Lecture 1

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Topics:

- How is this course organized?
- Brief math recap
- Introduction to Electrostatics

1

Objective

- Both integral and differential formulation of E&M
- Goal: look at Maxwell's equations

Generalized Forms of Maxwell's Equations

Differential Form	Integral Form	Remarks
$\nabla \cdot \mathbf{D} = \rho_v$	$\oint_S \mathbf{D} \cdot d\mathbf{S} = \int_v \rho_v \, dv$	Gauss's law
$\nabla \cdot \mathbf{B} = 0$	$\oint_S \mathbf{B} \cdot d\mathbf{S} = 0$	Nonexistence of isolated magnetic charge*
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint_L \mathbf{E} \cdot d\mathbf{l} = -\frac{\partial}{\partial t} \int_S \mathbf{B} \cdot d\mathbf{S}$	Faraday's law
$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$	$\oint_L \mathbf{H} \cdot d\mathbf{l} = \int_S \left(\mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}\right) \cdot d\mathbf{S}$	Ampere's circuit law

*This is also referred to as Gauss's law for magnetic fields.

… and be able to tell what they really mean!

2

Textbook

Engineering Electromagnetics, William H. Hayt

- ❑ **ADVANTAGE:**

Good physical concept description and enough examples and problems

David K. Cheng, "Field and wave electromagnetic"

Engineering Electromagnetics U.A Bakshi

- ❑ **ADVANTAGE:**

Lots of examples and solved problems

3

Home works

- How to solve the Home works?

1. Try to solve them by yourself first
2. Discuss problems with friends and study group
3. Write your own solution

4

Grades

- Exams 35% (two scheduled exams)
- Quizzes, Homework and attendance 5%
- Final Exam 60%
- Total 100%

More info on Quizzes and 5%:

4 Quizzes during a year each 1 degree.

Ask Questions…

- Come and talk to me if you have problems or questions:

➢ I attended class and sections and read the book but I still don’t understand concept xyz and …

➢ I cant understand the concept of gausses law

➢ general questions and help

Some Basic concepts

- Vector Analysis
- Coordinate systems
- Derivative
- Gradient of scalar fields
- Divergence of vector fields
- Curl of vector fields

7

VECTOR ANALYSIS – Vector Algebra

- ***Scalar and Vector Quantities***
- A *scalar is a quantity having only magnitude.*

Examples: voltage, current, charge, energy, temperature

- A *vector is a quantity having direction in addition* to magnitude.

Examples: velocity, acceleration, force

8

Unit Vectors

- We can write a real-valued vector as:

$$\overline{A} = \hat{a}_A A$$

where:

$$A = \left|\overline{A}\right| = \text{magnitude of the vector } \overline{A}$$

$$\hat{a}_A = \frac{\overline{A}}{\left|\overline{A}\right|} = \text{(dimensionless) unit vector in the direction of } \overline{A}$$

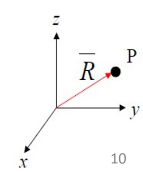
Two vectors are said to be equal if (and only if) they have the same magnitude and direction.

9

Vector's (Cont'd)

- ***Vector Addition***
- ***Vector Subtraction***
- ***Rules of Vector Addition***
- ***Product of a Scalar and a Vector***
- ***Position Vector:***

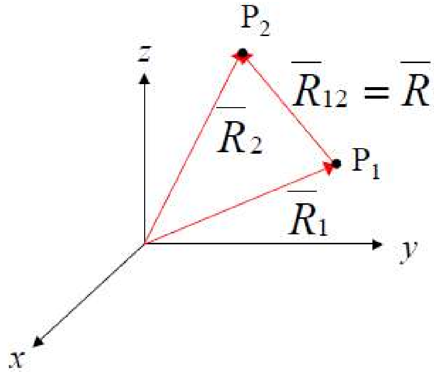
The ***position vector of a point in space is the*** directed distance from the origin to that point.



10

Distance Vector

- The ***distance vector is the directed distance from*** one point in space to another.



$$\overline{R}_{12} = \overline{R}_2 - \overline{R}_1$$

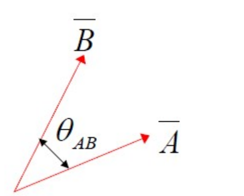
The distance between the points is the magnitude of the distance vector!

11

Vector Multiplication: Scalar (Dot) Product

- The ***scalar (dot) product of two vectors is a scalar*** that is denoted by $A \bullet B$

$$\overline{A} \bullet \overline{B} \equiv AB\cos\theta_{AB}$$



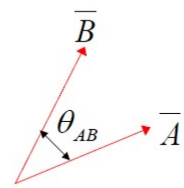
Note that $\overline{A} \bullet \overline{A} = A^2$

θ_{AB} is the smaller of the two angles between $\overline{A}$ and $\overline{B}$, i.e., $0 \le \theta_{AB} \le \pi$.

12

Vector Multiplication: Vector (Cross) Product

- The *vector (cross) product of two vectors is a* vector that is denoted by ***A× B***



$$\overline{A}\times\overline{B}\equiv\hat{a}_n AB\sin\theta_{AB}$$

unit vector in the direction determined by the right - hand rule (and thus perpendicular to the plane containing $\overline{A}$ and $\overline{B}$).

θ_{AB} is the smaller of the two angles between $\overline{A}$ and $\overline{B}$, i.e., $0\le\theta_{AB}\le\pi$.

Some Rules in Vector Products

$$\overline{A}\bullet\overline{B}=\overline{B}\bullet\overline{A}$$

$$\overline{A}\bullet\left(\overline{B}+\overline{C}\right)=\overline{A}\bullet\overline{B}+\overline{A}\bullet\overline{C}$$

$$\overline{A}\times\left(\overline{B}+\overline{C}\right)=\overline{A}\times\overline{B}+\overline{A}\times\overline{C}$$

$$\overline{B}\times\overline{A}=-\overline{A}\times\overline{B}$$

$$\overline{A}\times\left(\overline{B}\times\overline{C}\right)\neq\left(\overline{A}\times\overline{B}\right)\times\overline{C}$$

$$\overline{A}\bullet\left(\overline{B}\times\overline{C}\right)=\overline{B}\bullet\left(\overline{C}\times\overline{A}\right)=\overline{C}\bullet\left(\overline{A}\times\overline{B}\right)$$

$$\overline{A}\times\left(\overline{B}\times\overline{C}\right)=\overline{B}\left(\overline{A}\bullet\overline{C}\right)-\overline{C}\left(\overline{A}\bullet\overline{B}\right)$$

ORTHOGONAL COORDINATE SYSTEMS

Why do we need coordinate systems:

- The laws of electromagnetics (like all the laws of physics) are independent of a particular coordinate system.
- However, application of these laws to the solution of a particular problem imposes the need to use a suitable coordinate system.
- It is the shape of the boundary of the problem that determines the most suitable coordinate system to use in its solution.

15

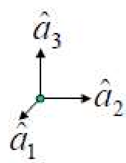
Orthogonal Right-Handed Coordinate Systems

- A ***coordinate system defines a set of three*** reference directions at each and every point in space.
- The ***origin of the coordinate system is the*** reference point relative to which we locate every other point in space.
- A ***position vector defines the position of a point in*** space relative to the origin.
- These three reference directions are referred to as ***coordinate directions, and are usually taken to be*** mutually perpendicular (*orthogonal).*

16

- Unit vectors along the coordinate direction are referred to as ***base vectors.***
- In any of the orthogonal coordinate systems, an arbitrary vector can be expressed in term of a superposition of the three base vectors.
- Consider base vectors such that

$$\hat{a}_1 \times \hat{a}_2 = \hat{a}_3$$
$$\hat{a}_2 \times \hat{a}_3 = \hat{a}_1$$
$$\hat{a}_3 \times \hat{a}_1 = \hat{a}_2$$



17

Three coordinate Systems:

- There are three orthogonal right-handed coordinate systems:

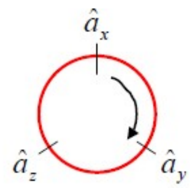
  – Cartesian (x, y, z)
  – cylindrical (r, ϕ, z)
  – spherical (R, θ, ϕ)

18

Cartesian Coordinates

- The point *$P(x_1,y_1,z_1)$ is located as the intersection* of three mutually perpendicular planes: $x=x_1$, $y=y_1$, $z=z_1$.
- The base vectors are $\hat{a}_x$, $\hat{a}_y$, $\hat{a}_z$
- The base vectors satisfy the following relations:

$$\hat{a}_x \times \hat{a}_y = \hat{a}_z$$
$$\hat{a}_y \times \hat{a}_z = \hat{a}_x$$
$$\hat{a}_z \times \hat{a}_x = \hat{a}_y$$



19

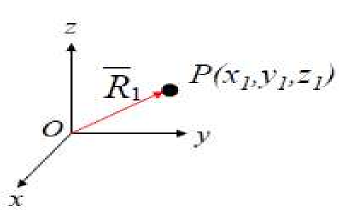
Cartesian Coordinates (Cont'd)

- Also:

$$\hat{a}_x \bullet \hat{a}_x = 1, \quad \hat{a}_x \bullet \hat{a}_y = \hat{a}_x \bullet \hat{a}_z = 0$$
$$\hat{a}_y \bullet \hat{a}_y = 1, \quad \hat{a}_y \bullet \hat{a}_x = \hat{a}_y \bullet \hat{a}_z = 0$$
$$\hat{a}_z \bullet \hat{a}_z = 1, \quad \hat{a}_z \bullet \hat{a}_x = \hat{a}_z \bullet \hat{a}_y = 0$$

The position vector to the point $P(x_1,y_1,z_1)$ is given by

$$\overline{R}_1 = \hat{a}_x x_1 + \hat{a}_y y_1 + \hat{a}_z z_1$$



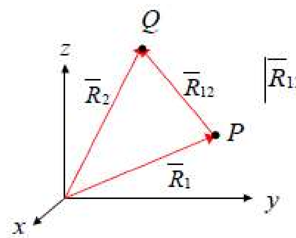
20

Cartesian Coordinates (Cont'd)

- Distance Vector:

The distance vector to the point $Q(x_2,y_2,z_2)$ from the point $P(x_1,y_1,z_1)$ is given by

$$\overline{R}_{12} = \overline{R}_2 - \overline{R}_1$$
$$= \hat{a}_x(x_2 - x_1) + \hat{a}_y(y_2 - y_1) + \hat{a}_z(z_2 - z_1)$$



$$\left|\overline{R}_{12}\right| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

21

Cartesian Coordinates (Cont'd)

- Consider an arbitrary vector in Cartesian coordina

$$\overline{A} = \hat{a}_x A_x + \hat{a}_y A_y + \hat{a}_z A_z$$

$$\boxed{\begin{aligned} A_x &= \hat{a}_x \bullet \overline{A} \\ A_y &= \hat{a}_y \bullet \overline{A} \\ A_z &= \hat{a}_z \bullet \overline{A} \end{aligned}}$$

- Consider another arbitrary vector:tes:

$$\overline{B} = \hat{a}_x B_x + \hat{a}_y B_y + \hat{a}_z B_z$$

22

Cartesian Coordinates (Cont'd)

- Dot and cross product in Cartesian coordinate:
  - Scalar (dot) product:

$$\overline{A} \bullet \overline{B} = A_x B_x + A_y B_y + A_z B_z$$

  - Vector (cross) product:

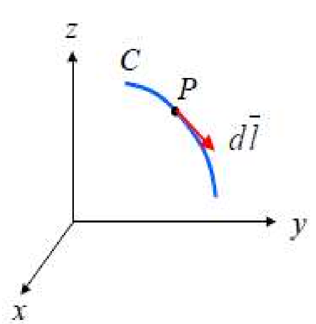
$$\overline{A} \times \overline{B} = \begin{vmatrix} \hat{a}_x & \hat{a}_y & \hat{a}_z \\ A_x & A_y & A_z \\ B_x & B_y & B_z \end{vmatrix}$$
$$= \hat{a}_x \left(A_y B_z - A_z B_y \right) + \hat{a}_y \left(A_z B_x - A_x B_z \right)$$
$$+ \hat{a}_z \left(A_x B_y - A_y B_x \right)$$

23

Cartesian Coordinates (Cont'd)

- The ***differential length vector*** is the distance vector from the point *P(x,y,z)* to the adjacent point *Q(x+dx,y+dy,z+dz)*.

$$d\overline{l} = \hat{a}_x dx + \hat{a}_y dy + \hat{a}_z dz$$

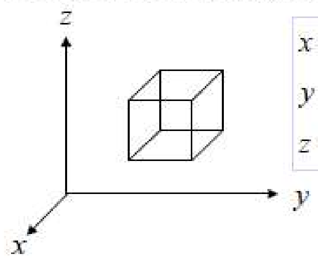


Note that the differential lengths *dx*, *dy* and *dz* are not independent but depend on the specific path along which *P* and *Q* lie.

24

Cartesian Coordinates (Cont'd)

- A *differential surface vector* at a point on a coordinate equal to a constant surface is defined as the cross product of the differential length vectors in the other two coordinate directions with the order of the vectors chosen such that the differential surface vector points in the direction of increasing coordinate.



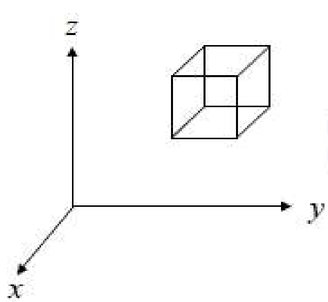
$$x = \text{constant}, \quad d\overline{S} = \hat{a}_y dy \times \hat{a}_z dz = \hat{a}_x\, dy\, dz$$

$$y = \text{constant}, \quad d\overline{S} = \hat{a}_z dz \times \hat{a}_x dx = \hat{a}_y\, dx\, dz$$

$$z = \text{constant}, \quad d\overline{S} = \hat{a}_x dx \times \hat{a}_y dy = \hat{a}_z\, dx\, dy$$

Cartesian Coordinates (Cont'd)

- The *differential volume element* at a point within a region is defined as the scalar triple product of the differential length changes in each of the three coordinate directions with the order of the vectors chosen such that the differential volume element is positive.



$$dV = \hat{a}_x dx \bullet \left(\hat{a}_y dy \times \hat{a}_z dz\right) = dx\, dy\, dz$$

Cylindrical Coordinates

- The point $P(r_1, \phi_1, z_1)$ is located as the intersection of three mutually perpendicular surfaces: $r=r_1$ (a circular cylinder), $\phi=\phi_1$ (a half-plane containing the z-axis), $z=z_1$ (a plane).
- The base vectors are $\hat{a}_r, \hat{a}_\phi, \hat{a}_z$

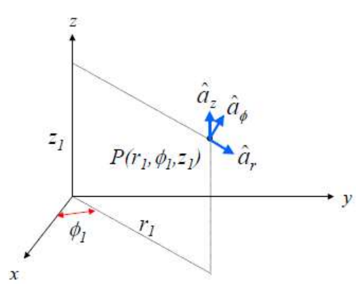
  $\hat{a}_r$ is a unit vector in the direction of increasing r

  $\hat{a}_\phi$ is a unit vector in the direction of increasing ϕ

  $\hat{a}_z$ is a unit vector in the direction of increasing z

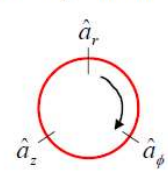
27

Cylindrical Coordinates (Cont'd)



- The base vectors satisfy the following relations:

$$\hat{a}_r \times \hat{a}_\phi = \hat{a}_z$$
$$\hat{a}_\phi \times \hat{a}_z = \hat{a}_r$$
$$\hat{a}_z \times \hat{a}_r = \hat{a}_\phi$$

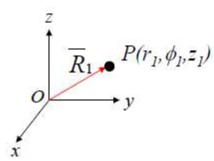


28

Cylindrical Coordinates (Cont'd)

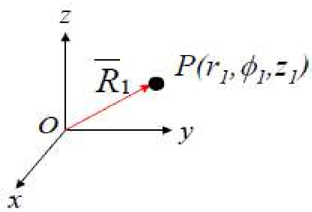
- In contrast to Cartesian coordinates, the base vectors in cylindrical coordinates are functions of position.
- Specifically, th
  depend on the
  - The positi ven
    by $\overline{R}_1$

- The position vector to the point $P(r_1,\phi_1,z_1)$ is given by $\overline{R}_1 = \hat{a}_r r_1 + \hat{a}_z z_1$



Note that the position vector has no component in the ϕ-direction. The dependence of the position vector on ϕ_1 is implicit in $\hat{a}_r$

on



vector has no component in the ϕ-direction. The dependence of the position vector on ϕ_1 is implicit in $\hat{a}_r$

29

Cylindrical Coordinates (Cont'd)

- Consider an arbitrary vector in cylindrical coordinates:

$$\overline{A} = \hat{a}_r A_r + \hat{a}_\phi A_\phi + \hat{a}_z A_z$$

$$A_r = \hat{a}_r \bullet \overline{A}$$
$$A_\phi = \hat{a}_\phi \bullet \overline{A}$$
$$A_z = \hat{a}_z \bullet \overline{A}$$

- Consider another arbitrary vector:

$$\overline{B} = \hat{a}_r B_r + \hat{a}_\phi B_\phi + \hat{a}_z B_z$$

30

Cylindrical Coordinates (Cont'd)

- Scalar (dot) product:

$$\overline{A} \bullet \overline{B} = A_r B_r + A_\phi B_\phi + A_z B_z$$

- Vector (cross) product:

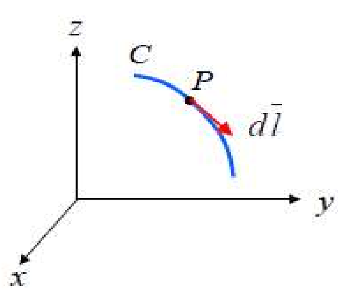
$$\overline{A} \times \overline{B} = \begin{vmatrix} \hat{a}_r & \hat{a}_\phi & \hat{a}_z \\ A_r & A_\phi & A_z \\ B_r & B_\phi & B_z \end{vmatrix}$$
$$= \hat{a}_r \left(A_\phi B_z - A_z B_\phi \right) + \hat{a}_\phi \left(A_z B_r - A_r B_z \right)$$
$$+ \hat{a}_z \left(A_r B_\phi - A_\phi B_r \right)$$

31

Cylindrical Coordinates (Cont'd)

- The ***differential length vector*** is the distance vector from the point $P(r,\phi,z)$ to the adjacent point $Q(r+dr,\phi+d\phi,z+dz)$.

$$d\overline{l} = \hat{a}_r dr + \hat{a}_\phi r d\phi + \hat{a}_z dz$$



Note that the differential lengths $d\phi$, $d\phi$ and dz are not independent but depend on the specific path along which P and Q lie.

32

Cylindrical Coordinates (Cont'd)

differential surface vector

$$r = \text{constant}, \quad d\overline{S} = \hat{a}_\phi r d\phi \times \hat{a}_z dz = \hat{a}_r \, r d\phi \, dz$$
$$\phi = \text{constant}, \quad d\overline{S} = \hat{a}_z dz \times \hat{a}_r dr = \hat{a}_\phi \, dr \, dz$$
$$z = \text{constant}, \quad d\overline{S} = \hat{a}_r dr \times \hat{a}_\phi r d\phi = \hat{a}_z \, r dr \, d\phi$$

differential volume element

$$dV = \hat{a}_r dr \bullet \left(\hat{a}_\phi r d\phi \times \hat{a}_z dz\right) = r dr \, d\phi \, dz$$

33

Relationships Between Cylindrical and Rectangular Coordinates

$$x = r\cos\phi \qquad r = \sqrt{x^2 + y^2}$$
$$y = r\sin\phi \qquad \phi = \arctan\left(\frac{y}{x}\right)$$
$$\hat{a}_r = \hat{a}_x \cos\phi + \hat{a}_y \sin\phi \qquad \hat{a}_x = \hat{a}_r \cos\phi - \hat{a}_\phi \sin\phi$$
$$\hat{a}_\phi = -\hat{a}_x \sin\phi + \hat{a}_y \cos\phi \qquad \hat{a}_y = \hat{a}_r \sin\phi + \hat{a}_\phi \cos\phi$$

34

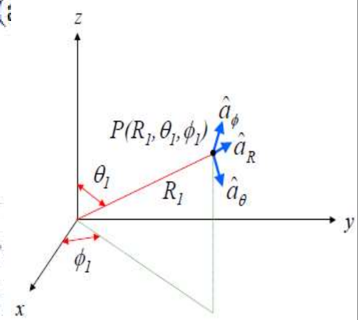
Spherical Coordinates

- The point $P(R_1, \theta_1, \phi_1)$ is located as the intersection of three mutually perpendicular surfaces: $R=R_1$ (a sphere), $\theta=\theta_1$ (a cone), and $\phi=\phi_1$ (a half-plane containing the z-axis).
- The base vectors are $\hat{a}_R, \hat{a}_\theta, \hat{a}_\phi$

  $\hat{a}_R$ is a unit vector in the direction of increasing r

  $\hat{a}_\theta$ is a unit vector in the direction of increasing θ

  $\hat{a}_\phi$ is a unit vector in the direction of increasing ϕ



35

Spherical Coordinates (Cont'd)

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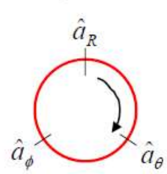
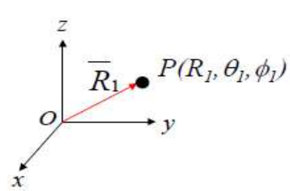
The base vectors satisfy the following relations:

$$\hat{a}_R \times \hat{a}_\theta = \hat{a}_\phi$$
$$\hat{a}_\theta \times \hat{a}_\phi = \hat{a}_R$$
$$\hat{a}_\phi \times \hat{a}_R = \hat{a}_\theta$$



The position vector to the point $P(R_1, \theta_1, \phi_1)$ is given by

$$\overline{R}_1 = \hat{a}_R R_1$$



Note that the position vector has no component in either the θ-direction or the ϕ-direction. The dependence of the position vector on θ_1 and ϕ_1 is implicit in $\hat{a}_R$

36

Consider an arbitrary vector in cylindrical coordinates:

$$\overline{A} = \hat{a}_R A_R + \hat{a}_\theta A_\theta + \hat{a}_\phi A_\phi$$

$$A_R = \hat{a}_R \bullet \overline{A}$$
$$A_\theta = \hat{a}_\theta \bullet \overline{A}$$
$$A_\phi = \hat{a}_\phi \bullet \overline{A}$$

Consider another arbitrary vector:

$$\overline{B} = \hat{a}_R B_R + \hat{a}_\theta B_\theta + \hat{a}_\phi B_\phi$$

Scalar (dot) product:

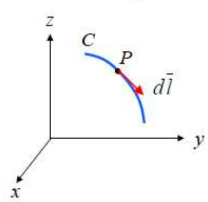
$$\overline{A} \bullet \overline{B} = A_R B_R + A_\theta B_\theta + A_\phi B_\phi$$

Vector (cross) product:

$$\overline{A} \times \overline{B} = \begin{vmatrix} \hat{a}_R & \hat{a}_\theta & \hat{a}_\phi \\ A_R & A_\theta & A_\phi \\ B_R & B_\theta & B_\phi \end{vmatrix}$$
$$= \hat{a}_R (A_\theta B_\phi - A_\phi B_\theta) + \hat{a}_\theta (A_\phi B_R - A_R B_\phi) + \hat{a}_\phi (A_R B_\theta - A_\theta B_R)$$

- The ***differential length vector*** is the distance vector from the point $P(R, \theta, \phi)$ to the adjacent point $Q(R+dR, \theta+d\theta, \phi+d\phi)$.

$$d\overline{l} = \hat{a}_R dR + \hat{a}_\theta R\, d\theta + \hat{a}_\phi R \sin\theta\, d\phi$$



Note that the differential lengths dR, $d\theta$ and $d\phi$ are not independent but depend on the specific path along which P and Q lie.

$$dl_R = \hat{a}_R \bullet d\overline{l} = dR$$
$$dl_\theta = \hat{a}_\theta \bullet d\overline{l} = R\, d\theta$$
$$dl_\phi = \hat{a}_\phi \bullet d\overline{l} = R \sin\theta\, d\phi$$

differential surface vector

$$R = \text{constant}, \quad d\overline{S} = \hat{a}_\theta R d\theta \times \hat{a}_\phi R \sin\theta \, d\phi = \hat{a}_R \, R^2 \sin\theta \, d\theta \, d\phi$$

$$\theta = \text{constant}, \quad d\overline{S} = \hat{a}_\phi R \sin\theta \, d\phi \times \hat{a}_R dR = \hat{a}_\theta \, R \sin\theta \, dR \, d\phi$$

$$\phi = \text{constant}, \quad d\overline{S} = \hat{a}_R dR \times \hat{a}_\phi R d\theta = \hat{a}_\phi \, R dR \, d\theta$$

differential surface vector

$$dV = \hat{a}_R dR \bullet \left(\hat{a}_\theta R d\theta \times \hat{a}_\phi R \sin\theta \, d\phi \right) = R^2 \sin\theta \, dR \, d\theta \, d\phi$$

39

Relationships Between Spherical and Rectangular Coordinates

$$x = R \sin\theta \cos\phi \qquad R = \sqrt{x^2 + y^2 + z^2}$$

$$y = R \sin\theta \sin\phi \qquad \theta = \arctan\left(\frac{\sqrt{x^2 + y^2}}{z} \right)$$

$$z = R \cos\theta \qquad \phi = \arctan\left(\frac{y}{x} \right)$$

$$\hat{a}_R = \hat{a}_x \sin\theta \cos\phi + \hat{a}_y \sin\theta \sin\phi + \hat{a}_z \cos\theta$$

$$\hat{a}_\theta = \hat{a}_x \cos\theta \cos\phi + \hat{a}_y \cos\theta \sin\phi - \hat{a}_z \sin\theta$$

$$\hat{a}_\phi = -\hat{a}_x \sin\phi + \hat{a}_y \cos\phi$$

$$\hat{a}_x = \hat{a}_R \sin\theta \cos\phi + \hat{a}_\theta \cos\theta \cos\phi - \hat{a}_\phi \sin\phi$$

$$\hat{a}_y = \hat{a}_R \sin\theta \sin\phi + \hat{a}_\theta \cos\theta \sin\phi + \hat{a}_\phi \cos\phi$$

$$\hat{a}_z = \hat{a}_R \cos\theta - \hat{a}_\theta \sin\theta$$

40

INTRODUCTION TO ELECTROMAGNETIC ENGINEERING

Fall 2014

Course Objective

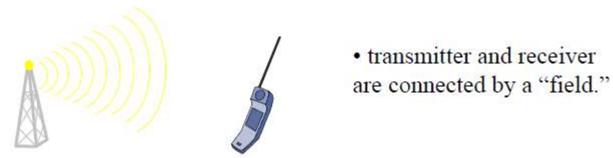
Students:

- Review vector calculus, complex numbers and circuit concepts.
- Understand the fundamentals of Electrostatics.
- Understand the fundamentals of Magnetostatics.
- Understand boundary value problems.
- Understand the characteristics of materials and their interactions with electric and magnetic fields.
- Understand Maxwell's equations.
- Understand electromagnetic wave concepts.
- Understand fundamental transmission line concepts.

Why is Electromagnetics Important?

Knowledge of electromagnetics is required to explain certain technologies:

Antenna



high speed/high density integrated circuits

Propagation delay

43

How to deal with Electromagnetic

- Electric and magnetic fields:
  - are three-dimensional
  - are vectors
  - vary in space as well as time
- Then:

– Solution of electromagnetics problems requires a high level of abstract thinking - it is not possible to solve them by finding the right formula in which to plug the numbers.

– Students must develop a deep physical understanding where math becomes a powerful tool rather than a crutch.

44

Definition of Electromagnetism?

- Electromagnetism is one of the four fundamental forces of physics.
- Electromagnetics is the study of the effect of charges at rest and charges in motion.
- The subject of electromagnetics may be divided into three branches:
  - electrostatics: charges at rest
  - magnetostatics: charges in steady motion (DC)
  - electrodynamics: charges in time-varying motion

45

SI (International System of) Units

Quantity	Unit	Abbreviation
length	meter	m
mass	kilogram	k
time	second	s
current	ampere	A
temperature	kelvin	K
luminous intensity	candela	cd

46

Fundamental Vector Field Quantities in Electromagnetics

- Electric field intensity $\left(\overline{E}\right)$
  units = volts per meter (V/m = kg m/A/s^3)
- Electric flux density (electric displacement) $\left(\overline{D}\right)$
  units = coulombs per square meter (C/m^2 = A s /m^2)
- Magnetic field intensity $\left(\overline{H}\right)$
  units = amps per meter (A/m)
- Magnetic flux density $\left(\overline{B}\right)$
  units = teslas = webers per square meter
  (T = Wb/ m^2 = kg/A/s^3)

47

Fundamental Vector Field Quantities in Electromagnetics (Cont'd)

- A ***field is a spatial distribution of a quantity; in*** general, it can be either *scalar or vector in nature.*
- When an event in one place has an effect on something at a different location, we talk about the events as being connected by a field.
- In general, the fundamental vector field quantities in electromagnetics are vector functions of both position (in three-dimensional space) and time.

48

Three Universal Constants

- the velocity of an electromagnetic wave (e.g., light) in free space (perfect vacuum)

$$c \approx 3 \times 10^8 \text{ m/s}$$

- the permeability of free space

$$\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$$

- the permittivity of free space

$$\varepsilon_0 \approx 8.854 \times 10^{-12} \text{ F/m}$$

49

Relationships Involving the Three Universal Constants

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

In free space:

$$\overline{B} = \mu_0 \overline{H}$$

$$\overline{D} = \varepsilon_0 \overline{E}$$

50