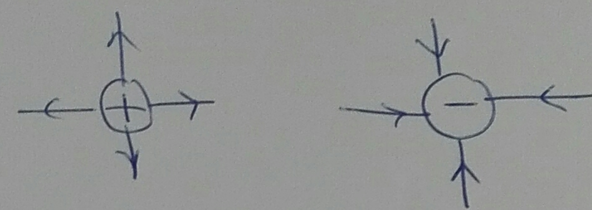
Ch. 22 Electric Fields

- $\vec{E} = \frac{K|q|}{r^2}\hat{r}$

point charge



- Continuous charge distribution

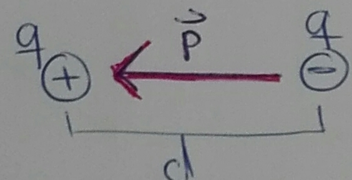
$\lambda = Q/\text{Length}$

$\sigma = Q/\text{Area}$

$\rho = Q/\text{Volume}$

- Force on a point charge in an $\vec{E} \Rightarrow \vec{F} = q\vec{E}$

- Electric dipole $\vec{p}$



$p = qd$

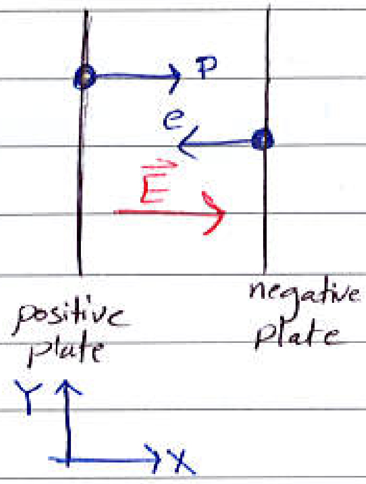
$\vec{\tau} = \vec{p} \times \vec{E} \Rightarrow pE\sin\theta = |\vec{\tau}|$

$U = -\vec{p}\cdot\vec{E} = -pE\cos\theta \Rightarrow$
- greatest value (pE) $(\theta = \pi)$
- zero $p \perp E$
- Least value $(-pE)$ $\theta = 0°$

22-7 Two large parallel copper plates are 8.0 cm apart and have a uniform electric field between them. An electron is released from the negative plate at the same time that a proton is released from the positive plate. Neglect the force of the particles on each other and find their distance from the positive plate when they pass each other. (Does it surprise you that you need not to know the electric field to solve this problem)?

$\Rightarrow$ pass each other $X_p = X_e$

use $\Delta X = X - X_0 = v_0 t + \frac{1}{2} a t^2$



v_0 (for both) $= 0$

- proton $\Rightarrow X - 0 = \frac{1}{2} a_p t^2$
- electron $\Rightarrow X - 0.08 = \frac{1}{2} a_e t^2$

$$X = X \Rightarrow \frac{1}{2} a_p t^2 = 0.08 + \frac{1}{2} a_e t^2$$

$$\boxed{t^2 = \frac{2(0.08)}{a_p - a_e}}$$

$$X(\text{proton}) = \frac{1}{2} a_p t^2 = \frac{1}{2} a_p \frac{2(0.08)}{a_p - a_e} = \frac{0.08\, a_p}{a_p - a_e}$$

use Newton's 2^{nd} law $\Rightarrow F = ma$

<u>proton</u> $eE = m_p a_p \Rightarrow a_p = \frac{eE}{m_p}$

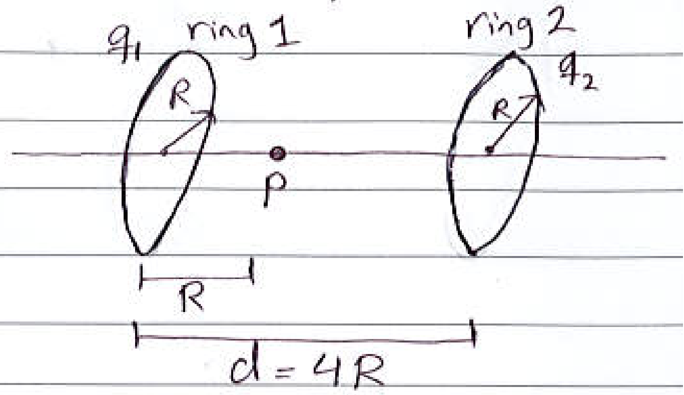
electron $-eE = m_e a_e \Rightarrow a_e = \frac{-eE}{m_e}$

$$X = 0.08\left[\frac{m_e}{m_e + m_p}\right] = 44\,\mu m$$

$m_e = 9.11 \times 10^{-31}$ kg

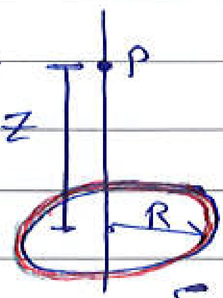
$m_p = 1.67 \times 10^{-27}$ Kg

22-9 Two parallel nonconducting rings with their central axes along a common line. Ring 1 has uniform charge q_1 and radius R; ring 2 has uniform charge q_2 and the same radius R. The rings are separated by distance $d = 4.0R$. The net electric field at point P on the common line, at distance R from ring 1, is zero. What is the ratio q_1/q_2 ?



$E(P) = 0$, $\frac{q_1}{q_2} = ?$

Use

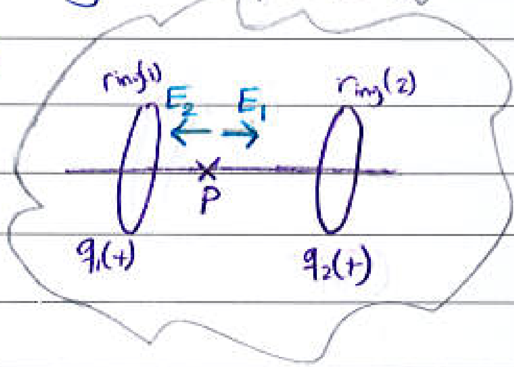


$$E_{\text{charged Ring}} = \frac{qZ}{4\pi\epsilon_0 [R^2 + Z^2]^{3/2}}$$

$(+q) \Rightarrow$ away from the ring

$(-q) \Rightarrow$ toward the ring

Note!!



$\Rightarrow$ Both q_1, q_2 Same signs

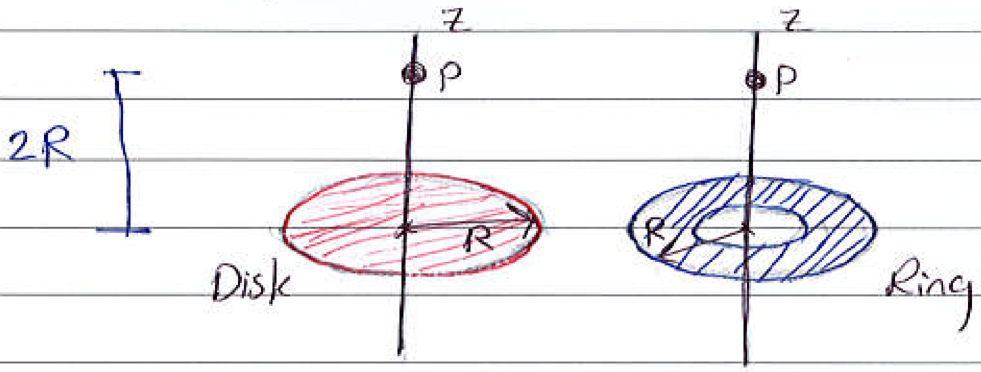
$$E_{\text{Left ring}} = E_{\text{Right ring}}$$

$$\frac{K q_1 R}{[R^2 + R^2]^{3/2}} = \frac{K q_2 (3R)}{[(3R)^2 + R^2]^{3/2}}$$

$$\frac{q_1}{(2R^2)^{3/2}} = \frac{3 q_2}{(10R^2)^{3/2}}$$

$$\Rightarrow \frac{q_1}{q_2} = 3\left(\frac{2}{10}\right)^{3/2} = 0.268$$

22-17 Suppose you design an apparatus in which a uniformly charged disk of radius R is to produce an electric field. The field magnitude is most important along the central perpendicular axis of the disk, at a point P at distance 2.00R from the disk. Cost analysis suggests that you switch to a ring of the same ~~other~~ outer radius R but with inner radius R/4.00. Assume that the ring will have the same surface charge density as the origional disk. If you switch to the ring, by what percentage will you decrease the electric field magnitude at P?



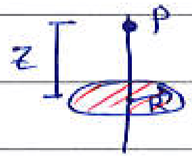
outer radius R

inner radius R/4

Both have the same surface charge density (σ)

Use

$$E(\text{charged disk}) = \frac{\sigma}{2\epsilon_0}\left[1 - \frac{z}{\sqrt{z^2+R^2}}\right]$$



infinite sheet $R \to \infty \Rightarrow E = \frac{\sigma}{2\epsilon_0}$

$$E_{\substack{\text{Disk}\\0\to R}} = \frac{\sigma}{2\epsilon_0}\left[1 - \frac{2R}{\sqrt{4R^2+R^2}}\right] = \frac{\sigma}{2\epsilon_0}\left[1 - \frac{2}{\sqrt{5}}\right]$$

$$E_{\text{Ring}} = E_{\substack{\text{Disk}\\0\to R}} - E_{\substack{\text{Disk}\\0\to R/4}} = E_{\text{Disk}} - \frac{\sigma}{2\epsilon_0}\left[1 - \frac{2R}{\sqrt{4R^2+\left(\frac{R}{4}\right)^2}}\right]$$

$$= E_{\text{Disk}} - \frac{\sigma}{2\epsilon_0}\left[1 - \frac{2}{\sqrt{\frac{65}{16}}}\right]$$

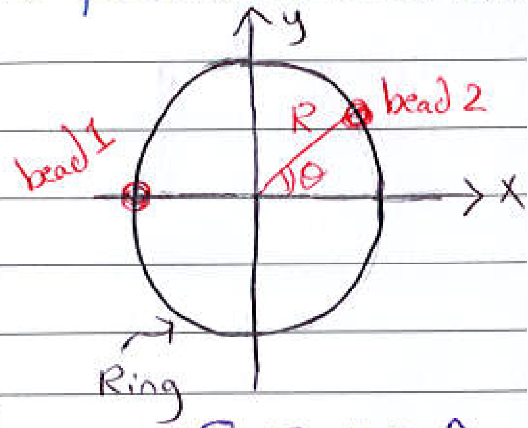
$1 - \frac{8}{\sqrt{65}}$

$$\text{Percentage} = \frac{E_{Disk} - E_{Ring}}{E_{Disk}} \times 100\,\%$$

$$= \frac{E_{Disk} - E_{Disk} + E_{Disk\,0 \to R/4}}{E_{Disk}} \times 100\,\%$$

$$= \frac{1 - 8/\sqrt{65}}{1 - 2/\sqrt{5}} = 7.31\,\%$$

22-24 A plastic ring of radius $R = 43.0$ cm. Two small charged beads are on the ring: Bead 1 of charge $+2.00\,\mu C$ is fixed in place at the left side; bead 2 of charge $+6.00\,\mu C$ can be moved along the ring. The two beads produce a net electric field of magnitude E at the center of the ring. At what positive and negative value of angle θ should bead 2 be positioned such that $E = 2.00 \times 10^5$ N/C ?



$$E_1 = +E_1 \hat{\imath}$$

$$E_2 = 3E_1 \left[-\cos\theta \, \hat{\imath} - \sin\theta \, \hat{\jmath}\right]$$

$$E_{tot} = E_1 \left[(1 - 3\cos\theta)\hat{\imath} - 3\sin\theta \, \hat{\jmath}\right]$$

$$\left\{ E = \frac{Kq}{r^2}\hat{r}, \quad q_2 = 3q_1 \right.$$

$$|E_{tot}| = E_1 \sqrt{(1 - 3\cos\theta)^2 + (-3\sin\theta)^2}$$

$$= E_1 \sqrt{1 - 6\cos\theta + 9\cos^2\theta + 9\sin^2\theta}$$

$$= E_1 \sqrt{1 - 6\cos\theta + 9} = E_1\sqrt{10 - 6\cos\theta}$$

$$\Rightarrow \left(\frac{E_{tot}}{E_1}\right)^2 = 10 - 6\cos\theta$$

$$\cos\theta = \frac{1}{6}\left[10 - \left(\frac{E_{tot}}{E_1}\right)^2\right]$$

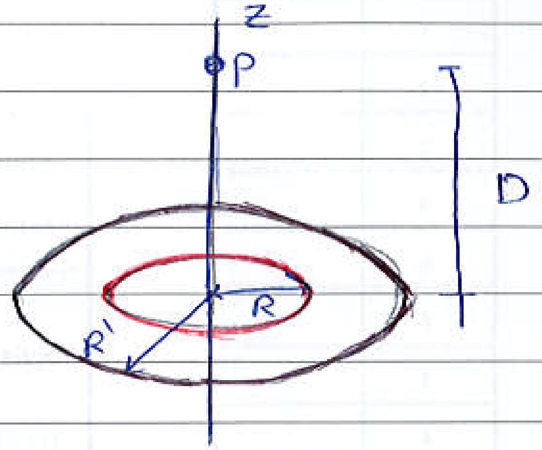
use $E_{tot} = 2 \times 10^5$ N/C

$$E_1 = \frac{K \times 2 \times 10^{-6}}{R^2} = 9.7 \times 10^4 \text{ N/C}$$

$$\Rightarrow \cos\theta = 0.96$$

$$\boxed{\theta = 15.59^\circ, -15.59^\circ}$$

22-26 Two concentric rings of radii R and $R' = 4.00R$, that lie on the same plane. Point P lies on the central z axis, at distance $D = 2.00R$ from the center of the rings, the smaller ring has uniformly distributed charge $+Q$. In terms of Q, what is the uniformly distributed charge on the larger ring if the net electric field at P is zero?



$$E(P) = 0$$

use $$E(P)_{Ring} = \frac{Kqz}{(z^2+R^2)^{3/2}}$$

$$E_{Small\ Ring} = E_{Larg\ Ring}$$

$$\frac{K\,Q\,(2R)}{((2R)^2+R^2)^{3/2}} = \frac{K\,q\,(2R)}{((2R)^2+(4R)^2)^{3/2}}$$

$$\frac{Q}{(5)^{3/2}} = \frac{q}{(20)^{3/2}}$$

$$q = \left(\frac{20}{5}\right)^{3/2} Q = \left(\frac{4}{2}\right)^{3/2} Q = 8Q$$

and must be negative

$$\boxed{q_{Large\ Ring} = -8Q}$$

$\boxed{22-40}$ An electric dipole consists of charges $+2e$ and $-2e$ separated by 0.85 nm. It is in an electric field of strength 3.4×10^6 N/C. Calculate the magnitude of the torque on the dipole when the dipole moment is a) parallel to, b) perpendicular to, and a) antiparallel to the electric field $\vec{E}$?

$$\vec{\tau} = \vec{p} \times \vec{E} = pE \sin\theta$$

a) $\vec{p} \parallel \vec{E}$, $\theta = \text{zero}$ $\sin 0 = 0$, $\vec{\tau} = 0$

b) $\vec{p} \perp \vec{E}$, $\theta = \pi/2$, $\sin \pi/2 = 1$ use $p = qd$

$$\vec{\tau} = 2edE = 2 \times 1.6 \times 10^{-19} \times 0.85 \times 10^{-9} \times 3.4 \times 10^{6}$$

$$\vec{\tau} = 9.248 \times 10^{-22} \text{ N.m} \quad [J]$$

c) $\vec{p}$ antiparallel $\vec{E}$, $\theta = 180$, $\sin(180) = 0$, $\vec{\tau} = 0$

$\boxed{22-41}$ How much work required to turn an electric dipole 180° in a uniform electric field of magnitude $E = 46.0$ N/C if the dipole moment has a magnitude of $p = 3.02 \times 10^{-25}$ C.m and the initial angle is 23°?

$$W_{\text{external agent}} = +\Delta U \quad , \quad U = -\vec{p} \cdot \vec{E} = -pE\cos\theta$$

$$W = -pE\left[\cos(180° + 23°) - \cos(23°)\right]$$

$$= -pE\left[\cos 23° \cos 180° - \sin 23° \xcancel{\sin 180}^{\,0} - \cos(23°)\right]$$

$$= 2pE\cos(23°) = 2 \times 3.02 \times 10^{-25} \times 46 \cos(23°)$$

$$\boxed{W = 2.56 \times 10^{-23} \text{ J}}$$

$\boxed{22\text{-}45}$ A charged particle produces an electric field with a magnitude of 2.0 N/C at a point that is 50 cm away from the particle. What is the magnitude of the field at an additional distance of 25 cm?

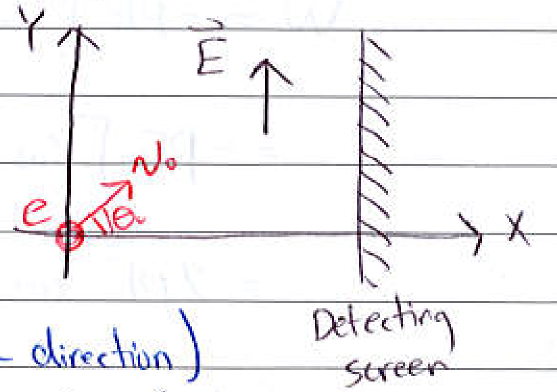
$$\vec{E}(r = 50\text{ cm}) = \frac{Kq}{(0.5)^2} = 2\text{ N/C}$$

$$Kq = (0.5)^2 \times 2$$

$$\vec{E}\left(r = (50+25)\text{cm} = 0.75\text{m}\right) = \frac{Kq}{(0.75)^2}$$

$$\vec{E}(r = 0.75\text{m}) = \frac{2\,(0.5)^2}{(0.75)^2} = 0.89\text{ N/C}$$

$\boxed{22\text{-}50}$ An electron is shot at an initial speed of $v_0 = 4.00 \times 10^6 \frac{m}{s}$, at angle $\theta_0 = 40°$ from an x-axis. It moves through a uniform electric field $\vec{E} = 5.00$ N/C $\hat{j}$. A screen for detecting electrons is positioned parallel to the y-axis, at distance $x = 3.00$ m. In unit vector-notation, what is the velocity of the electron when it hits the screen?



$\Rightarrow$ Newton's 2^{nd} Law

$F = ma = qE$

$\rightarrow a_x = 0, \quad a_y = \frac{-eE}{m}$

(No component of E in the x-direction)

- $v_{0x} = v_{fx} = 4 \times 10^6 \cos 40° = 3.06 \times 10^6 \frac{m}{s}$

- $x = v_x t$

$$t = \left(\frac{v_{0x}}{x}\right)^{-1} = \frac{3}{4 \times 10^6 \cos 40} = 980\text{ ns}$$

$v_{fy} = v_{oy} + at$

$= v_o \sin 40^\circ - \frac{eE}{m} t$

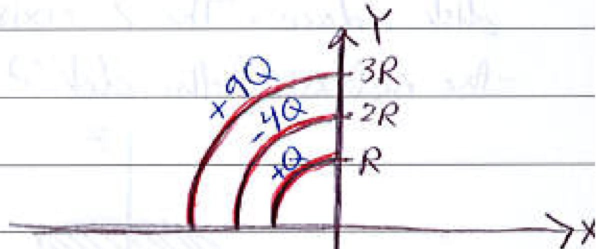
$= 4 \times 10^6 \sin 40^\circ - \frac{1.6 \times 10^{-19}}{9.1 \times 10^{-31}} \times 5 \times 980 \times 10^{-9}$

$v_{fy} = 1.71 \times 10^6 \ \frac{m}{s}$

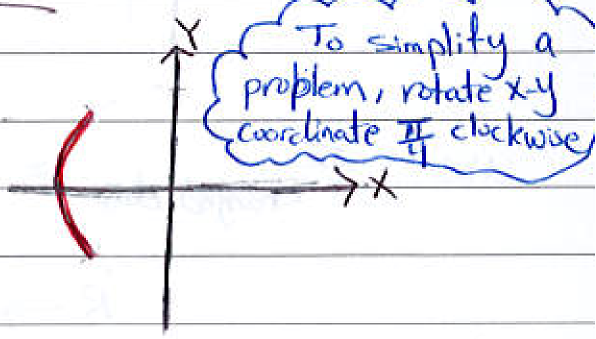
$v_f = 3.06 \times 10^6 \ \frac{m}{s} \ \hat{i} + 1.71 \times 10^6 \ \frac{m}{s} \ \hat{j}$

$\boxed{22\text{-}59}$ Three circular arcs centered on the origion of a coordinate system. On each arc, the uniformly distributed charge is given interms of $Q = 4.00 \ \mu C$. The radii are given terms of $R = 5.00$ cm. What are the a) magnitude and b) direction (relative to the positive x-direction) of the net electric field at the origin due to the arcs?

$E(r=0, \text{origin}) = ?$



use $E = \frac{k\lambda}{r} \sin\theta \Big]_{-\frac{\pi}{4}}^{\pi/4} = \sqrt{2} \frac{k\lambda}{r}$



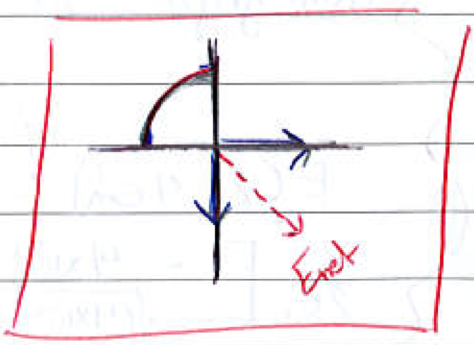
$\lambda = \frac{Q}{\text{Length}}$

$\text{Length} = \frac{2\pi r}{4}$

$\lambda_1 = \frac{Q(4)}{2\pi R} = \frac{2Q}{\pi R}$ (+x)

$\lambda_2 = \frac{4Q(4)}{2\pi \, 2R} = \frac{4Q}{\pi R}$ (− x)

$\lambda_3 = \frac{9Q(4)}{2\pi \, 3R} = \frac{6Q}{\pi R}$ (+ x)

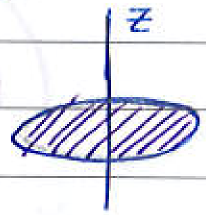


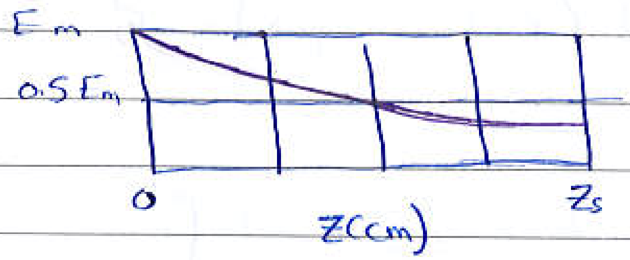
$$\vec{E} = \sqrt{2}\,K\left[\frac{2Q}{\pi R^2} - \frac{4Q}{\pi R(2R)} + \frac{6Q}{\pi R(3R)}\right]$$

$$\vec{E} = 2\sqrt{2}\,\frac{KQ}{\pi R^2}$$

$$\vec{E} = 1.3\times10^7\ N/C\ [-45^\circ]$$

$\boxed{22-54}$ A circular disk that is uniformly charged. The central z-axis is perpendicular to the disk face, with the origin at the disk. Below Figure gives the magnitude of the electric field along that axis in terms of the maximum magnitude E_m at the disk surface. The z-axis scale is set by z_s = 8.00 cm. What is the radius of the disk?





use $E_{\text{charged disk}} = \frac{\sigma}{2\epsilon_0}\left[1 - \frac{z}{\sqrt{z^2+R^2}}\right]$,

$R \to \infty$, $E = \frac{\sigma}{2\epsilon_0}$ (max. magnitude)

From graph at $z = 4$ cm, $E_{Disk} = 0.5\,E_m$

where $E_m = \frac{\sigma}{2\epsilon_0}$ (max. magnitude)

$$E(z=4\text{cm}) = \frac{1}{2}E_m = \frac{1}{2}\frac{\sigma}{2\epsilon_0}$$

$$\frac{\sigma}{2\epsilon_0}\left[1 - \frac{4\times10^{-2}}{\sqrt{(4\times10^{-2})^2+R^2}}\right] = \frac{1}{2}\frac{\sigma}{2\epsilon_0} \implies$$

$$1 - \frac{0.04}{\sqrt{(0.04)^2 + R^2}} = \frac{1}{2}$$

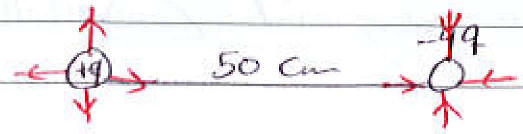
$$\frac{1}{2} = \frac{0.04}{\sqrt{(0.04)^2 + R^2}}$$

$$(0.04)^2 + R^2 = (0.04 \times 2)^2$$

$$R = 0.0693 \text{ m} = 6.9 \text{ cm}$$

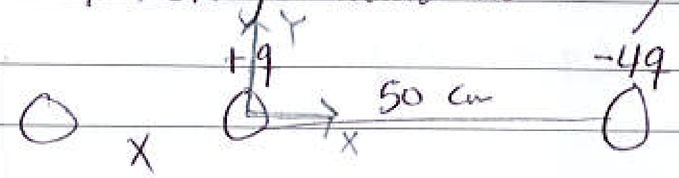
1) $q_1 = 2.1 \times 10^{-8}\,C$ at $x = 20\,cm$

$q_2 = -4q_1$ at $x = 70\,cm$



between the two, both fields point right, so they will not cancel

- to the right of both charges, individual fields point in opposite directions, so they could cancel. But, the right charge is greater and would be closer to this point (of zero field), the field from the left charge would not be great enough to cancel it.

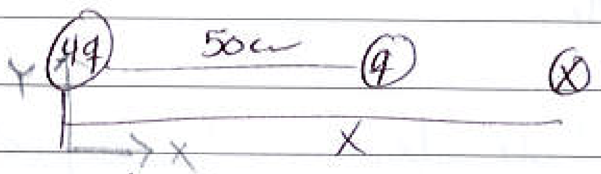


$$\frac{kq}{x^2} = \frac{k\,4q}{(x+50)^2} \Rightarrow \frac{1}{x^2} = \frac{4}{(x+50)^2}$$

$$2x = x + 50 \Rightarrow x = 50\,cm$$

$$\Rightarrow \boxed{x = -30\,cm}$$

b) the particles are interchanged



$$\frac{k\,4q}{x^2} = \frac{kq}{(x-50)^2} \Rightarrow \frac{4}{x^2} = \frac{1}{(x-50)^2}$$

$$2(x-50) = x \rightarrow 2x - 100 = x$$

$$x = 100$$

$$\Rightarrow x = 120\,cm = 1.2\,m$$

4 a) charge = $-300e$, circular arc of radius 4.00 cm, $\theta = 40°$

linear charge density λ?

$Q = -300e = -300 \times 1.6 \times 10^{-19}\,C$

$\theta = 40° \times \frac{\pi}{180} = 0.698\,rad$

$L = r\theta = (0.04 \times 0.698) = 0.02792\,m$

$Q = 1.719 \times 10^{-15}\,C/m$

b) circular disk of radius 2.00 cm

$\sigma = q/A$, $A = \pi r^2$

$\sigma = \frac{Q}{A} = \frac{-300e}{\pi(0.02)^2} = 3.82 \times 10^{-14}\,C/m^2$

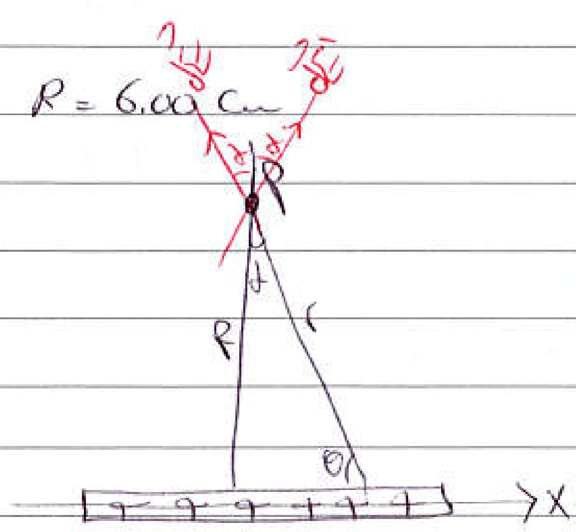
c) surface of a sphere of radius 4.00 cm, $\sigma = ?$

$\sigma = \frac{-300e}{4\pi(0.04)^2} = 2.39 \times 10^{-15}\,C/m^2$

d) sphere of radius 2.00 cm

$\rho = \frac{Q}{V} = \frac{-300e}{\frac{4}{3}\pi(0.02)^3} = 1.43 \times 10^{-12}\,C/m^3$

10 $q = 9.25\,pC$, $L = 16\,cm$, $R = 6.00\,cm$



$\vec{dE} = \frac{k\,dq}{r^2}\hat{r}$

$\vec{dE_x} = -dE \sin\alpha\,\hat{i} + dE' \sin\alpha\,\hat{i}$

$= $ zero by symmetric

$\vec{E_y} = \int dE \cos\alpha\,\hat{j} = \int \frac{k\,dq}{r^2} \cos\alpha\,\hat{j}$

$q = \lambda x \implies dq = \lambda\,dx$

$$\vec{E}_y = k\int_{-L/2}^{L/2} \frac{dx\,\lambda}{r^2}\cos\alpha\,\hat{j} = k\lambda\int_{-L/2}^{L/2}\frac{\cos\alpha\,dx}{(x^2+R^2)}\,\hat{j}$$

$$\cos\alpha = \frac{R}{r} = \frac{R}{(x^2+R^2)^{1/2}}$$

$$= k\lambda\,\hat{j}\int_{-L/2}^{L/2}\frac{R\,dx}{(x^2+R^2)^{3/2}} = 2k\lambda R\,\hat{j}\int_0^{L/2}\frac{dx}{(x^2+R^2)^{3/2}}$$

$$\tan\alpha = x/R\,,\quad x = R\tan\alpha$$

$$dx = R\sec^2\alpha\,d\alpha$$

$$(x^2+R^2)^{3/2} = (R^2\tan^2\alpha + R^2)^{3/2} = (R^2\sec^2\alpha)^{3/2}$$
$$= R^3\sec^3\alpha$$

$$\Rightarrow \int\frac{R\sec^2\alpha\,d\alpha}{R^3\sec^3\alpha} = \frac{1}{R^2}\int\frac{d\alpha}{\sec\alpha} = \frac{1}{R^2}\int\cos\alpha\,d\alpha$$

$$\Rightarrow \vec{E}_y = \frac{\lambda R}{2\pi\epsilon_0}\frac{1}{R^2}\,\hat{j}\int\cos\alpha\,d\alpha$$

$$= \frac{\lambda}{2\pi\epsilon_0 R}\,\hat{j}\,\sin\alpha = \frac{\lambda x}{2\pi\epsilon_0 R(x^2+R^2)^{1/2}}\Bigg]_0^{L/2}$$

$$\vec{E}_y = \frac{\lambda L/2}{2\pi\epsilon_0 R\left(\frac{L^2}{4}+R^2\right)^{1/2}}\,\hat{j}$$

$$= \frac{\lambda L\,\hat{j}}{2\pi\epsilon_0 R(L^2+4R^2)^{1/2}} \qquad q = \lambda L$$

$$= 13.86\ N/C\ \hat{j} \qquad q = 9.25\ pC$$

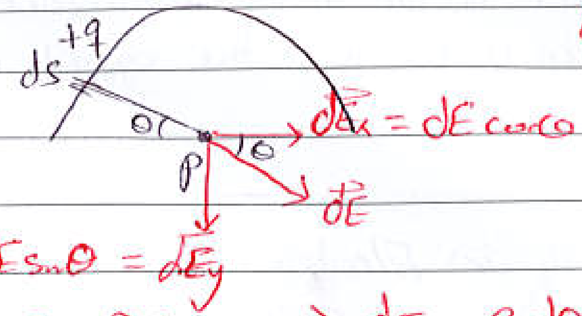
λ

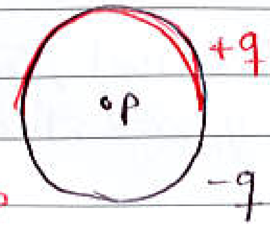
$L = 16$ cm

$R = 6$ cm

$\boxed{11}$ Two curved Plastic rods , $q = 15\,pC$, $R = 4.25\,cm$

① $\vec{E}$ from $(+q)$





$q = \lambda s$, $s = R\theta \Rightarrow ds = R\,d\theta$

$dq = \lambda\,ds$

$dq = \lambda R\,d\theta$ $\qquad r = R = \text{const}$

$$\vec{E}_y = -\int \frac{k\,dq}{R^2}\sin\theta\,\hat{j} = \frac{-k}{R^2}\int \lambda R\sin\theta\,d\theta$$

$$= -\frac{k\lambda}{R}\int_0^{\pi}\sin\theta\,d\theta = \frac{k\lambda}{R}\cos\theta\,\hat{j}\Big]_0^{\pi} = -\frac{2k\lambda}{R}\hat{j}$$

$$\vec{E}_y = -\frac{2\lambda}{4\pi\epsilon_0 R}\hat{j} = \frac{-\lambda}{2\pi\epsilon_0 R}\hat{j}$$

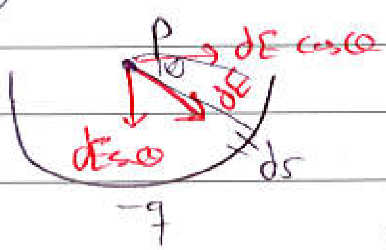
use $\lambda = q/s = q/\pi R \Rightarrow q = \pi R\lambda$

$\Rightarrow \lambda_+ = \frac{q}{\pi R} = 1.12 \times 10^{-10}\ C/m$

$\lambda_- = \frac{-q}{\pi R} = -1.12 \times 10^{-10}\ C/m$

$E_y^+ = -47.46\ N/C\ \hat{j}$ $\quad (-90^\circ)$

② $\vec{E}$ from $(-q)$



$\Rightarrow |E_y^+| = |E_y^-|$ and in the same direction

$$\boxed{\vec{E} = 94.8\ N/C\ \hat{j}}$$

$E_+ = \frac{2k\lambda}{R}$

$E_- = E_+$

$\Rightarrow \vec{E} = \frac{4k\lambda}{R}(-\hat{j})$

$\lambda = \frac{q}{\pi R}$

$\vec{E} = 4k\frac{q}{\pi R^2}(-\hat{j})$

$= 95.2\ N/C\ [-90^\circ]$

$\boxed{23}$ 10.0 g block, $q = +8.00 \times 10^{-5}$ C is placed in
$\vec{E} = (3000\hat{i} - 6000\hat{j})$ N/C

a) Electrostatic force on the block?

$\vec{F} = q\vec{E} = 8 \times 10^{-5} (3000\hat{i} - 6000\hat{j})$
$= 0.24\hat{i} - 0.48\hat{j}$ N , 0.537 N $= |\vec{F}|$

$\tan\theta = 2$

$\theta \sim 63.4°$

b) block is released from rest at the origion at $t = 0$ then at $t = 3$ s, what are its x,y coordinate and its speed?

$v_i = 0$, $x_i = y_i = 0$ (origion)

$x_f - x_i = v_{ix} t + \frac{1}{2} a_x t^2$

$x = \frac{1}{2} a_x t^2$ $(F_x = m a_x)$

$x = \frac{1}{2} \frac{F_x}{m} t^2 = \frac{0.24 (3)^2}{2(0.01)} = 108$ m

$F_y = -0.48$ N , $Y = \frac{-0.48 (3)^2}{2(0.01)} = -216$ m

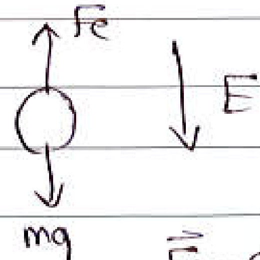
e) $V_f = V_i + at$

$V_{fx} = \cancel{V_{ix}}^{0} + a_x t$ $V_{fy} = \cancel{V_{iy}}^{0} + a_y t$

$S = \sqrt{(V_{fx})^2 + (V_{fy})^2} = 161$ m/s

$\boxed{33}$ $r_{oil\text{-}drop} = 1.64\ \mu m$
$\rho = 0.851$ g/cm^3
$\vec{E} = 3.20 \times 10^5$ N/C is applied (downward)

a) Find the charge on the drop, interms of e?



The oil drop suspended in chamber
$\Rightarrow$ net force = Zero
$\Sigma\vec{F} = 0$
$F_e = F_g$

$\vec{F_e} = q\vec{E}$
(E, F_e in opposite direction $\Rightarrow$ q -ve)

$$mg = qE$$

$$q = \frac{mg}{E} \quad , m = \rho V = \rho \frac{4}{3}\pi r^3$$

$$q = 0.851 \frac{g}{cm^3} \frac{10^6 cm^3}{1 m^3} \frac{1 kg}{10^3 g} \times \frac{4}{3}\pi r^3 \left(\frac{g}{E}\right)$$

$$\frac{q}{1.6\times10^{-19}} = 3\bar{e}$$

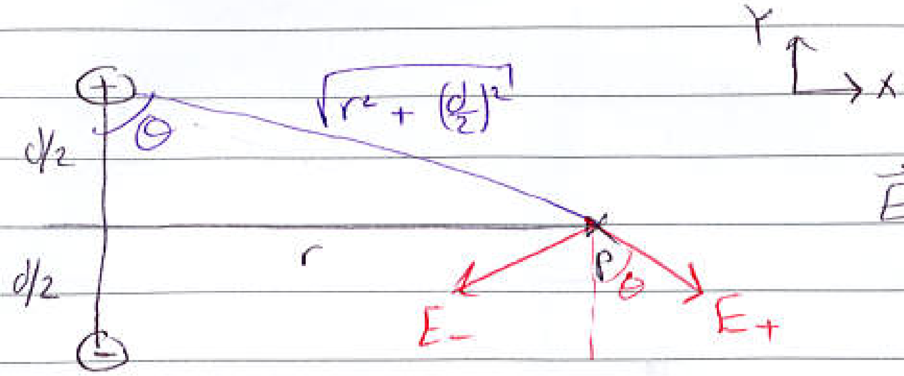
$\ast$ E downward , Fe upward $\Rightarrow$ the charge on the particle is $-3e$

b) If the drop had an additional electron, would it move upward or downward?

$q = -4e \rightsquigarrow F_e > mg$

$\Rightarrow$ move upward.

$\boxed{55}$ Electric dipole



$\vec{E}(p) = ??$

$r \gg d$

By symmetric E_x cancelled

$$E_{y+} = \frac{kq}{\left[r^2 + (\frac{d}{2})^2\right]} \cos\theta \quad , \cos\theta = \frac{d/2}{\left[r^2 + (\frac{d}{2})^2\right]^{1/2}}$$

$$= \frac{kqd}{2\left[r^2 + (\frac{d}{2})^2\right]^{3/2}}$$

$$E_{y+} = E_{y-}$$

$$\vec{E}(p) = -\frac{kqd}{\left[r^2 + (\frac{d}{2})^2\right]^{3/2}} \hat{j}$$

$$r \gg d \Rightarrow \vec{E} = -\frac{kqd}{r^3} \hat{j}$$

✓