AP® Physics C: Electricity and Magnetism
2008 Free-Response Questions

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# TABLE OF INFORMATION FOR 2008 and 2009

## CONSTANTS AND CONVERSION FACTORS

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

| 1 unified atomic mass unit, $u$ | $1$ | Planck’s constant, $h$ | $6.63 \times 10^{-34}$ J·s |
| Planck’s constant, $h$ | $6.63 \times 10^{-34}$ J·s | $e$ | $1.60 \times 10^{-19}$ C |
| Vacuum permittivity, $\varepsilon_0$ | $8.85 \times 10^{-12}$ C$^2$/N·m$^2$ | Coulomb’s law constant, $k = 1/4\pi\varepsilon_0$ | $9.0 \times 10^9$ N·m$^2$/C$^2$ |
| Vacuum permeability, $\mu_0$ | $4\pi \times 10^{-7}$ (T·m)/A | Magnetic constant, $k' = \mu_0/4\pi$ | $10^{-7}$ (T·m)/A |
| 1 atmosphere pressure, $1$ atm | $1.0 \times 10^5$ N/m$^2$ | $1.0 \times 10^5$ Pa |

## UNIT SYMBOLS

<table>
<thead>
<tr>
<th>UNIT</th>
<th>SYMBOLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>meter, m</td>
<td>mole, mol</td>
</tr>
<tr>
<td>kilogram, kg</td>
<td>watt, W</td>
</tr>
<tr>
<td>second, s</td>
<td>farad, F</td>
</tr>
<tr>
<td>ampere, A</td>
<td>joule, J</td>
</tr>
<tr>
<td>kelvin, K</td>
<td>coulomb, C</td>
</tr>
<tr>
<td>hertz, Hz</td>
<td>volt, V</td>
</tr>
<tr>
<td>newton, N</td>
<td>ohm, Ω</td>
</tr>
<tr>
<td>pascal, Pa</td>
<td>degree Celsius, °C</td>
</tr>
<tr>
<td>electron-volt, eV</td>
<td></td>
</tr>
</tbody>
</table>

## PREFIXES

<table>
<thead>
<tr>
<th>Factor</th>
<th>Prefix</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^9$</td>
<td>giga</td>
<td>G</td>
</tr>
<tr>
<td>$10^6$</td>
<td>mega</td>
<td>M</td>
</tr>
<tr>
<td>$10^3$</td>
<td>kilo</td>
<td>k</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>centi</td>
<td>c</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>milli</td>
<td>m</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>micro</td>
<td>µ</td>
</tr>
<tr>
<td>$10^{-9}$</td>
<td>nano</td>
<td>n</td>
</tr>
<tr>
<td>$10^{-12}$</td>
<td>pico</td>
<td>p</td>
</tr>
</tbody>
</table>

## VALUES OF TRIGONOMETRIC FUNCTIONS FOR COMMON ANGLES

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>$0^\circ$</th>
<th>$30^\circ$</th>
<th>$45^\circ$</th>
<th>$60^\circ$</th>
<th>$90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin \theta$</td>
<td>0</td>
<td>1/2</td>
<td>3/4</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$\cos \theta$</td>
<td>1</td>
<td>$\sqrt{3}/2$</td>
<td>3/4</td>
<td>1</td>
<td>$\sqrt{3}/2$</td>
</tr>
<tr>
<td>$\tan \theta$</td>
<td>0</td>
<td>$\sqrt{3}$</td>
<td>3</td>
<td>1</td>
<td>$\sqrt{3}$</td>
</tr>
</tbody>
</table>

The following conventions are used in this exam.

I. Unless otherwise stated, the frame of reference of any problem is assumed to be inertial.

II. The direction of any electric current is the direction of flow of positive charge (conventional current).

III. For any isolated electric charge, the electric potential is defined as zero at an infinite distance from the charge.
### MECHANICS

\[ v = v_0 + at \]
\[ x = x_0 + v_0t + \frac{1}{2}at^2 \]
\[ v^2 = v_0^2 + 2a(x - x_0) \]
\[ \sum F = F_{\text{net}} = ma \]
\[ F = \frac{dp}{dt} \]
\[ J = \int F \, dt = \Delta p \]
\[ p = mv \]
\[ F_{\text{fric}} \leq \mu N \]
\[ W = \int \mathbf{F} \cdot d\mathbf{r} \]
\[ K = \frac{1}{2}mv^2 \]
\[ P = \frac{dW}{dt} \]
\[ P = F \cdot \mathbf{v} \]
\[ \Delta U_g = mgh \]
\[ a_c = \frac{v^2}{r} = \omega^2 r \]
\[ \tau = r \times F \]
\[ \sum \tau = \tau_{\text{net}} = I\alpha \]
\[ I = \int r^2 \, dm = \sum mr^2 \]
\[ r_{cm} = \frac{\sum mr}{\sum m} \]
\[ \nu = r\omega \]
\[ \mathbf{L} = r \times \mathbf{p} = I\omega \]
\[ K = \frac{1}{2}I\omega^2 \]
\[ \mathbf{F}_G = -\frac{Gm_1m_2}{r^2} \mathbf{r} \]
\[ \omega = \omega_0 + at \]
\[ U_G = -\frac{Gm_1m_2}{r} \]
\[ \theta = \theta_0 + \omega_0 t + \frac{1}{2}at^2 \]

### ELECTRICITY AND MAGNETISM

\[ F = \frac{1}{4\pi \varepsilon_0} \frac{q_1 q_2}{r^2} \]
\[ \mathbf{E} = \frac{\mathbf{F}}{q} \]
\[ \int \mathbf{E} \cdot d\mathbf{A} = \frac{Q}{\varepsilon_0} \]
\[ E = \frac{dV}{dr} \]
\[ V = \frac{1}{4\pi \varepsilon_0} \sum_i \frac{q_i}{r_i} \]
\[ U_E = \frac{qV}{4\pi \varepsilon_0} \frac{q_1 q_2}{r} \]
\[ C = \frac{Q}{V} \]
\[ C_p = \sum C_i \]
\[ \frac{1}{C_s} = \sum \frac{1}{C_i} \]
\[ I = \frac{dQ}{dt} \]
\[ U_c = \frac{1}{2}QV = \frac{1}{2}CV^2 \]
\[ \oint \mathbf{B} \cdot d\ell = \mu_0 I \]
\[ d\mathbf{B} = \frac{\mu_0}{4\pi} \frac{I \, d\ell \times \mathbf{r}}{r^3} \]
\[ \mathbf{F} = \int \mathbf{l} \, d\ell \times \mathbf{B} \]
\[ I = Neu_d A \]
\[ V = IR \]
\[ R_s = \sum R_i \]
\[ \frac{1}{R_p} = \sum \frac{1}{R_i} \]
\[ P = IV \]
\[ \mathbf{F}_M = q \mathbf{v} \times \mathbf{B} \]
\[ U_L = \frac{1}{2}LI^2 \]
GEOMETRY AND TRIGONOMETRY

Rectangle
\[ A = bh \]

Triangle
\[ A = \frac{1}{2}bh \]

Circle
\[ A = \pi r^2 \]
\[ C = 2\pi r \]

Parallelepiped
\[ V = \ell wh \]

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
\[ a^2 + b^2 = c^2 \]
\[ \sin \theta = \frac{a}{c} \]
\[ \cos \theta = \frac{b}{c} \]
\[ \tan \theta = \frac{a}{b} \]

CALCULUS

\[ \frac{df}{dx} = \frac{df}{du} \cdot \frac{du}{dx} \]
\[ \frac{d}{dx} \left( x^n \right) = nx^{n-1} \]
\[ \frac{d}{dx} \left( e^x \right) = e^x \]
\[ \frac{d}{dx} \left( \ln x \right) = \frac{1}{x} \]
\[ \frac{d}{dx} \left( \sin x \right) = \cos x \]
\[ \frac{d}{dx} \left( \cos x \right) = -\sin x \]
\[ \int x^n \, dx = \frac{1}{n+1} x^{n+1}, \ n \neq -1 \]
\[ \int e^x \, dx = e^x \]
\[ \int \ln |x| \, dx \]
\[ \int \sin x \, dx = -\cos x \]
E&M. 1.

A metal sphere of radius $a$ contains a charge $+Q$ and is surrounded by an uncharged, concentric, metallic shell of inner radius $b$ and outer radius $c$, as shown above. Express all algebraic answers in terms of the given quantities and fundamental constants.

(a) Determine the induced charge on each of the following and explain your reasoning in each case.
   
   i. The inner surface of the metallic shell
   
   ii. The outer surface of the metallic shell

(b) Determine expressions for the magnitude of the electric field $E$ as a function of $r$, the distance from the center of the inner sphere, in each of the following regions.
   
   i. $r < a$
   
   ii. $a < r < b$
   
   iii. $b < r < c$
   
   iv. $c < r$
(c) On the axes below, sketch a graph of $E$ as a function of $r$.

![Graph of E vs. r]

(d) An electron of mass $m_e$ carrying a charge $-e$ is released from rest at a very large distance from the spheres. Derive an expression for the speed of the particle at a distance $10r$ from the center of the spheres.
E&M. 2.

In the circuit shown above, \( A \) and \( B \) are terminals to which different circuit components can be connected.

(a) Calculate the potential difference across \( R_2 \) immediately after the switch \( S \) is closed in each of the following cases.

i. A 50 \( \Omega \) resistor connects \( A \) and \( B \).

ii. A 40 mH inductor connects \( A \) and \( B \).

iii. An initially uncharged 0.80 \( \mu \text{F} \) capacitor connects \( A \) and \( B \).

(b) The switch gets closed at time \( t = 0 \). On the axes below, sketch the graphs of the current in the 100 \( \Omega \) resistor \( R_3 \) versus time \( t \) for the three cases. Label the graphs \( R \) for the resistor, \( L \) for the inductor, and \( C \) for the capacitor.
E&M. 3.

The circular loop of wire in Figure 1 above has a radius of \( R \) and carries a current \( I \). Point \( P \) is a distance of \( \frac{R}{2} \) above the center of the loop. Express algebraic answers to parts (a) and (b) in terms of \( R, I, \) and fundamental constants.

(a)

i. State the direction of the magnetic field \( B_1 \) at point \( P \) due to the current in the loop.

ii. Calculate the magnitude of the magnetic field \( B_1 \) at point \( P \).

A second identical loop also carrying a current \( I \) is added at a distance of \( R \) above the first loop, as shown in Figure 2 above.

(b) Determine the magnitude of the net magnetic field \( B_{\text{net}} \) at point \( P \).

A small square loop of wire in which each side has a length \( s \) is now placed at point \( P \) with its plane parallel to the plane of each loop, as shown in Figure 3 above. For parts (c) and (d), assume that the magnetic field between the two circular loops is uniform in the region of the square loop and has magnitude \( B_{\text{net}} \).

(c) In terms of \( B_{\text{net}} \) and \( s \), determine the magnetic flux through the square loop.

(d) The square loop is now rotated about an axis in its plane at an angular speed \( \omega \). In terms of \( B_{\text{net}}, s, \) and \( \omega \), calculate the induced emf in the loop as a function of time \( t \), assuming that the loop is horizontal at \( t = 0 \).

END OF EXAM