

# PHYS 301 Notes

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## Midterm 1

### Calculus Review

#### Spherical Coordinates:

Sometimes, spherical coordinates are easier to work with than cartesian coordinates. When using spherical coordinates, there are some key things to note:

1. The coordinates themselves::  
 $\phi$ : Equatorial Azimuth  $[0, 2\pi]$  (from the “ $x$ ” axis)  
 $\theta$ : Axial Azimuth  $[0, \pi]$  (from the “ $z$ ” axis)  
 $r$ : Radial Distance

2. The infinitesimal displacement is different:

$$d\vec{l} = dr \hat{r} + r d\theta \hat{\theta} + r \sin \theta d\phi \hat{\phi}$$

3. The volume element is different:

$$d\tau = r^2 \sin \theta dr d\theta d\phi$$

Cylindrical Coordinates:: See textbook, this would be too redundant.

#### Rules for Irrotational Fields/Conservative Fields:

1.  $\vec{\nabla} \times \vec{F} = \vec{0}$  everywhere.
2.  $\int_a^b \vec{F} \cdot d\vec{l}$  is independent of path, for any given end points.
3.  $\oint \vec{F} \cdot d\vec{l} = 0$  for any closed loop.
4.  $\vec{F}$  is the gradient of some scalar function:  $\vec{F} = -\nabla V$ .

It is important to note that since  $\vec{E} = -\nabla V$ , then all electrostatic fields are irrotational.

#### Rules for Divergence-less fields.:

1.  $\vec{\nabla} \cdot \vec{F} = 0$  everywhere.
2.  $\int \vec{F} \cdot d\vec{a}$  is independent of surface, for any given boundary line.
3.  $\oint \vec{F} \cdot d\vec{a} = 0$  for any closed surface.
4.  $\vec{F}$  is the curl of some vector function.

Taylor Expansions: Often, it is difficult to obtain limits for when one quantity gets significantly larger than another in equations describing fields or potentials. Thus, the Taylor Expansion is helpful for this. Take for example a quantity  $a$  and a quantity  $b$ . For  $b \gg a$ , it is useful to try to bring the equation into a form such that  $\left(\frac{a}{b}\right)^n, n \in \mathbb{N}$ . Since  $b \gg a$ , then we can say that  $\frac{a}{b} \approx 0$ . Thus, a Taylor series centered around  $x = 0$  is obtained, which can be evaluated with the expression:

$$f(x) \approx f(0) + f'(0) \cdot x + f''(0) \cdot \frac{x^2}{2} + \cdots + \frac{f^{(n)}(0) x^n}{n!}$$

Generally, it is best practice to evaluate the Taylor series up until the degree of the largest polynomial in the original function.

## Electric Fields

It is important to recognize the notation in the Griffith's textbook, which is used primarily for this course when working with Fields and directions:

$\vec{r}$ : distance from the origin to a "field point".

$\vec{r}'$ : distance from the origin to the charge

$\vec{r}_{\text{sep}}$ : distance from the charge to the "field point"

Thus, it is given that  $\vec{r}_{\text{sep}} = \vec{r} - \vec{r}'$ .

Now, while working with Coulomb's law, we can define the electric field due to a point charge to be:

$$\vec{E} = \frac{1}{4\pi\epsilon_0} \frac{q}{||\vec{r}_{\text{sep}}||^2} \vec{r}_{\text{sep}}$$

Types of Field Integrations: There exist three main types of field integrations:

<u>Line Charge</u>	<u>Surface Charge</u>	<u>Volume Charge</u>
$\vec{E}(\vec{r}) = \frac{1}{4\pi\epsilon_0} \int \frac{\lambda(\vec{r}')}{  \vec{r}_{\text{sep}}  ^2} \vec{r}_{\text{sep}} dl'$	$\vec{E}(\vec{r}) = \frac{1}{4\pi\epsilon_0} \int \frac{\sigma(\vec{r}')}{  \vec{r}_{\text{sep}}  ^2} \vec{r}_{\text{sep}} da'$	$\vec{E}(\vec{r}) = \frac{1}{4\pi\epsilon_0} \int \frac{\rho(\vec{r}')}{  \vec{r}_{\text{sep}}  ^2} \vec{r}_{\text{sep}} d\tau'$

Gauss's Law: Gauss's law is as follows:

$$\oint \vec{E} \cdot d\vec{a} = \frac{Q_{\text{encl}}}{\epsilon_0} \qquad \vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

By knowing the geometry and symmetry of a situation however, Gauss's law can require no integration whatsoever. This is when we know that field is the same for every point on a surface.

## Electric Potential

The potential of a point in a field relative to another is defined as:

$$V(\vec{r}) \equiv - \int_{\mathcal{O}}^{\vec{r}} \vec{E} \cdot d\vec{l}$$

Which is often referred to as the potential difference between two points:

$$V(\vec{b}) - V(\vec{a}) = - \int_{\vec{a}}^{\vec{b}} \vec{E} \cdot d\vec{l}$$

It is also to be noted the relation between field and potential:

$$\vec{E} = -\nabla V$$

Remark: it is important to note that unlike electric field, electric potential is a scalar. It has no direction, and should be handled accordingly.

Potential can also be obtained for a volume charge:

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0} \int \frac{\rho(\vec{r}')}{||\vec{r}_{\text{sep}}||} d\tau'$$

Similar formulae can be extrapolated for line and surface charge distributions, analogous to those for electric fields.

However, the formula for point charges is important to note:

$$V(\vec{r}) = \frac{1}{4\pi\epsilon_0} \sum_{i=0}^n \frac{q_i}{||\vec{r}_{\text{sep}}||}$$

## Work and Energy in Electrostatics

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To calculate the work that it takes to get from one point to another in a field, we can use a work integral. We can also employ the potential difference.

$$W = \int_{\mathbf{a}}^{\mathbf{b}} \vec{F} \cdot d\vec{l} = -Q \int_{\mathbf{a}}^{\mathbf{b}} \vec{E} \cdot d\vec{l} = Q[V(\vec{b}) - V(\vec{a})]$$

It is important to note that for the second form of this integral uses **negative**  $Q$ , not positive. This is because the integral by default describes the amount of work that the field does, not the work that is required. One can use a positive value of  $Q$  if trying to find out how much work the field does.

It is also to be noted that the potential of a system is the work that is required to create the system per unit charge.

Work and Point Charges: We can also describe the amount of work that it takes to assemble a collection of point charges:

$$W = \frac{1}{2} \sum_{i=1}^n q_i V(\vec{r}_i)$$

Work of a Continuous Charge Distribution: To describe the amount of energy that a charge distribution has, or the amount of energy required to create it in empty space, the following formula can be used:

$$W = \frac{\epsilon_0}{2} \int_{\text{all space}} E^2 d\tau$$

## Boundary Conditions

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One of the important equations in the relationships between  $\rho$ ,  $V$ , and  $E$  is  $\nabla^2 V = -\frac{\rho}{\epsilon_0}$ . However, this equation often leaves one with a number of undetermined coefficients from the integration. Thus, it is important to investigate the boundary conditions of fields and potentials.

From this, a set of important boundary conditions emerges for a boundary at  $a$ .

- Continuity of Potential: Since  $\nabla V = -\vec{E}$ , it is known that potential should be continuous along all space. Thus,

$$V_{\text{above}}(a) = V_{\text{below}}(a)$$

- Preservation of Field: For any field interacting with a surface charge, by Gauss's law, it is known that the difference between the field above and the field below is simply the surface charge density over the permittivity of free space:

$$\vec{E}_{\text{above}} - \vec{E}_{\text{below}} = \frac{\sigma}{\epsilon_0} \hat{n}$$

Where  $\hat{n}$  is the normal vector of the boundary surface. The presence of the normal vector is important, because it requires the boundary surface to have symmetry with the field above and the field below.

- Bounding of Potential (not general): Since it is known that potential should generally be bounded over all space (except in some cases), it is appropriate to say that

$$V(0) \text{ is bounded.}$$

This is generally more true for configurations with spherical symmetry.

- Zero Potential at Infinity (not general): For many spherically-symmetric examples, it is known that the potential at infinity is zero. Thus, it can be said that:

$$V(\infty) = 0.$$

## Uniqueness of Solutions

Given the relationship  $\nabla^2 V = -\frac{\rho}{\epsilon_0}$ , there exists the case that  $\rho = 0$ , for which a distinct set of attributes arise:

1.  $V$  has no local maxima nor minima inside. The maxima and minima are located on the surrounding boundaries.
2.  $V$  is smooth and continuous, everywhere.
3.  $V(\vec{r})$  is the average of  $V$  over surface of any surrounding sphere:  $V(\vec{r}) = \frac{1}{4\pi R^2} \oint V dA$ .
4.  $V$  is unique, as the solution of the Laplace equation is uniquely determined if  $V$  is specified on the boundary surface around the volume.

Earnshaw's Theorem: As a sidenote, is important to note Earnshaw's Theorem, which states that:

A charged particle cannot be held in a stable equilibrium by electrostatic forces alone.

This can be analyzed using divergence amongst other methods of analysis.

## Conductors

At a base level, conductors are materials in which electrons are free to move inside of the material. Because of this, [ideal] conductors are able to rearrange their charges, allowing them to have special properties:

1.  $\vec{E} = 0$  inside a conductor. In short, charges move to oppose any external  $\vec{E}$  fields. This can also be interpreted under the principle that if there was any field inside a conductor, the free electrons would be moving, and hence not *electrostatic*.
2. Any net charges reside on the surface of a conductor.
3.  $\rho = 0$  inside a conductor. Since there is no field inside a conductor, Gauss's law requires that there is no enclosed charge, thus, there is no charge density. One may make the argument for the surface charges, however, since they are equal in magnitude, they cancel.
4. A conductor is an equipotential. Since there is no field inside a conductor, given the relationship  $\nabla V = -\vec{E}$ , the potential  $V$  must be a constant.
5.  $\vec{E}$  is normal to the surface of a conductor. This is because any non-normal direction of field would result in fields inside the conductor. (Unsure of this)

## Capacitance

As a purely geometrical property, we can define **capacitance** as the ratio of charge to voltage. Thus, it is defined as:

$$C \equiv \frac{Q}{V}.$$

As a practical device, capacitors are capable of storing energy. Thus, it is important to define the amount of energy that a capacitor can store for a given charge  $Q$  and capacitance  $C$ :

$$W = \int_0^Q \left( \frac{q}{C} \right) dq = \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} C V^2$$