AP® P ebra-Based Exa

Friday , 2024

SECTIO

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AP® PHYSICS 2 TABLE OF INFORMATION

CONSTANTS AND CONVERSION FACTORS

Proton mass,	$m_p = 1.67 \times 10^{-27}$ kg	Electron charge magnitude,	$e = 1.60 \times 10^{-19}$ C
Neutron mass,	$m_n = 1.67 \times 10^{-27}$ kg	1 electron volt,	$1\text{ eV} = 1.60 \times 10^{-19}$ J
Electron mass,	$m_e = 9.11 \times 10^{-31}$ kg	Speed of light,	$c = 3.00 \times 10^8$ m/s
Avogadro's number,	$N_0 = 6.02 \times 10^{23}$ mol^{-1}	Universal gravitational constant,	$G = 6.67 \times 10^{-11}$ m^3/kg·s^2
Universal gas constant,	$R = 8.31$ J/(mol·K)	Acceleration due to gravity at Earth's surface,	$g = 9.8$ m/s^2
Boltzmann's constant,	$k_B = 1.38 \times 10^{-23}$ J/K		

1 unified atomic mass unit,	$1\text{ u} = 1.66 \times 10^{-27}$ kg $= 931$ MeV/c^2
Planck's constant,	$h = 6.63 \times 10^{-34}$ J·s $= 4.14 \times 10^{-15}$ eV·s
	$hc = 1.99 \times 10^{-25}$ J·m $= 1.24 \times 10^3$ eV·nm
Vacuum permittivity,	$\varepsilon_0 = 8.85 \times 10^{-12}$ C^2/N·m^2
Coulomb's law constant,	$k = 1/4\pi\varepsilon_0 = 9.0 \times 10^9$ N·m^2/C^2
Vacuum permeability,	$\mu_0 = 4\pi \times 10^{-7}$ (T·m)/A
Magnetic constant,	$k' = \mu_0/4\pi = 1 \times 10^{-7}$ (T·m)/A
1 atmosphere pressure,	$1\text{ atm} = 1.0 \times 10^5$ N/m^2 $= 1.0 \times 10^5$ Pa

UNIT SYMBOLS	meter,	m	mole,	mol	watt,	W	farad,	F
	kilogram,	kg	hertz,	Hz	coulomb,	C	tesla,	T
	second,	s	newton,	N	volt,	V	degree Celsius,	°C
	ampere,	A	pascal,	Pa	ohm,	Ω	electron volt,	eV
	kelvin,	K	joule,	J	henry,	H		

PREFIXES		
Factor	Prefix	Symbol
10^{12}	tera	T
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

VALUES OF TRIGONOMETRIC FUNCTIONS FOR COMMON ANGLES							
θ	0°	30°	37°	45°	53°	60°	90°
$\sin\theta$	0	1/2	3/5	$\sqrt{2}/2$	4/5	$\sqrt{3}/2$	1
$\cos\theta$	1	$\sqrt{3}/2$	4/5	$\sqrt{2}/2$	3/5	1/2	0
$\tan\theta$	0	$\sqrt{3}/3$	3/4	1	4/3	$\sqrt{3}$	∞

The following conventions are used in this exam.

I. The frame of reference of any problem is assumed to be inertial unless otherwise stated.
II. In all situations, positive work is defined as work done on a system.
III. The direction of current is conventional current: the direction in which positive charge would drift.
IV. Assume all batteries and meters are ideal unless otherwise stated.
V. Assume edge effects for the electric field of a parallel plate capacitor unless otherwise stated.
VI. For any isolated electrically charged object, the electric potential is defined as zero at infinite distance from the charged object.

AP® PHYSICS 2 EQUATIONS

MECHANICS

$v_x = v_{x0} + a_x t$

$x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$

$v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$

$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$

$|\vec{F}_f| \le \mu |\vec{F}_n|$

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

$\vec{p} = m\vec{v}$

$\Delta \vec{p} = \vec{F} \Delta t$

$K = \frac{1}{2} m v^2$

$\Delta E = W = F_{\parallel} d = F d \cos\theta$

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

$\theta = \theta_0 + \omega_0 t + \frac{1}{2} \alpha t^2$

$\omega = \omega_0 + \alpha t$

$x = A\cos(\omega t) = A\cos(2\pi f t)$

$x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$

$\vec{\alpha} = \frac{\sum \vec{\tau}}{I} = \frac{\vec{\tau}_{net}}{I}$

$\tau = r_{\perp} F = rF\sin\theta$

$L = I\omega$

$\Delta L = \tau \Delta t$

$K = \frac{1}{2} I \omega^2$

$|\vec{F}_s| = k|\vec{x}|$

a = acceleration
A = amplitude
d = distance
E = energy
F = force
f = frequency
I = rotational inertia
K = kinetic energy
k = spring constant
L = angular momentum
ℓ = length
m = mass
P = power
p = momentum
r = radius or separation
T = period
t = time
U = potential energy
v = speed
W = work done on a system
x = position
y = height
α = angular acceleration
μ = coefficient of friction
θ = angle
τ = torque
ω = angular speed

$U_s = \frac{1}{2} k x^2$

$\Delta U_g = mg\Delta y$

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

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

$T_p = 2\pi\sqrt{\frac{\ell}{g}}$

$|\vec{F}_g| = G\frac{m_1 m_2}{r^2}$

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

$U_G = -\frac{G m_1 m_2}{r}$

ELECTRICITY AND MAGNETISM

$|\vec{F}_E| = \frac{1}{4\pi\varepsilon_0} \frac{|q_1 q_2|}{r^2}$

$\vec{E} = \frac{\vec{F}_E}{q}$

$|\vec{E}| = \frac{1}{4\pi\varepsilon_0} \frac{|q|}{r^2}$

$\Delta U_E = q\Delta V$

$V = \frac{1}{4\pi\varepsilon_0} \frac{q}{r}$

$|\vec{E}| = \left|\frac{\Delta V}{\Delta r}\right|$

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

$C = \kappa\varepsilon_0 \frac{A}{d}$

$E = \frac{Q}{\varepsilon_0 A}$

$U_C = \frac{1}{2} Q\Delta V = \frac{1}{2} C(\Delta V)^2$

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

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

$P = I\,\Delta V$

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

$R_s = \sum_i R_i$

$\frac{1}{R_p} = \sum_i \frac{1}{R_i}$

$C_p = \sum_i C_i$

$\frac{1}{C_s} = \sum_i \frac{1}{C_i}$

$B = \frac{\mu_0 I}{2\pi r}$

A = area
B = magnetic field
C = capacitance
d = distance
E = electric field
$\mathcal{E}$ = emf
F = force
I = current
ℓ = length
P = power
Q = charge
q = point charge
R = resistance
r = separation
t = time
U = potential (stored) energy
V = electric potential
v = speed
κ = dielectric constant
ρ = resistivity
θ = angle
Φ = flux

$\vec{F}_M = q\vec{v} \times \vec{B}$

$|\vec{F}_M| = |q\vec{v}||\sin\theta||\vec{B}|$

$\vec{F}_M = I\vec{\ell} \times \vec{B}$

$|\vec{F}_M| = |I\vec{\ell}||\sin\theta||\vec{B}|$

$\Phi_B = \vec{B} \cdot \vec{A}$

$\Phi_B = |\vec{B}|\cos\theta|\vec{A}|$

$\mathcal{E} = -\frac{\Delta\Phi_B}{\Delta t}$

$\mathcal{E} = B\ell v$

AP® PHYSICS 2 EQUATIONS

FLUID MECHANICS AND THERMAL PHYSICS

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

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

$P = P_0 + \rho g h$

$F_b = \rho V g$

$A_1 v_1 = A_2 v_2$

$P_1 + \rho g y_1 + \frac{1}{2}\rho v_1^2 = P_2 + \rho g y_2 + \frac{1}{2}\rho v_2^2$

$\frac{Q}{\Delta t} = \frac{kA\,\Delta T}{L}$

$PV = nRT = Nk_BT$

$K = \frac{3}{2}k_BT$

$W = -P\Delta V$

$\Delta U = Q + W$

A = area
F = force
h = depth
k = thermal conductivity
K = kinetic energy
L = thickness
m = mass
n = number of moles
N = number of molecules
P = pressure
Q = energy transferred to a system by heating
T = temperature
t = time
U = internal energy
V = volume
v = speed
W = work done on a system
y = height
ρ = density

MODERN PHYSICS

$E = hf$

$K_{max} = hf - \phi$

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

$E = mc^2$

E = energy
f = frequency
K = kinetic energy
m = mass
p = momentum
λ = wavelength
ϕ = work function

WAVES AND OPTICS

$\lambda = \frac{v}{f}$

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

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

$\frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f}$

$|M| = \left|\frac{h_i}{h_o}\right| = \left|\frac{s_i}{s_o}\right|$

$\Delta L = m\lambda$

$d\sin\theta = m\lambda$

d = separation
f = frequency or focal length
h = height
L = distance
M = magnification
m = an integer
n = index of refraction
s = distance
v = speed
λ = wavelength
θ = angle

GEOMETRY AND TRIGONOMETRY

Rectangle
$A = bh$

Triangle
$A = \frac{1}{2}bh$

Circle
$A = \pi r^2$
$C = 2\pi r$

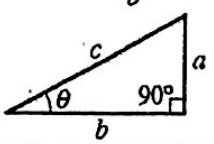
Rectangular solid
$V = \ell w h$

Cylinder
$V = \pi r^2 \ell$
$S = 2\pi r\ell + 2\pi r^2$

Sphere
$V = \frac{4}{3}\pi r^3$
$S = 4\pi r^2$

A = area
C = circumference
V = volume
S = surface area
b = base
h = height
ℓ = length
w = width
r = radius

Right triangle
$c^2 = a^2 + b^2$
$\sin\theta = \frac{a}{c}$
$\cos\theta = \frac{b}{c}$
$\tan\theta = \frac{a}{b}$



PHYSICS 2

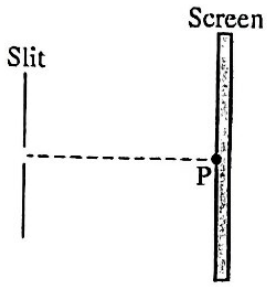
SECTION I

Time—1 hour and 30 minutes

50 Questions

Note: To simplify calculations, you may use $g = 10\ m/s^2$ in all problems.

Directions: Each of the questions or incomplete statements below is followed by four suggested answers or completions. Select the one that is best in each case and then fill in the corresponding circle on the answer sheet.



Note: Figure not drawn to scale.

1. Light of wavelength λ is incident upon a single slit. Point P is located on a screen directly across from the slit, as shown. A diffraction pattern consisting of a central bright spot and alternating dark and bright spots is created on the screen. At a later time, light of wavelength 1.5λ is incident upon the slit and a new diffraction pattern is created on the screen. Which of the following is a correct claim about the new pattern as compared to the original pattern?

(A) The center of the central bright spot is shifted above Point P.

(B) The center of the central bright spot is shifted below Point P.

(C) The distance between two adjacent dark spots on the screen is decreased.

(D) The distance between two adjacent dark spots on the screen is increased.

2. A closed container of known fixed volume V is filled with an ideal gas. In different trials of an experiment, the temperature T of the gas is changed and the resulting pressure P of the gas inside the container is measured. Which of the following best describes how known quantities could be graphed and how the slope of the best-fit line of the graph could be analyzed to determine the number N of molecules of the gas?

(A) Plot P as a function of T and then set the slope equal to N.

(B) Plot P as a function of T and then set the slope equal to $\frac{Nk_B}{V}$.

(C) Plot P as a function of $\frac{1}{T}$ and then set the slope equal to N.

(D) Plot P as a function of $\frac{1}{T}$ and then set the slope equal to $\frac{Nk_B}{V}$.

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3. A nonconducting rod with negative net charge is held close to but does not touch one side of a neutral conducting sphere that is initially connected to ground. The connection to ground is removed. The rod is then moved far away from the sphere. Which of the following claims is correct about the charge on the sphere after the rod is moved far away from the sphere?

(A) The net charge is negative.

(B) The net charge is positive.

(C) The net charge is zero, and the sphere is polarized.

(D) The net charge is zero, and the sphere is not polarized.

4. A circuit consists of a battery of known emf $\mathcal{E}$, a resistor of variable resistance R_{var}, and a resistor of unknown resistance R_u that are connected in series. A student varies R_{var} and measures the resulting current I in the circuit for several known values of R_{var}. The student creates a graph that can be used to determine R_u. Which of the following correctly indicates quantities that could be graphed to determine R_u and how a feature of the graph is related to R_u?

(A) I is plotted as a function of $\frac{\mathcal{E}}{R_{var}}$. The slope of the best-fit line is equal to $\frac{1}{R_u}$.

(B) I is plotted as a function of $\frac{\mathcal{E}}{R_{var}}$. The vertical intercept of the best-fit line is equal to $\frac{1}{R_u}$.

(C) $\frac{\mathcal{E}}{I}$ is plotted as a function of R_{var}. The slope of the best-fit line is equal to R_u.

(D) $\frac{\mathcal{E}}{I}$ is plotted as a function of R_{var}. The vertical intercept of the best-fit line is equal to R_u.

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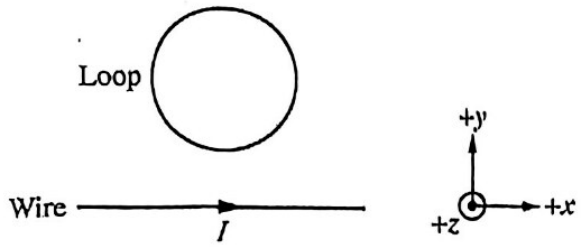
Questions 5 and 6 refer to the following material.



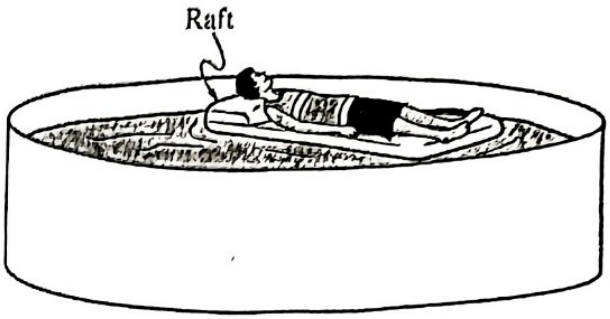
A conducting loop is positioned in the xy-plane directly above a long, straight wire that has current I in the $+x$-direction, as shown.

5. Which of the following actions would induce a clockwise current in the loop?

   (A) Moving the loop in the $+y$-direction
   (B) Moving the loop in the $-y$-direction
   (C) Rotating the loop clockwise about the center of the loop in the xy-plane
   (D) Rotating the loop counterclockwise about the center of the loop in the xy-plane

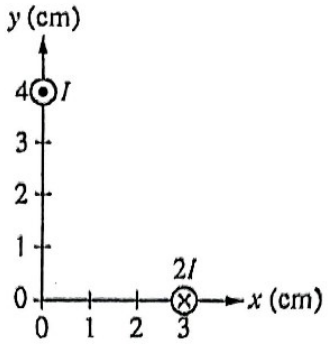
6. Which of the following changes to the current I in the wire would induce a constant, clockwise current in the loop?

   (A) Increasing I at a constant rate
   (B) Increasing I at an increasing rate
   (C) Decreasing I at a constant rate
   (D) Decreasing I at an increasing rate



7. A person stands waist-deep in water in a small pool beside a raft that floats on the surface of tl water. The person then climbs on top of the rafi and lies at rest, floating on the water, as shown. How does the height of the water level in the pool change, if at all, when the person climbs c top of the raft?

   (A) The height of the water level in the pool increases.
   (B) The height of the water level in the pool decreases.
   (C) The height of the water level in the pool i: unchanged.
   (D) The change in the height of the water leve cannot be determined without knowing the relative masses of the person and the raft.



8. Two parallel current-carrying wires are positioned on the x- and y-axes and are perpendicular to the plane of the page, as shown. One wire carries current I out of the page, and the other wire carries current $2I$ into the page. Which of the following arrows best represents the direction of the net magnetic field due to the two wires at the origin?

(A) 

(B) 

(C) 

(D) 

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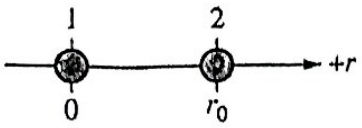

Figure 1

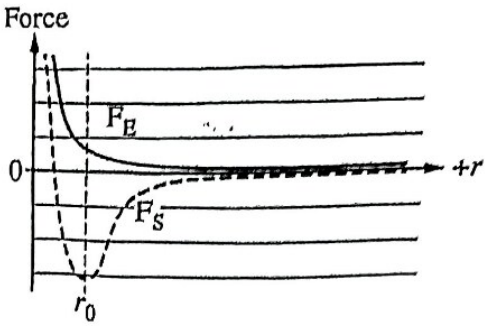

Figure 2

9. Figure 1 shows protons 1 and 2 that are separated by distance $r = r_0$ in the nucleus of an atom. An electrostatic force F_E and a strong force F_S are exerted on Proton 2 by Proton 1. The graph in Figure 2 represents the relative forces F_E and F_S as functions of the separation distance r between the protons while the nucleus. Which of the following claims is correct about the net force exerted on Proton 2 by Proton 1 ?

(A) The magnitude of the net force approaches zero as r decreases.
(B) The magnitude of the net force always increases as r increases.
(C) At $r = r_0$, the net force is directed toward Proton 1.
(D) At $r = r_0$, the net force is directed away from Proton 1.

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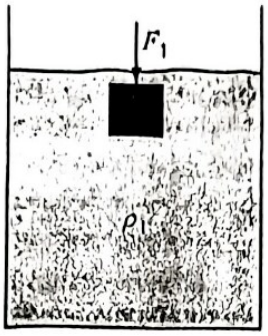
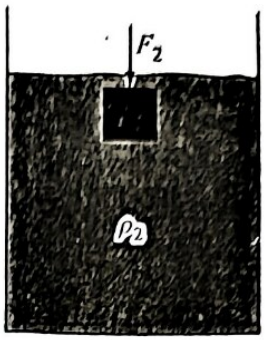


Scenario 1



Scenario 2

10. In Scenario 1, a downward force of magnitude F_1 is exerted on a block so that the block remains at rest and completely submerged in a container of liquid of density ρ_1. In Scenario 2, a downward force of magnitude F_2 is exerted on an identical block so that the block remains at rest and is completely submerged in a container of liquid of density $\rho_2 = 2\rho_1$, as shown. F_1 and F_2 are then measured when the blocks are at various depths below the surface of the liquids. Which of the following statements comparing F_2 to F_1 is correct?

(A) $F_2 < F_1$ at all depths, and F_2 and F_1 are constant as depth increases.
(B) $F_2 < F_1$ at all depths, and F_2 and F_1 increase as depth increases.
(C) $F_2 > F_1$ at all depths, and F_2 and F_1 are constant as depth increases.
(D) $F_2 > F_1$ at all depths, and F_2 and F_1 increase as depth increases.

11. A sealed, insulated container with a movable piston is filled with an ideal gas. During a thermal process, the gas expands, but energy does not transfer into or out of the gas by heating or cooling. Which claim is correct about the temperature T of the gas during the process and provides a valid justification?

(A) T increases because the volume of the gas increases.
(B) T decreases because the gas does work on the piston.
(C) T stays the same because the pressure of the gas stays the same.
(D) T stays the same because no energy is transferred into or out of the gas by heating or cooling.

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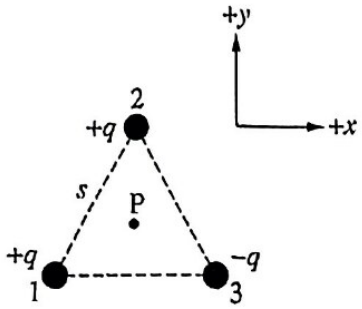
Questions 12 - 14 refer to the following material.



Note: Figure not drawn to scale.

Small spheres 1, 2, and 3 are held in place at the corners of an equilateral triangle of side length s, as shown. Spheres 1 and 2 each have positive charge $+q$, and Sphere 3 has negative charge $-q$. Point P is located at the center of the triangle. The electric potential at Point P due to the three spheres is V_0. The electric potential energy of the three-sphere system is U_0.

12. Spheres 1 and 3 are held in place at their original positions. Sphere 2 is then moved very far away from spheres 1 and 3. The electric potential energy of the three-sphere system is now U_f. Which of the following is equal to the ratio $\frac{U_f}{U_0}$?

(A) -1

(B) $-\frac{1}{3}$

(C) $\frac{1}{3}$

(D) 1

13. Spheres 1, 2, and 3 are held in place at their original positions. Sphere 2 is then released from rest. Which of the following best describes the direction in which Sphere 2 accelerates immediately after release and correctly indicates whether the electric potential energy of the three-sphere system increases or decreases?

	Acceleration Direction	Electric Potential Energy
A	$+x$-direction	Increases
B	$+x$-direction	Decreases
C	$-x$-direction	Increases
D	$-x$-direction	Decreases

(A) A
(B) B
(C) C
(D) D

14. Spheres 1, 2, and 3 are held in place at their original positions. Sphere 4 (not shown) with positive charge $+2q$ is placed at Point P. Sphere 4 is then released from rest. When Sphere 4 reaches a location where the electric potential due to spheres 1, 2, and 3 is $\frac{V_0}{3}$, Sphere 4 has kinetic energy K. Which of the following expressions is equal to K ?

(A) $\frac{1}{3}qV_0$
(B) $\frac{2}{3}qV_0$
(C) $\frac{4}{3}qV_0$
(D) $\frac{8}{3}qV_0$

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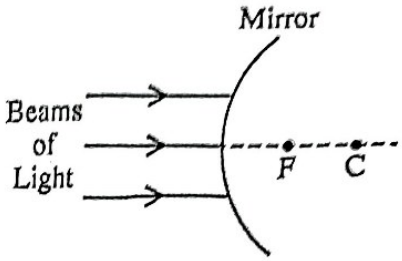
15. In an experiment, a student is asked to determine the dielectric constant κ of a material that is between the plates of different circular parallel-plate capacitors. The student measures the capacitances C of multiple capacitors and their respective radii r. The capacitors have the same plate separation d but have different values of r. The student creates a graph that can be used to determine κ. Which of the following best indicates the quantities graphed and the equation for the slope of the best-fit line that can be used to determine κ ?

(A) C is plotted as a function of r and slope $= \kappa\varepsilon_0$.

(B) C is plotted as a function of r and slope $= \dfrac{\pi\kappa\varepsilon_0}{d}$.

(C) C is plotted as a function of r^2 and slope $= \kappa\varepsilon_0$.

(D) C is plotted as a function of r^2 and slope $= \dfrac{\pi\kappa\varepsilon_0}{d}$.



16. Parallel beams of light from a distant object ar incident on a convex mirror. The focal point o1 the mirror is at Point F. The center of curvatur of the mirror is at Point C, as shown. Which o1 the following best predicts the location of the resulting image?

(A) Between the mirror and Point F

(B) Point F

(C) Between points F and C

(D) Point C

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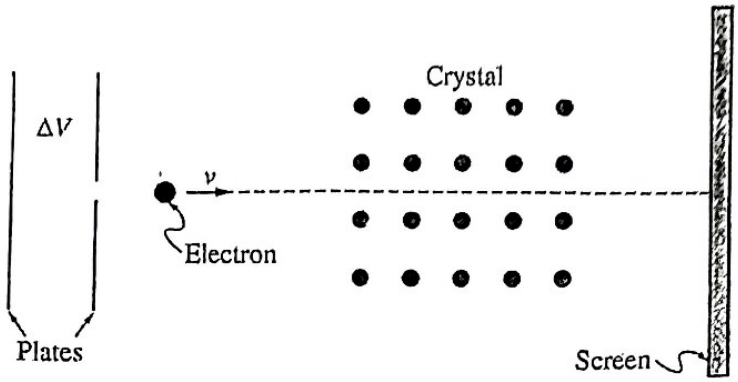
Questions 17 and 18 refer to the following material.



Note: Figure not drawn to scale.

Parallel charged plates are used to accelerate electrons from rest through potential difference ΔV. Each electron exits the two-plate system with speed v and then passes through a crystal, as shown. The atoms in the crystal are equally spaced. After exiting the crystal, the electrons collide with a screen. A resulting diffraction pattern of maxima and minima is observed. The spacing between adjacent maxima is y_0.

17. The original setup is modified so that each electron is accelerated through potential difference $2\Delta V$ before passing through the crystal. The new spacing between adjacent maxima is y_{new}. Which of the following correctly predicts y_{new} ?

(A) $y_{new} = \frac{y_0}{2}$

(B) $y_{new} = \frac{y_0}{\sqrt{2}}$

(C) $y_{new} = \sqrt{2}y_0$

(D) $y_{new} = 2y_0$

18. Which of the following correctly indicates whether the wave model or the particle model of matter best explains the diffraction pattern and provides a valid justification?

(A) Wave model, because electrons can be modeled as electromagnetic waves.

(B) Wave model, because the diffraction pattern is a result of wave superposition.

(C) Particle model, because electrons are elementary particles.

(D) Particle model, because the atoms of the crystal can be modeled as particles.

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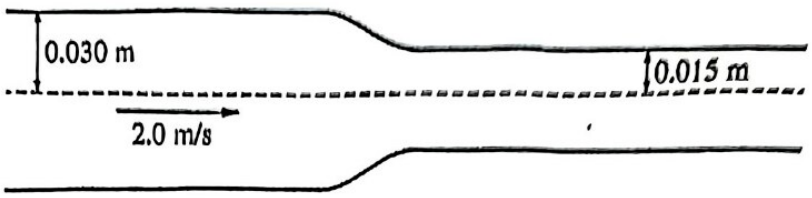
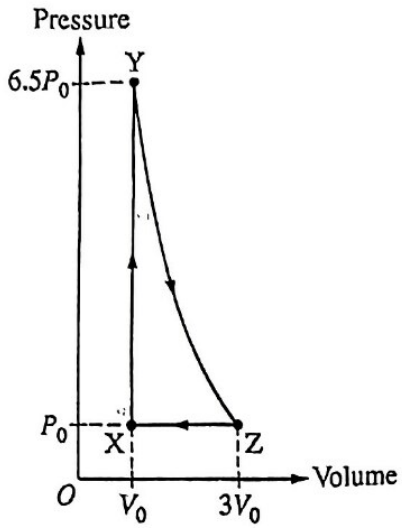


19. Water of density 1000 kg/m^3 flows at 2.0 m/s through a wide section of a horizontal pipe of radius 0.030 m. The pressure of the water in the wide section is 300,000 Pa. The water then flows into a narrow section of radius 0.015 m, as shown. Which of the following is equal to the pressure of the water in the narrow section of the pipe?

(A) 150,000 Pa
(B) 270,000 Pa
(C) 330,000 Pa
(D) 600,000 Pa

Questions 20 - 22 refer to the following material.



An ideal gas is in a sealed container that has a movable piston. The gas is taken through thermodynamic Cycle X → Y → Z → X, where states X, Y, and Z are plotted on the pressure-volume diagram shown. Process Y → Z is adiabatic.

20. Which of the following correctly compares the temperatures T_X and T_Y of the gas in states X and Y, respectively, and provides a valid justification?

(A) $T_X > T_Y$, because negative work is done on the gas during Process X → Y.

(B) $T_X > T_Y$, because energy is transferred out of the gas by cooling during Process X → Y.

(C) $T_X < T_Y$, because positive work is done on the gas during Process X → Y.

(D) $T_X < T_Y$, because energy is transferred into the gas by heating during Process X → Y.

21. Which of the following best describes the motion of the piston and the average kinctic energy K_{avg} of the molecules of gas in Process Y → Z ?

(A) The piston is moved outward quickly, and K_{avg} is constant.

(B) The piston is moved outward quickly, and K_{avg} changes.

(C) The piston is moved outward slowly, and K_{avg} is constant.

(D) The piston is moved outward slowly, and K_{avg} changes.

22. Which of the following expressions is equal to the work done on the gas by the piston in Process Z → X ?

(A) $-3P_0V_0$

(B) $-2P_0V_0$

(C) $2P_0V_0$

(D) $3P_0V_0$

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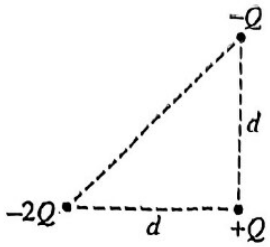


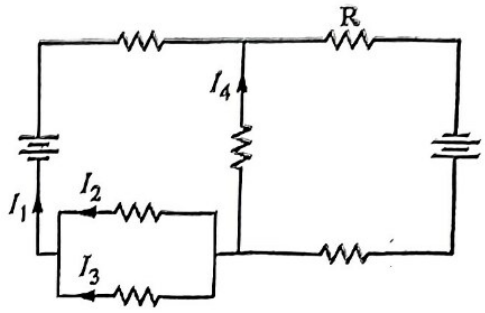
23. Three charged spheres are placed at the corners of a right triangle with side length d. One sphere has positive charge $+Q$ and the other spheres have negative charges $-Q$ and $-2Q$, as shown. Which of the following expressions is equal to the magnitude of the net electric force exerted on the sphere with positive charge $+Q$ in the bottom-right corner?

(A) $\frac{kQ^2}{d^2}$

(B) $\sqrt{3}\frac{kQ^2}{d^2}$

(C) $\sqrt{5}\frac{kQ^2}{d^2}$

(D) $3\frac{kQ^2}{d^2}$



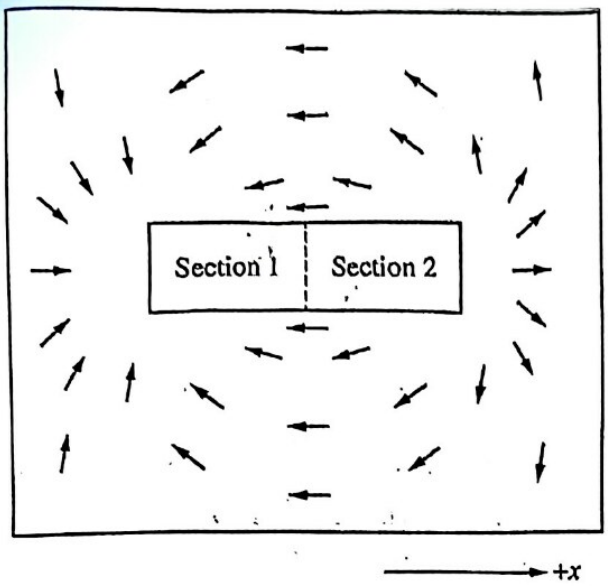
24. A circuit consists of two batteries and six resistors. The directions of currents I_1, I_2, I_3, and I_4 in the circuit are shown. Which of the following expressions is equal to the current in the resistor labeled R ?

(A) $I_1 + I_4$

(B) $I_1 - I_4$

(C) $I_1 + I_2 + I_3 + I_4$

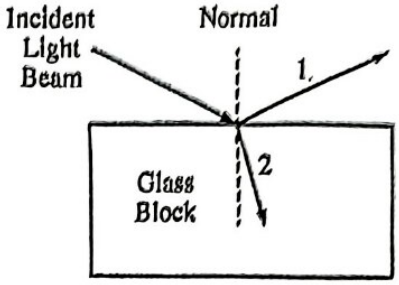
(D) $I_1 + I_2 + I_3 - I_4$



25. Each arrow in the diagram represents the direction that a compass needle would point when placed at that location in the magnetic field that surrounds a ferromagnetic bar magnet. Which of the following indicates the most common direction of the magnetic field inside sections 1 and 2 of the magnet?

	Section 1	Section 2
A	$-x$-direction	$-x$-direction
B	$-x$-direction	$+x$-direction
C	$+x$-direction	$-x$-direction
D	$+x$-direction	$+x$-direction

(A) A
(B) B
(C) C
(D) D



26. A student performs an experiment to determine the index of refraction n_g of a glass block. In the experiment, a beam of light in air is incident on the block. The incident beam is partially reflected as Beam 1 and partially refracted as Beam 2, as shown. Which of the following indicates the beam the student should use to determine n_g and provides a valid justification?

(A) Beam 1, because the change in frequency of the light as the light is ieflected from the block depends on n_g.
(B) Beam 1, because the angle of reflection depends on n_g.
(C) Beam 2, because the change in frequency of the light as the light enters the block depends on n_g.
(D) Beam 2, because the angle of refraction depends on n_g.

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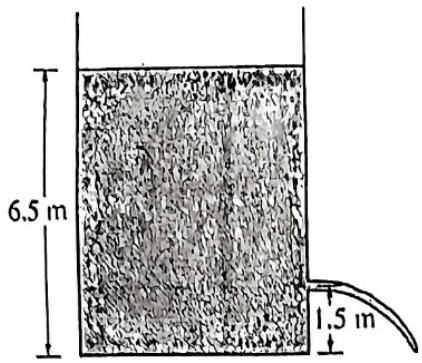
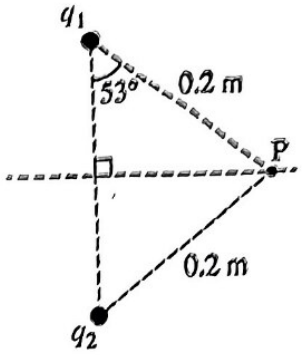


27. A large tank that is open to air is filled with water. The surface of the water is 6.5 m above the bottom of the tank. One side of the tank has a small hole that is located 1.5 m above the bottom of the tank through which water exits the tank, as shown. Which of the following is approximately equal to the speed of the water exiting the tank at the instant shown?

(A) 5.5 m/s
(B) 10.0 m/s
(C) 11.4 m/s
(D) 12.6 m/s

28. A sealed, insulated container is filled with one mole of ideal Gas X. An identical container is filled with one mole of a different ideal gas, Gas Y. The total mass of Gas X is less than the total mass of Gas Y, but the gases have the same temperature. The average speeds of the molecules of gases X and Y are v_X and v_Y, respectively. The average kinetic energies of the molecules of gases X and Y are K_X and K_Y, respectively. Which of the following correctly compares v_X to v_Y and K_X to K_Y ?

(A) $v_X < v_Y$ and $K_X = K_Y$
(B) $v_X < v_Y$ and $K_X < K_Y$
(C) $v_X > v_Y$ and $K_X = K_Y$
(D) $v_X > v_Y$ and $K_X > K_Y$



29. A sphere with charge $q_1 = -4.0$ nC and a sphere with charge $q_2 = +4.0$ nC are held at rest. The two spheres and Point P are on the vertices of a triangle, as shown. Point P is 0.2 m from each sphere. Which of the following best represents the magnitude of the net electric field at Point P ?

(A) 1.1×10^3 N/C
(B) 1.4×10^3 N/C
(C) 1.8×10^3 N/C
(D) 5.0×10^3 N/C

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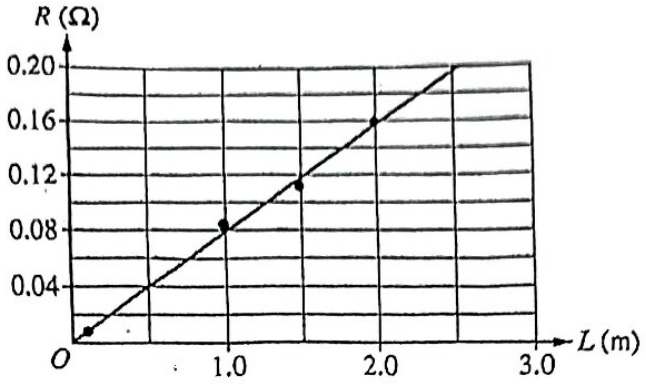

30. A student is asked to determine the resistivity ρ of a wire with a diameter of 5.0×10^{-4} m. The student measures the resistance R of the wire for different lengths L of the wire. The student uses the results to create the plot of R as a function of L and the best-fit line shown. Which of the following is approximately equal to ρ ?

(A) $0.8 \times 10^{-8}\ \Omega \cdot \text{m}$

(B) $1.6 \times 10^{-8}\ \Omega \cdot \text{m}$

(C) $3.0 \times 10^{-8}\ \Omega \cdot \text{m}$

(D) $6.0 \times 10^{-8}\ \Omega \cdot \text{m}$

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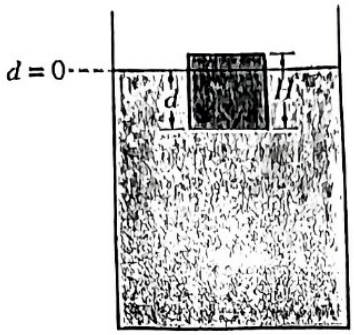


Figure 1

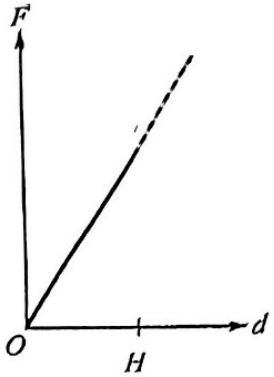


Figure 2

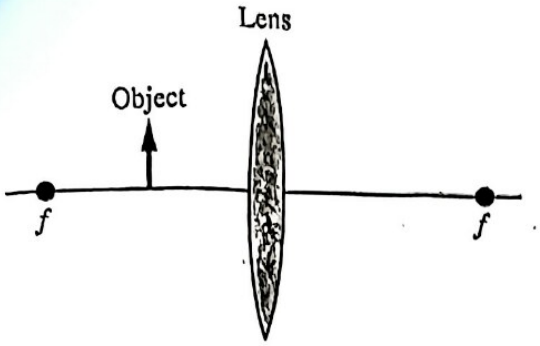
31. A block of height H is lowered into a tank of liquid, as shown in Figure 1. The depth d of the block is defined as the distance from the surface of the liquid to the bottom of the block. The solid line in the graph shown in Figure 2 represents the magnitude F of the buoyant force exerted on the block by the liquid as a function of d. A student claims that the dashed line in Figure 2 correctly represents F as a function of depth d for $d > H$ (when $d > H$, the block is fully submerged and is being lowered). Which of the following indicates whether the claim is correct or incorrect and provides a valid justification?

(A) Correct, because the pressure due to molecular collisions on the top surface of the block increases as d increases.

(B) Correct, because the pressure due to molecular collisions on the bottom surface of the block increases as d increases.

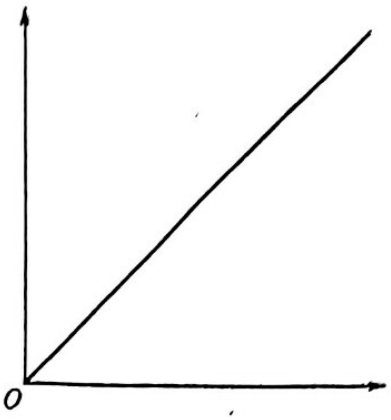
(C) Incorrect, because the pressure difference due to molecular collisions on the top and bottom surfaces of the block is constant as d increases.

(D) Incorrect, because the pressure difference due to molecular collisions on the top and bottom surfaces of the block increases as d increases.



32. An object is located between a converging lens and one of the focal points f of the lens, as shown. Which of the following describes the image produced by the lens?

(A) Upright and reduced
(B) Upright and enlarged
(C) Inverted and reduced
(D) Inverted and enlarged



33. A container is filled with an ideal gas. The following quantities can be varied in different experiments with the gas.

- volume V of the container
- number n of moles of the gas
- temperature T of the gas
- pressure P of the gas

In one experiment, one quantity is changed, one other quantity is measured, and the remaining two quantities are held constant. The graph shown of the best-fit line relates the measured and changed quantities. Which of the following indicates the measured and changed quantities that could be plotted to create the graph?

(A) P as a function of $\frac{1}{T}$
(B) P as a function of V
(C) V as a function of n
(D) T as a function of n

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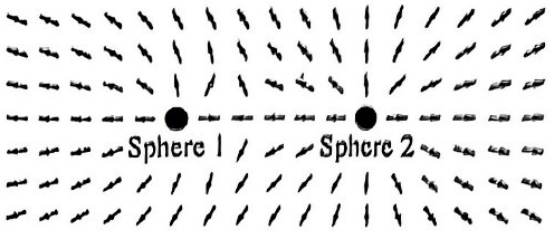

34. The arrows in the figure represent the directions of a field near spheres 1 and 2, which are held at rest. Sphere 1 has a net charge of absolute value $|Q_1|$ and mass m_1. Sphere 2 has a net charge of absolute value $|Q_2|$ and mass m_2. Which of the following correctly indicates which type of field is represented and describes how the corresponding property of spheres 1 and 2 compares?

	Field Represented	How Property of Spheres 1 and 2 Compares
A	Electric	$\|Q_1\| > \|Q_2\|$
B	Electric	$\|Q_1\| < \|Q_2\|$
C	Gravitational	$m_1 > m_2$
D	Gravitational	$m_1 < m_2$

(A) A
(B) B
(C) C
(D) D

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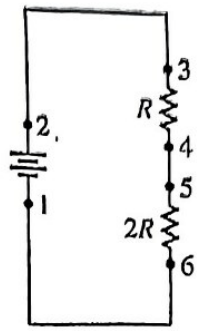
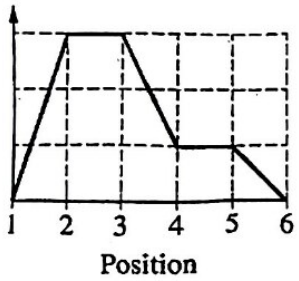
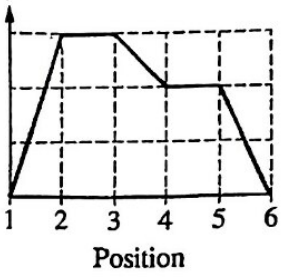


35. A circuit consists of a battery that is connected in series to two resistors, one of resistance R and the other of resistance $2R$. Positions 1, 2, 3, 4, 5, and 6 are labeled in the diagram. Which of the following graphs best represents the electric potential V for points along the circuit between positions 1 through 6 ?

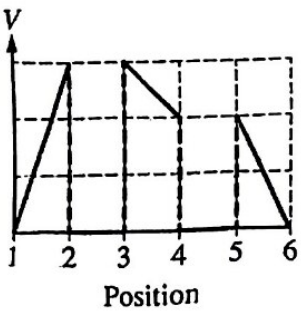
(A)



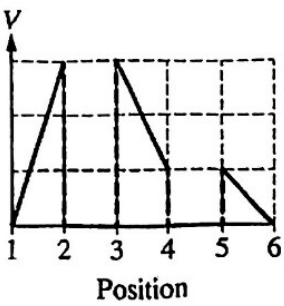
(B)



(C)



(D)



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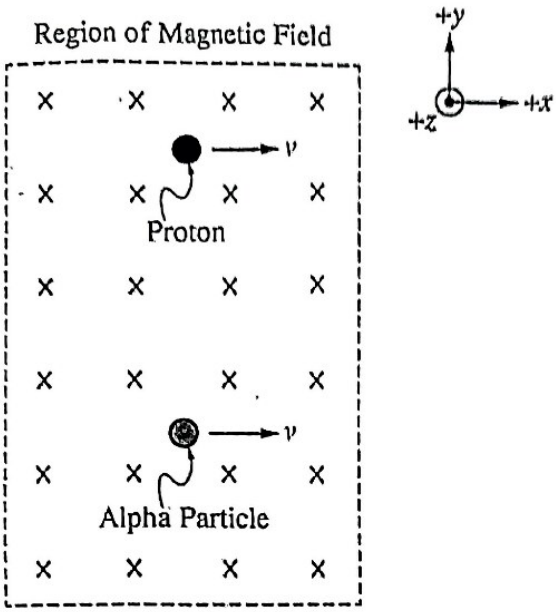


Note: Figure not drawn to scale.

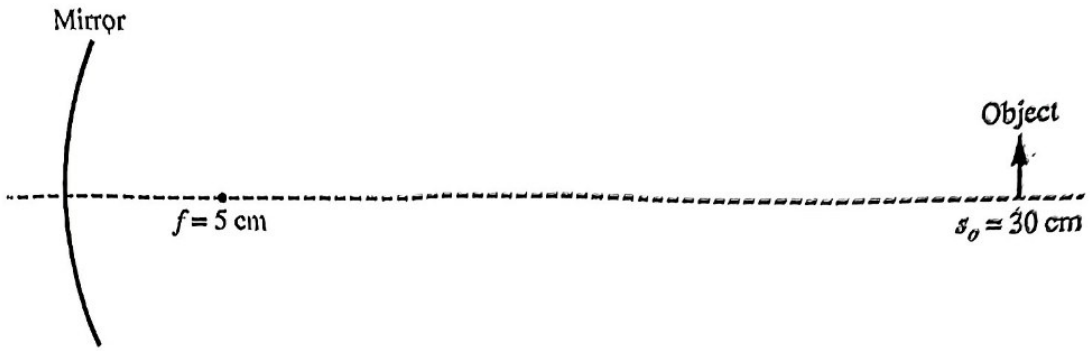
36. At the instant shown, a proton and an alpha particle ($^4_2$He with positive charge $+2e$) are both moving with velocity v in the $+x$-direction in a region of uniform magnetic field that is directed into the page in the -z-direction. The magnitudes of the forces exerted on the proton -and the alpha particle by the magnetic field are F_p and F_α, respectively. Which of the following correctly relates F_p and F_α ?

(A) $F_p = \frac{F_\alpha}{4}$

(B) $F_p = \frac{F_\alpha}{2}$

(C) $F_p = 2F_\alpha$

(D) $F_p = 4F_\alpha$



37. An object is placed a distance $s_o = 30$ cm in front of a concave mirror that has a focal length of $f = 5$ cm, as shown. Which of the following correctly indicates the distance s_i of the resulting image from the mirror and the absolute value $|M|$ of the magnification of the image?

	s_i (cm)	$\lvert M \rvert$
A	$\frac{1}{6}$	$\frac{1}{5}$
B	$\frac{1}{6}$	5
C	6	$\frac{1}{5}$
D	6	5

(A) A
(B) B
(C) C
(D) D

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Questions 38 and 39 refer to the following material.

Photon	Wavelength (nm)
1	620
2	155

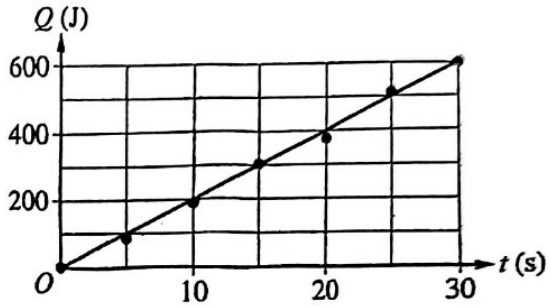
The emission spectrum of a gas is observed. The table indicates the observed wavelengths of two photons, 1 and 2, that are emitted from the gas.

38. Photon 3 is emitted from the gas with an energy of 0.6 eV. Which of the following correctly compares energies E_1, E_2, and E_3 of photons 1, 2, and 3, respectively?

(A) $E_1 > E_2 > E_3$
(B) $E_1 > E_3 > E_2$
(C) $E_2 > E_1 > E_3$
(D) $E_3 > E_2 > E_1$

39. Photons 1 and 2 are incident on a metal plate with a work function of 6.0 eV. Which of the photons, if either, could result in the ejection of an electron from the metal?

(A) Photon 1 only
(B) Photon 2 only
(C) Both photons 1 and 2
(D) Neither Photon 1 nor Photon 2 will result in the ejection of electrons from the metal.



40. A cylindrical rod has a length of 0.80 m and a radius of 0.25 m. The rod is connected between two objects that have a constant temperature difference of 60 K. Data are collected of the energy Q transferred by the rod as a function of time t. The data are used to create the graph shown. Which of the following values is most nearly equal to the thermal conductivity of the rod?

(A) $1.1 \frac{\text{W}}{\text{m·K}}$
(B) $1.4 \frac{\text{W}}{\text{m·K}}$
(C) $64 \frac{\text{W}}{\text{m·K}}$
(D) $82 \frac{\text{W}}{\text{m·K}}$

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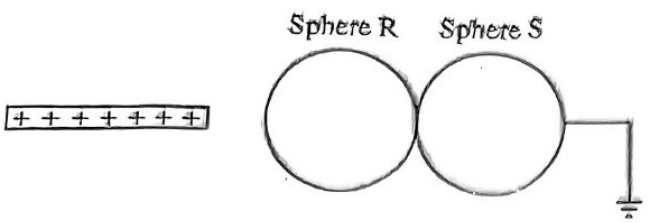


Figure 1

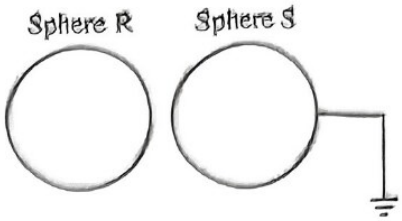
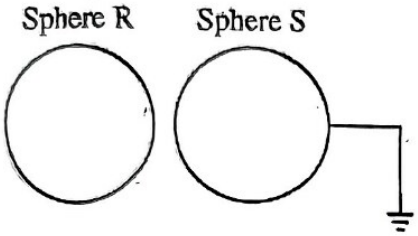
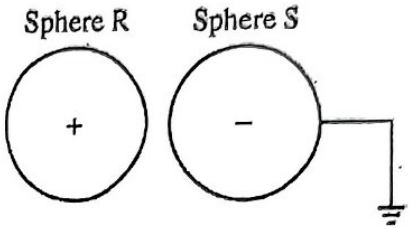
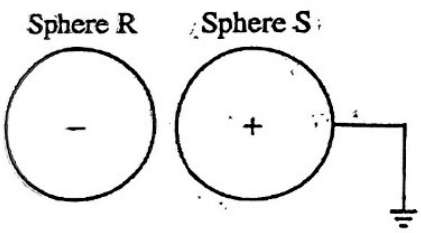


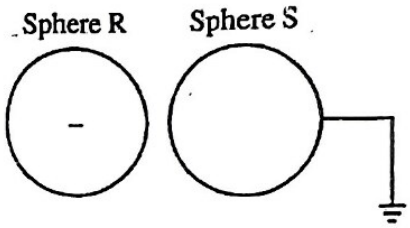
Figure 2

41. Identical conducting spheres R and S are touching, and Sphere S is connected to ground. An insulating rod with a positive net charge is brought near to, but does not touch, Sphere R, as shown in Figure 1. Then, Sphere R is moved so that Sphere R is close to, but no longer touches, Sphere S. Finally, the rod is moved far away from the spheres, as shown in Figure 2. Which of the following best represents the net charges of the spheres in Figure 2 ?

(A) 

(B) 

(C) 

(D) 

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42. A student must experimentally determine the resistivity ρ of a cylindrical resistor of unknown resistance. Which of the following indicates the equipment and measuring devices that are necessary to experimentally determine ρ ?

(A) Voltmeter and ruler

(B) Battery, ruler, and wires

(C) Ammeter, battery, voltmeter, and wires

(D) Ammeter, battery, ruler, voltmeter, and wires

43. Monochromatic light passes through a small slit of width w. An interference pattern of bright and dark spots is formed on a screen that is a distance D away from the slit. The distance between the center of the central bright spot and the center of an adjacent dark spot is y. Which of the following claims is correct?

(A) The frequency of the light is approximately $\frac{cD}{2wy}$.

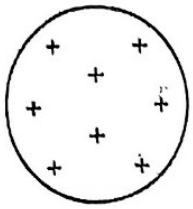
(B) The frequency of the light is approximately $\frac{2cD}{wy}$.

(C) The wavelength of the light is approximately $\frac{wy}{D}$.

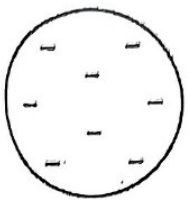
(D) The wavelength of the light is approximately $\frac{wy}{2D}$.

44. A beam of photons is incident on a solid metal sphere that is initially neutral. Each photon has an energy that is greater than the work function of the metal. Each of the following figures represents the cross section of the sphere with a possible distribution of excess charge on the surface of and inside the sphere after the photons interact with the sphere. Which figure best represents the distribution of excess charge?

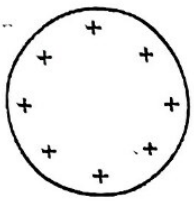
(A)



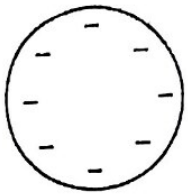
(B)

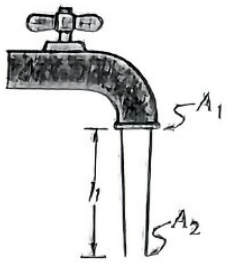


(C)



(D)





45. The figure shows water that flows in a continuous stream from a pipe with cross-sectional area A_1. The water exits the pipe with initial speed vy toward the ground. After the water has fallen a distance h, the cross-sectional area of the stream is A_2. Which of the following is equal to the ratio $\frac{A_1}{A_2}$?

(A) $\frac{v_1}{\sqrt{v_1^2 - 2gh}}$

(B) $\frac{v_1}{\sqrt{v_1^2 + 2gh}}$

(C) $\frac{\sqrt{v_1^2 - 2gh}}{v_1}$

(D) $\frac{\sqrt{v_1^2 + 2gh}}{v_1}$

Directions: For each of the questions or incomplete statements below, two of the suggested answers will be correct. For each of these questions, you must select both correct choices to earn credit. No partial credit will be earned if only one correct choice is selected. Select the two that are best in each case and then fill in the corresponding circles that begin with number 131 on the answer sheet.

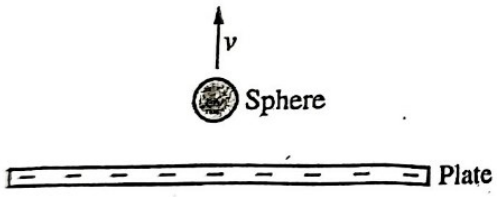
131. Ideal gas molecules are in a thermally insulated container that has a movable piston at one end. The piston is moved outward. Which of the following claims are correct about the gas molecules as the piston is moved? Select two answers.

(A) The average speed of the molecules increases.

(B) The force exerted on the piston by the molecules increases.

(C) The pressure due to the molecules decreases.

(D) The number of collisions each second between the molecules and the piston decreases.



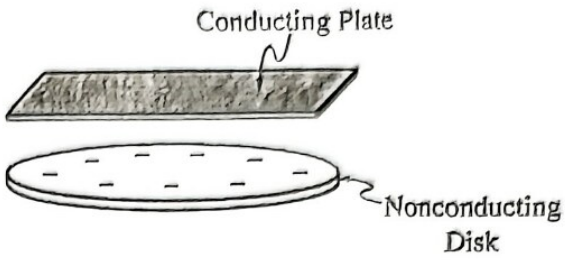
132. A nonconducting plate with a negative net charge is held at rest. At the instant shown, a conducting sphere with a net charge of zero is moving at speed v away from the plate. Gravitational effects are negligible. Which of the following claims are correct at the instant shown? Select two answers.

(A) The net force exerted on the sphere is zero.

(B) The momentum of the sphere is decreasing in magnitude.

(C) The electrical potential energy of the plate-sphere system is increasing.

(D) The acceleration of the sphere is in the same direction as the velocity of the sphere.



133. A nonconducting disk has a uniformly distributed net negative charge. A conducting plate with a net charge of zero is held near the disk, as shown. A wire is then used to connect the plate to ground. The wire is then cut, and the plate is moved far away from the disk. Which of the following claims are correct? Select two answers.

(A) A net movement of electrons occurs from the plate to ground immediately after the wire connects the plate to ground.

(B) The plate and disk attract each other as the plate is moved away from the disk.

(C) The plate has a net charge of zero when the plate is far away from the disk.

(D) The electric potential energy of the disk-plate system decreases as the plate is moved away from the disk.

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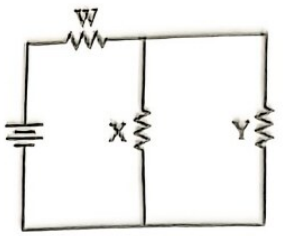

134. A circuit consists of a battery and identical resistors W, X, and Y, as shown. A fourth identical resistor, Resistor Z, is added to the circuit so that the current in Resistor Y decreases. Which of the following correctly describe where Resistor Z could have been added into the circuit? Select two answers.

(A) In parallel with Resistor W

(B) In series with Resistor X

(C) In parallel with Resistor Y

(D) In series with the battery



135. The figure shows two energy levels of a hypothetical isolated atom. The atom is initially in the $n = 2$ state. The atom then transitions to the $n = 1$ state. Which of the following statements are correct? Select two answers.

(A) A photon is absorbed by the atom during the transition.

(B) 5.0 eV of energy transfers out of the atom during the transition.

(C) The net charge of the atom changes by 1.60×10^{-19} C during the transition.

(D) The magnitude of the change in the momentum of the atom during the transition is approximately 2.7×10^{-27} kg · m/s.

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GO ON TO THE NEXT PAGE.

END OF SECTION I

IF YOU FINISH BEFORE TIME IS CALLED, YOU MAY
CHECK YOUR WORK ON THIS SECTION.

DO NOT GO ON TO SECTION II UNTIL YOU ARE TOLD TO DO SO.

MAKE SURE YOU HAVE DONE THE FOLLOWING:

- PLACED YOUR AP ID LABEL ON YOUR ANSWER SHEET
- WRITTEN AND GRIDDED YOUR AP ID CORRECTLY ON YOUR ANSWER SHEET
- TAKEN THE AP EXAM LABEL FROM THE FRONT OF THIS BOOKLET AND PLACED IT ON YOUR ANSWER SHEET

AP® Physics 2: Algebra-Based Ex

Friday afternoon, May 17, 2024

SECTION II: Free Response, Reference

DO NOT OPEN THIS BOOKLET UNTIL YOU ARE TOLD TO DO SO.

Instructions

This booklet may be used for reference and/or scratch work as you a
free-response questions, but no credit will be given for the work sho
Write your answers in the separate Section II: Free Response bookle

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or use of any part of this test is prohibited and may result in cancellation of scores and possible prosecution to the ful

AP® PHYSICS 2 TABLE OF INFORMATION

CONSTANTS AND CONVERSION FACTORS

Proton mass,	$m_p = 1.67 \times 10^{-27}$ kg	Electron charge magnitude,	$e = 1.60 \times 10^{-19}$ C
Neutron mass,	$m_n = 1.67 \times 10^{-27}$ kg	1 electron volt,	1 eV $= 1.60 \times 10^{-19}$ J
Electron mass,	$m_e = 9.11 \times 10^{-31}$ kg	Speed of light,	$c = 3.00 \times 10^{8}$ m/s
Avogadro's number,	$N_0 = 6.02 \times 10^{23}$ mol^{-1}	Universal gravitational constant,	$G = 6.67 \times 10^{-11}$ m^3/kg·s^2
Universal gas constant,	$R = 8.31$ J/(mol·K)	Acceleration due to gravity at Earth's surface,	$g = 9.8$ m/s^2
Boltzmann's constant,	$k_B = 1.38 \times 10^{-23}$ J/K		

1 unified atomic mass unit,	$1\text{ u} = 1.66 \times 10^{-27}$ kg $= 931$ MeV/c^2
Planck's constant,	$h = 6.63 \times 10^{-34}$ J·s $= 4.14 \times 10^{-15}$ eV·s
	$hc = 1.99 \times 10^{-25}$ J·m $= 1.24 \times 10^{3}$ eV·nm
Vacuum permittivity,	$\varepsilon_0 = 8.85 \times 10^{-12}$ C^2/N·m^2
Coulomb's law constant,	$k = 1/4\pi\varepsilon_0 = 9.0 \times 10^{9}$ N·m^2/C^2
Vacuum permeability,	$\mu_0 = 4\pi \times 10^{-7}$ (T·m)/A
Magnetic constant,	$k' = \mu_0/4\pi = 1 \times 10^{-7}$ (T·m)/A
1 atmosphere pressure,	1 atm $= 1.0 \times 10^{5}$ N/m^2 $= 1.0 \times 10^{5}$ Pa

UNIT SYMBOLS								
	meter,	m	mole,	mol	watt,	W	farad,	F
	kilogram,	kg	hertz,	Hz	coulomb,	C	tesla,	T
	second,	s	newton,	N	volt,	V	degree Celsius,	°C
	ampere,	A	pascal,	Pa	ohm,	Ω	electron volt,	eV
	kelvin,	K	joule,	J	henry,	H		

PREFIXES		
Factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

VALUES OF TRIGONOMETRIC FUNCTIONS FOR COMMON ANGLES							
θ	0°	30°	37°	45°	53°	60°	90°
$\sin\theta$	0	1/2	3/5	$\sqrt{2}/2$	4/5	$\sqrt{3}/2$	1
$\cos\theta$	1	$\sqrt{3}/2$	4/5	$\sqrt{2}/2$	3/5	1/2	0
$\tan\theta$	0	$\sqrt{3}/3$	3/4	1	4/3	$\sqrt{3}$	∞

The following conventions are used in this exam.

I. The frame of reference of any problem is assumed to be inertial unless otherwise stated.
II. In all situations, positive work is defined as work done on a system.
III. The direction of current is conventional current: the direction in which positive charge would drift.
IV. Assume all batteries and meters are ideal unless otherwise stated.
V. Assume edge effects for the electric field of a parallel plate capacitor unless otherwise stated.
VI. For any isolated electrically charged object, the electric potential is defined as zero at infinite distance from the charged object.

AP® PHYSICS 2 EQUATIONS

MECHANICS

$v_x = v_{x0} + a_x t$

$x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$

$v_x^2 = v_{x0}^2 + 2a_x (x - x_0)$

$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$

$|\vec{F}_f| \le \mu |\vec{F}_n|$

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

$\vec{p} = m\vec{v}$

$\Delta \vec{p} = \vec{F} \Delta t$

$K = \frac{1}{2} m v^2$

$\Delta E = W = F_{\parallel} d = F d \cos\theta$

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

$\theta = \theta_0 + \omega_0 t + \frac{1}{2} \alpha t^2$

$\omega = \omega_0 + \alpha t$

$x = A\cos(\omega t) = A\cos(2\pi f t)$

$x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$

$\vec{\alpha} = \frac{\sum \vec{\tau}}{I} = \frac{\vec{\tau}_{net}}{I}$

$\tau = r_{\perp} F = r F \sin\theta$

$L = I\omega$

$\Delta L = \tau \Delta t$

$K = \frac{1}{2} I \omega^2$

$|\vec{F}_s| = k|\vec{x}|$

a = acceleration
A = amplitude
d = distance
E = energy
F = force
f = frequency
I = rotational inertia
K = kinetic energy
k = spring constant
L = angular momentum
ℓ = length
m = mass
P = power
p = momentum
r = radius or separation
T = period
t = time
U = potential energy
v = speed
W = work done on a system
x = position
y = height
α = angular acceleration
μ = coefficient of friction
θ = angle
τ = torque
ω = angular speed

$U_s = \frac{1}{2} k x^2$

$\Delta U_g = mg \Delta y$

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

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

$T_p = 2\pi \sqrt{\frac{\ell}{g}}$

$|\vec{F}_g| = G \frac{m_1 m_2}{r^2}$

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

$U_G = -\frac{G m_1 m_2}{r}$

ELECTRICITY AND MAGNETISM

$|\vec{F}_E| = \frac{1}{4\pi\varepsilon_0} \frac{|q_1 q_2|}{r^2}$

$\vec{E} = \frac{\vec{F}_E}{q}$

$|\vec{E}| = \frac{1}{4\pi\varepsilon_0} \frac{|q|}{r^2}$

$\Delta U_E = q \Delta V$

$V = \frac{1}{4\pi\varepsilon_0} \frac{q}{r}$

$|\vec{E}| = \left| \frac{\Delta V}{\Delta r} \right|$

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

$C = \kappa \varepsilon_0 \frac{A}{d}$

$E = \frac{Q}{\varepsilon_0 A}$

$U_C = \frac{1}{2} Q \Delta V = \frac{1}{2} C (\Delta V)^2$

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

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

$P = I \Delta V$

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

$R_s = \sum_i R_i$

$\frac{1}{R_p} = \sum_i \frac{1}{R_i}$

$C_p = \sum_i C_i$

$\frac{1}{C_s} = \sum_i \frac{1}{C_i}$

$B = \frac{\mu_0 I}{2\pi r}$

A = area
B = magnetic field
C = capacitance
d = distance
E = electric field
$\mathcal{E}$ = emf
F = force
I = current
ℓ = length
P = power
Q = charge
q = point charge
R = resistance
r = separation
t = time
U = potential (stored) energy
V = electric potential
v = speed
κ = dielectric constant
ρ = resistivity
θ = angle
Φ = flux

$\vec{F}_M = q\vec{v} \times \vec{B}$

$|\vec{F}_M| = |q\vec{v}| \sin\theta |\vec{B}|$

$\vec{F}_M = I\vec{\ell} \times \vec{B}$

$|\vec{F}_M| = |I\vec{\ell}| \sin\theta |\vec{B}|$

$\Phi_B = \vec{B} \cdot \vec{A}$

$\Phi_B = |\vec{B}| \cos\theta |\vec{A}|$

$\mathcal{E} = -\frac{\Delta \Phi_B}{\Delta t}$

$\mathcal{E} = B\ell v$

AP® PHYSICS 2 EQUATIONS

FLUID MECHANICS AND THERMAL PHYSICS

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

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

$P = P_0 + \rho g h$

$F_b = \rho V g$

$A_1 v_1 = A_2 v_2$

$P_1 + \rho g y_1 + \frac{1}{2}\rho v_1^2 = P_2 + \rho g y_2 + \frac{1}{2}\rho v_2^2$

$\frac{Q}{\Delta t} = \frac{kA\,\Delta T}{L}$

$PV = nRT = Nk_BT$

$K = \frac{3}{2}k_BT$

$W = -P\Delta V$

$\Delta U = Q + W$

A = area
F = force
h = depth
k = thermal conductivity
K = kinetic energy
L = thickness
m = mass
n = number of moles
N = number of molecules
P = pressure
Q = energy transferred to a system by heating
T = temperature
t = time
U = internal energy
V = volume
v = speed
W = work done on a system
y = height
ρ = density

WAVES AND OPTICS

$\lambda = \frac{v}{f}$

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

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

$\frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f}$

$|M| = \left|\frac{h_I}{h_o}\right| = \left|\frac{s_i}{s_o}\right|$

$\Delta L = m\lambda$

$d\sin\theta = m\lambda$

d = separation
f = frequency or focal length
h = height
L = distance
M = magnification
m = an integer
n = index of refraction
s = distance
v = speed
λ = wavelength
θ = angle

MODERN PHYSICS

$E = hf$

$K_{max} = hf - \phi$

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

$E = mc^2$

E = energy
f = frequency
K = kinetic energy
m = mass
p = momentum
λ = wavelength
ϕ = work function

GEOMETRY AND TRIGONOMETRY

Rectangle
$A = bh$

Triangle
$A = \frac{1}{2}bh$

Circle
$A = \pi r^2$
$C = 2\pi r$

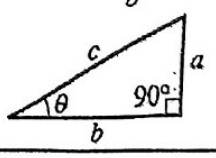
Rectangular solid
$V = \ell wh$

Cylinder
$V = \pi r^2 \ell$
$S = 2\pi r\ell + 2\pi r^2$

Sphere
$V = \frac{4}{3}\pi r^3$
$S = 4\pi r^2$

A = area
C = circumference
V = volume
S = surface area
b = base
h = height
ℓ = length
w = width
r = radius

Right triangle
$c^2 = a^2 + b^2$
$\sin\theta = \frac{a}{c}$
$\cos\theta = \frac{b}{c}$
$\tan\theta = \frac{a}{b}$



Begin your response to **QUESTION 1** on this page.

PHYSICS 2

SECTION II

Time—1 hour and 30 minutes

4 Questions

Directions: Questions 1 and 4 are short free-response questions that require about 20 minutes each to answer and are worth 10 points each. Questions 2 and 3, are long free-response questions that require about 25 minutes each to answer and are worth 12 points each. Show your work for each part in the space provided after that part.

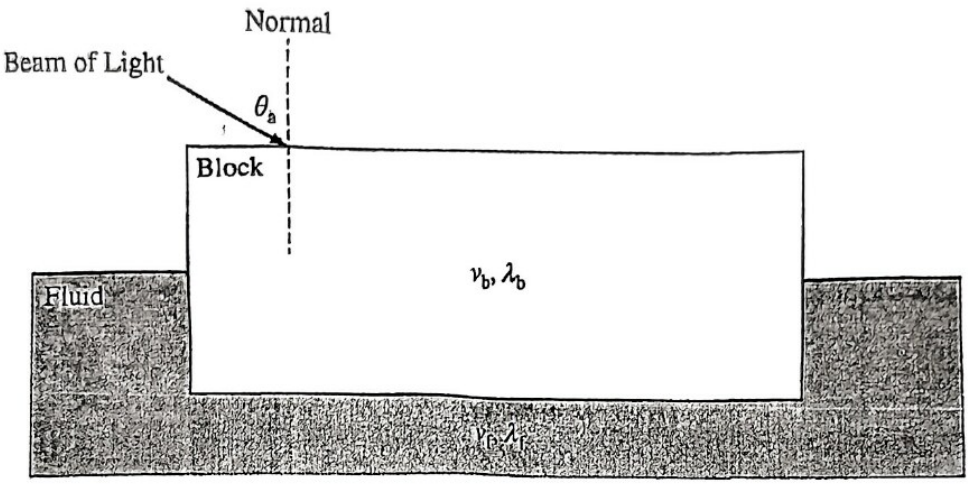


Figure 1

1. (10 points, suggested time 20 minutes)

A transparent plastic block floats in a fluid. A beam of light of a single wavelength in air (index of refraction $n_a = 1$) is incident on the top side of the block at an angle θ_a from the normal, as shown in Figure 1. The speeds of the light in the block and in the fluid are v_b and v_f, respectively, such that $c > v_f > v_b$. The light exits the bottom side of the block at an angle θ_f from the normal (not shown). The wavelengths of the light in the air, the block, and the fluid are λ_a, λ_b, and λ_f, respectively.

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AP® PHYSICS 2 EQUATIONS

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

$$P = P_0 + \rho g h$$

$$F_b = \rho V g$$

$$A_1 v_1 = A_2 v_2$$

$$P_1 + \rho g y_1 + \frac{1}{2}\rho v_1^2 = P_2 + \rho g y_2 + \frac{1}{2}\rho v_2^2$$

$$\frac{Q}{\Delta t} = \frac{kA\,\Delta T}{L}$$

$$PV = nRT = Nk_BT$$

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

$$\frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f}$$

$$|M| = \left|\frac{h_i}{h_o}\right| = \left|\frac{s_i}{s_o}\right|$$

$$\Delta L = m\lambda$$

$$d\sin\theta = m\lambda$$

d = separation
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θ = angle

MODERN PHYSICS

$$E = hf$$

$$K_{max} = hf - \phi$$

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

$$E = mc^2$$

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f = frequency
K = kinetic energy
m = mass
p = momentum
λ = wavelength
ϕ = work function

GEOMETRY AND TRIGONOMETRY

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Rectangular solid
$V = \ell wh$

Cylinder
$V = \pi r^2 \ell$
$S = 2\pi r\ell + 2\pi r^2$

Sphere
$V = \frac{4}{3}\pi r^3$
$S = 4\pi r^2$

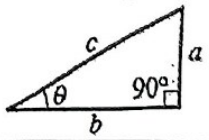
A = area
C = circumference
V = volume
S = surface area
b = base
h = height
ℓ = length
w = width
r = radius

Right triangle
$c^2 = a^2 + b^2$

$\sin\theta = \frac{a}{c}$

$\cos\theta = \frac{b}{c}$

$\tan\theta = \frac{a}{b}$



Question 1

Continue your response to **QUESTION 1** on this page.

(a) **Compare** λ_a, λ_b, and λ_f by ranking the wavelengths from greatest to least in the following spaces. Use 1 for the greatest wavelength, 2 for the next greatest wavelength, and so on. If any of the wavelengths are the same, use the same number for their ranking.

____ λ_a ____ λ_b ____ λ_f

Justify your ranking.

(b) For parts (b)(i) and (b)(ii), express your answers only in terms of θ_a, v_b, θ_f, and physical constants, as appropriate.

i. **Derive** an expression for the angle of refraction θ_b of the light in the block.

ii. **Derive** an expression for the index of refraction n_f of the fluid.

Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

Continue your response to **QUESTION 1** on this page.

The block is removed from the fluid. A new beam of light consists of both red and green light, each of a single wavelength in air. The beam is incident on the top side of the block at an angle θ_a from the normal, as shown in Figure 2. The speeds of the red light and the green light in the block are v_R and v_G, respectively, such that $c > v_R > v_G$.

(c) Complete the following tasks on the diagram provided in Figure 2.

- **Draw** lines to represent the entire paths of the red light and the green light as the light travels through the block and then exits the bottom side of the block.
- Clearly **label** the paths of the red light and the green light on your diagram.
- If any of the lines you drew are parallel to each other, **label** the lines "Parallel."

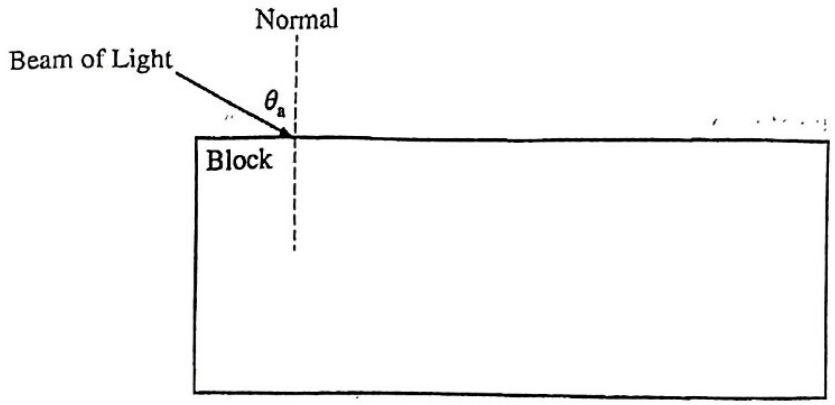


Figure 2

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Question 2

Begin your response to **QUESTION 2** on this page.

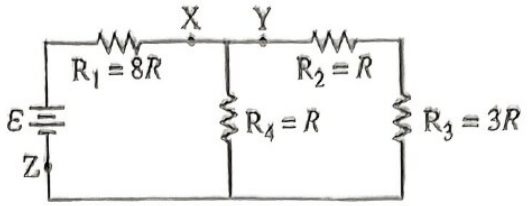

Figure 1

2. (12 points, suggested time 25 minutes)

The circuit shown in Figure 1 consists of an ideal battery of emf $\mathcal{E}$ and four resistors, R_1, R_2, R_3, and R_4, of resistances $8R$, R, $3R$, and R, respectively.

(a) **Compare** the current at the labeled points X, Y, and Z by ranking the currents from greatest to least in the following spaces.

Use 1 for the greatest current, 2 for the next-greatest current, and so on. If any of the currents are the same, use the same number for their ranking.

____ X ____ Y ____ Z

Justify your ranking.

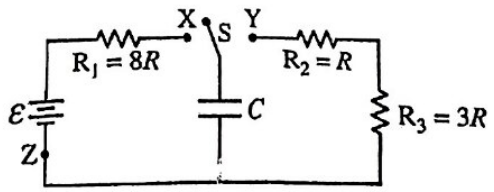

Figure 2

Resistor R_4 is then replaced with an uncharged capacitor of capacitance C that is connected to Switch S, which is initially open and can be closed to positions X or Y, as shown in Figure 2.

At time t_X, the switch is closed to Position X. The capacitor becomes fully charged. At a later time t_Y, the switch is then closed to Position Y.

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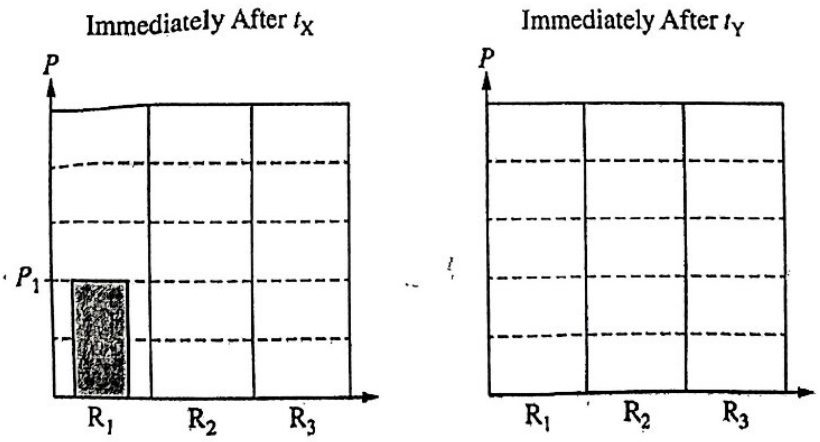
(b) Express your answers to parts (b)(i) and (b)(ii) in terms of numerical values, $\mathcal{E}$, and R only.

i. Immediately after time t_X, the current at Position X is I_X. Determine an expression for I_X.

ii. Immediately after time t_Y, the current at Position Y is I_Y. Derive an expression for I_Y.

(c) On the grids provided, complete the bar chart for each resistor immediately after time t_X and immediately after time t_Y. The bar shown on the grid represents the power P_1 dissipated by Resistor R_1 immediately after t_X. Both grids are drawn with the same scale.

- Draw a bar to represent the instantaneous power P dissipated by each resistor.
- The height of each bar should be proportional to the value of P represented by that bar, relative to P_1.
- If the value of P is zero, write a "0" in that column.



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(d) Immediately after time t_X, the total instantaneous power dissipated by the circuit is P_X. Immediately after time t_Y, the total instantaneous power dissipated by the circuit is P_Y. A student claims that P_Y is equal to P

State whether the student's claim is correct or incorrect. Justify your answer by referring to the expressions derived in parts (b)(i) and (b)(ii) or to the bar charts drawn in part (c).

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Question 3

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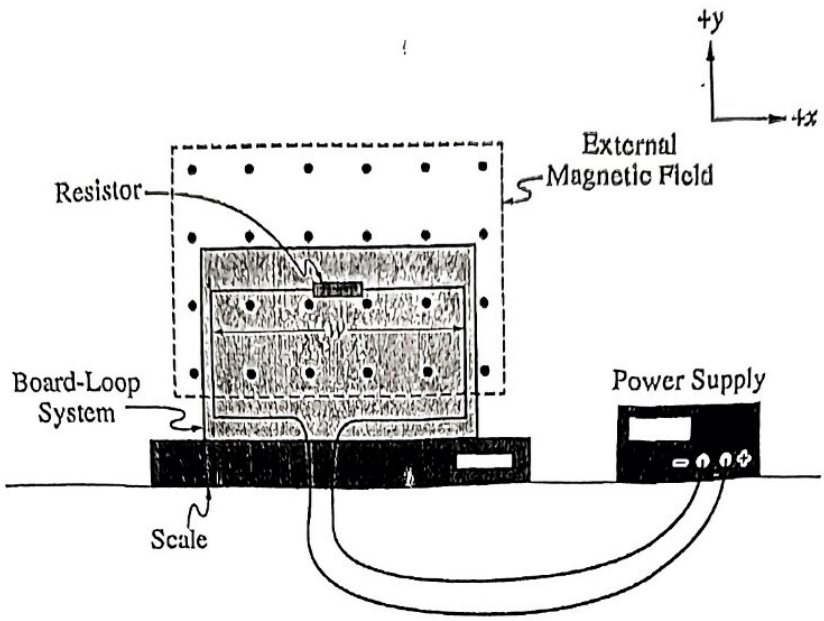

3. (12 points, suggested time 25 minutes)

In an experiment, a scientist wants to collect data that could be used to graphically determine the resistance R of a resistor. A circuit consisting of a power supply of variable emf $\mathcal{E}$, the resistor, and wires of negligible resistance is arranged in a rectangular loop. The width of the loop is w. The loop is attached to a board that rests vertically on top of a scale. The scale is zeroed so that none of the readings include the weight of the board-loop system.

Later, a region of external uniform magnetic field of known, constant magnitude B is directed out of the page such that only part of the loop is within the magnetic field, as shown. When the magnetic field is on, the scale gives a reading of magnitude F_{scale}.

(a) On the dot shown, representing the board-loop system, **draw** an arrow to represent the direction of the magnetic force exerted on the board-loop system by the external magnetic field. The force must be represented by a distinct arrow starting on, and pointing away from, the dot.

Briefly **justify** your answer.

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(b) **Derive** an expression for R. Express your answer in terms of $\mathcal{E}$, w, B, F_{scale}, and physical constants, as appropriate.

(c) **Describe** a procedure to collect data that could be used to graphically determine R by using the setup provided. The emf $\mathcal{E}$ may be read from the power supply, and F_{scale} may be read from the scale, but no other electronic equipment is available.

- In your description, include the measurements to be made along with the corresponding equipment needed. Assume equipment usually found in a school physics laboratory is available.
- Provide enough detail so that someone else could replicate the experiment, including any steps necessary to reduce experimental uncertainty.

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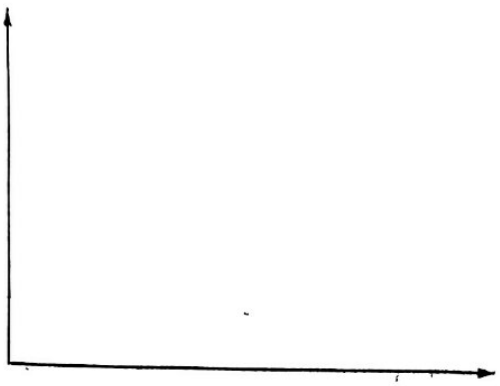
(d)

i. On the axes provided, complete the following tasks to represent collected data that would allow the scientist to graphically determine R from a best-fit curve or line.

- **Label** the quantities the scientist could graph on the vertical and horizontal axes.
- **Sketch** a line or curve that represents the expected trend of the collected data.



ii. **Describe** how the sketch of the curve or line in part (d)(i) would be used to determine R.

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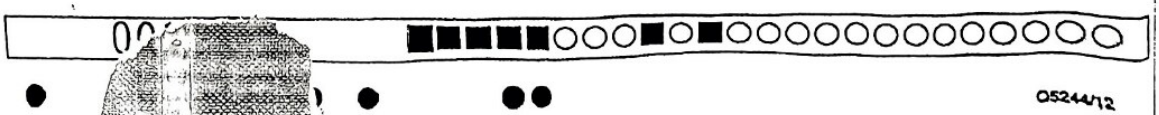

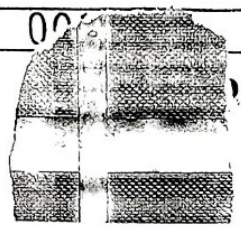

Question 4

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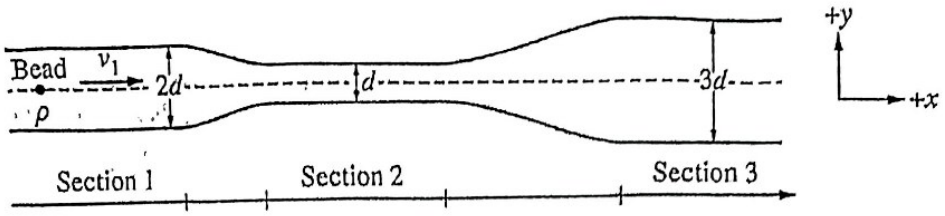

Figure 1. Side View

4. (10 points, suggested time 20 minutes)

Cylindrical sections 1, 2, and 3 of a closed pipe are completely filled with moving water of density ρ. The diameters of sections 1, 2, and 3 are $2d$, d, and $3d$, respectively. A small bead of mass m and density ρ travels with the water through the center of each section, as shown in Figure 1. The velocity of the bead and the water in Section 1 is v_1 in the $+x$-direction.

(a) **Derive** an expression for the magnitude Δp of the change in momentum of the bead from immediately before the bead exits Section 1 to immediately after the bead enters Section 3. Express your answer in terms of m, v_1, and physical constants, as appropriate.

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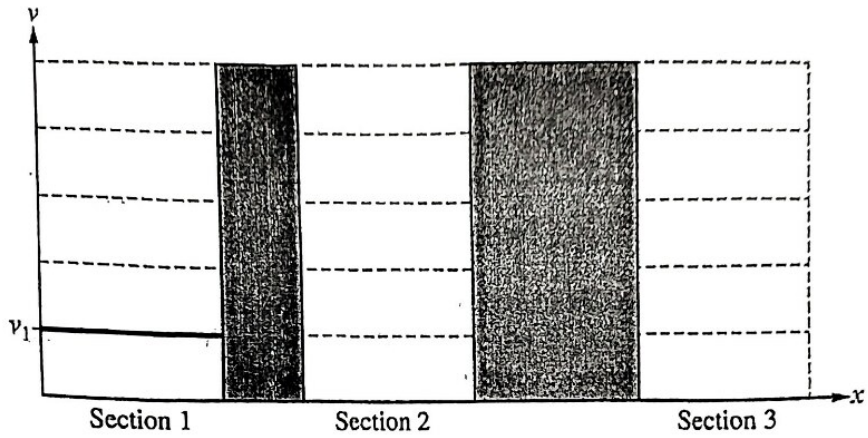
(b) On the following axes, **sketch** a graph of the speed v of the bead as a function of horizontal position x as the bead travels with the water through sections 2 and 3. The sketch for Section 1 is provided. It is not necessary to sketch in the shaded regions, which represent the connecting segments between the labeled sections.



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Question 4

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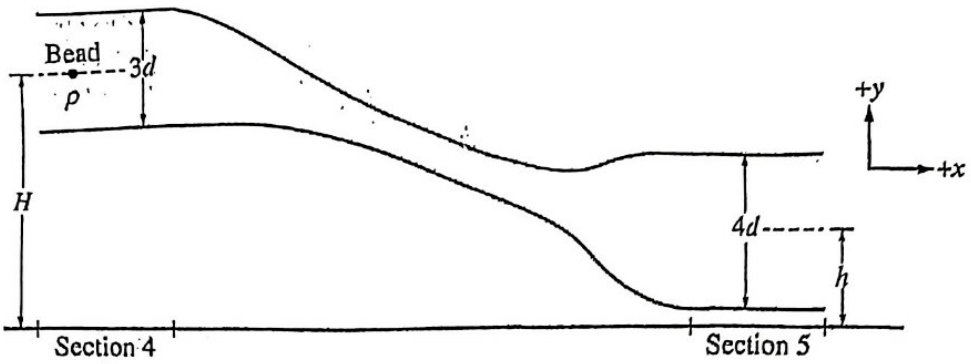

Figure 2. Side View

The bead continues to travel with the water through the centers of different closed sections of the pipe. Cylindrical sections 4 and 5 have diameters $3d$ and $4d$, respectively. The distance between the ground and the centers of sections 4 and 5 are H and h, respectively, where $H > h$, as shown in Figure 2.

The pressures in sections 4 and 5 are P_4 and P_5, respectively.

(c) In a coherent, paragraph-length response, **indicate** whether P_5 is greater than, less than, or equal to P_4. **Justify** your answer.

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