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# **AP<sup>®</sup> Physics C: Electricity and Magnetism 2016 Free-Response Questions**

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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 Neutron mass, $m_n = 1.67 \times 10^{-27}$ kg Electron mass, $m_e = 9.11 \times 10^{-31}$ kg Avogadro's number, $N_0 = 6.02 \times 10^{23}$ mol <sup>-1</sup> Universal gas constant, $R = 8.31$ J/(mol·K) Boltzmann's constant, $k_B = 1.38 \times 10^{-23}$ J/K	Electron charge magnitude, $e = 1.60 \times 10^{-19}$ C 1 electron volt, $1 \text{ eV} = 1.60 \times 10^{-19}$ J Speed of light, $c = 3.00 \times 10^8$ m/s Universal gravitational constant, $G = 6.67 \times 10^{-11}$ (N·m <sup>2</sup> )/kg <sup>2</sup> Acceleration due to gravity at Earth's surface, $g = 9.8$ m/s <sup>2</sup>
1 unified atomic mass unit, Planck's constant, Vacuum permittivity, Coulomb's law constant, $k = 1/(4\pi\epsilon_0) = 9.0 \times 10^9$ (N·m <sup>2</sup> )/C <sup>2</sup> Vacuum permeability, Magnetic constant, $k' = \mu_0/(4\pi) = 1 \times 10^{-7}$ (T·m)/A 1 atmosphere pressure,	$1 \text{ u} = 1.66 \times 10^{-27}$ kg = 931 MeV/c <sup>2</sup> $h = 6.63 \times 10^{-34}$ J·s = $4.14 \times 10^{-15}$ eV·s $hc = 1.99 \times 10^{-25}$ J·m = $1.24 \times 10^3$ eV·nm $\epsilon_0 = 8.85 \times 10^{-12}$ C <sup>2</sup> /(N·m <sup>2</sup> ) $\mu_0 = 4\pi \times 10^{-7}$ (T·m)/A $1 \text{ atm} = 1.0 \times 10^5$ N/m <sup>2</sup> = $1.0 \times 10^5$ 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 <sup>9</sup>	giga	G
10 <sup>6</sup>	mega	M
10 <sup>3</sup>	kilo	k
10 <sup>-2</sup>	centi	c
10 <sup>-3</sup>	milli	m
10 <sup>-6</sup>	micro	μ
10 <sup>-9</sup>	nano	n
10 <sup>-12</sup>	pico	p

VALUES OF TRIGONOMETRIC FUNCTIONS FOR COMMON ANGLES							
$\theta$	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

$v_x = v_{x0} + a_x t$ $x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$ $v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$ $\bar{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$ $\vec{F} = \frac{d\vec{p}}{dt}$ $\vec{J} = \int \vec{F} dt = \Delta\vec{p}$ $\vec{p} = m\vec{v}$ $ \vec{F}_f  \leq \mu  \vec{F}_N $ $\Delta E = W = \int \vec{F} \cdot d\vec{r}$ $K = \frac{1}{2} m v^2$ $P = \frac{dE}{dt}$ $P = \vec{F} \cdot \vec{v}$ $\Delta U_g = mg\Delta h$ $a_c = \frac{v^2}{r} = \omega^2 r$ $\vec{\tau} = \vec{r} \times \vec{F}$ $\bar{\alpha} = \frac{\sum \vec{\tau}}{I} = \frac{\vec{\tau}_{net}}{I}$ $I = \int r^2 dm = \sum mr^2$ $x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$ $v = r\omega$ $\vec{L} = \vec{r} \times \vec{p} = I\vec{\omega}$ $K = \frac{1}{2} I \omega^2$ $\omega = \omega_0 + \alpha t$ $\theta = \theta_0 + \omega_0 t + \frac{1}{2} \alpha t^2$	<p><math>a</math> = acceleration  <math>E</math> = energy  <math>F</math> = force  <math>f</math> = frequency  <math>h</math> = height  <math>I</math> = rotational inertia  <math>J</math> = impulse  <math>K</math> = kinetic energy  <math>k</math> = spring constant  <math>\ell</math> = length  <math>L</math> = angular momentum  <math>m</math> = mass  <math>P</math> = power  <math>p</math> = momentum  <math>r</math> = radius or distance  <math>T</math> = period  <math>t</math> = time  <math>U</math> = potential energy  <math>v</math> = velocity or speed  <math>W</math> = work done on a system  <math>x</math> = position  <math>\mu</math> = coefficient of friction  <math>\theta</math> = angle  <math>\tau</math> = torque  <math>\omega</math> = angular speed  <math>\alpha</math> = angular acceleration  <math>\phi</math> = phase angle</p> $\vec{F}_s = -k\Delta\vec{x}$ $U_s = \frac{1}{2} k (\Delta x)^2$ $x = x_{max} \cos(\omega t + \phi)$ $T = \frac{2\pi}{\omega} = \frac{1}{f}$ $T_s = 2\pi \sqrt{\frac{m}{k}}$ $T_p = 2\pi \sqrt{\frac{\ell}{g}}$ $ \vec{F}_G  = \frac{Gm_1 m_2}{r^2}$ $U_G = -\frac{Gm_1 m_2}{r}$
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### ELECTRICITY AND MAGNETISM

$ \vec{F}_E  = \frac{1}{4\pi\epsilon_0} \left  \frac{q_1 q_2}{r^2} \right $ $\vec{E} = \frac{\vec{F}_E}{q}$ $\oint \vec{E} \cdot d\vec{A} = \frac{Q}{\epsilon_0}$ $E_x = -\frac{dV}{dx}$ $\Delta V = -\int \vec{E} \cdot d\vec{r}$ $V = \frac{1}{4\pi\epsilon_0} \sum_i \frac{q_i}{r_i}$ $U_E = qV = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r}$ $\Delta V = \frac{Q}{C}$ $C = \frac{\kappa \epsilon_0 A}{d}$ $C_p = \sum_i C_i$ $\frac{1}{C_s} = \sum_i \frac{1}{C_i}$ $I = \frac{dQ}{dt}$ $U_C = \frac{1}{2} Q\Delta V = \frac{1}{2} C(\Delta V)^2$ $R = \frac{\rho \ell}{A}$ $\vec{E} = \rho \vec{J}$ $I = Nev_d A$ $I = \frac{\Delta V}{R}$ $R_s = \sum_i R_i$ $\frac{1}{R_p} = \sum_i \frac{1}{R_i}$ $P = I\Delta V$	<p><math>A</math> = area  <math>B</math> = magnetic field  <math>C</math> = capacitance  <math>d</math> = distance  <math>E</math> = electric field  <math>\mathcal{E}</math> = emf  <math>F</math> = force  <math>I</math> = current  <math>J</math> = current density  <math>L</math> = inductance  <math>\ell</math> = length  <math>n</math> = number of loops of wire per unit length  <math>N</math> = number of charge carriers per unit volume  <math>P</math> = power  <math>Q</math> = charge  <math>q</math> = point charge  <math>R</math> = resistance  <math>r</math> = radius or distance  <math>t</math> = time  <math>U</math> = potential or stored energy  <math>V</math> = electric potential  <math>v</math> = velocity or speed  <math>\rho</math> = resistivity  <math>\Phi</math> = flux  <math>\kappa</math> = dielectric constant</p> $\vec{F}_M = q\vec{v} \times \vec{B}$ $\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I$ $d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{\ell} \times \hat{r}}{r^2}$ $\vec{F} = \int I d\vec{\ell} \times \vec{B}$ $B_s = \mu_0 n I$ $\Phi_B = \int \vec{B} \cdot d\vec{A}$ $\mathcal{E} = \oint \vec{E} \cdot d\vec{\ell} = -\frac{d\Phi_B}{dt}$ $\mathcal{E} = -L \frac{dI}{dt}$ $U_L = \frac{1}{2} LI^2$
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## 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

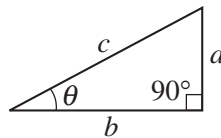
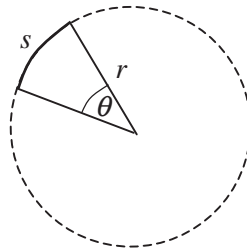
$\ell$  = length

$w$  = width

$r$  = radius

$s$  = arc length

$\theta$  = angle



### CALCULUS

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

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

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

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

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

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

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

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

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

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

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

### VECTOR PRODUCTS

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

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

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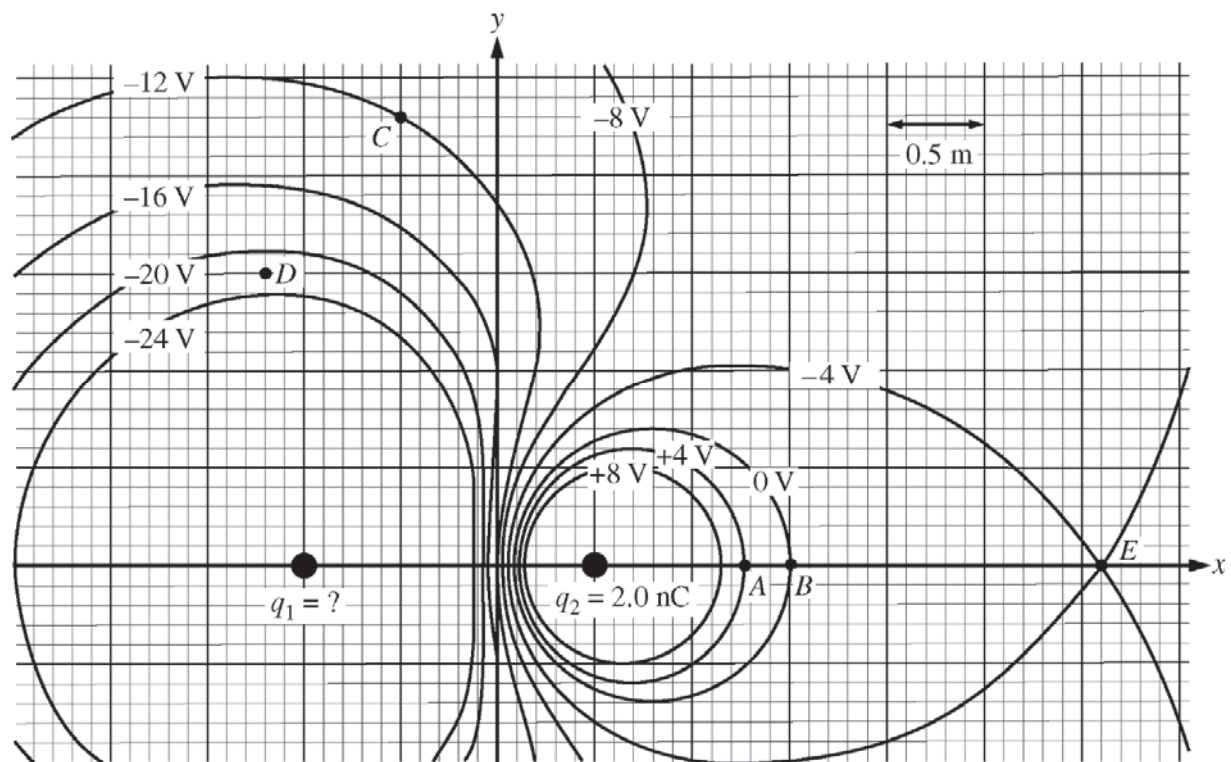
**PHYSICS C: ELECTRICITY AND MAGNETISM**

**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.

Two point charges,  $q_1$  and  $q_2$ , are fixed in place on the  $x$ -axis at positions  $x_1 = -1.00$  m and  $x_2 = +0.50$  m, respectively. Charge  $q_2$  has a value of  $+2.0$  nC. Values of electric potential are illustrated by the given equipotentials in the diagram shown above, which is drawn to scale.

- Calculate the value of  $q_1$ .
- At point C on the diagram, draw a vector representing the direction of the electric field at that point.
- Calculate the approximate magnitude of the electric field strength at point D on the diagram.
- The equipotential labeled  $0$  V is the cross section of a nearly spherical surface. Calculate the electric flux for this surface.

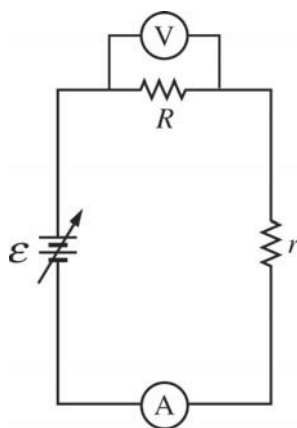
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- (e) A proton is placed at point A and then released from rest.
- Calculate the work done by the electric field on the proton as it moves from point A to point E.
  - Calculate the speed of the proton when it reaches point E.
- (f) An electron is released from rest at point B. Which of the following indicates the direction of the initial acceleration, if any, of the electron?

- Up                       Down  
 Left                       Right  
 Into the page             Out of the page  
 The direction is undefined since the acceleration is zero.

Justify your answer.

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E&M.2.

The circuit shown above consists of a source of variable emf  $\mathcal{E}$ , an ideal ammeter A, an ideal voltmeter V, a resistor of resistance  $R$ , and a sample of wire with resistance  $r$ .

(a) How does the current through the wire sample compare with the current through the resistor  $R$  ?

- It is greater through  $R$ .                       It is greater through the sample.  
 It is the same through both.                       It depends on the resistance of the sample.

Justify your answer.

(b) How does the potential difference across the wire sample compare with the potential difference across the resistor  $R$  ?

- It is greater across  $R$ .                       It is greater across the sample.  
 It is the same across both.                       It depends on the resistance of the sample.

Justify your answer.

With the sample of wire in place, the emf of the source is set to a given value. The current through and potential difference across the resistor  $R$  are measured. This is repeated for several values of emf, and the data are recorded in the table below.

$\mathcal{E}$ (V)	$V_R$ (V)	$I_R$ (A)		
0.250	0.179	0.162		
0.500	0.335	0.327		
0.750	0.520	0.490		
1.000	0.670	0.687		

(c) Indicate below which quantities should be graphed to yield a straight line that could be used to calculate a numerical value for the resistance of the wire sample.

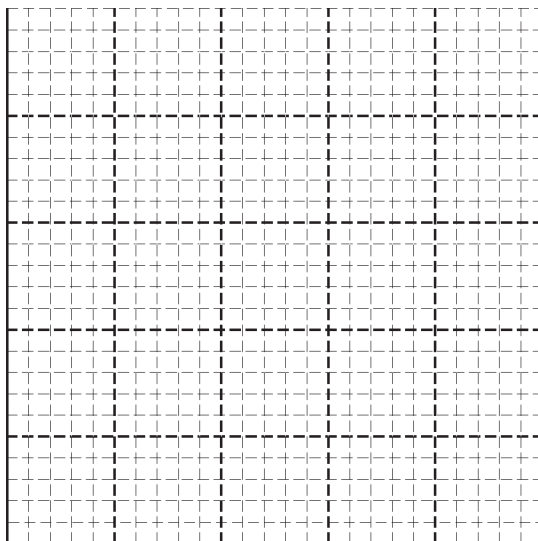
Horizontal axis: \_\_\_\_\_

Vertical axis: \_\_\_\_\_

You may use the remaining columns in the table above, as needed, to record any quantities that you indicated that are not given.

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(d) On the grid below, plot the straight line data points from part (c). Clearly scale and label all axes, including units if appropriate. Draw a straight line that best represents the data.



(e) Use your straight line to calculate the value of the resistance of the wire sample.

(f) The wire sample has a length of 3.00 m and a radius of  $1.00 \times 10^{-3}$  m . Calculate the resistivity of the material from which the wire sample is made.

(g)

i. Suppose the ammeter used to collect these data was not ideal. Would the actual value of the resistance of the wire sample be greater than, less than, or equal to that calculated in part (e) ?

\_\_\_ Greater than    \_\_\_ Less than    \_\_\_ Equal to

Justify your answer.

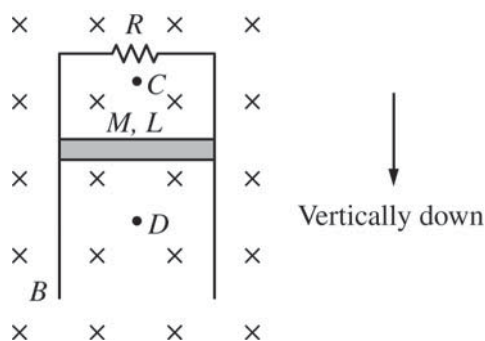
ii. If the ideal voltmeter is replaced by a voltmeter that is not ideal and the experiment is repeated, would the readings of the ideal ammeter be greater than, less than, or equal to those in the data chart before part (c) ?

\_\_\_ Greater than    \_\_\_ Less than    \_\_\_ Equal to

Justify your answer.



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E&M.3.

A conducting bar of mass  $M$ , length  $L$ , and negligible resistance is connected to two long vertical conducting rails of negligible resistance. The two rails are connected by a resistor of resistance  $R$  at the top. The entire apparatus is located in a magnetic field of magnitude  $B$  directed into the page, as shown in the figure above. The bar is released from rest and slides without friction down the rails.

(a) What is the direction of the current in the resistor?

\_\_\_ Left    \_\_\_ Right

(b)

i. Is the magnitude of the net magnetic field above the bar at point  $C$  greater than, less than, or equal to the magnitude of the net magnetic field before the bar is released?

\_\_\_ Greater than    \_\_\_ Less than    \_\_\_ Equal to

Justify your answer.

ii. While the bar is above point  $D$ , is the magnitude of the net magnetic field at point  $D$  greater than, less than, or equal to the magnitude of the net magnetic field before the bar is released?

\_\_\_ Greater than    \_\_\_ Less than    \_\_\_ Equal to

Justify your answer.

Express your answers to parts (c) and (d) in terms of  $M$ ,  $L$ ,  $R$ ,  $B$ , and physical constants, as appropriate.

(c) Write, but do NOT solve, a differential equation that could be used to determine the velocity of the falling bar as a function of time  $t$ .

(d) Determine an expression for the terminal velocity  $v_T$  of the bar.

Express your answers to parts (e) and (f) in terms of  $v_T$ ,  $M$ ,  $L$ ,  $R$ ,  $B$ , and physical constants, as appropriate.

(e) Derive an expression for the power dissipated in the resistor when the bar is falling at terminal velocity.

(f) Using your differential equation from part (c), derive an expression for the speed of the falling bar  $v(t)$  as a function of time  $t$ .

**STOP**

**END OF EXAM**