PHYSICS 110A, WINTER 2017
ELECTRICITY AND MAGNETISM

Assignment Six, Due Friday, March 2, 5:00 pm.

[1.] A hydrogen atom acts as if it had an electrostatic potential

$$\phi(r) = \frac{q}{4\pi\epsilon_0 r}(1 + \frac{r}{a_0})e^{-2r/a_0} ,$$

where q is the charge on the proton and $a_0 = \hbar^2/m_e q^2 = 0.529\dot{A}$ is the Bohr radius.
(a) Find the corresponding charge density and interpret the various terms physically.
(b) Verify by *explicit* integration that your resulting charge density from part (a) indeed produces the original potential.
(c) What is the net charge inside a sphere of radius a_0? What is the electric field strength at this distance?

[2.] Solve for the potential in the region between two concentric spherical shells of radii a and b, given the potentials $V_a(\theta)$ and $V_b(\theta)$. Your objective should be to write the coefficients of an expansion of the potential as integrals involving the (unknown) functions V_a and V_b. Choose some specific form of the functions that you find particularly amusing (and not too hard!) and do the integrals.

[3.] A sphere of radius R has a potential $V(r,\theta) = V_0 \cos^2\theta$ on its surface. Determine the potential outside the sphere.

[4.] Griffiths 3-15.

[5.] Griffiths 3-21.

[6.] Griffiths 3-23.

[7.] Griffiths 3-14.

1-1

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$\boxed{\text{NB: Sol'ns are in CGS units.}}$

$\boxed{3.}$ Hydrogen atom has potential $\Phi(r) = q/r\,(1+r/a_0)\,e^{-2r/a_0}$
where q is charge on proton and $a_0 = \hbar^2/m_e q^2 \approx 0.529$ Å
is Bohr radius

a) Find $\rho(r)$ and interpret physically.

We know that $\nabla^2 \Phi(r) = -4\pi\rho(r)$. In a case like this, there is no θ and φ dependence and the Laplacian is $\frac{1}{r}\,d^2/dr^2\, r$

Thus for $r \neq 0$

$$\rho_e(r) = -\frac{1}{4\pi}\frac{1}{r}\frac{d^2}{dr^2}\, q\,(1+r/a_0)\,e^{-2r/a_0}$$

$$= -q/4\pi r \frac{d}{dr}\left(1/a_0\, e^{-2r/a_0} + -2/a_0\,(1+r/a_0)\,e^{-2r/a_0}\right)$$

$$= -q/4\pi r \left(\cancel{-2/a_0^2}\, e^{-2r/a_0} + 4/a_0^2\,(\cancel{1}+r/a_0)\,e^{-2r/a_0} - \cancel{2/a_0^2}\, e^{-2r/a_0}\right)$$

$$\rho_e(r) = -\frac{q}{\pi a_0^3}\, e^{-2r/a_0} \quad \text{for } r \neq 0$$

when $r=0$ we must recognize $\nabla^2 \frac{1}{r} = -4\pi\,\delta(\vec{r})$ so that we get an extra term

$$\rho_p(r) = -\frac{1}{4\pi}\,-4\pi q\,\delta(\vec{r}) = q\,\delta(\vec{r})$$

All together $\rho(\vec{r}) = q\,\delta(\vec{r}) - q\,\frac{1}{\pi a_0^3}\, e^{-2r/a_0}$

The physical interpretation is clear. The first term is the charge density of the proton which is localized exactly at $r=0$. The second term is the charge density of the electron "cloud" around the proton. In fact, the ground state wave function is $\psi_0(r) = 1/\sqrt{4\pi}\; 2/a_0^{3/2}\, e^{-r/a_0}$ (Baym) so that $|\psi_0(r)|^2 = \frac{1}{4\pi}\frac{4}{a_0^3}\, e^{-2r/a_0} = 1/\pi a_0^3\, e^{-2r/a_0}$. Thus the second term is simply $-q\,|\psi_0(r)|^2$ as expected.

1-2

We might also comment that we expect the atom to be electrically neutral overall. So we verify that

$$Q_{TOT} = \int \rho(\vec{r})\,dV = q + \int_0^\infty 4\pi r^2 \frac{-q}{\pi a_0^3} e^{-2r/a_0}\,dr$$

$$= q\left(1 - \frac{4}{a_0^3}\int_0^\infty r^2 e^{-2r/a_0}\,dr\right) \qquad \text{let } u = +2r/a_0 \quad dr = a_0/2\,du$$

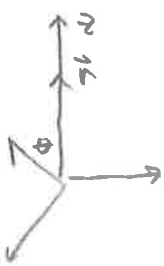
$$= q\left(1 - \frac{4}{a_0^3}\left(\frac{a_0}{2}\right)^3 \int_0^\infty u^2 e^{-u}\,du\right) \qquad \text{But } \int_0^\infty u^n e^{-u}\,du = n!$$

$$= q\left(1 - \tfrac{1}{2}\,2!\right) = 0$$

Thus $Q_{TOT} = 0$
The total charge density integrates to zero - the H atom is electrically neutral.

(b) verify by explicit integration that $\rho(r)$ reproduces $\Phi(r)$.

$$\Phi(\vec{r}) = \int \frac{\rho(\vec{r}\,')\,d\vec{r}\,'}{|\vec{r}-\vec{r}\,'|}$$



Choose for convenience $\vec{r}$ to lie along $\hat{z}$-axis, then
$|\vec{r}-\vec{r}\,'|^2 = r^2 - 2rr'\cos\theta + r'^2$ and hence

$$\Phi(r) = q\int \frac{\delta(\vec{r}\,') - 1/\pi a_0^3\, e^{-2r'/a_0}}{\sqrt{r^2 - 2rr'\cos\theta' + r'^2}}\,d\vec{r}\,' \qquad \text{where } \delta(\vec{r}\,') = \delta(r')\delta(\theta')\delta(\phi')\frac{1}{r'^2\sin\theta'}$$
$$d\vec{r}\,' = r'^2\sin\theta'\,d\theta'\,d\phi'\,dr'$$

$$= q\int_0^\infty r'^2\,dr'\int_0^{2\pi} d\phi'\int_0^\pi \sin\theta'\,d\theta'\left\{\frac{\delta(r')\delta(\theta')\delta(\phi')}{r'^2\sin\theta'} - \frac{1}{\pi a_0^3}e^{-2r'/a_0}\right\}\frac{1}{\sqrt{r'^2 - 2rr'\cos\theta'}}$$

$$= q/r - \frac{2\pi q}{\pi a_0^3}\int_0^\infty r'^2\,dr'\,\frac{1}{rr'}\sqrt{r^2 - 2rr'\cos\theta + r'^2}\,\Big|_0^\pi\, e^{-2r'/a_0}$$

$$\Phi(r) = q/r\left\{1 - \frac{2}{a_0^3}\int_0^\infty dr'\,r'\left(|r+r'| - |r-r'|\right)e^{-2r'/a_0}\right\}$$

$$= q/r\left\{1 - 2/a_0^3\left[\int_0^r dr'\,r'\,2r'\,e^{-2r'/a_0} + \int_r^\infty dr'\,r'\,2r\,e^{-2r'/a_0}\right]\right\}$$

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3.
1-3

Now $\int_0^r r' e^{-2r'/a_0} dr' = -r' a_0/2\, e^{-2r'/a_0}\Big|_0^r + a_0/2 \int_0^r e^{-2r'/a_0} dr'$

$$= -r\, a_0/2\, e^{-2r/a_0} + a_0/2(-a_0/2) e^{-2r'/a_0}\Big|_0^r$$

$$= -r a_0/2\, e^{-2r/a_0} + a_0^2/4 - a_0^2/4\, e^{-2r/a_0}$$

and so $\int_0^r r'^2 e^{-2r'/a_0} dr' = -r'^2 \frac{a_0}{2} e^{-2r'/a_0}\Big|_0^r + \frac{a_0}{2} 2 \int_0^r r' e^{-2r'/a_0} dr'$

$$= -a_0 r^2/2\, e^{-2r/a_0} + a_0 \left(-r a_0/2\, e^{-2r/a_0} + a_0^2/4 - a_0^2/4\, e^{-2r/a_0}\right)$$

Also $\int_r^\infty dr'\, r' e^{-2r'/a_0} = -\frac{a_0}{2} r' e^{-2r'/a_0}\Big|_r^\infty + a_0/2 \int_r^\infty e^{-2r'/a_0}$

$$= \frac{a_0}{2} r e^{-2r/a_0} - a_0^2/4\, e^{-2r'/a_0}\Big|_r^\infty = \frac{a_0}{2} r e^{-2r/a_0} + \frac{a_0^2}{4} e^{-2r/a_0}$$

Thus, all together

$$\phi(r) = q/r \Big\{ 1 - \frac{2}{a_0^3}\left[-a_0 r^2 - a_0^2 r - a_0^3/2 + a_0 r^2 + a_0^2/2\, r\right] e^{-2r/a_0} - 2/a_0^3 \left[a_0^3/2 \right] \Big\}$$

$$= q/r\, (-2/a_0^3)\left(-\frac{a_0^2}{2} r - a_0^3/2\right) e^{-2r/a_0}$$

$$\boxed{\phi(r) = q/r\, (1 + r/a_0) e^{-2r/a_0}}$$

as required.

(c) calculate net charge in sphere of radius a_0

$$Q(a_0) = \int_0^{a_0} 4\pi r^2 dr\; q\left(\frac{\delta(r)}{4\pi r^2} - \frac{1}{\pi a_0^3} e^{-2r/a_0}\right)$$

$$= q - \frac{4q}{a_0^3}\int_0^{a_0} r^2 e^{-2r/a_0} dr = q - \frac{4q}{a_0^3}\left\{ -r^2 \frac{a_0}{2} e^{-2r/a_0}\Big|_0^{a_0} + a_0 \int_0^{a_0} r e^{-2r/a_0}\right.$$

$$= q\left(1 - \frac{4}{a_0^3}\left(-\frac{a_0^3}{2} e^{-2} + \frac{a_0^2}{2} r e^{-2r/a_0}\Big|_0^{a_0} + \frac{a_0^2}{2}\int_0^{a_0} e^{-2r/a_0} dr\right)\right)$$

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$$Q(a_0) = q\left(1 - \frac{4}{a_0^3}\left(-\frac{a_0^3}{2e^2} - \frac{a_0^3}{2e^2} + \frac{a_0^3}{4}\; e^{-2r/a_0}\Big|_0^{a_0}\right)\right)$$

$$= q\left(1 - \frac{4}{a_0^3}\left(-a_0^3/e^2 + a_0^3/4e^2 + a_0^3/4\right)\right)$$

$$= q\left(1 + \frac{4}{e^2} + \frac{1}{e^2} + 1\right) = 5q/e^2$$

$$\boxed{Q(a_0) = \frac{5}{e^2}q = .677\,q}$$

One way to look at this is to say a sphere of radius a_0 contains the proton charge $+q$ and $(1 - 5/e^2) = 32.3\,\%$ of the total electron charge $-q$.

The electric field strength at a_0 is given by Gauss' law

$$E(a_0)\,\cancel{4\pi}\, a_0^2 = \cancel{4\pi}\, Q(a_0)$$

$$E(a_0) = \frac{5}{e^2}\,q/a_0^2$$

In MKS units $E(a_0) = \frac{5}{e^2}\,\frac{1.609\cdot10^{-19}}{(.529\cdot10^{-10})^2}\,9\cdot10^9 = 3.5\cdot10^{11}\ \frac{\text{volts}}{\text{m}}$

$$\boxed{E(a_0) = 3.5\cdot10^{9}\ \frac{\text{volts}}{\text{cm}}}$$

According to Jackson p820 $1\ \text{volt/m} = \frac{1}{3}\cdot10^{-4}\ \frac{\text{statvolt}}{\text{cm}}$

So that $\boxed{E(a_0) = 1.17\cdot10^{7}\ \frac{\text{statvolt}}{\text{cm}}}$

This can also be computed directly:

$$E(a_0) = \frac{5}{e^2}\,q/a_0^2 = \frac{5}{e^2}\,\frac{4.8\cdot10^{-10}\,\text{statcoul}}{(.529\cdot10^{-8}\,\text{cm})^2} = 1.17\cdot10^{7}\ \frac{\text{statvolt}}{\text{cm}}$$

2-1

$\boxed{2}$ The general soln of Laplace's eqn in spherical coordinates obeying azimuthal symmetry, as in problem 1, is

$$V(r,\theta) = \sum_{\ell=0}^{\infty}\left[A_\ell r^\ell + B_\ell r^{-(\ell+1)}\right] P_\ell(\cos\theta)$$

In contrast to problem 1, since we are confined to $a<r<b$ we cannot let $r \to \infty$ (or $r \to 0$) so we cannot conclude $A_\ell = 0$ (or $B_\ell = 0$).

Fortunately, we have two functions $V_a(\theta)$ and $V_b(\theta)$ whose information is sufficient.

$$V_a(\theta) \equiv V(a,\theta) = \sum_{\ell=0}^{\infty}\left[A_\ell a^\ell + B_\ell a^{-(\ell+1)}\right] P_\ell(\cos\theta)$$

$$V_b(\theta) \equiv V(b,\theta) = \sum_{\ell=0}^{\infty}\left[A_\ell b^\ell + B_\ell b^{-(\ell+1)}\right] P_\ell(\cos\theta)$$

From the orthogonality of the Legendre polynomials

$$\int_{-1}^{1} P_n(x)\, P_m(x)\, dx = 2\delta_{nm}/(2n+1)$$

or, in terms of $x = \cos\theta$

$$\int_0^\pi P_n(\cos\theta) P_m(\cos\theta) \sin\theta\, d\theta = 2\delta_{nm}/(2n+1)$$

If we multiply $*$ by $P_n(\cos\theta)\sin\theta$ and integrate,

$$\int_0^\pi V_a(\theta)\, P_n(\cos\theta)\sin\theta\, d\theta = \left(A_n a^n + B_n a^{-(n+1)}\right)\frac{2}{2n+1}$$

$$\int_0^\pi V_b(\theta)\, P_n(\cos\theta)\sin\theta\, d\theta = \left[A_n b^n + B_n b^{-(n+1)}\right] 2/_{2n+1}$$

Calling the integrals on the left hand side I_{an} and I_{bn} for short

$$* \qquad \frac{2n+1}{2} I_{an} = A_n a^n + B_n / a^{n+1}$$

$$** \qquad \frac{2n+1}{2} I_{bn} = A_n b^n + B_n / b^{n+1}$$

If we multiply $*$ by a^{n+1} and $**$ by b^{n+1} and subtract

$$\frac{2n+1}{2} I_{an}\, a^{n+1} - \frac{2n+1}{2} I_{bn}\, b^{n+1} = A_n\left(a^{2n+1} - b^{2n+1}\right)$$

whence

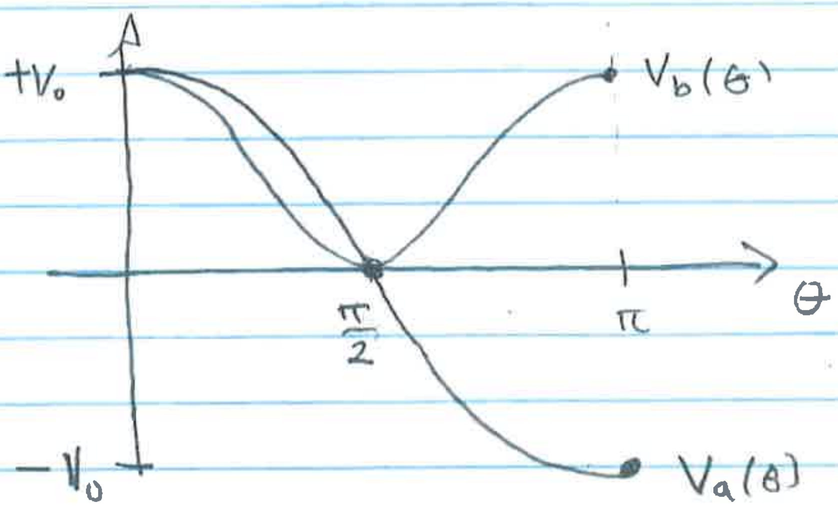
$$A_n = \frac{2n+1}{2}\left(\frac{1}{a^{2n+1} - b^{2n+1}}\right)\left(I_{an}\, a^{n+1} - I_{bn}\, b^{n+1}\right)$$

There is a similar expression for B_n:

$$B_n = \frac{2n+1}{2}\left(\frac{b^{2n+1}\, a^{2n+1}}{a^{2n+1} - b^{2n+1}}\right)\left(I_{an}/a^n - I_{bn}/b^n\right)$$

You are asked to do an "amusing" case.

How about $V_a(\theta) = V_0 \cos\theta \qquad V_b(\theta) = V_0 \cos^2\theta$



Clearly $V_a(\theta) = P_1(\cos\theta)$ so that $I_{a(n=1)} = \frac{2}{3} V_0$

with all other $I_{an} = 0$. Likewise $I_{b(n=1)} = {}^2\!/_3\, V_0$

and $I_{b(n=2)} = {}^2\!/_3\, {}^2\!/_5\, V_0$ with all other $I_{bn} = 0$ because

$V_b(\theta) = {}^2\!/_3\, P_2(\cos\theta) + P_1(\cos\theta)$

We conclude all A_n and B_n vanish except for $n=1$ and $n=2$ and, as an example of a nonvanishing term

$$A_1 = \frac{3}{2}\left(\frac{1}{a^3-b^3}\right)\left(\frac{2}{3}a^2 - \frac{2}{3}b^2\right)V_0$$

$$= \frac{a^2-b^2}{a^3-b^3}\, V_0 .$$

similar expressions for $A_2, B_1, B_2, \ldots$

$\boxed{3.}$

We know the sol'n of Laplace's eqn with azimuthal symmetry is

$$(*) \qquad V(r,\theta) = \sum_{\ell=0}^{\infty} \left[A_\ell r^\ell + B_\ell r^{-(\ell+1)}\right] P_\ell(\cos\theta)$$

Solving outside the sphere allows $r \to \infty$ so we need $A_\ell = 0 \ \forall \ell$.

The B_ℓ are determined by the boundary condition on the sphere's surface. Since

$$P_0(x) = 1$$
$$P_1(x) = x \qquad \Longrightarrow \qquad x^2 = \frac{2}{3} P_2(x) + P_1(x)$$
$$P_2(x) = 3/2\,(x^2 - 1)$$

$$V(R,\theta) = V_0 \cos^2\theta = V_0\left[\frac{2}{3} P_2(\cos\theta) + P_1(\cos\theta)\right]$$

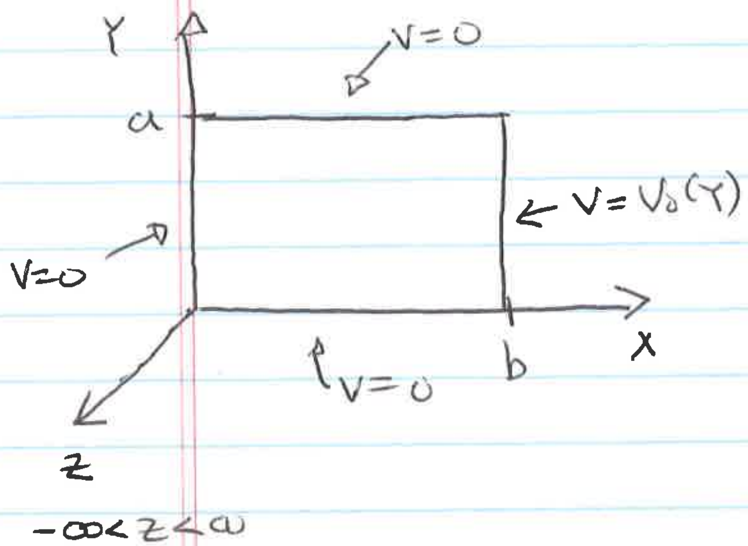
Clearly then

$$V(r,\theta) = V_0 \left(\frac{R}{r}\right)^2 P_1(\cos\theta) + V_0 \frac{2}{3}\left(\frac{R}{r}\right)^3 P_2(\cos\theta)$$

satisfies bdy conditions and is also of the general form $(*)$. Obviously we can easily do any sort of polynomial $V(R,\theta)$ by just decomposing it in $P_\ell(\cos\theta)$.

4-)

$\boxed{4}$ (Griffiths 3-15)



We did this problem in class!

separate $\nabla^2 V = 0$

$$V(x,y) = f(x)g(y)$$

$$\frac{1}{f}\frac{d^2f}{dx^2} = \frac{1}{g}\frac{d^2g}{dy^2} = -k^2$$

$$g(y) = \sin ky \; ; \; \cos ky$$

Eliminated by $V(x,0)=0$

$k = \frac{n\pi}{a}$ since $V(x,a)=0$

$$f(x) = e^{+kx} \; ; \; e^{-kx} \rightsquigarrow \cosh kx \; ; \; \sinh kx$$

eliminated by $V(0,y)=0$

$$* \quad V(x,y) = \sum_{1}^{\infty} A_n \sinh \frac{n\pi x}{a} \sin \frac{n\pi y}{a}$$

set $x=b$ $\quad V(x=b,y) = V_0(y)$

$$V_0(y) = \sum_{1}^{\infty} A_n \sinh \frac{n\pi b}{a} \sin \frac{n\pi y}{a}$$

orthogonality of $\{\sin \frac{n\pi y}{a}\}$

$$\int_0^a V_0(y) \sin \frac{m\pi y}{a}\, dy = A_m \sinh \frac{m\pi b}{a} \frac{a}{2}$$

$$A_m = \frac{2}{a} \frac{1}{\sinh \frac{m\pi b}{a}} \int_0^a V_0(y) \sin \frac{m\pi y}{a}\, dy$$

combined with $*$ is a full solution.

$\boxed{5}$ (Griffiths 3-21)

Potential of charged metal sphere in uniform E_0.

Griffiths Example 8 concluded an uncharged sphere had $V(r,\theta) = -E_0\left(r - \frac{R^3}{r^2}\right)\cos\theta$

with $V=0$ on sphere surface $r=R$.

Clearly this must be part of our solution since this is what we must get if $Q=0$. We also know answer for $E_0 = 0$ is $V(r,\theta) = \frac{1}{4\pi\epsilon_0} Q/r$

By superposition principle

$$V(r,\theta) = \frac{1}{4\pi\epsilon_0}\frac{Q}{r} - E_0\left(r - R^3/r^2\right)\cos\theta$$

where does this vanish? Obviously at $r=\infty$ and $\theta = \pi/2$.

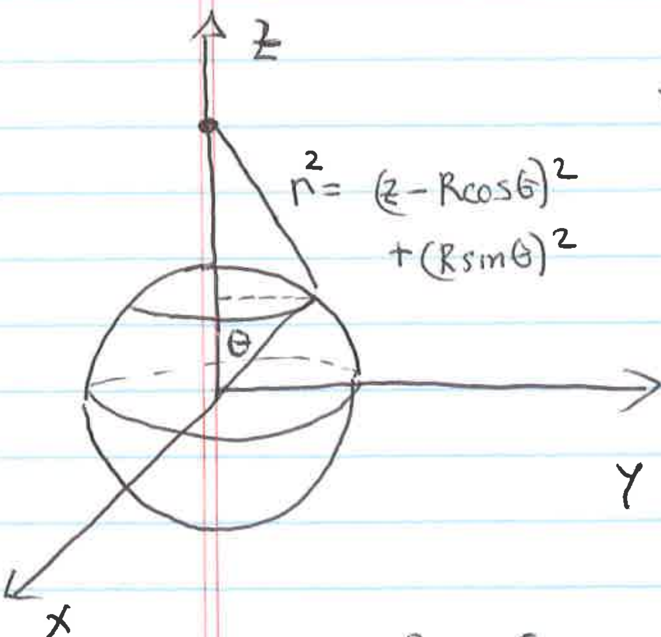
6-1

$\boxed{6}$ (Griffiths 3-23)

spherical shell radius R with $-\sigma_0$ for $z>0$

and $-\sigma_0$ for $z<0$. We can compute V along

the $\hat{z}$ axis by explicit integration



$$V(z) = +\int_0^{\pi/2} d\theta \, \frac{1}{4\pi\epsilon_0} \frac{\overbrace{2\pi R\sin\theta \, R d\theta \, \sigma}^{dq}}{(z^2-2zR\cos\theta+R^2)^{1/2}}$$

$$- \int_{\pi/2}^{\pi} \quad '' \quad \text{(same integrand)}$$

$$V(z) = \frac{R^2\sigma}{2\epsilon_0}\left\{ (z^2-2zR\cos\theta+R^2)^{1/2}\frac{1}{zR}\Big|_0^{\pi/2} - (\ )\Big|_{\pi/2}^{\pi} \right\}$$

$$= \frac{R^2\sigma}{2\epsilon_0}\left\{ \left(\sqrt{z^2+R^2}\,\frac{1}{zR} - \frac{z-R}{zR}\right) - \left(\frac{z+R}{zR} - \sqrt{z^2+R^2}\,\frac{1}{zR}\right)\right\}$$

$$= \frac{R\sigma}{2z\epsilon_0}\left\{ 2\sqrt{z^2+R^2} - z + R - z - R \right\}$$

$$= \frac{R\sigma}{\epsilon_0}\left\{ \frac{\sqrt{z^2+R^2}}{z} - 1 \right\}$$

6-2

along the z axis $\theta = 0$ and $\begin{cases} z = r \\ \cos\theta = 1 \end{cases}$ so the

general sol'n to Laplace's Eqn

$$V(r,\theta) = \sum_{\ell=0}^{\infty} \left(A_\ell r^\ell + B_\ell / r^{\ell+1} \right) P_\ell(\cos\theta)$$

vanish
since V does not
diverge at $r = \infty$

$$V(z) \equiv V(r, \theta = 0) = \sum_{\ell=0}^{\infty} B_\ell / r^{\ell+1} = \frac{R\sigma}{\epsilon_0} \left\{ \frac{\sqrt{r^2 + R^2}}{r} - 1 \right\}$$

$$\left(1 + R^2/r^2\right)^{1/2} - 1$$

$$1 + \frac{1}{2}\frac{R^2}{r^2} - \frac{1}{8}\left(\frac{R^2}{r^2}\right)^2 + \frac{1}{16}\left(\frac{R^2}{r^2}\right)^3 - 1$$

$B_0 = 0$

$B_1 = \frac{R\sigma}{\epsilon_0} \frac{1}{2} R^2$

$B_2 = 0 = B_4 = B_6$

$B_3 = \frac{R\sigma}{\epsilon_0} \left(-\frac{1}{8} R^4 \right)$

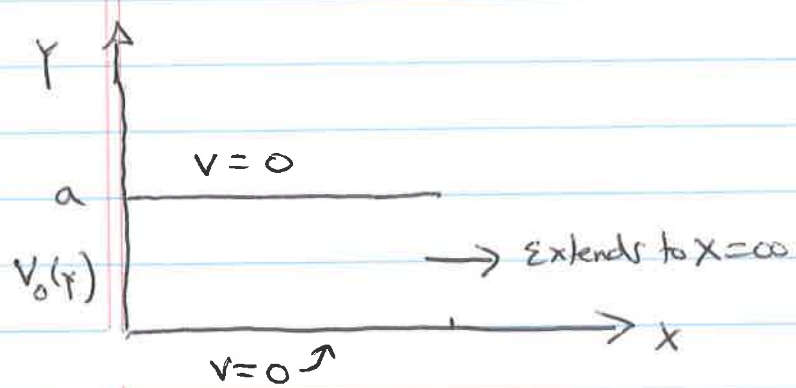
$B_5 = \frac{R\sigma}{\epsilon_0} \left(\frac{1}{16} R^5 \right)$

$$V(r,\theta) = \frac{\sigma R}{2\epsilon_0} \left\{ \frac{R^2}{r^2} - \frac{R^4}{4r^4} + \frac{R^6}{8r^6} \cdots \right\}$$

7-1

$\boxed{7}$ (Griffiths 3-14)

We are asked for the charge density $\sigma(y)$ on the strip at $x=0$ for Example 3 in text.



The general solution was

$$V(xy) = \sum_{n=1}^{\infty} C_n e^{-n\pi X/a} \sin\frac{n\pi Y}{a} \qquad \text{(Eq. 30)}$$

$$C_n = 2/a \int_0^a V_0(y) \sin\frac{n\pi Y}{a}\, dy \qquad \text{(Eq. 34)}$$

and for $V_0(y) = V_0$ $\quad C_n = \begin{cases} 0 & n \text{ even} \\ \frac{4V_0}{n\pi} & n \text{ odd} \end{cases}$ (Eq 35)

normal component of E

Recall that E_n is σ/ϵ_0 just outside conductor (by Gauss's Law)

$$E_n = -\frac{\partial V(x,y)}{\partial x}\Bigg|_{x=0} = \sum_{n=1}^{\infty} C_n \frac{n\pi}{a} e^{-n\pi X/a} \sin\frac{n\pi Y}{a}\Bigg|_{x=0}$$

$$E_n = \sum_{n=1}^{\infty} C_n \frac{n\pi}{a} \sin\frac{n\pi Y}{a} \qquad \leftarrow \text{general } V_0(y)$$

7-2

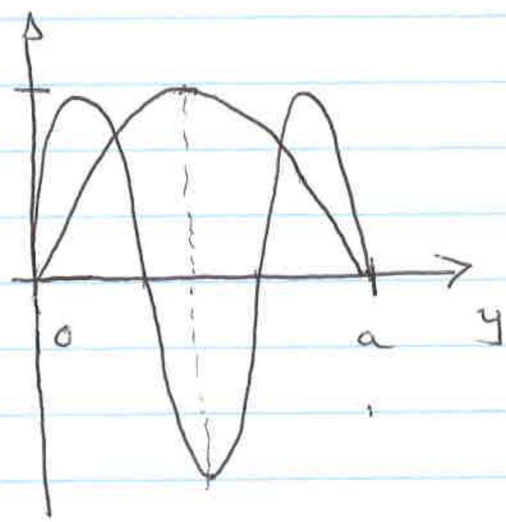
For $V_0(y) = V_0$ $\quad c_n = \begin{cases} 0 & n \text{ even} \\ \frac{4V_0}{n\pi} & n \text{ odd} \end{cases}$

and hence using $\sigma = \epsilon_0 E_n$

$$\sigma(y) = \sum_{n \text{ odd}} \frac{4V_0\epsilon_0}{n\pi} \frac{n\pi}{a} \sin\frac{n\pi y}{a}$$

$$\sigma(y) = \sum_{n \text{ odd}} \frac{4V_0\epsilon_0}{a} \sin\frac{n\pi y}{a}$$

Try sketching



Does the sum converge?!