PHY 712 Electrodynamics
12-12:50 AM MWF Olin 103
Plan for Lecture 4:

Reading: Chapter 1 - 3 in JDJ

Electrostatic potentials

1. **One, two, and three dimensions (Cartesian coordinates)**
2. **Mean value theorem for the electrostatic potential**

1

Colloquium: "Prediction and Inverse Design of Sustainable Energy Materials"

Dr. Ongun Ozcelik
Theoretical and Computational Chemistry
University of California, San Diego
George P. Williams, Jr. Lecture Hall, (Olin 101)
Wednesday, January 22, 2020 at 3:00 PM

There will be a reception in the Olin Lounge at approximately 4 PM following the colloquium. All interested persons are cordially invited to attend.

2

PHY 712 Electrodynamics

MWF 12-12:50 PM	OPL 103	http://www.wfu.edu/~natalie/s20phy712/

Instructor: Natalie Holzwarth	**Phone:**758-5510	**Office:**300 OPL	**e-mail:**natalie@wfu.edu

Course schedule for Spring 2020

(Preliminary schedule -- subject to frequent adjustment.)

	Lecture date	JDJ Reading	Topic	HW	Due date
1	Mon: 01/13/2020	Chap. 1 & Appen.	Introduction, units and Poisson equation	#1	01/17/2020
2	Wed: 01/15/2020	Chap. 1	Electrostatic energy calculations	#2	01/22/2020
3	Fri: 01/17/2020	Chap. 1	Electrostatic potentials and fields	#3	01/24/2020
	Mon: 01/20/2020	No class	Martin Luther King Holiday		
4	Wed: 01/22/2020	Chap. 1 - 3	Poisson's equation in 2 and 3 dimensions	#4	01/27/2020
5	Fri: 01/24/2020	Chap. 1 - 3	Brief introduction to numerical methods		
6	Mon: 01/27/2020	Chap. 2 & 3	Image charge constructions		
7	Wed: 01/29/2020	Chap. 2 & 3	Cylindrical and spherical geometries		
8	Fri: 01/31/2020	Chap. 3 & 4	Spherical geometry and multipole moments		
9	Mon: 02/03/2020	Chap. 4	Dipoles and Dielectrics		

3

Poisson Equation

$$\nabla^2 \Phi_P(\mathbf{r}) = -\frac{\rho(\mathbf{r})}{\varepsilon_0}$$

Solution to Poisson equation using Green's function $G(\mathbf{r},\mathbf{r}')$:

$$\Phi(\mathbf{r}) = \frac{1}{4\pi\varepsilon_0}\int_V d^3r'\,\rho(\mathbf{r}')G(\mathbf{r},\mathbf{r}') +$$

$$\frac{1}{4\pi}\int_S d^2r'\left[G(\mathbf{r},\mathbf{r}')\nabla'\Phi(\mathbf{r}') - \Phi(\mathbf{r}')\nabla' G(\mathbf{r},\mathbf{r}')\right]\cdot\hat{\mathbf{r}}'.$$

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 4

4

Poisson equation for one-dimensional system

$$\frac{d^2\Phi_P(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon_0}$$

Example solution:

$$\Phi_P(x) = \frac{1}{4\pi\varepsilon_0}\int_{-\infty}^{\infty} G(x,x')\rho(x')dx' + C_1 + C_2 x$$

where $G(x,x') = 4\pi x_<$ where $x_<$ is the smaller of x and x';
C_1 and C_2 are constants.

Check:

$$\Phi_P(x) = \frac{1}{\varepsilon_0}\left\{\int_{-\infty}^{x} x'\rho(x')dx' + x\int_x^{\infty}\rho(x')dx'\right\} + C_1 + C_2 x$$

$$\frac{d\Phi_P(x)}{dx} = \frac{1}{\varepsilon_0}\int_x^{\infty}\rho(x')dx' + C_2 \quad\Rightarrow \frac{d^2\Phi_P(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon_0}$$

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 5

5

General procedure for constructing Green's function for one-dimensional system using 2 independent solutions of the homogeneous equations

Consider two independent solutions to the homogeneous equation

$$\nabla^2\phi_i(x) = 0$$

where $i = 1$ or 2. Let

$$G(x,x') = \frac{4\pi}{W}\phi_1(x_<)\phi_2(x_>).$$

This notation means that $x_<$ should be taken as the smaller of x and x' and $x_>$ should be taken as the larger.

"Wronskian": $W \equiv \frac{d\phi_1(x)}{dx}\phi_2(x) - \phi_1(x)\frac{d\phi_2(x)}{dx}.$

Beautiful method; but only works in one dimension.

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 6

6

Orthogonal function expansions and Green's functions

Suppose we have a "complete" set of orthogonal functions $\{u_n(x)\}$ defined in the interval $x_1 \leq x \leq x_2$ such that

$$\int_{x_1}^{x_2} u_n(x)u_m(x)\,dx = \delta_{nm}.$$

We can show that the completeness of this functions implies that

$$\sum_{n=1}^{\infty} u_n(x)u_n(x') = \delta(x-x').$$

This relation allows us to use these functions to represent a Green's function for our system. For the 1-dimensional Poisson equation, the Green's function satisfies

$$\frac{\partial^2}{\partial x^2}G(x,x') = -4\pi\delta(x-x').$$

7

Orthogonal function expansion -- continued

Suppose the orthogonal functions satisfy an eigenvalue equation:

$$\frac{d^2}{dx^2}u_n(x) = -\alpha_n u_n(x)$$

where the functions $u_n(x)$ also satisfy the appropriate boundary conditions, then we can construct the Green's function:

$$G(x,x') = 4\pi\sum_n \frac{u_n(x)u_n(x')}{\alpha_n}.$$

Check:

$$\frac{d^2}{dx^2}G(x,x') = 4\pi\sum_n \frac{\left(-\alpha_n u_n(x)\right)u_n(x')}{\alpha_n} = -4\pi\sum_n u_n(x)u_n(x')$$

$$= -4\pi\delta(x-x')$$

8

Example

For example, consider the previous example in the interval $-a \leq x \leq a$:

$$\rho(x) = \begin{cases} 0 & \text{for } x < -a \\ -\rho_0 & \text{for } -a < x < 0 \\ +\rho_0 & \text{for } 0 < x < a \\ 0 & \text{for } x > a \end{cases}$$

We want to solve the Poisson equation with boundary condition $d\Phi(-a)/dx = 0$ and $d\Phi(a)/dx = 0$. We may choose

$u_n(x) = \sqrt{\frac{1}{a}}\sin\left(\frac{[2n+1]\pi x}{2a}\right)$ and the corresponding Green's function

$$G(x,x') = \frac{4\pi}{a}\sum_{n=0}^{\infty} \frac{\sin\left(\frac{[2n+1]\pi x}{2a}\right)\sin\left(\frac{[2n+1]\pi x'}{2a}\right)}{\left(\frac{[2n+1]\pi}{2a}\right)^2}.$$

9

Example -- continued

This form of the one-dimensional Green's function only allows us to find a solution to the Poisson equation within the interval $-a \le x \le a$ from

$$\Phi(x) = \frac{1}{4\pi\varepsilon_0}\int_{-a}^{a} dx'\, G(x,x')\rho(x') + C_1$$

$$\Rightarrow \Phi(x) = \frac{\rho_0 a^2}{\epsilon_0}\left(16\sum_{n=0}^{\infty}\frac{\sin\left(\frac{[2n+1]\pi x}{2a}\right)}{([2n+1]\pi)^3} + \frac{1}{2}\right),$$

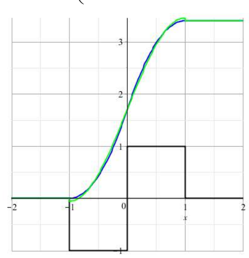
choosing C_1 so that $\Phi(-a) = 0$.

$$\text{Exact result: } \Phi(x) = \begin{cases} 0 & \text{for } x < -a \\ \frac{\rho_0}{2\varepsilon_0}(x+a)^2 & \text{for } -a < x < 0 \\ -\frac{\rho_0}{2\varepsilon_0}(x-a)^2 + \frac{\rho_0 a^2}{\varepsilon_0} & \text{for } 0 < x < a \\ \frac{\rho_0}{\varepsilon_0}a^2 & \text{for } x > a \end{cases}$$

10

Example -- continued

$$\Phi(x) = \frac{\rho_0 a^2}{\epsilon_0}\left(16\sum_{n=0}^{\infty}\frac{\sin\left(\frac{[2n+1]\pi x}{2a}\right)}{([2n+1]\pi)^3} + \frac{1}{2}\right)$$



11

Orthogonal function expansions in 2 and 3 dimensions

$$\nabla^2\Phi(\mathbf{r}) \equiv \frac{\partial^2\Phi(\mathbf{r})}{\partial x^2} + \frac{\partial^2\Phi(\mathbf{r})}{\partial y^2} + \frac{\partial^2\Phi(\mathbf{r})}{\partial z^2} = -\rho(\mathbf{r})/\epsilon_0.$$

Let $\{u_n(x)\}$, $\{v_n(y)\}$, $\{w_n(z)\}$ denote complete orthogonal function sets in the x, y, and z dimensions, respectively. The Green's function construction becomes:

$$G(x,x',y,y',z,z') = 4\pi\sum_{lmn}\frac{u_l(x)u_l(x')v_m(y)v_m(y')w_n(z)w_n(z')}{\alpha_l + \beta_m + \gamma_n},$$

where

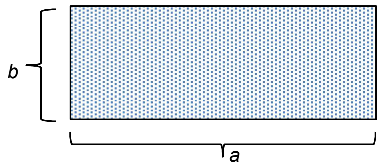
$$\frac{d^2}{dx^2}u_l(x) = -\alpha_l u_l(x), \quad \frac{d^2}{dy^2}v_m(y) = -\beta_m v_m(y), \text{ and } \frac{d^2}{dz^2}w_n(z) = -\gamma_n w_n(z).$$

(See Eq. 3.167 in Jackson for example.)

12

Details of a two-dimensional example --

Example:



Two dimensional box with sides a and b with boundary conditions: $\Phi(0,y)=\Phi(a,y)=\Phi(x,0)=\Phi(x,b)=0$

$$\nabla^2\Phi(\mathbf{r}) \equiv \frac{\partial^2\Phi(\mathbf{r})}{\partial x^2}+\frac{\partial^2\Phi(\mathbf{r})}{\partial y^2} = -\rho(\mathbf{r})/\epsilon_0.$$

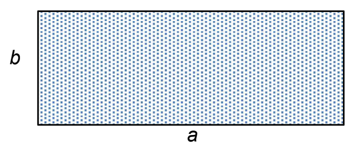
$$G(x,x',y,y') = 4\pi\sum_{lm}\frac{u_l(x)u_l(x')v_m(y)v_m(y')}{\alpha_l+\beta_m},$$

$$\text{where } \frac{d^2}{dx^2}u_l(x) = -\alpha_l u_l(x), \quad \frac{d^2}{dy^2}v_m(x) = -\beta_m v_m(y)$$

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 13

13

Two dimensional example continued --



$$u_l(x)=\sqrt{\frac{2}{a}}\sin\left(\frac{l\pi x}{a}\right) \quad v_m(y)=\sqrt{\frac{2}{b}}\sin\left(\frac{m\pi y}{b}\right) \quad \text{with} \quad \alpha_n=\left(\frac{l\pi}{a}\right)^2 \quad \beta_n=\left(\frac{m\pi}{b}\right)^2$$

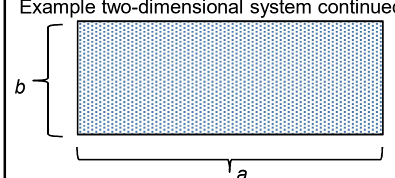
$$G(x,x',y,y') = 4\pi\sum_{lm}\frac{u_l(x)u_l(x')v_m(y)v_m(y')}{\alpha_l+\beta_m}$$

$$=\frac{16}{\pi ab}\sum_{lm}\frac{\sin\left(\frac{l\pi x}{a}\right)\sin\left(\frac{l\pi x'}{a}\right)\sin\left(\frac{m\pi y}{b}\right)\sin\left(\frac{m\pi y'}{b}\right)}{\left(\frac{l}{a}\right)^2+\left(\frac{m}{b}\right)^2}$$

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 14

14

Example two-dimensional system continued --



Two dimensional box with sides a and b with boundary conditions: $\Phi(0,y)=\Phi(a,y)=\Phi(x,0)=\Phi(x,b)=0$

$$\Phi(\mathbf{r}) = \frac{1}{4\pi\varepsilon_0}\int_V d^3r'\,\rho(\mathbf{r}')G(\mathbf{r},\mathbf{r}') +$$

Don't know this term — Know this term=0

$$\frac{1}{4\pi}\int_S d^2r'\left[G(\mathbf{r},\mathbf{r}')\nabla'\Phi(\mathbf{r}') - \Phi(\mathbf{r}')\nabla'G(\mathbf{r},\mathbf{r}')\right]\cdot\hat{\mathbf{r}}'.$$

➔By design $G(\mathbf{r},\mathbf{r}')$ vanishes on boundary.

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 15

15

Example #1: $\rho(x,y)=\rho_0\sin\left(\frac{\pi x}{a}\right)\sin\left(\frac{\pi y}{b}\right)$

Example #2: $\rho(x,y)=\rho_0$

$$\Phi(\mathbf{r})=\frac{1}{4\pi\varepsilon_0}\int_V d^3r'\rho(\mathbf{r}')G(\mathbf{r},\mathbf{r}')$$

For this case:

$$G(x,x',y,y')=\frac{16}{\pi ab}\sum_{lm}\frac{\sin\left(\frac{l\pi x}{a}\right)\sin\left(\frac{l\pi x'}{a}\right)\sin\left(\frac{m\pi y}{b}\right)\sin\left(\frac{m\pi y'}{b}\right)}{\left(\frac{l}{a}\right)^2+\left(\frac{m}{b}\right)^2}$$

For example #1: $\Phi(x,y)=\frac{\rho_0 a^2b^2}{\epsilon_0\pi^2(a^2+b^2)}\sin\left(\frac{\pi x}{a}\right)\sin\left(\frac{\pi y}{b}\right)$

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 16

16

Combined orthogonal function expansion and homogeneous solution construction of Green's function in 2 and 3 dimensions.

An alternative method of finding Green's functions for a second order ordinary differential equations (in 1 dimension) is based on a product of two independent solutions of the homogeneous equation, $\phi_1(x)$ and $\phi_2(x)$:

$$G(x,x')=K\phi_1(x_<)\phi_2(x_>),\ \text{where}\ K\equiv\frac{4\pi}{\frac{d\phi_1}{dx}\phi_2-\phi_1\frac{d\phi_2}{dx}},$$

where $x_<$ denotes the smaller of x and x'.

For the two and three dimensional cases, we can use this technique in one of the dimensions in order to reduce the number of summation terms. These ideas are discussed in Section 3.11 of Jackson.

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 17

17

Green's function construction -- continued

For the two dimensional case, for example, we can assume that the Green's function can be written in the form:

$$G(x,x',y,y')=\sum_n u_n(x)u_n(x')g_n(y,y')\ \text{where}\ \frac{d^2}{dx^2}u_n(x)=-\alpha_n u_n(x)$$

The y dependence of this equation will have the required behavior, if we choose: $\left[-\alpha_n+\frac{\partial^2}{\partial y^2}\right]g_n(y,y')=-4\pi\delta(y-y'),$

which in turn can be expressed in terms of the two independent solutions $v_{n_1}(y)$ and $v_{n_2}(y)$ of the homogeneous equation:

$$\left[\frac{d^2}{dy^2}-\alpha_n\right]v_{n_i}(y)=0,$$

and the Wronskian constant: $K_n\equiv\frac{dv_{n_1}}{dy}v_{n_2}-v_{n_1}\frac{dv_{n_2}}{dy}$

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 18

18

$$\left[-\alpha_n + \frac{\partial^2}{\partial y^2}\right] g_n(y,y') = -4\pi\delta(y-y'),$$

$$g_n(y,y') = \frac{4\pi}{K_n} v_{n_1}(y_<) v_{n_2}(y_>)$$

where: $\left[\frac{d^2}{dy^2} - \alpha_n\right] v_{n_i}(y) = 0,$

and $K_n \equiv \frac{dv_{n_1}}{dy} v_{n_2} - v_{n_1}\frac{dv_{n_2}}{dy}$

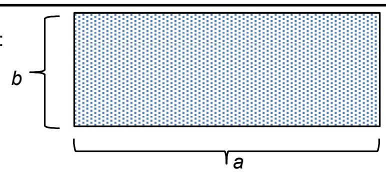
For example, choose $v_{n_1}(y) = \sinh(\sqrt{\alpha_n}\, y)$ and $v_{n_2}(y) = \sinh(\sqrt{\alpha_n}(b-y))$

where $K_n = \sqrt{\alpha_n}\sinh(\sqrt{\alpha_n}\, b)$

using the identity: $\cosh(r)\sinh(s) + \sinh(r)\cosh(s) = \sinh(r+s)$

19

Example:



Two dimensional box with sides a and b with boundary conditions: *Φ(0,y)=Φ(a,y)=Φ(x,0)=Φ(x,b)=0*

$$\Phi(\mathbf{r}) = \frac{1}{4\pi\varepsilon_0}\int_V d^3r'\,\rho(\mathbf{r}')G(\mathbf{r},\mathbf{r}') +$$

Don't know this term

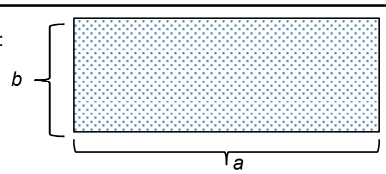
Know this term

$$\frac{1}{4\pi}\int_S d^2r'\left[G(\mathbf{r},\mathbf{r}')\nabla'\Phi(\mathbf{r}') - \Phi(\mathbf{r}')\nabla' G(\mathbf{r},\mathbf{r}')\right]\cdot\hat{\mathbf{r}}'.$$

$$G(x,x',y,y') = \sum_n u_n(x)u_n(x')\frac{4\pi}{K_n} v_{n_1}(y_<)v_{n_2}(y_>).$$

20

Example:



Two dimensional box with sides a and b with boundary conditions: *Φ(0,y)=Φ(a,y)=Φ(x,0)=Φ(x,b)=0*

For this type of problem, it is necessary to construct $G(x,x',y,y')$ so that it vanishes on the boundary:

$$G(x,x',y,0) = G(x,x',y,b) = G(x,0,y,y') = G(x,a,y,y') = 0$$

21

$$G(x,x',y,y') = \sum_n u_n(x) u_n(x') \frac{4\pi}{K_n} v_{n_1}(y_<) v_{n_2}(y_>).$$

$$\frac{d^2}{dx^2} u_n(x) = -\alpha_n u_n(x) \quad \text{where} \quad u_n(0) = u_n(a) = 0$$

$$\Rightarrow u_n(x) = \sqrt{\frac{2}{a}} \sin\left(\frac{n\pi x}{a}\right) \qquad \alpha_n = \left(\frac{n\pi}{a}\right)^2$$

$$\left[\frac{d^2}{dy^2} - \left(\frac{n\pi}{a}\right)^2\right] v_{n_i}(y) = 0$$

$$v_{n_1}(y) = \sinh\left(\frac{n\pi}{a} y\right) \qquad v_{n_2}(y) = \sinh\left(\frac{n\pi}{a}(b-y)\right)$$

$$K_n = \frac{n\pi}{a} \sinh\left(\frac{n\pi b}{a}\right)$$

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 22

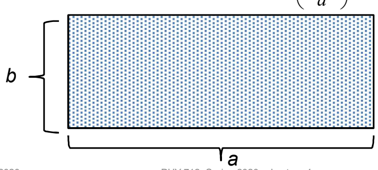
22

Green's function construction -- continued

$$G(x,x',y,y') = \sum_n u_n(x) u_n(x') K_n v_{n_1}(y_<) v_{n_2}(y_>).$$

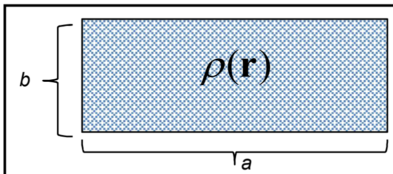
For example, a Green's function for a two-dimensional rectangular system with $0 \leq x \leq a$ and $0 \leq y \leq b$, which vanishes on the rectangular boundaries:

$$G(x,x',y,y') = 8 \sum_{n=1}^{\infty} \frac{\sin\left(\frac{n\pi x}{a}\right) \sin\left(\frac{n\pi x'}{a}\right) \sinh\left(\frac{n\pi y_<}{a}\right) \sinh\left(\frac{n\pi}{a}(b-y_>)\right)}{n \sinh\left(\frac{n\pi b}{a}\right)}.$$



1/22/2020 PHY 712 Spring 2020 -- Lecture 4 23

23



$$\Phi(\mathbf{r}) = \frac{1}{4\pi\varepsilon_0} \int_V d^3r' \rho(\mathbf{r}') G(\mathbf{r},\mathbf{r}') +$$

$$\frac{1}{4\pi} \int_S d^2r' \left[G(\mathbf{r},\mathbf{r}')\nabla'\Phi(\mathbf{r}') - \Phi(\mathbf{r}')\nabla' G(\mathbf{r},\mathbf{r}')\right] \cdot \hat{\mathbf{r}}'.$$

=0

$$G(x,x',y,y') = 8 \sum_{n=1}^{\infty} \frac{\sin\left(\frac{n\pi x}{a}\right) \sin\left(\frac{n\pi x'}{a}\right) \sinh\left(\frac{n\pi y_<}{a}\right) \sinh\left(\frac{n\pi}{a}(b-y_>)\right)}{n \sinh\left(\frac{n\pi b}{a}\right)}.$$

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 24

24

$$G(x,x',y,y') = 8\sum_{n=1}^{\infty} \frac{\sin\left(\frac{n\pi x}{a}\right)\sin\left(\frac{n\pi x'}{a}\right)\sinh\left(\frac{n\pi y_<}{a}\right)\sinh\left(\frac{n\pi}{a}(b-y_>)\right)}{n\sinh\left(\frac{n\pi b}{a}\right)}.$$

Example: $\rho(x,y) = \rho_0 \sin\left(\frac{\pi x}{a}\right)\sin\left(\frac{\pi y}{b}\right)$

$$\Phi(\mathbf{r}) = \frac{1}{4\pi\varepsilon_0}\int_V d^3r' \rho(\mathbf{r}')G(\mathbf{r},\mathbf{r}')$$

In this example, only n=1 contributes because

$$\int_0^a dx' \sin\left(\frac{\pi x'}{a}\right)\sin\left(\frac{n\pi x'}{a}\right) = \frac{a}{2}\delta_{1n}$$

$$\Phi(x,y) = \frac{8\rho_0}{4\pi\epsilon_0}\frac{a}{2\sinh(\pi a/b)}\sin\left(\frac{\pi x}{a}\right)\times$$

$$\left(\sinh\left(\frac{\pi(b-y)}{a}\right)\int_0^y dy' \sin\left(\frac{\pi y'}{b}\right)\sinh\left(\frac{\pi y'}{a}\right) + \sinh\left(\frac{\pi y}{a}\right)\int_y^b dy' \sin\left(\frac{\pi y'}{b}\right)\sinh\left(\frac{\pi(b-y')}{a}\right)\right)$$

When the dust clears: $\Phi(x,y) = \frac{\rho_0}{\epsilon_0}\frac{a^2b^2}{\pi^2(a^2+b^2)}\sin\left(\frac{\pi x}{a}\right)\sin\left(\frac{\pi y}{b}\right)$

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 25

25

A useful theorem for electrostatics
The mean value theorem (Problem 1.10 in Jackson)

The "mean value theorem" value theorem (problem 1.10 of your textbook) states that the value of $\Phi(\mathbf{r})$ at the arbitrary (charge-free) point $\mathbf{r}$ is equal to the average of $\Phi(\mathbf{r}')$ over the surface of any sphere centered on the point $\mathbf{r}$ (see Jackson problem #1.10). One way to prove this theorem is the following. Consider a point $\mathbf{r}' = \mathbf{r} + \mathbf{u}$, where $\mathbf{u}$ will describe a sphere of radius R about the fixed point $\mathbf{r}$. We can make a Taylor series expansion of the electrostatic potential $\Phi(\mathbf{r}')$ about the fixed point $\mathbf{r}$:

$$\Phi(\mathbf{r}+\mathbf{u}) = \Phi(\mathbf{r}) + \mathbf{u}\cdot\nabla\Phi(\mathbf{r}) + \frac{1}{2!}(\mathbf{u}\cdot\nabla)^2\Phi(\mathbf{r}) + \frac{1}{3!}(\mathbf{u}\cdot\nabla)^3\Phi(\mathbf{r}) + \frac{1}{4!}(\mathbf{u}\cdot\nabla)^4\Phi(\mathbf{r}) + \cdots. \quad (1)$$

According to the premise of the theorem, we want to integrate both sides of the equation 1 over a sphere of radius R in the variable $\mathbf{u}$:

$$\int_{\text{sphere}} dS_u = R^2\int_0^{2\pi} d\phi_u \int_{-1}^{+1} d\cos(\theta_u). \quad (2)$$

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 26

26

Mean value theorem – continued

We note that

$$R^2\int_0^{2\pi} d\phi_u \int_{-1}^{+1} d\cos(\theta_u) 1 = 4\pi R^2,$$

$$R^2\int_0^{2\pi} d\phi_u \int_{-1}^{+1} d\cos(\theta_u)\mathbf{u}\cdot\nabla = 0,$$

$$R^2\int_0^{2\pi} d\phi_u \int_{-1}^{+1} d\cos(\theta_u)(\mathbf{u}\cdot\nabla)^2 = \frac{4\pi R^4}{3}\nabla^2,$$

$$R^2\int_0^{2\pi} d\phi_u \int_{-1}^{+1} d\cos(\theta_u)(\mathbf{u}\cdot\nabla)^3 = 0,$$

and

$$R^2\int_0^{2\pi} d\phi_u \int_{-1}^{+1} d\cos(\theta_u)(\mathbf{u}\cdot\nabla)^4 = \frac{4\pi R^6}{5}\nabla^4.$$

Since $\nabla^2\Phi(\mathbf{r}) = 0$, the only non-zero term of the average is thus the first term:

$$R^2\int_0^{2\pi} d\phi_u \int_{-1}^{+1} d\cos(\theta_u)\Phi(\mathbf{r}+\mathbf{u}) = 4\pi R^2\Phi(\mathbf{r}),$$

or

$$\Phi(\mathbf{r}) = \frac{1}{4\pi R^2}\, R^2\int_0^{2\pi} d\phi_u \int_{-1}^{+1} d\cos(\theta_u)\Phi(\mathbf{r}+\mathbf{u}) \equiv \frac{1}{4\pi R^2}\int_{\text{sphere}} dS_u\Phi(\mathbf{r}+\mathbf{u}).$$

Since this result is independent of the radius R, we see that we have the theorem.

1/22/2020 PHY 712 Spring 2020 -- Lecture 4 27

27

Summary: Mean value theorem

$$\Phi(\mathbf{r}) = \frac{1}{4\pi R^2} \int R^2 d\Omega_u \ \Phi(\mathbf{r}+\mathbf{u})$$