflected beam then enters a region containing only the same magnetic field. Determine the selected speed, force directions in the selector, circular radius, orbital period, and whether doubling speed changes the period. Use proton mass 1.67×10^{-27} kg and charge 1.602×10^{-19} C.

ANSWER SPACE

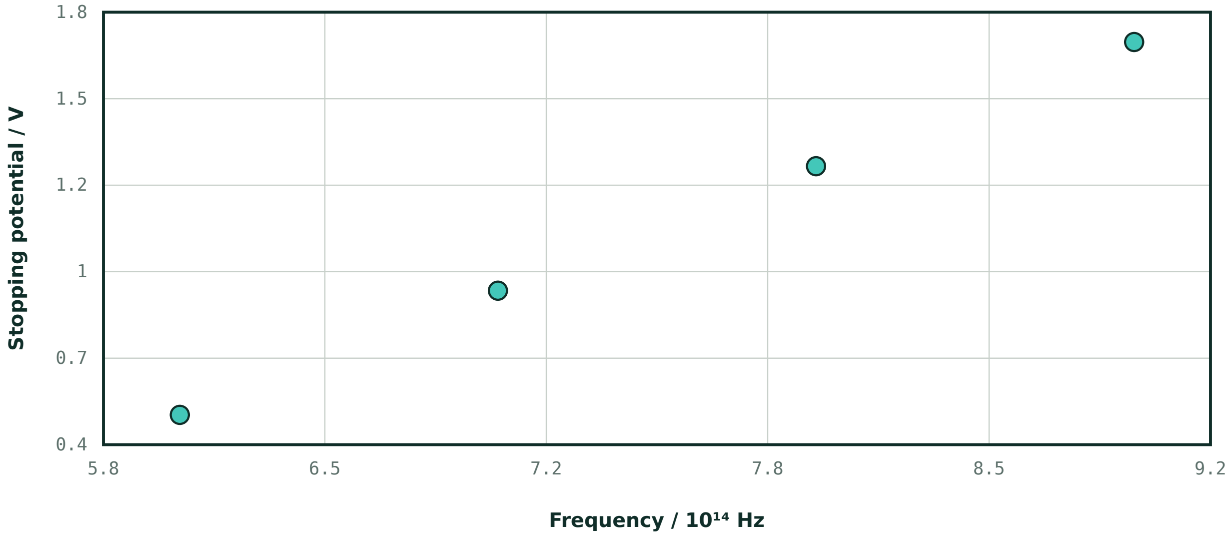
Determine Planck's constant from stopping voltage

[14]

A metal is illuminated at several frequencies. Measured (frequency in 10^{14} Hz, stopping potential in V) pairs are (6.0, 0.482), (7.0, 0.895), (8.0, 1.309), and (9.0, 1.722). Treat the best-fit line through the rounded data as having gradient 0.4135 V per 10^{14} Hz and intercept -2.00 V. Determine Planck's constant, work function and threshold frequency. Predict the effects of doubling intensity above threshold, and explain why classical wave theory fails here. Use $e = 1.602 \times 10^{-19}$ C.

Stopping-potential observations

The four measurements from the prompt are shown without a fitted line so the gradient and intercept remain part of the analysis.



ANSWER SPACE

Integrate a position-dependent force

[11]

A 2.00 kg particle moves along +x with speed 1.00 m s^{-1} at x = 0. From x = 0 to x = 3.00 m the net force is $F(x) = 12x - 3x^2$ newtons, with x in metres. Determine the work, final speed, position and value of the maximum force, and the impulse during the motion if the travel time is 1.20 s and the final velocity remains positive. Explain why the impulse cannot be found from the area under F(x) without time information.

ANSWER SPACE

An Atwood machine with pulley inertia

[14]

Masses $m_1 = 3.00$ kg and $m_2 = 2.00$ kg are joined by a light non-slip cord over a uniform-disk pulley of mass 1.00 kg and radius 0.200 m. The axle is frictionless and the system is released from rest. Determine the acceleration, both cord tensions and pulley angular acceleration. After the heavier mass falls 0.800 m, find its speed using energy and show consistency with constant-acceleration kinematics.

ANSWER SPACE

Compare connected and isolated dielectric insertion

[14]

A 6.00 μF parallel-plate capacitor is charged to 12.0 V. A dielectric of constant $\kappa = 3.00$ completely fills the gap. Compare two cases: A, the battery is disconnected before insertion; B, the ideal 12.0 V battery remains connected. For each case find final capacitance, charge, voltage and stored energy. Determine the external work in case A for quasistatic insertion and explain the direction of the dielectric force.

ANSWER SPACE

Mechanical power and motional emf

[12]

A conducting rod of length 0.500 m slides right at constant 4.00 m s^{-1} on horizontal rails in a uniform 0.800 T magnetic field into the page. The total circuit resistance is 2.00 Ω. Determine the motional emf, current magnitude and direction, magnetic force on the rod, external force required, and mechanical power. Verify power conservation and explain what changes if the rod speed doubles.

ANSWER SPACE

AP Physics · Extended Paper 2

A balanced original practice paper with long-form reasoning, calculations, and supplied-data graphs.

CANDIDATE NAME			
CLASS / GROUP		**DATE**	

PAPER	TIME	QUESTIONS	TOTAL MARKS
2	**185 min**	**10**	**136**

INSTRUCTIONS

- Answer every free-response question in the space provided.
- Show the physics principles and mathematical steps that support each claim.
- Label diagrams and explain how experimental evidence would test a model.
- Answer in the spaces provided and label any additional pages clearly.

INFORMATION

- The total mark for this paper is 136.
- Marks for each task are shown in brackets.
- The detailed marking guide begins after Paper 2.

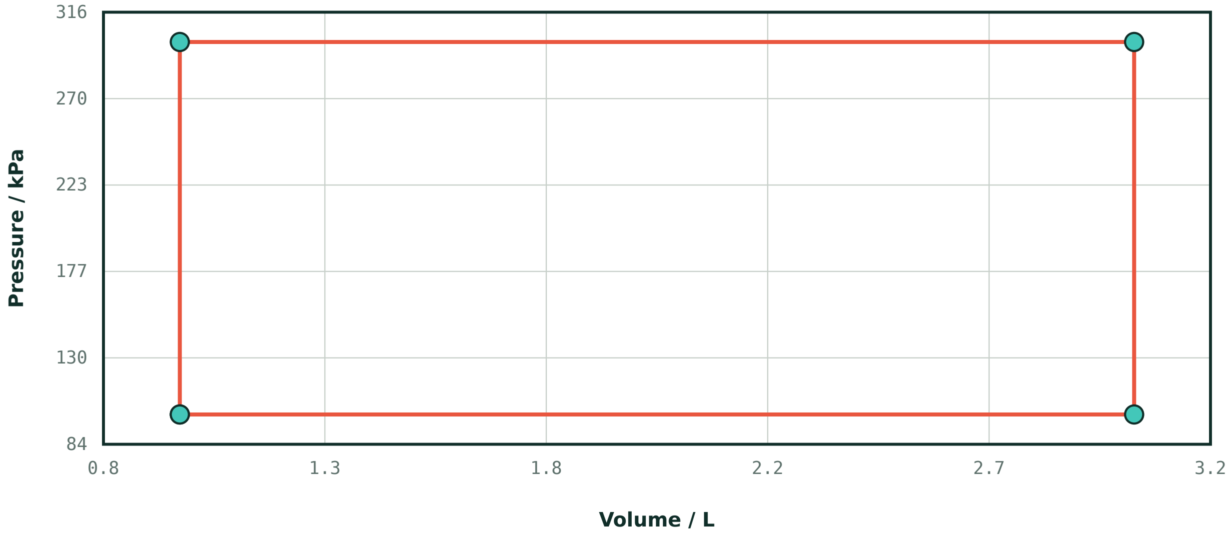
Energy accounting for a cyclic heat engine

[14]

An ideal gas follows the clockwise rectangular cycle A(1.0 L, 100 kPa) → B(1.0 L, 300 kPa) → C(3.0 L, 300 kPa) → D(3.0 L, 100 kPa) → A. During B→C it absorbs 900 J, during D→A it rejects 300 J, during A→B it absorbs 100 J and during C→D it rejects 300 J. Use 1 kPa·L = 1 J. Determine the work on every leg, net work, changes in internal energy on B→C and D→A, total heat over the cycle, and efficiency. Explain the clockwise sign.

Specified pressure-volume cycle

The four vertices and closing point supplied in the prompt are joined in order; area and direction must be interpreted by the student.



ANSWER SPACE

Rolling dynamics down an incline

[12]

A uniform solid cylinder of mass 2.00 kg rolls without slipping down a 25.0° incline through a vertical drop of 1.20 m. Its moment of inertia is $I = \frac{1}{2}mR^2$. Determine its translational acceleration, the static-friction magnitude and direction, and its speed after the drop. Explain why static friction does no mechanical work in the ideal rolling model and compare the speed with that of a frictionless sliding block.

ANSWER SPACE

Design and diagnose a Venturi flow meter

[13]

Water of density 1000 kg m^{-3} flows steadily through a horizontal pipe whose area narrows from 8.00×10^{-4} m^2 to 4.00×10^{-4} m^2. The upstream speed is 1.50 m s^{-1} and pressure is 180 kPa. Model the flow as incompressible and non-viscous. Determine the volume flow rate, narrow-section speed and pressure. Then explain how a real pressure reading affected by viscosity would change the inferred flow rate, and outline a calibration procedure.

ANSWER SPACE

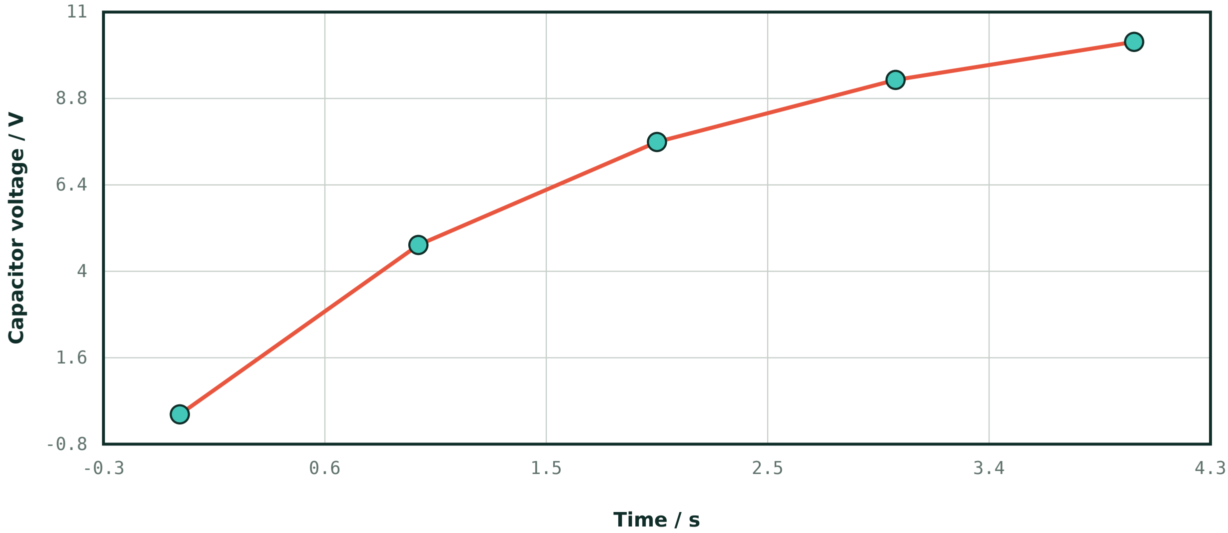
Extract an RC time constant from charging data

[14]

A 220 µF capacitor charges through an unknown resistor from a 12.0 V ideal supply. Recorded (time in s, capacitor voltage in V) pairs are (0, 0), (1, 4.72), (2, 7.59), (3, 9.32), and (4, 10.38). Determine the time constant and resistance, the charge at 4.0 s, and the current at 2.0 s. Explain a linearized graph that could test the exponential model and how voltmeter input resistance could bias the result.

Capacitor charging observations

Measured capacitor voltage values listed in the prompt; a smooth curve is shown only to connect sequential measurements.



ANSWER SPACE

Image formation and an experimental focal length

[12]

A 2.00 cm object is 18.0 cm in front of a thin converging lens of focal length 12.0 cm. Determine the image location, magnification, image height and whether the image can be projected. The lens is then used in a classroom experiment with several object distances. Describe a graph that determines focal length without relying on a single trial, and identify two alignment controls.

ANSWER SPACE

Classify equilibria in a quartic potential

[15]

A 0.500 kg particle moves in one dimension with potential $U(x) = ax^4 - bx^2$, where $a = 20.0$ J m^{-4} and $b = 4.00$ J m^{-2}. Determine all equilibrium positions and classify their stability. Find the small-oscillation angular frequency about either stable equilibrium, the barrier energy relative to a minimum, and the turning points for total energy $E = -0.100$ J. Explain why a particle with $E = -0.100$ J cannot cross from one well to the other.

ANSWER SPACE

Escape from a circular orbit

[13]

A spacecraft is in a circular orbit at radius $r = 2R_E$ from Earth's centre. Use $GM_E = 3.986 \times 10^{14}$ m^3 s^{-2} and $R_E = 6.37 \times 10^6$ m. Find its circular speed, orbital period and specific mechanical energy. Determine the local escape speed and the minimum instantaneous tangential speed increase that places it on a zero-energy escape trajectory. Explain why the engine energy per kilogram is not simply $\frac{1}{2}(\Delta v)^2$.

ANSWER SPACE

Field and potential of a charged solid cylinder

[15]

A very long nonconducting solid cylinder of radius $R = 0.0200$ m has uniform volume charge density $\rho = 4.00 \times 10^{-6}$ C m^{-3}. Neglect end effects. Derive $E(r)$ for $r < R$ and $r > R$, then calculate E at $r = 0.0100$ m and $r = 0.0400$ m. Find $V(0) - V(R)$, and sketch the qualitative E-r graph through $r = 2R$. Use $\varepsilon_0 = 8.854 \times 10^{-12}$ F m^{-1}.

ANSWER SPACE

Current growth in an LR circuit

[12]

An ideal 9.00 V battery, 15.0 Ω resistor and 0.300 H inductor are connected in series at $t = 0$. The inductor initially carries no current. Determine the time constant, initial current gradient, current and inductor voltage at $t = 0.0400$ s, and magnetic energy then. Explain the inductor voltage immediately after closing and long afterward, and describe one safe way to observe the transient.

ANSWER SPACE

Derive the field on the axis of a charged ring

[16]

A thin ring of radius $R = 0.100$ m carries total uniform charge $Q = +4.00$ nC. A field point lies on its axis $x = 0.0500$ m from the centre. Starting from Coulomb's law, derive the axial electric field and calculate its magnitude and the potential there, taking $V = 0$ at infinity. Show the $x \ll R$ approximation, compare it numerically here, and explain why the transverse field components cancel.

ANSWER SPACE

TEACHER COPY

Detailed marking guide

AP Physics

How to use this guide

Award credit for equivalent correct physics expressed clearly. The numbered solution stages show a complete route, not the only valid route. Use the stated common mistake as feedback rather than as a penalty beyond the lost physics marks.

PAPERS	QUESTIONS	TOTAL MARKS
2	**20**	**261**

This guide is original GioPhysics material. It is not an official awarding-body mark scheme and must not be used to predict a grade boundary.

Reconstruct a journey from a velocity graph

[12]

EXPECTED CONCLUSION

Accelerations: +2.0, 0 and -3.0 m s^{-2}. Displacement = 18.0 m; distance = 19.3 m; reversal at 6.33 s. Position rises with changing gradient, becomes linear, reaches a maximum at reversal, then falls.

REASONING AND MARKING CHECKPOINTS

01

Acceleration is the velocity-time gradient. The three gradients are (4-0)/(2-0) = 2.0 m s^{-2}, zero, and (-2-4)/(7-5) = -3.0 m s^{-2}.

02

Displacement is signed area. The first triangle contributes 4 m, the rectangle contributes 12 m, and the final trapezium contributes (4 + -2)(2)/2 = 2 m, giving 18 m.

03

On the final line v = 4 - 3(t-5). Setting v = 0 gives t = 6.33 s. Splitting that interval at the crossing gives 2.67 m forward and 0.67 m backward.

04

Total distance is therefore 4 + 12 + 2.67 + 0.67 = 19.3 m. Distance exceeds the magnitude of displacement because the cart travels backward after the turning instant.

05

The position graph's gradient equals velocity: it steepens initially, is straight from 2-5 s, flattens to a maximum at 6.33 s, then slopes downward. Finite video frame spacing averages velocity and can blur rapid acceleration; scale calibration and parallax also matter.

COMMON MISTAKE

Adding signed graph areas when asked for total distance, so the backward portion is incorrectly subtracted instead of counted as travelled length.

Collision followed by spring compression

[13]

EXPECTED CONCLUSION

The combined speed is 1.20 m s^{-1}, collision energy loss is 2.88 J, and maximum compression is 0.0894 m. Momentum is approximately conserved over the short collision; post-collision kinetic energy becomes spring energy afterward.

REASONING AND MARKING CHECKPOINTS

01

During the brief collision, the spring has not yet compressed appreciably and external horizontal impulse is negligible. Momentum conservation gives (0.200)(6.00) = (1.000)v, hence v = 1.20 m s^{-1}.

02

Initial kinetic energy is $\frac{1}{2}(0.200)(6.00)^2 = 3.60$ J. Immediately after impact it is $\frac{1}{2}(1.000)(1.20)^2 = 0.720$ J.

03

The collision is perfectly inelastic, so the lost mechanical energy is 3.60 - 0.720 = 2.88 J. It becomes deformation, thermal energy and sound rather than disappearing.

04

After impact, negligible track losses let 0.720 J convert into elastic energy: $\frac{1}{2}kx^2 = 0.720$. Thus $x = \sqrt{(1.44/180)} = 0.0894$ m.

05

Measure force against compression slowly with a calibrated force sensor. A straight F-x graph through the origin supports constant k; the area beneath that graph should match the stored energy used here.

COMMON MISTAKE

Conserving kinetic energy through the sticking collision, which predicts too much post-impact speed and therefore too large a spring compression.

Energy and timing in a spring oscillator

[11]

EXPECTED CONCLUSION

ω = 12.6 rad s^{-1}, T = 0.497 s, E = 0.2048 J, v = 0.790 m s^{-1}, and the first arrival is at 0.0709 s. Damping produces a decaying envelope and slightly longer period.

REASONING AND MARKING CHECKPOINTS

01

For an ideal mass-spring oscillator, $\omega = \sqrt{k/m} = \sqrt{64.0/0.400}$ = 12.65 rad s^{-1} and $T = 2\pi/\omega$ = 0.497 s.

02

At a turning point all energy is elastic, so $E = \frac{1}{2}kA^2 = \frac{1}{2}(64.0)(0.0800)^2$ = 0.2048 J.

03

Energy conservation at x gives $\frac{1}{2}mv^2 = \frac{1}{2}k(A^2-x^2)$. Thus $v = \omega\sqrt{A^2-x^2}$ = 0.790 m s^{-1}; the first passage is toward negative x.

04

With $x = A\cos\omega t$, $\cos\omega t$ = 0.0500/0.0800 = 0.625. Therefore $t = \cos^{-1}(0.625)/12.65$ = 0.0709 s.

05

Damping removes energy each cycle, so successive extrema lie inside a decreasing envelope. The oscillation becomes slightly slower for modest damping, while the fixed spring's force still vanishes at the same equilibrium location.

COMMON MISTAKE

Using x rather than amplitude A to calculate the total energy, which confuses instantaneous elastic energy with the oscillator's constant total energy.

Field, potential and work between two charges

[12]

EXPECTED CONCLUSION

$E = 8.99 \times 10^5$ N C^{-1} to +x; $V = 8.99 \times 10^4$ V; external work = 1.80×10^{-4} J; a positive test charge accelerates toward +x.

REASONING AND MARKING CHECKPOINTS

01

At the midpoint, the positive source repels a positive test charge to the right. The negative source attracts it to the right, so the two field magnitudes add rather than subtract.

02

$E = k(3.00 \times 10^{-6} + 1.00 \times 10^{-6})/(0.200)^2 = 8.99 \times 10^5$ N C^{-1} in the +x direction.

03

Potential is scalar and includes charge signs: $V = k[(3.00 \times 10^{-6})/0.200 - (1.00 \times 10^{-6})/0.200] = 8.99 \times 10^4$ V.

04

Slow transfer changes electric potential energy by qV, so the external work is $(2.00 \times 10^{-9})(8.99 \times 10^4) = 1.80 \times 10^{-4}$ J.

05

The released positive charge accelerates with E toward +x. Potential can cancel algebraically at a point while field vectors do not; field depends on the spatial gradient of potential, not simply its value.

COMMON MISTAKE

Subtracting the electric-field magnitudes because the source charges have opposite signs, even though both field vectors point right at the midpoint.

Select and bend a proton beam

[12]

EXPECTED CONCLUSION

$v = 4.00 \times 10^6$ m s^{-1}; electric force upward and magnetic force downward; $r = 0.209$ m; $T = 3.28 \times 10^{-7}$ s. Doubling speed doubles radius but not period.

REASONING AND MARKING CHECKPOINTS

01

For a positive proton, electric force follows E and points upward. With velocity right and B out of the page, $v \times B$ points downward, so magnetic force can cancel it.

02

Undeflected motion requires $qE = qvB$. Charge cancels, giving $v = E/B = (8.00 \times 10^5)/0.200 = 4.00 \times 10^6$ m s^{-1}.

03

In the magnetic-only region, qvB supplies centripetal force: $qvB = mv^2/r$. Thus $r = mv/(qB) = 0.209$ m.

04

The period is circumference divided by speed: $T = 2\pi r/v = 2\pi m/(qB) = 3.28 \times 10^{-7}$ s.

05

Doubling v doubles r because magnetic force scales with v while required centripetal force scales with v^2/r. The ratio r/v and therefore the non-relativistic period remain unchanged.

COMMON MISTAKE

Using $qE + qvB = 0$ without first establishing the vector directions, which often produces an unexplained negative speed or reverses the selector fields.

Determine Planck's constant from stopping voltage

[14]

EXPECTED CONCLUSION

$h = 6.62 \times 10^{-34}$ J s, work function = 2.00 eV, threshold frequency = 4.84×10^{14} Hz. Doubling intensity doubles photocurrent under unsaturated collection but does not change stopping voltage.

REASONING AND MARKING CHECKPOINTS

01 Einstein's equation $hf = \Phi + K_{max}$ and $eV_s = K_{max}$ combine to $V_s = (h/e)f - \Phi/e$.

02 Because the horizontal axis unit is 10^{14} Hz, $h/e = 0.4135/(10^{14})$ V s. Therefore $h = e(4.135 \times 10^{-15}) = 6.62 \times 10^{-34}$ J s.

03 The vertical intercept is $-\Phi/e = -2.00$ V. Hence $\Phi = 2.00$ eV $= 3.204 \times 10^{-19}$ J.

04 At threshold $V_s = 0$, so $f_0 = \Phi/h$, equivalently $2.00/(4.135 \times 10^{-15}) = 4.84 \times 10^{14}$ Hz.

05 Greater intensity means more photons per second, so unsaturated photocurrent doubles, but each photon retains energy hf and the stopping potential is unchanged. Classical intensity-based energy transfer cannot explain an immediate threshold frequency or intensity-independent maximum electron energy.

COMMON MISTAKE

Reading the displayed gradient as 0.4135 V Hz^{-1} and missing the 10^{14} scale factor on the frequency axis.

Integrate a position-dependent force

[11]

EXPECTED CONCLUSION

Work = 27.0 J, final speed = 5.29 m s^{-1}, maximum force 12.0 N at x = 2.00 m, and impulse = 8.58 N s.

REASONING AND MARKING CHECKPOINTS

01

Work is the spatial integral: $W = \int_0^3 (12x-3x^2)dx = [6x^2-x^3]_0^3 = 54-27 = 27.0$ J.

02

The initial kinetic energy is $\frac{1}{2}(2.00)(1.00)^2 = 1.00$ J. Work-energy gives $K_f = 28.0$ J, so $v_f = \sqrt{2K_f/m} = 5.29$ m s^{-1}.

03

Differentiate the force: $dF/dx = 12-6x$. The interior maximum occurs at x = 2.00 m and has $F = 12(2)-3(2^2) = 12.0$ N.

04

Impulse equals momentum change, not spatial force area: $J = m(v_f-v_i) = 2.00(5.29-1.00) = 8.58$ N s.

05

The area under F against x is work because dx is displacement. Impulse requires $\int F\,dt$; the supplied travel time alone would not determine it from an F-x curve, but the momentum result does.

COMMON MISTAKE

Interpreting the area under a force-position graph as impulse; its units are N m and it represents work, not momentum change.

An Atwood machine with pulley inertia

[14]

EXPECTED CONCLUSION

a = 1.78 m s^{-2}; T_1 = 24.1 N, T_2 = 23.2 N; α = 8.92 rad s^{-2}; speed after 0.800 m = 1.69 m s^{-1}.

REASONING AND MARKING CHECKPOINTS

01

For the descending mass, $m_1g-T_1 = m_1a$. For the rising mass, $T_2-m_2g = m_2a$. The unequal tensions provide the pulley's angular acceleration.

02

Pulley torque is $(T_1-T_2)R = I\alpha$ with $I = \frac{1}{2}MR^2$ and $\alpha = a/R$, hence $T_1-T_2 = \frac{1}{2}Ma$.

03

Combining equations gives $(m_1-m_2)g = (m_1+m_2+M/2)a$. Thus $a = 9.81/5.50 = 1.78$ m s^{-2}.

04

$T_1 = m_1(g-a) = 24.1$ N and $T_2 = m_2(g+a) = 23.2$ N. Their difference supplies the required torque; $\alpha = a/R = 8.92$ rad s^{-2}.

05

The net lost gravitational energy $(m_1-m_2)gh$ becomes $\frac{1}{2}(m_1+m_2)v^2 + \frac{1}{2}I(v/R)^2 = \frac{1}{2}(m_1+m_2+M/2)v^2$. This gives $v = 1.69$ m s^{-1}, equal to $\sqrt{(2ah)}$.

COMMON MISTAKE

Using one common cord tension on both sides of a pulley with rotational inertia, which would leave no net torque to accelerate that pulley.

Compare connected and isolated dielectric insertion

[14]

EXPECTED CONCLUSION

Both cases C_f = 18.0 μF. A: Q = 72.0 μC, V = 4.00 V, U = 144 μJ, W_{ext} = -288 μJ. B: Q = 216 μC, V = 12.0 V, U = 1.296 mJ. The dielectric is pulled inward.

REASONING AND MARKING CHECKPOINTS

01

Full insertion multiplies capacitance by κ, so C_f = 3.00(6.00 μF) = 18.0 μF. Initial charge is C_0V_0 = 72.0 μC and initial energy is $\frac{1}{2}C_0V_0^2$ = 432 μJ.

02

In case A, isolated charge remains 72.0 μC. Thus $V_f = Q/C_f$ = 4.00 V and $U_f = Q^2/(2C_f)$ = 144 μJ.

03

For quasistatic insertion with no battery exchange, $W_{ext} = \Delta U$ = 144-432 = -288 μJ. The negative sign means the field does +288 μJ of mechanical work while pulling the dielectric inward.

04

In case B, voltage remains 12.0 V. Then $Q_f = C_fV$ = 216 μC and $U_f = \frac{1}{2}C_fV^2$ = 1.296 mJ; the battery supplies additional charge and energy.

05

Insertion increases capacitance. At fixed charge this lowers field energy; at fixed voltage the battery-capacitor system also favors insertion after battery work is included. In both physical cases the net electromagnetic force draws the dielectric farther between the plates.

COMMON MISTAKE

Assuming charge and voltage are both unchanged during dielectric insertion; which one is fixed depends on whether the capacitor remains connected to a battery.

Mechanical power and motional emf

[12]

EXPECTED CONCLUSION

emf = 1.60 V; current = 0.800 A counterclockwise; magnetic force = 0.320 N left; external force = 0.320 N right; power = 1.28 W. Doubling speed doubles current and force and quadruples power.

REASONING AND MARKING CHECKPOINTS

01

The swept-loop flux increases into the page. Lenz's law requires an induced field out of the page, so the current is counterclockwise.

02

Motional emf is $\varepsilon = BLv = (0.800)(0.500)(4.00) = 1.60$ V. Ohm's law gives $I = \varepsilon/R = 0.800$ A.

03

The rod's current direction and field give a magnetic force opposing motion. Its magnitude is $F = BIL = (0.800)(0.800)(0.500) = 0.320$ N left.

04

Constant speed requires an external 0.320 N force right. Mechanical input power is $Fv = (0.320)(4.00) = 1.28$ W, equal to $I^2R = (0.800)^2(2.00) = 1.28$ W.

05

Since ε and I scale with v, magnetic drag scales with v and required mechanical power Fv scales with v^2. Doubling speed therefore gives twice the current and force but four times the heating power.

COMMON MISTAKE

Choosing a current that reinforces the increasing into-page flux; Lenz's law requires the induced magnetic field to oppose the flux change.

Energy accounting for a cyclic heat engine

[14]

EXPECTED CONCLUSION

Leg works: 0, +600 J, 0, -200 J; net work = +400 J. ΔU_{BC} = +300 J; ΔU_{DA} = -100 J. Net heat = +400 J and efficiency = 40.0% for total input 1000 J.

REASONING AND MARKING CHECKPOINTS

01

Isochoric legs A→B and C→D have $\Delta V = 0$, so $W_{by} = 0$. At constant pressure, B→C gives W = 300(3-1) = +600 J.

02

For D→A, W = 100(1-3) = -200 J. Net work is therefore +400 J, also the rectangular area (300-100)(3-1) in kPa·L.

03

Using $\Delta U = Q - W_{by}$, B→C has ΔU = 900-600 = +300 J. D→A has Q = -300 J and W = -200 J, giving ΔU = -100 J.

04

A complete cycle returns to the initial thermodynamic state, so total $\Delta U = 0$ and $Q_{net} = W_{net}$ = +400 J. This also constrains the combined heat on the two vertical legs.

05

The stated remaining absorption makes total heat input 900 + 100 = 1000 J. Efficiency is W_{net}/Q_{in} = 400/1000 = 40.0%. Clockwise traversal means high-pressure expansion and low-pressure compression, hence positive work by the gas.

COMMON MISTAKE

Using the entire area under the high-pressure expansion as net work while forgetting the negative work during the low-pressure compression leg.

Rolling dynamics down an incline

[12]

EXPECTED CONCLUSION

$a = 2.76$ m s^{-2} down the slope; static friction = 2.76 N up the slope; final speed = 3.96 m s^{-1}. A sliding block would be faster at 4.85 m s^{-1}.

REASONING AND MARKING CHECKPOINTS

01

Translation along the slope gives $mg \sin\theta - f = ma$. Rotation about the centre gives $fR = I\alpha$, and no slip gives $\alpha = a/R$.

02

With $I = \frac{1}{2}mR^2$, the torque equation gives $f = \frac{1}{2}ma$. Substitution into translation yields $mg \sin\theta = 3ma/2$, so $a = (2/3)g \sin 25° = 2.76$ m s^{-2}.

03

The friction is $f = \frac{1}{2}ma = 2.76$ N and points uphill. It supplies the uphill torque needed to increase the cylinder's angular speed while the centre accelerates downhill.

04

Energy gives $mgh = \frac{1}{2}mv^2 + \frac{1}{2}I(v/R)^2 = \frac{3}{4}mv^2$. Therefore $v = \sqrt{(4gh/3)} = 3.96$ m s^{-1}.

05

The instantaneous contact point is at rest relative to the fixed slope, so ideal static friction transfers no energy at that point. A frictionless slider has $v = \sqrt{(2gh)} = 4.85$ m s^{-1} because none of its energy is rotational.

COMMON MISTAKE

Assuming friction must point downhill because the cylinder moves downhill; its actual role is to provide the torque that spins the cylinder up.

Design and diagnose a Venturi flow meter

[13]

EXPECTED CONCLUSION

Flow rate = 1.20×10^{-3} m^3 s^{-1}, narrow speed = 3.00 m s^{-1}, and ideal narrow pressure = 176.6 kPa. Viscous loss enlarges the pressure drop and makes an ideal calibration overestimate flow.

REASONING AND MARKING CHECKPOINTS

01

Continuity for steady incompressible flow requires $A_1v_1 = A_2v_2$. The volume rate is $Q = (8.00 \times 10^{-4})(1.50) = 1.20 \times 10^{-3}$ m^3 s^{-1}.

02

The narrow speed is $v_2 = Q/A_2 = (1.20 \times 10^{-3})/(4.00 \times 10^{-4}) = 3.00$ m s^{-1}.

03

Equal heights allow $P_1 + ½\rho v_1^2 = P_2 + ½\rho v_2^2$. Hence $P_2 = 180000 + 500(1.50^2\text{-}3.00^2) = 176625$ Pa, or 176.6 kPa.

04

Viscosity dissipates mechanical energy and produces an extra pressure loss beyond the ideal Bernoulli drop. Interpreting that larger drop with an ideal equation would infer a flow rate that is too high.

05

Calibrate by collecting a measured volume for a measured time at several valve settings while recording pressure difference. Plot actual Q against $\sqrt{\Delta P}$, repeat readings, include uncertainties, and use the empirical curve rather than assuming an ideal coefficient.

COMMON MISTAKE

Treating pressure as greater in the faster narrow section, or ignoring that real viscous loss adds to the ideal speed-related pressure difference.

Extract an RC time constant from charging data

[14]

EXPECTED CONCLUSION

$\tau \approx 2.00$ s, $R \approx 9.09$ kΩ, $q(4\text{ s}) = 2.28$ mC, and $i(2\text{ s}) = 0.486$ mA. Plot $\ln(12-V_C)$ against t; its gradient should be $-1/\tau$.

REASONING AND MARKING CHECKPOINTS

01

For charging, $V_C = \varepsilon(1-e^{-t/\tau})$. At $t = \tau$, $V_C = 0.632\varepsilon = 7.58$ V. The 2.0 s reading is 7.59 V, so $\tau \approx 2.00$ s.

02

Since $\tau = RC$, $R = 2.00/(220 \times 10^{-6}) = 9.09 \times 10^{3}\ \Omega$. The units seconds per farad reduce to ohms.

03

At 4.0 s the charge is $q = CV_C = (220 \times 10^{-6})(10.38) = 2.28 \times 10^{-3}$ C.

04

Current is $i = (\varepsilon/R)e^{-t/\tau}$. At 2.0 s this is $(12.0/9090)e^{-1} = 4.86 \times 10^{-4}$ A.

05

Rearrange to $\ln(\varepsilon-V_C) = \ln \varepsilon - t/\tau$; a straight line tests the exponential model. A finite voltmeter resistance in parallel with the capacitor provides leakage, lowering the final voltage and distorting the inferred time constant unless included in the effective circuit.

COMMON MISTAKE

Taking the time to reach half the supply voltage as the time constant; an RC charging circuit reaches 63.2% of its final voltage at one τ.

Image formation and an experimental focal length

[12]

EXPECTED CONCLUSION

The image is 36.0 cm beyond the lens, magnification -2.00, height -4.00 cm; it is real, inverted and projectable. Plot $1/d_i$ against $1/d_o$; intercept = $1/f$.

REASONING AND MARKING CHECKPOINTS

01

Use the thin-lens equation $1/f = 1/d_o + 1/d_i$ with the real-is-positive convention. Then $1/d_i = 1/12.0 - 1/18.0 = 1/36.0\ \text{cm}^{-1}$.

02

Thus $d_i = +36.0$ cm. The positive image distance places a real image on the far side of the lens, so a screen can intercept it.

03

Magnification $m = -d_i/d_o = -36.0/18.0 = -2.00$. The image height is $mh_o = (-2.00)(2.00\ \text{cm}) = -4.00$ cm; the sign denotes inversion.

04

Rearrange to $1/d_i = -1/d_o + 1/f$. Plot $y = 1/d_i$ against $x = 1/d_o$; an ideal gradient is -1 and the y-intercept is $1/f$.

05

Keep object, lens centre and screen centre on one horizontal optical axis, and keep each plane perpendicular to it. Repeat focus judgments in both directions to reduce subjective focusing bias.

COMMON MISTAKE

Using magnification as $+d_i/d_o$ and reporting an upright image despite a real converging-lens image having negative magnification under the stated convention.

Classify equilibria in a quartic potential [15]

EXPECTED CONCLUSION

Equilibria: $x = 0$ unstable and $x = \pm 0.316$ m stable. Small-oscillation $\omega = 5.66$ rad s^{-1}; barrier above either minimum = 0.200 J. For $E = -0.100$ J, turning points in x^2 are 0.0293 and 0.1707 m^2, so the two wells remain disconnected.

REASONING AND MARKING CHECKPOINTS

01

Force is $F = -dU/dx = -(4ax^3-2bx)$. Equilibrium requires $2x(2ax^2-b) = 0$, giving $x = 0$ and $x = \pm\sqrt{(b/2a)} = \pm 0.316$ m.

02

Stability follows from $U'' = 12ax^2-2b$. At $x = 0$, $U'' = -8.00$ N m^{-1}, a local maximum; at either nonzero point $U'' = 4b = 16.0$ N m^{-1}, a minimum.

03

Near a minimum, U is approximately quadratic with effective spring constant U''. Hence $\omega = \sqrt{(U''/m)} = \sqrt{(16.0/0.500)} = 5.66$ rad s^{-1}.

04

The minimum potential is $-b^2/(4a) = -0.200$ J while $U(0) = 0$, so the central barrier is 0.200 J above either minimum.

05

Set $20x^4-4x^2 = -0.100$ and let $y = x^2$: $20y^2-4y+0.100 = 0$ gives $y = 0.0293$ or 0.1707 m^2. Since $E < U(0)$, the central region is classically forbidden and trajectories stay in one well.

COMMON MISTAKE

Calling every zero-force point stable; equilibrium stability requires inspecting curvature or the force direction on both sides of the point.

Escape from a circular orbit

[13]

EXPECTED CONCLUSION

Circular speed = 5.59 km s^{-1}, period = 1.43 × 10^4 s, specific energy = -1.56 × 10^7 J kg^{-1}, escape speed = 7.91 km s^{-1}, and minimum Δv = 2.32 km s^{-1}.

REASONING AND MARKING CHECKPOINTS

01

Circular gravity supplies centripetal acceleration, so $v_c = \sqrt{GM/r} = \sqrt{3.986 \times 10^{14}/(1.274 \times 10^7)} = 5.59 \times 10^3$ m s^{-1}.

02

The period is $T = 2\pi r/v_c = 2\pi\sqrt{r^3/GM} = 1.43 \times 10^4$ s, about 3.97 h.

03

Specific orbital energy is $\varepsilon = v_c^2/2 - GM/r = -GM/(2r) = -GM/(4R_E) = -1.56 \times 10^7$ J kg^{-1}.

04

Zero total energy at the burn point requires $v_{esc} = \sqrt{2GM/r} = \sqrt{2}v_c = 7.91$ km s^{-1}. A tangential prograde burn therefore needs $\Delta v = 7.91-5.59 = 2.32$ km s^{-1}.

05

Kinetic-energy change is $\frac{1}{2}(v_{esc}^2-v_c^2) = v_c\Delta v + \frac{1}{2}(\Delta v)^2$. The cross term matters because the spacecraft already has substantial orbital velocity before the burn.

COMMON MISTAKE

Calculating the required engine energy as though the spacecraft started from rest, which omits the large cross term involving its existing orbital speed.

Field and potential of a charged solid cylinder

[15]

EXPECTED CONCLUSION

Inside $E = \rho r/(2\varepsilon_0)$; outside $E = \rho R^2/(2\varepsilon_0 r)$. $E(0.0100\text{ m}) = E(0.0400\text{ m}) = 2.26 \times 10^3\text{ N C}^{-1}$. $V(0) - V(R) = 45.2$ V.

REASONING AND MARKING CHECKPOINTS

01

Choose a coaxial Gaussian cylinder of length L. Cylindrical symmetry makes E radial and constant on its curved surface; flux through the flat ends is zero.

02

For $r < R$, $E(2\pi rL) = \rho\pi r^2L/\varepsilon_0$, so $E = \rho r/(2\varepsilon_0)$. At 0.0100 m this is $2.26 \times 10^3\text{ N C}^{-1}$.

03

For $r > R$, the enclosed charge is $\rho\pi R^2L$. Therefore $E = \rho R^2/(2\varepsilon_0 r)$, giving $2.26 \times 10^3\text{ N C}^{-1}$ at 0.0400 m.

04

Potential difference is $V(0)-V(R) = \int_0^R E(r)dr = \rho R^2/(4\varepsilon_0) = 45.2$ V. Potential falls outward along the outward field.

05

The E-r graph starts at zero, rises linearly to $\rho R/(2\varepsilon_0)$ at R, stays continuous there, then falls as $1/r$. A jump would incorrectly imply a surface-charge sheet added at R.

COMMON MISTAKE

Using the entire cylinder charge inside an inner Gaussian surface, which incorrectly makes the field diverge at the central axis.

Current growth in an LR circuit

[12]

EXPECTED CONCLUSION

$\tau = 0.0200$ s; $(di/dt)_0 = 30.0$ A s^{-1}; $i(0.0400$ s$) = 0.519$ A; $V_L = 1.22$ V; $U_L = 0.0404$ J.

REASONING AND MARKING CHECKPOINTS

01
The LR time constant is $\tau = L/R = 0.300/15.0 = 0.0200$ s. The final current is $\varepsilon/R = 0.600$ A.

02
At $t = 0$ the current is zero, so the resistor drop is zero and $L(di/dt) = \varepsilon$. Therefore the initial gradient is $9.00/0.300 = 30.0$ A s^{-1}.

03
Current growth follows $i = (\varepsilon/R)(1-e^{-t/\tau})$. At $t = 0.0400$ s $= 2\tau$, $i = 0.600(1-e^{-2}) = 0.519$ A.

04
The inductor voltage is $\varepsilon e^{-t/\tau} = 9.00e^{-2} = 1.22$ V. Stored magnetic energy is $\frac{1}{2}Li^2 = 0.0404$ J.

05
Initially self-induction takes the full battery voltage and opposes rapid current change; at steady state $di/dt = 0$ and its voltage tends to zero. Observe voltage with a properly rated data logger and include a flyback path before opening the circuit to suppress a damaging voltage spike.

COMMON MISTAKE

Treating the inductor as an open circuit forever or as a wire immediately, rather than recognizing that its effective behaviour changes during the transient.

Derive the field on the axis of a charged ring

[16]

EXPECTED CONCLUSION

$E_x = kQx/(x^2+R^2)^{3/2} = 1.29 \times 10^3$ N C^{-1} away from the ring; $V = kQ/\sqrt{x^2+R^2} = 322$ V. The small-x approximation gives 1.80×10^3 N C^{-1} and is not accurate at $x/R = 0.5$.

REASONING AND MARKING CHECKPOINTS

01

Every ring element is the same distance $s = \sqrt{x^2+R^2}$ from the field point. An element dq contributes magnitude $k\,dq/s^2$.

02

Components perpendicular to the axis cancel pairwise for diametrically opposite elements. The axial component is $dE_x = (k\,dq/s^2)(x/s) = kx\,dq/s^3$.

03

Integrating around the ring gives $E_x = kQx/(x^2+R^2)^{3/2}$. Substitution yields 1.29×10^3 N C^{-1} in the +x direction for positive Q and positive x.

04

Potential adds as a scalar: $V = \int k\,dq/s = kQ/\sqrt{x^2+R^2} = 322$ V. Differentiating $-dV/dx$ reproduces the field expression.

05

For $x \ll R$, the denominator is approximately R^3, so $E_x \approx kQx/R^3 = 1.80 \times 10^3$ N C^{-1}. Here $x/R = 0.5$ is not very small, and the approximation overestimates the exact field by about 40%.

COMMON MISTAKE

Treating the ring as a point charge at distance x, which ignores the finite distance $\sqrt{x^2+R^2}$ from every charge element.