Applied Physics for Engineers **(PHY121)**

Magnetism (part-5)

LECTURE # 17

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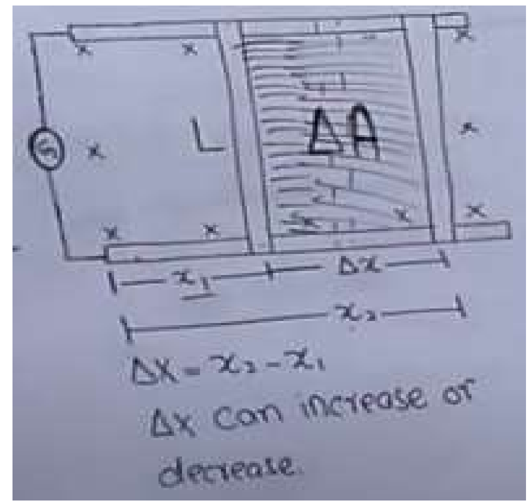
Outlines

1. Faraday's law of Electromagnetic Induction
2. The Lenz's law
3. Electromagnetic waves
4. Maxwell's equations

Faraday's law of Electromagnetic Induction

The average emf induced in a conductor of N loops is equal to the negative of the rate at which magnetic flux changes w.r.t. time.

$$\varepsilon_{av} = -N\,\frac{\Delta\varphi}{\Delta t}$$



Derivation

As we know the expression for motional emf,

$$\varepsilon = -vBL \qquad \text{..... (1)}$$

Because

$$S = vt$$

$$\Rightarrow \quad v = S/t = \Delta x/\Delta t$$

So eq (1) becomes,

$$\varepsilon = -\frac{\Delta x}{\Delta t}\mathrm{B}L = -\frac{B(L\Delta x)}{\Delta t} = -\frac{B(\Delta A)}{\Delta t}$$

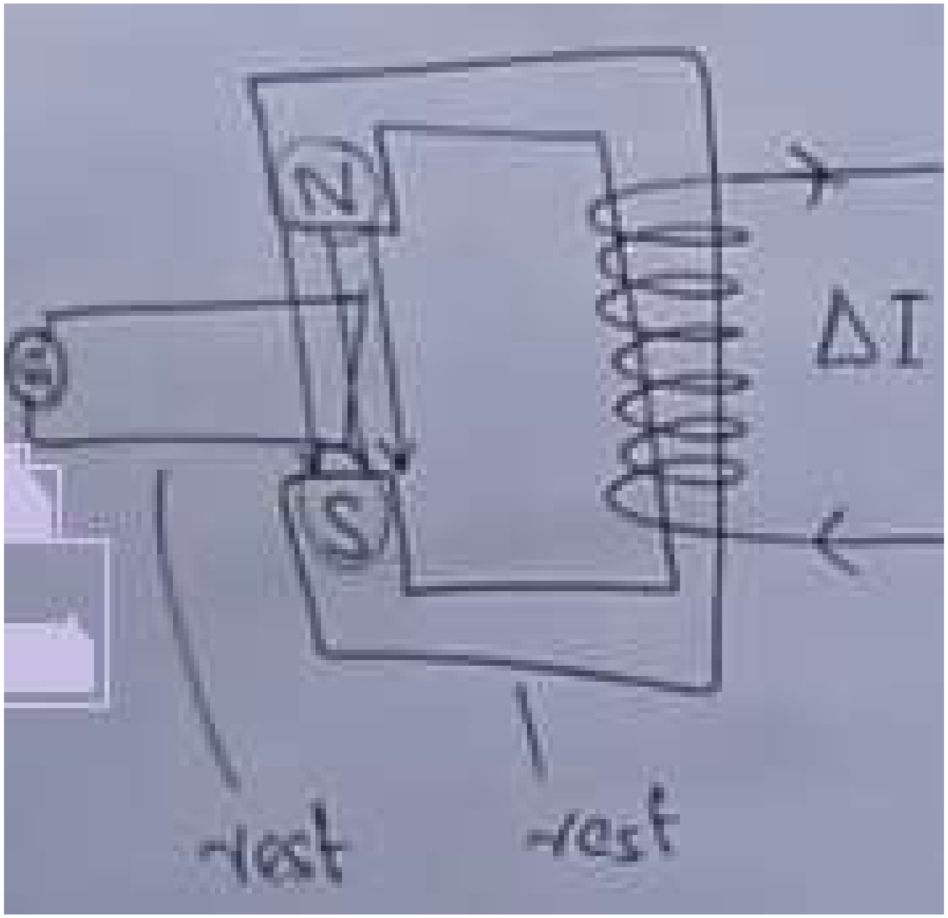
$$\varepsilon = -\frac{\Delta\varphi}{\Delta t}$$ Because $\Delta\varphi = \mathbf{B}\,.\Delta\boldsymbol{A}$

If this conductor having N loops then, it becomes

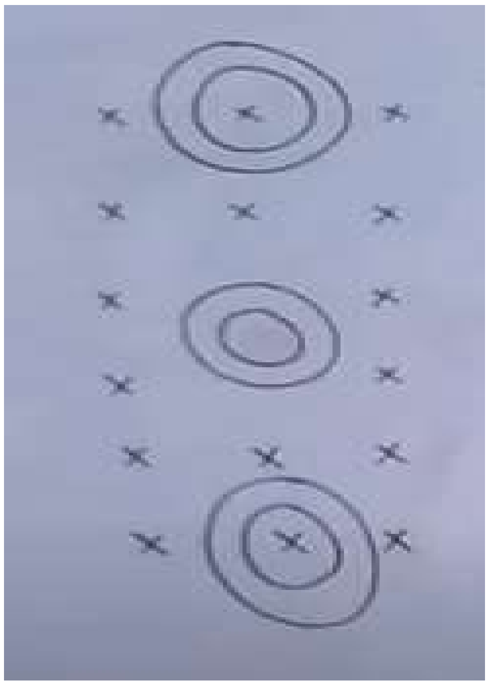
$$\varepsilon = -N\,\frac{\Delta\varphi}{\Delta t}$$

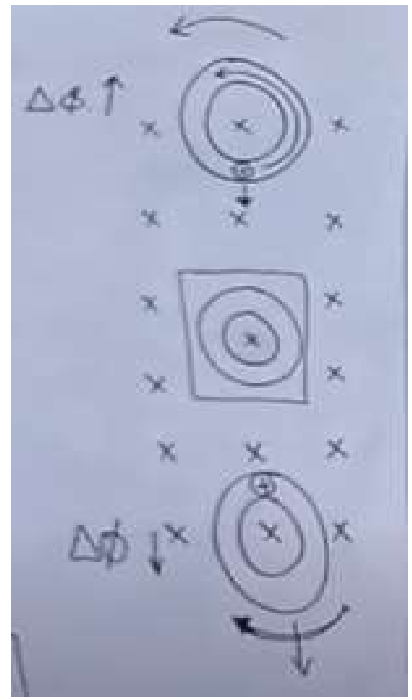
Why this law is called a backbone of Electromagnetic Induction?

- **Let's take again an example of electromagnetic induction in which we have an electromagnet and place a coil with a galvanometer in the field of electromagnet. Both magnet and coil are at rest. Only the current flowing through the electromagnet is changing say Δ*I*. Due to change in current (Δ*I*), strength of field is changes which induces current in the coil. As coil and electromagnet are at rest, so we cannot use the equation of electromagnetic induction i.e., $\varepsilon = -vBL$. Because the unknown value of '*v*'. But Faraday used this equation and derived general equation of electromagnetic induction which can be used in all applications of electromagnetic induction.**



An example to understand the negative sign appears in Faraday’s law equation





$$\varepsilon = -\mathrm{N}\,\frac{\Delta\varphi}{\Delta t}$$

EMF is produced in the opposition of change of flux w.r.t. time.

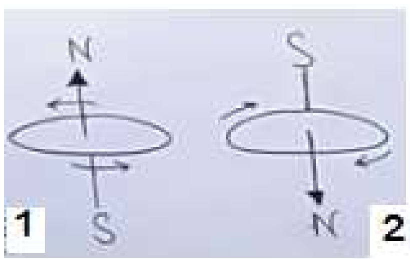
The Lenz's law

The direction of induced current is always such as to oppose the cause which produces it.

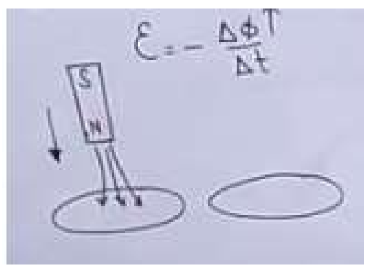
Note: this law is not applicable to emf because it is applicable of close circuit rather than open circuit.

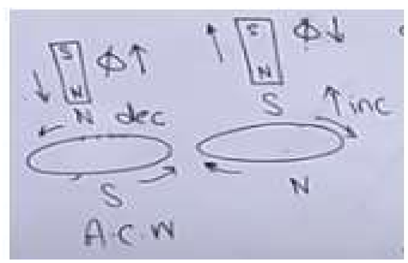
To understand Lenz's law properly, we will follow the following examples.

Example#01



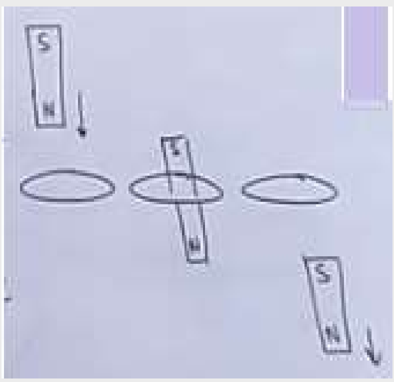
Two rings having currents anti-clockwise and clockwise directions in 1 & 2 respectively



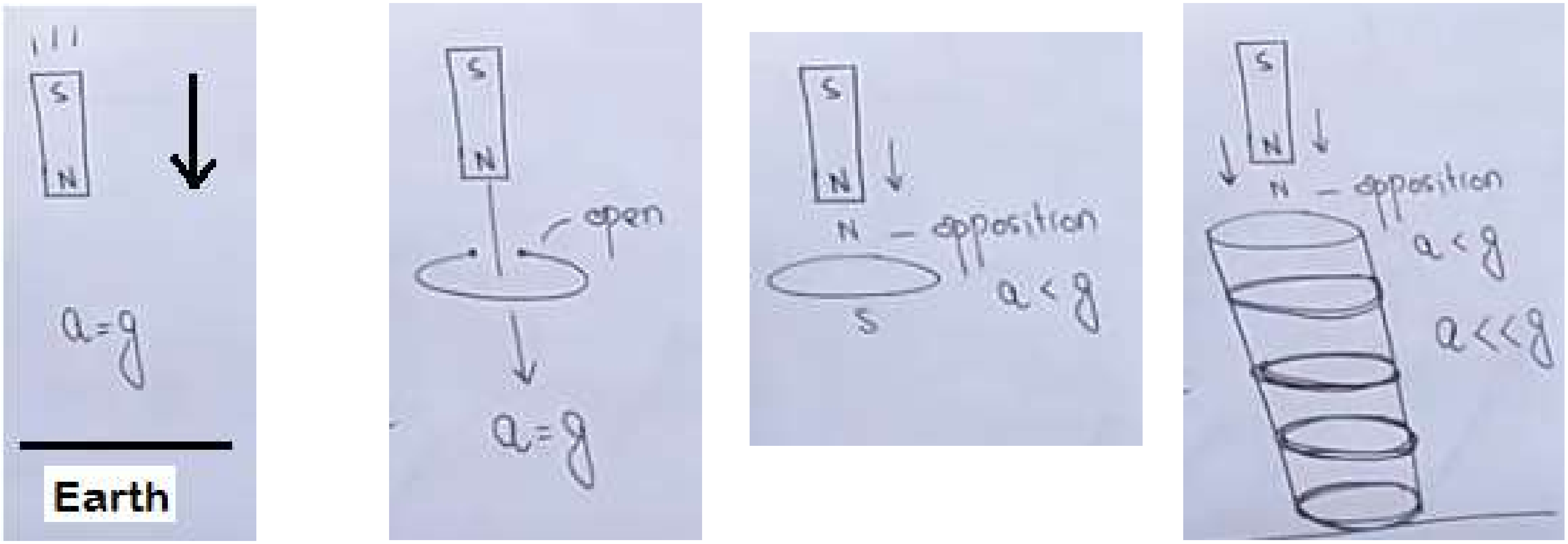


Ring#01
When flux increases, induced current opposes its cause in anticlockwise direction.

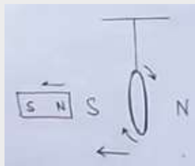
Ring#02
When flux decreases, induced current opposes its cause in clockwise direction.

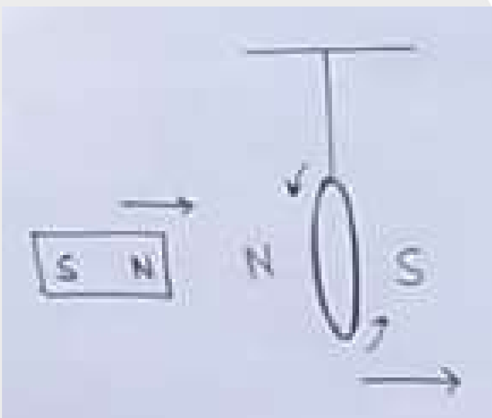


Example#02


S
N
a=g
Earth
S
N
open
a=g
S
N
N – opposition
S
a<g
S
N
N – opposition
a<g
a<<g

Example#03





Example#04

Electromagnetic Waves

- Mechanical waves require the presence of a medium.
- Electromagnetic waves can propagate through empty space.
- Maxwell's equations form the theoretical basis of all electromagnetic waves that propagate through space at the speed of light.
- Hertz confirmed Maxwell's prediction when he generated and detected electromagnetic waves in 1887.
- Electromagnetic waves are generated by oscillating electric charges.
- Electromagnetic waves carry energy and momentum.
- Electromagnetic waves cover many frequencies.

Modifications to Ampère's Law

- Ampère's Law is used to analyze magnetic fields created by currents:

$$\int \vec{B} \, . \, \overrightarrow{ds} = \mu_o I$$

- But, this form is valid only if any electric fields present are constant in time.
- Maxwell modified the equation to include time-varying electric fields.
- Maxwell's modification was to add a term.

Modifications to Ampère's Law, cont

- The additional term included a factor called the **displacement current**, I_d.

$$I_d = \varepsilon_o \frac{d\Phi_E}{dt}$$

- This term was then added to Ampère's Law.
- This showed that magnetic fields are produced both by conduction currents and by time-varying electric fields.

The general form of Ampère's Law is

$$\int \vec{B}\,.\,\overrightarrow{ds} = \mu_o(I + I_d) = \mu_o I + \mu_o \varepsilon_o \frac{d\Phi_E}{dt}$$

- Sometimes called Ampère-Maxwell Law

Maxwell’s Equations

•In his unified theory of electromagnetism, Maxwell showed that electromagnetic waves are a natural consequence of the fundamental laws expressed in these four equations:

$$\int \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{q}{\varepsilon_o}$$ **(Gauss’ law)**

$$\int \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = 0$$ **(Gauss’ law in Magnetism)**

$$\int \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = -\frac{d\Phi_B}{dt}$$ **(Faraday’s law of Induction)**

$$\int \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_o I + \mu_o \varepsilon_o \frac{d\Phi_E}{dt}$$ **(Ampère-Maxwell law)**

Lorentz Force Law

•Once the electric and magnetic fields are known at some point in space, the force acting on a particle of charge *q* can be found.

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

•Maxwell's equations with the Lorentz Force Law completely describe all classical electromagnetic interactions.

Properties of em Waves

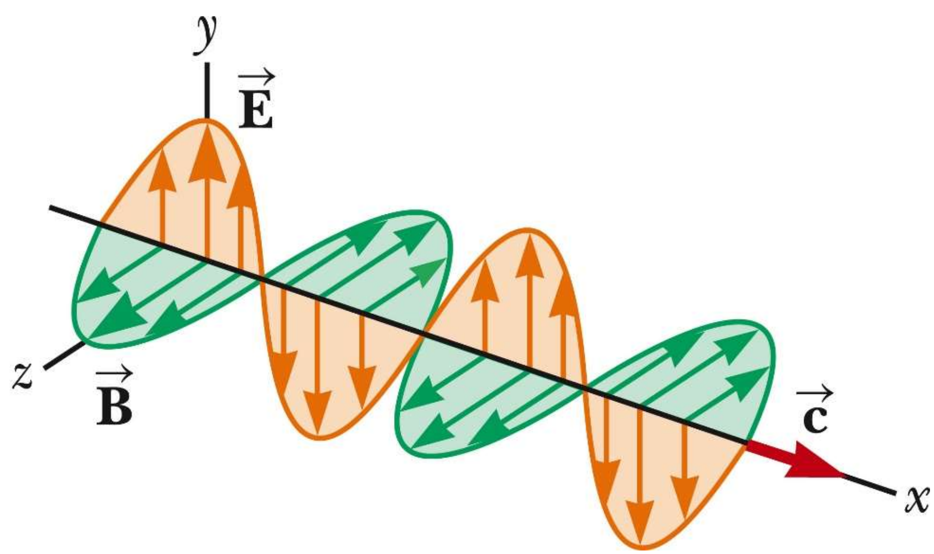
- The solutions of Maxwell's third and fourth equations are wave-like, with both *E* and *B* satisfying a wave equation.
- Electromagnetic waves travel at the speed of light:

$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}}$$

  - This comes from the solution of Maxwell's equations.

Properties of em Waves, 2

- The components of the electric and magnetic fields of plane electromagnetic waves are perpendicular to each other and perpendicular to the direction of propagation.
    - This can be summarized by saying that electromagnetic waves are transverse waves.
- The figure represents a sinusoidal em wave moving in the *x* direction with a speed *c*.



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