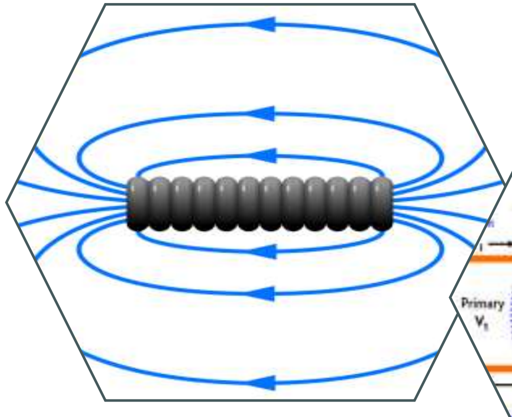

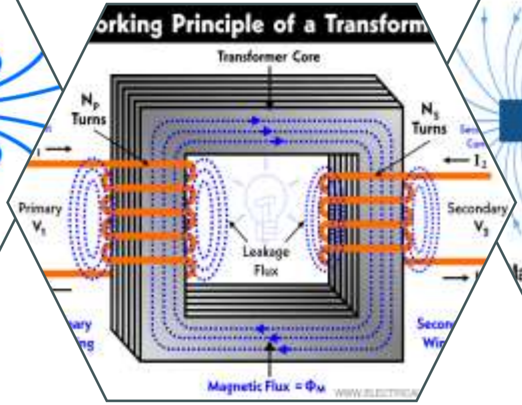

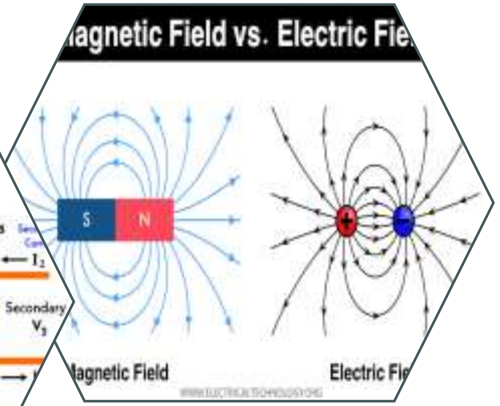

Electromagnetic Field & Waves

Prepared by :
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Basic Course Information

Course Title	Electromagnetic Field & Waves
Course Code	EEE 0714-2201
Credit	03
Marks	150

SYNOPSIS/RATIONALE

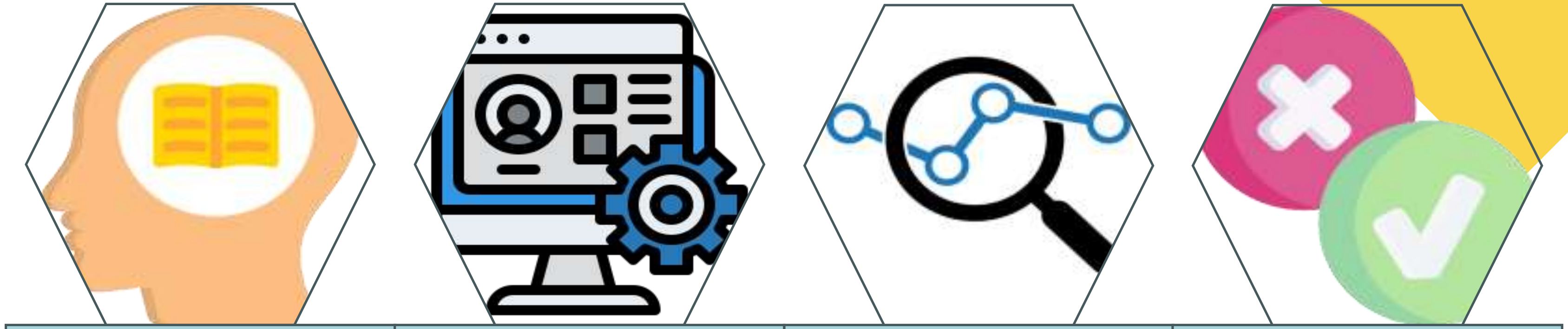
Electromagnetic fields and waves are manifested and manipulated in a vast number of natural and man-made systems. Applications that rely on the utilization of electromagnetic fields and waves include wireless communications, circuits, computer interconnects and peripherals, optical fiber links and components, microwave communications and radar, antennas, sensors, micro-electromechanical systems, motors, and power generation and transmission. The course covers the types and propagation of electromagnetic waves and their importance in electrical and telecommunications engineering.

OBJECTIVE

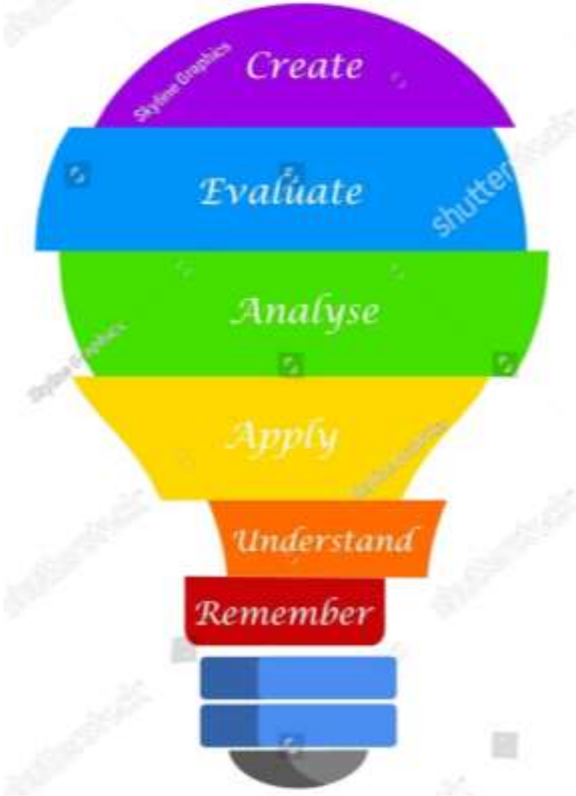
The objectives of the course are:

- Understand basic concepts of electromagnetic theory, principles of electromagnetic radiation, Electromagnetic boundary conditions and electromagnetic wave propagation.
- Understand how the motion of charges leads to radiation, and implications in equipment design.
- Demonstrate knowledge and understanding of electromagnetic fields in simple electronic/photonic configurations and apply electromagnetic theory to simple practical situations.
- Analyze interactions of electromagnetic waves with materials and interfaces
- Understand electric and magnetic properties of matter.
- Apply computational electromagnetics in engineering

Course Learning Outcome (CLO)



CLO-1:	CLO-2:	CLO-3:	CLO-4:
Explain basic law of electric and magnetic fields, properties of charge, electric and magnetic fields.	Execute performance analysis of diverse types of medium for wave propagation. Maxwell's equations.	Design various kinds of antenna subject to specific requirements.	Conduct experiments for analysis of medium and antenna performance.



ASSESSMENT PATTERN

CIE- Continuous Internal Evaluation (90 Marks)

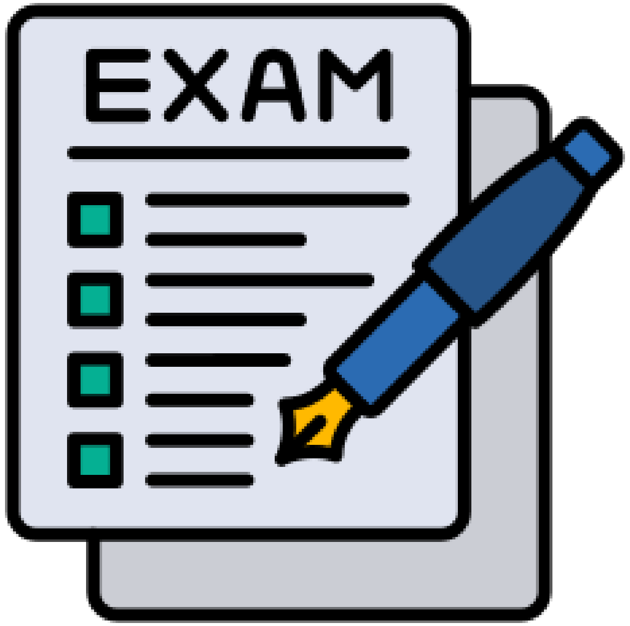
Bloom's Category Marks (out of 90)	Tests Mid-term (45)
Remember	08
Understand	08
Apply	08
Analyze	08
Evaluate	08
Create	05

Class Test	**15**
Presentation	**15**
Attendance	**15**

ASSESSMENT PATTERN

SEE- Semester End Examination (60 Marks)

Bloom's Category	Tests
Remember	**10**
Understand	**10**
Apply	**10**
Analyze	**10**
Evaluate	**10**
Create	**10**



COURSE CONTENT

Sl. No.	Topic Title	Description
1	Electrostatics and Magnetostatics	Covers the fundamental concepts of electric and magnetic fields using vector methods, including Coulomb’s law and field intensity.
2	Fields in Dielectrics and Conductors	Explores the behavior of electric fields in dielectric and conductive materials, including boundary conditions.
3	Boundary Conditions	Discusses the conditions at the interface between different materials for both electric and magnetic fields.
4	Time-Varying Fields & Maxwell's Equations	Focuses on time-dependent electric and magnetic fields, deriving and applying Maxwell's equations, and introducing the Poynting vector.
5	Uniform Plane Waves	Studies the properties, transmission, and reflection of uniform plane electromagnetic waves, including skin effect and surface resistance.
6	Waveguides and Radiation Systems	Introduces the principles of waveguides, including modes of propagation, and provides an overview of radiation systems.

Time distributions

Week	Topic Title	Time Allocated (Hours)	Remarks
1	Introduction to Electromagnetic Fields & Waves	2	Overview of course and fundamental concepts.
2	Electrostatics: Fields and Potentials	2	Basics of electrostatic fields and Coulomb’s law.
3	Electrostatics: Energy and Flux	2	Understanding energy density and electric flux.
4	Magnetostatics: Forces and Fields	2	Concepts of magnetic fields and Ampere's law.
5	Fields in Dielectrics and Conductors	2	Behavior of materials in electric fields.
6	Boundary Conditions	2	Analysis of field interactions at material boundaries.
7	Time-Varying Fields: Maxwell's Equations	2	Derivation and application of Maxwell’s equations.
8	Time-Varying Fields: Poynting Vector	2	Introduction to energy flow in electromagnetic fields.
9	Uniform Plane Waves: Transmission & Reflection	2	Basics of wave propagation and reflection at boundaries.

Time distributions

Week	Topic Title	Time Allocated (Hours)	Remarks
10	Uniform Plane Waves: Skin Effect and Resistance	2	Analysis of current distribution and resistance.
11	Waveguides: Modes and Propagation	2	Introduction to waveguides and their properties.
12	Waveguides: Applications and Practical Design	2	Exploring practical uses of waveguides.
13	Radiation Systems: Basics	2	Overview of radiation and antenna principles.
14	Radiation Systems: Applications	2	Application of radiation systems in communication.
15	Electromagnetic Compatibility	2	Analysis of compatibility and interference issues.
16	Problem Solving & Case Studies	2	Hands-on problem solving and real-world case studies.
17	Revision and Final Review	2	Comprehensive review of all topics.

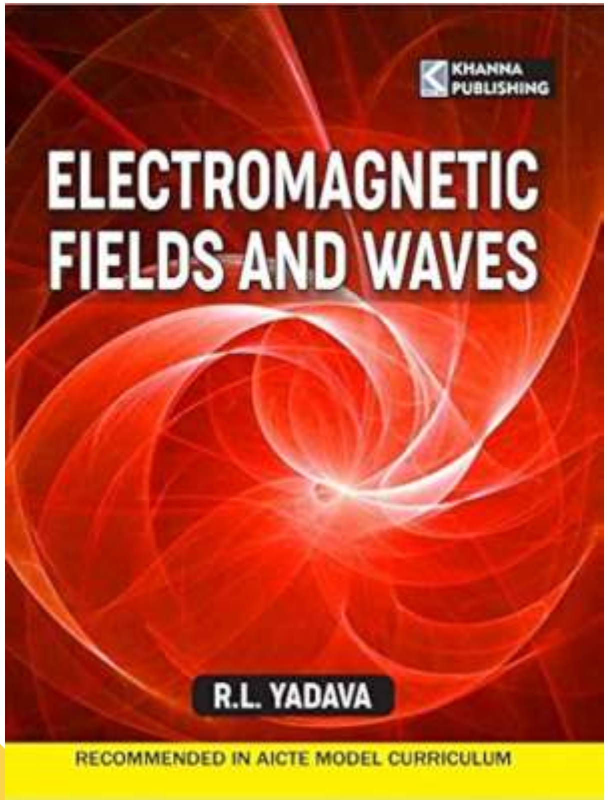
Course Schedule

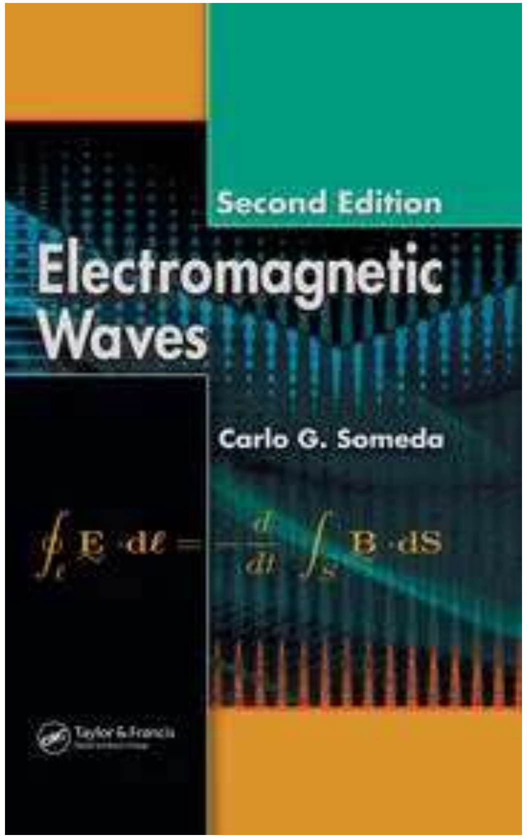
Week	Topic	CLO Mapping	Delivery Method
1	Introduction to Electromagnetic Fields & Waves	CLO 1	Lecture, Discussion
2	Electrostatics: Fields and Potentials	CLO 1	Lecture, Problem Solving
3	Electrostatics: Energy and Flux	CLO 1	Lecture, Hands-on Examples
4	Magnetostatics: Forces and Fields	CLO 1	Lecture, Derivations, Discussion
5	Fields in Dielectrics and Conductors	CLO 2	Lecture, Problem Solving
6	Boundary Conditions	CLO 2	Lecture, Real-World Examples
7	Time-Varying Fields: Maxwell's Equations	CLO 2, CLO 4	Lecture, Group Activity
8	Time-Varying Fields: Poynting Vector	CLO 2, CLO 4	Lecture, Case Study Discussion
9	Uniform Plane Waves: Transmission & Reflection	CLO 3, CLO 4	Lecture, Interactive Simulation

Course Schedule(Cont.)

Week	Topic	CLO Mapping	Delivery Method
10	Uniform Plane Waves: Skin Effect and Resistance	CLO 1	Lecture, Discussion
11	Waveguides: Modes and Propagation	CLO 1	Lecture, Problem Solving
12	Waveguides: Applications and Practical Design	CLO 1	Lecture, Hands-on Examples
13	Radiation Systems: Basics	CLO 1	Lecture, Derivations, Discussion
14	Radiation Systems: Applications	CLO 2	Lecture, Problem Solving
15	Electromagnetic Compatibility	CLO 2	Lecture, Real-World Examples
16	Problem Solving & Case Studies	CLO 2, CLO 4	Lecture, Group Activity
17	Revision and Final Review	CLO 2, CLO 4	Lecture, Case Study Discussion

Reference Books



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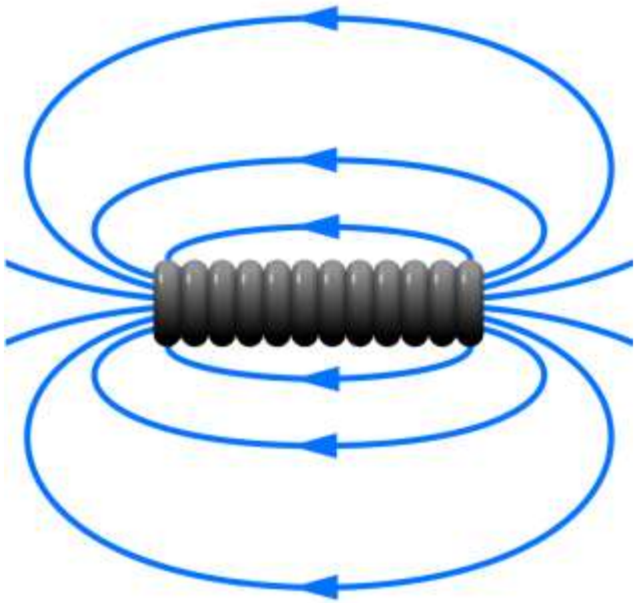
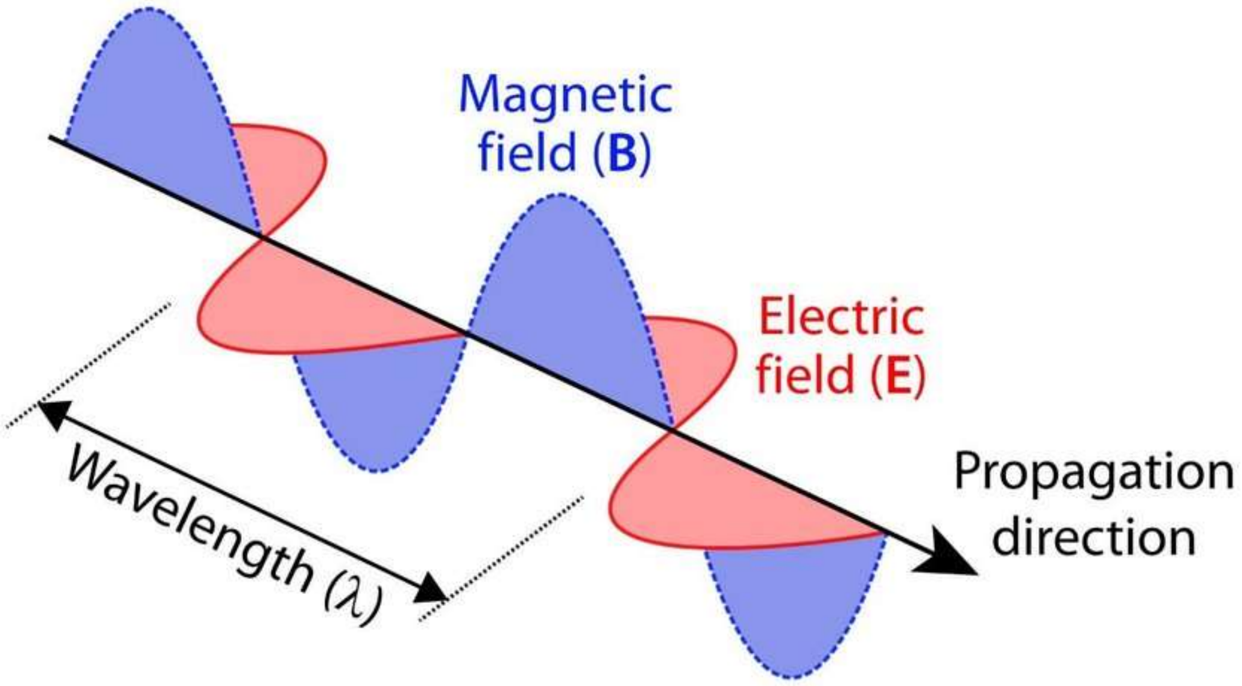
Introduction to Electromagnetic Fields & Waves



Introduction to EMF

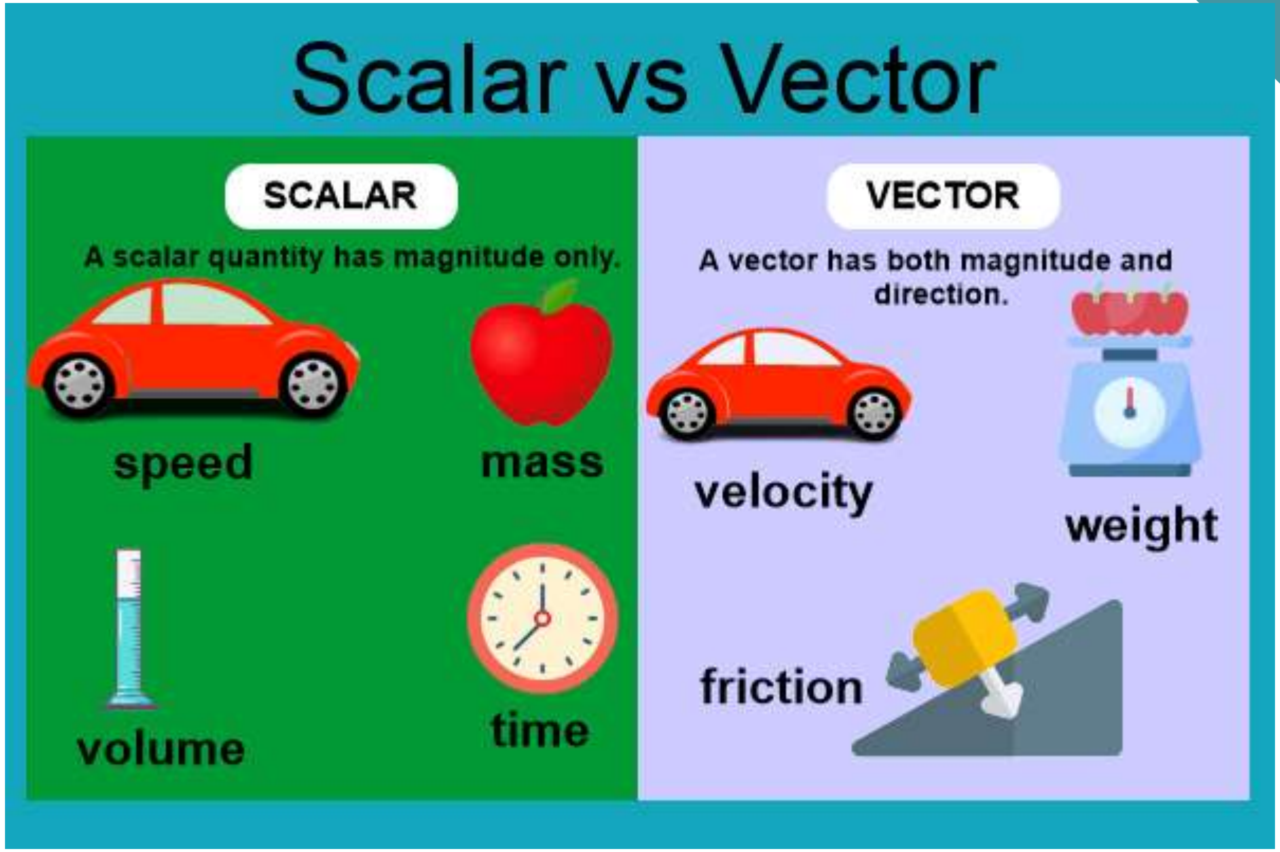
Electromagnetics (EM) is a branch of physics or electrical engineering in which electric and magnetic phenomena are studied.



Scalar Vs Vector

Scalar Quantities: The physical quantities which are specified with the magnitude or size alone are scalar quantities. For example, length, speed, work, mass, density, etc.

Vector Quantities: Vector quantities refer to the physical quantities characterized by the presence of both magnitude as well as direction.



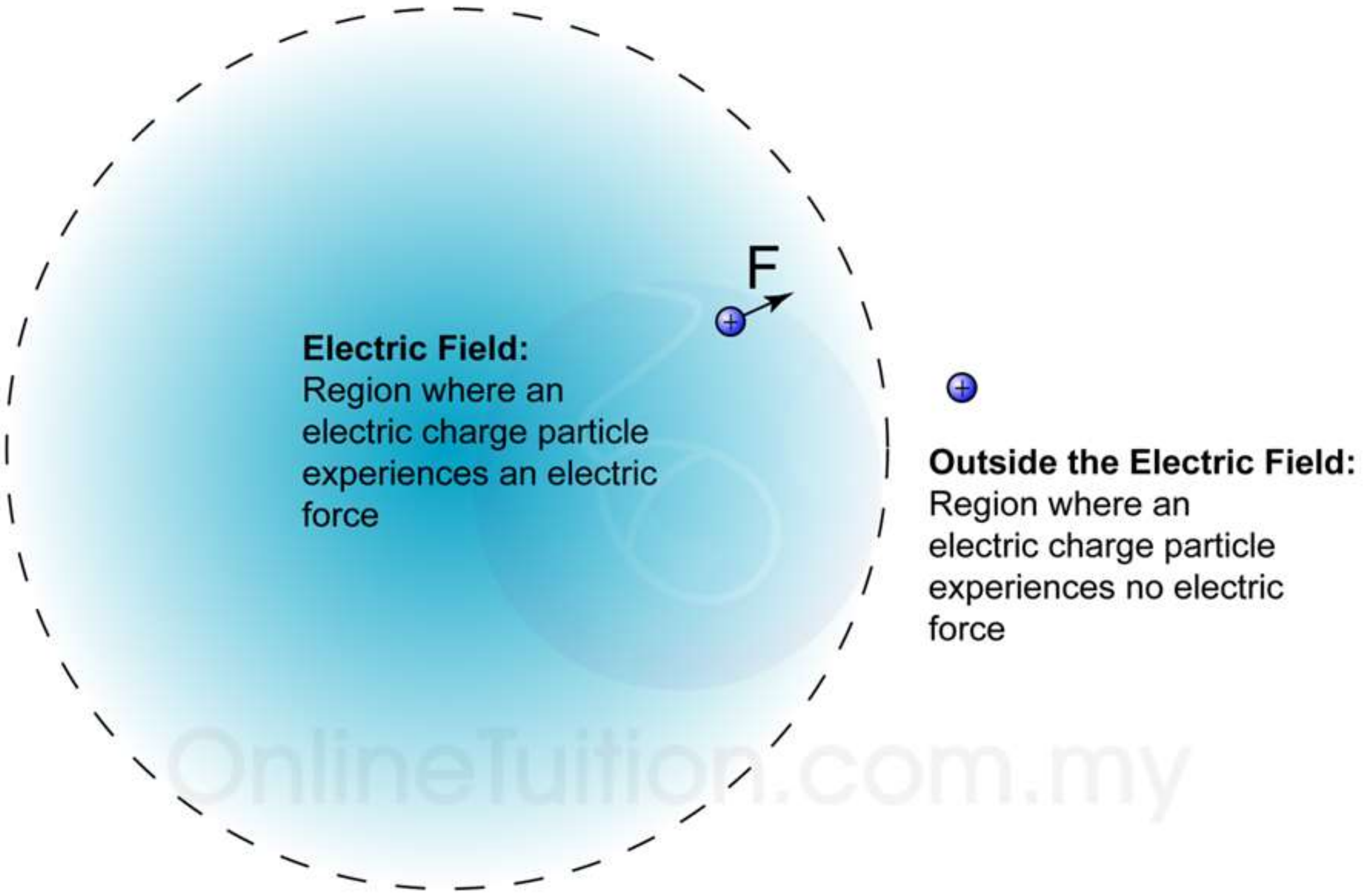
Field

- A field is a function that specifies a particular quantity everywhere in a region.

- If the quantity is scalar (or vector), the field is said to be a scalar (or vector) field.

- Examples of scalar fields are temperature distribution in a building, sound intensity in a theater, electric potential in a region, and refractive index of a stratified medium.

- The gravitational force on a body in space and the velocity of raindrops in the atmosphere are examples of vector fields.

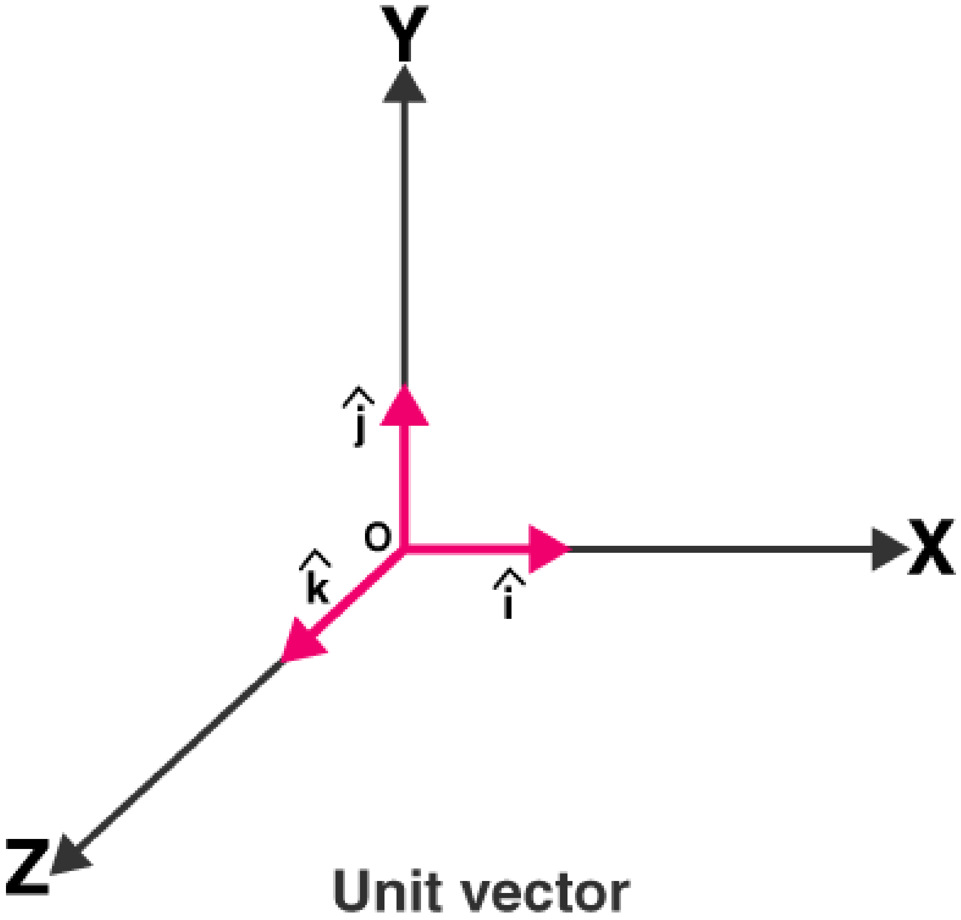


Special Vector

UNIT VECTOR

The magnitude of A is a scalar written as A or |A|. A unit vector is defined as a vector whose magnitude is unity (i.e., 1) and its direction is along A, that is,

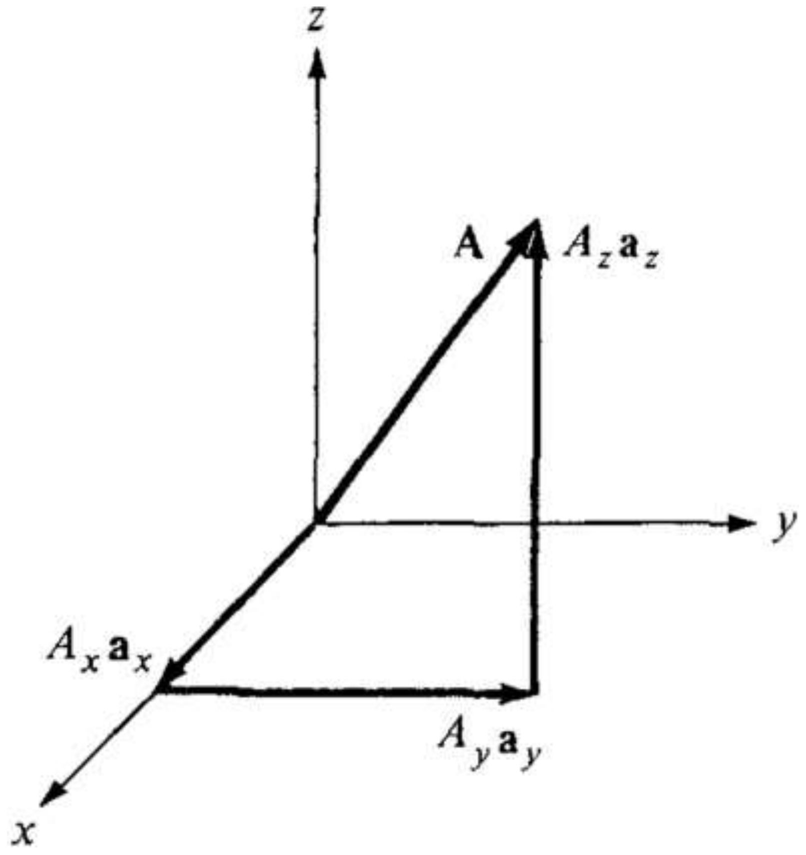
$$\mathbf{a}_A = \frac{\mathbf{A}}{|\mathbf{A}|} = \frac{\mathbf{A}}{A}$$



Representation of a vector with Unit vector

A vector (A) in Cartesian (or rectangular) coordinates may be represented as

$$(A_x, A_y, A_z) \qquad \text{or} \qquad A_x\mathbf{a}_x + A_y\mathbf{a}_y + A_z\mathbf{a}_z$$



Magnitude of a vector with Unit vector

The unit vectors $\mathbf{a}_x$, $\mathbf{a}_y$, and $\mathbf{a}_z$ and the components of **A** along the coordinate axes are shown in Fig. The magnitude of vector **A** is given by

$$A = \sqrt{A_x^2 + A_y^2 + A_z^2}$$

and the unit vector along A is given by

$$\mathbf{a}_A = \frac{A_x\mathbf{a}_x + A_y\mathbf{a}_y + A_z\mathbf{a}_z}{\sqrt{A_x^2 + A_y^2 + A_z^2}}$$

Operation of Vector

VECTOR ADDITION AND SUBTRACTION

Two vectors **A** and **B** can be added together to give another vector **C**; that is,

$$\mathbf{C} = \mathbf{A} + \mathbf{B}$$

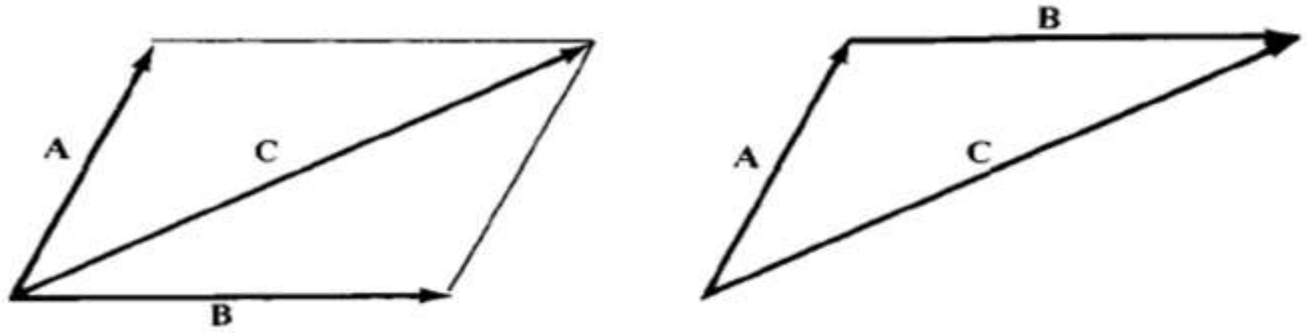
The vector addition is carried out component by component. Thus, if

A = (A_x, A_y, A_z) and **B** = (B_x,B_y,B_z).

$$\mathbf{C} = (A_x + B_x)\mathbf{a}_x + (A_y + B_y)\mathbf{a}_y + (A_z + B_z)\mathbf{a}_z$$

Vector subtraction is similarly carried out as

$$\mathbf{D} = \mathbf{A} - \mathbf{B} = \mathbf{A} + (-\mathbf{B})$$
$$= (A_x - B_x)\mathbf{a}_x + (A_y - B_y)\mathbf{a}_y + (A_z - B_z)\mathbf{a}_z$$



Vector addition C = A + B:

(a) parallelogram rule, (b) head-to-tail rule.

Three basic laws of algebra obeyed by any given vectors A, B, C, are summarized as follows:

Law	Addition	Multiplication
Commutative	$\mathbf{A} + \mathbf{B} = \mathbf{B} + \mathbf{A}$	$k\mathbf{A} = \mathbf{A}k$
Associative	$\mathbf{A} + (\mathbf{B} + \mathbf{C}) = (\mathbf{A} + \mathbf{B}) + \mathbf{C}$	$k(\ell\mathbf{A}) = (k\ell)\mathbf{A}$
Distributive	$k(\mathbf{A} + \mathbf{B}) = k\mathbf{A} + k\mathbf{B}$	

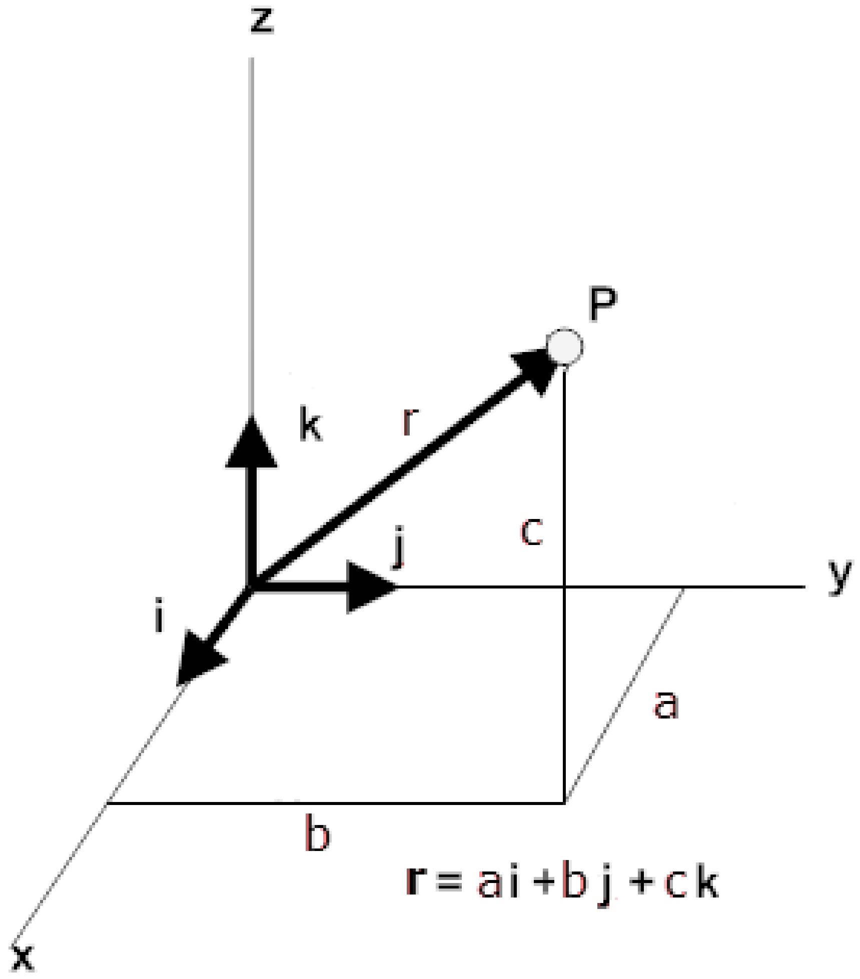
where k and l are scalars.

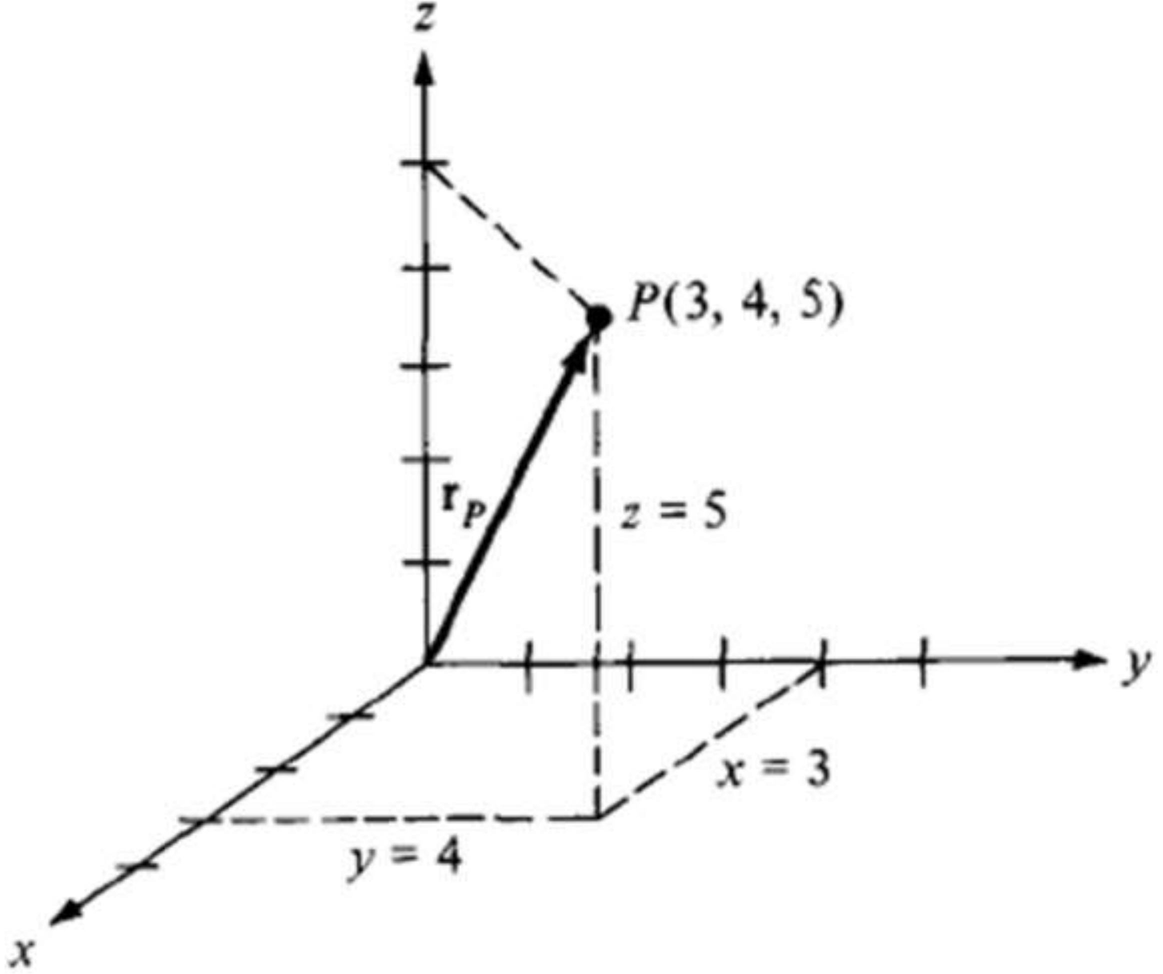
Position vector (or radius vector)

POSITION AND DISTANCE VECTORS

A "position vector" indicates the location of a point in space relative to a fixed origin, essentially describing both the distance and direction from the origin to that point,

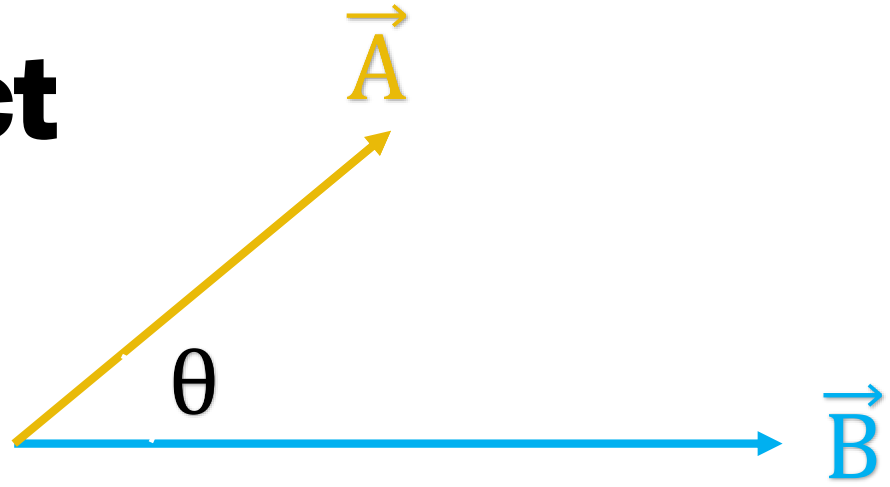
The **position vector** $\mathbf{r}_P$ (or **radius vector**) of point P is as the directed distance from the origin O to P; i.e.,





Visual Representation of a Position Vector.

Scalar product



$$\vec{A} \cdot \vec{B} = AB\cos\theta$$

Examples of scalar product

$$W = \vec{F} \cdot \vec{s}$$

$$W = Fs\cos\theta$$

W = work done

F = force

s = displacement

$$P = \vec{F} \cdot \vec{v}$$

$$P = Fv\cos\theta$$

P = power

F = force

v = velocity

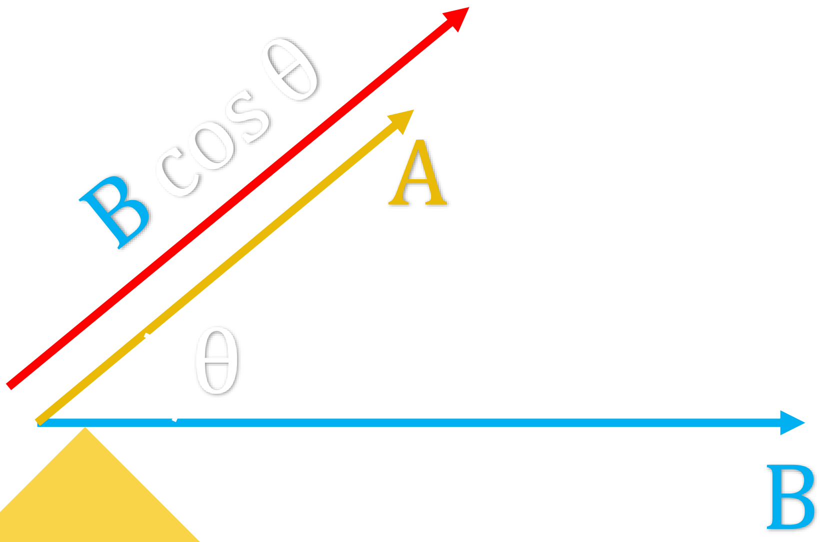
Geometrical meaning of Scalar dot product

A dot product can be regarded as the product of two quantities:

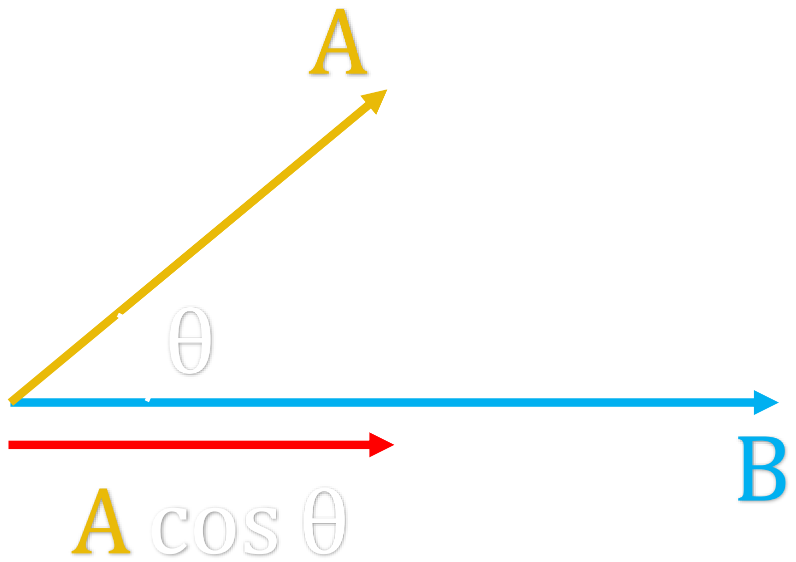
1. The magnitude of one of the vectors
2. The scalar component of the second vector along the direction of the first vector

Geometrical meaning of Scalar product

$$\vec{A} \cdot \vec{B} = A(B\cos\theta)$$



$$\vec{A} \cdot \vec{B} = (A\cos\theta)B$$



Properties of Scalar product

$$\vec{A} \cdot \vec{B} = AB\cos\theta$$

$$\vec{B} \cdot \vec{A} = BA\cos\theta$$

$$\vec{A} \cdot \vec{B} = \vec{B} \cdot \vec{A}$$

Calculating scalar product using components

Let us have

$$\vec{A} = A_x\hat{\imath} + A_y\hat{\jmath} + A_z\hat{k}$$

$$\vec{B} = B_x\hat{\imath} + B_y\hat{\jmath} + B_z\hat{k}$$

then

$$\vec{A}\cdot\vec{B} = \left(A_x\hat{\imath} + A_y\hat{\jmath} + A_z\hat{k}\right) \cdot \left(B_x\hat{\imath} + B_y\hat{\jmath} + B_z\hat{k}\right)$$

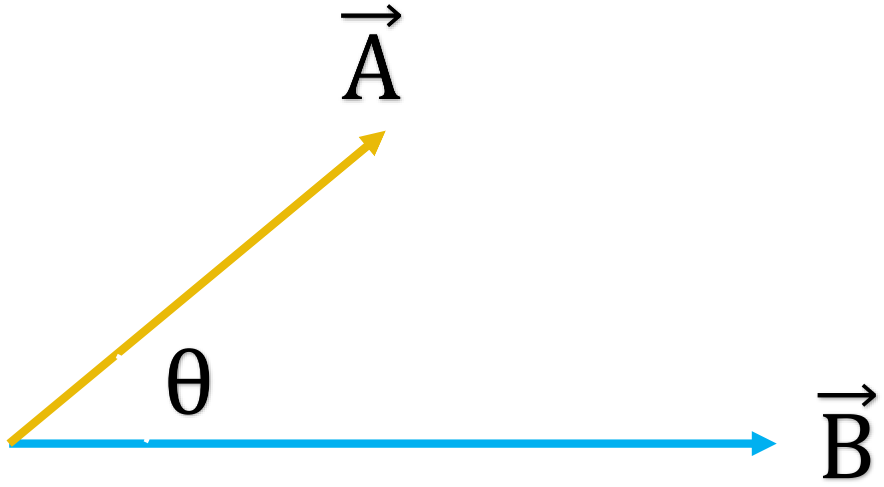
$$\vec{A}\cdot\vec{B} = A_x\hat{\imath}\cdot\left(B_x\hat{\imath} + B_y\hat{\jmath} + B_z\hat{k}\right) + A_y\hat{\jmath}\cdot\left(B_x\hat{\imath} + B_y\hat{\jmath} + B_z\hat{k}\right) + A_z\hat{k}\cdot\left(B_x\hat{\imath} + B_y\hat{\jmath} + B_z\hat{k}\right)$$

$$= A_xB_x\hat{\imath}\cdot\hat{\imath} + A_xB_y\hat{\imath}\cdot\hat{\jmath} + A_xB_z\hat{\imath}\cdot\hat{k} + A_yB_x\hat{\jmath}\cdot\hat{\imath} + A_yB_y\hat{\jmath}\cdot\hat{\jmath} + A_yB_z\hat{\jmath}\cdot\hat{k} + A_zB_x\hat{k}\cdot\hat{\imath} + A_zB_y\hat{k}\cdot\hat{\jmath} + A_zB_z\hat{k}\cdot\hat{k}$$

$$= A_xB_x(1) + A_xB_y(0) + A_xB_z(0) + A_yB_x(0) + A_yB_y(1) + A_yB_z(0) + A_zB_x(0) + A_zB_y(0) + A_zB_z(1)$$

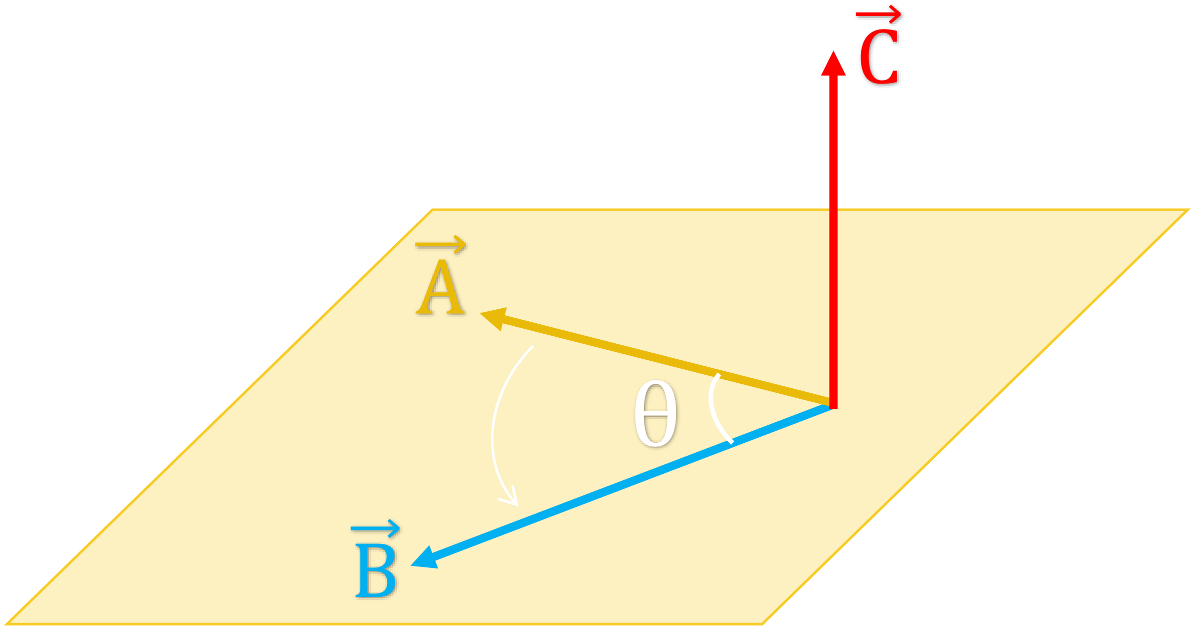
$$\vec{A}\cdot\vec{B} = A_xB_x + A_yB_y + A_zB_z$$

Vector product



$$\vec{A} \times \vec{B} = AB \sin\theta \, \hat{n} = \vec{C}$$

Right hand rule



Examples of vector product

$$\vec{\tau} = \vec{r} \times \vec{F}$$

$$\vec{\tau} = rF \sin\theta \, \hat{n}$$

τ = torque

r = position

F = force

$$\vec{L} = \vec{r} \times \vec{p}$$

$$\vec{L} = rp \sin\theta \, \hat{n}$$

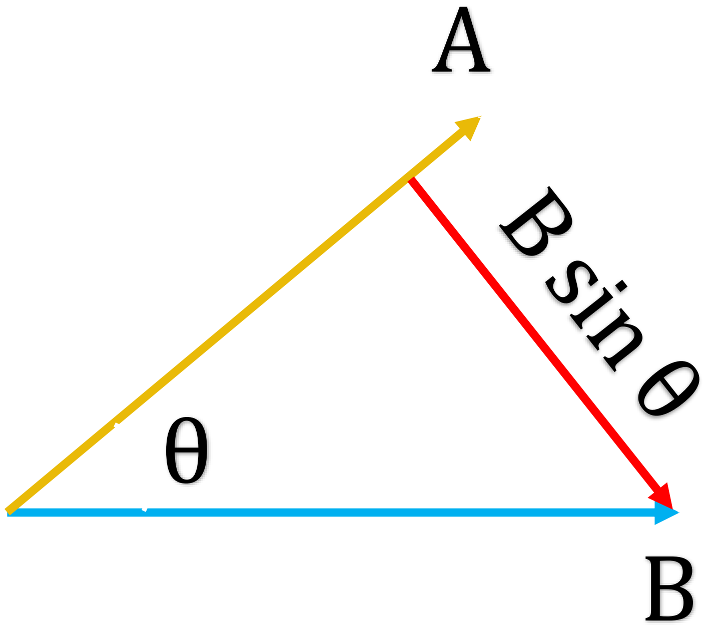
L = angular momentum

r = position

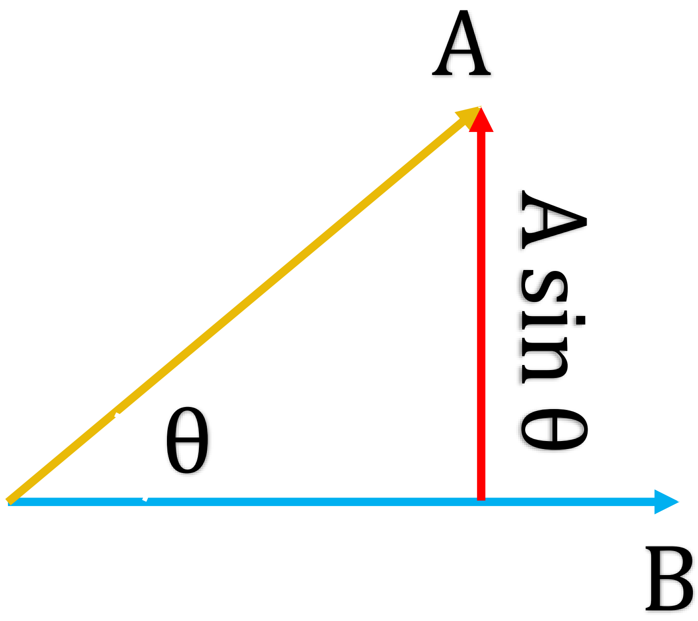
p = linear momentum

Geometrical meaning of Vector product

$$|\vec{A} \times \vec{B}| = A(B \sin\theta)$$



$$|\vec{A} \times \vec{B}| = (A \sin\theta)B$$



$|\vec{A} \times \vec{B}|$ = Area of parallelogram made by two vectors

Properties of Vector product

1

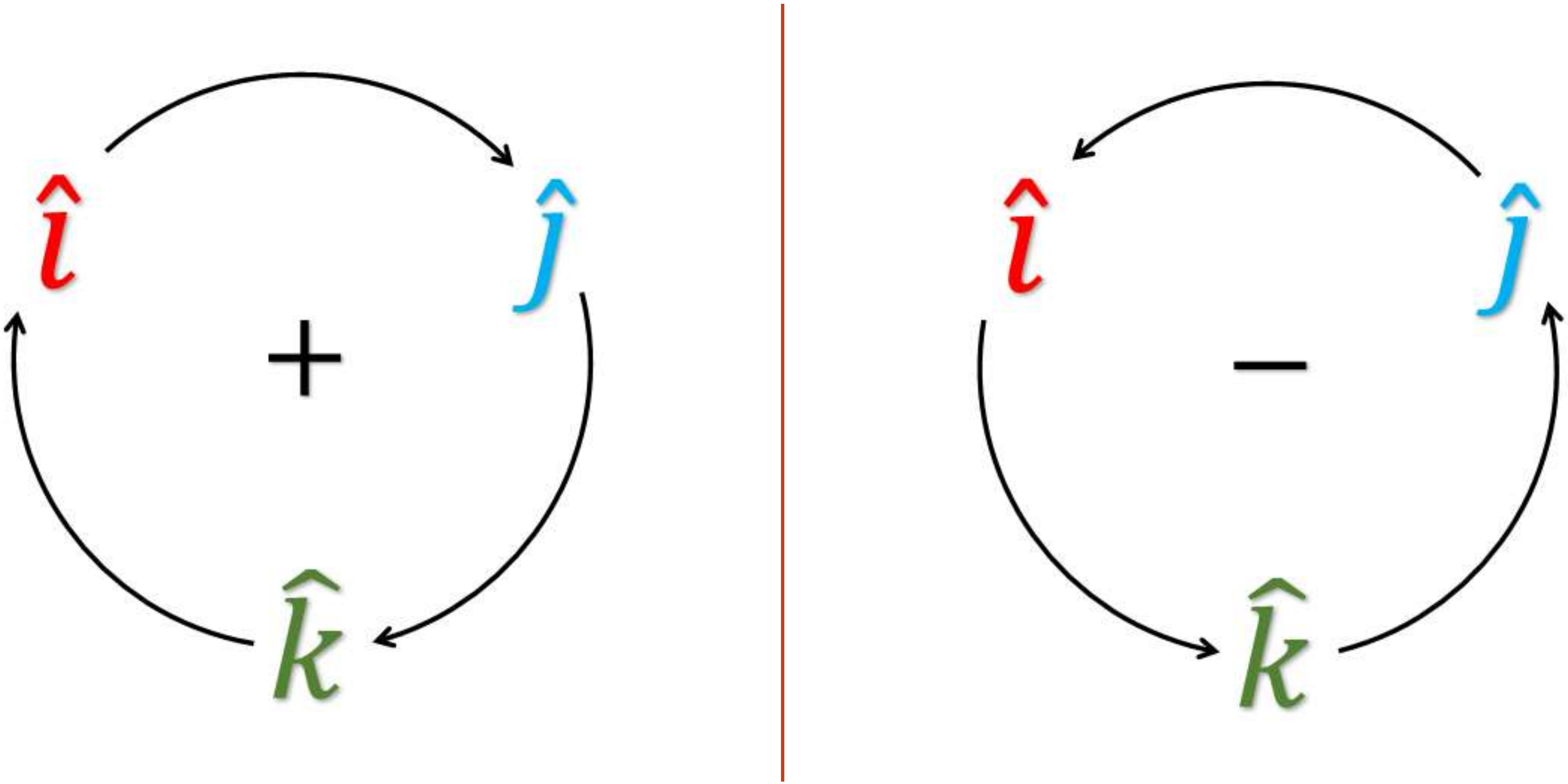
The vector product is anti-commutative.

$$\vec{A} \times \vec{B} = AB \sin\theta \, \hat{n}$$

$$\vec{B} \times \vec{A} = BA \sin\theta \, (-\hat{n}) = -AB \sin\theta \, \hat{n}$$

$$\vec{A} \times \vec{B} \neq \vec{B} \times \vec{A}$$

Aid to memory



Calculating vector product using components

Let us have

$$\vec{A} = A_x\hat{\imath} + A_y\hat{\jmath} + A_z\hat{k}$$

$$\vec{B} = B_x\hat{\imath} + B_y\hat{\jmath} + B_z\hat{k}$$

then

$$\vec{A} \times \vec{B} = \left(A_x\hat{\imath} + A_y\hat{\jmath} + A_z\hat{k}\right) \times \left(B_x\hat{\imath} + B_y\hat{\jmath} + B_z\hat{k}\right)$$

$$\vec{A} \times \vec{B} = A_x\hat{\imath} \times \left(B_x\hat{\imath} + B_y\hat{\jmath} + B_z\hat{k}\right) + A_y\hat{\jmath} \times \left(B_x\hat{\imath} + B_y\hat{\jmath} + B_z\hat{k}\right) + A_z\hat{k} \times \left(B_x\hat{\imath} + B_y\hat{\jmath} + B_z\hat{k}\right)$$

$$= A_xB_x\hat{\imath} \times \hat{\imath} + A_xB_y\hat{\imath} \times \hat{\jmath} + A_xB_z\hat{\imath} \times \hat{k} + A_yB_x\hat{\jmath} \times \hat{\imath} + A_yB_y\hat{\jmath} \times \hat{\jmath} + A_yB_z\hat{\jmath} \times \hat{k} + A_zB_x\hat{k} \times \hat{\imath} + A_zB_y\hat{k} \times \hat{\jmath} + A_zB_z\hat{k} \times \hat{k}$$

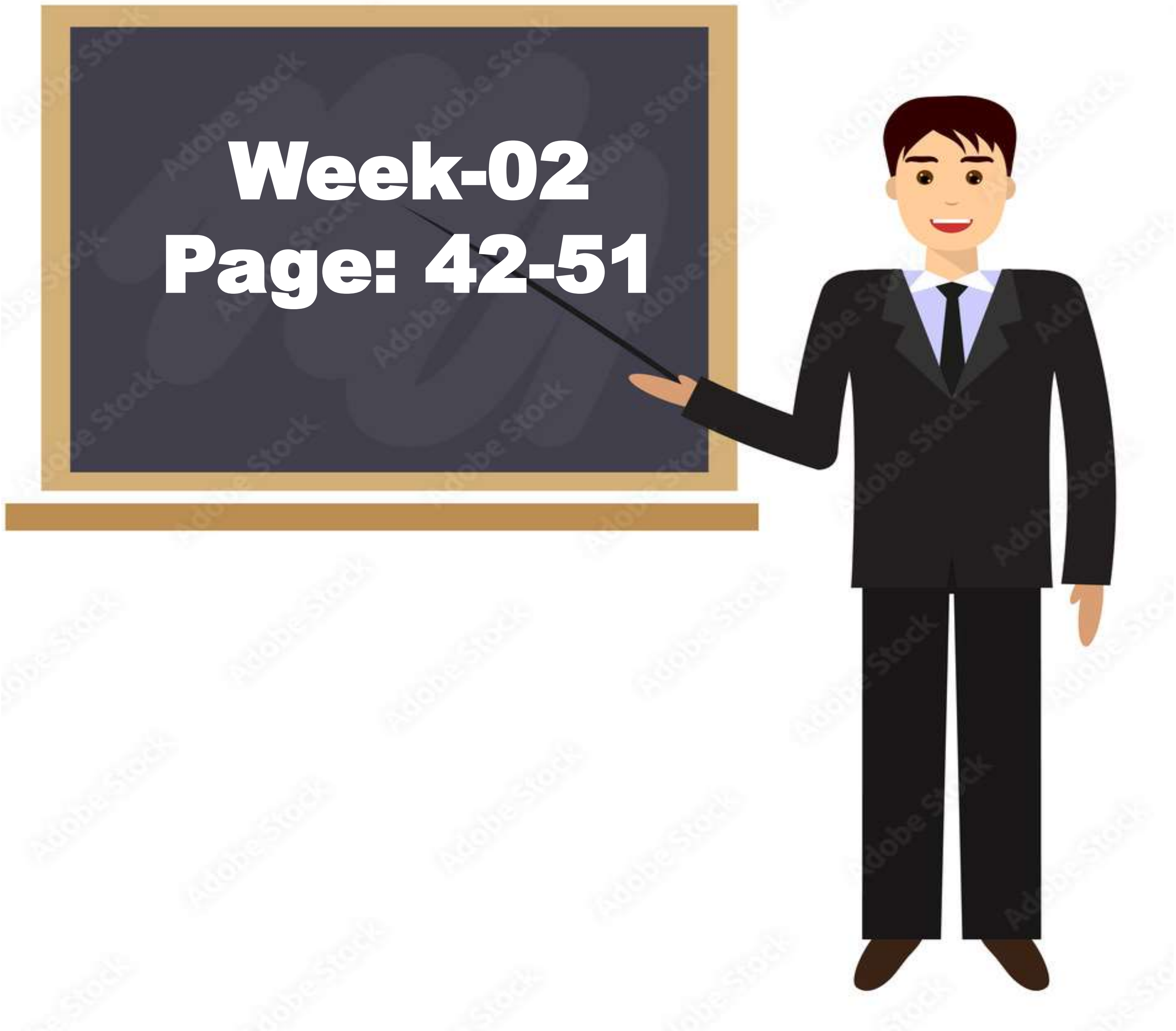
$$= A_xB_x(\vec{0}) + A_xB_y(\hat{k}) + A_xB_z(-\hat{\jmath}) + A_yB_x(-\hat{k}) + A_yB_y(\vec{0}) + A_yB_z(\hat{\imath}) + A_zB_x(\hat{\jmath}) + A_zB_y(-\hat{\imath}) + A_zB_z(\vec{0})$$

$$= A_yB_z(\hat{\imath}) - A_zB_y(\hat{\imath}) + A_zB_x(\hat{\jmath}) - A_xB_z(\hat{\jmath}) + A_xB_y(\hat{k}) - A_yB_x(\hat{k})$$

Calculating vector product using components

$$\vec{A} \times \vec{B} = \hat{\imath}\,(A_yB_z - A_zB_y) - \hat{\jmath}\,(A_xB_z - A_zB_x) + \hat{k}\,(A_xB_y - A_yB_x)$$

$$\vec{A} \times \vec{B} = \begin{vmatrix} \hat{\imath} & \hat{\jmath} & \hat{k} \\ A_x & A_y & A_z \\ B_x & B_y & B_z \end{vmatrix}$$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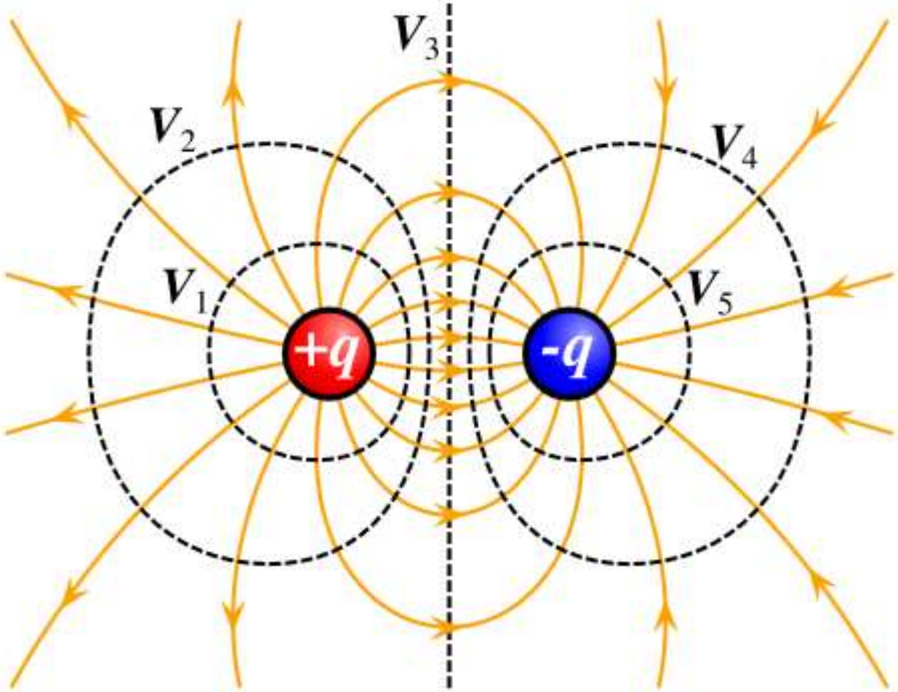
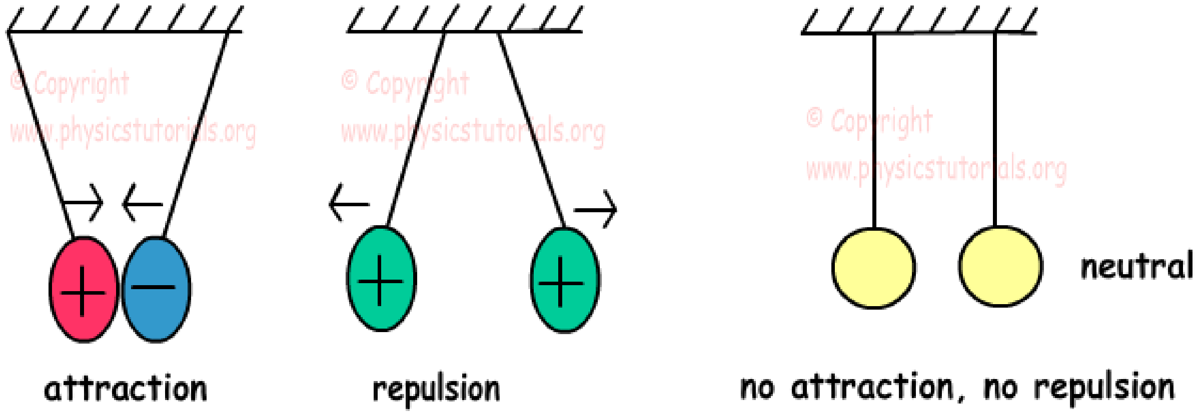
WEEK-02

Electrostatics: Fields and Potentials



Electrostatics

- **An electrostatic field is produced by a static charge distribution**.
- A typical example of such a field is found in a cathode-ray tube.
- Electrostatics is a fascinating subject that has grown up in diverse areas of application:
- **Electric power transmission**, **X-ray machines**, and **lightning protection** are associated with strong electric fields and will require a knowledge of electrostatics to understand and design suitable equipment.



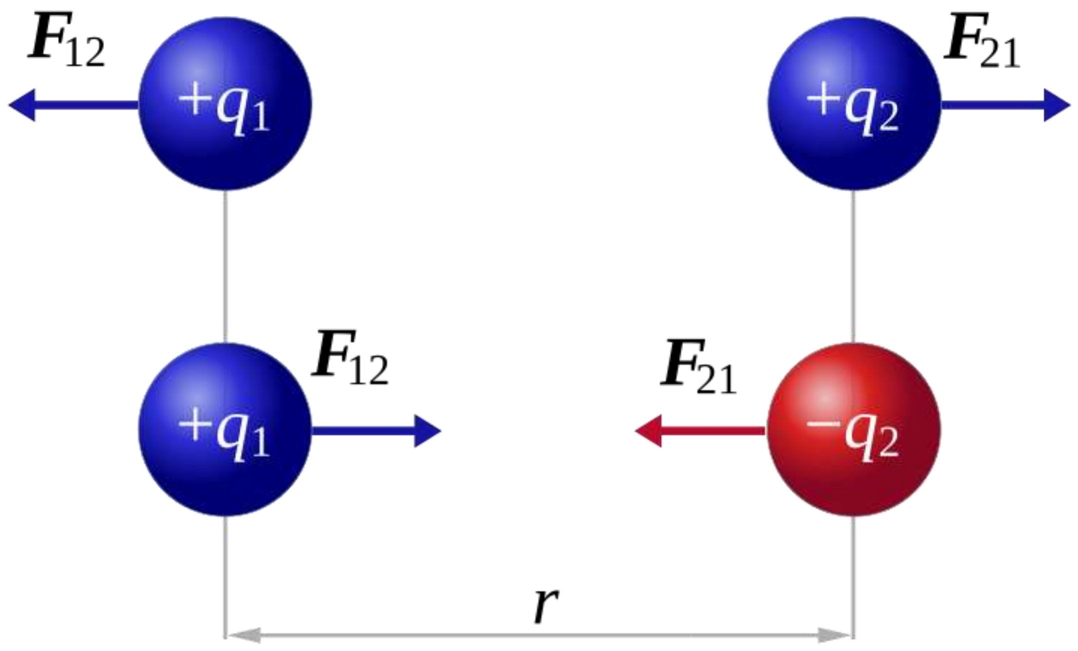
COULOMB'S LAW AND FIELD INTENSITY

Coulomb's law is an experimental law formulated in 1785 by the French colonel, Charles Augustin de Coulomb.

It deals with the force a point charge exerts on another point charge. By a point charge we mean a charge that is located on a body whose dimensions are much smaller than other relevant dimensions.

COULOMB'S LAW

According to **Coulomb's law**, the force of attraction or repulsion between two charged bodies is directly proportional to the product of their charges and inversely proportional to the square of the distance between them. It acts along the line joining the two charges considered to be point charges.



$$|\boldsymbol{F}_{12}| = |\boldsymbol{F}_{21}| = k_e \frac{|q_1 \times q_2|}{r^2}$$

COULOMB'S LAW

$$\varepsilon_o = 8.854 \times 10^{-12} \simeq \frac{10^{-9}}{36\pi} \text{ F/m}$$

$$\text{or } k = \frac{1}{4\pi\varepsilon_o} \simeq 9 \times 10^9 \text{ m/F}$$

Thus, the law becomes

$$F = \frac{Q_1 Q_2}{4\pi\varepsilon_o R^2}$$

If point charges Q_1 and Q_2 are located at points having position vectors $\mathbf{r}_1$ and $\mathbf{r}_2$, then the force $\mathbf{F}_{12}$ on Q_2 due to Q_1

COULOMB'S LAW

- Charges are generally measured in **coulombs**
- One coulomb is approximately **equivalent to 6 X 10^{18} electrons**;
- it is a very large unit of charge because one electron charge ***e*** **= -1.6019 X 10^{-19}** C.

- **Coulomb's law** states that the **force** ***F***
- **between two point charges Q_1 and Q_2 is:**

1. **Along the line joining them**
2. **Directly proportional to the product Q_1Q_2 of the charges**

Coulomb vector force on point changes Q1 and Q2.

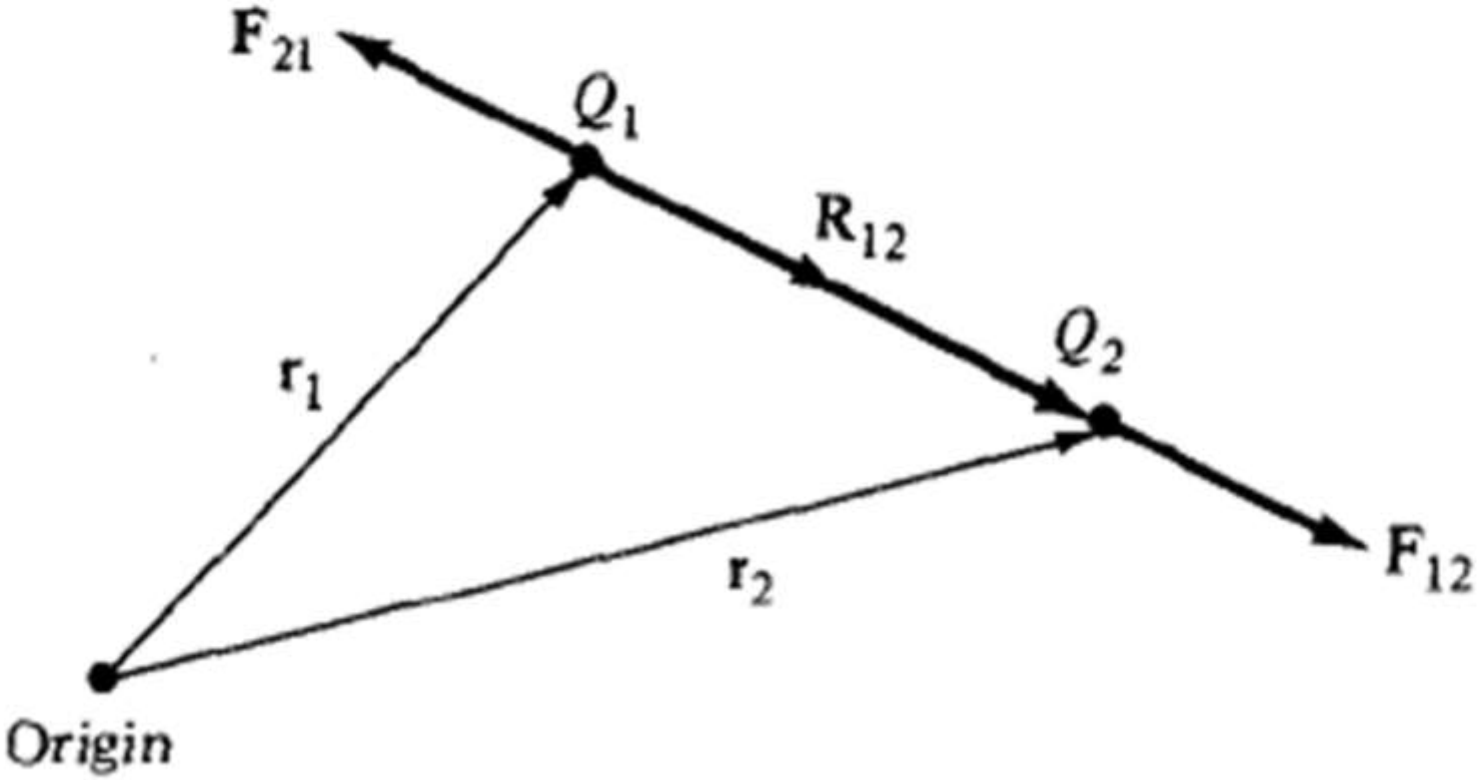


Fig. Coulomb vector force on point changes Q_1 and Q_2.

Coulomb vector force on point changes Q1 and Q2.

$$\mathbf{F}_{12} = \frac{Q_1 Q_2}{4\pi\varepsilon_o R^2}\mathbf{a}_{R_{12}}$$

where

$$\mathbf{R}_{12} = \mathbf{r}_2 - \mathbf{r}_1$$

$$R = |\mathbf{R}_{12}|$$

$$\mathbf{a}_{R_{12}} = \frac{\mathbf{R}_{12}}{R}$$

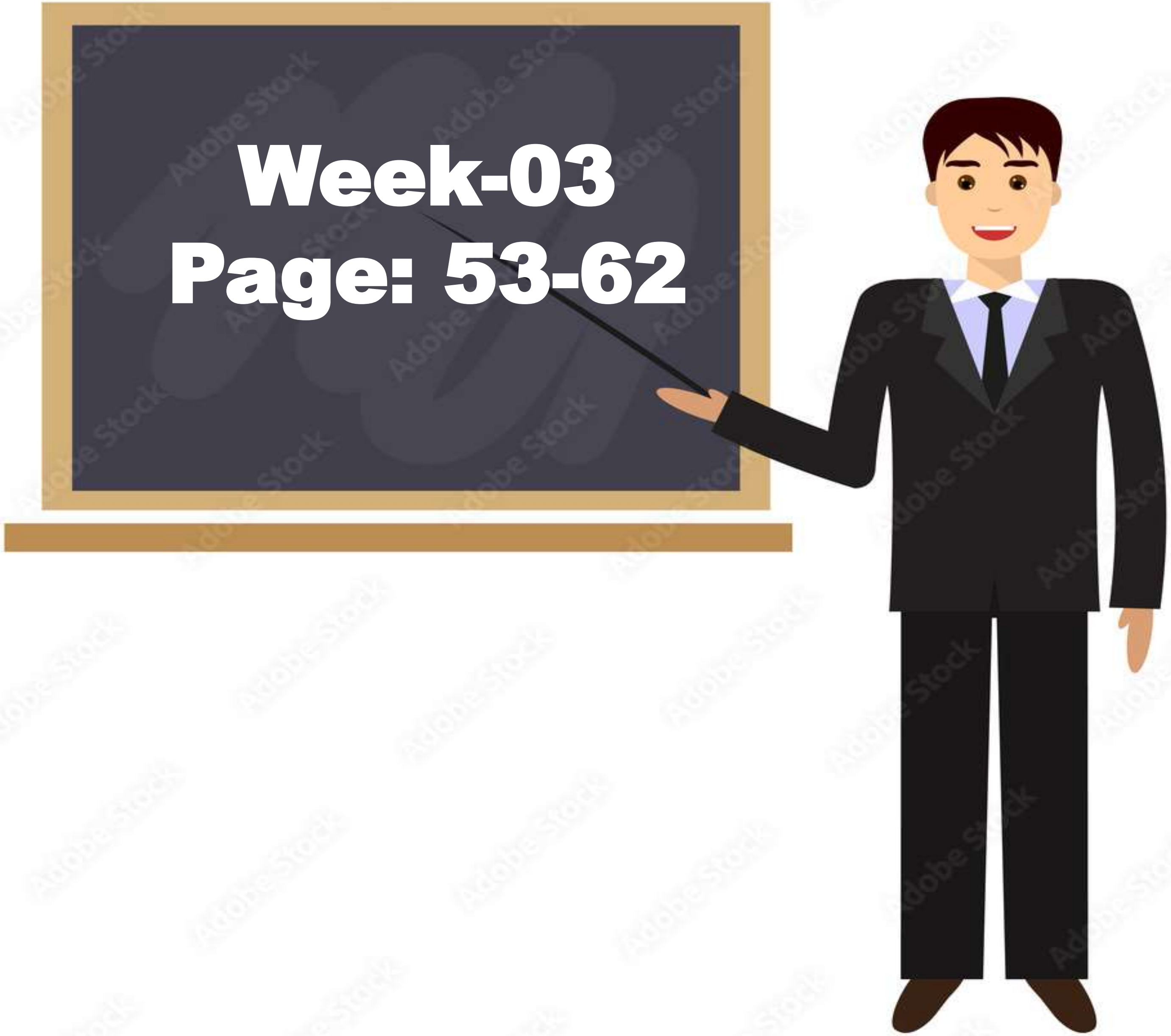
By substituting we may write as

$$\mathbf{F}_{12} = \frac{Q_1 Q_2}{4\pi\varepsilon_o R^3}\mathbf{R}_{12}$$

$$\mathbf{F}_{12} = \frac{Q_1 Q_2 (\mathbf{r}_2 - \mathbf{r}_1)}{4\pi\varepsilon_o |\mathbf{r}_2 - \mathbf{r}_1|^3}$$

Summary.

1. Like charges (charges of the same sign) repel each other while unlike charges attract.
2. The distance R between the charged bodies Q_1 and Q_2 must be large compared with the linear dimensions of the bodies; that is, Q_1 and Q_2 must be point charges.
3. Q_1 and Q_2 must be static (at rest).
4. The signs of Q_1 and Q_2 must be taken into account in eq. (3).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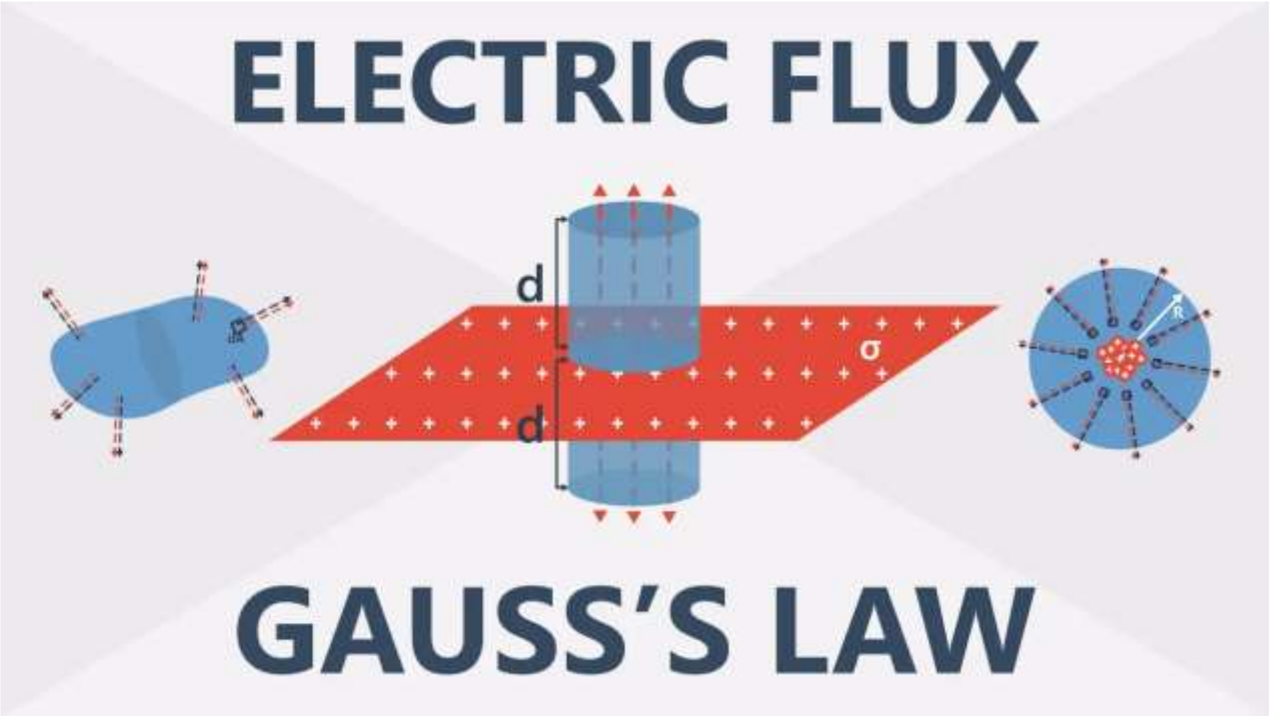
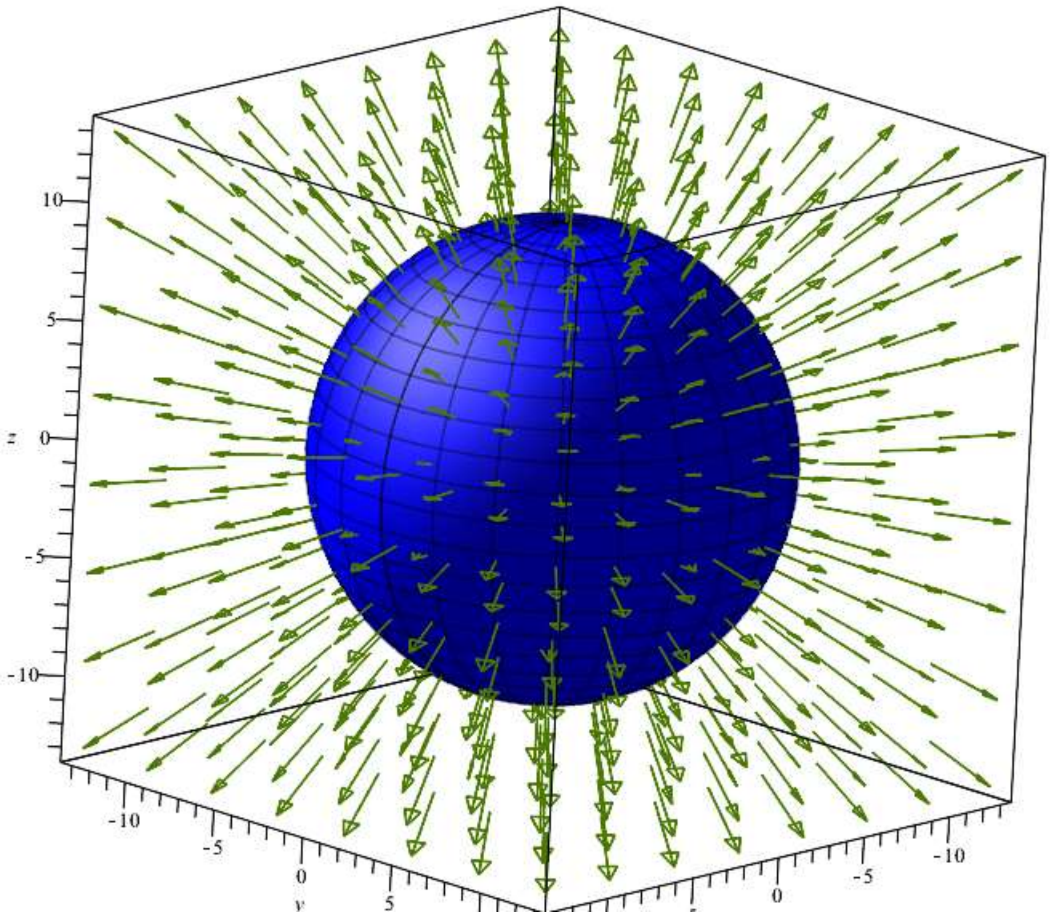
WEEK-03

Electrostatics: Energy and Flux



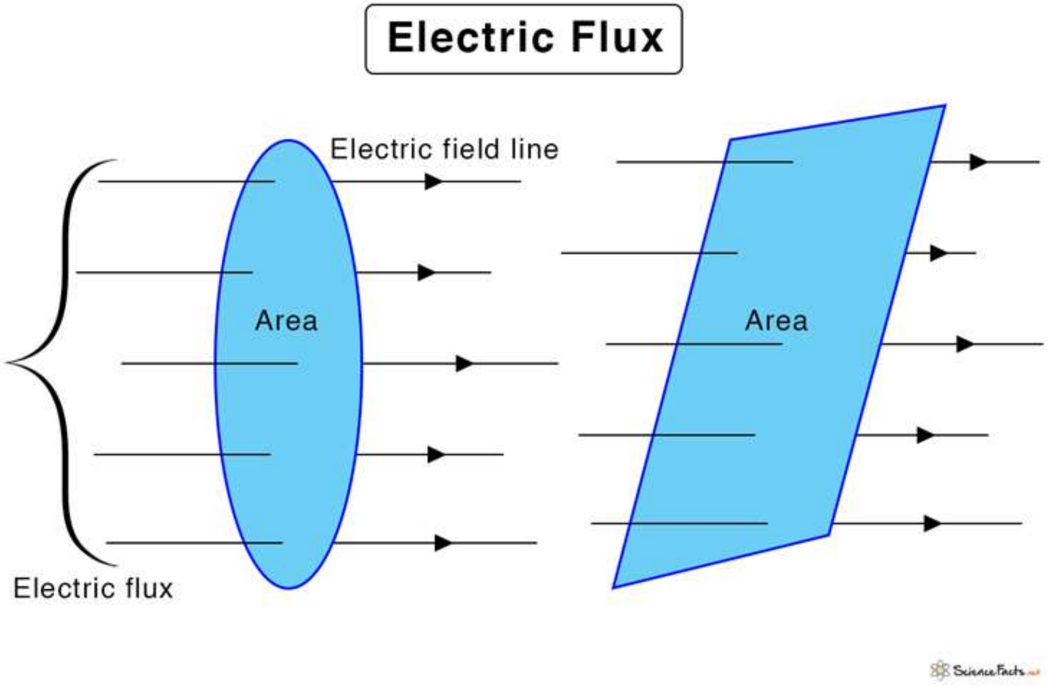
ELECTRIC FLUX

A measure of the total electric field passing through a given surface, calculated by multiplying the electric field component perpendicular to the surface by the surface area.

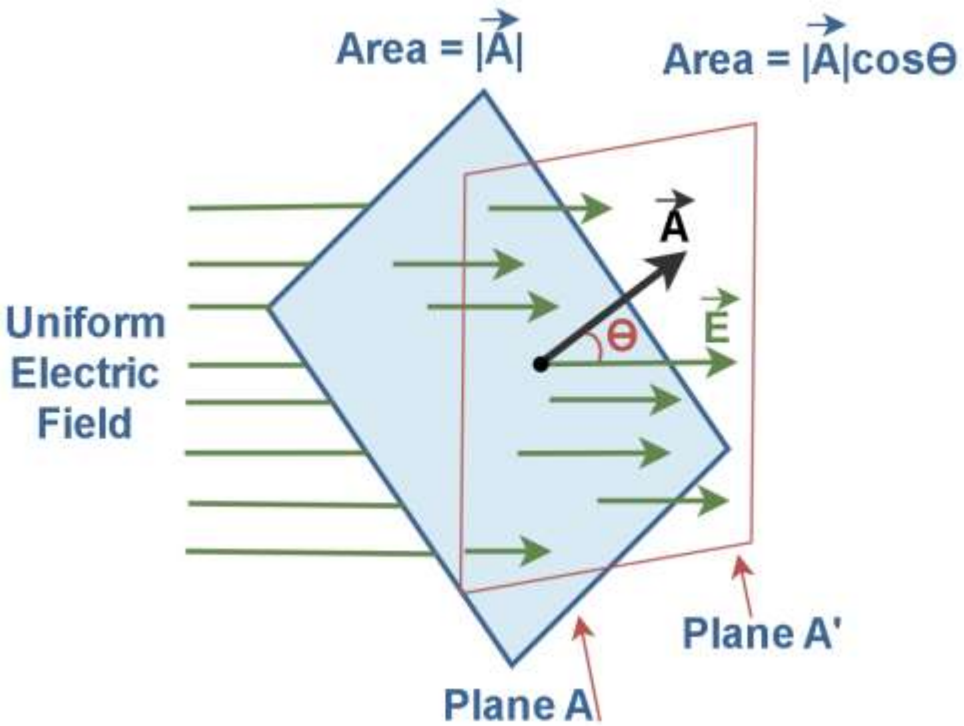


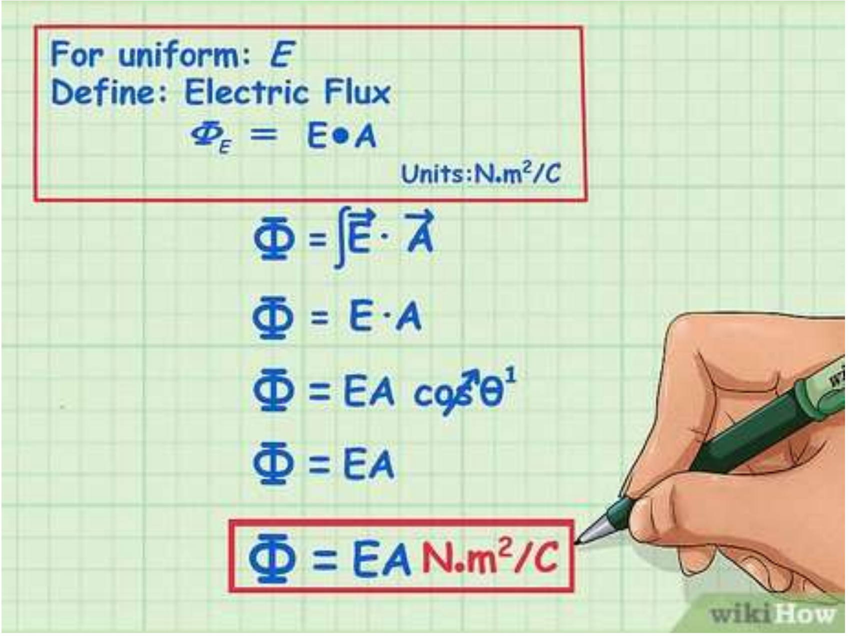
ELECTRIC FLUX

The total number of electric field lines passing a given area in a unit of time is defined as the electric flux.



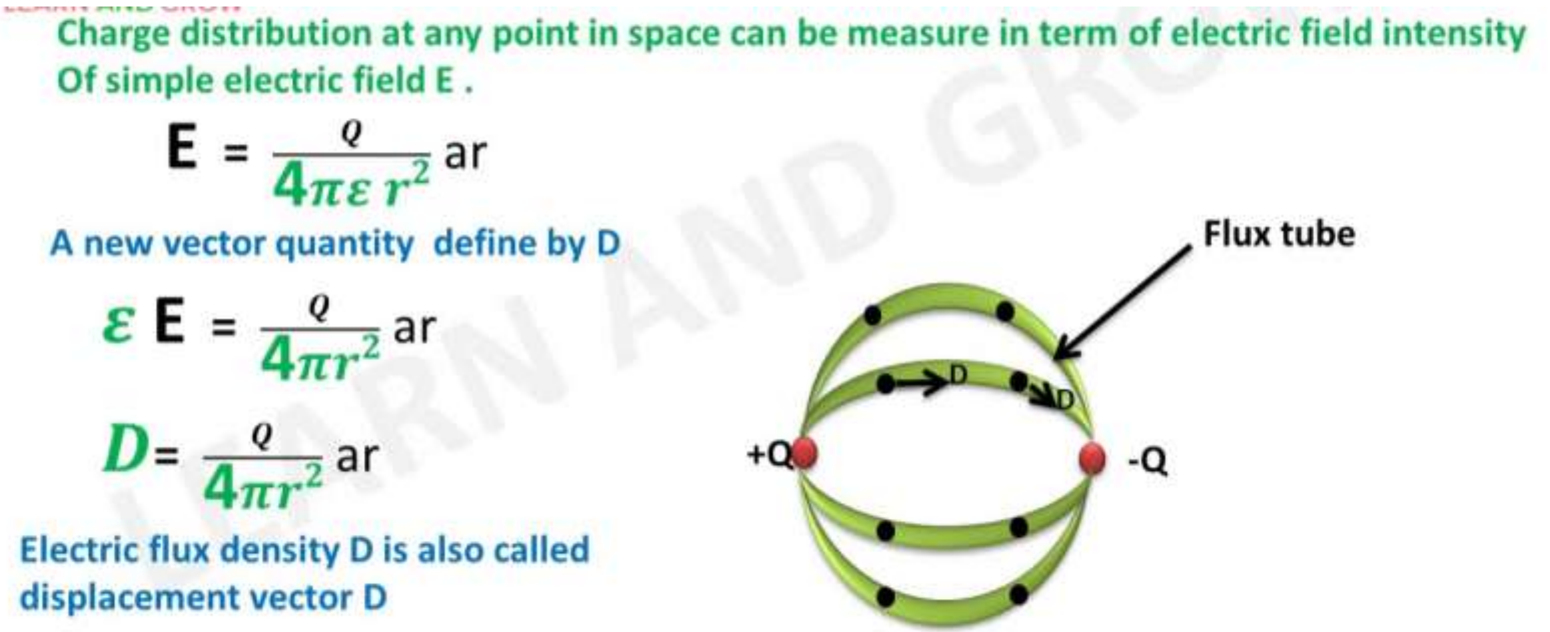
ELECTRIC FLUX (Formula)





ELECTRIC FLUX DENSITY

Electric flux density (D) is a vector field that measures the strength of an electric field at a given point. It's also known as the electric displacement field.



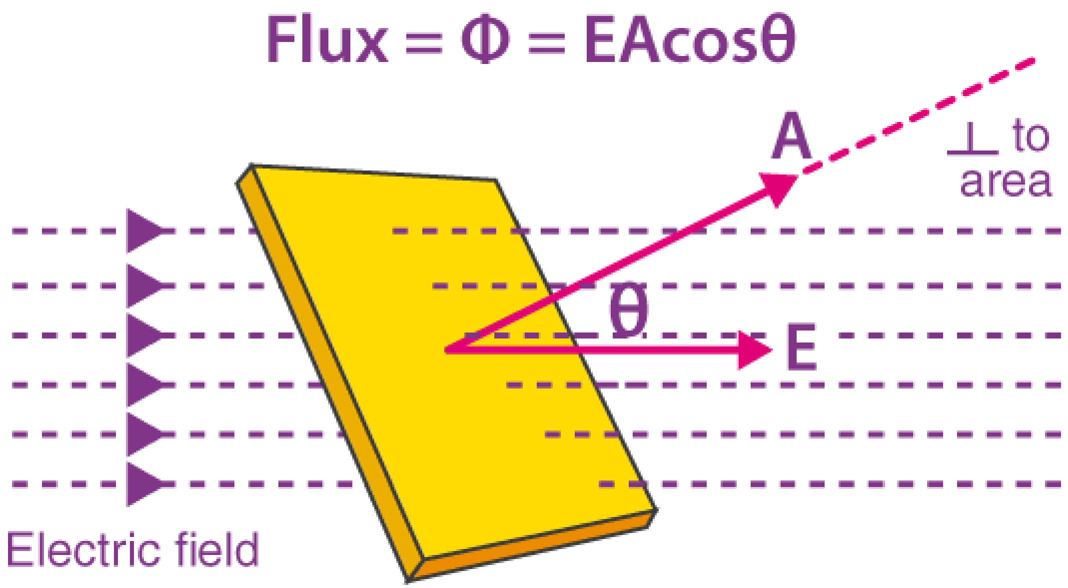
ELECTRIC FLUX DENSITY

What it measures

•The number of electric field lines that pass through a unit area

•The strength of an electric field generated by a free electric charge

•The electromagnetic effects of polarization and an electric field



Electric Field Intensity For a Point Charge

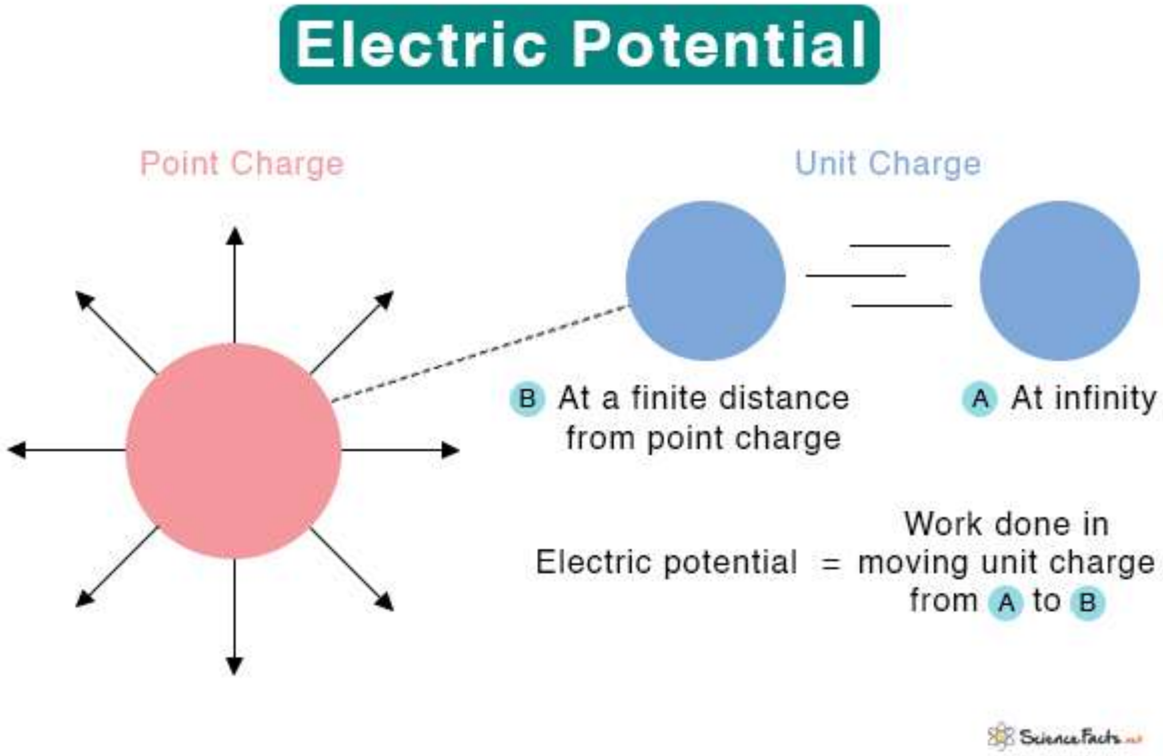
$$E = \frac{F}{q} = \frac{k \cdot \not{q} \cdot Q / d^2}{\not{q}} = \frac{k \cdot Q}{d^2}$$

$$\boxed{E = \frac{k \cdot Q}{d^2}}$$

Electric Potential

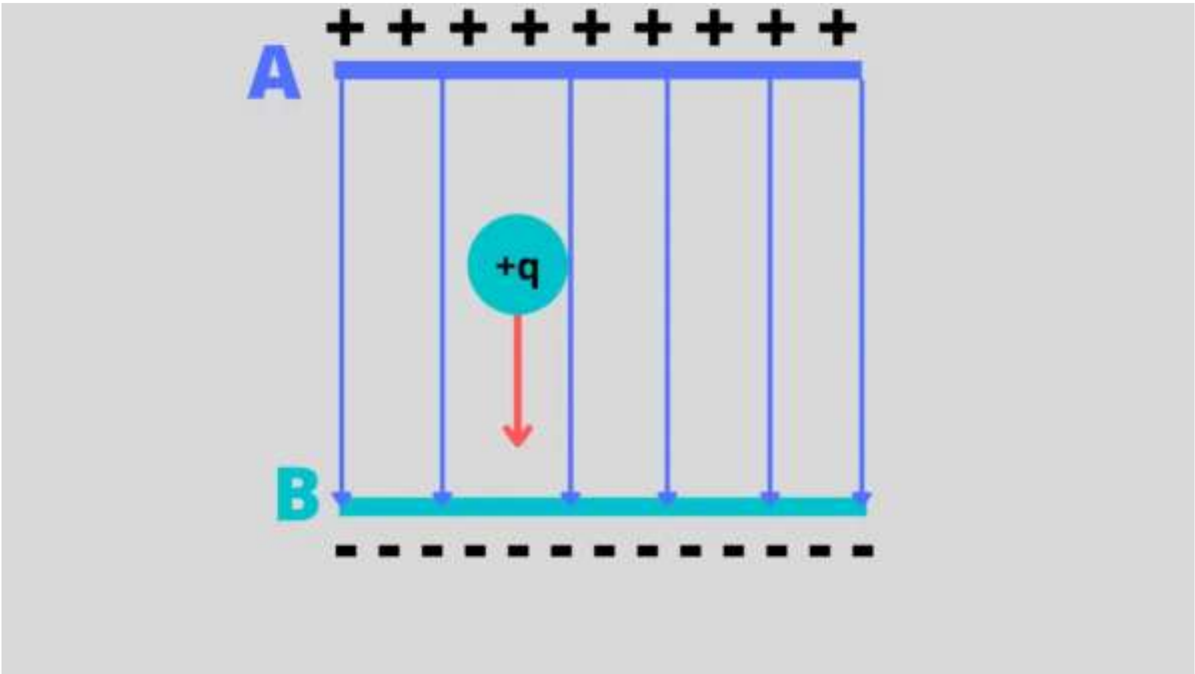
The electric field intensity was defined as the force on a unit test charge at that point at which we wish to find the value of this vector field.

If we attempt to move the test charge against the electric field, we have to exert a force equal and opposite to that exerted by the field, and this requires us to expend energy or do work.

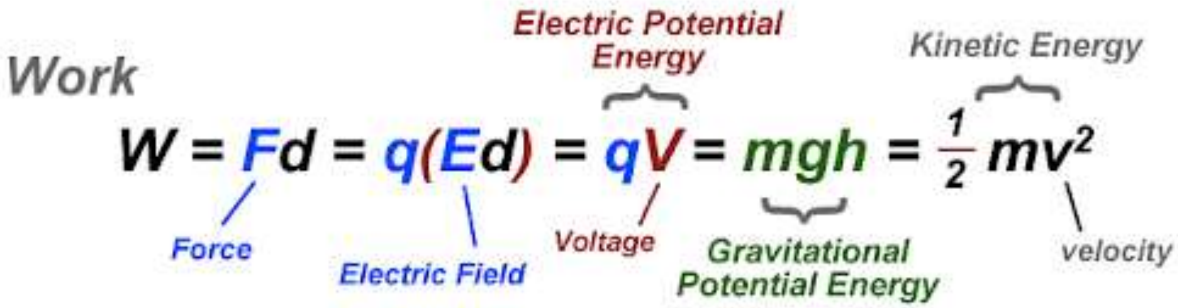


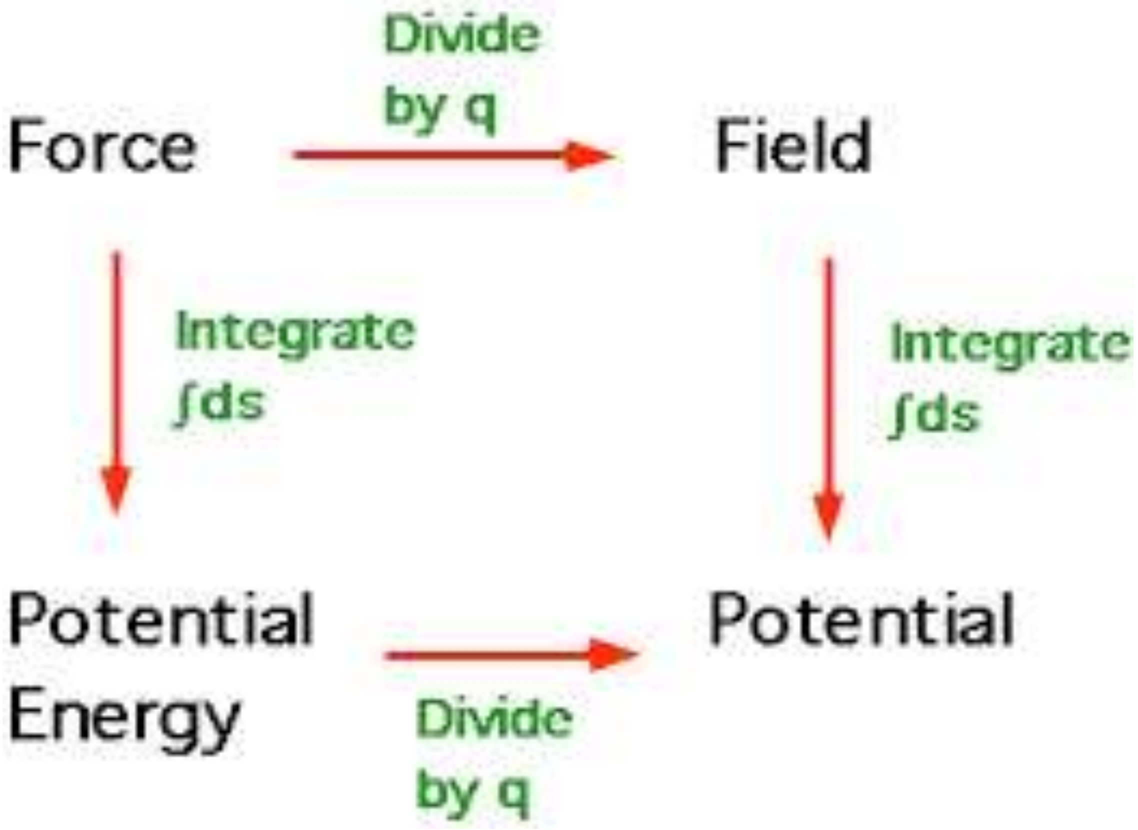
Electric Field Energy

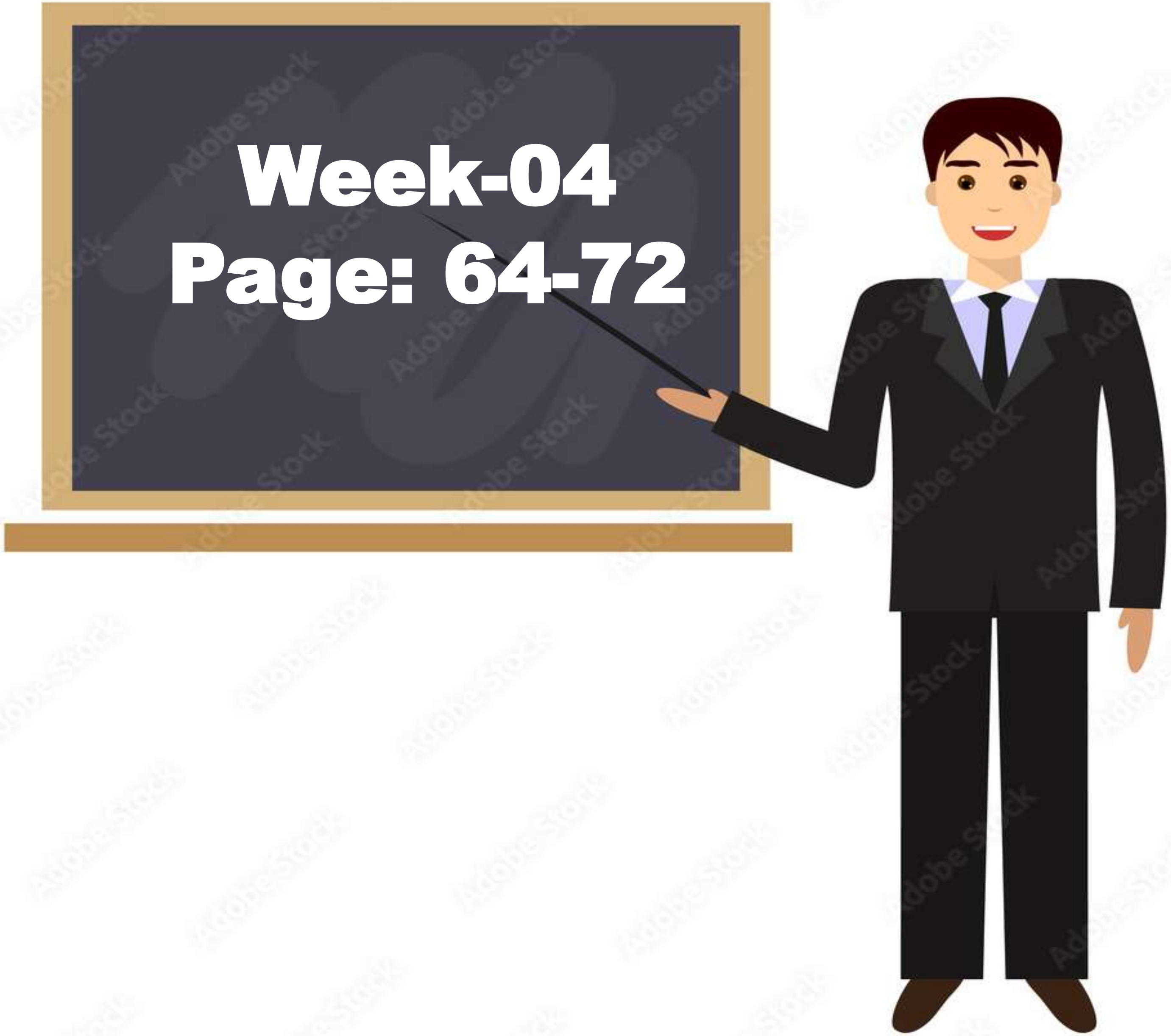
The electric field energy or electric potential energy is the energy required to move a charge through an electric field. It is the work done by a charged object in moving another charged object.



Electric Field Energy



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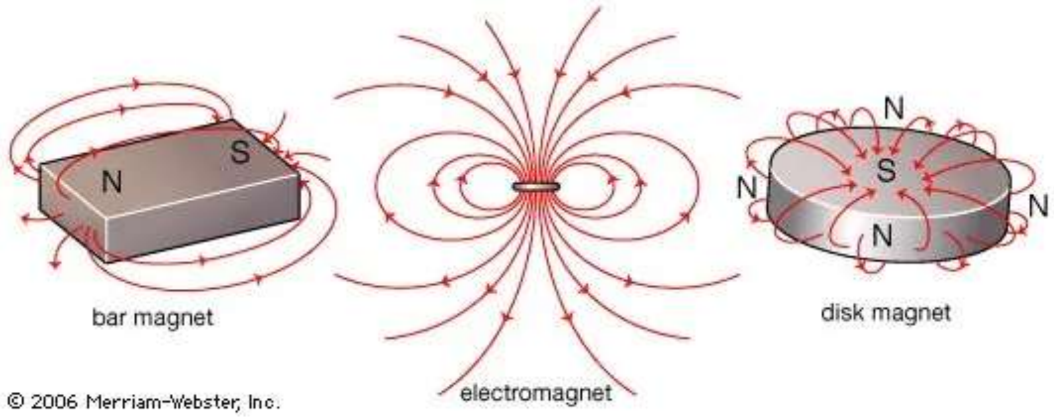
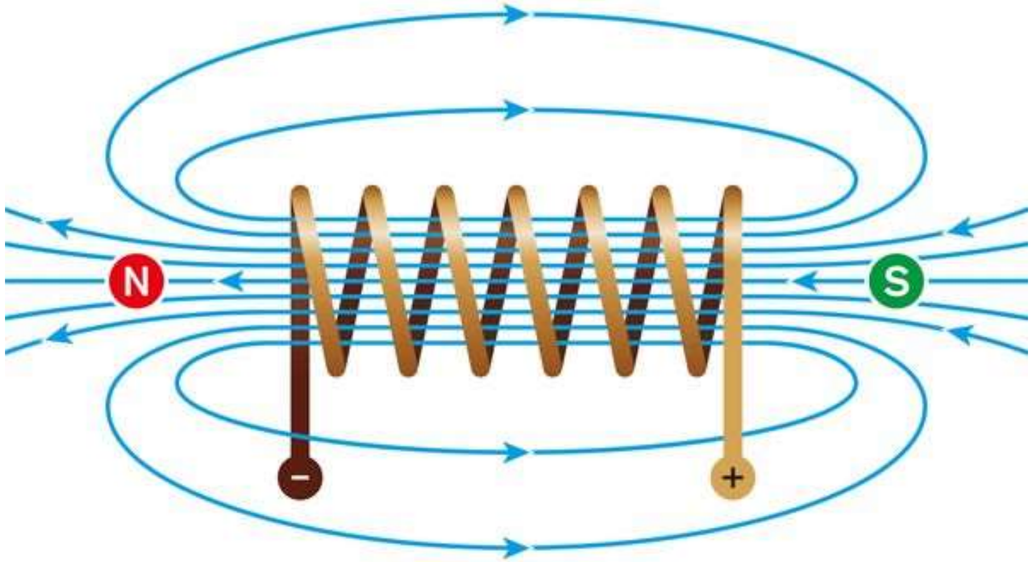
WEEK-04

Magnetostatics: Forces and Fields



Magnetostatics

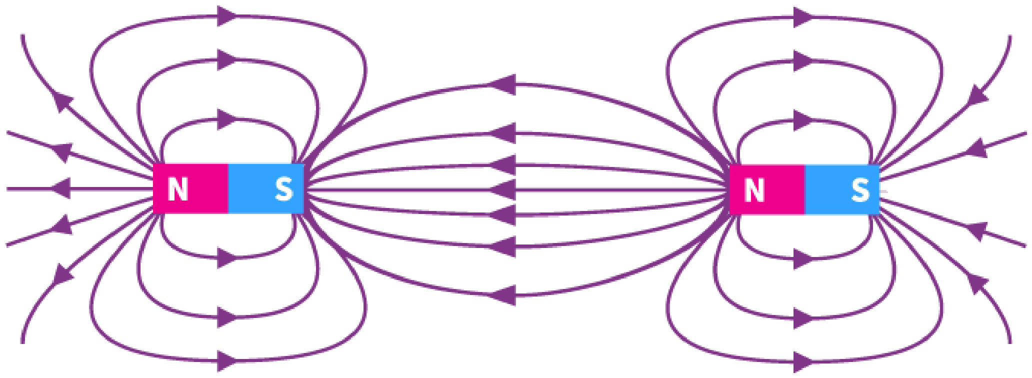
- Magnetostatics refers to the study of magnetic fields in situations where the currents are steady and unchanging, meaning the magnetic field remains constant over time; within this field, the primary force experienced is the magnetic force exerted on moving charges due to the presence of a magnetic field, typically described by the vector field "B" (magnetic flux density), and calculated using the Lorentz force law



Magnetic Field

Magnetic Field (B):

A magnetic field (B) is a physical field that describes the magnetic force on moving charges, electric currents, and magnetic materials. The strength of a magnetic field at a given point is called the magnetic flux density, which is measured in tesla (T).



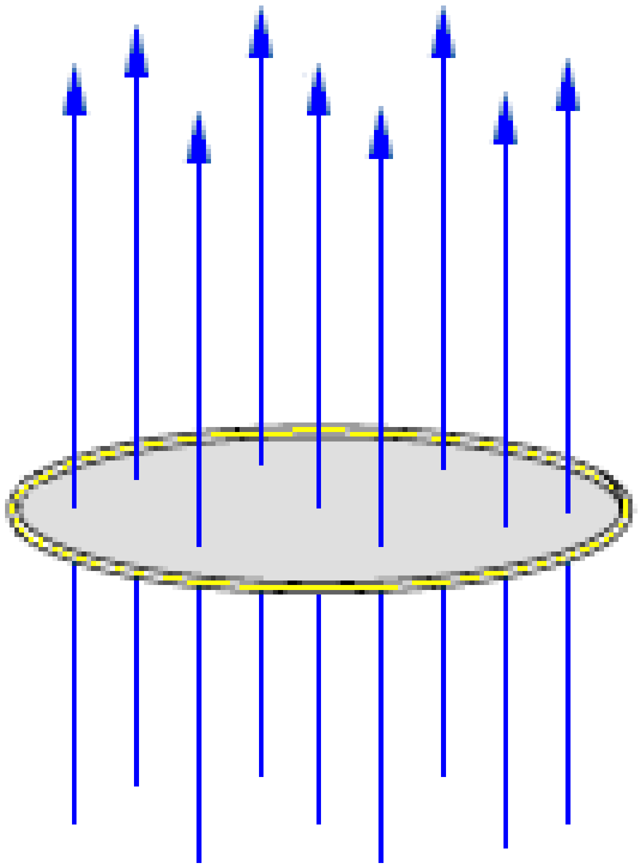
Magnetic Flux

Magnetic Flux:

The amount of magnetic field passing through a given area, measured in Weber (Wb).

Magnetic Field Lines:

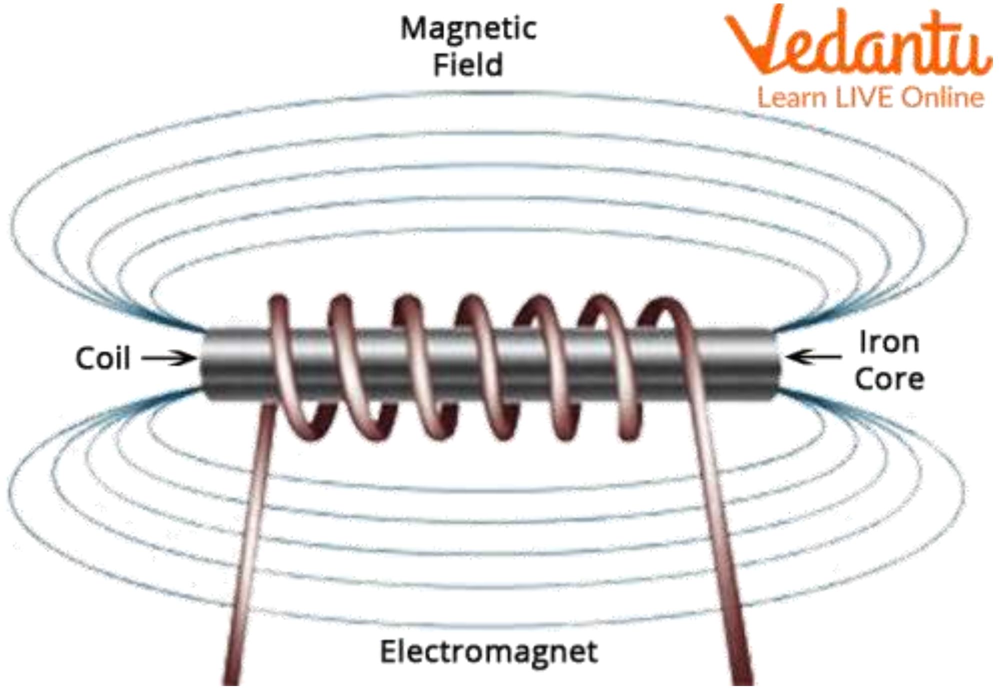
Imaginary lines used to visualize the direction of the magnetic field, where the lines are tangent to the field vector at any point



Electromagnets

Electromagnets:

Understanding the magnetic field generated by current-carrying coils to design electromagnets used in various applications like motors and generators.



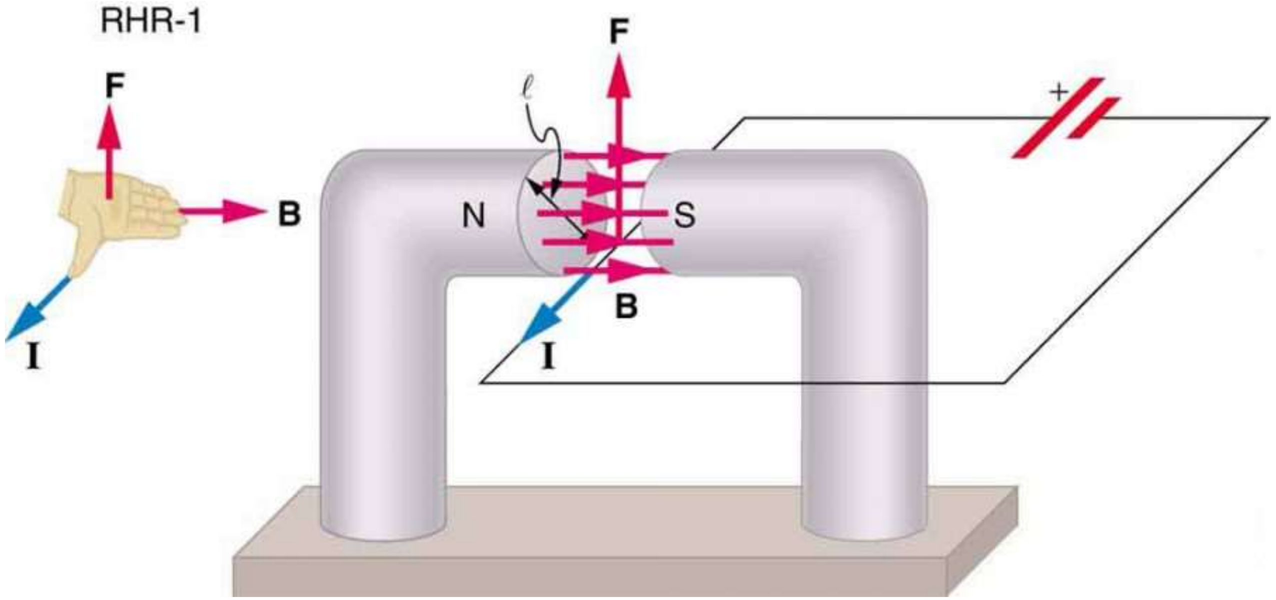
Magnetic forces on conductors

Magnetic forces on conductors:

Calculating the forces between current-carrying wires due to their magnetic fields.

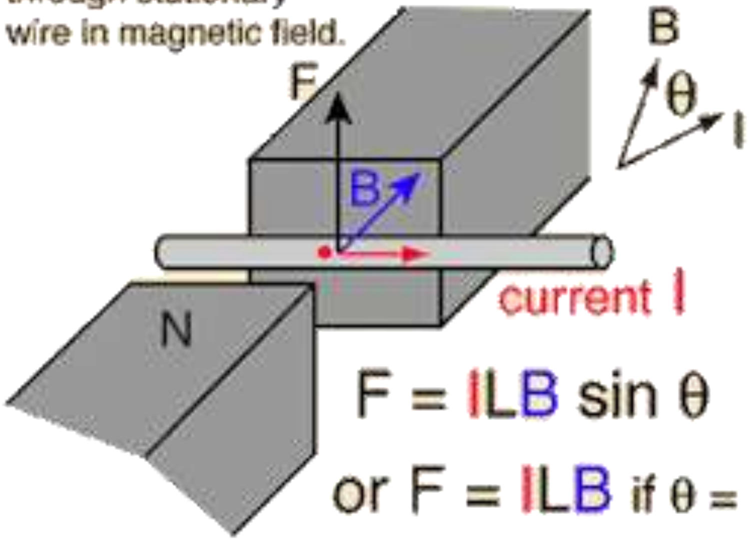
Direction of force:

The magnetic force on a moving charge is always perpendicular to both the velocity of the charge and the magnetic field



Magnetic forces on conductors

Positive charge moving through stationary wire in magnetic field.



$$F = ILB \sin\theta$$

or $F = ILB$ if $\theta = 90$

This relationship arises from the basic magnetic force:

$$F = qvB \sin\theta$$

which for a charge q traveling length L in a wire can be written

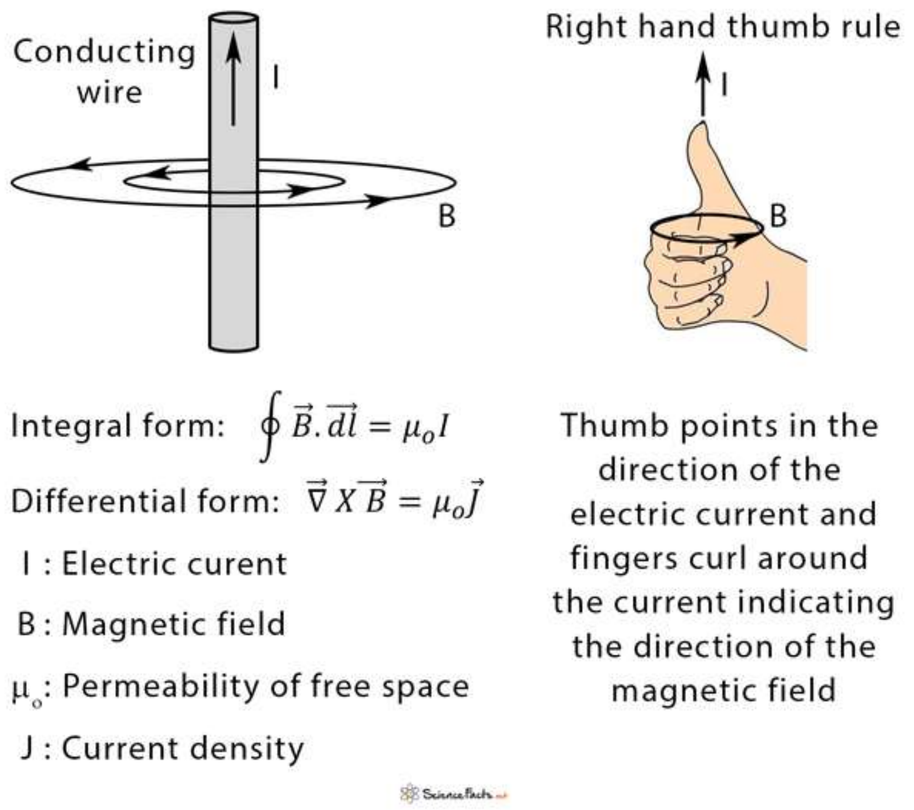
$$F = q\frac{L}{t}B \sin\theta$$

$$F = \frac{q}{t}LB \sin\theta$$

$$F = ILB \sin\theta$$

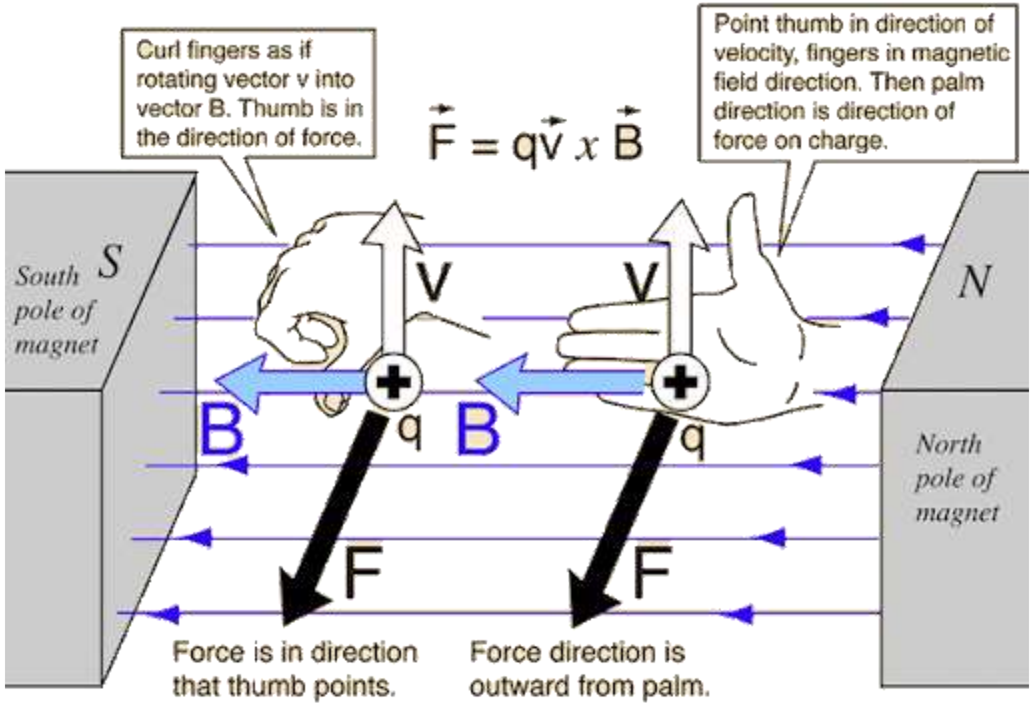
Ampere's Law:

This fundamental law relates the line integral of the magnetic field around a closed loop to the current enclosed by that loop, providing a means to calculate the magnetic field produced by a current distribution. o calculate the magnetic field produced by a current distribution



Lorentz force law:

Lorentz force law:
This equation describes the total force experienced by a charged particle in an electromagnetic field, including both electric and magnetic components.



$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

Electric force

Magnetic force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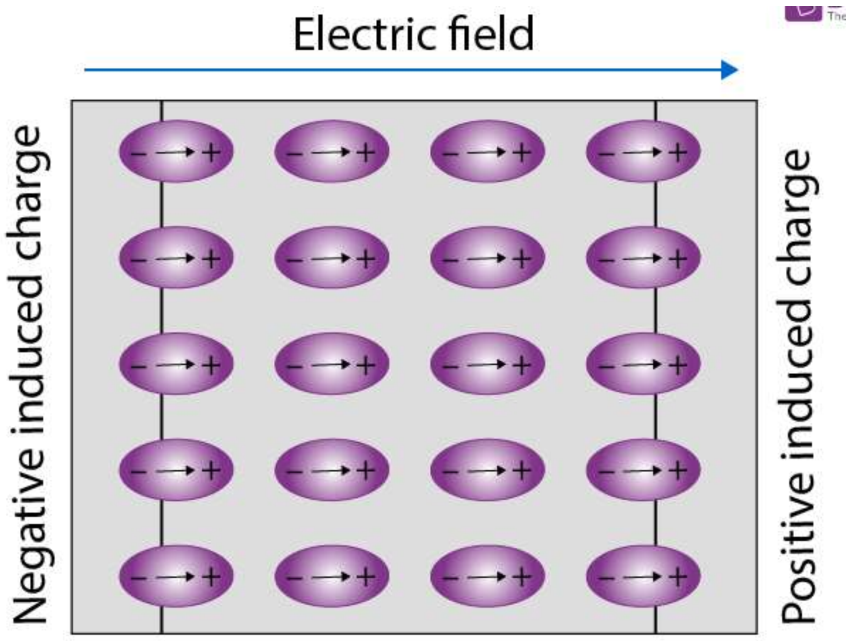
WEEK-05

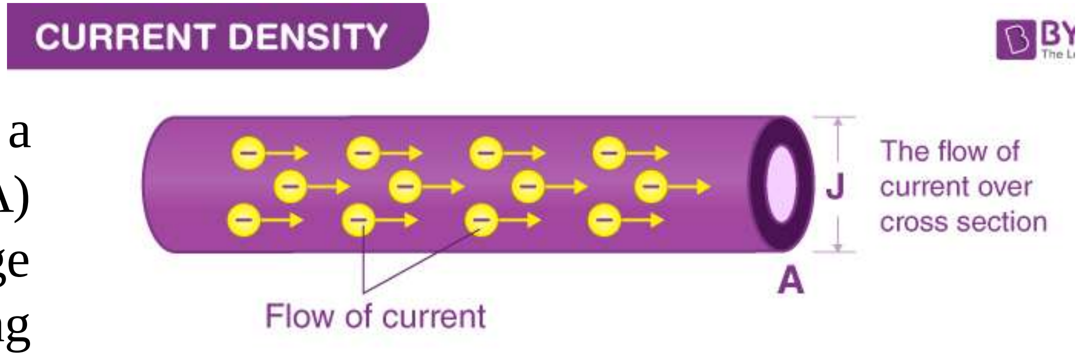
Fields in Dielectrics and Conductors



Current and Conductors

The current through the conductors and capacitors depend upon the fundamental electromagnetic principles.

Current and current density



Electric charges in motion constitute a current. The unit of current is the Ampere (A) defined as rate of movement of charge passing a given reference point (or crossing given reference plane) of one coulomb per second. Current is symbolized by ***I*** and

Current and Conductors

Current is thus defined as the motion of the positive charges, even though conduction in metal takes place through the motion of electrons.

In field theory we are usually interested in events occurring at a point rather than within some large region, and we shall find the concept of current density, measured inamperes per square meter (A/m2), more useful. Current density is a vector represented by J.

Current density may be related to the velocity of volume charge density at a point.

Current and Conductors

$$J = \frac{I}{A} \Rightarrow J = \frac{V}{RA} = \frac{VL}{RAL} = \frac{L}{RA} \times \frac{V}{L}$$

$$\frac{1}{\frac{RA}{L}} \times \frac{V}{L} = \frac{1}{\rho}E = \sigma E$$

$$\therefore J = \sigma E$$

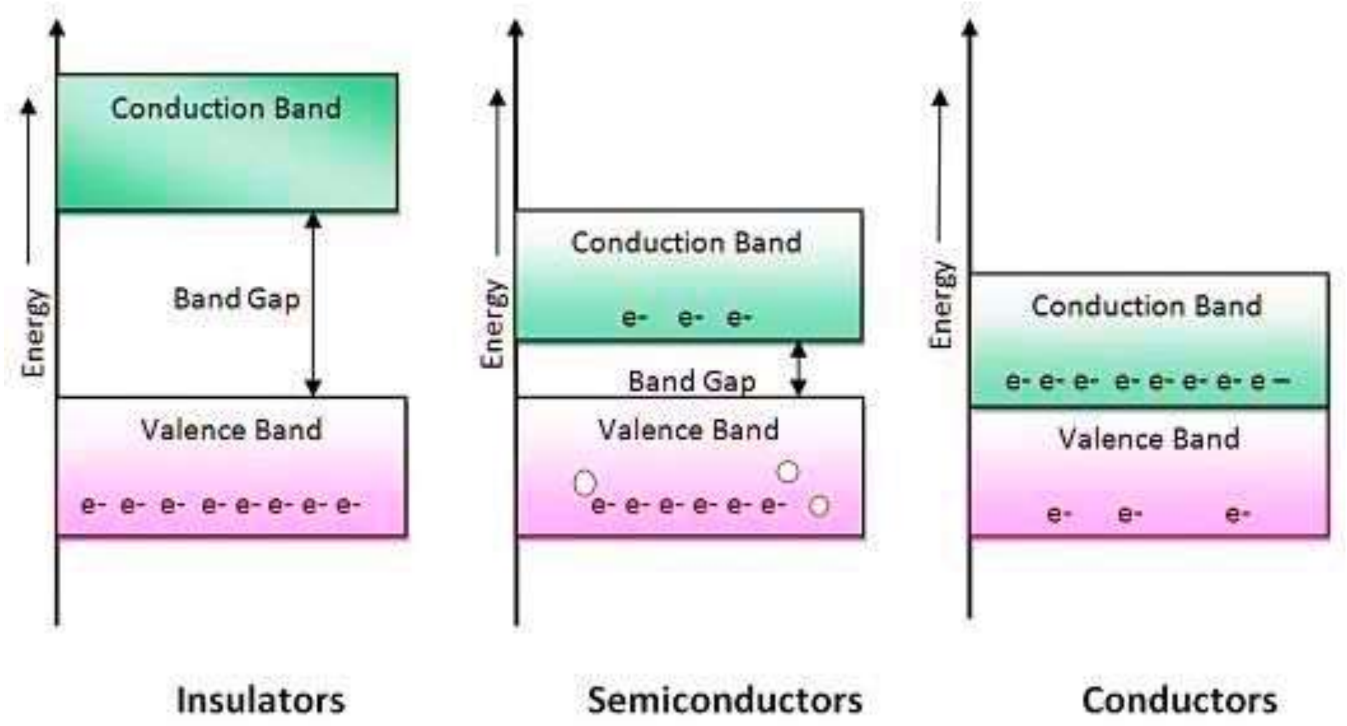
This last result shows very clearly that charge in motion constitutes a current. We call this type of current a convection current, and **J** or $\rho_v\mathbf{v}$ is the convection current density.

Metallic Conductors

In a crystalline solid, such as a metal or a diamond atoms are packed closely together, many more electrons are present, and many more permissible energy levels are available because of the interaction forces between adjacent atoms. We find that the energies which may be possessed by electrons are grouped into broad ranges, or “bands”, each band consisting of very numerous, closely spaced, discrete levels.

Metallic Conductors

At a temperature of absolute zero, the normal solid also has every level occupied, starting with the lowest and proceeding in order until all the electrons



The energy band structure in three different types of materials at 0 K. (a) The conductor exhibits no energy gap between the valence and conduction band. (b) The insulator shows a large energy gap. (c) The semiconductor has only a small energy gap.

Let us first consider the conductor. Here the valence electrons, or *conduction*, or *free*, electrons, move under the influence of an electric field. With a field **E**, an electron having a charge $Q = -e$ will experience a force

$$\mathbf{F} = -e\mathbf{E}$$

In free space the electron would accelerate and continuously increase its velocity (an energy); In the crystalline material the progress of the electron is impeded by continual collisions with the thermally excited crystalline lattice structure, and a constant average velocity soon attained.

This velocity v_d is termed the drift velocity and

it is linearly related to the electric field intensity by the mobility of the electrons in the given material. We designate mobility by the symbol μ, so that

$$v_d = -\mu_e \mathbf{E}$$

where μ_e is the mobility of the electron and is positive by definition. Then from equation (3) we can get the equation of current density in terms of drift velocity as follows:

$$\mathbf{J} = -p_e \mu_e \mathbf{E}$$

where ρ_e is the free-electron charge density, a negative value. The total charge density ρ_v is

zero because equal positive and negative charge is present in the neutral material. The negative value of ρ_e and the minus sign lead to a current density **J** that is in the same direction as the electric field intensity **E**.

The relationship between **J** and **E** for a metallic conductor, however, is specified by the conductivity σ (sigma),

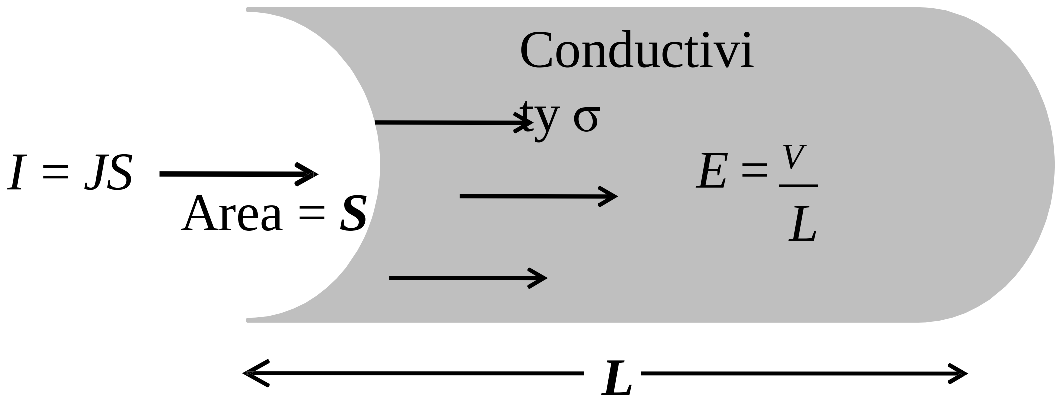
$$\mathbf{J} = \sigma \mathbf{E}$$

Equation (8) describes the relationship between voltage and current and it is called the point form of ***Ohm's law***.

If we now combine equation (7) and (8), the conductivity may be expressed in terms of the charge density and the electron mobility,

$$\sigma = -p_e \mu_e \qquad (9)$$

The application of Ohm’s law in point form to a macroscopic region leads to a more familiar form. Initially, let us assume that **J** and **E** are *uniform* as they are in the cylindrical region shown in the figure below.



Since they are uniform

$$I = \int_S \mathbf{J} . d\mathbf{S} = JS \qquad (10)$$

and

$$V_{ab} = -\int_b^a \mathbf{E} . d\mathbf{L} = -\mathbf{E}. \int_b^a dL = -\mathbf{E}.\mathbf{L}_{ba}$$

$$= \mathbf{E}.\mathbf{L}_{ba} \qquad (11)$$

or $$V = EL$$

Thus $$J = \frac{I}{S} = x E = \sigma \frac{V}{L}$$

or $$V = \frac{L}{\sigma S} I$$

The ratio of the potential difference between the two ends of the cylinder to the current entering the more positive end, however, is recognized from elementary circuit theory as the resistance of the cylinder, and therefore

$$V = I R \tag{12}$$

where

$$R = \frac{L}{\sigma S} \tag{13}$$

We may write the general expression of resistance when the fields are nonuniform,

$$R = \frac{V_{ab}}{I} = \frac{-\int_b^a \mathbf{E}.d\mathbf{L}}{\int_S \sigma \mathbf{E}.d\mathbf{S}} \qquad (14)$$

The line integral is taken between two equipotential surfaces in the conductor, and the surface integral is evaluated over the more positive of these two equipotentials.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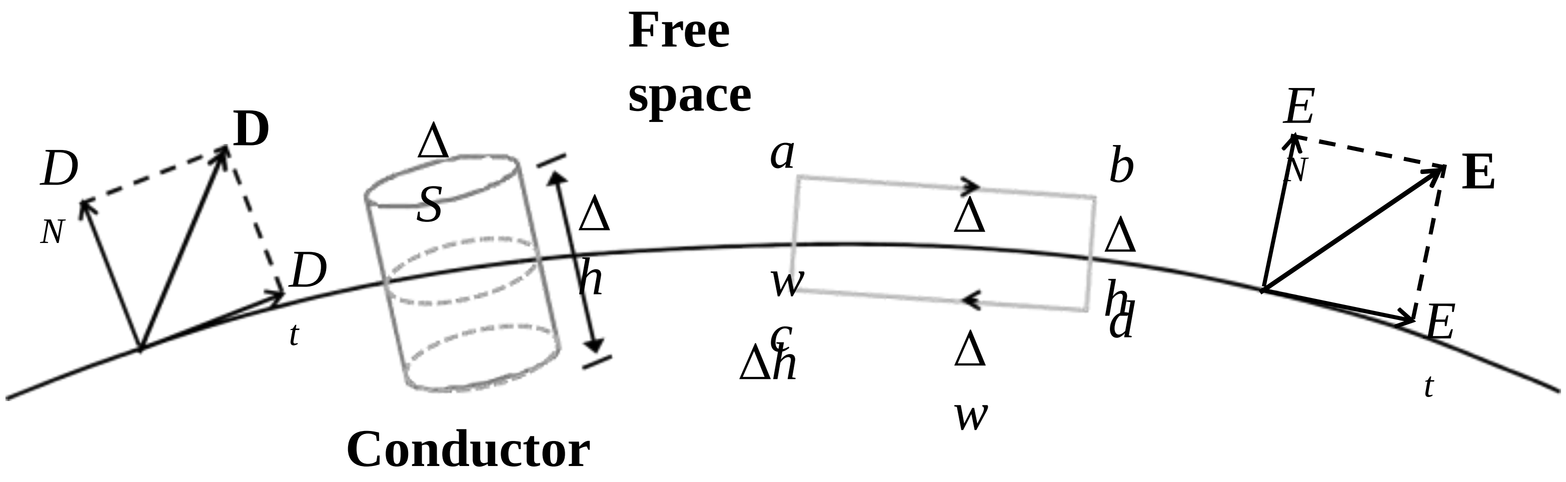
WEEK-06

Boundary Conditions

Conductor Properties and Boundary Conditions



Once again we must temporarily depart from our assumed static conditions and let time vary for a few microseconds to see what happens when the charge distribution is suddenly unbalanced within a conducting material.

Let us suppose, for a sake of the argument, that there suddenly appear a a number of electrons in the interior of conductor. Electric field set up by these

electrons are not counteracted by any positive charges, and the electrons therefore begin to accelerate away from each other. This continues until the electrons reach the surface of the conductor or until a number of electrons equal to the number injected have reached the surface.

Here the outward progress of the electrons is topped, for the material surrounding the conductor is an insulator not possessing a convenient conduction band. No charge may remain within conductor. If it did, the resulting electric field would force the charges to the surface.

Hence the final result (i) within a conductor is zero charge density, and a surface charge density resides on the exterior surface. This is one of the two characteristic of a good conductor.

The other characteristic, stated (ii) for static conditions in which no current may flow, follows directly from Ohm’ law: the electric field intensity within the conductor is zero. Physically we see that if an electric field were present, the conduction electrons would move and produce a current, thus leading to a nonstatic condition.

Summarizing for electrostatics, **no charge and no electric field may exist at any point within a conducting material**. **Charge may**, however, **appear on the surface as a surface charge density**, and our next investigation concerns the fields *external* to the conductor.

If the external field intensity is decomposed into two components **tangential** and one **normal** to the conductor surface, the tangential component is seen to be zero. If it were not zero, a tangential force would be applied to the elements of the surface charge, resulting in their motion and nonstatic conditions. Since static condition is assumed, the tangential electric field intensity and electric flux density are zero.

SEMICONDUCTORS

Many semiconductor properties is described by treating the hole as the positive charge of e, and a mobility, μ_h, and an effective mass comparable to that of the electron. Both

carriers (electrons and holes) move in an electric field, and they move in opposite directions, hence each contributes a component of the total current which in the same direction as that provided by the other.

The **conductivity** is therefore a function of

Dielectrics and Capacitance

The charge displacement principle constitutes an energy storage mechanism that becomes useful in the construction of capacitors. Furthermore, the response of the dielectric to time-varying

fields, particularly electromagnetic waves, is extremely important to the understanding of the many physical phenomena and to the development of useful devices.

The Nature of Dielectric Materials

A dielectric in an electric field can be viewed **as a free-space arrangement of microscopic electric dipoles** which are **composed of positive and negative charges** whose center do not coincide.

These are not free charges and **they cannot contribute to the conduction process**, rather, they are bound in place by atomic and molecular forces and **can only shift positions slightly in response to external fields**.

They are called bound charges, in contrast to the free charges that determine conductivity. **Bound charges can be treated as any other sources of the electrostatic field**. Therefore **we need to introduce the dielectric constant as a new parameter** or to deal with permittivities different from the permittivity of free space; however, the alternative would to be consider ***every charge within a piece of dielectric material***.

This is too great a price to pay for using all our previous equations in an unmodified form, and we shall therefore spend some time **theorizing about dielectrics in a quantitative way**; introducing **polarization P**, **permittivity** ε, and **relative permittivity** ε_r; and developing some quantitative relationships involving these new quantities.

The characteristic which all dielectric materials have common, whether they are solid, liquid, or gas, and whether or not they are crystalline in nature, **is their ability to store electric energy**. This store takes place by means of **a shift in the relative position of the internal**, **bound positive and negative charges**

against the normal molecular and atomic forces.

The actual mechanism of the charge displacement differs in the various dielectric

materials. Some molecules, termed polar molecules have a permanent displacement

existing between the centers of “gravity” of the positive and negative charges, and **each pair of charges acts as a dipole**.

Normally **the dipoles are oriented in a random way throughout the interior of the material**, and **the action of external field is to align these molecules, to some extend**,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WEEK-07

Time-Varying Fields: Maxwell's Equations

TIME VARYING FIELDS

Maxwell’s Equations

The two new concepts will be introduced:

(i) The electric field produced by a changing magnetic field and

(ii) the magnetic field produced by changing electric field.

The first of these concepts resulted from experimental research by Michael Faraday, and the second from the theoretical efforts by James Clerk Maxwell.

FARADAY'S LAW

Faraday's law is customarily stated as

$$\text{emf} = -\frac{d\varphi}{dt} \text{ V} \qquad (1)$$

The equation states that time-varying magnetic field produces an electromotive force (emf) which may establish a current in a suitable closed circuit.

A non-zero value of $d\varphi/dt$ may result from any of the following situations:

(i) A time-changing flux linking a stationary closed path

(ii) Relative motion between a steady flux and a close path

(iii) A combination of the two.

The minus sign in the equation states the situation of Lenz's law.

If the closed path is that taken by an N-turn filamentary conductor, it is often sufficiently accurate to consider the turns as coincident and let

$$\text{emf} = -N \frac{d\phi}{dt} \qquad (2)$$

where φ is now interpreted as the flux passing through any one of N coincident paths.

We need to define emf as used in equation (1) or (2). The emf is obviously a scalar, and (perhaps not so obviously) a dimensional check shows that it is measured in volts.

We define the emf as

$$emf = \oint \mathbf{E} \cdot d\mathbf{L} \qquad (3)$$

Replacing φ in equation (1) by the surface integral of **B** we have

$$emf = \oint \mathbf{E} \cdot d\mathbf{L} = -\frac{d}{dt}\int_s \mathbf{B} \cdot d\mathbf{S} \qquad (4)$$

We first consider a stationary path. The magnetic flux is the only time-varying quantity on the right side of (4), and a partial derivative may be taken under the integral sign

$$emf = \oint d\mathbf{L} = -\int_s \frac{\partial}{\partial t}\mathbf{B}\, d\mathbf{S} \qquad (5)$$

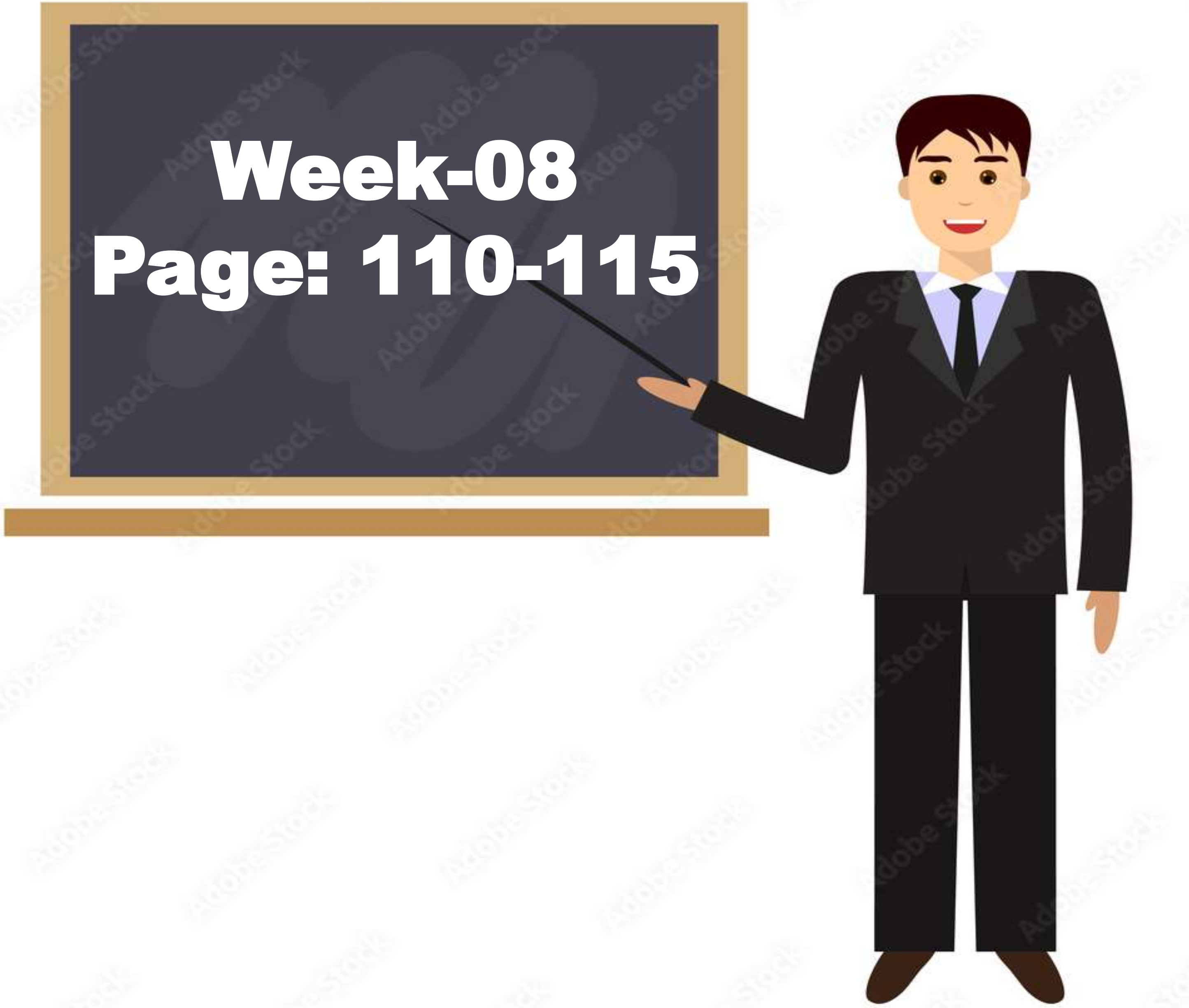
Now applying Stokes theorem in the left-hand side of equation (5) we have

$$\int_s (\nabla\times\mathbf{E})\, d\mathbf{S} = -\int_s \frac{\partial}{\partial t}\mathbf{B}\, d\mathbf{S} \qquad (6)$$

and

$$(\nabla\times\mathbf{E}) = -\frac{\partial \mathbf{B}}{\partial t} \qquad (7)$$

Equation (7) is the one of Maxwell's equation written in differential or point form, the form which they are most generally used.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WEEK-08

Time-Varying Fields: Poynting Vector

WAVE PROPAGATION IN LOSSY DIELECTRICS

A lossy dielectric is a medium in which an EM wave loses power as it propagates due to poor conduction.

In other words, a lossy dielectric is a partially conducting medium (imperfect dielectric or imperfect conductor) with $\sigma \neq 0$, as distinct from a lossless dielectric (perfect or good dielectric) in which $\sigma = 0$.

Consider a linear, isotropic, homogeneous, lossy dielectric medium that is charge free ($\rho_v = 0$). Assuming and suppressing the time factor $e^{\alpha t}$, Maxwell's equations become

$$\nabla \cdot \mathbf{E}_s = 0$$

$$\nabla \cdot \mathbf{H}_s = 0 \qquad (21)$$

$$\nabla \times \mathbf{E}_s = -j\omega\mu\mathbf{H}_s \qquad (22)$$

$$\nabla \times \mathbf{H}_s = (\sigma + j\omega\varepsilon)\mathbf{E}_s$$

Taking the curl of both sides of eq. (21) gives

$$\nabla \times \nabla \times \mathbf{E}_s = -j\omega\mu \, \nabla \times \mathbf{H}_s \qquad (23)$$

Applying the vector identity

$$\nabla(\nabla \cdot \mathbf{E}_s) - \nabla^2 \mathbf{E}_s = -j\omega\mu(\sigma + j\omega\varepsilon)\mathbf{E}_s$$

$$\nabla \cdot \mathbf{E}_s = 0$$

or

$$\boxed{\nabla^2 \mathbf{E}_s - \gamma^2 \mathbf{E}_s = 0} \quad (24)$$

where

$$\gamma^2 = j\omega\mu(\sigma + j\omega\varepsilon) \quad (25)$$

and γ is called the propagation constant (in per meter) of the medium. By a similar procedure, it can be shown that for the **H** field,

$$\nabla^2 \mathbf{H}_s - \gamma^2 \mathbf{H}_s = 0 \quad (26)$$

Since γ in eqs. (24) to (26) is a complex quantity, we may let

$$\boxed{\gamma = \alpha + j\beta} \tag{27}$$

We obtain α and β from eqs. (25) and (27) by noting that

$$-\mathrm{Re}\,\gamma^2 = \beta^2 - \alpha^2 = \omega^2\mu\varepsilon \tag{28}$$

and

$$|\gamma^2| = \beta^2 + \alpha^2 = \omega\mu\sqrt{\sigma^2 + \omega^2\varepsilon^2} \tag{29}$$

From eqs. (28) and (29), we obtain

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1 + \left[\frac{\sigma}{\omega\varepsilon}\right]^2} - 1\right]} \quad (30)$$

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1 + \left[\frac{\sigma}{\omega\varepsilon}\right]^2} + 1\right]} \quad (31)$$


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WEEK-09

Uniform Plane Waves: Transmission & Reflection

PLANE WAVES IN LOSSLESS DIELECTRICS

In a lossless dielectric, $\sigma << \omega\varepsilon$. It is a special case of that in the previous section

$$\sigma \simeq 0, \qquad \varepsilon = \varepsilon_o \varepsilon_r, \qquad \mu = \mu_o \mu_r \tag{49}$$

Substituting these into eqs. (30) and (31) gives

$$\alpha = 0, \qquad \beta = \omega\sqrt{\mu\varepsilon} \tag{50}$$

$$u = \frac{\omega}{\beta} = \frac{1}{\sqrt{\mu\varepsilon}}, \qquad \lambda = \frac{2\pi}{\beta} \tag{51}$$

Also

$$\eta = \sqrt{\frac{\mu}{\varepsilon}}\angle 0^\circ \tag{52}$$

and thus **E** and **H** are in time phase with each other.

PLANE WAVES IN FREE SPACE

In this case,

$$\boxed{\sigma = 0, \qquad \varepsilon = \varepsilon_o, \qquad \mu = \mu_o} \tag{53}$$

Then from (30) and (31) we have

$$\alpha = 0, \qquad \beta = \omega\sqrt{\mu_o\varepsilon_o} = \frac{\omega}{c} \tag{54}$$

$$u = \frac{1}{\sqrt{\mu_o\varepsilon_o}} = c, \qquad \lambda = \frac{2\pi}{\beta} \tag{55}$$

where c ≈ 3 X 10^8 m/s, the speed of light in a vacuum. The fact that EM wave travels in free space at the speed of light is significant. It shows that light is the manifestation of an EM wave. In other words, light is characteristically electromagnetic.

Putting (53) in (38) we get the **intrinsic impedance in free space**

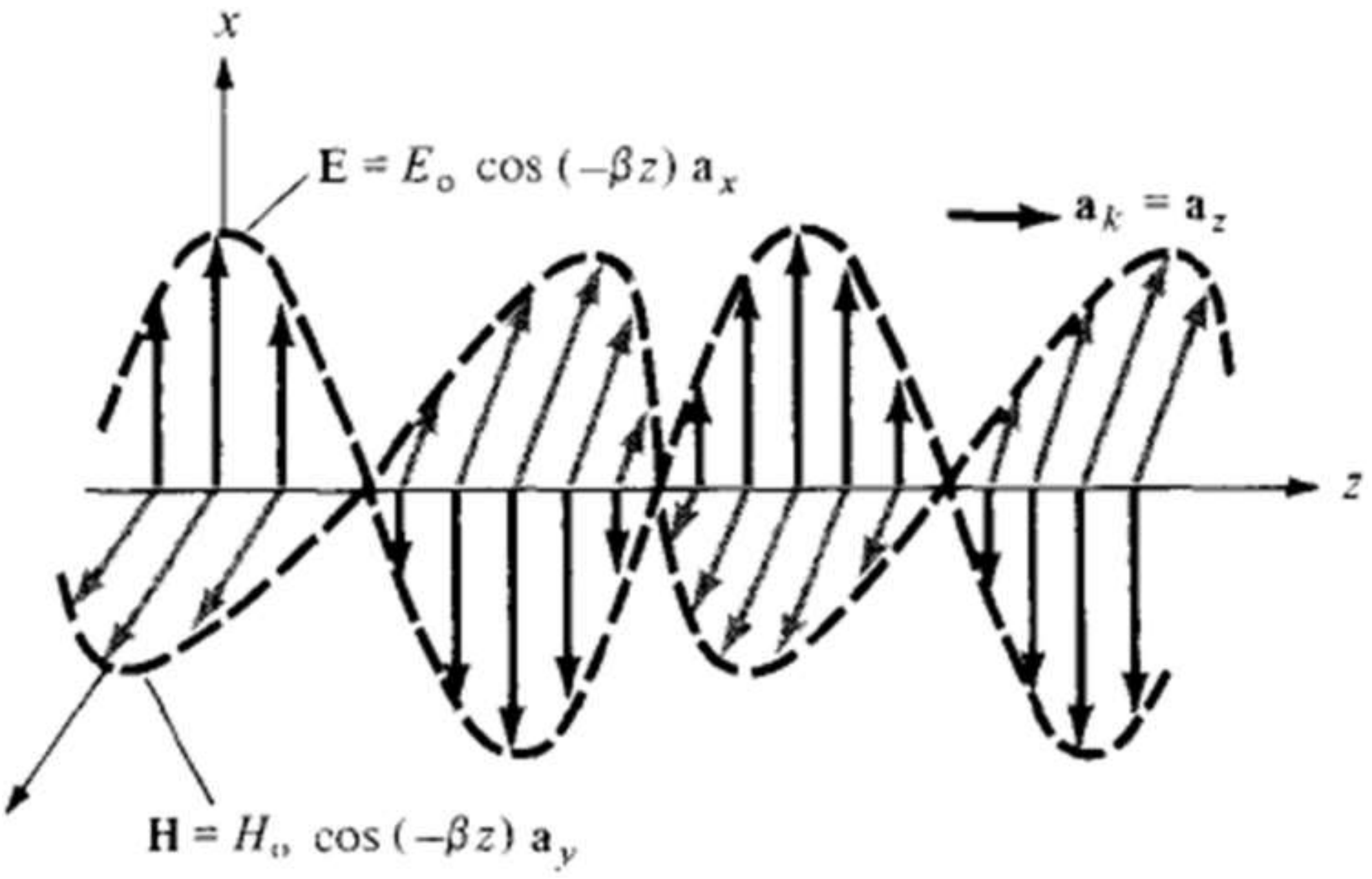
$$\eta_o = \sqrt{\frac{\mu_o}{\varepsilon_o}} = 120\pi \simeq 377\ \Omega \qquad (56)$$

So

$$\mathbf{E} = E_o \cos(\omega t - \beta z)\, \mathbf{a}_x \qquad (57)$$

Then

$$\mathbf{H} = H_o \cos(\omega t - \beta z)\, \mathbf{a}_y = \frac{E_o}{\eta_o} \cos(\omega t - \beta z)\, \mathbf{a}_y \qquad (58)$$



Plot of E and H as functions of *z* at *t* = 0.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WEEK-10

Uniform Plane Waves: Skin Effect and Resistance

PLANE WAVES IN GOOD CONDUCTORS

A perfect, or good conductor, is one in which $\sigma >> \omega\varepsilon$ we so that $\sigma / \omega\varepsilon \rightarrow \infty$; that is,

$$\boxed{\sigma \simeq \infty, \qquad \varepsilon = \varepsilon_o, \qquad \mu = \mu_o \mu_r} \tag{59}$$

Then from (30) and (31) we have

$$\alpha = \beta = \sqrt{\frac{\omega\mu\sigma}{2}} = \sqrt{\pi f \mu\sigma} \tag{60}$$

$$u = \frac{\omega}{\beta} = \sqrt{\frac{2\omega}{\mu\sigma}}, \qquad \lambda = \frac{2\pi}{\beta} \tag{61}$$

Als
o

$$\eta = \sqrt{\frac{\omega\mu}{\sigma}}\angle 45^\circ \quad (62)$$

and thus **E** leads **H** by 45°. If

$$\mathbf{E} = E_o e^{-\alpha z}\cos(\omega t - \beta z)\,\mathbf{a}_x \quad (63)$$

then

$$\mathbf{H} = \frac{E_o}{\sqrt{\frac{\omega\mu}{\sigma}}} e^{-\alpha z}\cos(\omega t - \beta z - 45^\circ)\,\mathbf{a}_y \quad (64)$$

Therefore, as E (or H) wave travels in a conducting medium, its amplitude is attenuated by the factor $e^{-\alpha z}$.

The distance δ, shown in figure below, through which the wave amplitude decreases by a factor e^{-1} (about 37%) is **called skin depth or penetration depth of the medium**;

that is, $$E_o e^{-\alpha\delta} = E_o e^{-1}$$

or $$\boxed{\delta = \frac{1}{\alpha}} \qquad (65a)$$

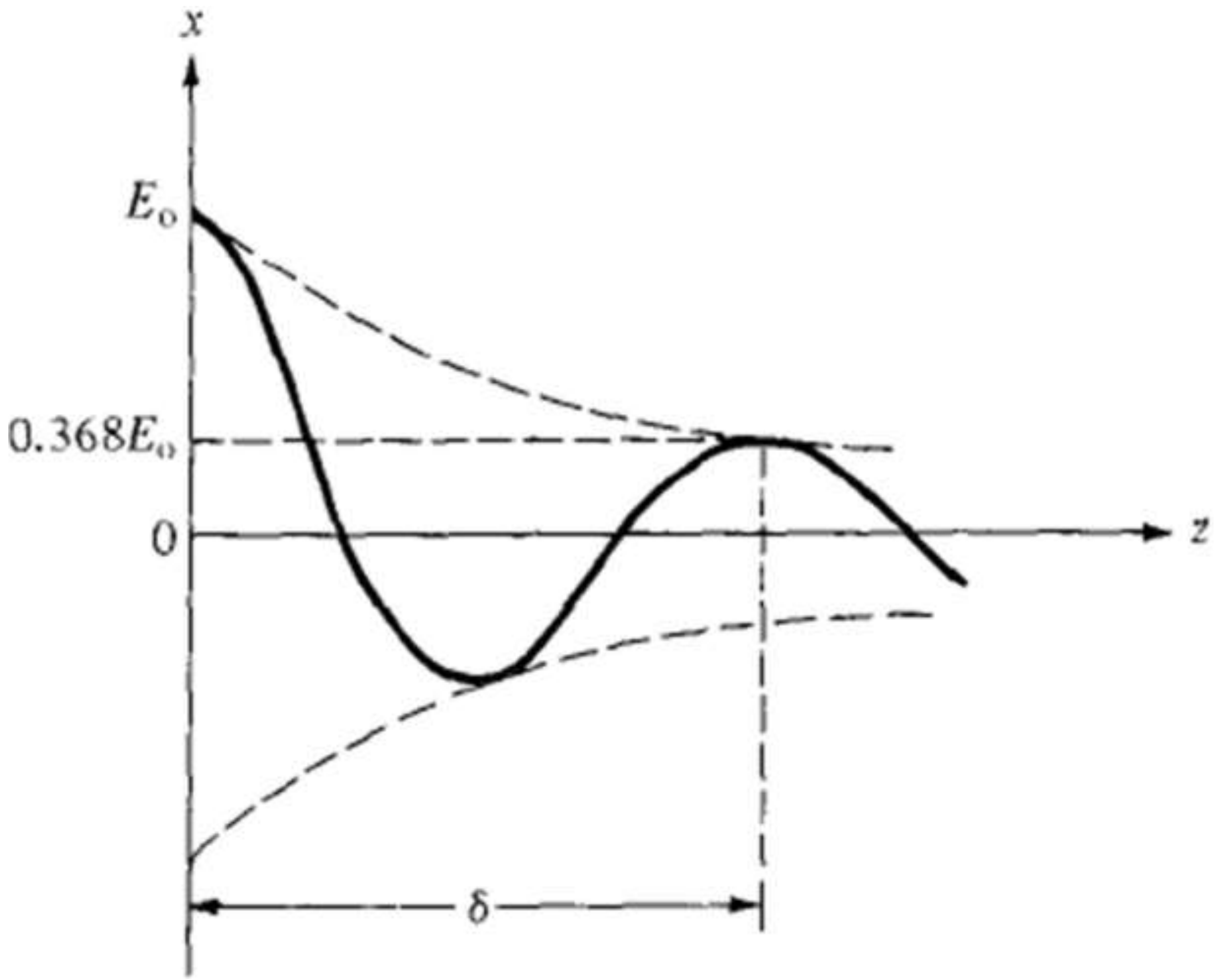


Illustration of skin depth.

The **skin depth** is a measure of the depth to which an EM wave can penetrate the medium.

Equation (65a) is generally valid for any material medium. For good conductors, eqs. (60) and (65a) give

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{65b}$$

Note from eqs. (60), (62), and (65b) that for a good conductor

$$\eta = \frac{1}{\sigma\delta}\sqrt{2}\, e^{j\pi/4} = \frac{1+j}{\sigma\delta} \tag{66}$$

We define the **surface or skin resistance** R_s (in Ω/m^2) as the real part of the η a good conductor. Thus from eq. (66)

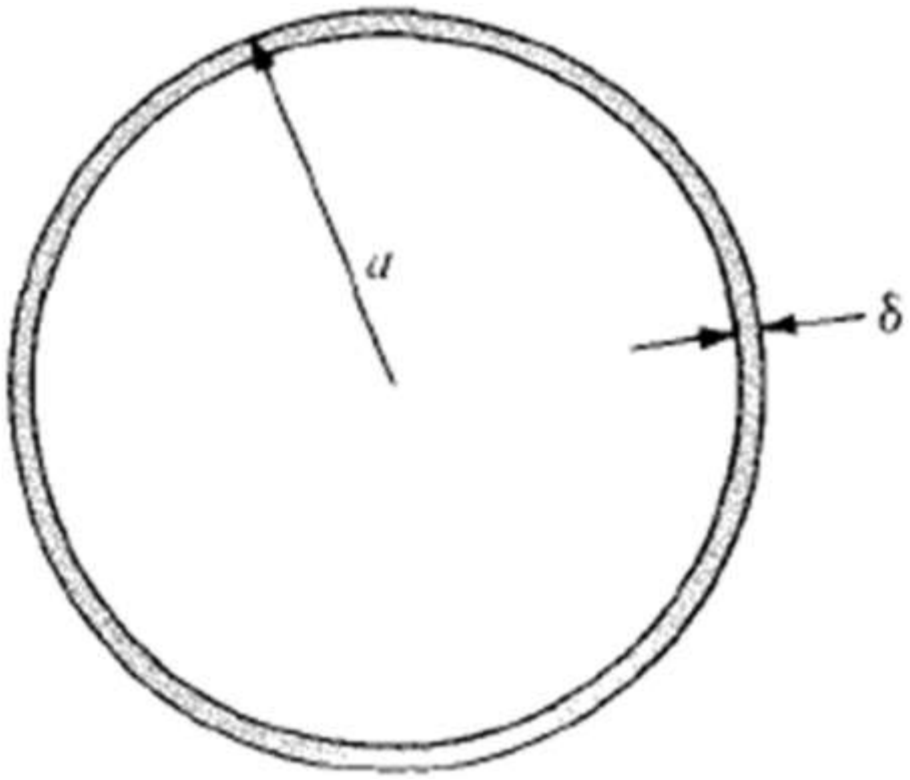
$$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\pi f \mu}{\sigma}} \tag{68}$$

This is the resistance of a unit width and unit length of the conductor. It is equivalent to the **dc resistance** for a unit length of the conductor having cross-sectional area 1Xδ.

Thus for a given width w and length l, the ac resistance is calculated using the familiar dc resistance relation of eq. (13) and assuming a uniform current flow in the conductor of thickness δ, that is,

$$R_{ac} = \frac{\ell}{\sigma \delta w} = \frac{R_s \ell}{w} \quad (69)$$

where $S = \delta w$. For a conductor wire of radius a (see Figure below), $w = 2\pi a$,



Skin depth at high frequencies, δ << *a*.

so

$$\frac{R_{ac}}{R_{dc}} = \frac{\dfrac{\ell}{\sigma 2\pi a\delta}}{\dfrac{\ell}{\sigma\pi a^2}} = \frac{a}{2\delta} \tag{70}$$

Since $\delta << a$ at high frequencies, this shows that R_{ac} is far greater than R_{dc}. In general, the ratio of the ac to the dc resistance starts at 1.0 for dc and very low frequencies and increases as the frequency increases.

Also, although the bulk of the current is nonuniformly distributed over a thickness of 5δ of the conductor, the power loss is the same as though it were uniformly distributed over a thickness of δ and zero elsewhere. This is one more reason why δ is referred to as the skin depth.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Waveguides: Modes and Propagation

Waveguides

A waveguide differs from a transmission line in some respects, although we may regard the latter as a special case of the former.

In the first place, a transmission line can support only a transverse electromagnetic (TEM) wave, whereas a waveguide can support many possible field configurations. Second, at microwave frequencies (roughly 3-300 GHz), transmission lines become inefficient due to skin effect and dielectric losses;

waveguides are used at that range of frequencies to obtain larger bandwidth and lower signal attenuation.

Moreover, a transmission line may operate from dc (f = 0) to a very high frequency; a waveguide can operate only above a certain frequency called the cutoff frequency and therefore **acts as a high-pass filter**. Thus, waveguides cannot transmit dc, and **they become excessively large at frequencies below microwave frequencies**.

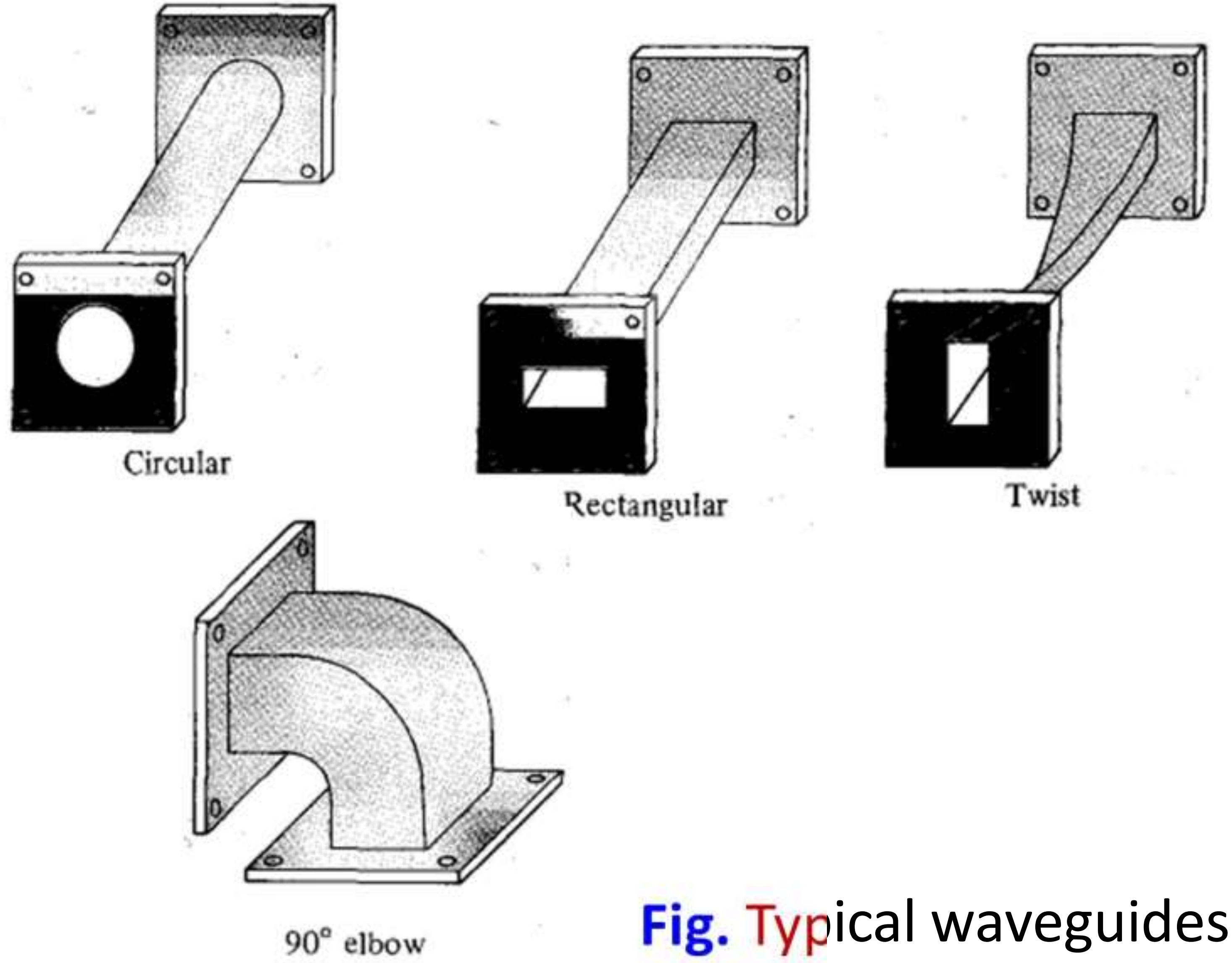


Fig. Typical waveguides.

Waveguides: Applications and Practical Design

WAVE PROPAGATION IN THE GUIDE

Examination of eq. (23) or (36) shows that the field components all involve the terms sine or cosine of $(m\pi/a)x$ or $(n\pi/b)y$ times $e^{-\gamma z}$.

$$\sin\theta = \frac{1}{2j}\left(e^{j\theta} - e^{-j\theta}\right) \quad (41a)$$

$$\cos\theta = \frac{1}{2}\left(e^{j\theta} + e^{-j\theta}\right) \quad (41b)$$

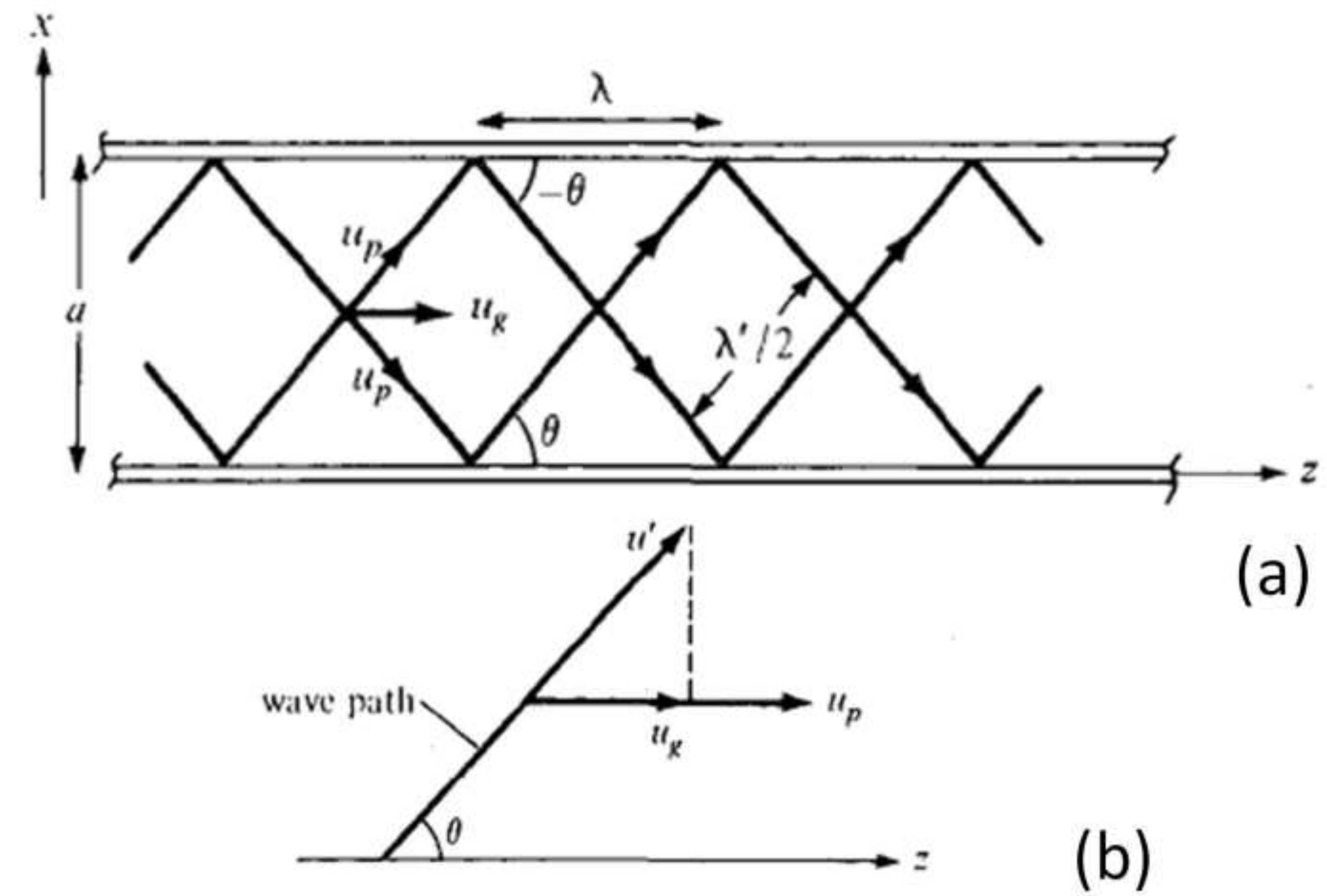
Since a wave within the waveguide can be resolved into a combination of plane waves reflected from the waveguide walls. For the **TE**$_{10}$ mode, for example,

$$\begin{aligned} E_{ys} &= -\frac{j\omega\mu a}{\pi} \sin\left(\frac{\pi x}{a}\right) e^{-j\beta z} \\ &= -\frac{\omega\mu a}{2\pi} (e^{j\pi x/a} - e^{-j\pi x/a})\, e^{-j\beta z} \\ &= \frac{\omega\mu a}{2\pi} [e^{-j\beta(z+\pi x/\beta a)} - e^{-j\beta(z-\pi x/\beta a)}] \end{aligned} \tag{42}$$

The first term of eq. (42) represents a wave traveling in the positive *z*-direction at an angle

$$\theta = \tan^{-1}\left(\frac{\pi}{\beta a}\right) \qquad (43)$$

with the *z*-axis. The second term of eq. (42) represents a wave traveling in the positive z-direction at an angle —θ. The field may be depicted as a sum of two plane TEM waves propagating along zigzag paths between the guide walls at $x = 0$ and $x = a$ as illustrated in Figure below.



(a) Decomposition of $\mathbf{TE}_{10}$ mode into two plane waves; (b) relationship between u', u_p, and u_g.

The decomposition of the $\mathbf{TE}_{10}$ mode into two plane waves can be extended to any **TE** and **TM** mode. When *n* and *m* are both different from zero, four plane waves result from the decomposition.

The wave component in the *z*-direction has a different wavelength from that of the plane waves. This wavelength along the axis of the guide is called the waveguide wavelength and is given by

$$\lambda = \frac{\lambda'}{\sqrt{1 - \left[\frac{f_c}{f}\right]^2}} \qquad (44)$$

where $\lambda' = u'/f$.

As a consequence of the zigzag paths, we have three types of velocity: the medium velocity u', the phase velocity u_p, and the group velocity u_g. Figure (b) above illustrates the relationship between the three different velocities. The medium velocity $u' = 1/\sqrt{\mu\varepsilon}$ is as explained in the previous sections. The phase velocity u_p is the velocity at which loci of constant phase are propagated down the guide and is given by eq. (31), that is,

$$u_p = \frac{\omega}{\beta} \tag{45a}$$

or

$$u_p = \frac{u'}{\cos\theta} = \frac{u'}{\sqrt{1 - \left[\frac{f_c}{f}\right]^2}} \tag{45b}$$

This shows that $u_p > u'$ since $\cos\theta \leq 1$. If $u' = c$, then u_p is greater than the speed of light in vacuum. **Does this violate Einstein's relativity theory that messages cannot travel faster than the speed of light?**

Not really, because information (or energy) in a waveguide generally does not travel at the phase velocity. Information travels at the group velocity, which must be less than the speed of light.

The group velocity u_g is the velocity with which the resultant repeated reflected waves are traveling down the guide and is given by

$$\boxed{u_g = \frac{1}{\partial\beta/\partial\omega}} \qquad (46a)$$

or

$$u_g = u' \cos\theta = u' \sqrt{1 - \left[\frac{f_c}{f}\right]^2} \qquad (46b)$$

Although the concept of group velocity is fairly complex and is beyond the scope of this chapter, a group velocity is essentially the velocity of propagation of the wave-packet envelope of a group of frequencies. It is the energy propagation velocity in the guide and is always less than or equal to u'. From eqs. (45) and (46), it is evident that

$$u_p u_g = u'^2 \tag{47}$$

EXAMPLE 12.4

A standard air-filled rectangular waveguide with dimensions a = 8.636 cm, b = 4.318 cm is fed by a 4-GHz carrier from a coaxial cable. Determine if a **TE**$_{10}$ mode will be propagated. If so, calculate the phase velocity and the group velocity.

Solution:

For the **TE**$_{10}$ mode, $f_c = u'/(2a)$. Since the waveguide is air-filled, $u' = c = 3 \text{ X } 10^8$. Hence,

$$f_c = \frac{3 \times 10^8}{2 \times 8.636 \times 10^{-2}} = 1.737 \text{ GHz}$$

As $f = 4$ GHz $> f_c$, the $\mathbf{TE}_{10}$ mode will propagate.

$$u_p = \frac{u'}{\sqrt{1 - (f_c/f)^2}} = \frac{3 \times 10^8}{\sqrt{1 - (1.737/4)^2}}$$
$$= 3.33 \times 10^8 \text{ m/s}$$

$$u_g = \frac{u'^2}{u_p} = \frac{9 \times 10^{16}}{3.33 \times 10^8} = 2.702 \times 10^8 \text{ m/s}$$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Radiation Systems: Basics

POWER TRANSMISSION AND ATTENUATION

To determine power flow in the waveguide, we first find the average Poynting vector

$$\mathcal{P}_{ave} = \frac{1}{2}\,\mathrm{Re}\,(\mathbf{E}_s \times \mathbf{H}_s^*) \qquad (48)$$

In this case, the Poynting vector is along the *z*-directi

$$\mathcal{P}_{ave} = \frac{1}{2}\,\mathrm{Re}\,(E_{xs}H_{ys}^* - E_{ys}H_{xs}^*)\mathbf{a}_z = \frac{|E_{xs}|^2 + |E_{ys}|^2}{2\eta}\,\mathbf{a}_z \qquad (49)$$

where $\eta = \eta_{TE}$ for TE modes or $\eta = \eta_{TM}$ for TM modes. The total average power transmitted across the cross section of the waveguide is

$$P_{ave} = \int \mathcal{P}_{ave} \cdot d\mathbf{S} = \int_{x=0}^{a} \int_{y=0}^{b} \frac{|E_{xs}|^2 + |E_{ys}|^2}{2\eta}\, dy\, dx \qquad (50)$$

Of practical importance is the attenuation in a lossy waveguide. In our analysis thus far, we have assumed lossless waveguides ($\sigma = 0$, $\sigma_c \approx \infty$) for which $\alpha = 0$, $\gamma = j\beta$.

When the dielectric medium is lossy ($\sigma \neq 0$) and the guide walls are not perfectly conducting ($\sigma_c \neq \infty$), there is a continuous loss of po… opagates along the guide. The power flow in the guide is of the form

$$P_{\text{ave}} = P_o e^{-2\alpha z} \tag{51}$$

In order that energy be conserved, the rate of decrease in P_{ave} must equal the time average power loss P_L per unit length, that is,

$$P_L = -\frac{dP_{ave}}{dz} = 2\alpha P_{ave} \tag{52}$$

or

$$\alpha = \frac{P_L}{2P_{ave}}$$

In general

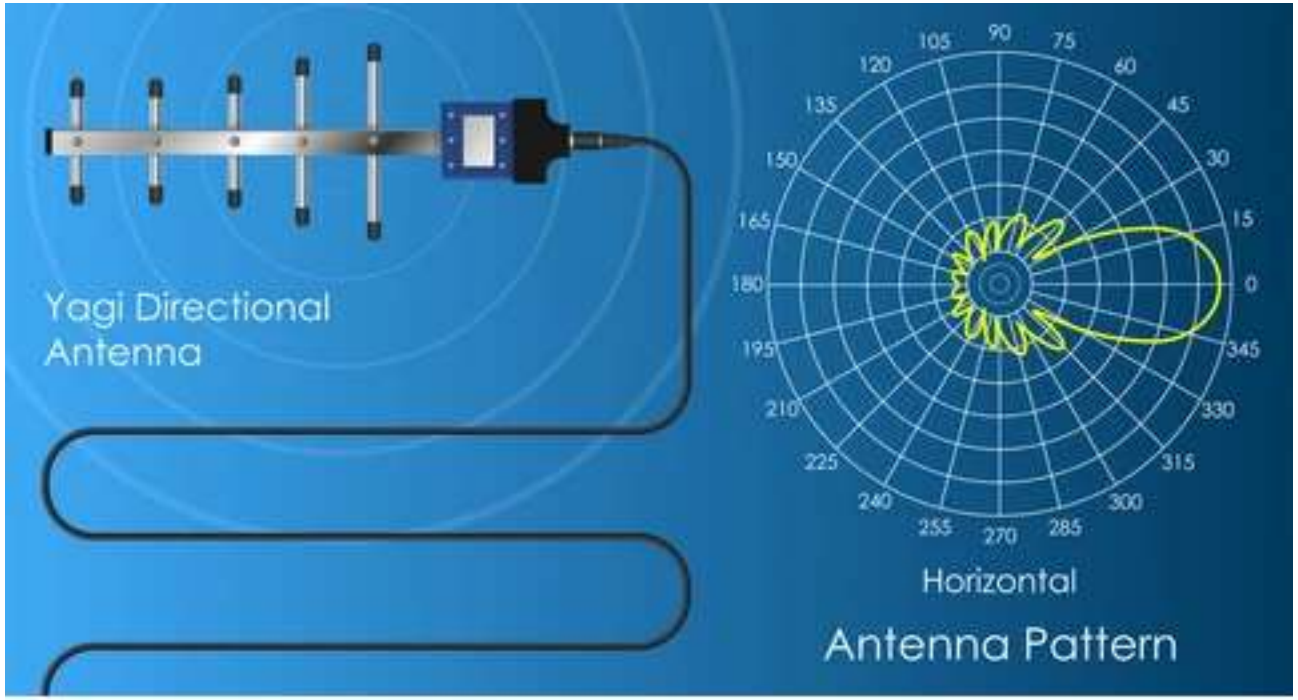
$$\alpha = \alpha_c + \alpha_d \tag{53}$$

where α_c and α_d are attenuation constants due to ohmic or conduction losses ($\sigma_c \neq \infty$) and dielectric losses ($\sigma \neq 0$), respectively.

Radiation Systems: Applications

Radiation Systems:

Radiation Systems: A radiation system refers to any setup designed to transmit or receive electromagnetic waves, such as antennas, transmitters, and receivers.



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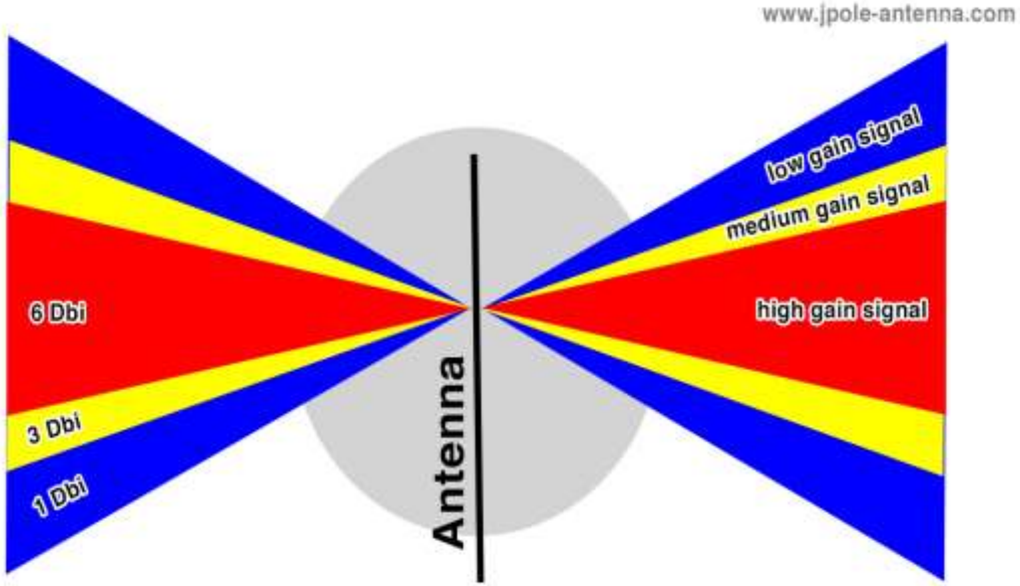
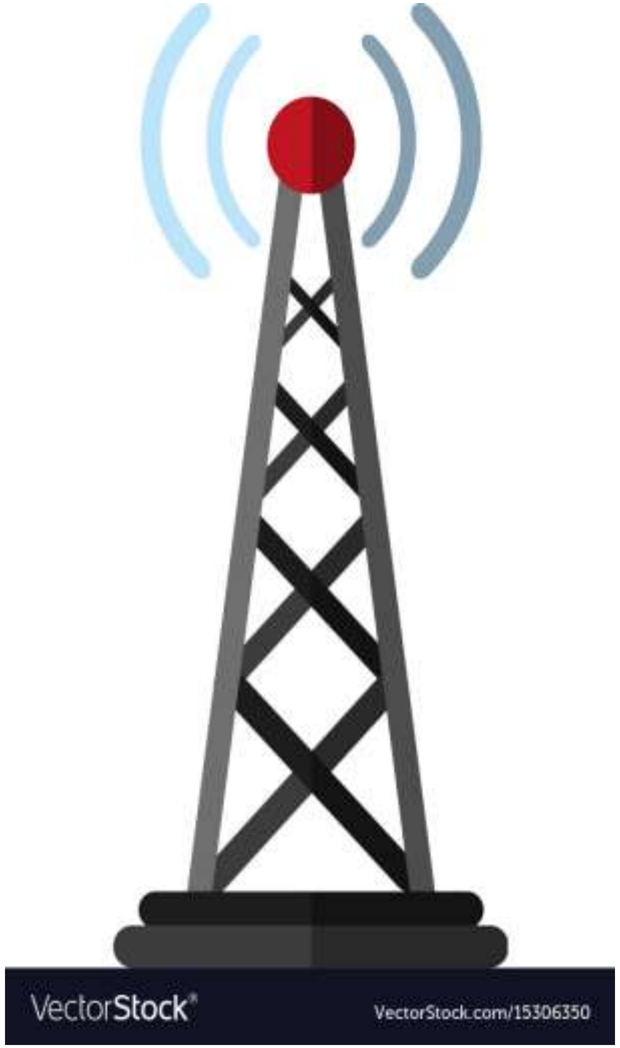
Key Components:

- **Antennas:** Transmit and receive electromagnetic waves.

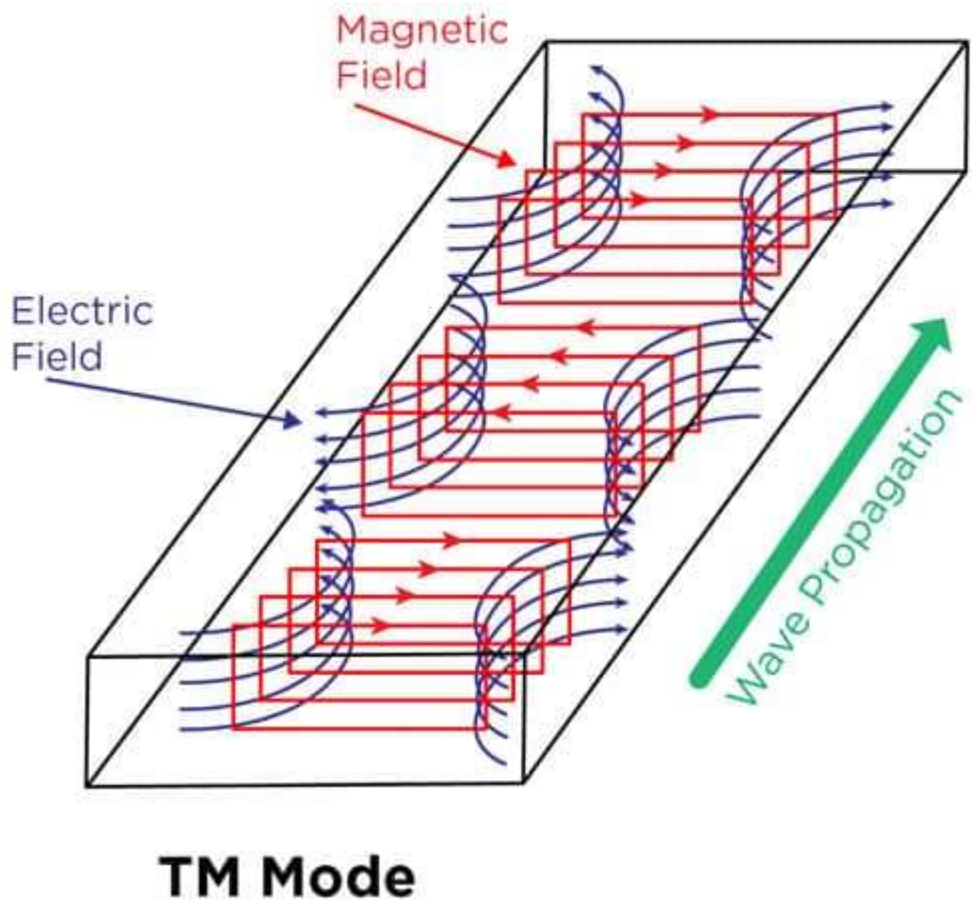




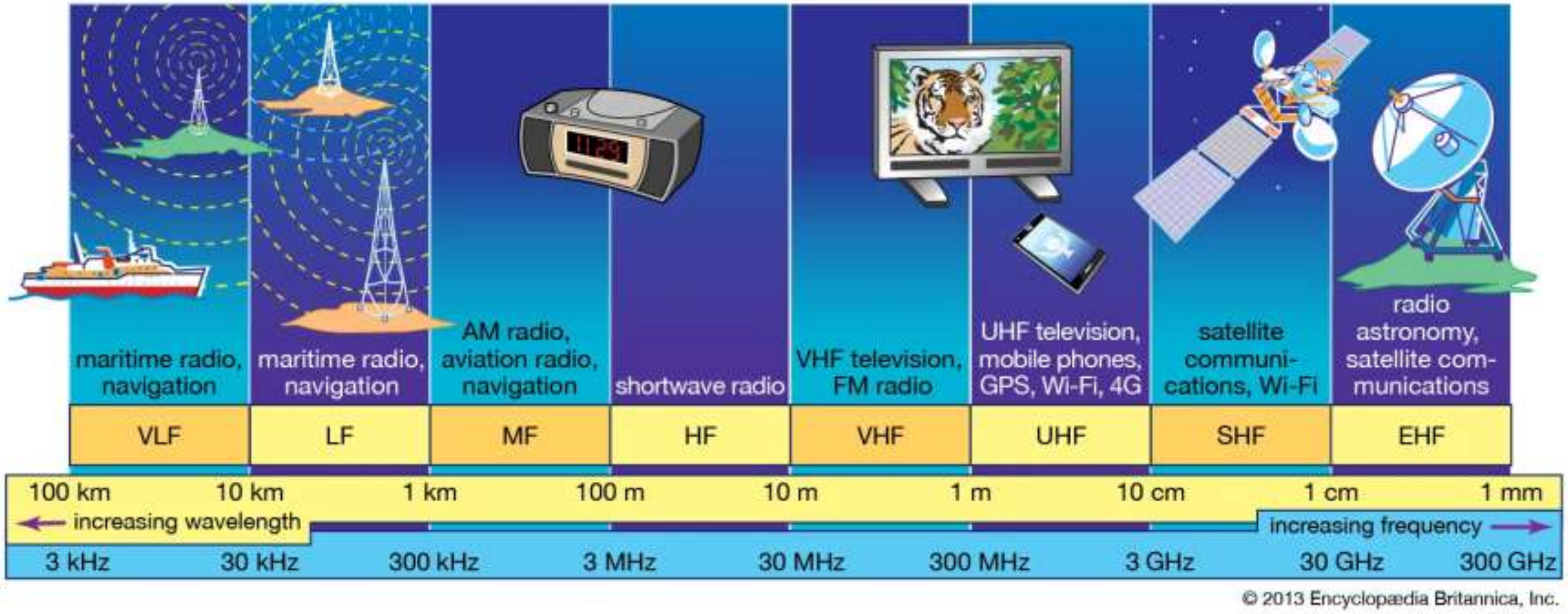
Transceivers:

- **Transceivers**: Convert electrical signals into electromagnetic waves and vice versa.

Waveguides and Feedlines: Carry signals between components.



Frequency Range: Operates across a wide spectrum, from low-frequency radio waves to high-frequency microwaves and beyond.

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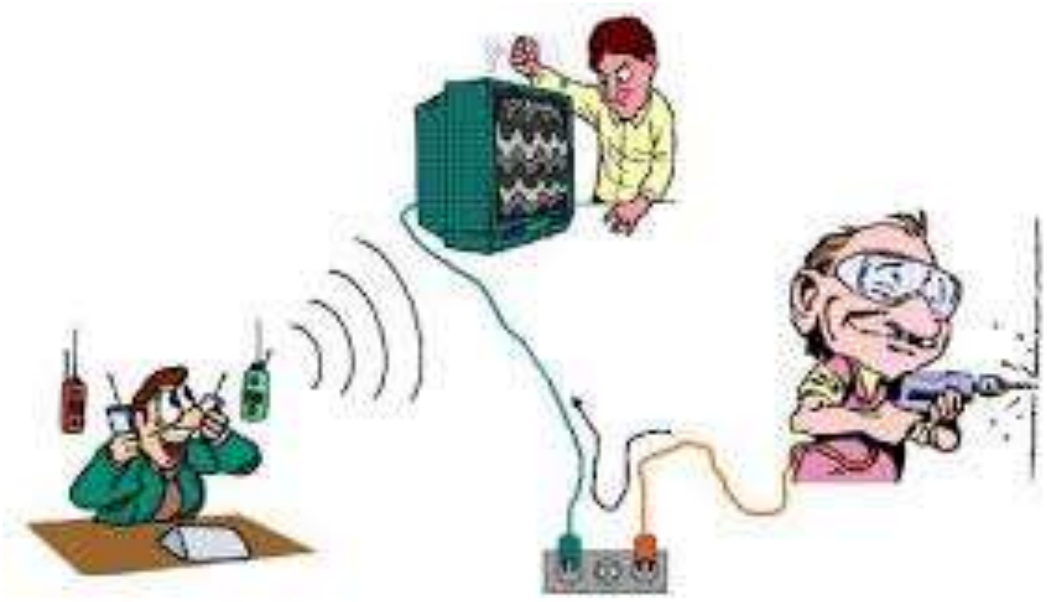
Electromagnetic Compatibility



Applications of Radiation Systems

Applications of Radiation Systems

1. **Communication Systems**:
    1. **Broadcasting**: AM/FM radio, TV.
    2. **Wireless Communication**: Cellular networks, Wi-Fi, satellite communication.
    3. **Marine and Aviation Communication**: Radar and navigation systems.

Remote Sensing and Monitoring:

Remote Sensing and Monitoring:

•**Weather Monitoring**: Weather radars, satellite imaging.

•**Earth Observation**: Soil moisture, ocean temperature measurement using microwaves.

•**Military Surveillance**: Radar systems for tracking and reconnaissance.

Medical Applications:

•**Imaging Systems**: MRI, CT, and radiography use electromagnetic waves for diagnostics.

•**Therapeutic Uses**: Radiation therapy for cancer treatment.

1. **Space and Astronomy**:
    1. **Space Communication**: Ground-to-satellite communication.
    2. **Radio Astronomy**: Observing celestial bodies via radio waves.
2. **Navigation**:
    1. **GNSS (Global Navigation Satellite Systems)**: GPS, Galileo, GLONASS.
    2. **LIDAR (Light Detection and Ranging)**: Used for mapping and autonomous vehicles.

Industrial Applications:

- **Material Testing**: Non-destructive testing using X-rays.
- **Automation**: Sensors using radio-frequency identification (RFID).
- **Microwave Heating**: Industrial drying, food processing.

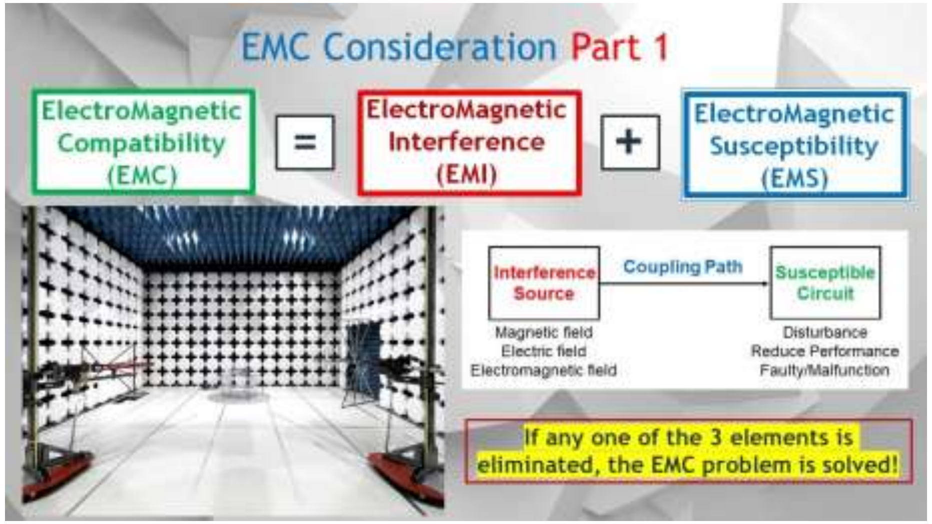
Electromagnetic Compatibility (EMC)

Electromagnetic Compatibility (EMC)

•**Definition**: The ability of a radiation system to operate in its electromagnetic environment without causing or experiencing interference.

•**Importance**:

- Ensures reliable operation of devices.
- Prevents interference between neighboring systems (e.g., in urban areas or hospitals).
- Complies with regulatory standards (FCC, ETSI, ITU).



Sources of Electromagnetic Interference (EMI)

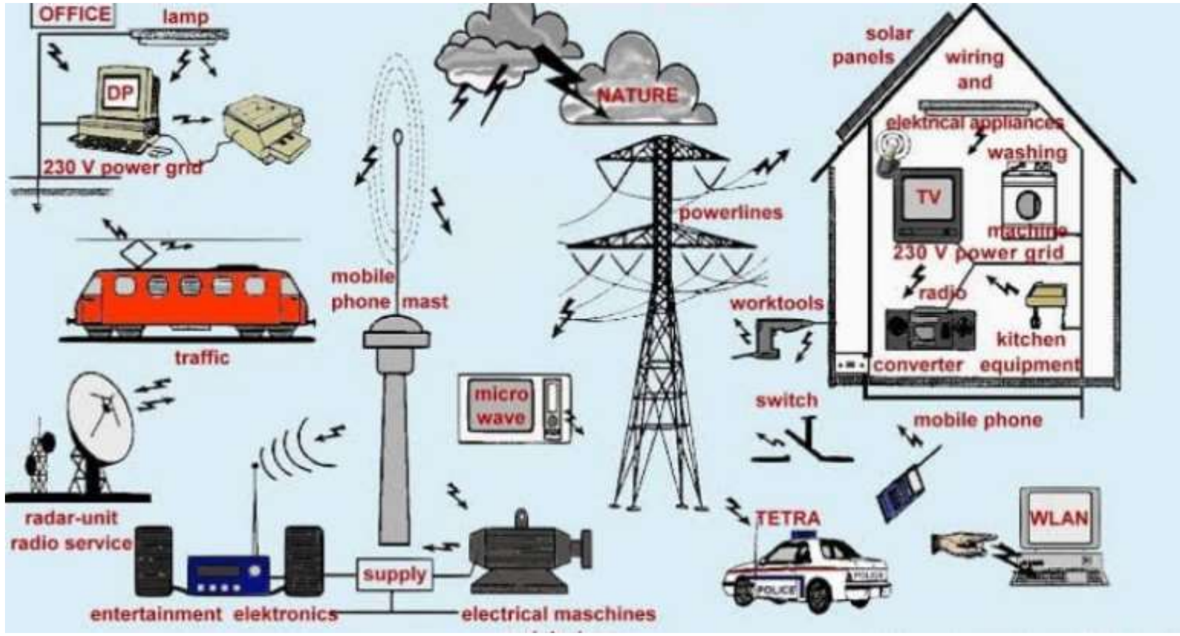
Sources of Electromagnetic Interference (EMI)

1.Natural Sources:

1. Lightning strikes.
2. Solar flares and cosmic radiation.

2.Man-Made Sources:

1. Electrical equipment (motors, relays, power lines).
2. Communication devices (radios, cell phones).
3. Industrial machinery.



EMC Design Considerations

EMC Design Considerations

1.Shielding:

1. Use metallic enclosures to block electromagnetic radiation.

2.Grounding:

1. Provide a low-impedance path for unwanted currents.

3.Filtering:

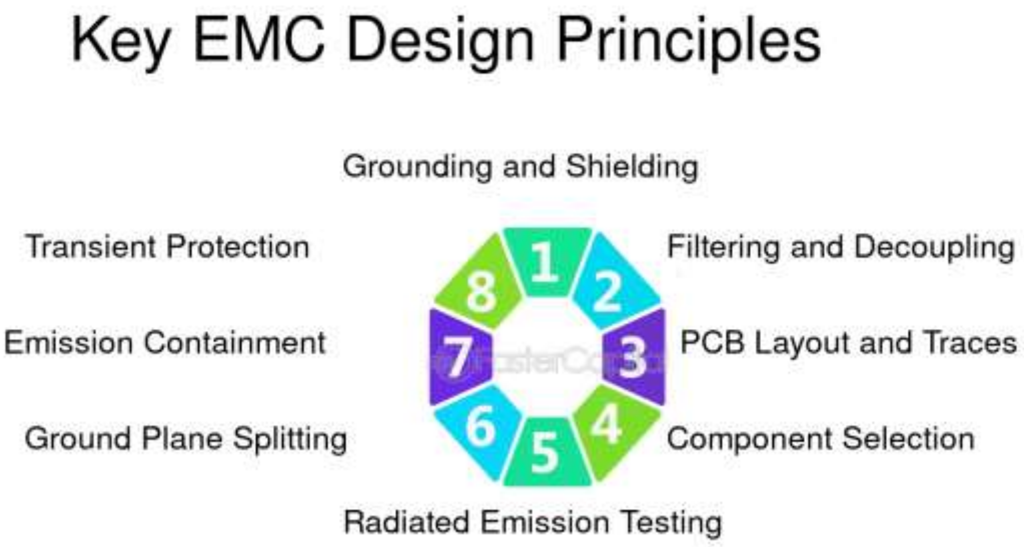
1. Remove unwanted frequencies using filters (low-pass, high-pass).

4.Component Layout:

1. Separate high-frequency and low-frequency components.

5.Regulatory Compliance:

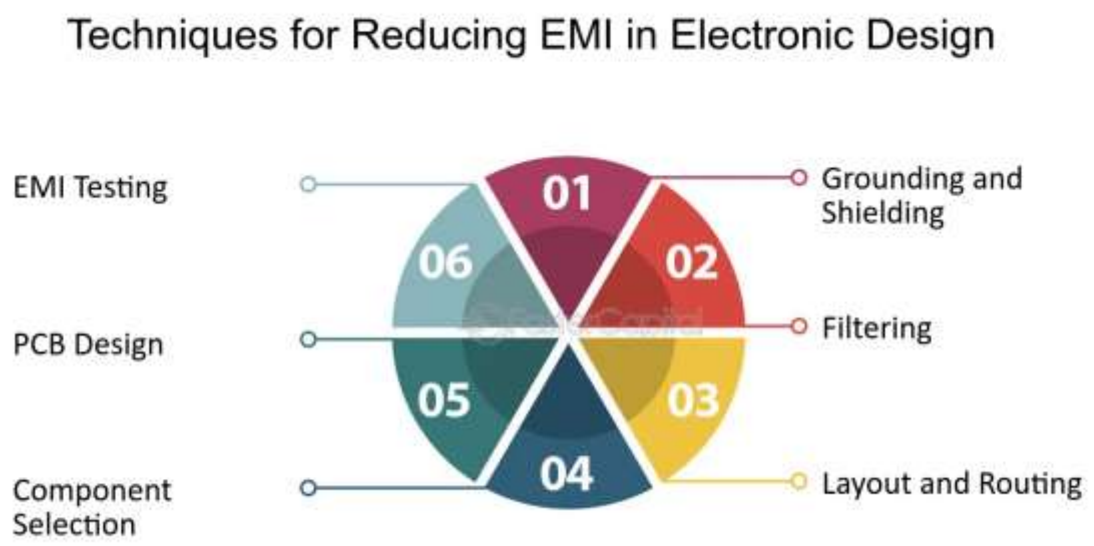
1. Follow standards like CISPR, IEEE, or FCC guidelines.



Techniques to Reduce EMI

Techniques to Reduce EMI

1. **Use of Ferrite Beads**: Suppress high-frequency noise.
2. **Twisted Pair Cabling**: Reduces inductive coupling.
3. **Proper PCB Design**:
    1. Minimize loop areas.
    2. Use ground planes.
4. **Optical Isolation**: Use optical fibers for signal transmission.



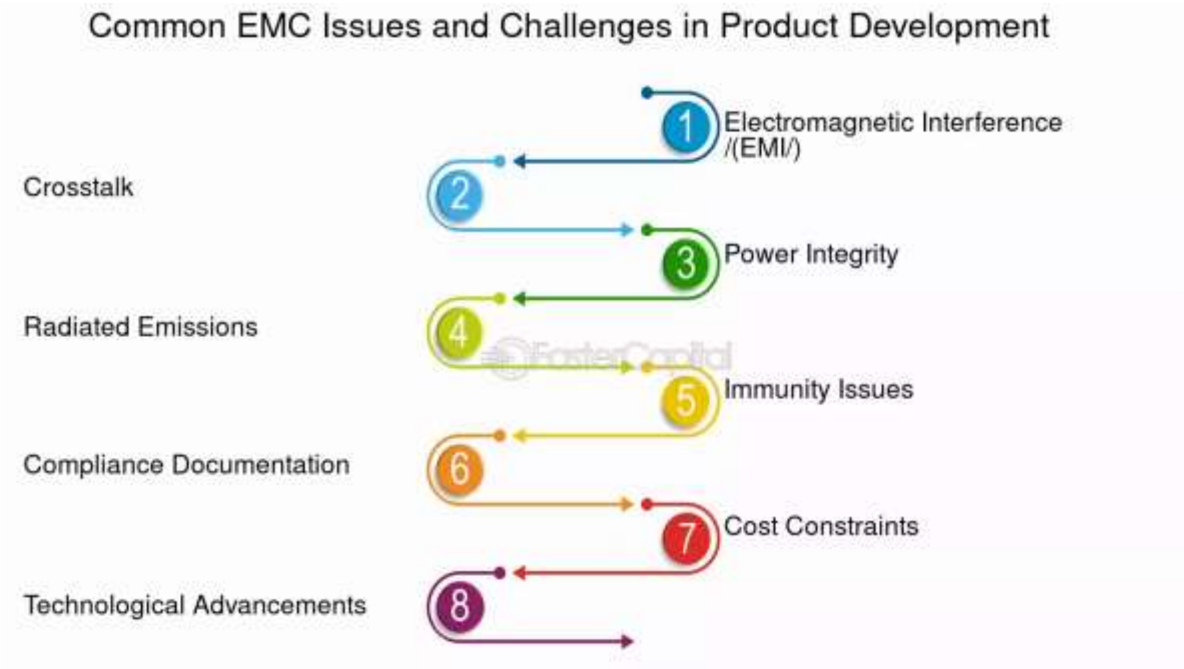
Challenges in Radiation Systems and EMC

Challenges in Radiation Systems and EMC

•**High-Density Environments**: Increasing device density leads to more potential interference.

•**Frequency Congestion**: Shared frequency bands require stricter EMC standards.

•**Technological Advancements**: Emerging 5G and IoT technologies demand robust radiation and EMC designs.



Problem Solving & Case Studies

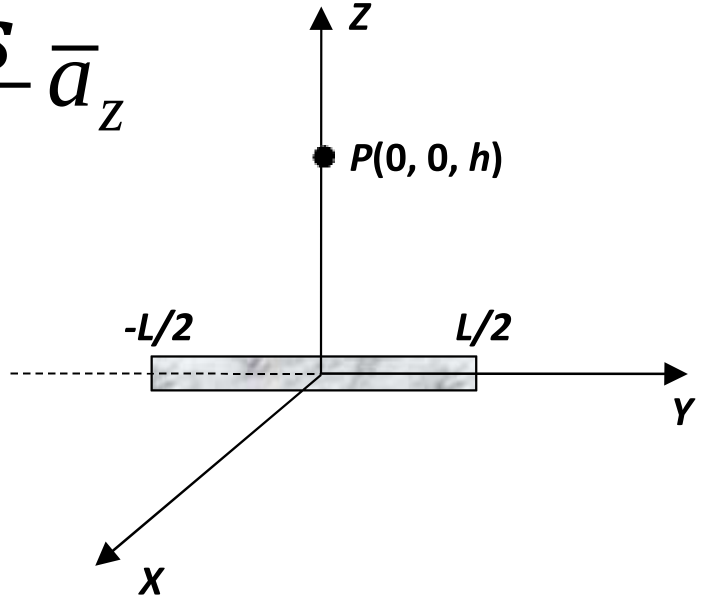
Some exercise problems and solutions

Example 1: Let a stationary square loop of wire lie in the x–y plane that contains a spatially homogeneous time-varying magnetic field. Find the voltage V(t) that could be detected between the two terminals that are separated by an infinitesimal distance.

Some exercise problems and solutions

Example 2: The lamp is approximated by a line charge density ρ_L C/m and placed in y-axis as shown below. Find the expression **E** at point *P* and show that the result approaches

$$E = \frac{\begin{matrix} p_L \\ 2\pi s \end{matrix}}{h}\,\bar{a}_z$$



Example 3: The potential field in a slab of dielectric material for which $\varepsilon_r = 1.6$ given by $V = -500x$, find **P** in the material.

Example 4: Does the potential $\varphi = \frac{1}{r}$ satisfy Laplace's equation where

$$r = \sqrt{(x^2 + y^2 + z^2)}$$

Example 4: Does the electric field in vacuum $\boldsymbol{E} = \boldsymbol{E_0} \cos(\boldsymbol{xt} - \boldsymbol{\beta x})\boldsymbol{a_x}$ satisfy Maxwell's equations? Under what circumstances would this field satisfy the equations?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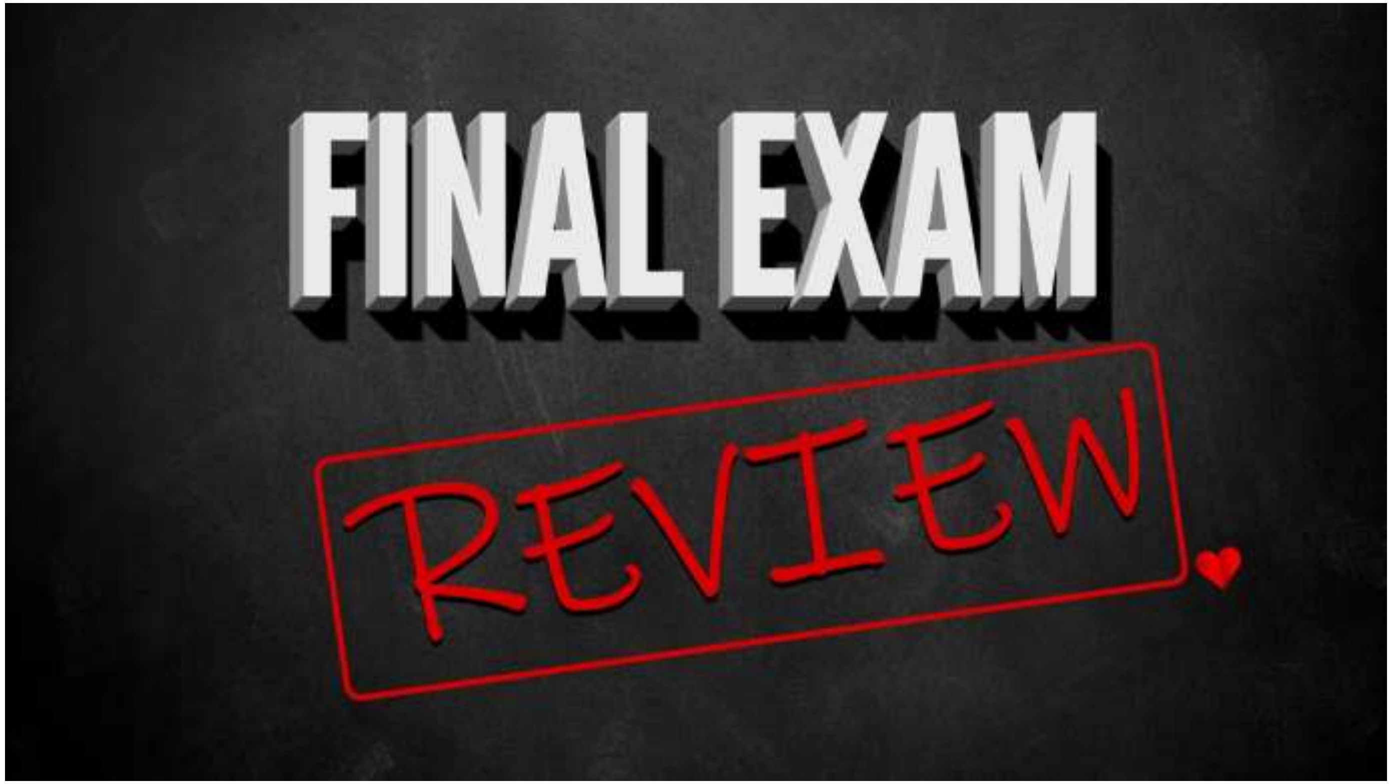
WEEK-17

Revision and Final Review

Revision and Final Review



Thank YOU !