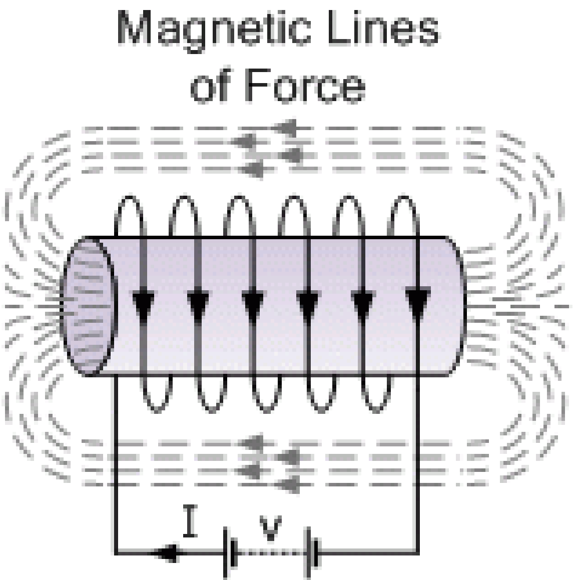
Electromagnetic Induction:

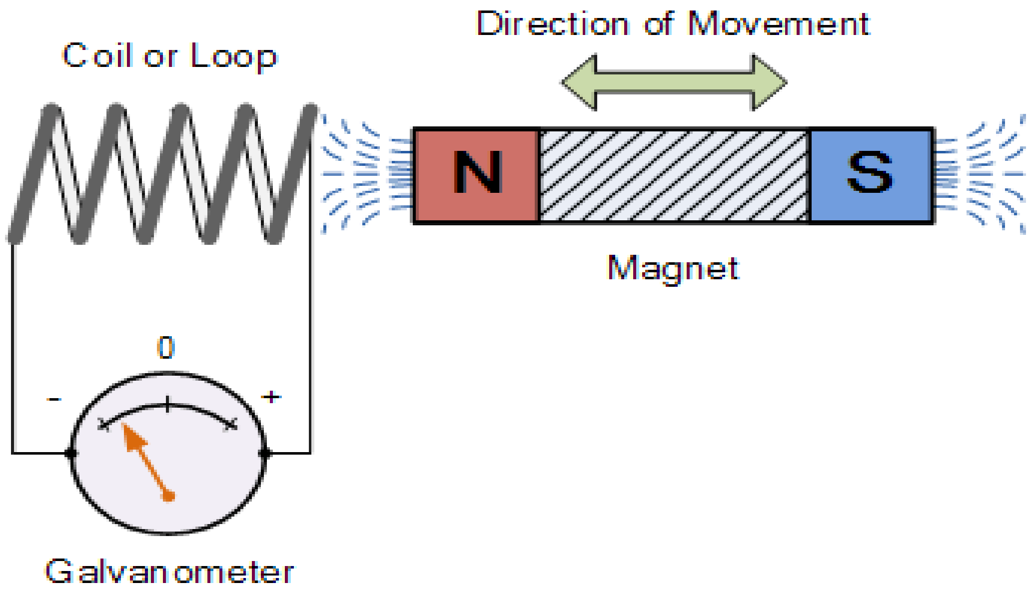
Electromagnetic Induction

- When a DC current passes through a long straight conductor a magnetizing force and a static magnetic field is developed around it.
- **Faraday's law of electromagnetic induction** (referred to as **Faraday's law**) is a basic law of electromagnetism predicting how a magnetic field will interact with an electric circuit to produce an electromotive force (EMF). This phenomenon is known as electromagnetic induction.
- Faraday's Laws of Electromagnetic Induction consists of two laws.
- The first law describes the induction of emf in a conductor

and the second law quantifies the emf produced in the conductor

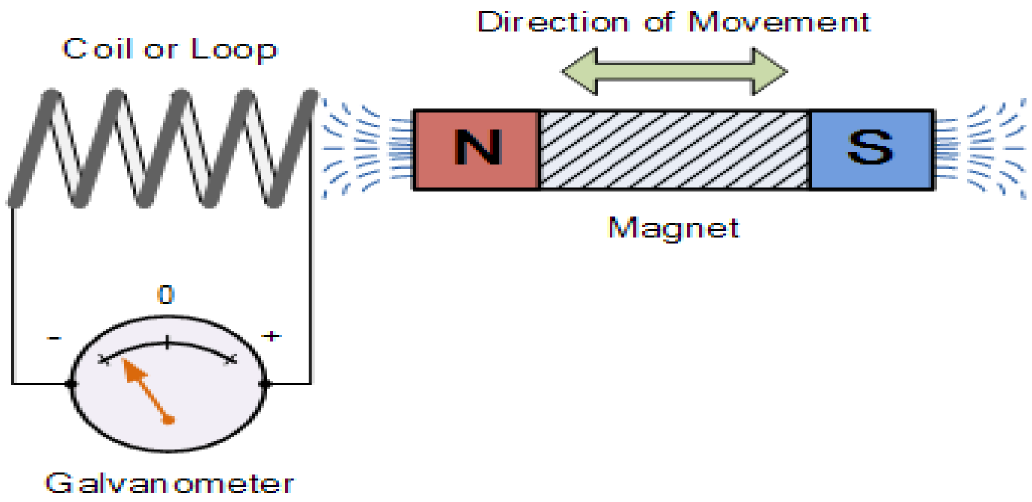


- **Electromagnetic Induction** was first discovered way back in the 1830's by **Michael Faraday**. Faraday noticed that when he moved a permanent magnet in and out of a coil or a single loop of wire it induced an ElectroMotive Force or emf, in other words a Voltage, and therefore a current was produced.
- By moving this bar magnet "in" and "out" of the coil a current would be induced into the coil by the physical movement of the magnetic flux inside it.



- Likewise, if we kept the bar magnet stationary and moved the coil back and forth within the magnetic field an electric current would be induced in the coil. Then by either moving the wire or changing the magnetic field we can induce a voltage and current within the coil and this process is known as **Electromagnetic Induction** and is the basic principle of operation of transformers, motors and generators.

So what Michael Faraday discovered was a way of producing an electrical current in a circuit by using only the force of a magnetic field and not batteries. This then lead to a very important law linking electricity with magnetism, **Faraday's Law of Electromagnetic Induction**. So how does this work?.



- When the magnet shown below is moved “towards” the coil, the pointer or needle of the Galvanometer, which is basically a very sensitive centre zero’ed moving-coil ammeter, will deflect away from its centre position in one direction only. When the magnet stops moving and is held stationary with regards to the coil the needle of the galvanometer returns back to zero as there is no physical movement of the magnetic field.
- Likewise, when the magnet is moved “away” from the coil in the other direction, the needle of the galvanometer deflects in the opposite direction with regards to the first indicating a change in polarity. Then by moving the magnet back and forth towards the coil the needle of the galvanometer will deflect left or right, positive or negative, relative to the directional motion of the magnet.

- Likewise, if the magnet is now held stationary and ONLY the coil is moved towards or away from the magnet the needle of the galvanometer will also deflect in either direction. Then the action of moving a coil or loop of wire through a magnetic field induces a voltage in the coil with the magnitude of this induced voltage being proportional to the speed or velocity of the movement.
- Then we can see that the faster the movement of the magnetic field the greater will be the induced emf or voltage in the coil, so for Faraday’s law to hold true there must be “relative motion” or movement between the coil and the magnetic field and either the magnetic field, the coil or both can move.

- When the magnet is held stationary at that position, the needle of galvanometer returns to zero position. Now when the magnet moves away from the coil, there is some deflection in the needle but opposite direction, and again when the magnet becomes stationary, at that point respect to the coil, the needle of the galvanometer returns to the zero position. Similarly, if the magnet is held stationary and the coil moves away, and towards the magnet, the galvanometer similarly shows deflection. It is also seen that the faster the change in the magnetic field, the greater will be the induced EMF or voltage in the coil.

Position of magnet	Deflection in galvanometer
Magnet at rest	No deflection in the galvanometer
Magnet moves towards the coil	Deflection in galvanometer in one direction
Magnet is held stationary at same position (near the coil)	No deflection in the galvanometer
Magnet moves away from the coil	Deflection in galvanometer but in the opposite direction
Magnet is held stationary at the same position (away from the coil)	No deflection in the galvanometer

- **Faraday’s First Law**
- Any change in the magnetic field of a coil of wire will cause an emf to be induced in the coil. This emf induced is called induced emf and if the conductor circuit is closed, the current will also circulate through the circuit and this current is called induced current. Method to change the magnetic field:

1. By moving a magnet towards or away from the coil
2. By moving the coil into or out of the magnetic field
3. By changing the area of a coil placed in the magnetic field
4. By rotating the coil relative to the magnet

Faraday's Second Law

- It states that the magnitude of emf induced in the coil is equal to the rate of change of flux linkage. The flux linkage of the coil is the product of the number of turns in the coil and flux associated with the coil.

$$E = N \frac{d\phi}{dt}$$

Consider, a magnet is approaching towards a coil. Here we consider two instants at time T_1 and time T_2.

Flux linkage with the coil at time, $T_1 = N\phi_1\ wb$

Flux linkage with the coil at time, $T_2 = N\phi_2\ wb$

Change in flux linkage, $N(\phi_2 - \phi_1)$

Let this change in flux linkage be, $\phi = (\phi_2 - \phi_1)$

So, the Change in flux linkage $N\phi$

Now the rate of change of flux linkage $\frac{N\phi}{t}$

Take derivative on right-hand side we will get $N\frac{\mathrm{d}\phi}{\mathrm{d}t}$

The rate of change of flux linkage $E = N\frac{d\phi}{dt}$

How To Increase EMF Induced in a Coil

- By increasing the number of turns in the coil i.e N, from the formulae derived above it is easily seen that if the number of turns in a coil is increased, the induced emf also gets increased.
- By increasing magnetic field strength i.e B surrounding the coil- Mathematically, if magnetic field increases, flux increases and if flux increases emf induced will also get increased. Theoretically, if the coil is passed through a stronger magnetic field, there will be more lines of force for the coil to cut and hence there will be more emf induced.
- By increasing the speed of the relative motion between the coil and the magnet – If the relative speed between the coil and magnet is increased from its previous value, the coil will cut the lines of flux at a faster rate, so more induced emf would be produced.

Applications of Faraday’s Law

- Following are the fields where Faraday’s law finds applications:

1. Electrical equipment like transformers works on the basis of Faraday’s law.
2. Induction cooker works on the basis of mutual induction which is the principle of Faraday’s law.
3. By inducing an electromotive force into an electromagnetic flowmeter, the velocity of the fluids is recorded.
4. Electric guitar and electric violin are the musical instruments that find an application of Faraday’s law.
5. Maxwell’s equation is based on the converse of Faraday’s laws which states that change in the magnetic field brings a change in the electric field.

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Flemings left and right-hand rules

- Whenever a current carrying conductor comes under a magnetic field, there will be a force acting on the conductor. The direction of this force can be found using Fleming's Left Hand Rule.
- Similarly if a conductor is forcefully brought under a magnetic field, there will be an induced current in that conductor. The direction of this force can be found using Fleming's Right Hand Rule.

- In both Fleming’s left and right hand rules, there is a relation between the magnetic field, the current and force. This relation is directionally determined by **Fleming’s Left Hand rule** and **Fleming’s Right Hand rule** respectively.
- These rules do not determine the magnitude but instead show the direction of any of the three parameters (magnetic field, current, force) when the direction of the other two parameters is known.
- **Fleming’s Left-Hand rule** is mainly applicable to electric motors and **Fleming’s Right-Hand rule** is mainly applicable to electric generators.

Fleming’s Left Hand Rule

- It is found that whenever a current carrying conductor is placed inside a magnetic field, a force acts on the conductor, in a direction perpendicular to both the directions of the current and the magnetic field.
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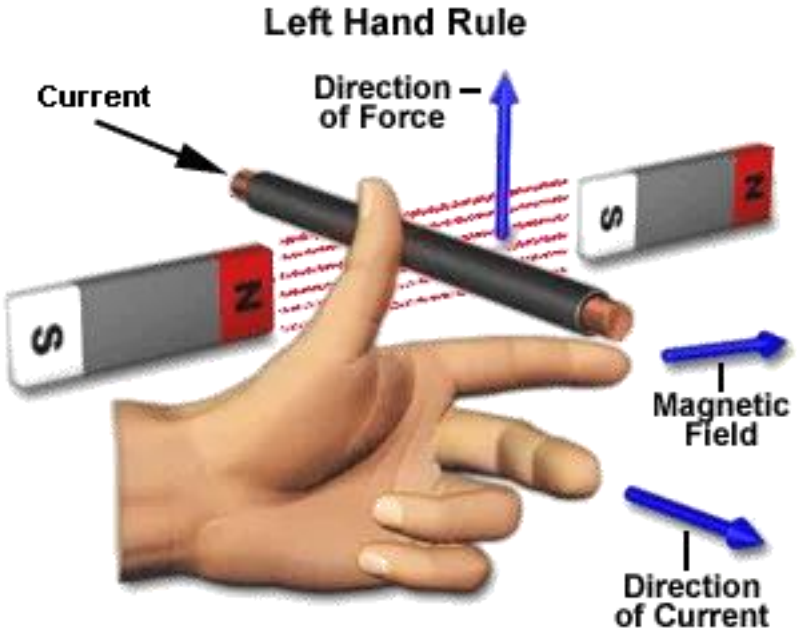
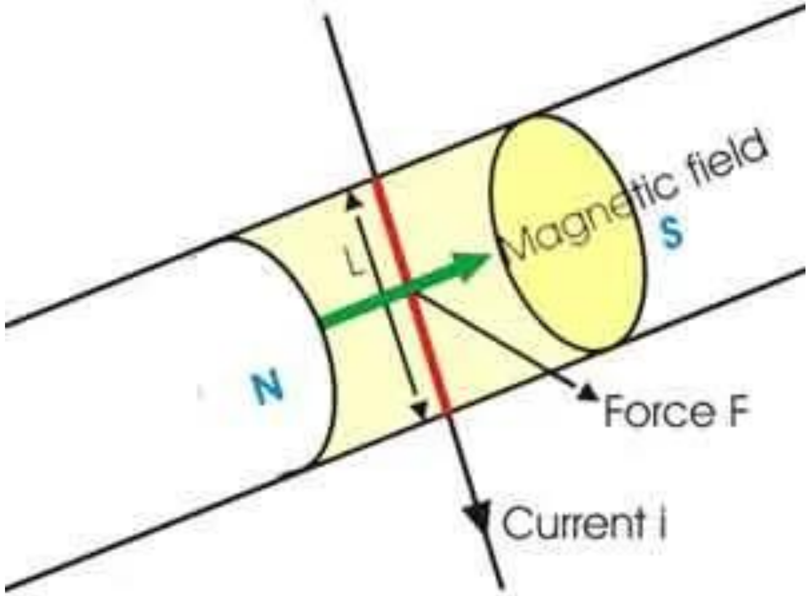
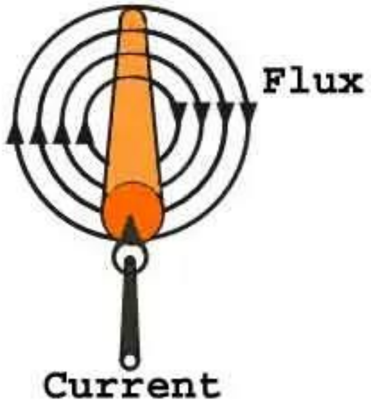


- In the figure below, a portion of a conductor of length 'L' is placed vertically in a uniform horizontal magnetic field (B) of strength 'H', produced by two magnetic poles N and S. If the current 'I' is flowing through this conductor, the magnitude of the force acting on the conductor is:

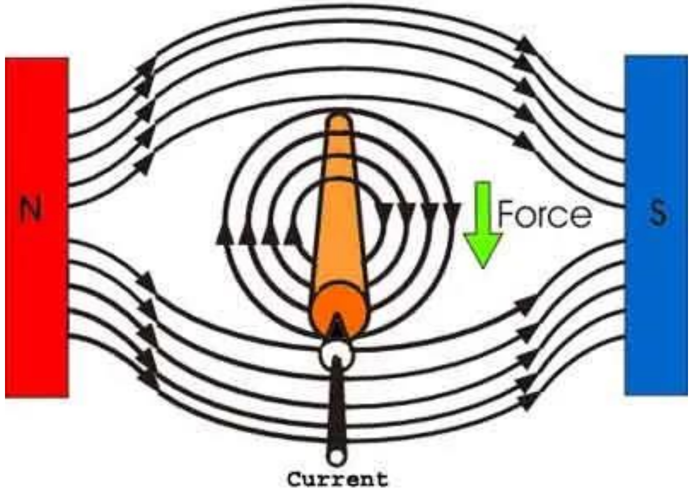
$$F = BiL$$



- Hold out your left hand with the forefinger, second finger and thumb at the right angle to one another. If the forefinger represents the direction of the field and the second finger represents that of the current, then thumb gives the direction of the force.
- While current flows through a conductor, one magnetic field is induced around it. The magnetic field can be imagined by considering numbers of closed magnetic lines of force around the conductor. The direction of magnetic lines of force can be determined by Maxwell's corkscrew rule or right-hand grip rule. As per these rules, the direction of the magnetic lines of force (or flux lines) is clockwise if the current is flowing away from the viewer, that is if the direction of current through the conductor is inward from the reference plane as shown in the figure.



- Now if a horizontal magnetic field is applied externally to the conductor, these two magnetic fields i.e. field around the conductor due to the current through it and the externally applied field will interact with each other. We observe in the picture that the magnetic lines of force of external magnetic field are from N to S pole that is from left to right.
- The magnetic lines of force of external magnetic field and magnetic lines of force due to the current in the conductor are in the same direction above the conductor, and they are in the opposite direction below the conductor. Hence there will be larger numbers of co-directional magnetic lines of force above the conductor than that of below the conductor.
- Consequently, there will be a larger concentration of magnetic lines of force in a small space above the conductor. As magnetic lines of force are no longer straight lines, they are under tension like stretched rubber bands.

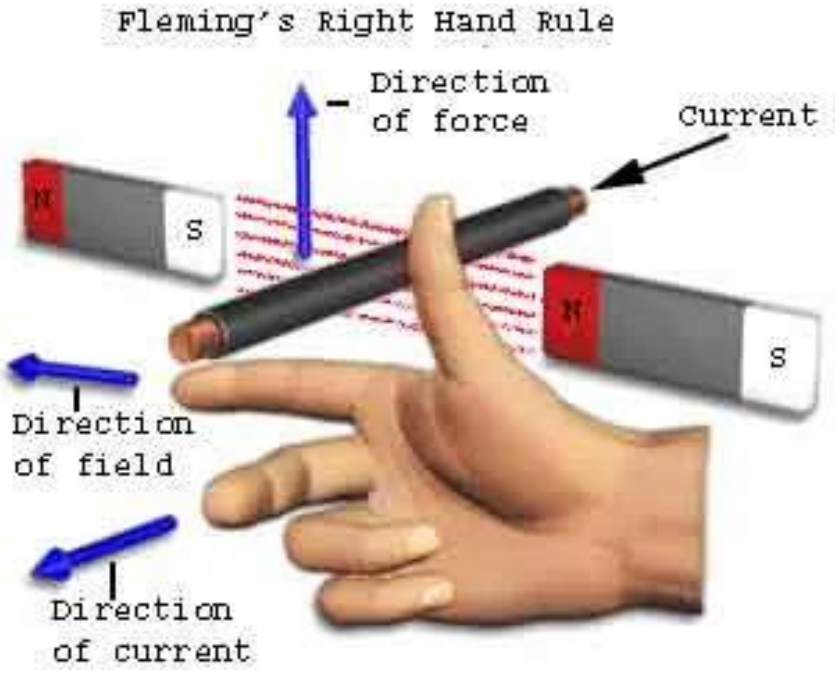


- As a result, there will be a force which will tend to move the conductor from the more concentrated magnetic field to less concentrated magnetic field, that is from the present position to downwards. Now if you observe the direction of the current, force and magnetic field in the above explanation, you will find that the directions are according to the Fleming left-hand rule.

Fleming Right Hand Rule

- As per Faraday’s law of electromagnetic induction, whenever a conductor moves inside a magnetic field, there will be an induced current in it. If this conductor gets forcefully moved inside the magnetic field, there will be a relation between the direction of applied force, magnetic field and the current. This relation among these three directions is determined by **Fleming’s right-hand Rule**.

This rule states “Hold out the right hand with the first finger, second finger and thumb at the right angle to each other. If forefinger represents the direction of the line of force, the thumb points in the direction of motion or applied force, then second finger points in the direction of the induced current”.



Lenz's Law of Electromagnetic Induction

- Faraday's Law tells us that inducing a voltage into a conductor can be done by either passing it through a magnetic field, or by moving the magnetic field past the conductor and that if this conductor is part of a closed circuit, an electric current will flow. This voltage is called an **induced emf** as it has been induced into the conductor by a changing magnetic field due to electromagnetic induction with the negative sign in Faraday's law telling us the direction of the induced current (or polarity of the induced emf).
- But a changing magnetic flux produces a varying current through the coil which itself will produce its own magnetic field as we saw in the Electromagnets tutorial. This self-induced emf opposes the change that is causing it and the faster the rate of change of current the greater is the opposing emf. This self-induced emf will, by Lenz's law oppose the change in current in the coil and because of its direction this self-induced emf is generally called a **back-emf**.

- But according to Faraday's law of electromagnetic induction, the rate of change of flux linkage is equal to induced emf.

- Considering Lenz's Law.
- Where:
- Flux Φ in Wb = B.A
- B = magnetic field strength
- A = area of the coil

$$E = -N\frac{d\phi}{dt}$$

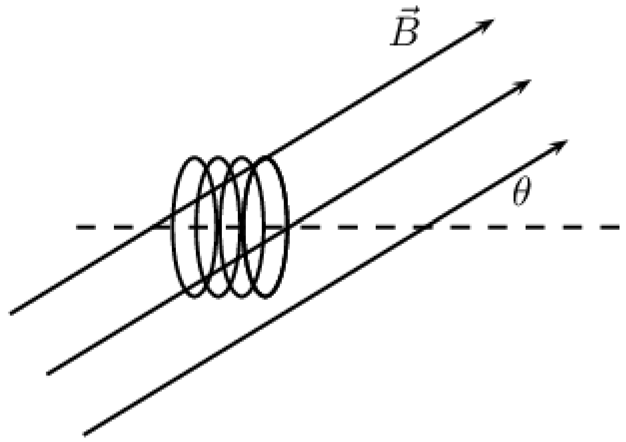
- **Lenz's Law** states that: " the direction of an induced emf is such that it will always opposes the change that is causing it". In other words, an induced current will always OPPOSE the motion or change which started the induced current in the first place and this idea is found in the analysis of Inductance.
- Likewise, if the magnetic flux is decreased then the induced emf will oppose this decrease by generating and induced magnetic flux that adds to the original flux.
- Lenz's law is one of the basic laws in electromagnetic induction for determining the direction of flow of induced currents and is related to the law of conservation of energy.
- According to the law of conservation of energy which states that the total amount of energy in the universe will always remain constant as energy can not be created nor destroyed. Lenz's law is derived from Michael Faraday's law of induction.

- One final comment about Lenz’s Law regarding electromagnetic induction. We now know that when a relative motion exists between a conductor and a magnetic field, an emf is induced within the conductor.

- But the conductor may not actually be part of the coils electrical circuit, but may be the coils iron core or some other metallic part of the system, for example, a transformer. The induced emf within this metallic part of the system causes a circulating current to flow around it and this type of core current is known as an **Eddy Current**.

Example

Consider a circular coil of 4 turns with radius 3×10^{-2} mm. The solenoid is subjected to a varying magnetic field that changes uniformly from 0.4 T to 3.4 T in an interval of 27 s. The axis of the solenoid makes an angle of 35° to the magnetic field. Find the induced emf.



Solution

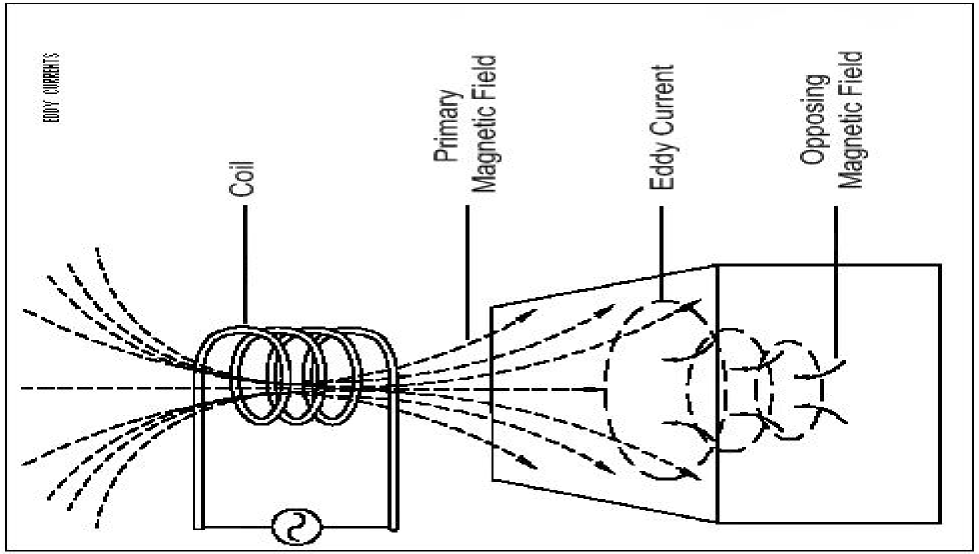
- $$E = N\frac{d\phi}{dt}$$
- ϕ=BAcosθ
  The area, A, will be πr^2. where is $3x10^{-2}$ mm
- N = 4 turns
- B_f = 3.4T
- Bi =0.3T

  t = 27s
- θ = 35^0
- answer $1.03x10^{-3}$ V
- The induced current is anti-clockwise as viewed from the direction of the increasing magnetic field.

$$\begin{aligned}\mathcal{E} &= N\frac{\Delta\phi}{\Delta t}\\ &= N\frac{\phi_f-\phi_i}{\Delta t}\\ &= N\frac{B_fA\cos(\theta)-B_iA\cos(\theta)}{\Delta t}\\ &= N\frac{A\cos(\theta)(B_f-B_i)}{\Delta t}\end{aligned}$$

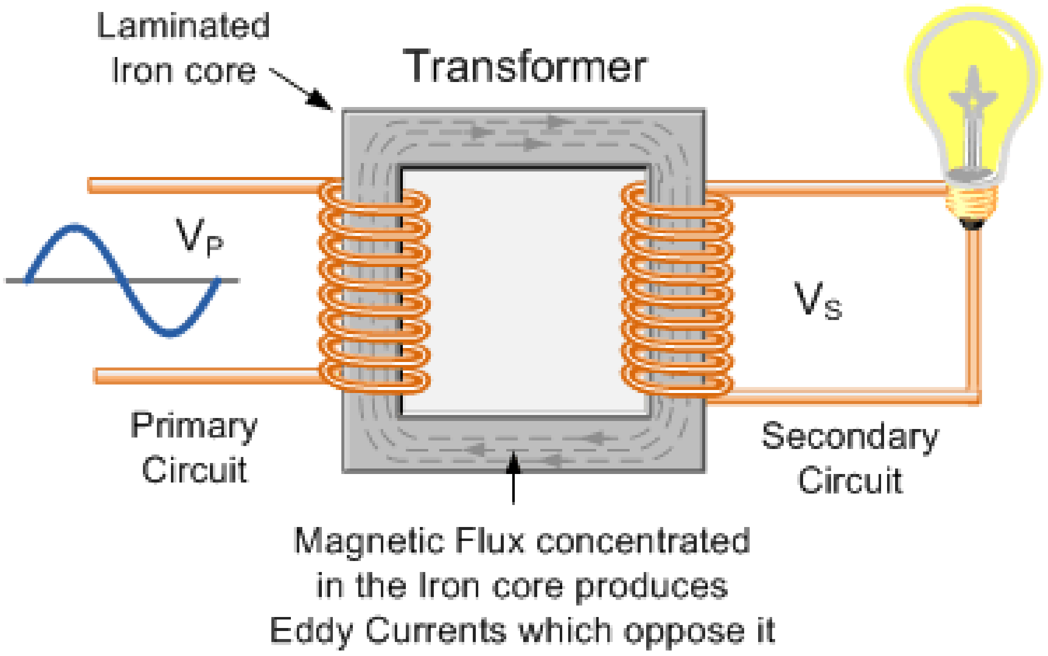
Eddy currents

- An eddy current is a current set up in a conductor in response to a changing magnetic field. They flow in closed loops in a plane perpendicular to the magnetic field. By Lenz law, the current swirls in such a way as to create a magnetic field opposing the change; for this to occur in a conductor, electrons swirl in a plane perpendicular to the magnetic field.
- Because of the tendency of eddy currents to oppose, eddy currents cause a loss of energy. Eddy currents transform more useful forms of energy, such as kinetic energy, into heat, which isn't generally useful.



Eddy Currents Circulating in a Transformer

The changing magnetic flux in the iron core of a transformer above will induce an emf, not only in the primary and secondary windings, but also in the iron core. The iron core is a good conductor, so the currents induced in a solid iron core will be large. Furthermore, the eddy currents flow in a direction which, by Lenz's law, acts to weaken the flux created by the primary coil. Consequently, the current in the primary coil required to produce a given B field is increased, so the hysteresis curves are fatter along the H axis.



Induction - Self Induction and Mutual Induction

What is Induction?

- Induction is the process by which an electrical conductor becomes electrified when near a charged body/by which a magnetizable body becomes magnetized when in a magnetic field or in the magnetic flux set up by a magnetomotive force, or by which an electromotive force is produced in a circuit by varying the magnetic field linked with the circuit.
- This definition of induction holds for a conductor. Induction is also known as inductance. L is used to represent the inductance and Henry is the SI unit of inductance.
- 1 Henry is defined as the amount of inductance required to produce an emf of 1 volt in a conductor when the current change in the conductor is at the rate of 1 Ampere per second.

Factors Affecting Inductance

- Following are the factors that affect the inductance:

1. The number of turns of the wire used in the inductor.
2. The material used in the core.
3. The shape of the core.

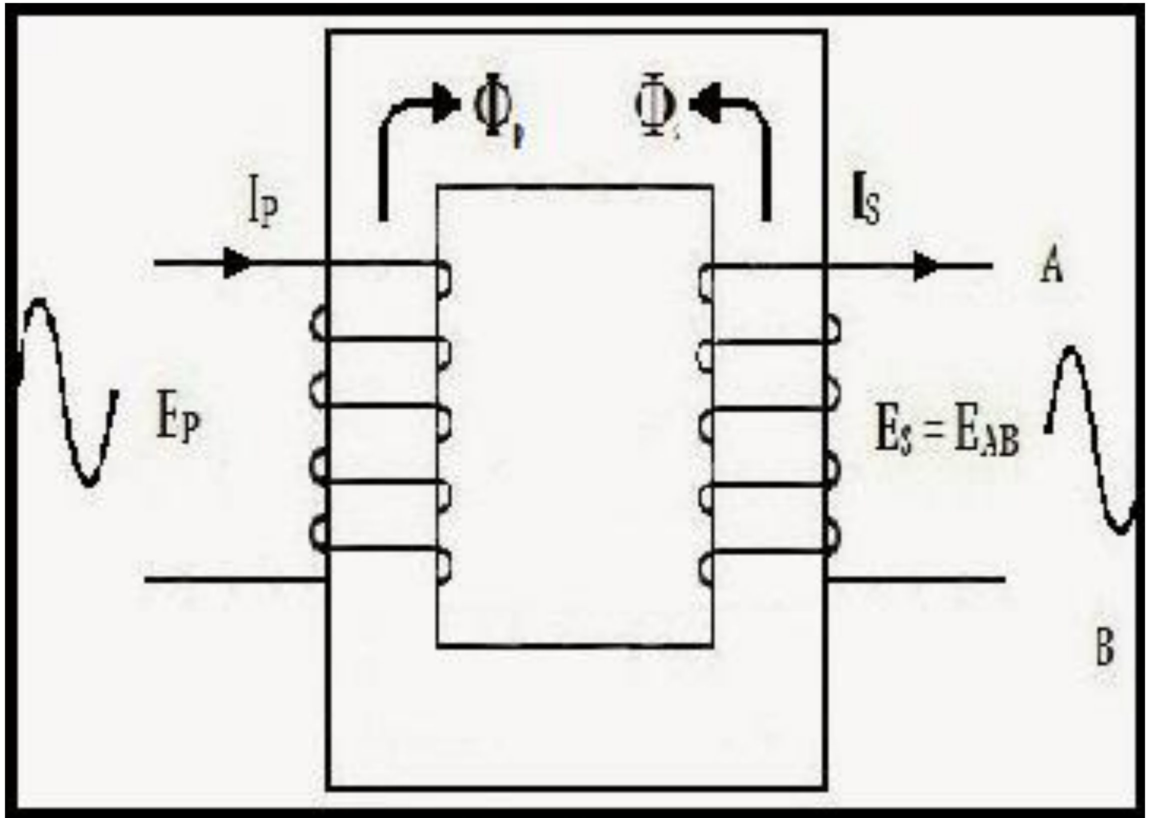
Electromagnetic Induction law was given by Faraday which states that by varying the magnetic flux electromotive force is induced in the circuit.
Hence, Inductance can be defined as the electromotive force generated to oppose the change in current at a particular time duration.
According to Faraday's Law:

Electromotive force $EMF = -L\frac{\Delta I}{\Delta t}$

Unit of Inductance = Volt Second/Ampere = Henry

Types of Inductance

- Two types of inductance are there:
- Self Induction
- Mutual Induction



If changing current flowing in a coil produces emf in the same coil, it is called self induction.

If changing current flowing through one coil produces emf in another coil, it is called mutual induction.

What is Self Induction?

When there is a change in the current or magnetic flux of the coil, an opposed induced electromotive force is produced. This phenomenon is termed as Self Induction. When the current starts flowing through the coil at any instant, it is found that, that the magnetic flux becomes directly proportional to the current passing through the circuit. The relation is given as:

$\Phi = LI$

Where L is termed as self-inductance of the coil or the coefficient of self-inductance. The self-inductance depends on the cross-sectional area, the permeability of the material, or the number of turns in the coil.

The rate of change of magnetic flux in the coil is given as,

$$e = -\frac{d\phi}{dt} = -\frac{d(LI)}{dt}$$

$$\text{or } e = -L\frac{dI}{dt}$$

Self Inductance Formula

$$L = N\frac{\phi}{I}$$

Where,

- L is the self inductance in Henry
- N is the number of turns
- Φ is the magnetic flux
- I is the current in amperes

What is Mutual Induction?

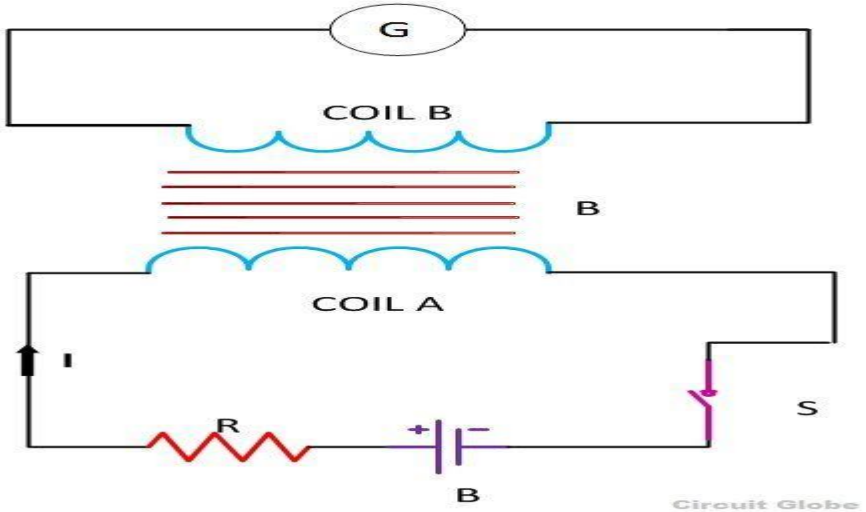
When two coils are placed close to each other. The two coils; coil 1 (Primary coil) and coil 2 (Secondary coil). To the coil 1, a battery, and a key is connected wherein the coil 2 a galvanometer is connected across it. When there is a change in the current or magnetic flux linked with two coils an opposing electromotive force is produced across each coil, and this phenomenon is termed as Mutual Induction. The relation is given as: $\Phi = M I$

Where M is termed as the mutual inductance of the two coils or the coefficient of the mutual inductance of the two coils.

The rate of change of magnetic flux in the coil is given as,

$$e = -\frac{d\phi}{dt} = -\frac{d(MI)}{dt}$$

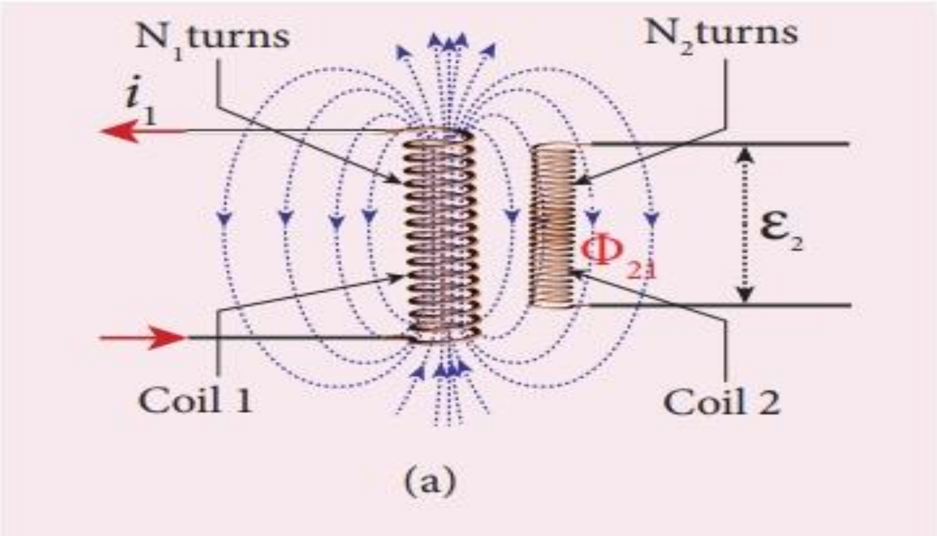
$$e = -M\frac{dI}{dt}$$



Mutual induction

When an electric current passing through a coil changes with time, an emf is induced in the neighbouring coil. This phenomenon is known as mutual induction and the emf is called mutually induced emf.

Consider two coils which are placed close to each other. If an electric current i_1 is sent through coil 1, the magnetic field produced by it is also linked with coil 2 as shown in Figure 4.22(a).



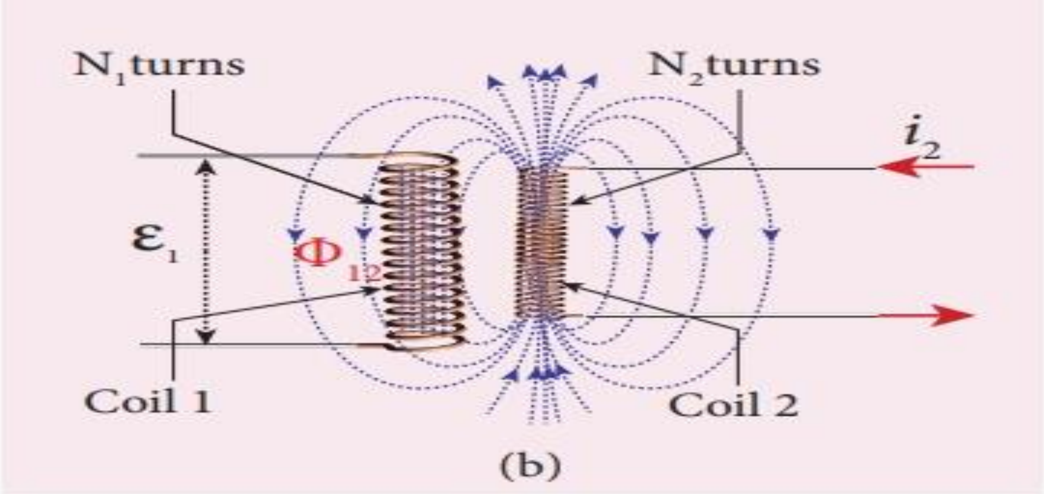


Figure 4.22 Mutual induction

Mutual Inductance Formula

$$M = \frac{\mu_0 \mu_r N_1 N_2 A}{l}$$

Where,

- μ_0 is the permeability of free space
- μ_r is the relative permeability of the soft iron core
- N is the number of turns in coil
- A is the cross-sectional area in m^2
- l is the length of the coil in m

Difference between Self and Mutual Inductance

Self induction	**Mutual induction**
Self inductance is the characteristic of the coil itself.	Mutual inductance is the characteristic of a pair of coils.
The induced current opposes the decay of current in the coil when the main current in the coil decreases.	The induced current developed in the neighboring coil opposes the decay of the current in the coil when the main current in the coil decreases.
The induced current opposes the growth of current in the coil when the main current in the coil increases.	The induced current developed in the neighboring coil opposes the growth of current in the coil when the main current in the coil increases.

Derivation of Inductance

Consider a DC source with its switch on. When the switch is turned on, the current flows from zero to a certain value such that there is a change in the rate of current flowing. Let φ be the change in flux due to current flow. The change in flux is with respect to time which is given as:

$\frac{d\phi}{dt}$ $\quad$ *Apply Faraday's law of electromagnetic induction,*

$E = N\frac{d\phi}{dt}$ $\quad$ *Where, N is the number of turns in the coil and E is the induced EMF across the coil*

From Lenz's law, we can write the above equation as; $E = -N\frac{d\phi}{dt}$ ....(1)

The rate of change of magnetic flux in the coil is given as; $E = -L\frac{di}{dt}$ ....(2)

comparing equation 1 and 2

$N\phi = Li$ $\quad$ *therefore,* $\quad Li = N\phi = NBA \quad (\phi = BA)$; *Where, B is the flux density and A is the area of the coil*

$$Hl = Ni$$

Where, H is the magnetizing force due to magnetic flux, l is length

i is current, N is the number of turns in the coil

$$B = \mu H$$

$$Li = NBA$$

$$L = \frac{NBA}{i} = \frac{N^2 BA}{Hl} = \frac{N^2 \mu HA}{Hl}$$

$$L = \frac{\mu N^2 A}{l} = \frac{\mu N^2 \pi r^2}{l} \qquad (A = \pi r^2); \text{Where, } r \text{ is the radius of the coil}$$

Example 1.

Consider a solenoid with 500 turns which are wound on an iron core whose relative permeability is 800. 40 cm is the length of the solenoid while 3 cm is the radius. The change in current is from 0 to 3 A. Calculate the average emf induced for this change in the current for time 0.4 second.

Solution

$$L = \frac{\mu N^2 A}{l} = \frac{\mu N^2 \pi r^2}{l} = \frac{\mu_r \mu_o N^2 \pi r^2}{l}$$

- Given:
- No.of turns, N = 500 turns
- Relative permeability, $\mu_r = 800$
- $\mu_0 = 4\pi \times 10^{-7}$ T m A^{-1},
- Length, l = 40 cm = 0.4 m
- Radius, r = 3 cm = 0.03 m
- Change in current, di = 3 – 0 = 3 A
- Change in time, dt = 0.4 sec
- Self-inductance is given as

$\mu = \mu_0 \mu_r$

Substituting the values we get
$(4)(3.14)(10^{-7})(800)(500^2)(3.14)(3\times10^{-2})^2/0.4$
L = 1.77 H
Magnitude of induced emf,
$\varepsilon = L\, di/dt = 1.77\times3/0.4$
$\varepsilon = 13.275$ V