MUTHAYAMMAL ENGINEERING COLLEGE
Rasipuram -637 408

DESIGNING YOUR FUTURE
Estd. 2000

COURSE CODE & TITLE -19ECC05/ECEELECTROMAGNETIC FIELDS

UNIT-1

BOOLEAN ALGEBRA AND LOGIC GATES

Presentation by
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AP-ECE

Lecture 2

SYLLABUS

- UNIT I ELECTROSTATICS 9 Hrs

Review of vector algebra and coordinate systems - Line, surface and volume integrals - Gradient of a scalar field, Divergence of a vector field - Divergence theorem - Curl of a vector field, Stoke's theorem, Helmholtz's theorem.- Electric field, Coulomb's law, Electric potential, Electric flux density and dielectric constant, Boundary conditions, Capacitance- Parallel plate capacitors, Electrostatic energy.

UNIT II MAGNETOSTATICS 9 Hrs

Lorentz force equation, Ampere's law, Vector magnetic potential, Biot-Savart law and applications, Magnetic field intensity and idea of relative permeability, Magnetic circuits, Behaviour of magnetic materials, Boundary conditions, Inductance and inductors, Magnetic energy, Magnetic forces and torques. UNIT III TIME-VARYING FIELDS AND MAXWELL's EQUATIONS 9 Hrs

Faraday's law- Maxwell’s Second Equation in integral form from Faraday’s Law- Displacement current – Ampere’s circuital law in integral form, Equation expressed in point form -Maxwell’s four equations in integral form and differential form - Electromagnetic boundary conditions, Wave equations and solutions, Time-harmonic fields.

SYLLABUS

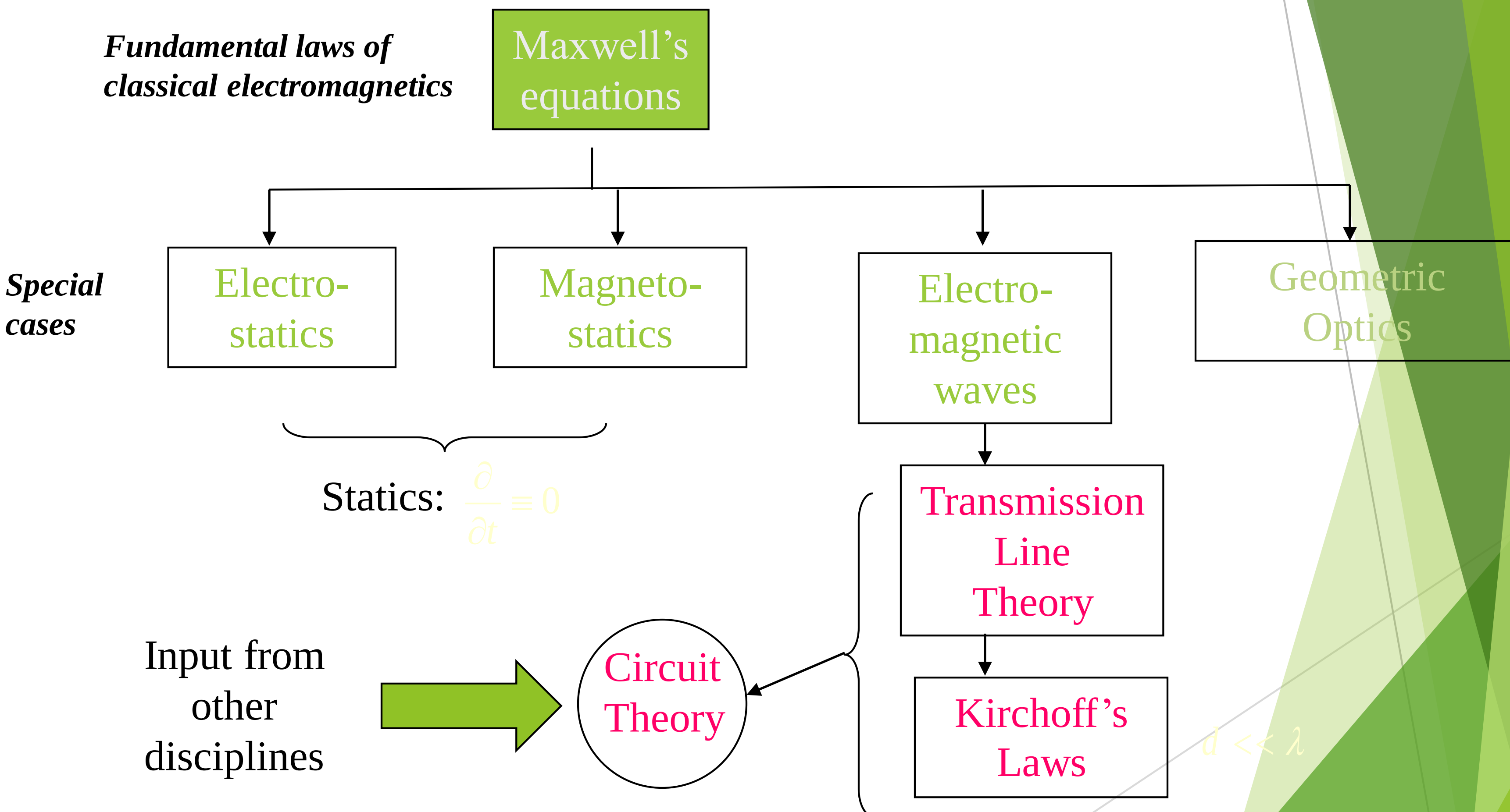
- UNIT IV TRANSMISSION LINES AT RADIO FREQUENCIES 9 Hrs Transmission line parameters- General solutions of transmission line –Wavelength, velocity of propagation - Waveform distortion – The distortion less line- Reflections on a line not terminated in Z0 - Reflection coefficient - Reflection factor and reflection loss - Standing Waves, Nodes, Standing wave Ratio- Smith chart and its application – Single stub matching using Smith chart
- UNIT V PLANE ELECTROMAGNETIC WAVES 9 Hrs Uniform Plane Waves – Maxwell's equation in Phasor form – Wave equation in Phasor form – Plane waves in free space and in a homogenous material - Wave equation for a conducting medium – Propagation in good conductors –, Skin effect. Group velocity, Electromagnetic power flow and Poynting vector, Normal incidence at a plane conducting boundary.

- TEXT BOOKS:
- John D Ryder, Networks, Lines and Fields , Prentice Hall India, 2010
- W.H. Hayt and J.A. Buck, Engineering Electromagnetics, TATA McGraw-Hill,2007

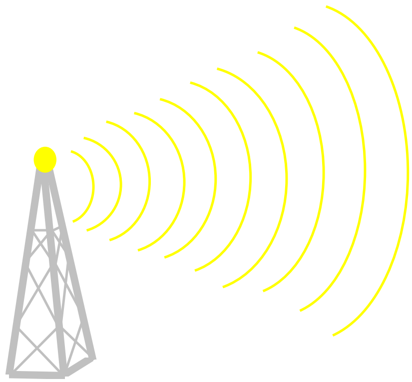
Introduction to Electromagnetic Fields

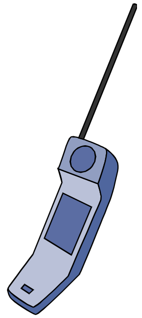
- Electromagnetics is the study of the effect of charges at rest and charges in motion.
- Some special cases of electromagnetics:
  - Electrostatics: charges at rest
  - Magnetostatics: charges in steady motion (DC)
  - Electromagnetic waves: waves excited by charges in time-varying motion

Introduction to Electromagnetic Fields



Introduction to Electromagnetic Fields





• transmitter and receiver are connected by a "field."

Introduction to Electromagnetic Fields

- 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”.
- A ***field*** is a spatial distribution of a quantity; in general, it can be either *scalar* or *vector* in nature.

Introduction to Electromagnetic Fields

- Electric and magnetic fields:
  - Are vector fields with three spatial components.
  - Vary as a function of position in 3D space as well as time.
  - Are governed by partial differential equations derived from Maxwell's equations.

Introduction to Electromagnetic Fields

- A ***scalar*** is a quantity having only an amplitude (and possibly phase).

Examples: voltage, current, charge, energy, temperature

- A ***vector*** is a quantity having direction in addition to amplitude (and possibly phase).

Examples: velocity, acceleration, force

Introduction to Electromagnetic Fields

- Fundamental vector field quantities in electromagnetics:
  - Electric field intensity $\left(\underline{E}\right)$

    units = volts per meter (V/m = kg m/A/s^3)
  - Electric flux density (electric displacement) $\left(\underline{D}\right)$

    units = coulombs per square meter (C/m^2 = A s /m^2)
  - Magnetic field intensity $\left(\underline{H}\right)$

    units = amps per meter (A/m)
  - Magnetic flux density $\left(\underline{B}\right)$

    units = teslas = webers per square meter (T = Wb/ m^2)

Introduction to Electromagnetic Fields

- Relationships involving the universal constants:

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \qquad \eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$$

In free space:

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

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

Introduction to Electromagnetic Fields

- Universal constants in electromagnetics:
  - Velocity of an electromagnetic wave (e.g., light) in free space (perfect vacuum)

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

  - Permeability of free space

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

  - Permittivity of free space:

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

  - Intrinsic impedance of free space:

$$\eta_0 \approx 120\pi \ \Omega$$

Maxwell's Equations

- *Maxwell's equations in integral form* are the fundamental postulates of classical electromagnetics - all classical electromagnetic phenomena are explained by these equations.
- Electromagnetic phenomena include electrostatics, magnetostatics, electromagnetostatics and electromagnetic wave propagation.
- The differential equations and boundary conditions that we use to formulate and solve EM problems are all derived from *Maxwell's equations in integral form*.

Maxwell’s Equations

- Various ***equivalence principles*** consistent with Maxwell’s equations allow us to replace more complicated electric current and charge distributions with ***equivalent magnetic sources***.
- These *equivalent magnetic sources* can be treated by a generalization of Maxwell’s equations.

Maxwell's Equations in Integral Form (Generalized to Include Equivalent Magnetic Sources)

$$\oint_C \underline{E} \cdot d\underline{l} = -\frac{d}{dt}\int_S \underline{B} \cdot d\underline{S} - \int_S \underline{K}_c \cdot d\underline{S} - \int_S \underline{K}_i \cdot d\underline{S}$$

$$\oint_C \underline{H} \cdot d\underline{l} = \frac{d}{dt}\int_S \underline{D} \cdot d\underline{S} + \int_S \underline{J}_c \cdot d\underline{S} + \int_S \underline{J}_i \cdot d\underline{S}$$

$$\oint_S \underline{D} \cdot d\underline{S} = \int_V q_{ev}\, dv$$

$$\oint_S \underline{B} \cdot d\underline{S} = \int_V q_{mv}\, dv$$

Adding the fictitious magnetic source terms is equivalent to living in a universe where magnetic monopoles (charges) exist.

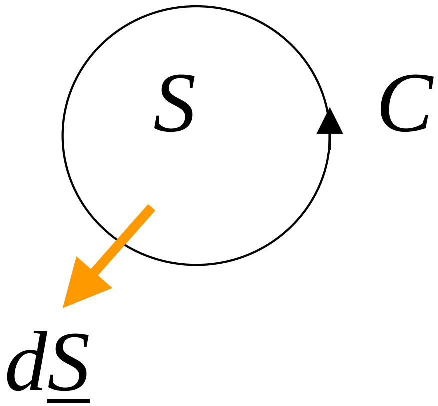
Continuity Equation in Integral Form (Generalized to Include Equivalent Magnetic Sources)

$$\oint_S \underline{J} \cdot d\,\underline{s} = -\frac{\partial}{\partial t}\int_V q_{ev}\,dv$$

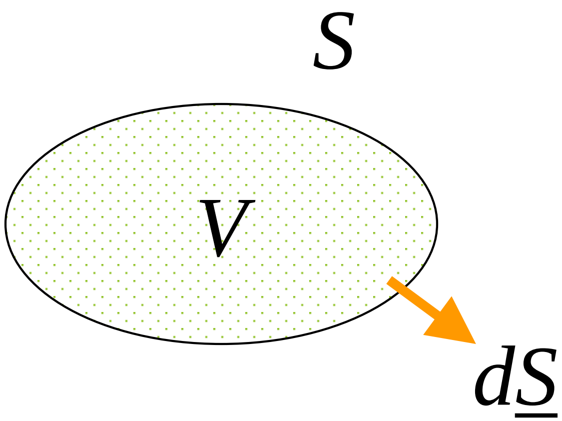
$$\oint_S \underline{K} \cdot d\,\underline{s} = -\frac{\partial}{\partial t}\int_V q_{mv}\,dv$$

- The *continuity equations* are implicit in Maxwell's equations.

Contour, Surface and Volume Conventions



- open surface S bounded by closed contour C
- $d\underline{S}$ in direction given by RH rule



- volume V bounded by closed surface S
- $d\underline{S}$ in direction outward from V

Electric Current and Charge Densities

- $\boldsymbol{J}_c$ = (electric) conduction current density (A/m^2)
- $\boldsymbol{J}_i$ = (electric) impressed current density (A/m^2)
- q_{ev} = (electric) charge density (C/m^3)

Magnetic Current and Charge Densities

- $\boldsymbol{K}_c$ = magnetic conduction current density (V/m^2)
- $\boldsymbol{K}_i$ = magnetic impressed current density (V/m^2)
- q_{mv} = magnetic charge density (Wb/m^3)

Maxwell's Equations - Sources and Responses

- Sources of EM field:
  - $\boldsymbol{K}_i$, $\boldsymbol{J}_i$, q_{ev}, q_{mv}
- Responses to EM field:
  - $\boldsymbol{E}$, $\boldsymbol{H}$, $\boldsymbol{D}$, $\boldsymbol{B}$, $\boldsymbol{J}_c$, $\boldsymbol{K}_c$

Maxwell's Equations in Differential Form (Generalized to Include Equivalent Magnetic Sources)

$$\nabla \times \underline{E} = -\frac{\partial \underline{B}}{\partial t} - \underline{K}_c - \underline{K}_i$$

$$\nabla \times \underline{H} = \frac{\partial \underline{D}}{\partial t} + \underline{J}_c + \underline{J}_i$$

$$\nabla \cdot \underline{D} = q_{ev}$$

$$\nabla \cdot \underline{B} = q_{mv}$$

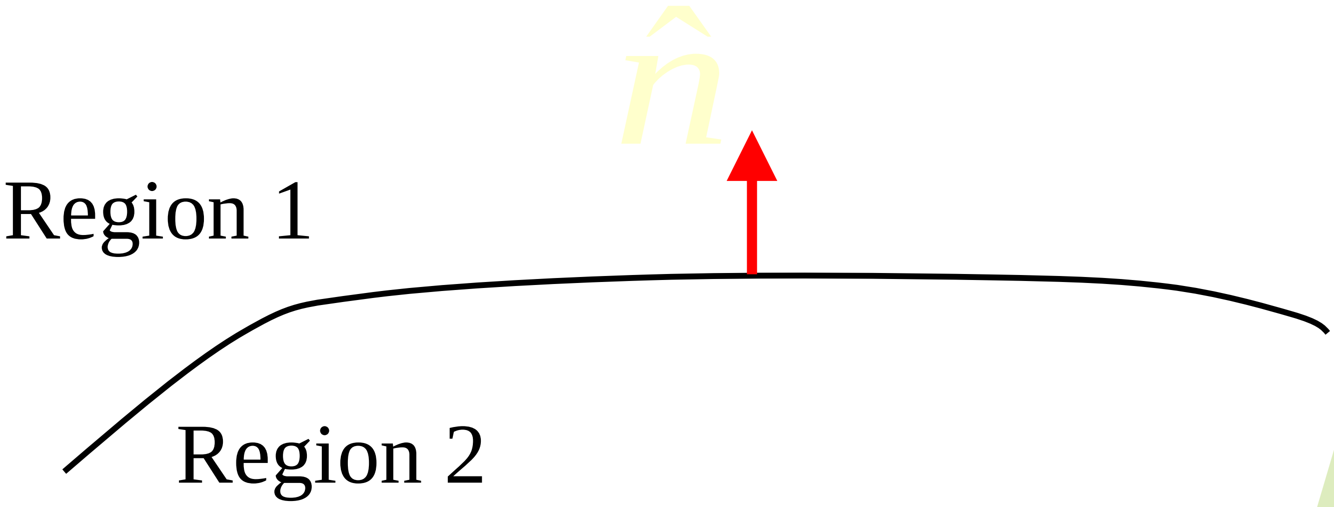
Continuity Equation in Differential Form (Generalized to Include Equivalent Magnetic Sources)

$$\nabla \cdot \underline{J} = -\frac{\partial q_{ev}}{\partial t}$$

$$\nabla \cdot \underline{K} = -\frac{\partial q_{mv}}{\partial t}$$

- The *continuity equations* are implicit in Maxwell's equations.

Electromagnetic Boundary Conditions



Electromagnetic Boundary Conditions

$$\hat{n}\times\left(\underline{E}_1-\underline{E}_2\right)=-\underline{K}_S$$

$$\hat{n}\times\left(\underline{H}_1-\underline{H}_2\right)=\underline{J}_S$$

$$\hat{n}\cdot\left(\underline{D}_1-\underline{D}_2\right)=q_{es}$$

$$\hat{n}\cdot\left(\underline{B}_1-\underline{B}_2\right)=q_{ms}$$

Surface Current and Charge Densities

- Can be either *sources of* or *responses to* EM field.
- Units:
  - $\boldsymbol{K}_s$ - V/m
  - $\boldsymbol{J}_s$ - A/m
  - q_{es} - C/m^2
  - q_{ms} - W/m^2

Electromagnetic Fields in Materials

- In time-varying electromagnetics, we consider $\boldsymbol{E}$ and $\boldsymbol{H}$ to be the "primary" responses, and attempt to write the "secondary" responses $\boldsymbol{D}$, $\boldsymbol{B}$, $\boldsymbol{J}_c$, and $\boldsymbol{K}_c$ in terms of $\boldsymbol{E}$ and $\boldsymbol{H}$.
- The relationships between the "primary" and "secondary" responses depends on the *medium* in which the field exists.
- The relationships between the "primary" and "secondary" responses are called ***constitutive relationships***.

Electromagnetic Fields in Materials

- Most general *constitutive relationships*:

$$\underline{D} = \underline{D}(\underline{E}, \underline{H})$$

$$\underline{B} = \underline{B}(\underline{E}, \underline{H})$$

$$\underline{J}_c = \underline{J}_c(\underline{E}, \underline{H})$$

$$\underline{K}_c = \underline{K}_c(\underline{E}, \underline{H})$$

Electromagnetic Fields in Materials

- In free space, we have:

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

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

$$\underline{J}_c = 0$$

$$\underline{K}_c = 0$$

Electromagnetic Fields in Materials

- In a ***simple medium***, we have:

$$\underline{D} = \varepsilon \underline{E}$$

$$\underline{B} = \mu \underline{H}$$

$$\underline{J}_c = \sigma \underline{E}$$

$$\underline{K}_c = \sigma_m \underline{H}$$

- ***linear*** (independent of field strength)
- ***isotropic*** (independent of position within the medium)
- ***homogeneous*** (independent of direction)
- ***time-invariant*** (independent of time)
- ***non-dispersive*** (independent of frequency)

Electromagnetic Fields in Materials

- ε = permittivity = $\varepsilon_r\varepsilon_0$ (F/m)
- μ = permeability = $\mu_r\mu_0$ (H/m)
- σ = electric conductivity = $\varepsilon_r\varepsilon_0$ (S/m)
- σ_m = magnetic conductivity = $\varepsilon_r\varepsilon_0$ (Ω/m)

Maxwell's Equations: Electromagnetic Waves

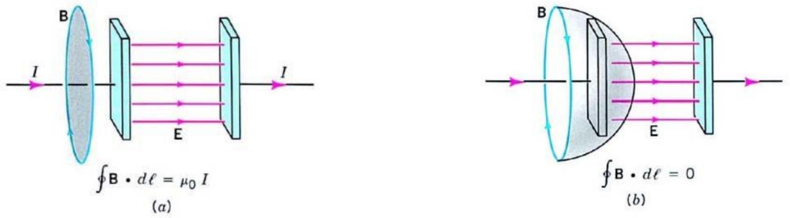
In 1845, Faraday demonstrated that a magnetic field produces a measurable effect on a beam of light. This prompted him to speculate that light involves oscillation of electric and magnetic field lines, but his limited mathematical ability prevent him from pursuing this idea.

Maxwell, a young admirer of Faraday, believed that the closeness of these two numbers, speed of light and the inverse square root of ε_0 and μ_0, was more than just coincidence and decide to develop Faraday's hypothesis.

In 1865, he predicted the existence of electromagnetic waves that propagate at the speed of light.

Displacement Current

The inadequacy of the Ampere's law does not give consistent answers for the following two choices.



Maxwell proposed that a new type of current, which he called displacement current, I_D, can be associated with the nonconductor between the plates. Thus Ampere's law should be written as

$$\oint \mathbf{B} \cdot d\mathbf{l} = \mu_o (I + I_D)$$

Displacement Current (II)

Where does the displacement current come from? The change of the electric flux with time.

Consider a parallel plate capacitor

$Q = \varepsilon_0 AE = \varepsilon_0 \Phi_E$

$$\frac{dQ}{dt} = \varepsilon_0 \frac{d\Phi_E}{dt} = I_D$$

With Maxwell's modification, Ampere's law becomes

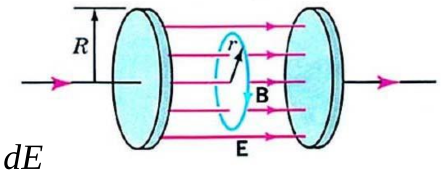
$$\oint B \cdot d\mathrm{l} = \mu_0 (I + \varepsilon_0 \frac{d\Phi_E}{dt})$$

Example 1

Use the Ampere-Maxwell law to find the magnetic field between the circular plates of a parallel-plate capacitor that is charging. The radius of the plates is *R*. Ignore the fringing field.

Solution:

$$\int \mathbf{B} \cdot d\mathrm{l} = B(2\pi r)$$



$$\Phi_E = E(\pi r^2)$$

$$B(2\pi r) = \mu_0 \varepsilon_0 (\pi r^2) \frac{dE}{dt}$$

$$B = \frac{1}{2} \mu_0 \varepsilon_0 r \frac{dE}{dt} \quad (r < R)$$

Maxwell's Equations

With the inclusion of Maxwell's contribution, we now display all the fundamental equations in electromagnetism. There are just four:

Gauss $\oint \mathbf{E} \cdot d\mathbf{A} = \frac{Q}{\varepsilon_0}$

Gauss $\oint \mathbf{B} \cdot d\mathbf{A} = 0$

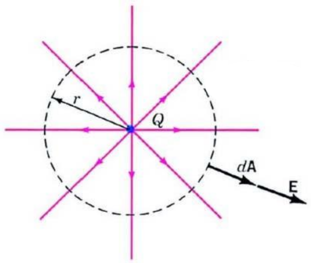
Faraday $\oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt}$

Ampere - Maxwell $\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 (I + \varepsilon_0 \frac{d\Phi_E}{dt})$

Gauss's Law

How much is the flux for a spherical Gaussian surface around a point charge?

The total flux through this closed Gaussi



$$\Phi_E = \oint \mathbf{E} \cdot \hat{\mathbf{n}} da = \frac{kQ}{r^2} \cdot 4\pi r^2$$

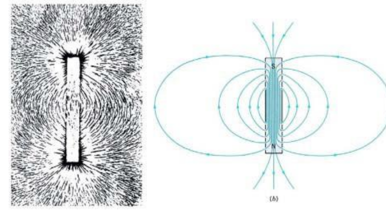
$$= 4\pi K Q = \frac{Q}{\varepsilon_0}$$

The net flux through a closed surface equals $1/\varepsilon_0$ times the net charge enclosed by the surface.

Can we prove the above statement for arbitrary closed shape?

The Magnetic Field

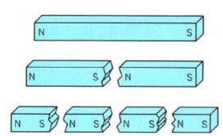
When iron filings are sprinkled around a bar magnet, they form a characteristic pattern that shows how the influence of the magnet spreads to the surrounding space.



The **magnetic field**, **B**, at a point along the tangent to a field line. The *direction* of **B** is that of the force on the north pole of a bar magnet, or the *direction* in which a compass needle points. The *strength* of the field is proportional to the number of lines passing through a unit area normal to the field (*flux density*).

The Magnetic Field: monopole?

If one try to isolate the poles by cutting the magnetic, a curious thing happens: One obtains two magnets. No matter how thinly the magnet is sliced, each fragment always have two poles. Even down to the atomic level, no one has found an isolated magnetic pole, called a monopole. Thus magnetic field lines form closed loops.



Outside a magnetic the lines emerge from the north pole and enter the south pole; *within* the magnet they are directed from the south pole to the north pole. The ***dots*** represents the tip of an arrow coming toward you. The ***cross*** represents the tail of an arrow moving away.

Faraday's Law and Lenz's Law

The generation of an electric current in a circuit implies the existence of an emf. Faraday's statement is nowadays expressed in terms of the magnetic flux:

$$V_{EMF} \propto \frac{d\Phi}{dt}$$

The induced emf along any closed path is proportional to the rate of change of magnetic flux through the area bounded by the path.

The derivative of magnetic flux is

$$\frac{d\Phi}{dt} = \frac{dB}{dt} A\cos\theta + B\frac{dA}{dt}\cos\theta - BA\sin\theta\frac{d\theta}{dt}$$

Faraday's Law

The emf is always opposite to the sign of the change in flux $\Delta\Phi$. This feature can be incorporated into Faraday's law by including a negative sign.

The modern statement of Faraday's law of electromagnetic induction is

$$V_{EMF} = -\frac{d\Phi}{dt}$$

Suppose that the loop is replaced by a coil with *N* turn. The net emf induced in a coil with *N* turns is

$$V_{EMF} = -N\frac{d\Phi}{dt}$$

Ampere’s Law

Ampere had several objections to the work of Biot and Sarvart. For example, accuracy and assumption.

He pursued his own line of experimental and theoretical research and obtained a different relation, now called Ampere’s law, between a current and the magnetic field it produces.

Although Ampere’s law can be derived from the Biot-Sarvart expression for d**B**, we will not do so. Instead, we can make it plausible by considering the field due to an infinite straight wire.

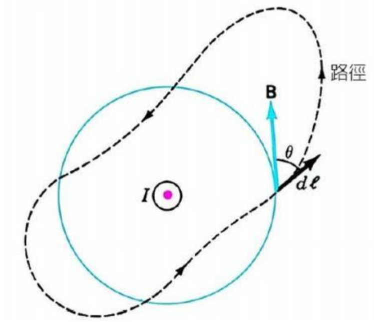
We know that the field lines are concentric circles for a infinite long, straight current-carrying wire.

$$B(2\pi r)=\mu_0 I$$

Ampere’s Law (II)

$B(2\pi r)=\mu_0 I$. We may interpret it as follows: $2\pi r$ is the length of a circular path around the wire, B is the component of the magnetic field tangential to the path, and I is the current through the area bounded by the path.

Ampere generalized this result to *the paths* and wires of *any shape*.



Derivation of the Wave Equation

Mathematical manipulation of Faraday's law and Ampere-Maxwell law leads directly to a wave equation for the electric and magnetic field.

Faraday's law	Ampere-Maxwell law
$\oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt}$	$\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 \left(I + \varepsilon_0 \frac{d\Phi_E}{dt}\right)$
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$

$$\nabla \times (\nabla \times \mathbf{E}) = -\frac{\partial (\nabla \times \mathbf{B})}{\partial t} \Rightarrow \nabla^2 \mathbf{E} = \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

Derivation of the Wave Equation (II)

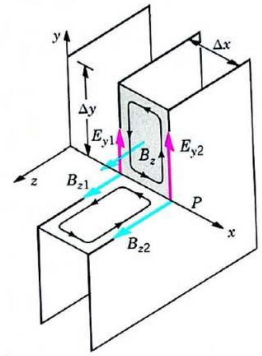
We will assume E and B vary in a certain way, consistent with Maxwell equations, and show that electromagnetic wave are a consequence of the application of Faraday's law and Ampere-Maxwell law.

$$\oint \mathbf{E} \cdot d\mathbf{l} = (E_{y2} - E_{y1})\Delta y$$

$$\Phi_B = B_z \Delta x \Delta y \quad \therefore \frac{\partial \Phi_B}{\partial t} = \frac{\partial B_z}{\partial t} \Delta x \Delta y$$

$$(E_{y2} - E_{y1})\Delta y = -\frac{\partial B_z}{\partial t} \Delta x \Delta y$$

$$\frac{\partial E_y}{\partial x} = -\frac{\partial B_z}{\partial t} \quad \text{(Faraday's law)}$$



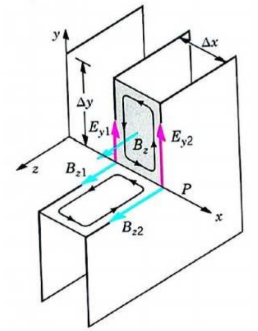
Derivation of the Wave Equation (III)

$$\oint \mathbf{B}\cdot d\mathbf{l} = (-B_{z2} + B_{z1})\Delta z$$

$$\Phi_E = E_y \Delta x \Delta z \quad \therefore \frac{\partial \Phi_E}{\partial t} = \frac{\partial E_y}{\partial t}\Delta x \Delta z$$

$$(B_{z2} - B_{z1})\Delta z = -\mu_0 \varepsilon_0 \frac{\partial E_y}{\partial t}\Delta x \Delta z$$

$$\frac{\partial B_z}{\partial x} = -\mu_0 \varepsilon_0 \frac{\partial E_y}{\partial t} \quad \text{(Ampere-Maxwell law)}$$



By taking the appropriate derivatives of these two equations, it is straightforward to obtain Maxwell's wave equation.

$$\frac{\partial^2 B_z}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B_z}{\partial t^2}, \qquad \frac{\partial^2 E_y}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E_y}{\partial t^2}$$

Electromagnetic Waves

We saw that a wave traveling along the x-axis with a wave speed v satisfies the wave equation:

$$\frac{\partial^2 y}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y}{\partial t^2}$$

From Faraday's law and Ampere-Maxell law, we can derive the following equations:

$$\frac{\partial^2 B_z}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B_z}{\partial t^2}, \qquad \frac{\partial^2 E_y}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E_y}{\partial t^2}$$

On comparing these with standard wave equation, we see that the wave speed is

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \quad (\mu_0 = 4\pi \times 10^{-7}\,\text{H/m and } \varepsilon_0 = 8.55\times 10^{-12}\,\text{F/m})$$

$$= 3.00 \times 10^8 \text{ m/s (speed of light in vacuum)}$$

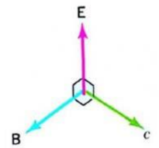
Electromagnetic Waves (II)

The simplest solution of the wave equations are plane wave

$$\frac{\partial^2 B_z}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B_z}{\partial t^2}, \quad B_z = B_0 \sin(kx - \omega t)$$

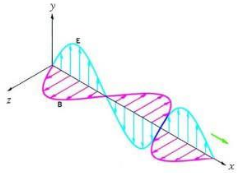
$$\frac{\partial^2 E_y}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E_y}{\partial t^2}, \quad E_y = E_0 \sin(kx - \omega t)$$

The electric *E* and magnetic *B* are in phase and are perpendicular to each other and also perpendicular to the direction of propagation.

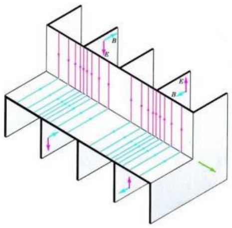


Electromagnetic Waves (III)

One representation of an electromagnetic wave traveling along the +x direction.



A representation of a plane electromagnetic wave in which the variation in the field strengths is depicted by the density of the field lines.



Energy Transport and the Poynting Vector

The energy density of the electric and magnetic fields in free space are given.

$$u_E = \frac{1}{2}\varepsilon_0 E^2;\ u_B = \frac{1}{2\mu_0}B^2$$

$$\text{Since } E = cB = \frac{1}{\sqrt{\mu_0\varepsilon_0}}B \ \Rightarrow\ u_E = u_B$$

The total energy density is therefore

$$u = \varepsilon_0 E^2 = \frac{B^2}{\mu_0} = \sqrt{\frac{\varepsilon_0}{\mu_0}}EB$$

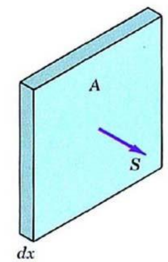
Energy Transport and the Poynting Vector (II)

Consider two planes, each of area A, a distance dx apart, and normal to the direction of propagation of the wave. The total energy in the volume between the planes is $dU=uAdx$.

The rate at which this energy through a unit area normal to the direction of propagation is

$$S = \frac{1}{A}\frac{dU}{dt} = \frac{1}{A}uA\frac{dx}{dt} = uc$$

$$S = uc = \frac{EB}{\mu_0}$$



The vector form of the Poynting vector is

$$\mathbf{S} = \frac{\mathbf{E}\times\mathbf{B}}{\mu_0}$$

Energy Transport and the Poynting Vector (III)

The magnitude of **S** is the intensity, that is instantaneous power that across a unit area normal to the direction of the propagation.

The direction of **S** is the direction of the energy flow.

In an electromagnetic wave, the magnitude of **S** fluctuates rapidly in time. Thus a more useful quantity, the average intensity, is

$$S_{av} = u_{av}c = \frac{EB}{2\mu_0}$$

The quantity S_{av}, measured in W/m^2 is the average power incident per unit area normal to the direction of propagation.

Example:

A radio station transmits a 10-kW signal at a frequency of 100 MHz. For simplicity, assume that it radiates as a point source. At a distance of 1 km from the antenna, find: (a) the amplitude of the electric and magnetic field strengths, and (b) the energy incident normally on a square plate of side 10 cm in 5 min.

Solution:

$$(a)\ S_{av} = \frac{\text{Average power}}{4\pi r^2} = \frac{E_0^2}{2\mu_0 c}$$

$$\Rightarrow \frac{10000}{4\pi 1000^2} \times 2 \times 4\pi \times 10^{-7} \times 3 \times 10^8 = E_0^2$$

$$\begin{cases} E_0 = 0.775\ \text{V/m} \\ B_0 = 2.58 \times 10^{-9}\ \text{T} \end{cases}$$

$$(b)\ \ \Delta U = S_{av}\Delta t = 2.4 \times 10^{-3}\ \text{J}$$

Momentum and Radiation Pressure

An electromagnetic wave transports linear momentum.

We state, without proof, that the linear momentum carried by an electromagnetic wave is related the energy it transport according to

$$p = \frac{U}{c}$$

If surface is perfectly reflecting, the momentum change of the wave is double, consequently, the momentum imparted to the surface is also doubled.

The force exerted by an electromagnetic wave on a surface may be related to the Poynting vector

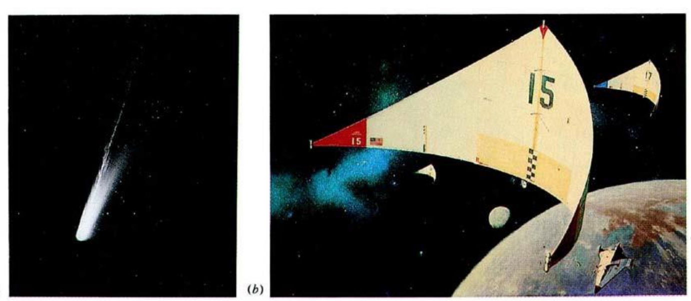
$$\underline{F} = \underline{\Delta p} = \underline{\Delta U} = \frac{SA}{Ac} = \underline{S} = u\,A \qquad \frac{A\Delta t}{c} \qquad Ac\Delta t$$

Momentum and Radiation Pressure (II)

The radiation pressure at normal incident is

$$F = S = u\,A \qquad c \qquad - \quad -$$

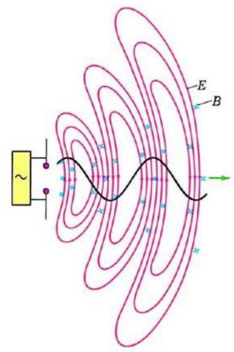
Examples: (a) the tail of comet, (b) A "solar sail"

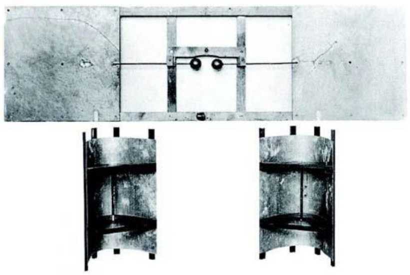


(a) (b)

Hertz's Experiment

When Maxwell's work was published in 1867 it did not receive immediate acceptance. It is Hertz who conclusively demonstrated the existence of electromagnetic wave.

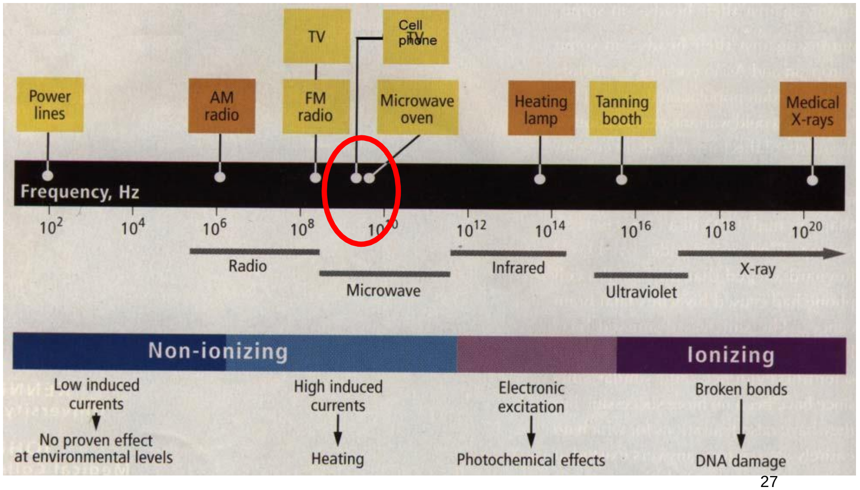




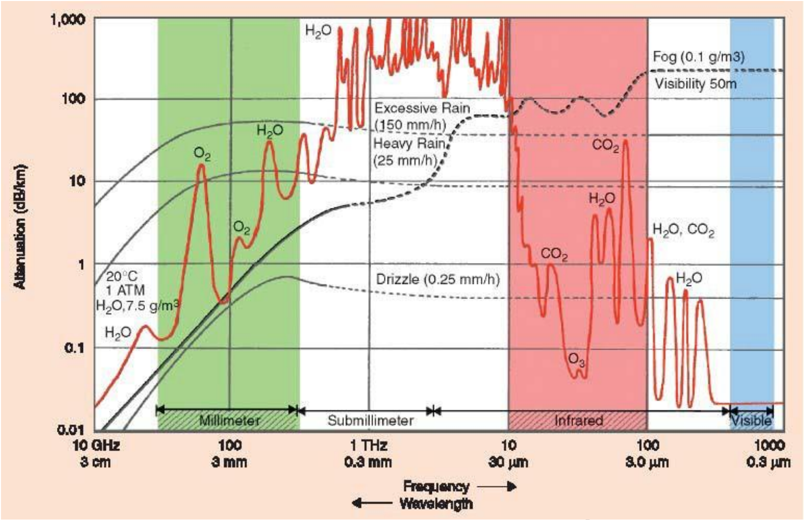
The Electromagnetic Spectrum

Electromagnetic waves span an immerse range of frequencies, from very long wavelength to extremely high energy r-way with frequency 10^{23} Hz. There is no theoretical limit to the high end.

Mainly Heating Effect in Micro/mm-Wave Spectrum



Windows for Research and Application Opportunities



Lecture 2

Spectrum to Be Exploited