Unit III

Electrodynamics

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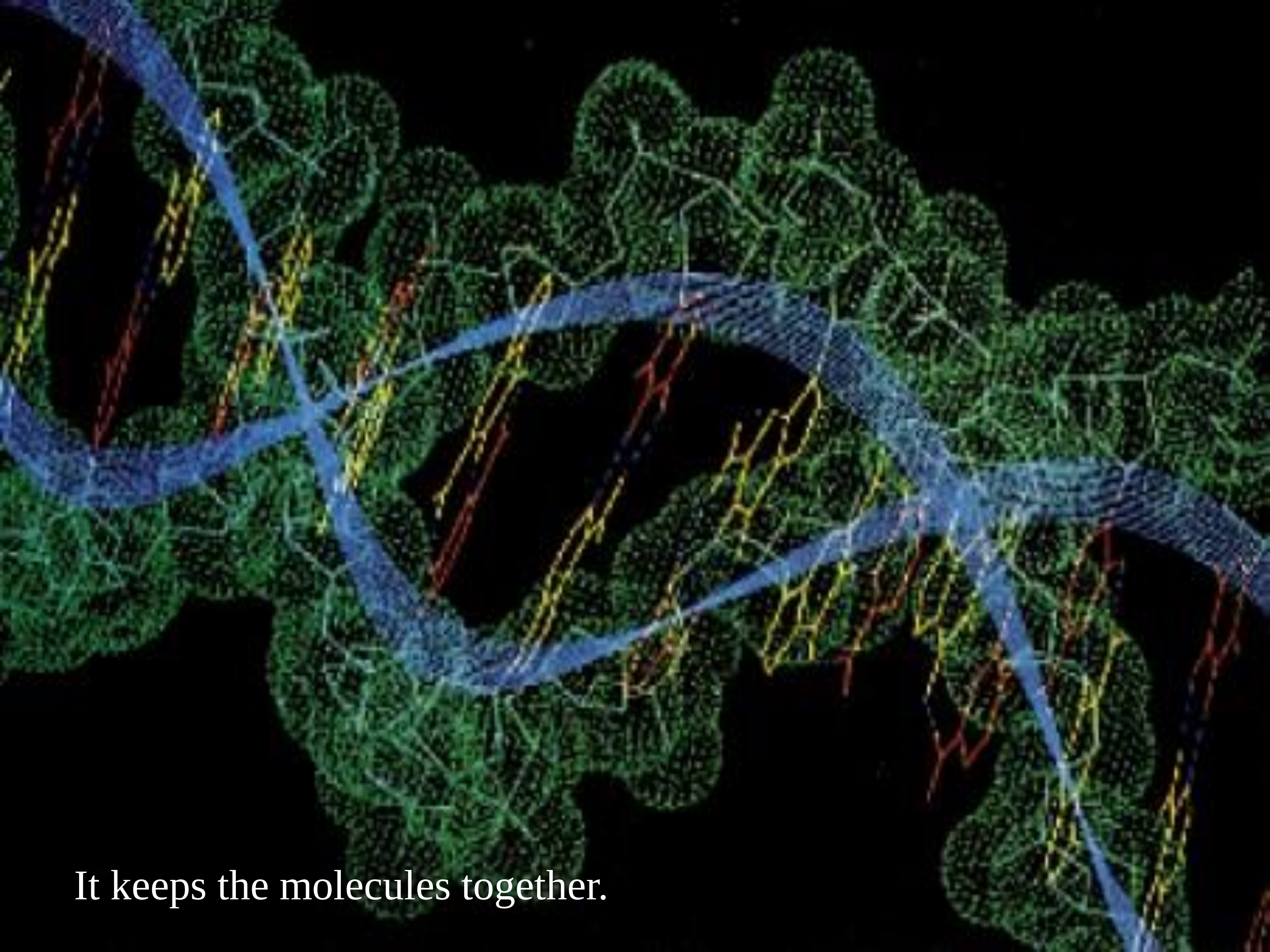
Natural phenomena are governed by the electromagnetic interaction.


It governs our man-made world as well.



It keeps the molecules together.

What is electrodynamics, and how does it fit into the general scheme of physics?

Electromagnetism is the theory two types of forces:

Electric force

Magnetic force

Classical Mechanics
Newton

small

Quantum Mechanics
Bohr, Heisenberg, Schrödinger, …

fast

Special Relativity
Einstein

Quantum Field Theory
Dirac, Pauli, Feynman, Schwinger, ….

Four kinds of forces - interactions

1.	Strong	Keeps nuclei and nucleons together.
2.	Electromagnetic	Most common phenomena.
3.	Weak	β-decay $n \to p + e + \nu$
4.	Gravitational	Keeps the Universe together.

Unification

electric + magnetic $\longrightarrow$ electromagnetic

electromagnetic + optic $\longrightarrow$ electrodynamic

electrodynamic + weak $\longrightarrow$ electroweak

Electric Charge (q, Q)

1. Charge exists as +q and –q. At the same point: +q-q=0
2. Charge is conserved (locally).
3. Charge is quantized. +q =n (+e), -q = m (-e), m, n, integer

electron: –e, positron: +e, proton: +e, C-nucleus: 6(+e)
Charge conservation in the micro world:
p + e -> n (electron capture)

Macro world: q ~10^{23}e

Quantization is unimportant. Imagine charge as some kind of jelly.

SI-Units

Systeme Internationale

Mechanics

length: meter (m)

mass: kilogram (kg)

time: second (s)

force: newton ($N = kg\,m\,s^{-2}$)

work: joule ($J = N\,m$)

Power: watt (W = J/s)

Electromagnetism

current: ampere (A)

charge: coulomb ($C = As$)

voltage: volt (V)

work: ($W\,s = V\,A\,s$)

power: watt ($W = V\,A$)

The equations of EM contain

$$\varepsilon_0 = 8.859 \times 10^{-12} \frac{As}{Vm}, \quad \mu_0 = 4\pi \times 10^{-7} \frac{Vs}{Am} = \frac{1}{\varepsilon_0 c^2}, \quad \frac{1}{4\pi\varepsilon_0} \approx 9 \times 10^9 \frac{Nm^2}{C^2} = 9 \times 10^9 \frac{Vm}{As}$$

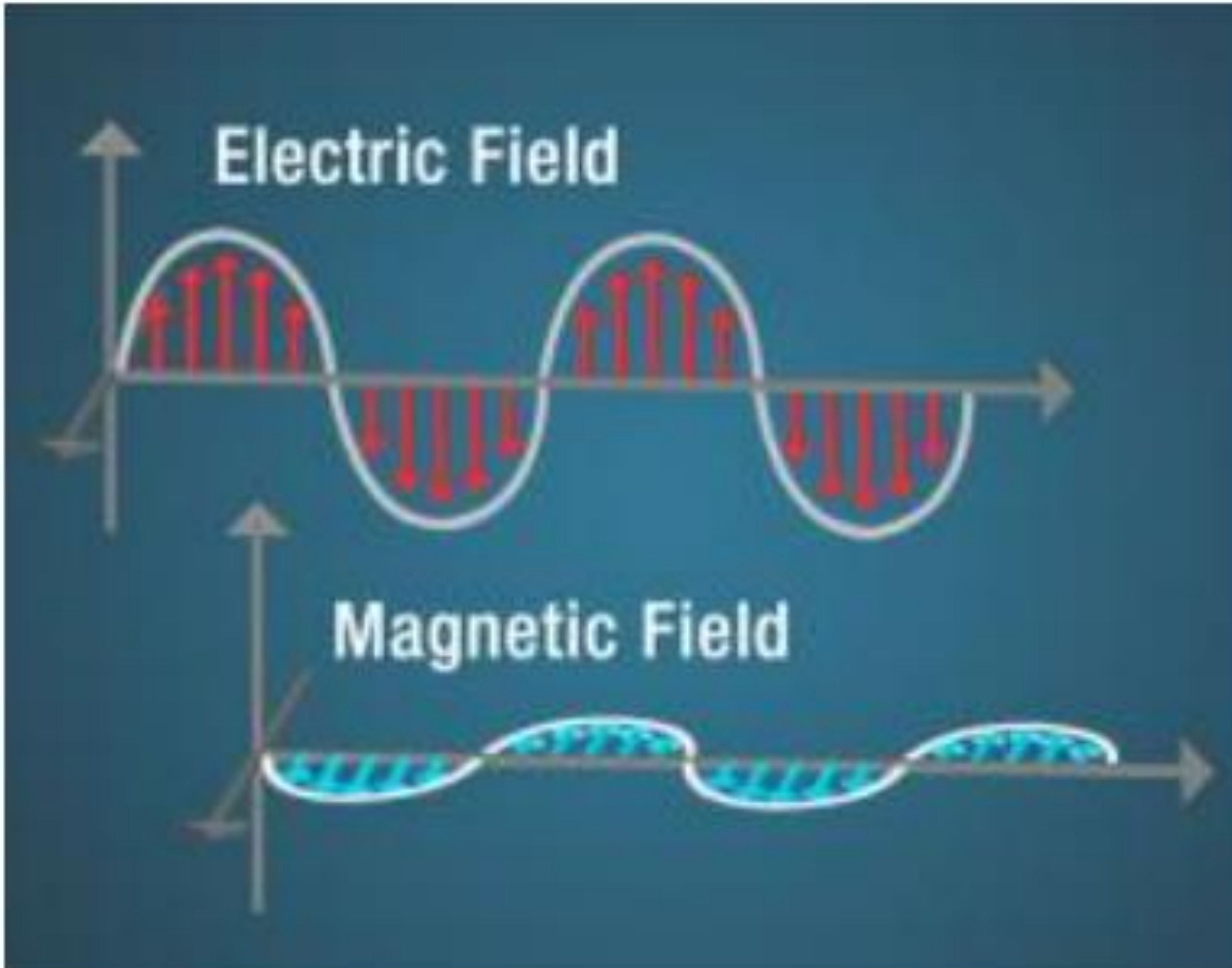
What are electromagnetic waves?

- How electromagnetic waves are formed
- How electric charges produce electromagnetic waves
- Properties of electromagnetic waves

Electromagnetic Waves…

- Do not need matter to transfer energy.
- Are made by vibrating electric charges and can travel through space by transferring energy between vibrating electric and magnetic fields.

- Electromagnetic waves or EM waves are waves that are created as a result of vibrations between an electric field and a magnetic field. In other words, EM waves are composed of oscillating magnetic and electric fields.
- Electromagnetic waves are formed when an electric field comes in contact with a magnetic field. They are hence known as ‘electromagnetic’ waves.
- The electric field and magnetic field of an electromagnetic wave are perpendicular (at right angles) to each other. They are also perpendicular to the direction of the EM wave.


Electric Field
Magnetic Field

Things to Remember

- **The higher the frequency, the more energy the wave has.**
- **EM waves do not require media in which to travel or move.**
- **EM waves are considered to be transverse waves because they are made of vibrating electric and magnetic fields at right angles to each other, and to the direction the waves are traveling.**
- Inverse relationship between wave size and frequency: as wavelengths get smaller, frequencies get higher.

Maxwell’s equations

•Maxwell’s four equations describe the electric and magnetic fields arising from distributions of electric charges and currents, and how those fields change in time.

• They were the mathematical distillation of decades of experimental observations of the electric and magnetic effects of charges and currents, plus the profound intuition of Michael Faraday.

•Maxwell’s own contribution to these equations is just the last term of the last equation—but the addition of that term had dramatic consequences. It made evident for the first time that varying electric and magnetic fields could feed off each other—these fields could propagate indefinitely through space, far from the varying charges and currents where they originated.

Maxwell`s Equations and Electromagnetic Waves

•Electromagnetism was developed by Michel faraday in 1791-1867and latter James Clerk Maxwell (1831-1879),put the law of electromagnetism in he form in which we know today. these laws are called Maxwells equation.

Scalar field: A scalar field is defined as that region of space whose each point is associated with scalar function ie. A continuous function which gives the value of a physical quantity like as flux, potential, temperature,etc.

Vector field: A vector field is specified by a continuous vector point function having magnitude and direction both changes from point to point in given region of field. The method of presentation of a vector field is called vector line.

Gradient , Divergence and curl

The rate of change of scalar and vector fields is denoted by a common operator called Del,or nebla is used which is writter as

$$\vec{\nabla} = i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\,\frac{\partial}{\partial z}$$

If $\phi(x, y,z)$ is a differentiable scalar function, its gradient is defined as

grad $\phi = \nabla\,\phi = (i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\,\frac{\partial}{\partial z})\phi$

$$\nabla\,\phi = i\frac{\partial \phi}{\partial x} + j\frac{\partial \phi}{\partial y} + k\,\frac{\partial \phi}{\partial z}$$

grad ϕ is a vector whose magnitude at any point is equal to the rate of change of ϕ at a point along a normal to the surface at the point.

When it is operated on a scalar, f, we get the gradient ∇f.

$$\nabla f = \frac{\partial f}{\partial x}\hat{i} + \frac{\partial f}{\partial y}\hat{j} + \frac{\partial f}{\partial z}\hat{k}.$$

In one dimension, the gradient is the derivative of the function.

The dot product of ∇ with a vector gives the divergence, which is a scalar.

The divergence of a vector field $\vec{v}(x, y, z) = v_x\hat{i} + v_y\hat{j} + v_z\hat{k}$ is

$$\nabla \cdot \vec{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}.$$

Curl

$$\nabla \times \mathbf{F} = \begin{vmatrix} \hat{\boldsymbol{\imath}} & \hat{\boldsymbol{\jmath}} & \hat{\boldsymbol{k}} \\ \dfrac{\partial}{\partial x} & \dfrac{\partial}{\partial y} & \dfrac{\partial}{\partial z} \\ F_x & F_y & F_z \end{vmatrix}$$

where $\mathbf{i}$, $\mathbf{j}$, and $\mathbf{k}$ are the unit vectors for the x-, y-, and z-axes, respectively. This exp

$$\nabla \times \mathbf{F} = \left(\frac{\partial F_z}{\partial y} - \frac{\partial F_y}{\partial z}\right)\hat{\boldsymbol{\imath}} + \left(\frac{\partial F_x}{\partial z} - \frac{\partial F_z}{\partial x}\right)\hat{\boldsymbol{\jmath}} + \left(\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y}\right)\hat{\boldsymbol{k}}$$

Gauss Divergence theorem

(Relation between surface and volume integration)

According to this theorem , the flux of a vector field $\vec{F}$ over any closed surface S is equal to the volume integral of the divergence of the vector field over the volume enclosed by the surface S.

$$\int_s \vec{F} \cdot d\vec{s} = \int_V \mathrm{div}\, \vec{F}\, dv \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Stokes Theorem

(Relation between surface and Line integration)

- The surface integral of the curl of a vector field $\vec{A}$ taken over an surface S is equal to the line integral of $\vec{A}$ around the closed curve.

$$\iint_s (\mathrm{Curl}\,\vec{A}).d\vec{s} = \oint \vec{A}.d\vec{l}$$

$$\iint_s (\vec{\nabla} \times \vec{A}).d\vec{s} = \oint \vec{A}.d\vec{l} \quad \text{......................}(2)$$

Fundamental laws of electricity and magnetism

- Gauss law of electrostatics

$$\oint \vec{E}.d\vec{s} = \frac{q}{\varepsilon_0} \text{.....................} (3)$$

i.e electric flux from a closed surface is equal $\frac{1}{\varepsilon_0}$ to the charge enclosed by the surface.

Gauss law of magnetostatics:

$$\oint \vec{B}.\,d\vec{s} = 0 \text{..........................} (4)$$

i.e the rate of change of magnetic flux from a closed surface is always equal to zero.

Continued.................

- Faradays law of electromagnetic induction: the rate of change of magnetic flux in a closed circuit induces an e.m.f which opposes the cause,i.e

$$e = -\frac{d\phi}{dt} \text{.............................}(5)$$

- Amperes law :

$$\oint \vec{B}.d\vec{l} = \mu_0 I \text{........................}(6)$$

the line integral of magnetic flux is equal to μ_0 times the current enclosed by the current loop.

Equation of continuity

- Electric current is defined as the rate of flow of charge i.e

$$i = -\frac{dq}{dt} \text{.................................}(1)$$

If dq charge is enclosed in a volume dv and is leaving a surface area ds then we have

$$i = \int_s \vec{J}\,.\,d\vec{s} \quad \text{and} \quad q = \int_v \rho\, dV$$

where J is the current density and ρ is the volume charge density .therefore eq (1) becomes

Continued...............

$$\int_s \vec{J}.d\vec{s} = -\frac{d}{dt}\int_v \rho\, dV$$

$$\int_s \vec{J}.d\vec{s} = -\int_v \frac{\partial \rho}{\partial t} dV \text{ ....(2)}$$

using gaus divergence theorem on L.H.S of equation 2 we get

$$\int_s \vec{J}.d\vec{s} = \int_v \text{div J } dV \quad \text{therefore equation 2 become}$$

$$\int_v \text{div J } dV = -\int_v \frac{\partial \rho}{\partial t} dV$$

$$\int_v (\text{div J } + \frac{\partial \rho}{\partial t}) dV = 0 \text{ for an arbitrary surface}$$

$$div\ \text{J} + \frac{\partial \rho}{\partial t} = 0 \text{ is called continuity equation.}$$