Welcome to

Aakash + BYJU'S NOTES

Electromagnetic Waves

Faraday's Experiment

Sir Michael Faraday
proposed the laws of electromagnetic induction. They were named after him as "Faraday's laws of EMI".

Change in magnetic flux produces an induced emf

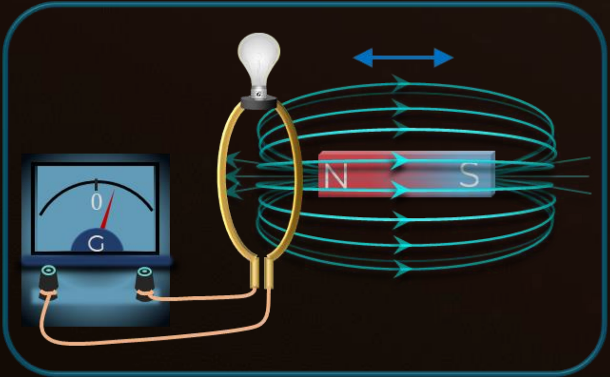
$$|\varepsilon| = \left|\frac{d\phi}{dt}\right|$$

Where, ε : Induced emf

$\frac{d\phi}{dt}$: Rate of change of magnetic flux

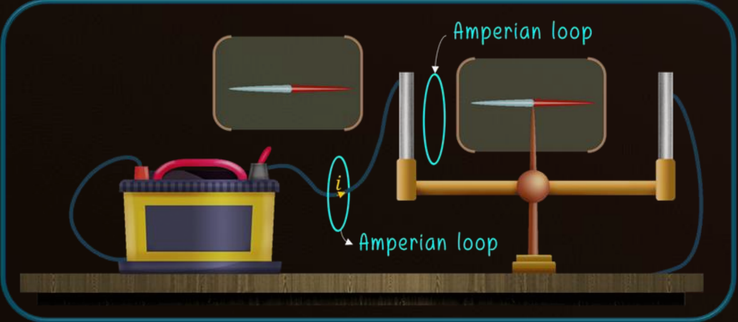
Faraday's Experiment

Faraday's first law: When the magnetic flux passing through a conducting loop changes with time, an emf is produced in the loop. For a closed circuit, current will flow through it.



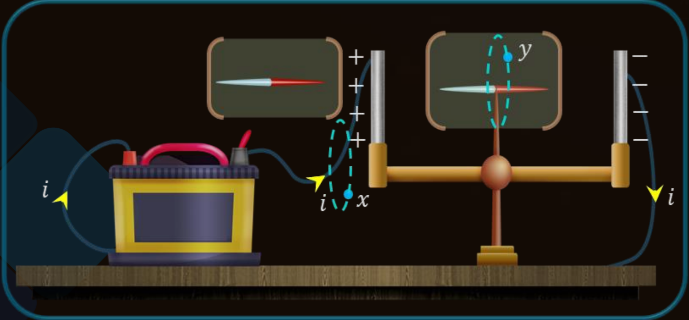
- Change in magnetic flux with time produces an induced emf.
- Does change in electric field with time produce a magnetic field too?

Maxwell's Experiment



- Two magnetic needles are placed, one is inside the capacitor and another one outside the capacitor.
- Maxwell observed deflection in both the needles.

Discrepancy in Ampere's law



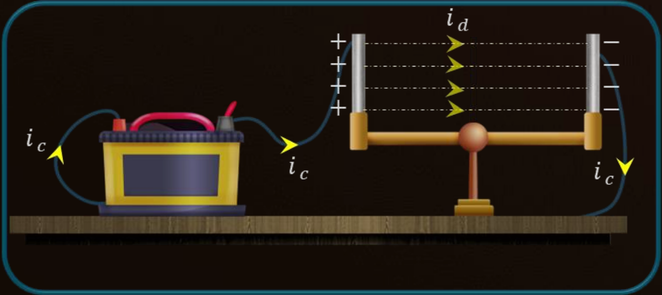
At point x: $\oint \vec{B} . d\vec{l} = \mu_0 i$

At point y: $\oint \vec{B} . d\vec{l} = \mu_0 (i) = 0$

There is a discrepancy in the Ampere's law and thus modification of Ampere's law is needed.

Displacement Current

Displacement current: A current which is developed due to changing electric field (or electric flux) is called displacement current.

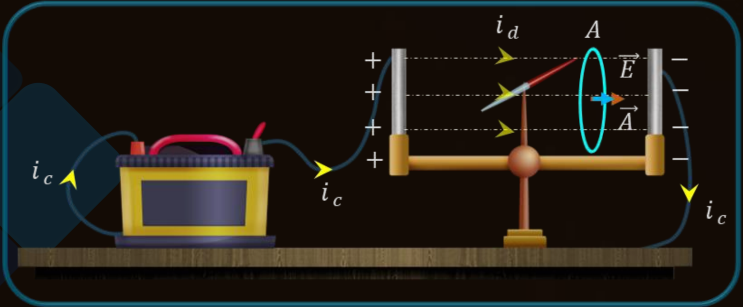


Displacement current: $i_d = \varepsilon_0 \frac{d\phi_E}{dt}$

Conduction current: $i_c = \frac{dq}{dt}$

Not only the current produces magnetic field, but a changing electric field also produces a magnetic field.

Discrepancy in Ampere's law



Displacement Current: $i_d = \varepsilon_0 \frac{d\phi_E}{dt}$

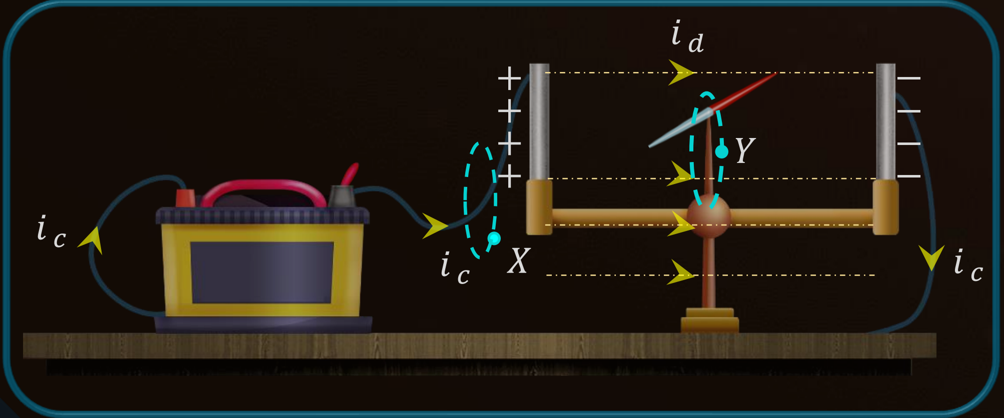
Conduction current: $i_c = \frac{dq}{dt}$

$$i_d = \varepsilon_0 \frac{d}{dt}(EA)$$

$$= \varepsilon_0 \frac{d}{dt}\left(\frac{q}{A\varepsilon_0}A\right)$$

$$\boxed{\therefore i_d = i_c}$$

Modification of Ampere's Circuital Law



At point X: $\oint \vec{B}.d\vec{l} = \mu_0 i_c$

At point Y: $\oint \vec{B}.d\vec{l} = \mu_0 i_d$

In general, $\oint \vec{B}.d\vec{l} = \mu_0(i_c + i_d)$

$$\oint \vec{B}.d\vec{l} = \mu_0\left(i_c + \varepsilon_0 \frac{d\phi_E}{dt}\right)$$

(Ampere-Maxwell's Law)

Where,

$\mu_0\varepsilon_0 \frac{d\phi_E}{dt}$ $\rightarrow$ Maxwell's correction

$\varepsilon_0 \frac{d\phi_E}{dt}$ $\rightarrow$ Displacement current

Properties of Displacement Current

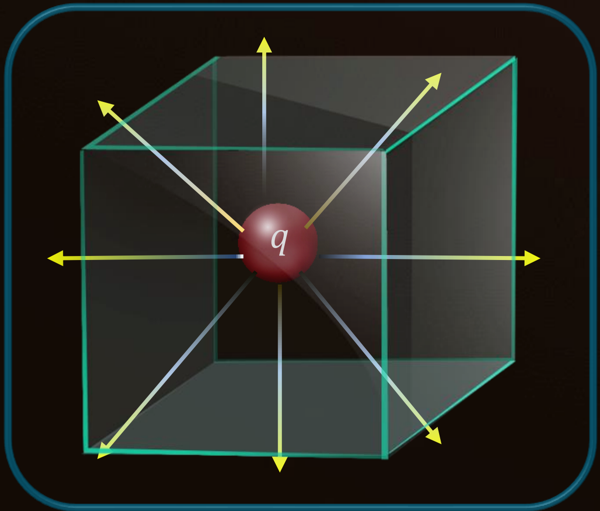
- Displacement current is not a conventional current.
- It exists only when there is a changing electric field (electric flux).
- Displacement current does not exist under steady state conditions.
- The conduction current and the displacement current together satisfy the property of continuity.

Maxwell’s Equations

Maxwell, in the process of unification of electricity and magnetism, brought together four already existing equations and modified them. He further stated that these four equations completely define electromagnetism.

- Gauss’s law in electrostatics
- Gauss’s law in magnetism
- Faraday's laws of electromagnetic induction
- Ampere-Maxwell’s law

Gauss's Law in Electrostatics



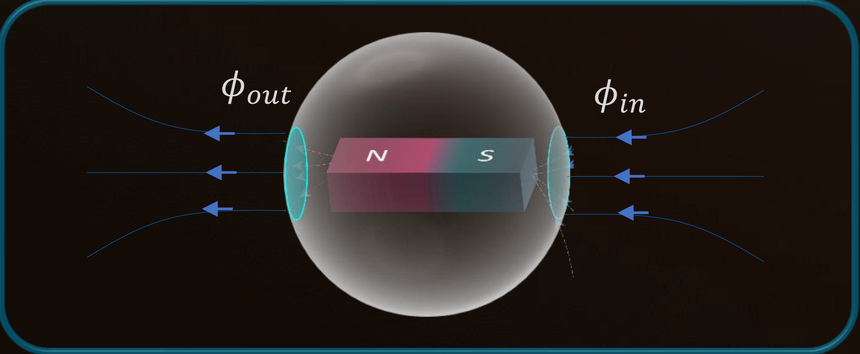
- Net electric flux through a closed surface is $\frac{1}{\varepsilon_0}$ times the total charge 'q' enclosed by surface.

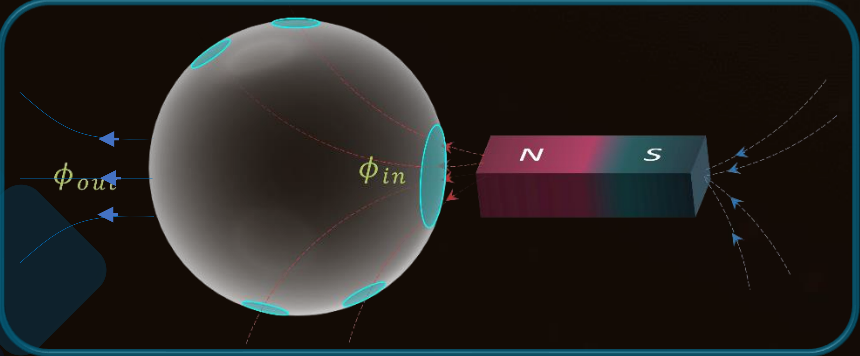
$$\phi_E = \frac{q_{enclosed}}{\varepsilon_0}$$

$$\boxed{\oint \vec{E}.d\vec{A} = \frac{q_{in}}{\varepsilon_o}}$$

- This law suggests that an isolated electric charge exists, and it produces an electric field.

Gauss's Law in Magnetism





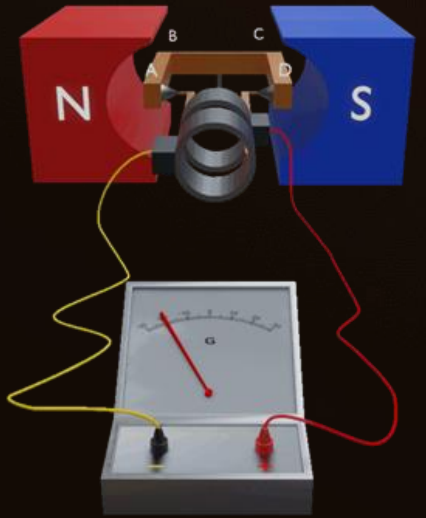
- Net magnetic flux through any closed surface is always zero.

$$\phi_B = 0$$

$$\boxed{\oint \vec{B}.d\vec{A} = 0}$$

- In both the cases, $\phi_{in} = \phi_{out}$
- This law suggests that magnetic monopoles do not exist.

Faraday's Law of Electromagnetic Induction



- Change in magnetic flux induces an emf.

$$\varepsilon = -\frac{d\phi_B}{dt}$$

- Changing magnetic field induces an electric field.

$$\oint \vec{E}.d\vec{l} = -\frac{d\phi_B}{dt}$$

Maxwell's Equations

$$\oint \vec{E}.d\vec{l} = \frac{q_{in}}{\varepsilon_0}$$

$$\oint \vec{B}.d\vec{A} = 0$$

$$\oint \vec{E}.d\vec{l} = -\frac{d\phi_B}{dt}$$

$$\oint \vec{B}.d\vec{l} = \mu_0\left(i_c + \varepsilon_0\frac{d\phi_E}{dt}\right)$$

Motion of a Charged Particle

- Charge
  - At rest

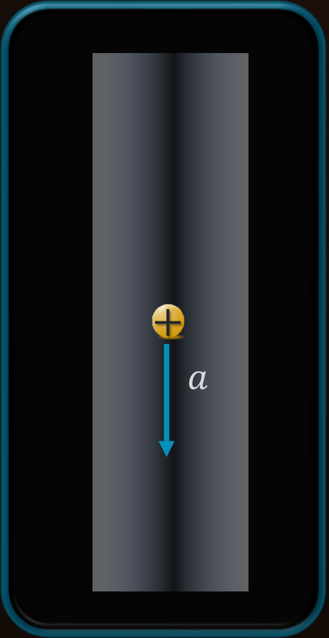
    $v = 0$

    Produces only electric field
  - Uniform Motion

    $v = \text{Constant}$

    Produces both electric and magnetic field

Accelerated Motion of a Charged Particle

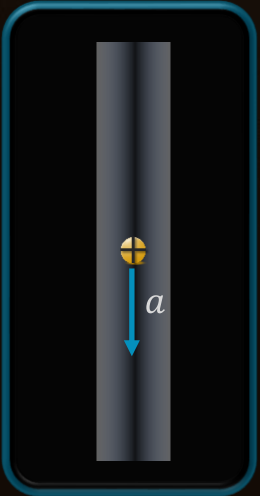


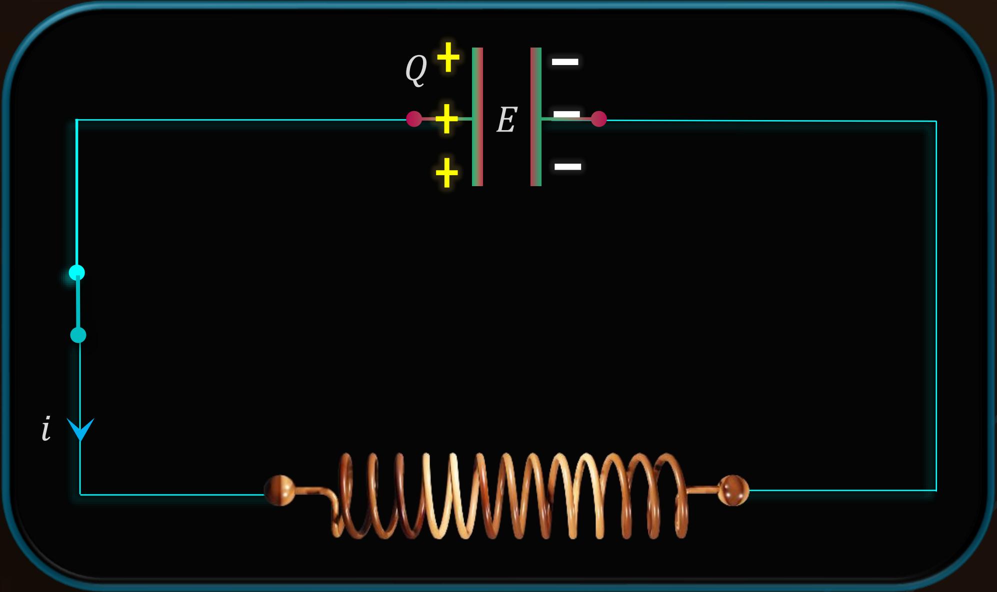
Accelerated Motion of a charged particle

Produces time varying electric and magnetic field

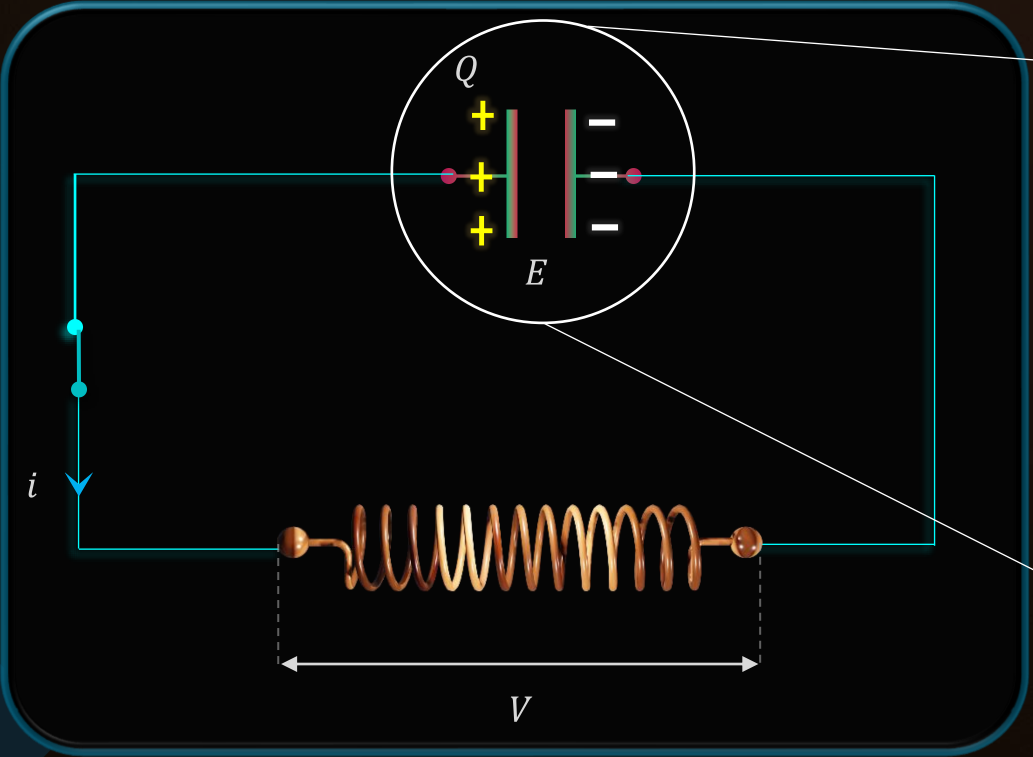
- An accelerated charged particle produces electric and magnetic fields which regenerate each other, and electromagnetic energy starts propagating through space, which is called Electromagnetic wave.
- The energy associated with the propagating wave comes at the expense of the energy of the source which moves the particle.

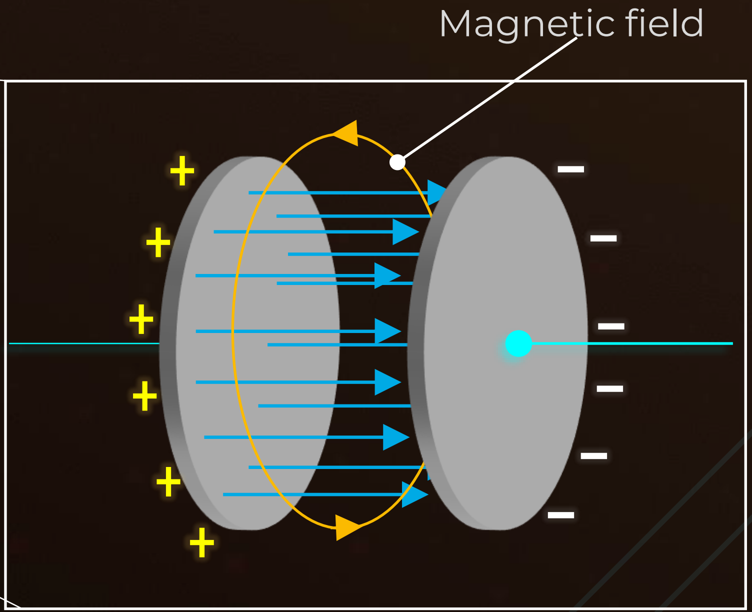
LC Circuit Analogy





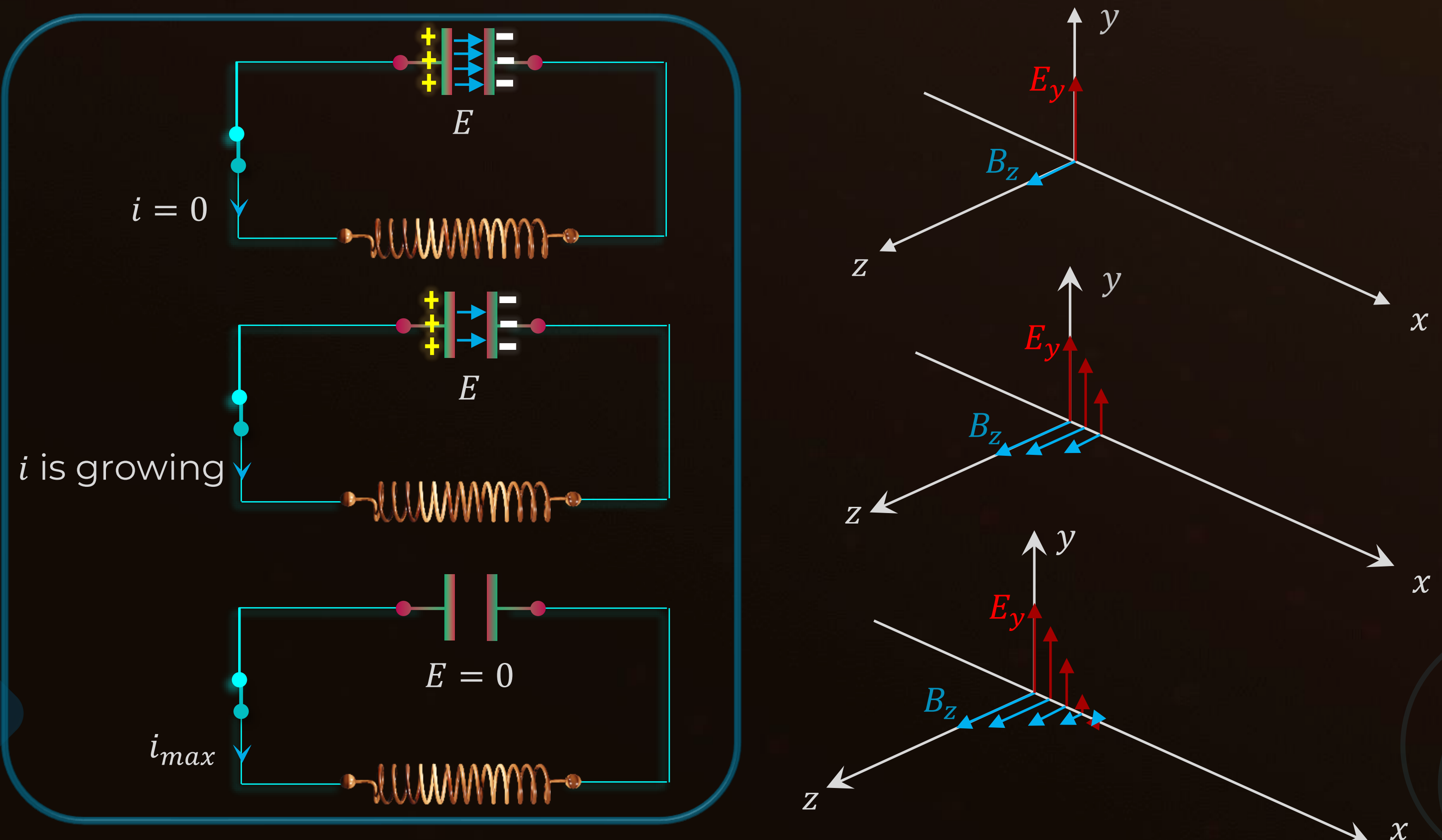
Oscillations in LC Circuit



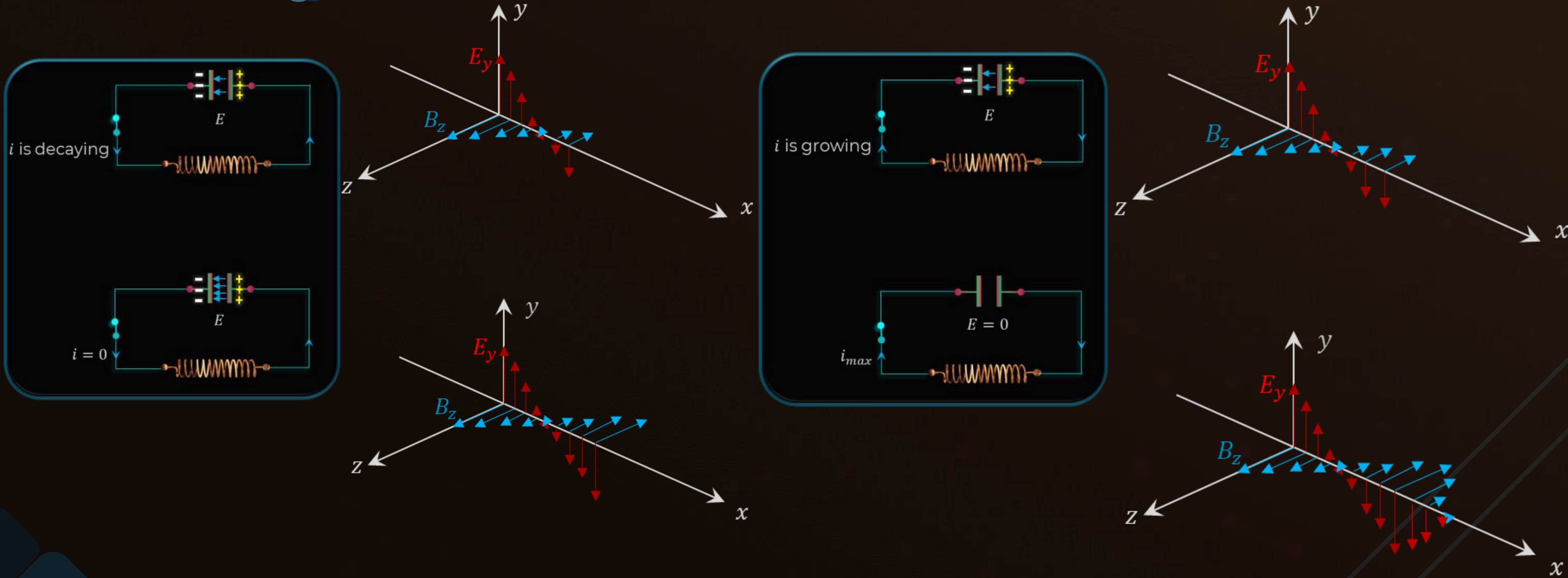


- Magnetic field is generated by changing electric field.
- Magnetic and electric field are perpendicular to each other.

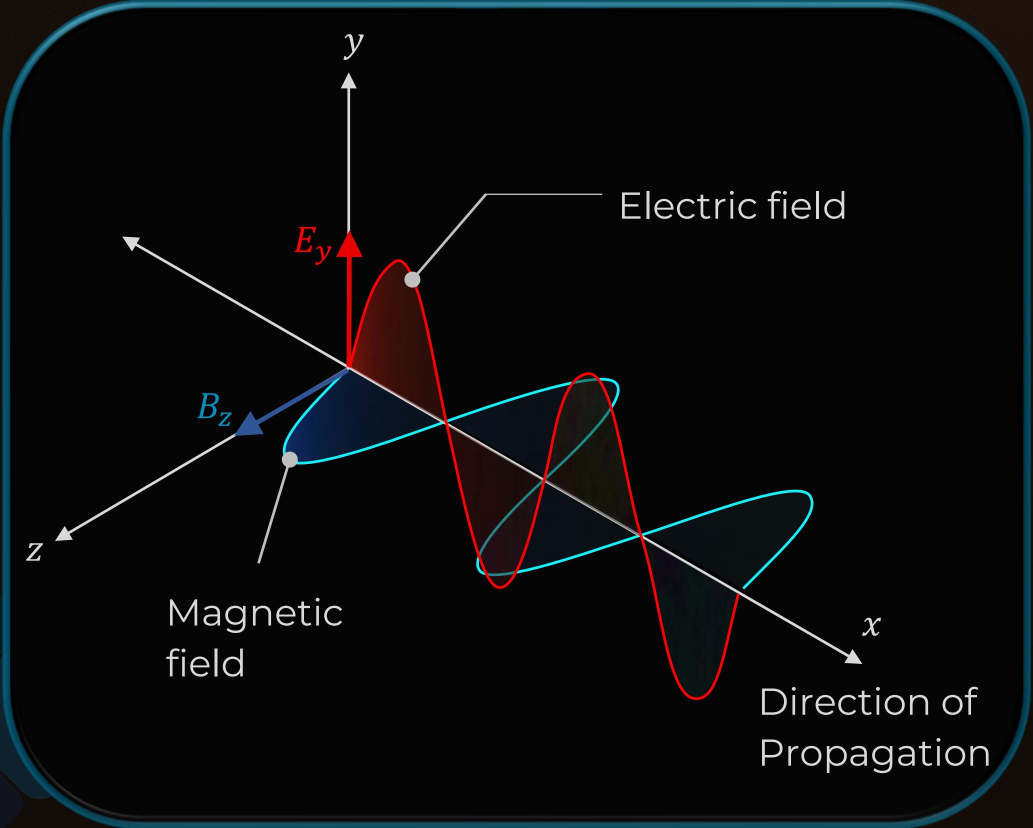
Oscillations in LC Circuit



Oscillations in LC Circuit



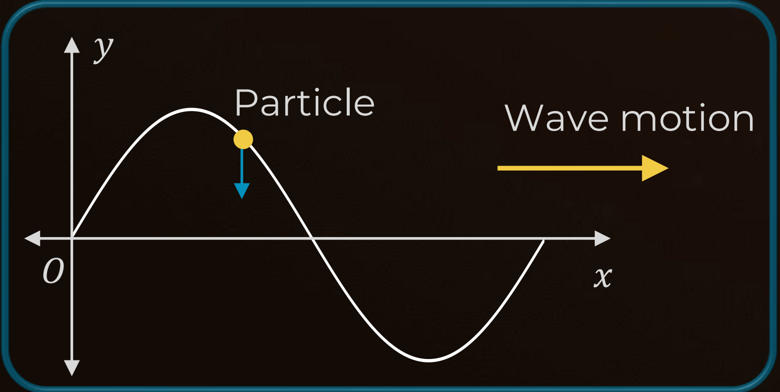
Transverse Nature of Electromagnetic Wave



- Electric and magnetic field vectors are perpendicular to each other.
- Both the vectors are perpendicular to the direction of propagation of the wave.
- This nature of electromagnetic wave is known as transverse nature.

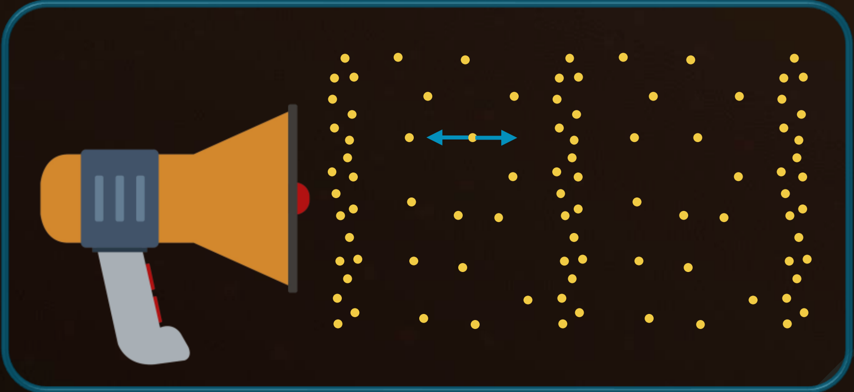
Transverse and Longitudinal Waves

Transverse Wave



- Particle motion is perpendicular to wave motion.
- It can travel in both vacuum and in a medium.
- It consists of troughs and crests.
- Eg: Electromagnetic waves, Ripples on water

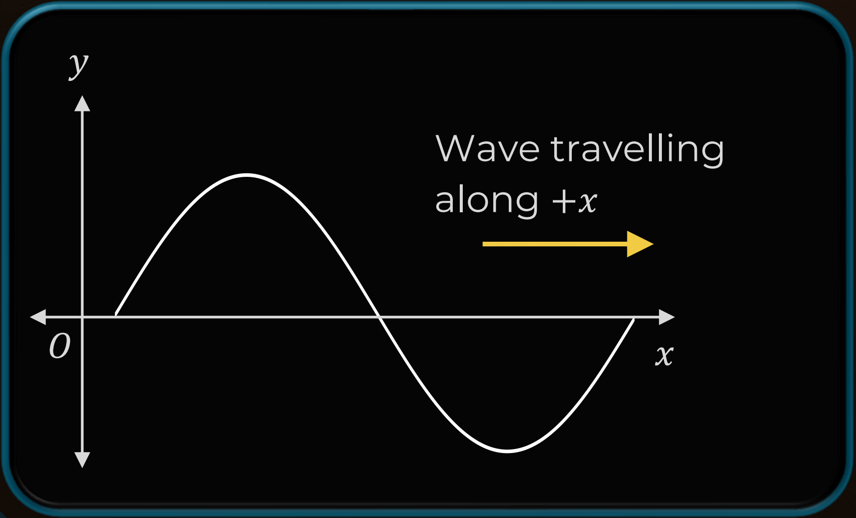
Longitudinal Wave



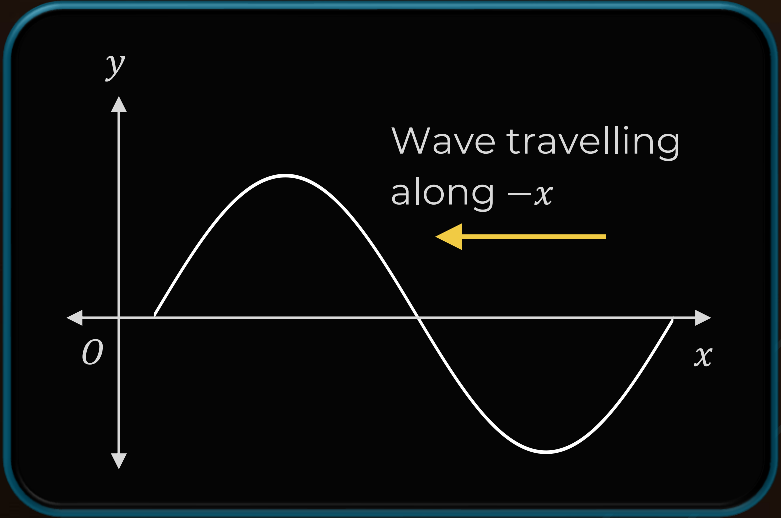
- Particle motion is parallel to wave motion.
- It requires a medium to travel.
- Consists of compressions and rarefactions.
- Eg: Sound waves

Equation of a Plane Progressive Wave

The y coordinate is a function of distance x and time t.



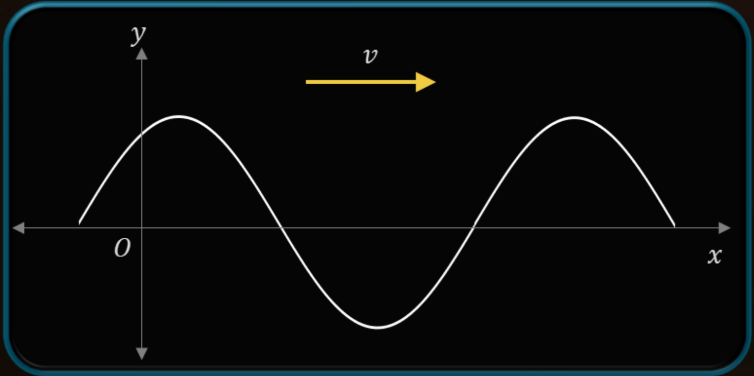
$$f(x,t) = y(x - \omega t + \phi)$$



$$f(x,t) = y(x + \omega t + \phi)$$

Wave Parameters

$$f(x,t) = A\sin(Kx \pm \omega t + \phi)$$



Amplitude (A): Distance from the mean position

Wave number (K): The number of radians per unit length.

Wavelength (λ): Distance between two successive crests or two successive troughs.

Time period (T): It is the time taken for one complete oscillation.

Frequency (f): Number of oscillations per unit time.

$$f = \frac{1}{T}$$

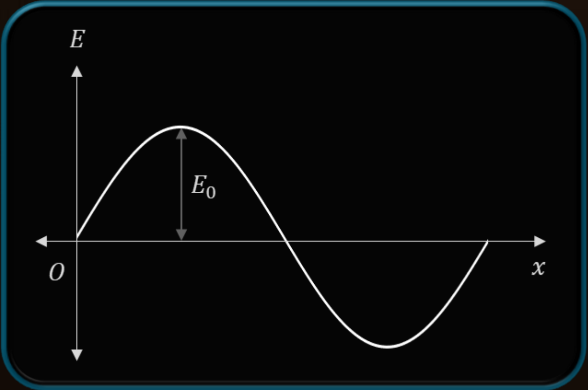
Angular frequency (ω): The angular displacement of any element of wave per unit time.

$$\omega = \frac{2\pi}{T} = 2\pi f$$

Phase constant: It describes how displaced is the wave from original position.

Speed of the wave (v): $v = \lambda f$

Equations for Electric Field and Magnetic field



The different equations for electric field is given by:

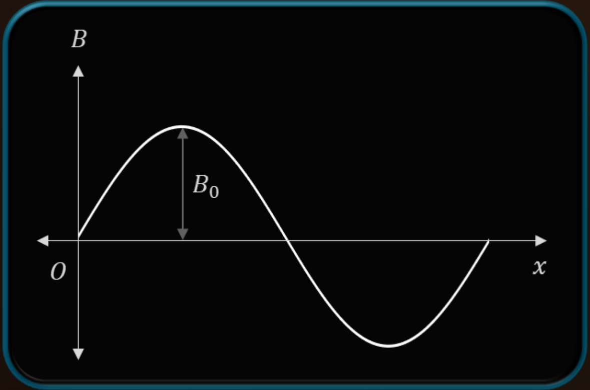
$$E = E_0 \sin(Kx - \omega t)$$

{Phase(ϕ) = 0}

$$E = E_0 \sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{T}t\right)$$

$$E = E_0 \sin\left(2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right)$$

$$E = E_0 \sin\left(2\pi\left(\frac{x}{\lambda} - ft\right)\right)$$



The different equations for magnetic field is given by:

$$B = B_0 \sin(Kx - \omega t)$$

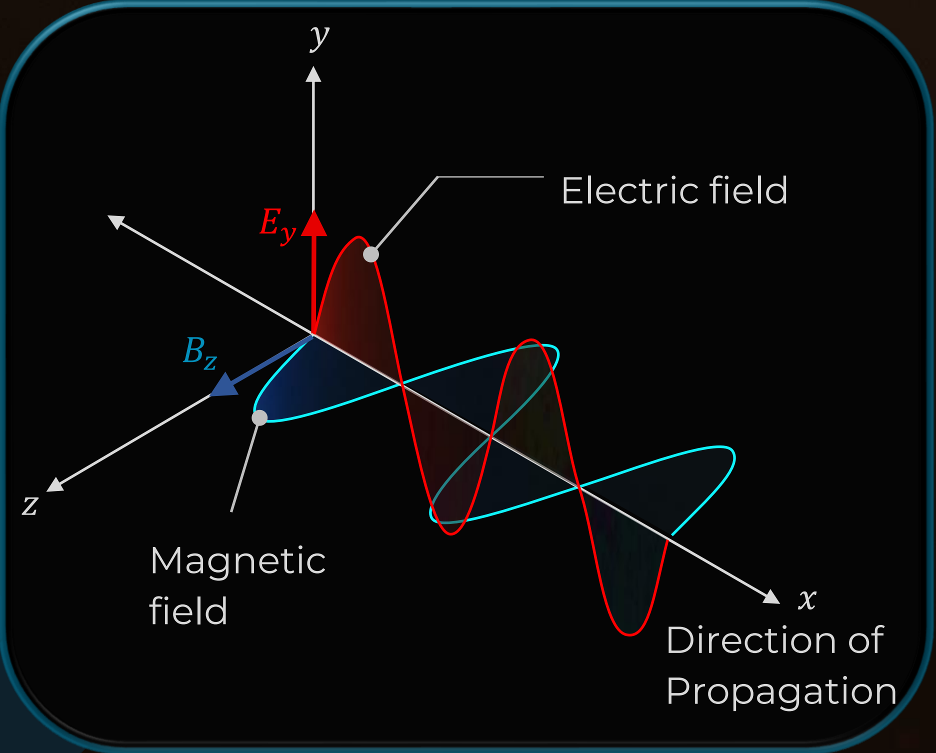
{Phase(ϕ) = 0}

$$B = B_0 \sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{T}t\right)$$

$$B = B_0 \sin\left(2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right)$$

$$B = B_0 \sin\left(2\pi\left(\frac{x}{\lambda} - ft\right)\right)$$

Direction of Electromagnetic Wave



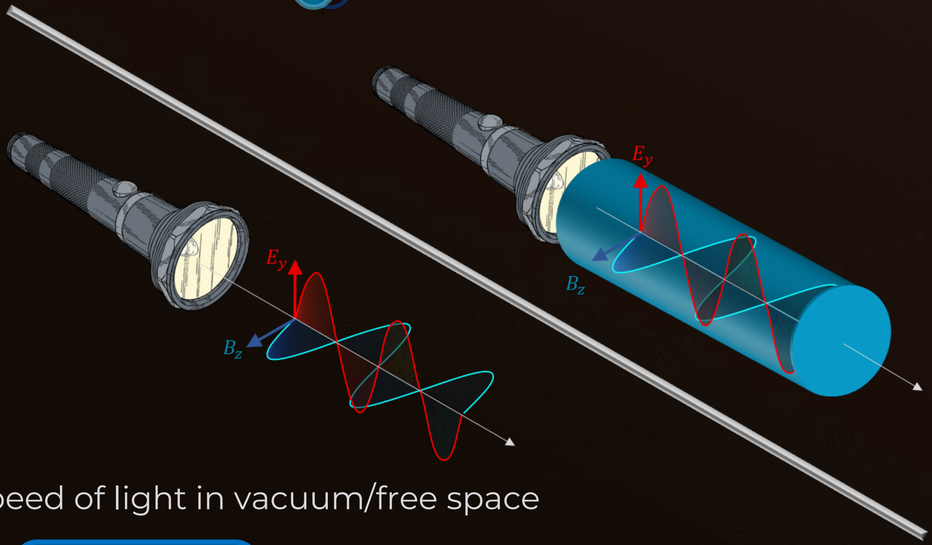
Electric and magnetic field are perpendicular to each other and also perpendicular to the direction of wave propagation.

$$\boxed{\hat{v} = \hat{E} \times \hat{B}}$$

Relation between peak value of $\vec{E}$ and $\vec{B}$ is:

$$\boxed{\frac{E_0}{B_0} = c}$$ $\{c\text{: Speed of light}\}$

Permittivity and Permeability of a Medium



Speed of light in vacuum/free space

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

Speed of light in other medium

$$v = \frac{1}{\sqrt{\mu_m \epsilon_m}}$$

Refractive index of medium (n):

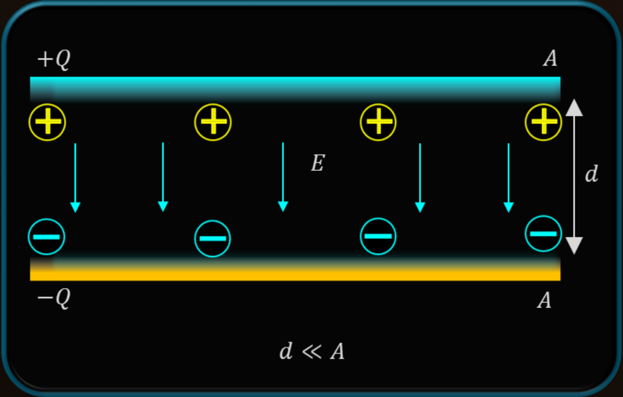
$$n = \frac{c}{v} = \frac{\sqrt{\mu_m \epsilon_m}}{\sqrt{\mu_0 \epsilon_0}} = \sqrt{\mu_r \epsilon_r}$$

Where,

$$\mu_r = \frac{\mu_m}{\mu_0}$$

$$\epsilon_r = \frac{\epsilon_m}{\epsilon_0}$$

Energy Density of Electric Field



$$U = \frac{1}{2} C V^2$$

$$V = E d$$

$$U = \frac{1}{2} \frac{\epsilon_0 A}{d} (Ed)^2 = \frac{1}{2} \epsilon_0 E^2 A d$$

$$U = \frac{1}{2} \epsilon_0 E^2 (Vol)$$

$$\boxed{\frac{U}{Vol} = \frac{1}{2} \epsilon_0 E^2}$$

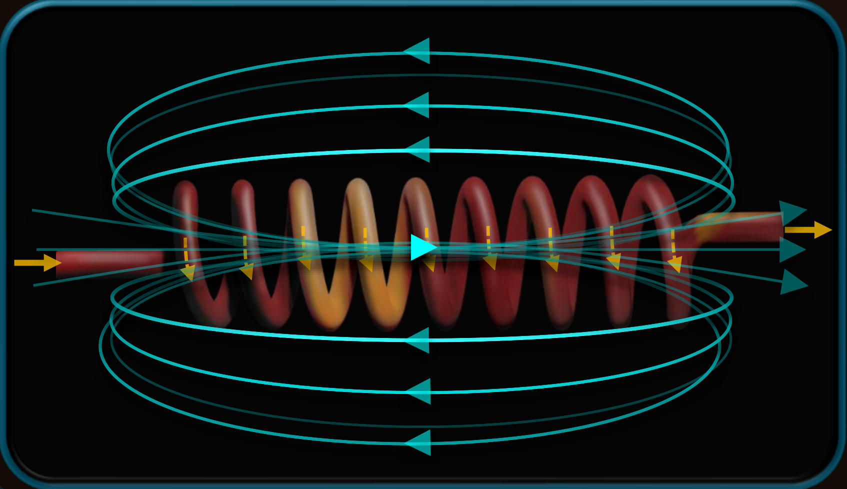
$$\frac{U}{Vol} = \frac{1}{2} \epsilon_0 E^2$$

$$E = E_0 \sin(Kx - \omega t)$$

$$\mu_E = \frac{1}{2} \epsilon_0 E_0^2 \underbrace{\sin^2(Kx - \omega t)}_{\text{Average} = \frac{1}{2}}$$

$$\boxed{(\mu_E)_{avg} = \frac{1}{4} \epsilon_0 E_0^2}$$

Energy Density of Magnetic Field



$$U = \frac{1}{2} L i^2$$

$$L = \mu_0 n^2 A l$$

$$i = \frac{B}{\mu_0 n}$$

$$U = \frac{1}{2} \frac{B^2}{\mu_0} A l$$

$$\frac{U}{Vol} = \frac{1}{2} \frac{B^2}{\mu_0}$$

$$(\mu_B)_{avg} = \frac{1}{4} \epsilon_0 B_0^2$$

Which of the following is true?

$$(\mu_E)_{avg} = \frac{1}{4}\epsilon_0 E_0^2$$

$$(\mu_E)_{avg} = \frac{1}{4}\epsilon_0 B_0^2$$

A $(\mu_E)_{Avg} = (\mu_B)_{Avg}$

B $(\mu_E)_{Avg} = 2(\mu_B)_{Avg}$

C $2(\mu_E)_{Avg} = (\mu_B)_{Avg}$

D $(\mu_E)_{Avg} = 4(\mu_B)_{Avg}$

Solution:

$$(\mu_E)_{Avg} = \frac{1}{4}\epsilon_0 E_0^2$$

$$\frac{E_0}{B_0} = c$$

$$c = \frac{1}{\sqrt{\mu_0\epsilon_0}}$$

$$(\mu_E)_{Avg} = \frac{1}{4}\epsilon_0 (B_0 c)^2$$

$$(\mu_E)_{Avg} = \frac{1}{4}\epsilon_0 {B_0}^2 \frac{1}{\mu_0\epsilon_0}$$

$$(\mu_E)_{Avg} = \frac{1}{4}{B_0}^2 \frac{1}{\mu_0}$$

$$(\mu_E)_{Avg} = (\mu_B)_{Avg}$$

Total Energy Density

$$\mu = \mu_E + \mu_B$$

$$\mu = \mu_E + \mu_E = 2\mu_E$$

$$\mu = 2 \times \frac{1}{4}\epsilon_0 E_0^2$$

$$\boxed{\mu = \frac{1}{2}\epsilon_0 E_0^2}$$

OR

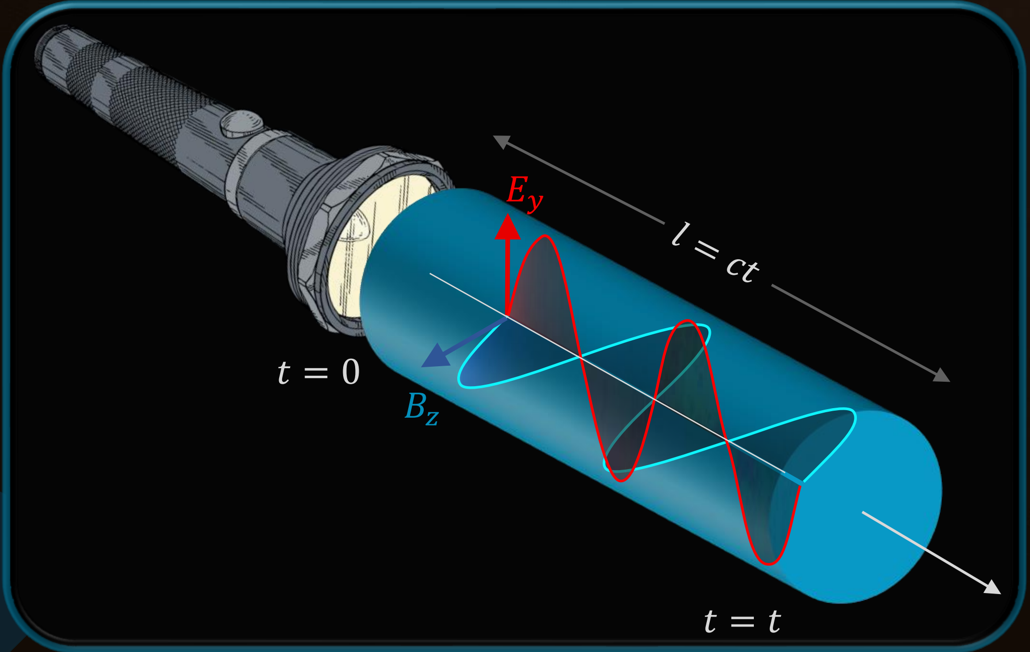
$$\mu = \mu_B + \mu_B = 2\mu_B$$

$$\mu = 2 \times \frac{1}{4\mu_0} B_0^2$$

$$\boxed{\mu = \frac{1}{2\mu_0} B_0^2}$$

Intensity of Electromagnetic Wave

The energy crossing per unit time, per unit area perpendicular to the direction of propagation is called intensity of the wave (I).



Energy (U)

$$U = \mu \times \text{volume}$$

$$\mu = \frac{1}{2}\epsilon_0 E_0^2$$

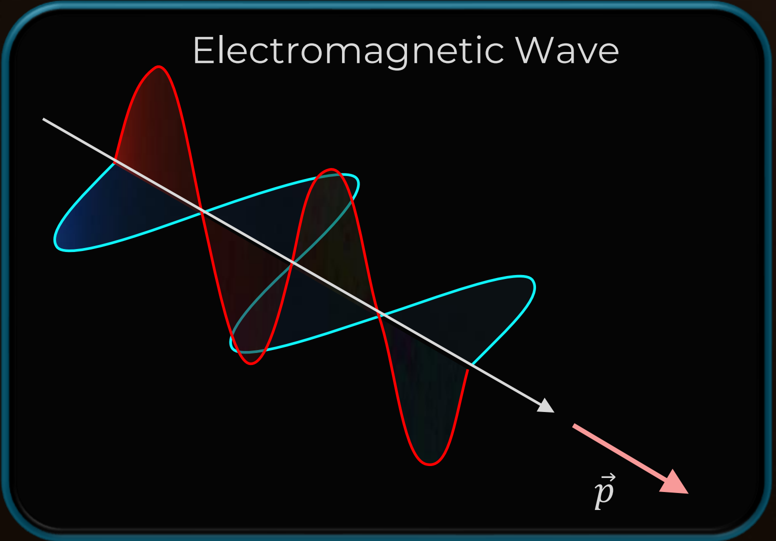
$$U = \frac{1}{2}\epsilon_0 E_0^2 \times A \times ct$$

Intensity:

$$I = \frac{\frac{1}{2}\epsilon_0 E_0^2 \times A \times ct}{At}$$

$$I = \frac{1}{2}\epsilon_0 E_0^2 c$$

Momentum of Electromagnetic Wave



Energy (U)

$$U = hf$$

Speed of light (c)

$$c = f\lambda$$

De-Broglie hypothesis

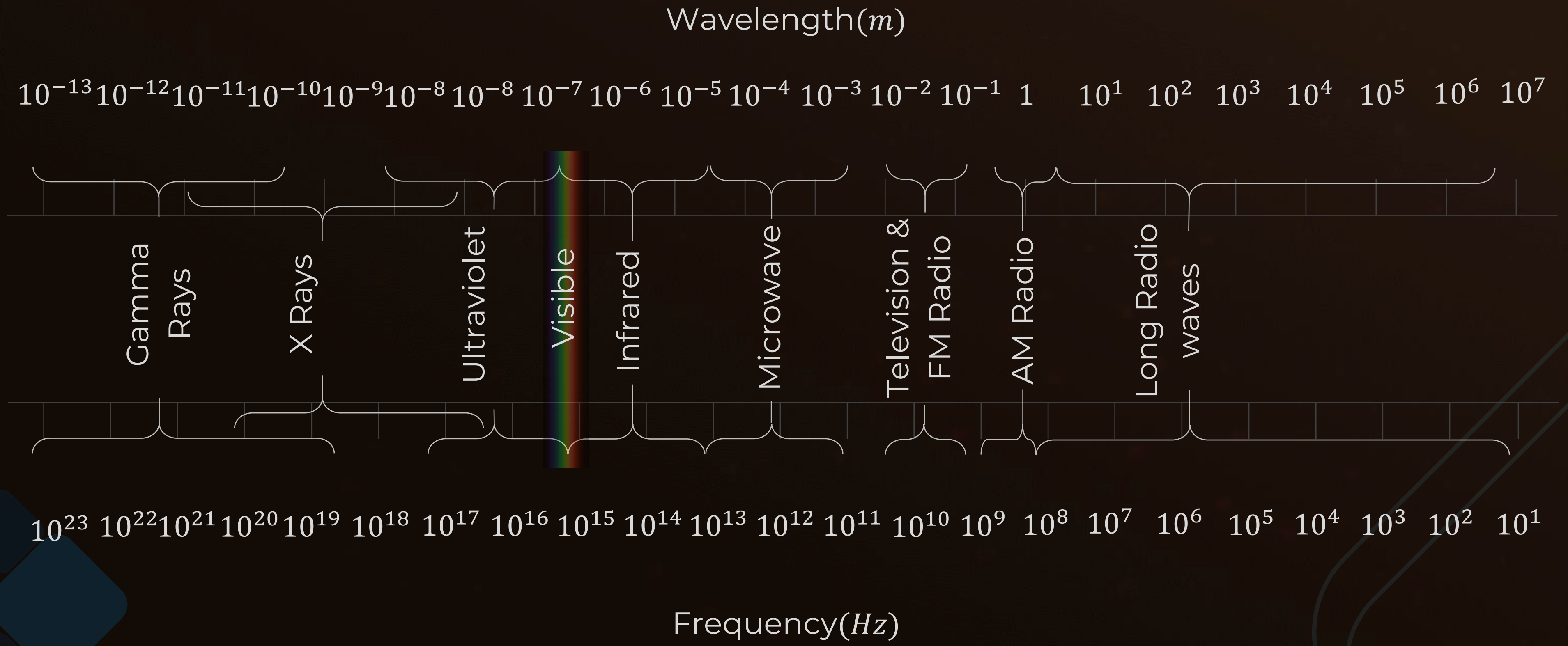
$$p = \frac{h}{\lambda}$$

$$U = \frac{hc}{\lambda}$$

$$U = pc$$

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

Electromagnetic Spectrum



Gamma Rays

They are produced by the disintegration of radioactive atomic nuclei.

- They are used in medicine to destroy cancer cells.
- Superhero Hulk was created from Gamma radiation.

X - Rays

X-rays are produced when fast moving electrons accelerates inside a metal target.

- They are widely used in medical diagnosis.
- In astronomy, X-rays are used to detect and study distant galaxies.

Ultraviolet Radiation

- UV-rays are produced by special lamps and very hot bodies (E.g., sun).

- Welders wear special glass shields to protect their eyes from large amount of UV produced by welding arcs.

Visible Light

It is the part of spectrum which is detected by the human eye.

Red
Orange
Yellow
GREEN
Blue
Indigo
Violet

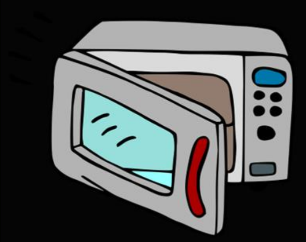
Infrared Radiation

They are produced by hot bodies and molecules. They are also known as Heat waves.

- They are used in thermal Imaging.
- Television remote emits infrared radiation, which is picked up by sensors in TV.
- Infrared sensors are used to detect body temperature.

Microwaves

These are low frequency waves produced by special vacuum tubes.



- Microwave ovens produce microwaves to heat the material inside.
- They are suitable for the radar system used in aircraft navigation.

Radio Waves

These are the electromagnetic waves with the longest wavelength.

- They are used in radio and television communication system.