AP® Physics C: Electricity and Magnetism Exam

SECTION I: Multiple Choice

2016

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

At a Glance

Total Time
45 minutes
Number of Questions
35
Percent of Total Score
50%
Writing Instrument
Pencil required
Electronic Device
Calculator allowed

Instructions

Section I of this exam contains 35 multiple-choice questions. For these questions, fill in only the circles for numbers 1 through 35 on your answer sheet. A table of information and lists of equations that may be helpful are in the booklet. Calculators, rulers and straightedges may be used in this section.

Indicate all of your answers to the multiple-choice questions on the answer sheet. No credit will be given for anything written in this exam booklet, but you may use the booklet for notes or scratch work. After you have decided which of the suggested answers is best, completely fill in the corresponding circle on the answer sheet. Give only one answer to each question. If you change an answer, be sure that the previous mark is erased completely. Here is a sample question and answer.

Sample Question	Sample Answer
Chicago is a (A) state (B) city (C) country (D) continent (E) village	Ⓐ ● Ⓒ Ⓓ Ⓔ

Use your time effectively, working as quickly as you can without losing accuracy. Do not spend too much time on any one question. Go on to other questions and come back to the ones you have not answered if you have time. It is not expected that everyone will know the answers to all of the multiple-choice questions.

Your total score on the multiple-choice section is based only on the number of questions answered correctly. Points are not deducted for incorrect answers or unanswered questions.

Form I
Form Code 4MBP4-S

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ADVANCED PLACEMENT PHYSICS C 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, $G = 6.67 \times 10^{-11}$ $\left(\text{N}\cdot\text{m}^2\right)/\text{kg}^2$
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, $1\text{ u} = 1.66 \times 10^{-27}\text{ kg} = 931\text{ MeV}/c^2$

Planck's constant, $h = 6.63 \times 10^{-34}\text{ J}\cdot\text{s} = 4.14 \times 10^{-15}\text{ eV}\cdot\text{s}$

$hc = 1.99 \times 10^{-25}\text{ J}\cdot\text{m} = 1.24 \times 10^{3}\text{ eV}\cdot\text{nm}$

Vacuum permittivity, $\varepsilon_0 = 8.85 \times 10^{-12}\ \text{C}^2/\left(\text{N}\cdot\text{m}^2\right)$

Coulomb's law constant, $k = 1/(4\pi\varepsilon_0) = 9.0 \times 10^{9}\ \left(\text{N}\cdot\text{m}^2\right)/\text{C}^2$

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, $1\text{ atm} = 1.0 \times 10^{5}\ \text{N/m}^2 = 1.0 \times 10^{5}$ 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^{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 assumptions are used in this exam.

I. The frame of reference of any problem is inertial unless otherwise stated.
II. The direction of current is the direction in which positive charges would drift.
III. The electric potential is zero at an infinite distance from an isolated point charge.
IV. All batteries and meters are ideal unless otherwise stated.
V. Edge effects for the electric field of a parallel plate capacitor are negligible unless otherwise stated.

ADVANCED PLACEMENT PHYSICS C EQUATIONS

MECHANICS

$v_x = v_{x0} + a_x t$

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

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

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

$\vec{F} = \frac{d\vec{p}}{dt}$

$\vec{J} = \int \vec{F}\, dt = \Delta\vec{p}$

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

$\left|\vec{F}_f\right| \le \mu \left|\vec{F}_N\right|$

$\Delta E = W = \int \vec{F} \bullet d\vec{r}$

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

$P = \frac{dE}{dt}$

$P = \vec{F} \bullet \vec{v}$

$\Delta U_g = mg\Delta h$

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

$\vec{\tau} = \vec{r} \times \vec{F}$

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

$I = \int r^2 dm = \sum m r^2$

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

$v = r\omega$

$\vec{L} = \vec{r} \times \vec{p} = I\vec{\omega}$

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

$\omega = \omega_0 + \alpha t$

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

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

$\vec{F}_s = -k\Delta\vec{x}$

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

$x = x_{\max} \cos(\omega t + \phi)$

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

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

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

$\left|\vec{F}_G\right| = \frac{G m_1 m_2}{r^2}$

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

ELECTRICITY AND MAGNETISM

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

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

$\oint \vec{E} \bullet d\vec{A} = \frac{Q}{\varepsilon_0}$

$E_x = -\frac{dV}{dx}$

$\Delta V = -\int \vec{E} \bullet d\vec{r}$

$V = \frac{1}{4\pi\varepsilon_0} \sum_i \frac{q_i}{r_i}$

$U_E = qV = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r}$

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

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

$C_p = \sum_i C_i$

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

$I = \frac{dQ}{dt}$

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

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

$\vec{E} = \rho\vec{J}$

$I = Nev_d A$

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

$R_s = \sum_i R_i$

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

$P = I\Delta V$

A = area
B = magnetic field
C = capacitance
d = distance
E = electric field
ε = emf
F = force
I = current
J = current density
L = inductance
ℓ = length
n = number of loops of wire per unit length
N = number of charge carriers per unit volume
P = power
Q = charge
q = point charge
R = resistance
r = radius or distance
t = time
U = potential or stored energy
V = electric potential
v = velocity or speed
ρ = resistivity
Φ = flux
κ = dielectric constant

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

$\oint \vec{B} \bullet d\vec{\ell} = \mu_0 I$

$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\, d\vec{\ell} \times \hat{r}}{r^2}$

$\vec{F} = \int I\, d\vec{\ell} \times \vec{B}$

$B_s = \mu_0 n I$

$\Phi_B = \int \vec{B} \circ d\vec{A}$

$\varepsilon = \oint \vec{E} \bullet d\vec{\ell} = -\frac{d\Phi_B}{dt}$

$\varepsilon = -L\frac{dI}{dt}$

$U_L = \frac{1}{2} L I^2$

ADVANCED PLACEMENT PHYSICS C EQUATIONS

GEOMETRY AND TRIGONOMETRY

Rectangle

$A = bh$

Triangle

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

Circle

$A = \pi r^2$

$C = 2\pi r$

$s = r\theta$

Rectangular Solid

$V = \ell wh$

Cylinder

$V = \pi r^2 \ell$

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

Sphere

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

$S = 4\pi r^2$

Right Triangle

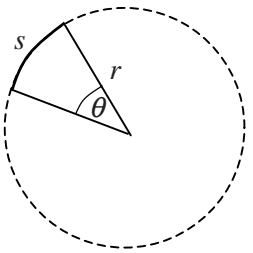
$a^2 + b^2 = c^2$

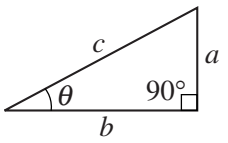
$\sin\theta = \frac{a}{c}$

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

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

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





CALCULUS

$$\frac{df}{dx} = \frac{df}{du}\frac{du}{dx}$$

$$\frac{d}{dx}\left(x^n\right) = nx^{n-1}$$

$$\frac{d}{dx}\left(e^{ax}\right) = ae^{ax}$$

$$\frac{d}{dx}(\ln ax) = \frac{1}{x}$$

$$\frac{d}{dx}[\sin(ax)] = a\cos(ax)$$

$$\frac{d}{dx}[\cos(ax)] = -a\sin(ax)$$

$$\int x^n\,dx = \frac{1}{n+1}x^{n+1},\ n \neq -1$$

$$\int e^{ax}\,dx = \frac{1}{a}e^{ax}$$

$$\int \frac{dx}{x+a} = \ln|x+a|$$

$$\int \cos(ax)\,dx = \frac{1}{a}\sin(ax)$$

$$\int \sin(ax)\,dx = -\frac{1}{a}\cos(ax)$$

VECTOR PRODUCTS

$\vec{A}\bullet\vec{B} = AB\cos\theta$

$\left|\vec{A}\times\vec{B}\right| = AB\sin\theta$

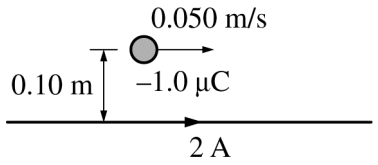
PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION I

Time—45 minutes

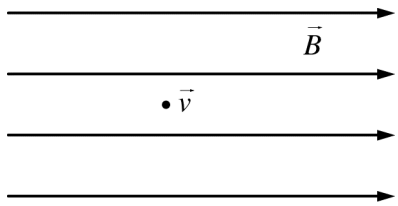
35 Questions

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



1. A small object of charge $-1.0\ \mu C$ that is 0.10 m above a long, straight wire moves at a speed of $0.050\ m/s$ parallel to the wire, as shown in the figure above. The current in the wire is 2 A. What is the magnitude and direction of the magnetic force on the object?

   (A) 2×10^{-13} N, toward the wire
   (B) 2×10^{-13} N, away from the wire
   (C) $4\pi \times 10^{-13}$ N, toward the wire
   (D) $4\pi \times 10^{-13}$ N, away from the wire
   (E) 0, direction is undefined



2. An electron travels through a uniform magnetic field $\vec{B}$ directed to the right. The electron's velocity $\vec{v}$ is directed out of the page, as shown in the figure above. The direction of the force on the electron due to the magnetic field at the instant shown is

   (A) toward the top of the page
   (B) toward the bottom of the page
   (C) to the left
   (D) to the right
   (E) into the page

3. Two long parallel wires have currents of I_1 and I_2 and are a distance d apart. The force per unit length exerted by one wire on the other is F/L. The current in each wire is doubled, and the distance between the wires is reduced to $d/2$. The new force per unit length is

   (A) $\frac{F}{2L}$
   (B) $\frac{F}{L}$
   (C) $\frac{2F}{L}$
   (D) $\frac{4F}{L}$
   (E) $\frac{8F}{L}$

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GO ON TO THE NEXT PAGE.

Questions 4-5

A capacitor is constructed of two large, identical, parallel metal plates separated by a small distance d. A battery fully charges the capacitor and is then disconnected.

4. The plate separation is now increased to a distance $2d$. Which of the following correctly describes the change, if any, of the voltage across the capacitor, the electric field between the plates, and the energy stored in the capacitor?

	Voltage	Electric Field	Energy
(A)	Does not change	Does not change	Does not change
(B)	Does not change	Doubles	Does not change
(C)	Doubles	Doubles	Does not change
(D)	Doubles	Does not change	Doubles
(E)	Doubles	Doubles	Doubles

5. If, instead of separating the plates, the empty space between the plates is filled with a slab of insulating material that has a dielectric constant $K = 2$, which of the following correctly describes the change, if any, of the voltage across the capacitor, the electric field between the plates, and the energy stored in the capacitor?

	Voltage	Electric Field	Energy
(A)	Halves	Halves	Halves
(B)	Halves	Halves	Does not change
(C)	Does not change	Does not change	Halves
(D)	Does not change	Halves	Halves
(E)	Does not change	Does not change	Does not change

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6. A capacitor stores energy U_1 when it holds charge Q. The same capacitor stores energy U_2 when it holds charge $16Q$. What is the ratio U_2/U_1?

(A) 8
(B) 16
(C) 64
(D) 128
(E) 256

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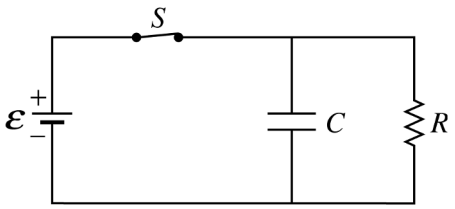
Questions 7-8



Switch S in the circuit shown above has been closed for a long time.

7. Which of the following is the correct expression for the current in the resistor?

   (A) $\frac{\mathcal{E}}{R}$

   (B) $\frac{C\mathcal{E}}{R}$

   (C) $C\mathcal{E}$

   (D) $\frac{\mathcal{E}}{RC}$

   (E) Zero

8. Suppose that the switch is opened at time $t = 0$. Which of the following combinations of a differential equation and an initial condition can be used to solve for the charge $Q(t)$ on the upper plate of the capacitor as a function of time t ?

	Differential Equation	Initial Condition
(A)	$\frac{Q}{C} - R\frac{dQ}{dt} = 0$	$Q(0) = C\mathcal{E}$
(B)	$\frac{Q}{C} - R\frac{dQ}{dt} = \mathcal{E}$	$Q(0) = 0$
(C)	$\frac{Q}{C} + R\frac{dQ}{dt} = \mathcal{E}$	$Q(0) = C\mathcal{E}$
(D)	$\frac{Q}{C} + R\frac{dQ}{dt} = 0$	$Q(0) = 0$
(E)	$\frac{Q}{C} + R\frac{dQ}{dt} = 0$	$Q(0) = C\mathcal{E}$

9. A nonconducting sphere of radius R has a uniform volume charge density ρ. At the surface of the sphere, the electric field strength is E. If a second sphere of radius $2R$ was created of the same material and with the same charge density, what would be the strength of the electric field at the surface of the second sphere?

   (A) $E/4$

   (B) $E/2$

   (C) E

   (D) $2E$

   (E) $4E$

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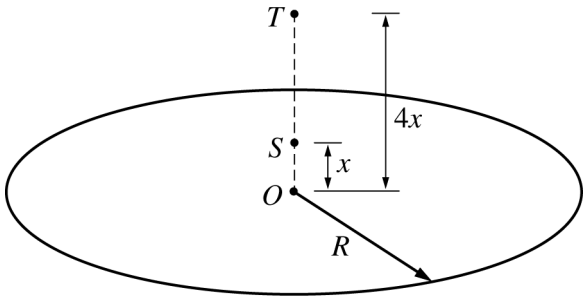
Questions 10-11



Note: Figure not drawn to scale.

The figure above shows a thin, circular nonconducting sheet of positive charge uniformly distributed over its area. The radius of the sheet is R. Point O is at the center of the sheet. Point S is a distance x from the center of the sheet, and point T is a distance $4x$ from the center of the sheet. Assume $R \gg x$.

10. If the magnitude of the electric field at point T is E_T, which of the following best represents the magnitude of the electric field at point S?

(A) $E_T/16$

(B) $E_T/4$

(C) E_T

(D) $4E_T$

(E) $16E_T$

11. A small sphere of mass m and charge $-q$ is released from rest at point T. If the electric potentials at points S and T are V_S and V_T, respectively, what is the speed of the sphere when it reaches point S? Ignore the effects of gravity.

(A) $\frac{2q}{m}(V_S + V_T)$

(B) $\frac{4q}{m}(V_S + V_T)$

(C) $\sqrt{\frac{q}{2m}(V_S - V_T)}$

(D) $\sqrt{\frac{q}{2m}(V_S + V_T)}$

(E) $\sqrt{\frac{2q}{m}(V_S - V_T)}$

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Questions 12-13

Capacitor	*K*	*L*	*M*	*N*
Plate area	*A*	*A*	2*A*	2*A*
Plate separation	*d*	2*d*	*d*	2*d*

The chart above shows the plate area and separation for four different air-filled parallel-plate capacitors: *K, L, M,* and *N*.

12. Each capacitor is charged such that the same electric field is created between the plates. Which of the following correctly ranks the charge stored on each capacitor?

(A) $(Q_M = Q_N) > (Q_K = Q_L)$
(B) $Q_M > Q_K > Q_N > Q_L$
(C) $(Q_K = Q_M) > (Q_L = Q_N)$
(D) $Q_K = Q_L = Q_M = Q_N$
(E) $Q_M > (Q_K = Q_N) > Q_L$

13. Each capacitor is charged such that the same potential difference exists across the plates. Which of the following correctly ranks the magnitude of electric field between the plates of each capacitor?

(A) $(E_M = E_N) > (E_K = E_L)$
(B) $E_M > E_K > E_N > E_L$
(C) $(E_K = E_M) > (E_L = E_N)$
(D) $E_K = E_L = E_M = E_N$
(E) $E_L > (E_K = E_N) > E_M$

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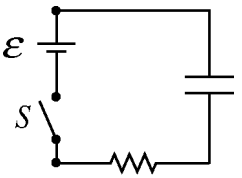
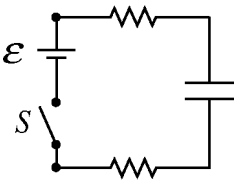
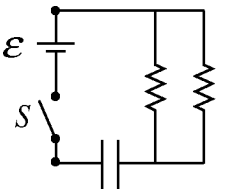
14. A parallel-plate capacitor stores 240 nC when fully charged by the application of a 12 V potential difference across its plates. What is its capacitance?

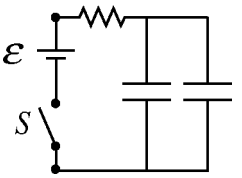
(A) 5.0×10^{-11} F
(B) 1.7×10^{-9} F
(C) 2.0×10^{-8} F
(D) 2.9×10^{-6} F
(E) 4.8×10^{-6} F

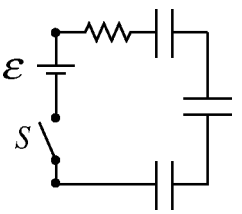
15. Identical resistors and identical uncharged capacitors are connected to identical ideal batteries of emf $\mathcal{E}$ in the circuits shown below. Each circuit has a switch *S* in the open position. In which circuit will the capacitors reach half their maximum charge in the least amount of time when switch *S* is closed?

(A)


(B)


(C)


(D)


(E)


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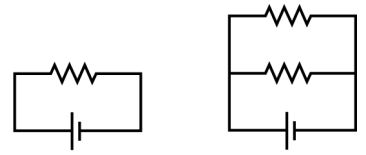
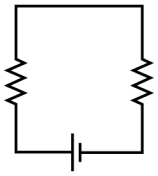
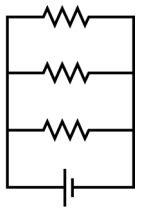


Circuit I

Circuit II



Circuit III



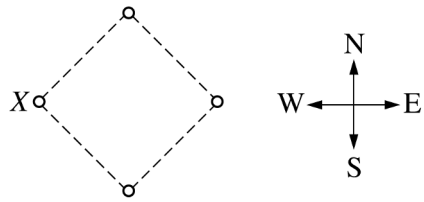
Circuit IV

16. All four circuits shown above contain identical ideal batteries and identical resistors. Which circuits draw the most and least power from the battery?

	Most Power	Least Power
(A)	I	II
(B)	I	V
(C)	II	III
(D)	IV	I
(E)	IV	III

17. The current in a $10\ \Omega$ resistor is given as a function of time t by the equation $I = I_0 e^{-\alpha t}$, where $I_0 = 4$ A and $\alpha = 2\ \text{s}^{-1}$. What is the total energy dissipated in the resistor from time $t = 0$ until the current becomes zero?

(A) 20 J
(B) 40 J
(C) 80 J
(D) 160 J
(E) 320 J



18. Four conducting wires perpendicular to the plane of the page are at the corners of a square, as shown in cross section in the figure above. The wires carry equal currents in the same direction. What is the direction of the total magnetic force on wire X caused by the other three wires?

(A) To the north
(B) To the south
(C) To the east
(D) To the west
(E) In none of the directions above, since the magnitude of the force is zero

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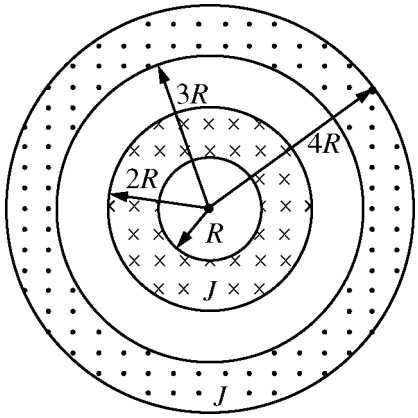
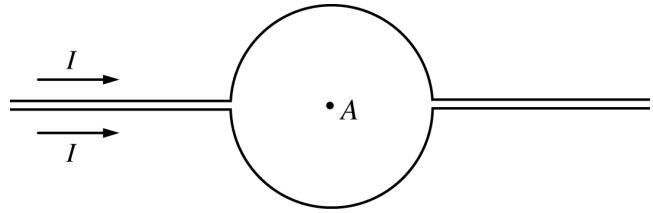


19. Two long, hollow, concentric conducting cylinders carry currents in opposite directions into and out of the plane of the page, as shown in the cross section above. The currents are unequal, but the current density J is the same for both cylinders. In which of the following regions can the net magnetic field be zero at some nonzero finite distance r from the central axis?

(A) $r < R$ only
(B) Both $r < R$ and $R < r < 2R$
(C) Both $r < R$ and $2R < r < 3R$
(D) Both $r < R$ and $3R < r < 4R$
(E) $r > 4R$ only



20. The middle sections of two long, straight wires are each bent into semicircular shapes. The two wires are placed close to each other in a plane as shown above. Point A is the center of the circle formed by the two wires. There is a current I in each wire. Which of the following best represents the direction of the magnetic field, if any, at point A due to the currents?

(A) ↓
(B) ↑
(C) ⊙ (Out of the page)
(D) ⊗ (Into the page)
(E) There is no direction, because the magnetic field is zero.

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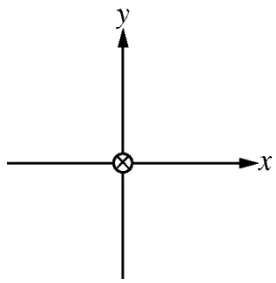
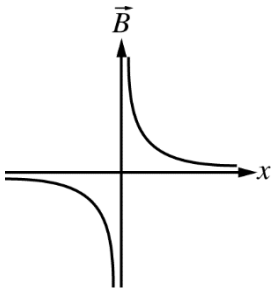
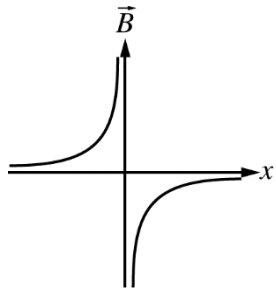


21. A long straight wire is located at the origin of an *xy*-coordinate system and is perpendicular to the *xy*-plane. The wire has a current that is directed into the page, as shown in the figure above. Which of the following graphs best represents the magnetic field $\vec{B}$ due to the current as a function of the position x along the *x*-axis? Assume a positive magnetic field to be directed in the +*y* direction.

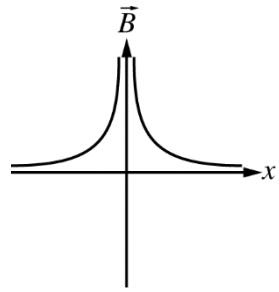
(A)



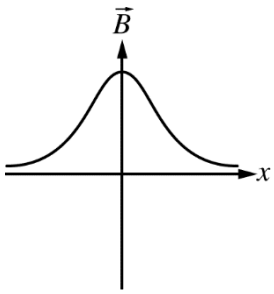
(B)



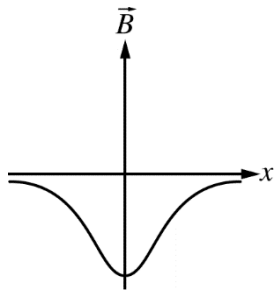
(C)



(D)



(E)



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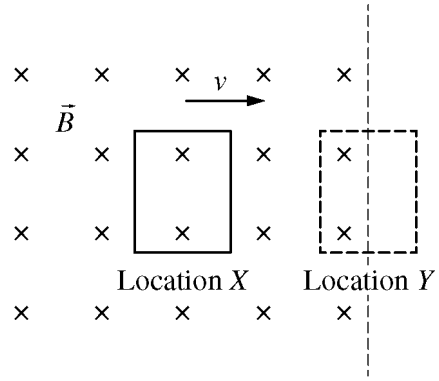

22. A loop of wire at location X is moving toward the right with constant speed v in a region of uniform magnetic field $\vec{B}$, which is perpendicular to the plane of the loop. The magnetic field region ends at the dashed line, as shown in the figure above. Later, the loop is at location Y and exiting the magnetic field with the same constant speed v. The process is then repeated with the loop moving at a speed of $2v$. Which of the following best describes the emf in the loop at the two positions shown when the process is repeated at a speed of $2v$?

	Emf at Location X	Emf at Location Y
(A)	Nonzero and halved	Nonzero and halved
(B)	Nonzero and doubled	Nonzero and doubled
(C)	Nonzero and doubled	Zero at both speeds
(D)	Zero at both speeds	Zero at both speeds
(E)	Zero at both speeds	Nonzero and doubled

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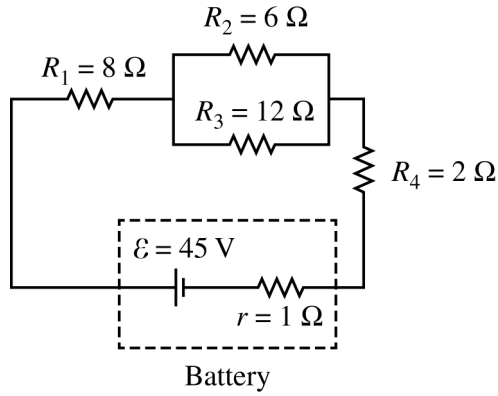
23. A long solenoid has 300 loops. The region inside the solenoid has a uniform magnetic field that is directed parallel to the axis of the solenoid. Each loop has an area 2×10^{-4} m^2. The magnetic field decreases at a constant rate from 0.5 T to zero. What is the time duration for the change in magnetic field if a potential difference of 10 V is induced between the ends of the solenoid while the field is decreasing?

(A) 1×10^{-5} s
(B) 3×10^{-5} s
(C) 3×10^{-3} s
(D) 1×10^{-2} s
(E) 3×10^{-2} s



Questions 24-25

The circuit represented in the figure above contains four resistors and a battery. The 45 V battery has a $1\ \Omega$ internal resistance.

24. Which of the following ranks the absolute values of the potential differences ΔV across the resistors from highest to lowest?

(A) $\Delta V_3 > \Delta V_1 > \Delta V_2 > \Delta V_4$
(B) $\Delta V_4 > \Delta V_2 > \Delta V_1 > \Delta V_3$
(C) $\Delta V_1 > \Delta V_4 > \Delta V_2 > \Delta V_3$
(D) $\Delta V_1 > (\Delta V_2 = \Delta V_3) > \Delta V_4$
(E) $\Delta V_4 > (\Delta V_2 = \Delta V_3) > \Delta V_1$

25. How much energy is dissipated by the battery's internal resistance in 60 s?

(A) 9 J
(B) 180 J
(C) 540 J
(D) 900 J
(E) 8100 J

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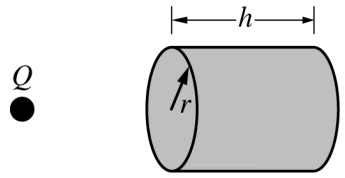


26. A closed cylindrical shell of volume $\pi r^2 h$ is placed close to an object with a charge of Q, as shown in the figure above. There are no other charged objects nearby. The electric flux through the closed cylindrical shell is

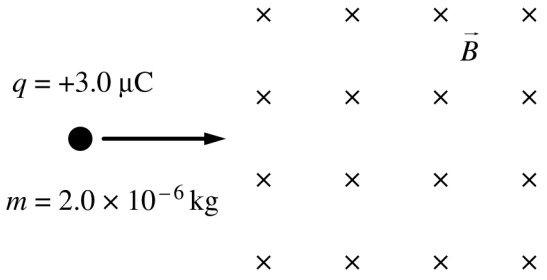
(A) 0
(B) Q/ε_0
(C) $\pi r^2 Q$
(D) $2\pi r h Q$
(E) $2\pi r^2 Q + 2\pi r h Q$

27. The electric field is zero everywhere within a certain region of space. The electric potential everywhere within the region

(A) must be zero
(B) must be uniform
(C) must be positive
(D) must be negative
(E) can be both positive and negative in different parts of the region

28. Two particles with positive charges q_1 and q_2 are both at rest and are very far apart. How much work would be done by external forces to bring the particles to rest at a distance d apart?

(A) Zero
(B) $\dfrac{kq_1q_2}{d}$
(C) $-\dfrac{kq_1q_2}{d}$
(D) $\dfrac{2kq_1q_2}{d}$
(E) $-\dfrac{2kq_1q_2}{d}$



29. A small object with a charge of $q = +3.0\ \mu\text{C}$ and a mass $m = 2.0 \times 10^{-6}$ kg enters a magnetic field of magnitude $B = 0.20$ T directed into the page, as shown in the figure above. If the speed of the object is 1000 m/s, the object's acceleration at the moment it enters the field is most nearly

(A) zero because the velocity is perpendicular to the magnetic field
(B) $300\ \text{m/s}^2$ toward the bottom of the page
(C) $300\ \text{m/s}^2$ toward the top of the page
(D) $600\ \text{m/s}^2$ toward the bottom of the page
(E) $600\ \text{m/s}^2$ toward the top of the page

30. A 0.20 m long wire carries a current of 15 A and lies perpendicular to a magnetic field. The magnetic force on the wire is measured to be 0.060 N. What is the magnitude of the magnetic field?

(A) 0.010 T
(B) 0.020 T
(C) 0.040 T
(D) 0.060 T
(E) 0.080 T

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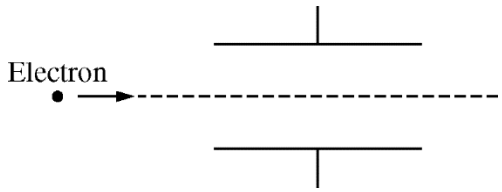
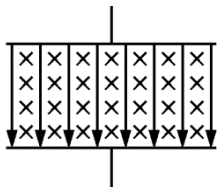
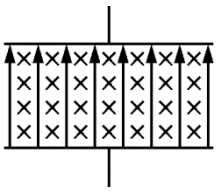


31. Uniform magnetic and electric fields exist between the two oppositely charged parallel plates shown in the figure above. An electron travels horizontally between the plates. Assuming gravitational effects to be negligible, which of the following diagrams shows a combination of electric and magnetic field directions that will allow the electron to travel undeflected?

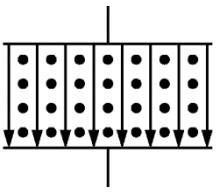
(A)



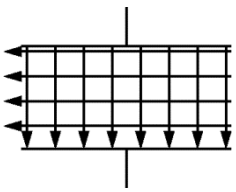
(B)



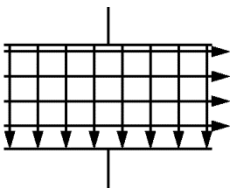
(C)



(D)



(E)



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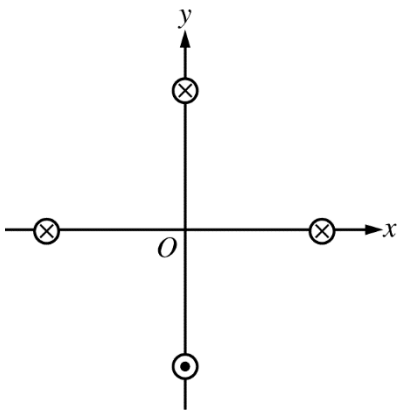
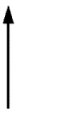


32. Four long, straight wires are perpendicular to the *xy*-plane. Each wire is the same distance from the origin *O*, as shown in the figure above. The wires have equal currents that are in the directions shown. Which of the following best represents the direction of the net magnetic field, if any, at the origin due to the four currents?

(A) 

(B)

(C) 

(D)

(E) Undefined because the net field is zero.

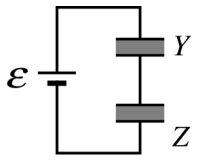


Figure 1

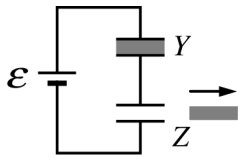


Figure 2

33. Two identical capacitors, Y and Z, are connected in series with an ideal battery, as shown in figure 1 above, and fully charged. Each capacitor has a dielectric slab of dielectric constant $\kappa > 1$ between its plates. If the dielectric slab is removed from capacitor Z, which of the following describes what happens to the voltage across each capacitor?

	Voltage across Capacitor *Y*	Voltage across Capacitor *Z*
(A)	Increases	Decreases
(B)	Increases	Increases
(C)	Remains the same	Remains the same
(D)	Decreases	Decreases
(E)	Decreases	Increases

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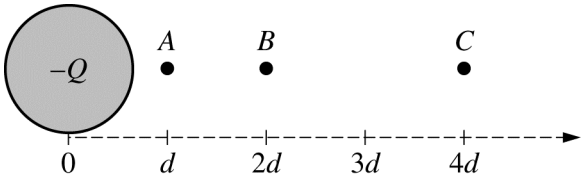
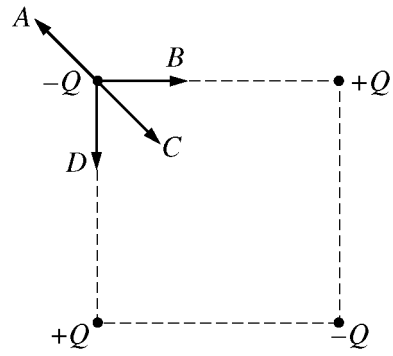


34. A particle of charge $+q$ is released from rest at position B, which is a distance $2d$ from the center of a fixed nonconducting sphere that has a charge of $-Q$ distributed uniformly throughout its volume, as shown in the figure above. When the particle reaches position A, which is a distance d from the center of the charged sphere, its kinetic energy is K_0. The same particle is now released from rest at position C, which is a distance $4d$ from the center of the nonconducting sphere. The kinetic energy of the particle when it again reaches position A is

(A) K_0
(B) $3K_0/2$
(C) $2K_0$
(D) $5K_0/2$
(E) $3K_0$



35. Four point charges of equal magnitude but different signs are arranged on the corners of a square as shown above. Which of the vectors shown represents the direction of the net force acting on the charge at the upper left-hand corner of the square due to the other charges?

(A) A
(B) B
(C) C
(D) D
(E) It has no direction because the force is zero.

S T O P

END OF ELECTRICITY AND MAGNETISM SECTION I

IF YOU FINISH BEFORE TIME IS CALLED,
YOU MAY CHECK YOUR WORK ON ELECTRICITY AND MAGNETISM SECTION I ONLY.

DO NOT TURN TO ANY OTHER TEST MATERIALS.

MAKE SURE YOU HAVE DONE THE FOLLOWING.

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

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AP® Physics C: Electricity and Magnetism Exam

SECTION II: Free Response

2016

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

At a Glance

Total Time
45 minutes
Number of Questions
3
Percent of Total Score
50%
Writing Instrument
Either pencil or pen with black or dark blue ink
Electronic Device
Calculator allowed
Weight
The questions are weighted equally.

IMPORTANT Identification Information

PLEASE PRINT WITH PEN:

1. First two letters of your last name ☐☐
   First letter of your first name ☐
2. Date of birth
   ☐☐ Month ☐☐ Day ☐☐☐☐ Year
3. Six-digit school code
   ☐☐☐☐☐☐
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Instructions

The questions for Section II are printed in this booklet. You may use any blank space in the booklet for scratch work, but you must write your answers in the spaces provided for each answer. A table of information and lists of equations that may be helpful are in the booklet. Calculators, rulers, and straightedges may be used in this section.

All final numerical answers should include appropriate units. Credit for your work depends on demonstrating that you know which physical principles would be appropriate to apply in a particular situation. Therefore, you should show your work for each part in the space provided after that part. If you need more space, be sure to clearly indicate where you continue your work. Credit will be awarded only for work that is clearly designated as the solution to a specific part of a question. Credit also depends on the quality of your solutions and explanations, so you should show your work.

Write clearly and legibly. Cross out any errors you make; erased or crossed-out work will not be scored. You may lose credit for incorrect work that is not crossed out.

Manage your time carefully. You may proceed freely from one question to the next. You may review your responses if you finish before the end of the exam is announced.

Form I
Form Code 4MBP4-S

82

ADVANCED PLACEMENT PHYSICS C 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, $G = 6.67 \times 10^{-11}$ $\left(\text{N}\cdot\text{m}^2\right)/\text{kg}^2$
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, $1\text{ u} = 1.66 \times 10^{-27}\text{ kg} = 931\text{ MeV}/c^2$

Planck's constant, $h = 6.63 \times 10^{-34}\text{ J}\cdot\text{s} = 4.14 \times 10^{-15}\text{ eV}\cdot\text{s}$

$hc = 1.99 \times 10^{-25}\text{ J}\cdot\text{m} = 1.24 \times 10^{3}\text{ eV}\cdot\text{nm}$

Vacuum permittivity, $\varepsilon_0 = 8.85 \times 10^{-12}\ \text{C}^2/\left(\text{N}\cdot\text{m}^2\right)$

Coulomb's law constant, $k = 1/(4\pi\varepsilon_0) = 9.0 \times 10^{9}\ \left(\text{N}\cdot\text{m}^2\right)/\text{C}^2$

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, $1\text{ atm} = 1.0 \times 10^{5}\ \text{N/m}^2 = 1.0 \times 10^{5}$ 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^{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 assumptions are used in this exam.

I. The frame of reference of any problem is inertial unless otherwise stated.
II. The direction of current is the direction in which positive charges would drift.
III. The electric potential is zero at an infinite distance from an isolated point charge.
IV. All batteries and meters are ideal unless otherwise stated.
V. Edge effects for the electric field of a parallel plate capacitor are negligible unless otherwise stated.

ADVANCED PLACEMENT PHYSICS C EQUATIONS

MECHANICS

$v_x = v_{x0} + a_x t$

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

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

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

$\vec{F} = \frac{d\vec{p}}{dt}$

$\vec{J} = \int \vec{F}\, dt = \Delta\vec{p}$

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

$\left|\vec{F}_f\right| \le \mu \left|\vec{F}_N\right|$

$\Delta E = W = \int \vec{F} \bullet d\vec{r}$

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

$P = \frac{dE}{dt}$

$P = \vec{F} \bullet \vec{v}$

$\Delta U_g = mg\Delta h$

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

$\vec{\tau} = \vec{r} \times \vec{F}$

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

$I = \int r^2 dm = \sum m r^2$

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

$v = r\omega$

$\vec{L} = \vec{r} \times \vec{p} = I\vec{\omega}$

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

$\omega = \omega_0 + \alpha t$

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

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

$\vec{F}_s = -k\Delta\vec{x}$

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

$x = x_{\max} \cos(\omega t + \phi)$

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

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

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

$\left|\vec{F}_G\right| = \frac{G m_1 m_2}{r^2}$

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

ELECTRICITY AND MAGNETISM

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

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

$\oint \vec{E} \bullet d\vec{A} = \frac{Q}{\varepsilon_0}$

$E_x = -\frac{dV}{dx}$

$\Delta V = -\int \vec{E} \bullet d\vec{r}$

$V = \frac{1}{4\pi\varepsilon_0} \sum_i \frac{q_i}{r_i}$

$U_E = qV = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r}$

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

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

$C_p = \sum_i C_i$

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

$I = \frac{dQ}{dt}$

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

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

$\vec{E} = \rho\vec{J}$

$I = Nev_d A$

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

$R_s = \sum_i R_i$

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

$P = I\Delta V$

A = area
B = magnetic field
C = capacitance
d = distance
E = electric field
ε = emf
F = force
I = current
J = current density
L = inductance
ℓ = length
n = number of loops of wire per unit length
N = number of charge carriers per unit volume
P = power
Q = charge
q = point charge
R = resistance
r = radius or distance
t = time
U = potential or stored energy
V = electric potential
v = velocity or speed
ρ = resistivity
Φ = flux
κ = dielectric constant

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

$\oint \vec{B} \bullet d\vec{\ell} = \mu_0 I$

$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\, d\vec{\ell} \times \hat{r}}{r^2}$

$\vec{F} = \int I\, d\vec{\ell} \times \vec{B}$

$B_s = \mu_0 n I$

$\Phi_B = \int \vec{B} \circ d\vec{A}$

$\varepsilon = \oint \vec{E} \bullet d\vec{\ell} = -\frac{d\Phi_B}{dt}$

$\varepsilon = -L\frac{dI}{dt}$

$U_L = \frac{1}{2} L I^2$

ADVANCED PLACEMENT PHYSICS C EQUATIONS

GEOMETRY AND TRIGONOMETRY

Rectangle

$A = bh$

Triangle

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

Circle

$A = \pi r^2$

$C = 2\pi r$

$s = r\theta$

Rectangular Solid

$V = \ell wh$

Cylinder

$V = \pi r^2 \ell$

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

Sphere

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

$S = 4\pi r^2$

Right Triangle

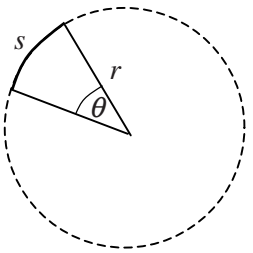
$a^2 + b^2 = c^2$

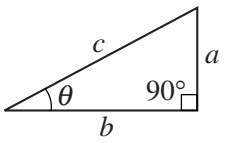
$\sin\theta = \frac{a}{c}$

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

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

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





CALCULUS

$$\frac{df}{dx} = \frac{df}{du}\frac{du}{dx}$$

$$\frac{d}{dx}\left(x^n\right) = nx^{n-1}$$

$$\frac{d}{dx}\left(e^{ax}\right) = ae^{ax}$$

$$\frac{d}{dx}(\ln ax) = \frac{1}{x}$$

$$\frac{d}{dx}[\sin(ax)] = a\cos(ax)$$

$$\frac{d}{dx}[\cos(ax)] = -a\sin(ax)$$

$$\int x^n\,dx = \frac{1}{n+1}x^{n+1},\ n \neq -1$$

$$\int e^{ax}\,dx = \frac{1}{a}e^{ax}$$

$$\int \frac{dx}{x+a} = \ln|x+a|$$

$$\int \cos(ax)\,dx = \frac{1}{a}\sin(ax)$$

$$\int \sin(ax)\,dx = -\frac{1}{a}\cos(ax)$$

VECTOR PRODUCTS

$\vec{A}\bullet\vec{B} = AB\cos\theta$

$\left|\vec{A}\times\vec{B}\right| = AB\sin\theta$

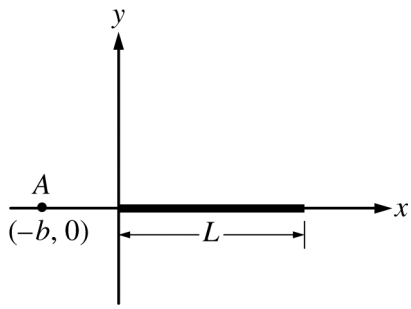
PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION II

Time—45 minutes

3 Questions

Directions: Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight. Show all your work in this booklet in the spaces provided after each part.



E&M.1.

A rod of length L lies along the x-axis with its left end at the origin, as shown in the figure above. The rod has a nonuniform linear charge density $\lambda = \alpha x$, where α is a positive constant.

(a) Determine the units of the constant α.

(b) Derive an expression for the total charge on the rod. Express your answer in terms of α, L, and physical constants, as appropriate.

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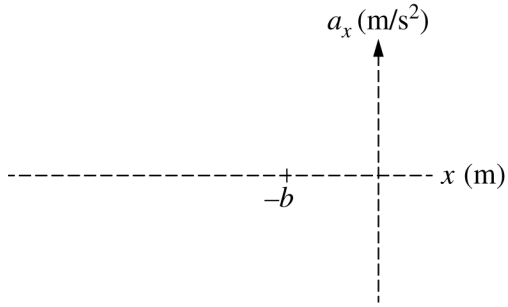
The rod is replaced with one of the same length but with a uniform positive linear charge density λ_0.

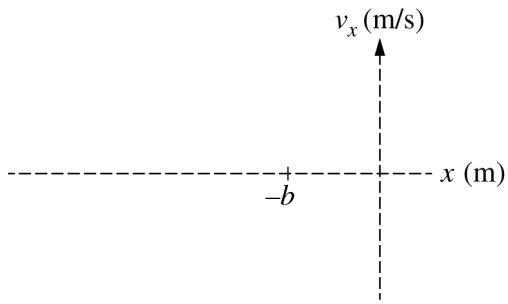
(c) Show that the electric field at point *A*, which is a distance *b* to the left of the rod, has a magnitude of $E = \dfrac{\lambda_0 L}{4\pi\varepsilon_0 b(b+L)}$.

(d) A proton is placed at point *A*, at position (–*b*, 0), near the positively charged rod and released from rest.

i. Sketch a graph of the horizontal component of the acceleration of the proton a_x as a function of its position *x* for the region in which the proton travels after it is released. Sketch any asymptote, but do not indicate its value.



ii. Sketch a graph of the horizontal component of the velocity of the proton v_x as a function of its position *x* for the region in which the proton travels after it is released. Sketch any asymptote but do not indicate its value.



Question 1 continues on next page.

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iii. Instead of a proton, an alpha particle (a particle with twice the charge and four times the mass of a proton) is now placed at point A. Is the magnitude of the initial acceleration of the alpha particle greater than, less than, or equal to the magnitude of the initial acceleration of the proton from part (d)i?

____ Greater than ____ Less than ____ Equal to

(e) Using the equation from part (c), show that the magnitude of the electric field at a point on the x-axis very far away from the rod is approximately equal to the electric field due to a point charge of magnitude $Q = \lambda_0 L$ located at the origin.

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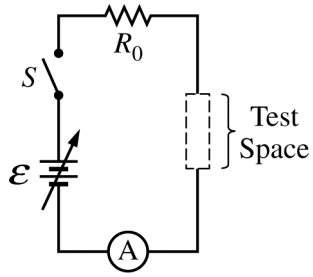

E&M.2.

The circuit above consists of a variable DC power supply, an ammeter A, a switch *S*, and a resistor of unknown resistance R_0 connected in series with a test space into which different circuit elements can be placed. In order to determine R_0, a wire of negligible resistance is placed in the test space. The power supply is set at various potential differences, and the current in the circuit is measured. The data are shown below.

$\mathcal{E}$(V)	2.00	4.00	6.00	8.00
Current (mA)	0.146	0.310	0.433	0.577

(a) Indicate below which quantities should be graphed to yield a straight line that has a slope that could be used to calculate a numerical value for the resistance R_0.

Horizontal axis: _____

Vertical axis: _____

Use the remaining rows in the table above, as needed, to record any quantities that you indicated that are not given.

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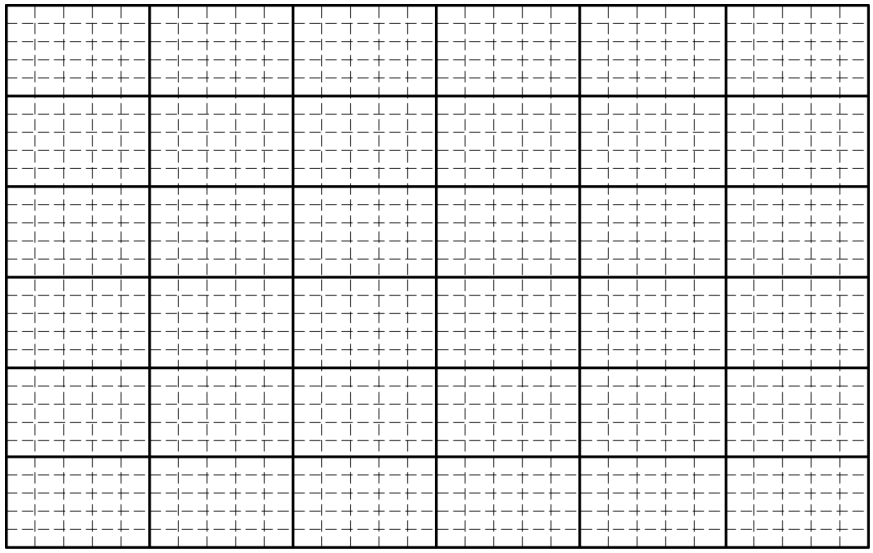
(b) Plot the straight line data points on the graph below. Clearly scale and label all axes, including units, if appropriate. Draw a straight line that best represents the data.



(c) Using your straight line, calculate an experimental value for R_0 .

Question 2 continues on next page.

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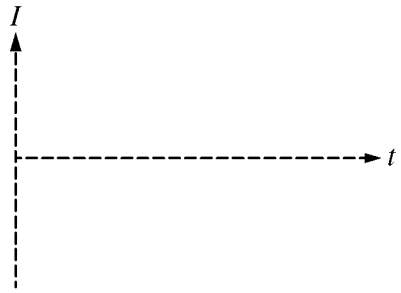
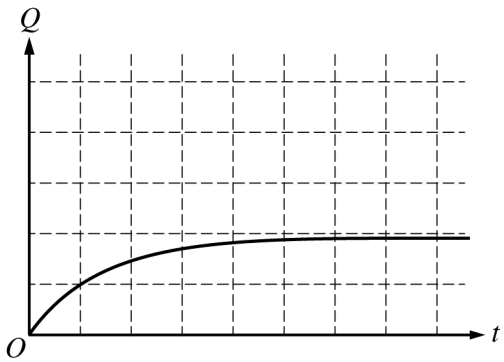
(d) The power supply is set to 4.00 V and an uncharged, air-filled capacitor is placed in the test space. The switch is closed at time $t = 0$, and the capacitor is allowed to fully charge.

i. On the axes shown, sketch the current I through the ammeter as a function of time t. Explicitly label any intercepts, asymptotes, maxima, or minima with numerical values or algebraic expressions, as appropriate.



ii. It is determined that the time constant is 0.045 s. The capacitor is charged to 4 V. Calculate the energy stored in the capacitor.

iii. The graph below shows the charge Q on the capacitor as a function of time t . The capacitor is discharged, and a dielectric with dielectric constant $\kappa = 2$ is inserted between the plates. The same charging procedure is repeated. On the graph below, sketch the curve showing the charge Q on the dielectric-filled capacitor as a function of time t .



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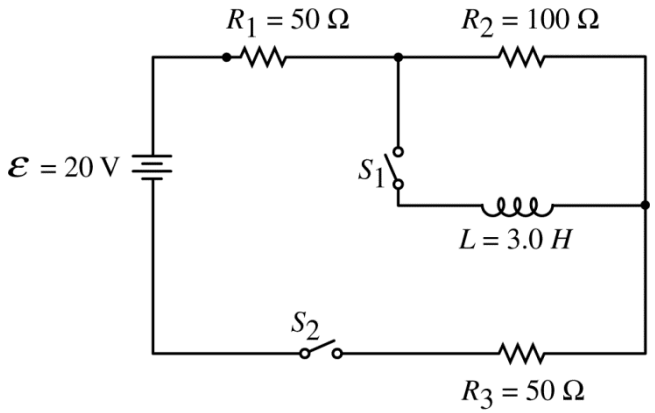

E&M.3.

An ideal battery is connected to three resistors, an ideal inductor, and two switches, as shown in the circuit above. Both switches are initially open. Switch S_2 is then closed.

(a) Calculate the voltage across resistor R_2.

Switch S_1 is then closed.

(b) Calculate the magnitude of the rate of change of the current through the inductor immediately after switch S_1 is closed.

(c) At time t after switch S_1 is closed, the instantaneous current through resistor R_2 is measured to be 0.020 A.

i. Calculate the current through resistor R_3 at time t.

ii. Calculate the energy stored in the inductor at time t.

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After a long time, the currents reach a steady value. Switch S_2 is then opened.

(d) Calculate the current through the inductor immediately after switch S_2 is opened.

(e) Write, but do NOT solve, a differential equation that can be used to determine the current through resistor R_2 at time t after switch S_2 is opened.

(f) Using the differential equation from part (e), derive an expression for the current through resistor R_2 as a function of time t after switch S_2 is opened.

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STOP

END OF EXAM

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- **CHECK TO SEE THAT YOUR AP NUMBER LABEL APPEARS IN THE BOX ON THE COVER.**
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