SECRET STUDENT NUMBER: STUDNUMBER

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$$
\begin{aligned}
\vec{a}\times(\vec{b}\times\vec{c}) &= \vec{b}(\vec{a}\cdot\vec{c})-\vec{c}(\vec{a}\cdot\vec{b}),\\
\vec{a}\cdot(\vec{b}\times\vec{c}) &= \vec{b}\cdot(\vec{c}\times\vec{a})=\vec{c}\cdot(\vec{a}\times\vec{b}),\\
(\vec{a}\times\vec{b})\cdot(\vec{c}\times\vec{d}) &= (\vec{a}\cdot\vec{c})(\vec{b}\cdot\vec{d})-(\vec{a}\cdot\vec{d})(\vec{b}\cdot\vec{c}),\\
\boldsymbol{\nabla}\times(\boldsymbol{\nabla}\psi) &= 0,\\
\boldsymbol{\nabla}\cdot(\boldsymbol{\nabla}\times\vec{a}) &= 0,\\
\boldsymbol{\nabla}\times(\boldsymbol{\nabla}\times\vec{a}) &= \boldsymbol{\nabla}(\boldsymbol{\nabla}\cdot\vec{a})-\nabla^2\vec{a},\\
\boldsymbol{\nabla}\cdot(\psi\vec{a}) &= \vec{a}\cdot\boldsymbol{\nabla}\psi+\psi\boldsymbol{\nabla}\cdot\vec{a},\\
\boldsymbol{\nabla}\times(\psi\vec{a}) &= \boldsymbol{\nabla}\psi\times\vec{a}+\psi\boldsymbol{\nabla}\times\vec{a},\\
\boldsymbol{\nabla}(\vec{a}\cdot\vec{b}) &= (\vec{a}\cdot\boldsymbol{\nabla})\vec{b}+(\vec{b}\cdot\boldsymbol{\nabla})\vec{a}+\vec{a}\times(\boldsymbol{\nabla}\times\vec{b})+\vec{b}\times(\boldsymbol{\nabla}\times\vec{a}),\\
\boldsymbol{\nabla}\cdot(\vec{a}\times\vec{b}) &= \vec{b}\cdot(\boldsymbol{\nabla}\times\vec{a})-\vec{a}\cdot(\boldsymbol{\nabla}\times\vec{b}),\\
\boldsymbol{\nabla}\times(\vec{a}\times\vec{b}) &= \vec{a}(\boldsymbol{\nabla}\times\vec{b})-\vec{b}(\boldsymbol{\nabla}\times\vec{a})+(\vec{b}\cdot\boldsymbol{\nabla})\vec{a}-(\vec{a}\cdot\boldsymbol{\nabla})\vec{b},\\
\boldsymbol{\nabla}\cdot\vec{r} &= 3,\\
\boldsymbol{\nabla}\times\vec{r} &= 0,\\
\boldsymbol{\nabla}\cdot\hat{r} &= 2/r,\\
\boldsymbol{\nabla}\times\hat{r} &= 0,\\
(\vec{a}\cdot\nabla)\hat{r} &= \frac{1}{r}[\vec{a}-\hat{r}(\vec{a}\cdot\hat{r})]=\frac{\vec{a}_\perp}{r}.
\end{aligned}
$$

$$
\begin{aligned}
\int_V d^3r\ \boldsymbol{\nabla}\cdot\vec{A} &= \int_S d\vec{S}\cdot\vec{A},\\
\int_V d^3r\ \boldsymbol{\nabla}\psi &= \int_S \psi\ d\vec{S},\\
\int_V d^3r\ \boldsymbol{\nabla}\times\vec{A} &= \int_S d\vec{S}\times\vec{A},\\
\int_V d^3r\ (\phi\nabla^2\psi+\boldsymbol{\nabla}\phi\cdot\boldsymbol{\nabla}\psi) &= \int_S \phi\ d\vec{S}\cdot\boldsymbol{\nabla}\psi,\\
\int_V d^3r\ (\phi\nabla^2\psi-\psi\nabla^2\phi) &= \int_S (\phi\boldsymbol{\nabla}\psi-\psi\boldsymbol{\nabla}\phi)\cdot d\vec{S},\\
\int_S (\boldsymbol{\nabla}\times\vec{A})\cdot d\vec{S} &= \oint d\vec{\ell}\cdot\vec{A},\\
\int_S d\vec{S}\times\boldsymbol{\nabla}\psi &= \oint_C d\vec{\ell}\ \psi.
\end{aligned}
$$

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\begin{aligned}
\nabla^2 &= \partial_r^2+\frac{2}{r}\partial_r-\frac{\ell(\ell+1)}{r^2},\\
\nabla^2 &= \partial_\rho^2+\frac{1}{\rho}\partial_\rho-\frac{m^2}{r^2},\\
\nabla^2\left(\frac{1}{r}\right) &= -4\pi\delta(\vec{r}).
\end{aligned}
$$

$$L^{\alpha}{}_{\beta} = \begin{bmatrix} \gamma & \gamma v & 0 & 0 \\ \gamma v & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

$$\begin{aligned}
F_{\alpha\beta} &= \begin{pmatrix} 0 & E_x & E_y & E_z \\ -E_x & 0 & -B_z & B_y \\ -E_y & B_z & 0 & -B_x \\ -E_z & -B_y & B_x & 0 \end{pmatrix}, \\
F^{\alpha\beta} &= \begin{pmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & -B_z & B_y \\ E_y & B_z & 0 & -B_x \\ E_z & -B_y & B_x & 0 \end{pmatrix}.
\end{aligned}$$

$$\begin{aligned}
m\frac{d}{d\tau}u^{\alpha} &= eF^{\alpha\beta}u_{\beta}, \\
\frac{d\vec{p}}{dt} &= e\vec{E} + e\vec{v}\times\vec{B}, \\
\omega_c &= \frac{eB}{\gamma m}, \\
\boldsymbol{\nabla}\cdot\vec{E} &= 4\pi J^0, \\
(\boldsymbol{\nabla}\times\vec{B}) - \partial_t\vec{E} &= 4\pi\vec{J}, \\
\boldsymbol{\nabla}\cdot\vec{B} &= 0, \\
\partial_t\vec{B} + \boldsymbol{\nabla}\times\vec{E} &= 0, \\
\partial_\alpha F^{\alpha\beta} &= 4\pi J^{\beta}, \\
\partial_\alpha \tilde{F}^{\alpha\beta} &= 0, \\
e^2 &= \frac{\hbar c}{137.036}, \\
T^{\alpha\beta} &= \pi^{\alpha}\partial^{\beta}\phi - g^{\alpha\beta}\mathcal{L}, \\
\pi^{\alpha} &\equiv \frac{\partial\mathcal{L}}{\partial(\partial_\alpha\phi)}, \\
T^{00} &= \frac{1}{8\pi}(E^2+B^2), \\
T^{0i} &= \frac{1}{4\pi}\epsilon_{ijk}E_jB_k, \\
T^{ij} = -T^{i}{}_{j} &= \frac{1}{8\pi}(\delta_{ij}(E^2+B^2) - 2E_iE_j - 2B_iB_j), \\
\vec{E} &= -\boldsymbol{\nabla}A_0 - \partial_t\vec{A} = -\boldsymbol{\nabla}\Phi - \partial_t\vec{A}, \quad \vec{B} = \boldsymbol{\nabla}\times\vec{A}.
\end{aligned}$$

$$\begin{aligned}
P_\ell(\cos\theta) &= \sqrt{\frac{4\pi}{2\ell+1}}Y_{\ell m=0}(\theta), \\
Y_{0,0} &= \frac{1}{\sqrt{4\pi}}, \quad Y_{1,0} = \sqrt{\frac{3}{4\pi}}\cos\theta, \\
Y_{1,\pm1} &= \mp\sqrt{\frac{3}{8\pi}}\sin\theta e^{i\pm\phi}, \quad Y_{2,0} = \sqrt{\frac{5}{16\pi}}(3\cos^2\theta - 1), \\
Y_{2,\pm1} &= \mp\sqrt{\frac{15}{8\pi}}\sin\theta\cos\theta e^{\pm i\phi}, \quad Y_{2,\pm2} = \sqrt{\frac{15}{32\pi}}\sin^2\theta e^{\pm2i\phi}, \\
Y_{\ell -m}(\theta,\phi) &= (-1)^m Y^*_{\ell m}(\theta,\phi), \\
\delta_{\ell\ell'}\delta_{mm'} &= \int d\Omega\; Y_{\ell,m}(\theta,\phi)Y_{\ell',m'}(\theta,\phi), \\
P_0(x) &= 1, \quad P_1(x) = x, \\
P_2(x) &= \frac{1}{2}(3x^2-1), \quad P_3(x) = \frac{1}{2}(5x^3-3x), \\
P_\ell(x=1) &= 1, \quad \int_{-1}^{1} dx\; P_\ell(x)P_{\ell'}(x) = \frac{2}{2\ell+1}\delta_{\ell\ell'}, \\
(3D) \quad \Phi &= \sum_{\ell m}\left(A_{\ell m}r^{\ell} + B_{\ell m}r^{-\ell-1}\right)Y_{\ell m}(\theta,\phi)e^{im\phi}, \\
(2D) \quad \Phi &= A_0\ln(\rho) + \sum_m e^{im\phi}\left(A_m \underset{\rho}{r}{}^{m} + B_m \underset{\rho}{r}{}^{-m}\right), \\
\Phi &= A_0J_0 = \sum_m e^{im\phi}\left(A_mJ_m(k\rho) + B_mN_m(k\rho)\right)e^{\pm kz}, \\
\Phi &= \frac{q}{r} + \frac{\vec{p}\cdot\vec{r}}{r^3} + \sum_m \frac{4\pi}{5r^3}q_{2m}(r)Y_{2m}(\theta,\phi), \\
\vec{E} &= -\frac{1}{r^3}\vec{p} + 3\frac{\vec{p}\cdot\vec{r}}{r^5}\vec{r} + \cdots, \\
\Phi(r,\theta,\phi) &= \sum_{\ell m}\frac{4\pi}{(2\ell+1)r^{\ell+1}}q_{\ell m}(r)Y_{\ell m}(\theta,\phi), \\
q_{22} &= \sqrt{\frac{15}{32\pi}}\int d^3r\;\rho(\vec{r})(x-iy)^2 = \sqrt{\frac{15}{288\pi}}(Q_{11} - 2iQ_{12} - Q_{22}), \\
q_{21} &= -\sqrt{\frac{15}{8\pi}}\int d^3r\;\rho(\vec{r})(x-iy)^{\cancel{2}}\,z = -\sqrt{\frac{15}{72\pi}}(Q_{13} - iQ_{23}), \\
q_{20} &= \sqrt{\frac{5}{16\pi}}\int d^3r\;\rho(\vec{r})(3z^2-r^2) = \sqrt{\frac{5}{16\pi}}Q_{33}, \\
Q_{ij} &\equiv \int d^3r\;(3r_ir_j - r^2\delta_{ij})\rho(\vec{r}), \\
U &= q\Phi_0 - \vec{p}\cdot\vec{E} - \frac{1}{6}Q_{ij}\partial_iE_j,
\end{aligned}$$

$$
\begin{aligned}
\nabla^2 A^\alpha &= -4\pi J^\alpha, \\
\vec{m} &= \frac{1}{2}\int d^3r\ \vec{r}\times\vec{J} = \frac{I}{2}\int\ \vec{r}\times d\vec{\ell}, \\
\vec{B} &= -\frac{\vec{m}}{r^3} + \frac{3\vec{r}}{r^5}(\vec{m}\cdot\vec{r}), \\
\mu_e &= g_e\frac{e\hbar}{2m_e}, \\
U &= \frac{(\vec{\mu}_N\cdot\vec{\mu}_e)}{r^3} - \frac{3(\vec{\mu}_N\cdot\vec{r})(\vec{\mu}_e\cdot\vec{r})}{r^5} - \frac{8\pi}{3}(\vec{\mu}_N\cdot\vec{\mu}_e)\delta^3(\vec{r}) \\
&\quad -e\frac{(\vec{\mu}_N\cdot\vec{L})}{mr^3}, \\
T_{00} &= \frac{1}{8\pi}\left(|\vec{E}|^2 + |\vec{B}|^2\right) \\
&= \frac{a_i^2 + b_i^2}{8\pi} = \frac{|\vec{a}|^2}{4\pi}\cos^2(\vec{k}\cdot\vec{r}-\omega t), \\
T_{0i} &= \epsilon_{ijk}\frac{E_jB_k}{4\pi} \\
&= \hat{k}_i\frac{|\vec{a}|^2}{4\pi}\cos^2(\vec{k}\cdot\vec{r}-\omega t), \\
T^{ij} = -T^i{}_j &= \frac{1}{8\pi}(\delta_{ij}(E^2+B^2) - 2E_iE_j - 2B_iB_j). \\
&= \frac{1}{4\pi}\left\{|\vec{a}|^2\delta_{ij} - a_ia_j - b_ib_j\right\}\cos^2(\vec{k}\cdot\vec{r}-\omega t), \\
\omega_s &= \omega\sqrt{\frac{1-v}{1+v}}, \\
(TM)\quad E_z &= \psi(x,y)e^{-i\omega t + ik_z z}, \\
\nabla_t^2\psi &= -(\omega^2 - k_z^2)\psi, \quad \Psi|_S = 0, \\
\vec{E}_t(x,y) &= \frac{ik_z}{(\omega^2-k_z^2)}e^{-i\omega t + ik_z z}\boldsymbol{\nabla}_t\psi(x,y), \\
\vec{B}_t(x,y) &= \left(\frac{\omega}{k_z}\right)\hat{z}\times\vec{E}_t, \\
(TE)\quad B_z &= \psi(x,y)e^{-i\omega t + ik_z z}, \\
(\hat{n}\cdot\boldsymbol{\nabla}_t)\psi(x,y)|_S &= 0, \\
\vec{B}_t(x,y) &= \frac{ik_z}{(\omega^2-k_z^2)}e^{-i\omega t + ik_z z}\boldsymbol{\nabla}_t\psi(x,y), \\
\vec{E}_t(x,y) &= -\left(\frac{\omega}{k_z}\right)\hat{z}\times\vec{B}_t.
\end{aligned}
$$

$$
\begin{aligned}
A^\alpha(x) &= \int d^4x'\ \frac{1}{|\vec{x}-\vec{x}'|}J^\alpha(x')\delta(x_0 - x_0' - |\vec{x}-\vec{x}'|), \\
\vec{E} &= e\left\{\frac{\hat{n}\times[(\hat{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{\beta}\cdot\hat{n})^3|\vec{x}|}\right\}, \\
\vec{B} &= \hat{n}\times\vec{E}.
\end{aligned}
$$

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\begin{aligned}
P &= \frac{2e^2}{3c}|\dot{\vec{\beta}}|^2 \quad \text{(Non.Rel.)}, \\
\frac{dP}{d\Omega} &= \frac{e^2}{4\pi(1-\vec{\beta}\cdot\hat{n})^6}|(\hat{n}-\vec{\beta})\times\dot{\vec{\beta}})|^2, \\
P &= \frac{2}{3c}e^2\gamma^6\left[\dot{\beta}^2 - |\vec{\beta}\times\dot{\vec{\beta}}|^2\right], \\
\frac{dP}{d\Omega} &= \frac{e^2}{4\pi(1-\beta\cos\theta)^5}|\dot{\vec{\beta}}|^2\sin^2\theta \quad \text{(linear)}, \\
P &= \frac{2e^2\dot{\beta}^2}{3c}\gamma^6 \quad \text{(linear)}, \\
\frac{dP}{d\Omega} &= \frac{e^2}{4\pi(1-\beta n_\beta)^5}|\dot{\vec{\beta}}|^2\left((1-\beta n_\beta)^2 - (1-\beta^2)n_r^2\right) \quad \text{(circular)}, \\
P &= \frac{2}{3c}e^2\dot{\beta}^2\gamma^4 \quad \text{(circular)}.
\end{aligned}
$$

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\begin{aligned}
\frac{dP}{d\Omega} &= \frac{1}{8\pi}\omega^4|\hat{n}\times\vec{p}|^2, \\
P &= \frac{\omega^4}{3}|\vec{p}|^2,
\end{aligned}
$$

$$
\begin{aligned}
\text{(Thomson)}\quad \sigma &= \frac{8\pi e^4}{3m^2}, \\
\frac{\Delta\lambda}{\lambda} &= \frac{\hbar\omega}{m}(1-\cos\theta_s).
\end{aligned}
$$

electron	$-2.00231930436182 \pm 0.00000000000052$
muon	$-2.0023318418 \pm 0.0000000013$
proton	$5.585694702 \pm 0.000000017$
neutron	$-3.82608545 \pm 0.00000090$

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LONG ANSWER SECTION

1. (15 pts) Consider an infinitely long thin cylindrical shell of radius R oriented along the z axis. The shell has a surface charge density,

$$\sigma = \sigma_0 \cos\phi.$$

Find the electric potential at all positions as a function of the transverse radius $r = \sqrt{x^2+y^2}$ and the azimuthal angle $\phi = \tan^{-1}(y/x)$.

$$\Phi = \begin{cases} (A/r)\cos\varphi, & r > R \\ Br\cos\varphi, & r < R \end{cases}$$

$$E_r = \begin{cases} (A/r^2)\cos\varphi, & r > R \\ -B\cos\varphi, & r < R \end{cases}$$

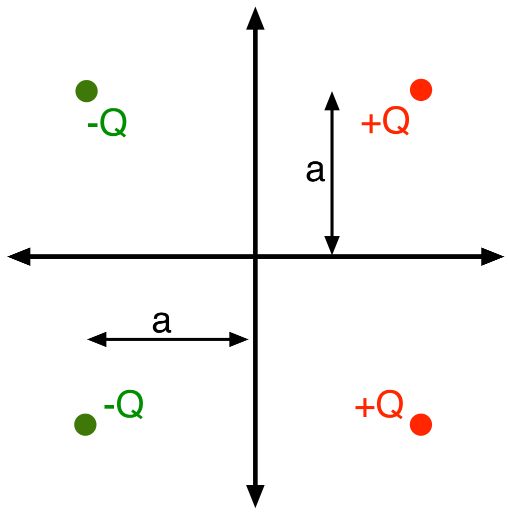
$$\frac{A}{R^2} + B = 4\pi\sigma_0, \quad A/R = BR$$

$$2A/R^2 = 4\pi\sigma_0, \quad A = 2\pi\sigma_0 R^2$$

$$B = 2\pi\sigma_0$$

$$\Phi = \begin{cases} \frac{2\pi\sigma_0 R^2}{r}, & r > R \\ 2\pi\sigma_0 r, & r < R \end{cases}$$

Extra workspace for #1



2. Consider a set of four charges: $+Q$ at $x = a, y = a, z = 0$, $+Q$ at $x = a, y = -a, z = 0$, $-Q$ at $x = -a, y = -a, z = 0$, $-Q$ at $x = -a, y = a, z = 0$.

   (a) (5 pts) For large distances r, the electric potential can be written as $\Phi(\vec{r}) = F(\theta, \phi)/r^n$. What is n?

   (b) (10 pts) Find $F(\theta, \phi)$, where θ and ϕ are spherical coordinates (defined around the z axis).

a) dipole, $n = 2$

b) $\vec{d} = 4aQ\hat{x}$

$$\Phi = \frac{\hat{x} \cdot \hat{r}}{r^2} = \frac{4aQ}{r^2} \sin\theta \cos\phi$$

$$F = 4aQ \sin\theta \cos\phi$$

Extra workspace for #2

3. An antenna is designed by circulating a current around a circular loop of radius R with its axis along the z direction. The current has the form

$$I(\phi, t) = I_0 \cos(\omega t - \phi),$$

where ϕ denotes is the azimuthal angle of a point on the loop.

   (a) (5 pts) Find the charge per unit length, $\lambda(\phi, t)$.

   (b) (10 pts) Find the radiated power.

a) $\partial_t \lambda = -\frac{1}{R} \partial_\varphi I_0 \cos(\omega t - \varphi)$

$$= -\frac{I_0}{R} \sin(\omega t - \varphi)$$

$$\lambda = \frac{I_0}{\omega R} \cos(\omega t - \varphi)$$

b) $p_x(t) = \int \lambda(\varphi) R d\varphi \; R\cos\varphi$

$$= \frac{I_0 R}{\omega} \int d\varphi \cos^2\varphi \cos\omega t$$

$$p_x = \frac{\pi I_0 R}{\omega}$$

$$p_y(t) = \frac{\pi I_0 R}{\omega} \sin\omega t$$

$$p_y = \frac{\pi I_0 R}{\omega}$$

$$P = \frac{\omega^4}{3}(p_x^2 + p_y^2) = \frac{2\pi^2}{3} I_0^2 R^2 \omega^2$$

OR

$$\frac{2\pi^2}{3c^3} I_0^2 R^2 \omega^2$$

Extra work space for #3

4. A rectangular wave guide has transverse dimensions, $0 < x < a$ and $0 < y < a$. For a transverse electric (TE) wave moving along the z axis with wave number k_z.

(a) (5 pts) Find the frequency of the propagating wave. Choose the solutions with the fewest nodes in the transverse wave function.

(b) (10 pts) Find the magnetic field $\vec{B}(x, y, z, t)$ for this solution.

(c) (5 pts) What is the group velocity of the wave?

a) $\omega^2 = \left(\frac{\pi}{a}\right)^2 + k^2$, $\omega = \sqrt{k^2 + (\pi^2/a^2)}$

b) $\psi = B_0 \cos\left(\frac{\pi x}{a}\right)$ (one direction can be constant)

$B_z = \psi e^{ikz - i\omega t} = B \cos\frac{\pi x}{a} e^{ikz - i\omega t}$

$\vec{B}_t = \left(\frac{ik}{\omega^2 - k^2} \nabla \psi\right) e^{ikz - i\omega t}$

$= \frac{-ik}{\omega^2 - k^2} \frac{\pi}{a} B_0 \hat{x} \sin\left(\frac{\pi x}{a}\right)$

$= \frac{-ika}{2\pi} B_0 \hat{x} \sin\left(\frac{\pi x}{a}\right)$

c) $v_z = \frac{d\omega}{dk} = \frac{k}{\omega} = \frac{k}{\sqrt{k^2 + \pi^2/a^2}}$

Extra work space for #4

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SHORT ANSWER SECTION

5. (3 pts each) Light is emitted from a distant source from early in the universe. Choose $>$, $<$ or $=$ for each answer

   (a) The initial frequency of the source is $>$ than the frequency of the light measured by a present-day observer.

   (b) If an observer moves toward the source, the observed frequency will be $>$ than the frequency measured by a static observer.

6. (4 pts) In terms of M_p/m_e (mass of proton to mass of electron) calculate the ratio of the radiative powers P_e/P_p emitted for a very high-energy circular accelerator of a given radius R that features either electron or proton beams of the same energy and same currents. Note: Magnetic fields would be quite different to hold particles to the same energy and radius. $\left(\frac{M_p}{M_e}\right)^4$

7. (3 pts each) Sally Slowpoke measures two events that both occur right in front of her nose separated by a time $\Delta\tau = 1.0$ second. Roberto Rapido travels by in his space ship at some speed $\vec{v}$. (Circle the correct answers)

   (a) The difference in the times of the two events Roberto measures, $\Delta t'$, will
      - always be positive
      - may be positive or negative depending on $\vec{v}$.

   (b) The distance between the two events measured by Robert will be
      - always $< c|\Delta\tau|$
      - greater or less than $c|\Delta\tau|$ depending on $\vec{v}$.

8. You wish to solve the following problem using the method of images:
   "A point charge Q is placed far outside a grounded conducting spherical shell of radius R. The position of the charge is $x = 0, y = 0, z = A >> R$." You are solving for the potential outside the shell.
   True or false: (4 pts)

   (a) The image charge is inside the sphere. T

   (b) The potential inside the sphere is constant. T

   (c) The magnitude of the image charge must be less than $|Q|$. T

9. (5 pts) Which of the following are odd under parity? Circle the answers.

   (a) $\vec{A}$ (the vector potential)

   (b) A_0 (the electric potential)

   (c) $\vec{E}$ (the electric field)

   (d) $\vec{B}$ (the magnetic field)

   (e) $\vec{E} \times \vec{B}$

   (f) $|\vec{B}|^2 - |\vec{E}|^2$

   (g) $|\vec{E}|^2 + |\vec{B}|^2$

   (h) $\vec{E} \cdot \vec{B}$

   (i) $J \cdot A$ (J is the electric current density)

10. Consider a system with non-zero electric and magnetic fields,

$$\vec{B} = B_z\hat{z}, \quad \vec{E} = E_x\hat{x},$$
$$E_x > 0, B_z > 0, \quad E_x > B_z.$$

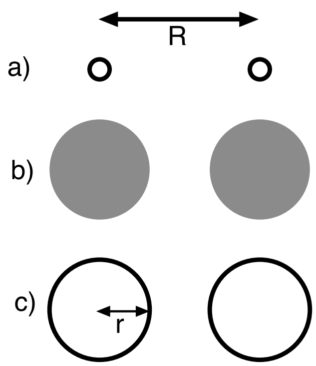
A charged particle is placed at the origin, initially with zero momentum. For each question answer True or False. (6 pts)

(a) There exists a reference frame where $\vec{B} = 0$. T

(b) At large times the coordinate $x \to \infty$. T

(c) At large times the coordinate $y \to \infty$. T

(d) At some parts of the trajectory the particle's momentum p_x would be negative. F



11. (4 pts) Consider the three charge configurations shown above:
(a) two point charges $+Q$ separated by R
(b) two spheres of radius $r < R/2$, each with charge $+Q$ uniformly spread throughout the volume, with the centers separated by R
(c) two spherical shells of radius $r < R/2$, each with charge $+Q$ uniformly spread throughout the surface, with the centers separated by R.

The work required to move the spheres (or points) from infinity to the separation R is labeled W_a, W_b and W_c for each configuration. Label each statement as true or false.

(a) $W_a > W_b$ F

(b) $W_a > W_c$ F

(c) $W_b > W_c$ F