Name:_____

Answer Sheet for AP Physics C: Electricity and Magnetism

Practice Exam, Section I

No.	Answer
1	
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No.	Answer
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AP® Physics C: Electricity and Magnetism Exam

SECTION I: Multiple Choice

2019

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 4PBP4-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,	$1\text{ u} = 1.66 \times 10^{-27}$ 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$^2/\left(\text{N}\cdot\text{m}^2\right)$
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,	$1\text{ atm} = 1.0 \times 10^{5}$ 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

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

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

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

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

$B_s = \mu_0 n I$

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

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

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

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

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

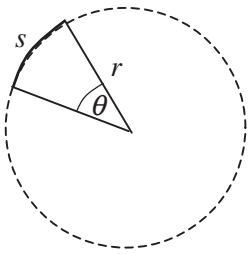
$a^2 + b^2 = c^2$

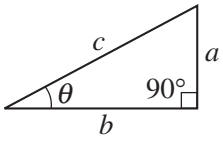
$\sin\theta = \frac{a}{c}$

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

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

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

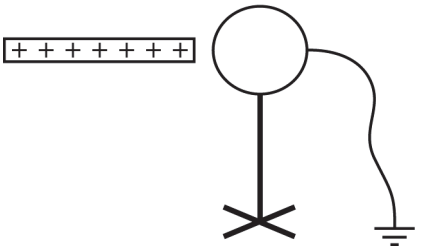
Time—45 minutes

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. Two positive point charges, both of magnitude 4.0×10^{-6} C, are situated along the x-axis at $x_1 = -2.0$ m and $x_2 = +2.0$ m. What is the electric potential at the origin of the xy-coordinate system?

   (A) -3.6×10^4 V
   (B) -1.8×10^4 V
   (C) 0 V
   (D) 1.8×10^4 V
   (E) 3.6×10^4 V



2. A grounded spherical conductor is on an insulating stand. A positively charged rod is brought close to the sphere but does not touch the sphere, as shown above. The rod is moved far away and then the grounding wire is removed. Which of the following describes the resulting charge on the sphere?

   (A) Positive
   (B) Negative
   (C) No net charge, but it is polarized with positive charges on the left side of the sphere
   (D) No net charge, but it is polarized with negative charges on the left side of the sphere
   (E) No net charge and no polarization

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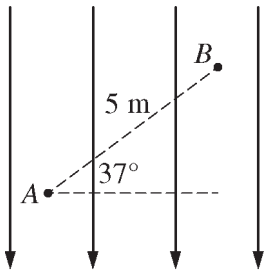
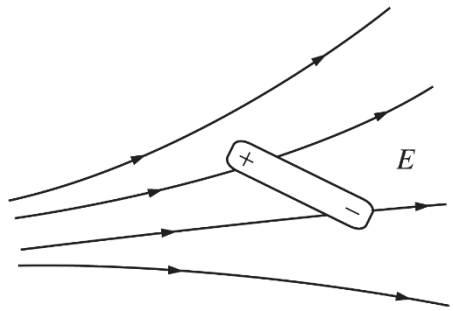


$E = 1000$ V/m

3. Points A and B shown above are in the plane of the page and 5 meters apart. The points are located in a uniform electric field of magnitude $1000\ \text{V/m}$ directed toward the bottom of the page. When a proton (of charge $+e$) moves from point A to point B, how much work is done on the proton by the electric field?

(A) −5000 eV
(B) −3000 eV
(C) +3000 eV
(D) +4000 eV
(E) +5000 eV



4. An electric dipole consisting of a positive charge and a negative charge held a fixed distance apart is at rest in an external, nonuniform electric field E, as shown in the figure above. Which of the following best describes the net torque and net force exerted on the dipole?

	Net Torque	Net Force
(A)	Clockwise	To the left
(B)	Clockwise	To the right
(C)	Counterclockwise	To the left
(D)	Counterclockwise	To the right
(E)	Zero	Zero

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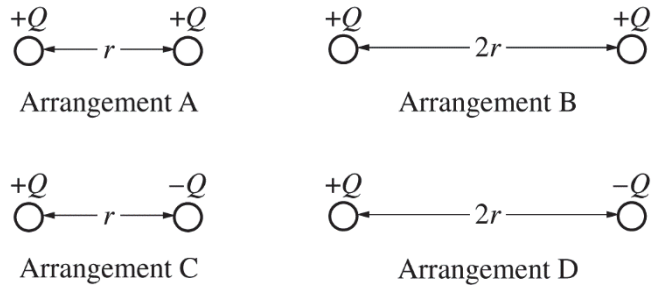
5. Which of the following must be true for a Gaussian surface through which the net flux is zero?

I. There are no charges inside the surface.
II. The net charge enclosed by the surface is zero.
III. The electric field is zero everywhere on the surface.

(A) I only
(B) II only
(C) III only
(D) I and II only
(E) I, II, and III



6. Four isolated arrangements of charged spheres are created for an experiment, as shown above. Which of the following correctly compares the electric potential energy U of the arrangements? Assume $U = 0$ when the charges are an infinite distance apart.

(A) $U_A > U_B > U_C > U_D$
(B) $U_A > U_C > U_B > U_D$
(C) $U_B > U_D > U_A > U_C$
(D) $U_D > U_C > U_B > U_A$
(E) $U_A > U_B > U_D > U_C$

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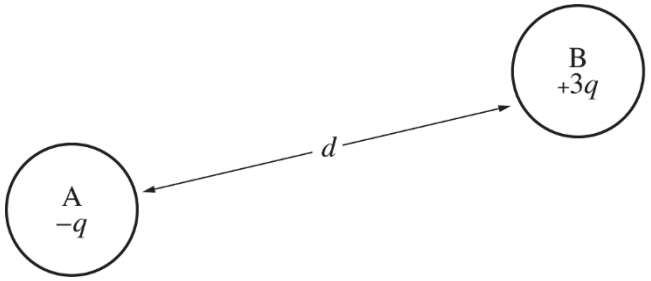
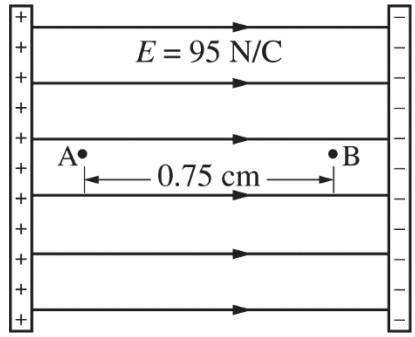


7. Conducting spheres A and B of charges $-q$ and $+3q$, respectively, are separated by a distance d, as shown in the figure above. Which of the following statements is true about the two spheres?

   (A) The magnitude of the force sphere A exerts on sphere B is three times larger than the magnitude of the force sphere B exerts on sphere A.
   (B) The magnitude of the force sphere B exerts on sphere A is three times larger than the magnitude of the force sphere A exerts on sphere B.
   (C) The force sphere B exerts on sphere A is equal in magnitude to the force sphere A exerts on sphere B.
   (D) If the spheres are free to move, the magnitude of the force sphere B exerts on sphere A will decrease as the spheres move.
   (E) If the spheres are brought into contact with each other and then returned to the positions shown, the two spheres will attract each other.



8. Two conducting plates hold equal and opposite charges that create an electric field of magnitude $E = 95\ \text{N/C}$ that is directed to the right, as shown in the figure above. Points A and B are 0.75 cm apart with A closer to the positive plate. A proton is released from rest at point A. What is the kinetic energy of the proton when it reaches point B ?

   (A) 0
   (B) $+1.14 \times 10^{-19}$ J
   (C) $+1.52 \times 10^{-17}$ J
   (D) $+1.92 \times 10^{-7}$ J
   (E) +71 J

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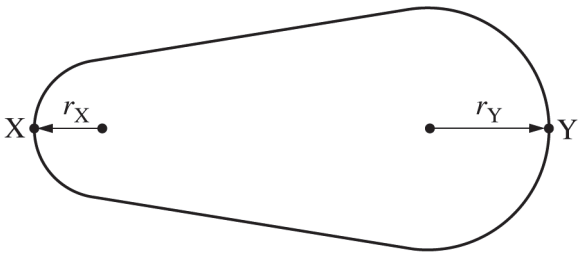
Questions 9-10



The figure above shows a cross section of a solid, isolated, metallic conductor in electrostatic equilibrium with a net charge $+Q$. The two ends of the conductor are spherical surfaces of radii r_X and r_Y, where $r_X < r_Y$. Points X and Y are on the conductor at each end.

9. Assuming that the electric potential is zero an infinite distance from the conductor, which of the following statements is true about the magnitude of the electric potential at points X and Y?

   (A) It is greater at point X than at point Y.
   (B) It is greater at point Y than at point X.
   (C) It is zero at both points X and Y.
   (D) It has the same nonzero value at both points X and Y.
   (E) There is not enough information to determine at which point, if either, the magnitude of the electric potential is greater.

10. Which of the following is true about the magnitude of the electric field just outside the surface of the conductor at points X and Y?

   (A) It is greater at point X than at point Y.
   (B) It is greater at point Y than at point X.
   (C) It is zero at both points X and Y.
   (D) It has the same nonzero value at both points X and Y.
   (E) There is not enough information to determine at which point, if either, the magnitude of the electric field is greater.

11. A parallel-plate capacitor is connected across a voltage V so that each plate of the capacitor collects a charge of magnitude Q. Which of the following is an expression for the energy stored in the capacitor?

   (A) QV
   (B) $\frac{Q}{V}$
   (C) $\frac{V}{Q}$
   (D) $\frac{1}{2}QV$
   (E) $\frac{1}{2}QV^2$

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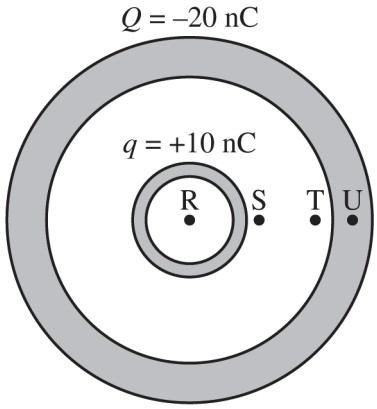
Questions 12-13



Two concentric spherical conducting shells and four labeled points are shown above. The outer shell has a net charge $Q = -20$ nC. The inner shell has a net charge $q = +10$ nC.

12. What is the charge on the outer surface of the outer shell?

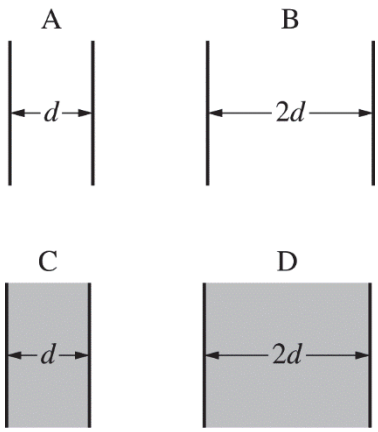
(A) –30 nC
(B) –20 nC
(C) –10 nC
(D) +10 nC
(E) +30 nC

13. The magnitudes of the electric fields at the four labeled points in the figure are E_R, E_S, E_T, and E_U, respectively. Which of the following correctly ranks the points according to the magnitude of their electric fields?

(A) $E_R = E_S = E_T = E_U$
(B) $E_S > E_T > (E_R = E_U)$
(C) $(E_S = E_T) > E_U > E_R$
(D) $E_T > E_S > E_R > E_U$
(E) $(E_S = E_T) > (E_R = E_U)$

14. A parallel plate capacitor is connected to a battery, fully charged, disconnected, and isolated from the battery. A dielectric slab is then inserted between the plates of the capacitor. Which of the following is a true statement about what happens when the dielectric slab is inserted?

(A) The magnitude of the electric field between the plates of the capacitor will increase.
(B) The potential difference between the plates of the capacitor will decrease.
(C) The capacitance of the capacitor will decrease.
(D) The charge stored on the capacitor will increase.
(E) The energy stored in the capacitor will increase.



15. Four parallel plate capacitors all have the same plate area and have the plate separations shown above. Both capacitors A and B have air between the plates, while the space between the plates of both capacitors C and D is filled with a dielectric slab of dielectric constant $\kappa = 2$. Which of the following correctly ranks the capacitors in order of their capacitance from largest to smallest ?

(A) B > (A = D) > C
(B) (A = C) > (B = D)
(C) C > (A = D) > B
(D) (B = D) > (A = C)
(E) D > C > B > A

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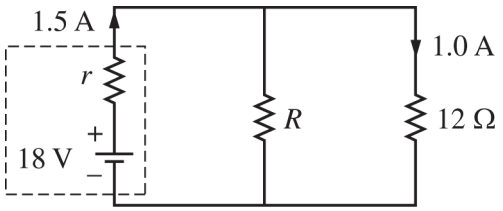
Questions 16-17



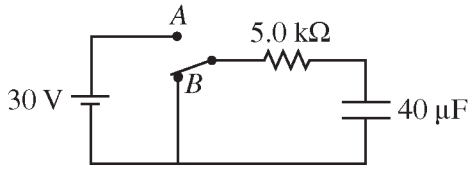
Two resistors of resistances R and 12 Ω are connected to a battery of emf 18 V, as shown in the figure above. The battery has an internal resistance of r. The current in the battery is 1.5 A, and the current in the 12 Ω resistor is 1.0 A.

16. What is the resistance R ?

(A) 7.2 Ω
(B) 12 Ω
(C) 18 Ω
(D) 24 Ω
(E) 45 Ω

17. What is the internal resistance of the battery?

(A) 4.0 Ω
(B) 6.0 Ω
(C) 12 Ω
(D) 18 Ω
(E) 36 Ω



18. The capacitor in the circuit represented above is uncharged when the switch is at position B. The switch is then moved to position A. What is the energy stored by the capacitor when the current in the circuit is 2.0 mA?

(A) 0.8 mJ
(B) 1.2 mJ
(C) 8.0 mJ
(D) 16 mJ
(E) 18 mJ

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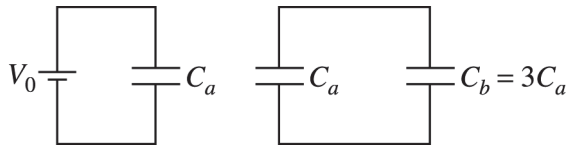
Questions 19-20



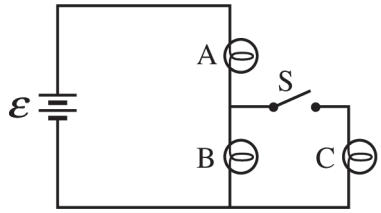
A capacitor of capacitance C_a is first charged to a voltage V_0, as shown above on the left. Without losing any charge, the capacitor is now disconnected from the voltage source and connected to a second initially uncharged capacitor of capacitance C_b that is three times C_a, and the circuit is allowed to reach equilibrium, as shown above on the right.

19. If Q_a is the new charge on capacitor C_a, the charge Q_b on capacitor C_b is given by

(A) 0
(B) $Q_a/3$
(C) $Q_a/2$
(D) Q_a
(E) $3Q_a$

20. The new voltage across capacitor C_a is V_a. How does this new voltage compare with the original voltage of V_0?

(A) $V_a > V_0$
(B) $V_a < V_0$
(C) $V_a = V_0$
(D) It depends on the value of C_a.
(E) It depends on the value of C_b.



21. A circuit contains three identical light bulbs and a switch S connected to an ideal battery of emf $\mathcal{E}$, as shown in the figure above. The switch is initially open and bulbs A and B have equal brightness, while C is not lit. What happens to the brightness of bulbs A and B when the switch S is closed and bulb C lights up?

	Bulb A	Bulb B
(A)	Remains the same	Becomes dimmer
(B)	Becomes dimmer	Becomes dimmer
(C)	Becomes brighter	Becomes dimmer
(D)	Becomes brighter	Not lit
(E)	Remains the same	Not lit

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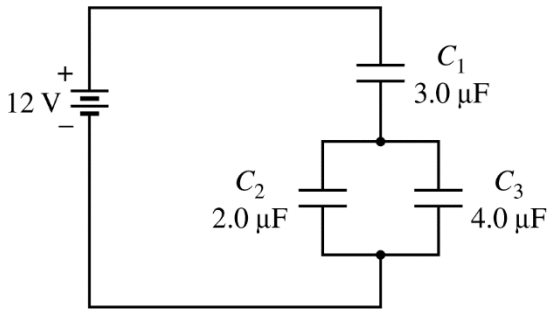
Questions 22-23



The circuit shown above has three capacitors and a 12 V battery. The capacitors are charged to steady state conditions.

22. What is the potential difference across capacitor C_1 ?

(A) 3.0 V
(B) 4.0 V
(C) 6.0 V
(D) 8.0 V
(E) 12 V

23. One of the capacitors is removed from the circuit and isolated. While it still holds all of its charge, a piece of ceramic with dielectric constant of 2 is inserted and completely fills the space between the plates. U_i is the energy stored in the capacitor before the dielectric was inserted, and U_f is the energy stored in the capacitor after the dielectric was inserted. What is the ratio U_f / U_i ?

(A) 1/4
(B) 1/2
(C) 1/1
(D) 2/1
(E) 4/1

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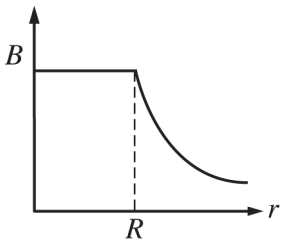
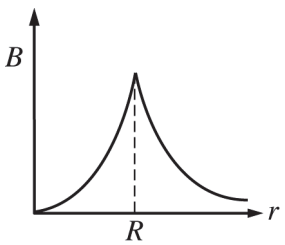
24. A long, straight wire of radius R carries current I. The current is distributed over the cross-sectional area of the wire with a uniform current density. Which of the following graphs best represents the magnetic field strength produced by the current as a function of the distance r from the center of the wire?

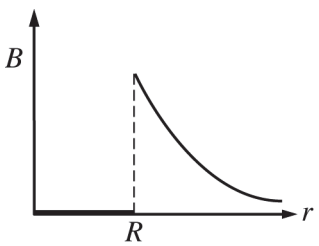
(A)



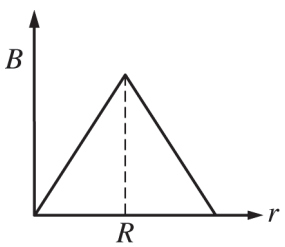
(B)



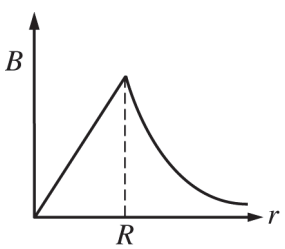
(C)



(D)



(E)



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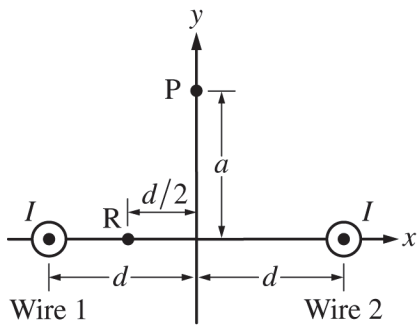
Questions 25-26



Two wires perpendicular to the x-axis have currents I directed out of the page, as shown above. Each wire is a distance d from the y-axis. Point P lies on the y-axis at the coordinate $(0, a)$, and point R lies on the x-axis at the coordinate $(-d/2,\ 0)$.

25. Which of the following expressions represents the magnitude of the magnetic field at point R?

(A) Zero

(B) $\frac{\mu_0 I}{2\pi d}$

(C) $\frac{\mu_0 I}{\pi d}$

(D) $\frac{4\mu_0 I}{3\pi d}$

(E) $\frac{2\mu_0 I}{3\pi d}$

26. Which of the following best represents the direction of the net magnetic field at point P?

(A) 

(B)

(C) 

(D)

(E) 

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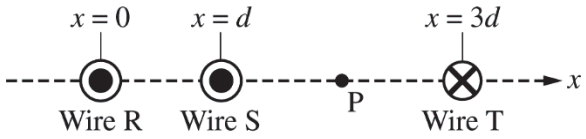
Questions 27-28



Three long, current-carrying wires are shown in the cross-sectional view above. The currents in wires R and S are out of the page, and the current in wire T is into the page. The currents in the wires have equal magnitude, and the wires are in the positions shown. Point P is halfway between wires S and T.

27. If B_S is the magnitude of the magnetic field at point P due to wire S, which of the following gives the magnitude and direction of the magnetic field at point P due to all three wires?

	Magnitude	Direction
(A)	$B_S/2$	Top of the page
(B)	$B_S/2$	Bottom of the page
(C)	B_S	Top of the page
(D)	$5B_S/2$	Top of the page
(E)	$5B_S/2$	Bottom of the page

28. To which of the following locations, if any, could wire S be moved so that the total magnetic force exerted on it by the other two wires is zero?

(A) $-d < x < 0$
(B) $0 < x < d$
(C) $d < x < 2d$
(D) $2d < x < 3d$
(E) There is no position in the vicinity of the wires at which the magnetic force on wire S would be zero.

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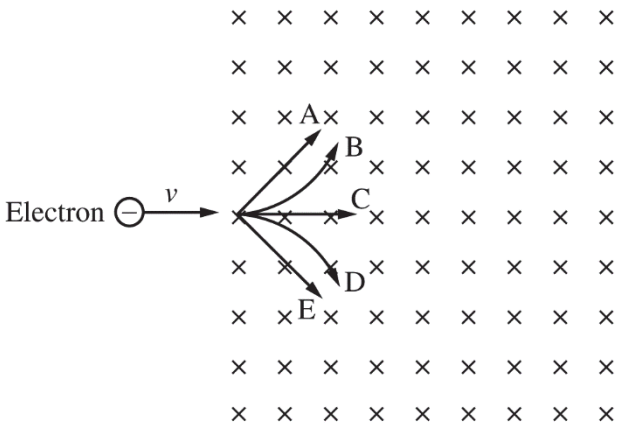
Questions 29-30



An electron is traveling with speed v when it enters a uniform magnetic field that is directed into the page, as shown above. Five paths in the magnetic field are labeled A, B, C, D, and E.

29. Which labeled path best shows the path the electron will follow as it travels through the magnetic field?

(A) Path A
(B) Path B
(C) Path C
(D) Path D
(E) Path E

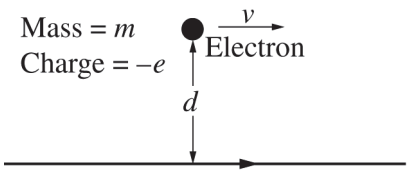
30. The electron is replaced with a proton that is traveling at the same speed v in the same direction as it enters the magnetic field. Which of the following best describes the motion of the proton as it passes through the magnetic field?

I. The speed of the proton changes less than the speed of the electron did.

II. The proton is deflected in the opposite direction.

III. The proton is deflected more than the electron.

(A) I only
(B) I and II only
(C) II only
(D) II and III only
(E) I, II and III



31. An electron of mass m and charge $-e$ is traveling to the right parallel to a wire with speed v. The electron is a distance d from the wire. The wire is carrying a current I to the right, as shown in the figure above. Which of the following gives the magnitude and direction of the force exerted on the electron by the current-carrying wire?

	Magnitude	Direction
(A)	$\frac{\mu_0 Iev}{2\pi d}$	Toward the top of the page
(B)	$\frac{\mu_0 Iev}{2\pi d}$	Out of the page
(C)	$\frac{\mu_0 Iev}{2\pi d}$	Into the page
(D)	$\frac{\mu_0 Iev}{2m\pi d}$	Toward the top of the page
(E)	$\frac{\mu_0 Iev}{2m\pi d}$	Out of the page

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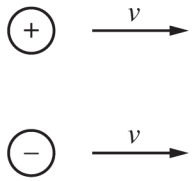
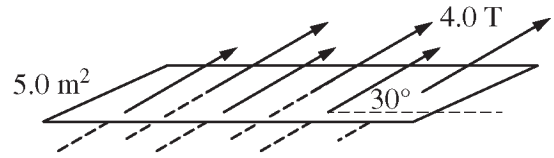


32. Two small spheres have equal and opposite charges and are travelling parallel to each other with speed v to the right, as shown above. What is the direction of the magnetic field midway between the spheres at the instant shown?

(A) Out of the page
(B) Into the page
(C) Toward the bottom of the page
(D) Toward the top of the page
(E) Undefined, since the magnitude of the magnetic field is zero.



33. A magnetic field of magnitude 4.0 T is directed at an angle of $30°$ to the plane of a rectangular loop of area $5.0\ m^2$, as shown above. What is the magnetic flux through the loop?

(A) $10\ T \cdot m^2$
(B) $12\ T \cdot m^2$
(C) $17\ T \cdot m^2$
(D) $20\ T \cdot m^2$
(E) $40\ T \cdot m^2$

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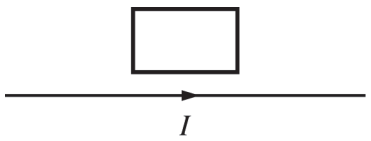
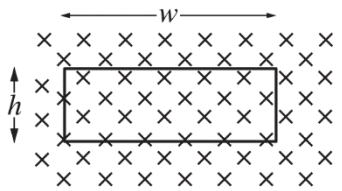


34. A rectangular conducting loop is located above a long, straight wire carrying a current I to the right, as shown in the figure above. The wire and loop are both in the plane of the page. Which of the following will induce a clockwise current in the loop?

(A) Decreasing the current in the wire
(B) Moving the loop to the right
(C) Moving the loop to the left
(D) Moving the loop up away from the wire
(E) Moving the loop down toward the wire



Magnetic field B into the page

35. A wire loop with width w and height h is in a magnetic field that is directed into the page, as shown in the figure above. The magnitude B of the magnetic field changes with time t. The magnitude of the resulting induced emf in the wire loop is given as a function of time by the equation $\mathcal{E} = \beta hwt^3$, where β is a positive constant in units of $\mathrm{T/s^4}$. Which of the following is a possible expression for the magnitude of the magnetic field?

(A) $\frac{1}{4}\beta t^3$

(B) $3\beta t^4$

(C) $3hw\beta t^2$

(D) $\frac{1}{4}hw\beta t^4$

(E) $\frac{1}{4}\beta t^4$

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GO ON TO THE NEXT PAGE.

AP® Physics C: Electricity and Magnetism Exam

SECTION II: Free Response

2019

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
   ☐☐☐☐☐☐
4. Unless I check the box below, I grant the College Board the unlimited right to use, reproduce, and publish my free-response materials, both written and oral, for educational research and instructional purposes. My name and the name of my school will not be used in any way in connection with my free-response materials. I understand that I am free to mark "No" with no effect on my score or its reporting.
   No, I do not grant the College Board these rights. ☐

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 4PBP4-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,	$1\text{ u} = 1.66 \times 10^{-27}$ 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$^2/\left(\text{N}\cdot\text{m}^2\right)$
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,	$1\text{ atm} = 1.0 \times 10^{5}$ 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

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

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

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

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

$B_s = \mu_0 n I$

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

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

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

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

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

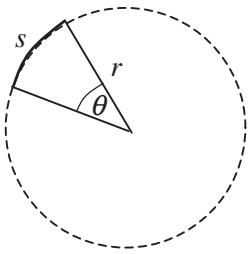
$a^2 + b^2 = c^2$

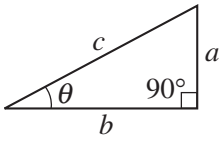
$\sin\theta = \frac{a}{c}$

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

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

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

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

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

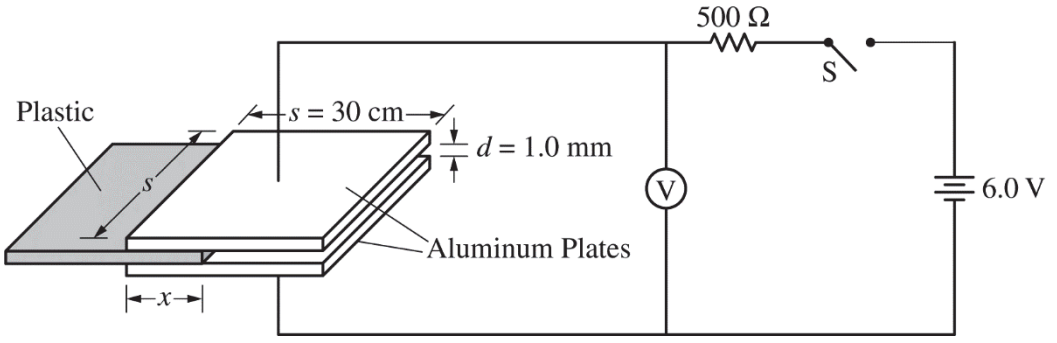
PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION II

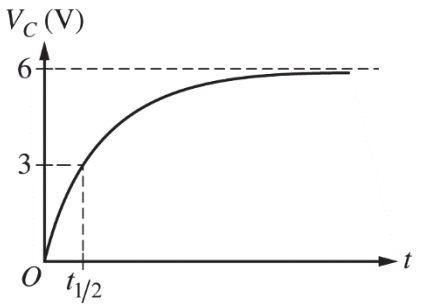
Time—45 minutes

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.



1. Students design an experiment to determine the unknown dielectric constant κ of a plastic material. A capacitor is created using two square aluminum plates of side length $s = 30$ cm that are separated by a distance $d = 1.0$ mm. This capacitor is placed in a circuit with an ideal 6.0-volt battery, a resistor of resistance $R = 500\ \Omega$, voltmeter V, and an open switch S, as shown above. A 1.0 mm thick piece of plastic is inserted between the aluminum plates. The distance x that the plastic is inserted between the plates can be varied, and the voltmeter is used to measure the potential difference V_C across the capacitor. The switch is closed, and readings from the voltmeter are recorded as a function of time t. The data are plotted to create the graph shown below.



The time $t_{1/2}$ shown above is the time for the capacitor to charge to half the potential difference of the battery.

(a) The potential difference across the capacitor as a function of time is modeled by the equation $V_C = V_{\text{MAX}}\left(1 - e^{-t/RC}\right)$, where $V_{\text{MAX}} = 6$ V. Derive an expression for the capacitance C of the capacitor. Express your answer in terms of $t_{1/2}$, R, and physical constants, as appropriate.

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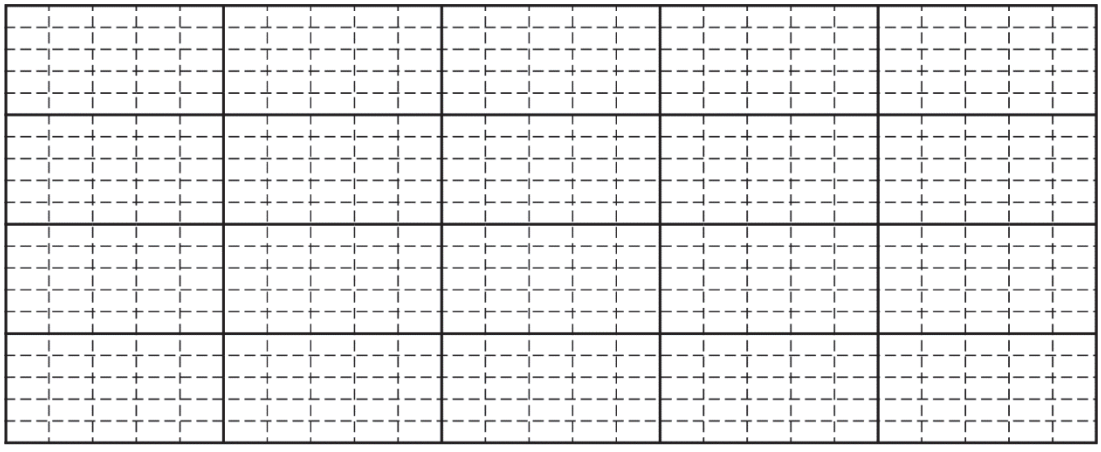
GO ON TO THE NEXT PAGE.

The data for x and $t_{1/2}$ are recorded for several trials and the value of C for each trial is calculated. The results are shown in the chart below.

x (m)	0.050	0.10	0.15	0.20	0.25
$t_{1/2}$ (μs)	0.44	0.63	0.75	0.88	1.10
C (nF)	1.27	1.82	2.16	2.54	3.17

(b) Plot the experimental value of the capacitance C as a function of the distance x on the graph below. Clearly scale and label all axes, including units if appropriate. Draw a straight line that best represents the data.



(c) The capacitor in the lab can be treated as two capacitors in parallel, one with the dielectric and one with air between the plates. Show that the capacitance can be expressed as $C = \frac{\varepsilon_0 s}{d}(s + x(\kappa - 1))$.

Question 1 continues on the next page.

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(d) Using the graph from part (b), calculate the value of the dielectric constant κ.

(e) The students now want to verify the value for the permittivity constant, ε_0. Using the graph from part (b), calculate an experimental value for ε_0.

(f) Assume the value found in part (e) is higher than the accepted value for the permittivity constant. State one possible physical reason for this error and explain how it could have caused this error.

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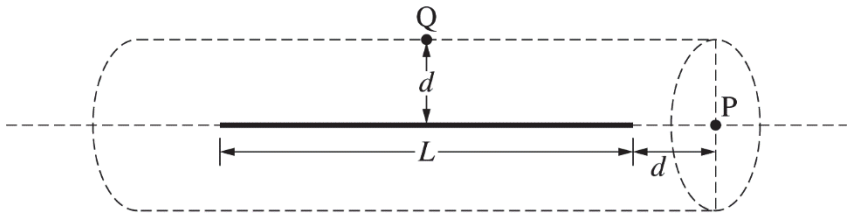

Figure 1

2. A thin wire of length L has a uniform charge density $+\lambda$. A cylindrical Gaussian surface of radius d is drawn with the wire along its central axis, as shown above. Point P is located at the center of one end of the cylinder, a distance d from the end of the wire. Point Q is on the edge of the cylinder directly above the center of the wire, as shown above.

   A student says, "Gauss's law can be used to find the electric flux Φ through the Gaussian surface."

   (a) Is the student's statement correct or incorrect?

   ____ Correct ____ Incorrect

   If you have chosen "Correct," use Gauss's law to find the electric flux Φ through the Gaussian surface.

   If you have chosen "Incorrect," explain why the student's reasoning is incorrect and why Gauss's law cannot be applied in this situation.

   (b) Two students discuss whether or not they can use Gauss's law to find the electric field at points P and Q. At which of the points, if either, is Gauss's law a useful method for finding the electric field?

   _____ At point P only ____ At point Q only

   _____ At both points P and Q ____ At neither point P nor point Q

   Justify your answer.

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(c) Assuming the electric potential is zero at infinity, show that the value for the electric potential at point P is given by the following expression.

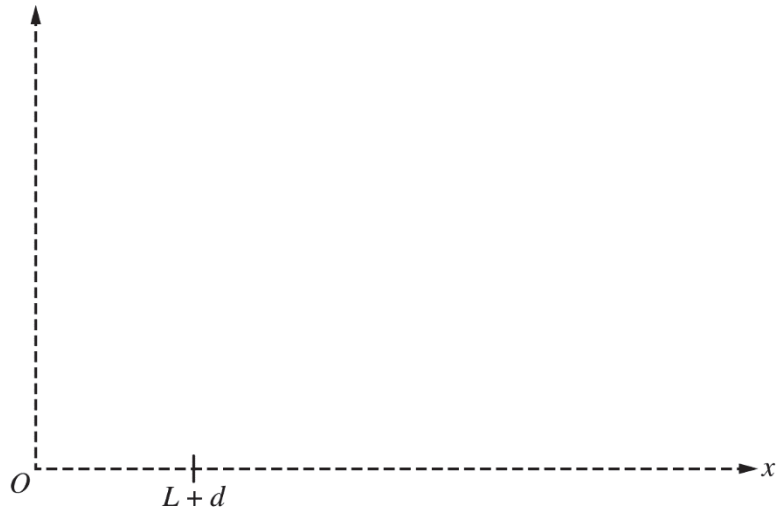
$$V = \frac{\lambda}{4\pi\varepsilon_0}\ln\left(\frac{L+d}{d}\right)$$



Figure 2

The wire is aligned along the x-axis with the origin at the left end of the wire, as shown in Figure 2 above.

(d) A positively charged particle of charge $+e$ and mass m is released from rest at point P. On the axes below, sketch the kinetic energy K of the particle, the potential energy U of the wire-particle system, and the total energy E_{tot} of the wire-particle system as functions of the particle's position x. Clearly label each sketch with K, U, and E_{tot}. Explicitly label any maximum with numerical values or algebraic expressions, as appropriate.



Question 2 continues on the next page.

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Figure 3

(e) Derive an expression for the magnitude of the electric field due to the wire as a function of the position along the x-axis, where $x > L$. Express your answer in terms of x, L, λ, and physical constants, as appropriate.

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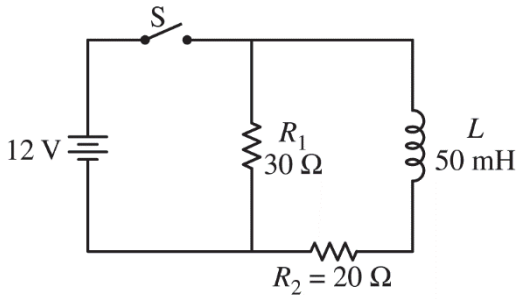

3. The circuit shown above is constructed using an ideal 12 V battery, an ideal switch S, and two resistors and an inductor with the values shown. Switch S is closed. After a long time, the circuit reaches steady-state conditions.

   (a) Calculate the current through R_1.

   (b) Calculate the current through the battery.

   The switch is then opened at time $t = 0$.

   (c) Determine the current in the inductor immediately after the switch is opened.

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(d)

i. Determine the current in resistor R_1 immediately after the switch is opened.

ii. Which of the following statements is correct about the current through R_1 immediately after the switch is opened?

_____ The current is up through R_1. _____ The current is down through R_1.

_____ There is no current through R_1.

Justify your answer.

(e) Immediately after the switch is opened, is the top end or bottom end of the inductor at the higher electric potential?

____ Top end ____ Bottom end

Justify your answer.

Question 3 continues on the next page.

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(f) On the axes below, sketch a graph of the potential difference V across the inductor as a function of time after the switch is opened. Explicitly label the vertical axis intercept with a numerical value.



(g) Write but DO NOT solve a differential equation that could be solved for the current through the inductor as a function of time after the switch is opened.

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STOP

END OF EXAM

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- **MAKE SURE YOU HAVE COMPLETED THE IDENTIFICATION INFORMATION AS REQUESTED ON THE FRONT AND BACK COVERS OF THE SECTION II BOOKLET.**
- **CHECK TO SEE THAT YOUR AP NUMBER LABEL APPEARS IN THE BOX ON THE COVER.**
- **MAKE SURE YOU HAVE USED THE SAME SET OF AP NUMBER LABELS ON ALL AP EXAMS YOU HAVE TAKEN THIS YEAR.**