call the const $\ell(\ell+1)$

For R

$$\frac{1}{R}\frac{d}{dr}\left(r^2\frac{dR}{dr}\right) - \ell(\ell+1) = 0$$

Solutions are of the form $\boxed{R(r) = a_\ell r^\ell + b_\ell r^{-(\ell+1)}}$
substitute in to verify

$$\frac{d}{dr}\left(r^2\frac{dR}{dr}\right) = \frac{d}{dr}\left(r^2\left(\ell a_\ell r^{\ell-1} - (\ell+1)b_\ell r^{-\ell-2}\right)\right)$$

$$= \frac{d}{dr}\left(\ell a_\ell r^{\ell+1} - (\ell+1)b_\ell r^{-\ell}\right)$$

$$= \ell(\ell+1)a_\ell r^\ell + \ell(\ell+1)b_\ell r^{-(\ell+1)} = \ell(\ell+1)R$$

For Θ :

$$\frac{1}{\Theta\sin\theta}\frac{d}{d\theta}\left(\sin\theta\frac{d\Theta}{d\theta}\right) - \frac{m^2}{\sin^2\theta} = -\ell(\ell+1)$$

let $x = \cos\theta$

$dx = -\sin\theta\, d\theta$

$d\theta = \dfrac{-dx}{\sin\theta}$ $\qquad 0 \leq \theta \leq \pi$

above becomes

solutions for $-1 \leq x \leq 1$ correspond to $\ell \geq 0$ integers

$$\frac{d}{dx}\left[(1-x^2)\frac{d\Theta}{dx}\right] + \left[\ell(\ell+1) - \frac{m^2}{1-x^2}\right]\Theta = 0$$

Called generalized Legendre Equation - solutions are called the associated Legendre functions.

ordinary Legendre polynomials are solutions for $m=0$

For the special case $m=0$, ie the solution has azimuthal symmetry and Φ does not depend on the angle φ (ie rotational symmetry about $\hat{z}$ axis),

We want the solutions to

$$\frac{d}{dx}\left[(1-x^2)\frac{d\Theta}{dx}\right] + \ell(\ell+1)\,\Theta = 0$$

The solutions are known as the Legendre polynomials, $P_\ell(x)$.

They are given, for ℓ integer, by

$$P_\ell(x) = \frac{1}{2^\ell \ell!}\left(\frac{d}{dx}\right)^\ell (x^2-1)^\ell \qquad \text{Rodriguez's formula}$$

The lowest ℓ polynomials are

$$P_0(x) = 1 \qquad\qquad P_2(x) = \tfrac{1}{2}(3x^2-1)$$
$$P_1(x) = x \qquad\qquad P_3(x) = \tfrac{1}{2}(5x^3-3x)$$

In general, $P_\ell(x)$ is a polynomial of order ℓ with only even powers if ℓ is even, and only odd powers if ℓ is odd. $\Rightarrow P_\ell(x) \begin{cases} \text{even in } x \text{ for } \ell \text{ even} \\ \text{odd in } x \text{ for } \ell \text{ odd} \end{cases}$

$P_\ell(x)$ is normalized so that $P_\ell(1) = 1$

Note: Legendre polynomials are only for integer $l \geq 0$.
What about solutions for non integer l?
The $P_l(x)$ give one solution for each integer l.
But $P_l(x)$ are defined by a 2nd order differential equation - shouldn't there be a 2nd independent solution for each l?
It turns out that these "2nd" solutions, as well as solutions for non integer l, all blow up at either $x=-1$ or $x=1$, ie at $\theta=0$ or $\theta=\pi$.
They therefore are physically unacceptable and we do not need to consider them. See Jackson 3.2

The Legendre polynomials are orthogonal and form a complete set of basis functions on the interval $-1 \leq x \leq 1$.

$$\int_{-1}^{1} dx\, P_l(x) P_m(x) = \int_0^{\pi} d\theta \sin\theta\, P_l(\cos\theta)\, P_m(\cos\theta) = \begin{cases} 0 & l \neq m \\ \dfrac{2}{2l+1} & l = m \end{cases}$$

$\Rightarrow$ we can expand any function $f(\theta)$, $0 \leq \theta \leq \pi$, as a linear combination of the $P_l(\cos\theta)$.
This is the reason they are useful for solving problems of Laplace's eqn with spherical boundary surfaces.

For $m \neq 0$, the solutions to (see Jackson 3.5)

$$\frac{d}{dx}\left[(1-x^2)\frac{d\Theta}{dx}\right] + \left[\ell(\ell+1) - \frac{m^2}{1-x^2}\right]\Theta = 0$$

are the associated Legendre functions $P_\ell^m(x)$.
For $P_\ell^m(x)$ to be finite in interval $-1 \leq x \leq 1$ one again finds that ℓ must be integer $\ell \geq 0$, and integer m must satisfy $|m| \leq \ell$, ie $m = -\ell, -\ell+1, \ldots, 0, \ldots, \ell-1, \ell$.
For each ℓ and m there is only one such non divergent solution.

It is typical to combine the solutions $P_\ell^m(\cos\theta)$ to the θ-part of the equation with the $\Phi_m(\varphi) = e^{im\varphi}$ solutions to the φ-part of the equation to define the spherical harmonics

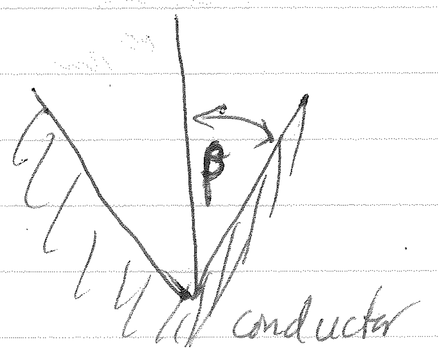
$$Y_{\ell m}(\theta, \varphi) \equiv \sqrt{\frac{2\ell+1}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}}\, P_\ell^m(\cos\theta)\, e^{im\varphi}$$

The $Y_{\ell m}$ are orthogonal

$$\int_0^{2\pi} d\varphi \int_0^{\pi} d\theta \sin\theta \; Y^*_{\ell' m'}(\theta,\varphi)\, Y_{\ell m}(\theta,\varphi) = \delta_{\ell\ell'}\delta_{mm'}$$

and are a complete set of basis functions for expanding any function $f(\theta,\varphi)$ defined on the surface of a sphere.

Behavior of fields near conical hole or sharp tip



we now want to solve the $\nabla^2\phi = 0$ with separation of variables, but now θ is restricted to range $0 \le \theta \le \beta$.

We still have azimuthal symmetry, but now, since we do not need solution to be finite for all $\theta \in [0, \pi]$, but only $\theta \in (0, \beta)$, we have more solutions to the (14) equation, ie l does not have to be integer, - still need $l \geq 0$ to be finite at $\theta = 0$.

see Jackson sec. 3.4 for details.

Exayles with azimuthal symmetry $m=0$

General solution to $\nabla^2\phi=0$ can be written in form

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

determine the A_ℓ ad B_ℓ from the bouday conditions of the particular problem.

(1) Suppose one is given $\phi(R,\theta) = \phi_0(\theta)$ on surface of sphere of radius R.

To find solution of $\nabla^2\phi=0$ inside sphere

ϕ should not diverge at origin $\Rightarrow B_\ell = 0$ for all ℓ

$$\phi(r,\theta) = \sum_{\ell=0}^{\infty} A_\ell r^\ell P_\ell(\cos\theta)$$

$$\Rightarrow \phi(R,\theta) = \phi_0(\theta) = \sum_{\ell=0}^{\infty} A_\ell R^\ell P_\ell(\cos\theta)$$

$$\Rightarrow \int_0^\pi d\theta \sin\theta\, \phi_0(\theta) P_m(\cos\theta) = \sum_{\ell=0}^{\infty} A_\ell R^\ell \int_0^\pi d\theta \sin\theta\, P_\ell(\cos\theta) P_m(\cos\theta)$$

$$= \sum_{\ell=0}^{\infty} A_\ell R^\ell \left(\frac{2}{2\ell+1}\right) \delta_{\ell m}$$

$$= A_m R^m \frac{2}{2m+1}$$

$$\boxed{A_m = \frac{2m+1}{2R^m} \int_0^\pi d\theta \sin\theta\, \phi_0(\theta) P_m(\cos\theta)}$$ gives solution

To find solution of $\nabla^2\phi = 0$ <u>outside</u> sphere

if require $\phi \to 0$ as $r \to 0$, then $A_\ell = 0$ for all ℓ

$$\phi(r,\theta) = \sum_{\ell=0}^{\infty} \frac{B_\ell}{r^{\ell+1}} P_\ell(\cos\theta)$$

$$\phi(R,\theta) = \phi_0(\theta) = \sum_{\ell=0}^{\infty} \frac{B_\ell}{R^{\ell+1}} P_\ell(\cos\theta)$$

gives solution $$\boxed{B_m = \frac{2m+1}{2} R^{m+1} \int_0^{\pi} d\theta \sin\theta \, \phi_0(\theta) P_m(\cos\theta)}$$

$$\boxed{B_m = A_m R^{2m+1}}$$

(2) Suppose one is given surface charge density $\sigma(\theta)$ fixed on surface of sphere of radius R. What is ϕ inside ad outside?

From previous example

$$\phi(r,\theta) = \begin{cases} \sum_{\ell=0}^{\infty} A_\ell r^\ell P_\ell(\cos\theta) & r < R \\ \sum_{\ell=0}^{\infty} \frac{B_\ell}{r^{\ell+1}} P_\ell(\cos\theta) & r > R \end{cases}$$

boundary conditions at $r = R$ on surface

(i) ϕ continuous

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

If an expansion in Legendre polynomials vanishes for all θ, then each coefficient in the expansion must vanish

$$\Rightarrow \quad A_\ell R^\ell = \frac{B_\ell}{R^{\ell+1}} \quad \Rightarrow \quad \boxed{B_\ell = A_\ell R^{2\ell+1}}$$

(ii) jump in electric field at σ

$$-\left.\frac{\partial \phi^{out}}{\partial r}\right|_{r=R} + \left.\frac{\partial \phi^{in}}{\partial r}\right|_{r=R} = 4\pi\sigma$$

$$\Rightarrow \sum_{\ell=0}^{\infty}\left[\frac{(\ell+1)B_\ell}{R^{\ell+2}} + \ell A_\ell R^{\ell-1}\right]P_\ell(\cos\theta) = 4\pi\sigma$$

$$\Rightarrow \sum_{\ell=0}^{\infty}\left[\frac{(\ell+1)A_\ell R^{2\ell+1}}{R^{\ell+2}} + \ell A_\ell R^{\ell-1}\right]\cdot P_\ell(\cos\theta)$$

$$\Rightarrow \sum_{\ell=0}^{\infty}(2\ell+1)R^{\ell-1}A_\ell P_\ell(\cos\theta) = 4\pi\sigma$$

$$(2m+1)R^{m-1}A_m\left(\frac{2}{2m+1}\right) = 4\pi\int_0^\pi d\theta\sin\theta\,\sigma(\theta)P_m(\cos\theta)$$

$$\boxed{A_m = \frac{4\pi}{2R^{m-1}}\int_0^\pi d\theta\sin\theta\,\sigma(\theta)\,P_m(\cos\theta)}$$

Suppose $\sigma(\theta) = k\cos\theta$ what is ϕ?

Note $\sigma(\theta) = k P_1(\cos\theta)$

hence only $A_1 \neq 0$ by orthogonality of $P_\ell(\cos\theta)$

$$A_1 = \frac{4\pi k}{2} \int_0^\pi d\theta \sin\theta \, P_1(\cos\theta) P_1(\cos\theta)$$

$$= \frac{4\pi k}{2}\left(\frac{2}{2+1}\right) = \frac{4}{3}\pi k$$

$$\Rightarrow \phi(r,\theta) = \begin{cases} \frac{4\pi}{3} k \, r\cos\theta & r < R \\ \frac{4\pi}{3} k \frac{R^3}{r^2} \cos\theta & r > R \end{cases}$$

we will see that potential <u>outside</u> the sphere is that of an ideal dipole with dipole moment

$$p = \frac{4}{3}\pi R^3 k$$

Inside the sphere, the potential $\phi = \frac{4\pi}{3} k z$ where $z = r\cos\theta$. The electric field inside the sphere is therefore the constant

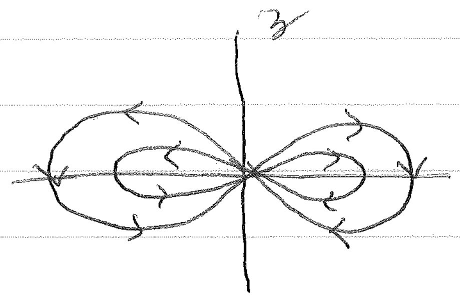
$$\vec{E} = -\vec{\nabla}\phi = -\frac{4}{3}\pi k \hat{z}$$

Outside the sphere the field is

$$\vec{E} = -\vec{\nabla}\phi = -\frac{\partial \phi}{\partial r}\,\hat{r} - \frac{1}{r}\frac{\partial \phi}{\partial \theta}\,\hat{\theta}$$

$$= \frac{8\pi}{3} k \frac{R^3}{r^3} \cos\theta\,\hat{r} + \frac{4\pi}{3} k \frac{R^3}{r^3} \sin\theta\,\hat{\theta}$$

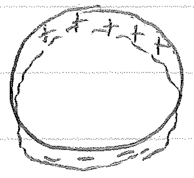
$$\vec{E} = \frac{4\pi}{3} R^3 k \frac{1}{r^3}\left[2\cos\theta\,\hat{r} + \sin\theta\,\hat{\theta}\right]$$



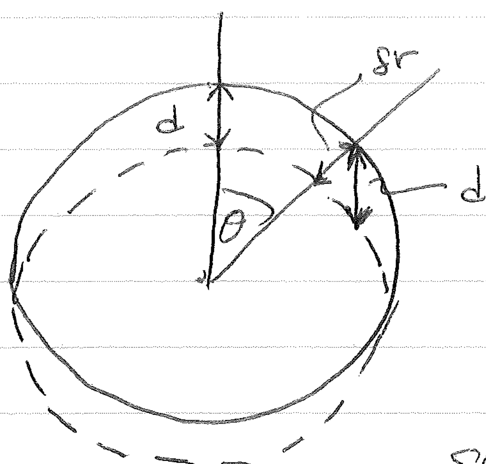
dipole field

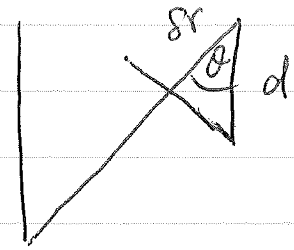
Physical example with $\sigma(\theta) = k\cos\theta$

Two spheres of radii R, with equal but opposite uniform charge densities ρ and $-\rho$, displaced by small distance $d \ll R$



surface charge σ builds up due to displacement
This is a uniformly "polarized" sphere





$d\cos\theta = \delta r$

surface charge is $\sigma(\theta) = \rho\,\delta r$

$= \rho d\cos\theta$

$$\boxed{\sigma(\theta) = \rho d\cos\theta}$$

$k \equiv \rho d \equiv \mathbb{P}$

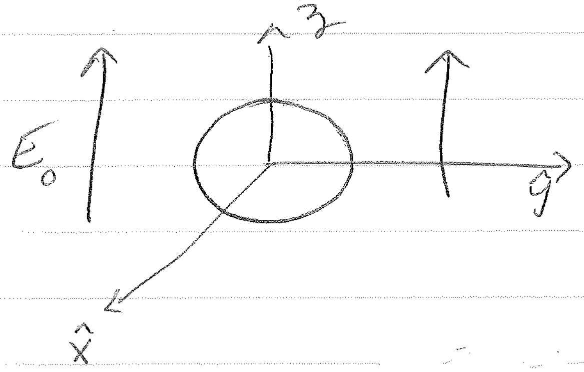
total dipole moment is $(\rho d)\frac{4}{3}\pi R^3$

polarization $= \dfrac{\text{dipole moment}}{\text{volume}} = \rho d \equiv \mathbb{P}$

$\vec{E}$ field inside a uniformly polarized sphere is constant. $\vec{E} = -\rho d\,\frac{4\pi}{3}\hat{z} = -\frac{4\pi\mathbb{P}}{3}\hat{z} = -\frac{4\pi}{3}\vec{\mathbb{P}}$

(3) Grounded Conducting sphere in uniform electric field $\vec{E} = E_0 \hat{z}$

as $r \to \infty$ far from sphere, $\vec{E} = E_0 \hat{z} \Rightarrow \phi = -E_0 z$
$= -E_0 r \cos\theta$



boundary conditions

$$\begin{cases} \phi(R,\theta) = 0 \\ \phi(r \to \infty, \theta) = -E_0 r \cos\theta \end{cases}$$

solution outside sphere has the form

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

From boundary condition as $r \to \infty$ we have
$A_\ell = 0$ all $\ell \neq 1$
$A_1 = -E_0$ since $P_1(\cos\theta) = \cos\theta$

$$\phi(r,\theta) = -E_0 r\cos\theta + \sum_{\ell=0}^{\infty} \frac{B_\ell}{r^{\ell+1}} P_\ell(\cos\theta)$$

From $\phi(R,\theta) = 0$ we have

$$0 = -E_0 R\cos\theta + \sum_{\ell=0}^{\infty} \frac{B_\ell}{R^{\ell+1}} P_\ell(\cos\theta)$$

$$\Rightarrow B_\ell = 0 \text{ all } \ell \neq 1$$

$$\frac{B_1}{R^2} = E_0 R \Rightarrow B_1 = E_0 R^3$$

So $$\boxed{\phi(r,\theta) = -E_0\left(r - \frac{R^3}{r^2}\right)\cos\theta}$$

1st ten is just potential $-E_0 r\cos\theta$ of the uniform applied electric field.

2nd ten is potential due to the induced surface charge on the surface - it is a dipole field

Induced charge density is

$$4\pi\sigma(\theta) = -\frac{\partial\phi}{\partial r}\Big|_{r=R} = E_0\left(1 + \frac{2R^3}{R^3}\right)\cos\theta$$

$$= 3E_0\cos\theta$$

$$\sigma(\theta) = \frac{3}{4\pi}E_0\cos\theta$$ like uniformly polarized sphere $k = \frac{3E_0}{4\pi} = P$

from ② we know that the field inside the sphere due to this σ is just $-\frac{4}{3}\pi k\hat{z} = -\frac{4}{3}\pi\frac{3E_0}{4\pi}\hat{z}$

$= -E_0\hat{z}$. This is just what is required so that the total field in the conducting sphere vanishes.

Can check that outside the sphere, $\vec{E} = -\vec{\nabla}\phi$ is normal to surface of sphere at $r=R$.