Level UGI- Semester 2

Magnetism Theory

PHY-1209-C-7 ECTS

Prerequisite Module Code (PHY-1102)

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Chapter One- Magnetic Field

Magnetism

Permanent magnets: exert forces on each other as well as on unmagnetized Fe pieces.

- The needle of a compass is a piece of magnetized Fe.

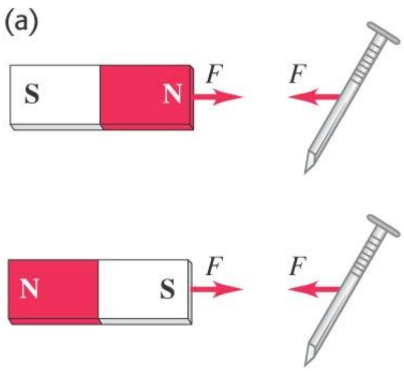
- If a bar-shaped permanent magnet is free to rotate, one end points north (north pole of magnet). - An object that contains Fe is not by itself magnetized, it can be attracted by either the north or South Pole of permanent magnet.

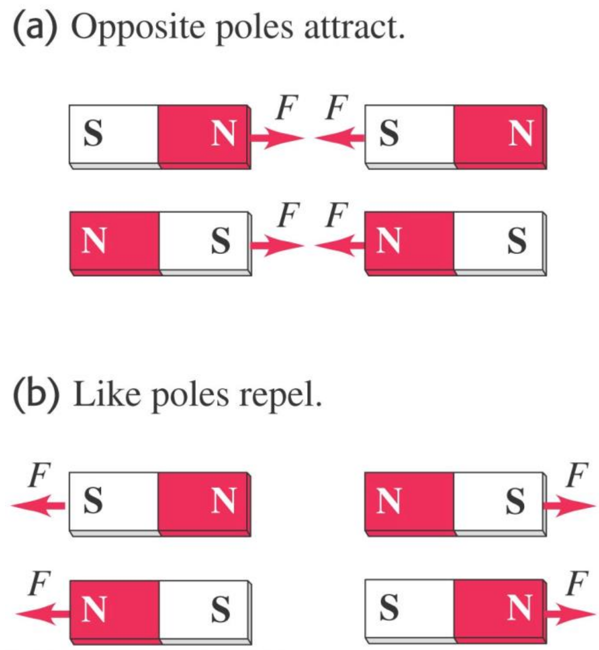
- A bar magnet sets up a magnetic field in the space around it and a second body responds to that field. A compass needle tends to align with the magnetic field at the needle's position.

- Magnets exert forces on each other just like charges. You can draw magnetic field lines just like you drew electric field lines.

- Magnetic north and south pole's behavior is not unlike electric charges. For magnets, like poles repel and opposite poles attract.

- A permanent magnet will attract a metal like iron with either the north or South Pole.





To introduce the concept of magnetic field properly, we introduced the concept of electric field. We represented electric interactions in two steps:-

Electric field

1. A distribution of electric charge at rest creates electric field E in the surrounding space.
2. The electric field exert a force F=q.E or any other charge q that is present in field.

We Can describe magnetic interactions in a similar way:-

Magnetic field

1. A moving charge or a Current Creates a magnetic field in the surrounding space (in addition its electric field).
2. The magnetic field exerts a force F on any other moving charge or Current that is present in the field.

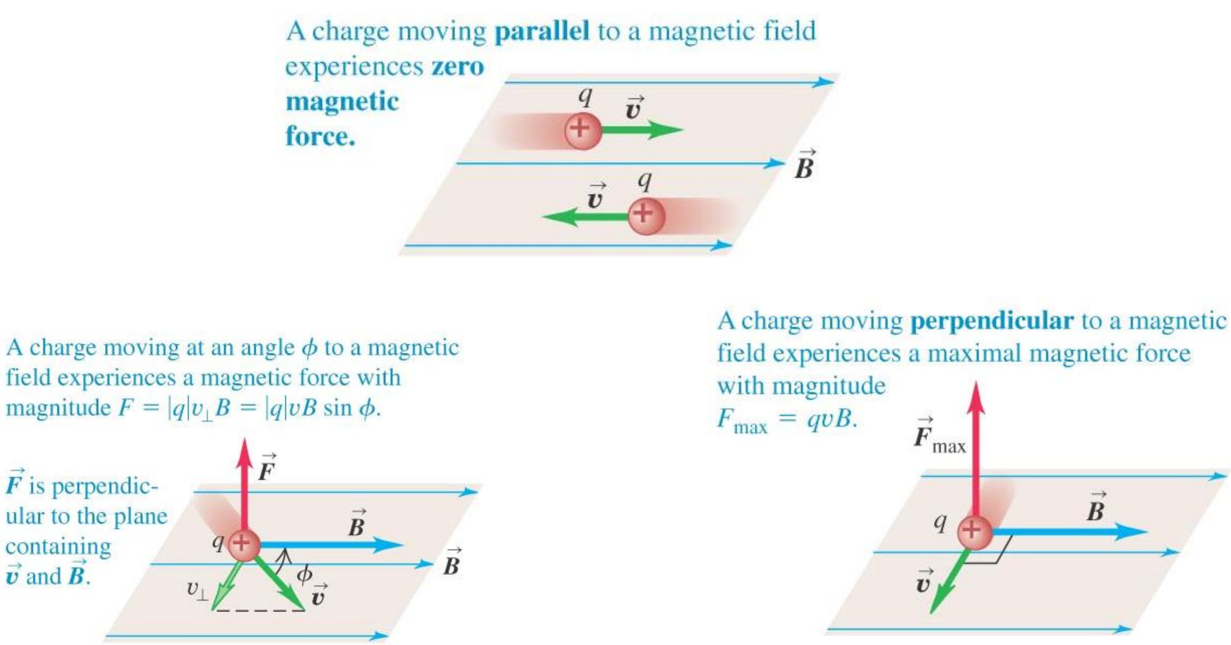
- The magnetic field is a vector field → vector quantity associated with each point in space.

$$F_m = |q| v_\perp B = |q| v \; B \sin\varphi \qquad \boxed{\vec{F}_m = q\vec{v} \times \vec{B}}$$

- $\vec{F}_m$ is always perpendicular to $\vec{B}$ and $\vec{v}$.

- The moving charge interacts with the fixed magnet. The force between them is at a maximum when the velocity of the charge is perpendicular to the magnetic field.

Interaction of magnetic force and charge



Magnetic force on Moving charges

There are four characteristics of the magnetic force on moving charge: -

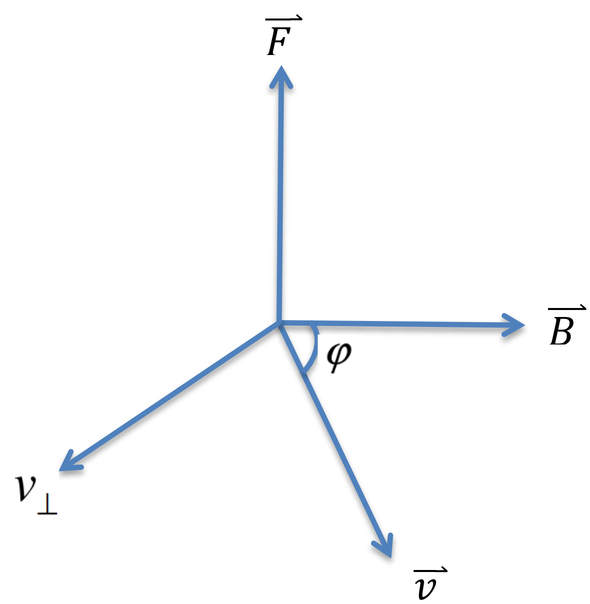
1- Its magnitude is proportional to the magnitude of the charge.
2. The magnitude of the force is also proportional magnitude to the magnitude, or strength of the field
3- The magnetic force depends on the particle's velocity
4. The magnetic force $\vec{F}$ doesn't has the same direction as the magnetic field $\vec{B}$ but instead is always perpendicular to both $\vec{B}$ and velocity $\vec{V}$.

The direction of $\vec{F}$ is always perpendicular to the plane containing $\vec{V}$ and $\vec{B}$. Its magnitude is given by: -

$$F_m = |q| v_{\perp} B = |q| v \; B \sin\varphi$$

Where $|q|$ is the charge; Ø is the angle measured from the direction of $\vec{V}$ to the directional of $\vec{B}$, as shown in the Figure:

$$\vec{F}_m = q\vec{v} \times \vec{B}$$



The unit of $\vec{B}$ is [1 N.s/C.m] or [1 N/A.m]

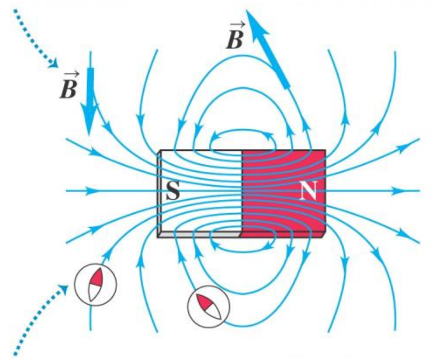
This unit is called the Tesla (T)

[1 T = 10^4 G]

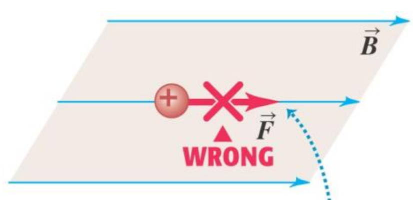
When a charged particle moves through a region of space where both electric and magnetic fields are present, both fields exert forces on the particle. The total forces $\vec{F}$ are the vector sum of the electric and magnetic forces:-

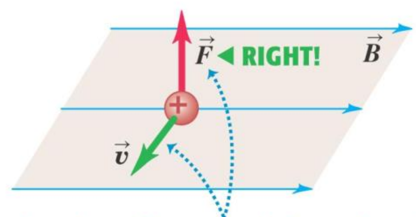
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

Magnetic Field Lines



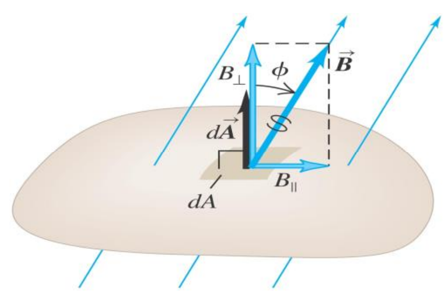
- Magnetic field lines may be traced from N toward S (analogous to the electric field lines).
- At each point they are tangent to magnetic field vector.
- The more densely packed the field lines, the stronger the field at a point.
- Field lines never intersect.
- The field lines point in the same direction as a compass (from N toward S).
- Magnetic field lines are not “lines of force”.
- Magnetic field lines have no ends → they continue through the interior of the magnet.





The direction of the magnetic force depends on the velocity $\vec{v}$, as expressed by the magnetic force law $\vec{F} = q\vec{v} \times \vec{B}$.

Magnetic Flux and Gauss’s Law for Magnetism



We define the magnetic flux $\emptyset_B$ through a surface just as we define electric flux $\emptyset_E$ is connection with Gauss's law. Can divide any surface into elements of area dA. From this Figure:-

$$B_\perp = B\cos\emptyset$$

Where $\emptyset$ is the angle between the direction of $\overrightarrow{B}$ and a line perpendicular to the surface.

We define the magnetic flux $d\emptyset_B$ through this area as:-

$$d\emptyset_B = B_\perp \, dA = B \cos\emptyset \; dA$$
$$= \overrightarrow{B} . d\vec{A}$$

The total magnetic flux through the surface is sum of the contribution from the individual area elements

$$\boxed{\Phi_B = \int B_\perp dA = \int B\cos\varphi \cdot dA = \int \vec{B} \cdot d\vec{A}}$$

If $\overrightarrow{B}$ is uniform over a plane surface with total area A, then

$$\boxed{\Phi_B = B_\perp A = BA\cos\varphi}$$

If $\overrightarrow{B}$ happens to be perpendicular to the surface, then [$\text{Cos}\,\emptyset = 1$] and the equation reduced to:-

$$\emptyset_B = B \; A$$

The SI unit of magnetic flux is equal to the unit of magnetic field (1T) times the unit of area ($1m^2$).

This unit is called the weber (1Wb).

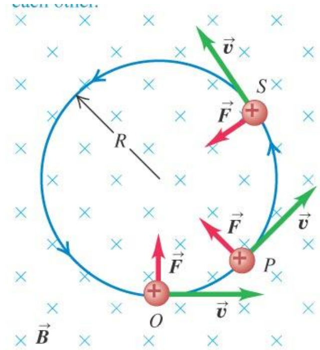
1 Weber ($1\ \text{Wb} = 1\ \text{T m}^2 = 1\ \text{N m / A}$)

- The total magnetic flux through a closed surface always Zero, then

$$\boxed{\Phi_B = \oint \vec{B} \cdot d\vec{A} = 0} \qquad \boxed{B = \frac{d\Phi_B}{dA_\perp}}$$

- This is called Gauss's law for magnetism.
- The magnetic field is equal to the flux per unit area across an area at right angles to the magnetic field = magnetic flux density.

Motion of Charged Particles in a Magnetic Field



- Motion of a changed particle, under the action of a magnetic field a lone is always motion with constant Speed.
- The centripetal acceleration is [$\frac{v^2}{R}$], and only the magnetic force acts, so from. Newton's Second law:-

$$F = ma \implies F = m\frac{v^2}{R}$$

$$[F = |q|\, v\, B = m\frac{v^2}{R}]$$

Where m is the mass of the Particle, solving this eq. for the radius R of the circular path, we find:-

$$R = \frac{mv}{|q|B}$$

We can also write this as:

$$R = \frac{P}{|q|B}$$

Where $P = mv$ is magnitude of the Particles momentum.

Angular speed (w) of the particle can be found

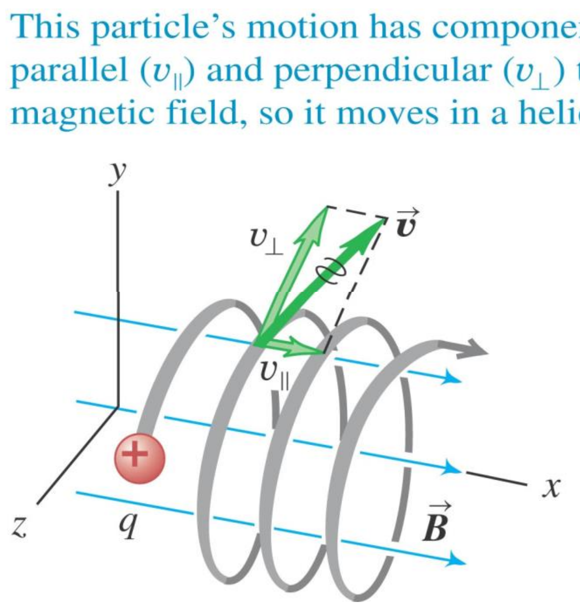
$$v = Rw \implies w \frac{v}{R}$$

We get:-

$$w = \frac{v}{R} = v\frac{|q|B}{mv}$$

$$w = \frac{|q|B}{m} \Leftarrow angular\ speed$$

- If v is not perpendicular to B ⇒ $v \parallel$ (parallel to B) constant because $[F \parallel = 0]$⇒ particle moves in a helix. (R same as before, with $v = v \perp$)



A charged particle will move in a plane perpendicular to the magnetic field.

Applications of Motion of Charged Particles

Thomson's e/m Experiment

Thomson used the idea just described to measure the ratio of charge to mass for the electron.
The speed $\vec{v}$ of electrons is determined by the accelerating potential V.
The gained Kinetic energy:-

K.E= (½ mv²).

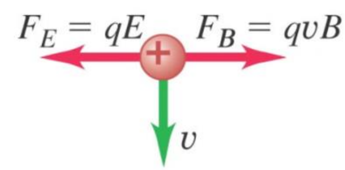
Equal the lost electric potential energy (eV); where (e) is the magnitude of electron charger then:

$$\frac{1}{2}mv^2 = eV$$

$$v^2 = \frac{2ev}{m} \qquad\qquad \therefore v = \sqrt{\frac{2eV}{m}}$$

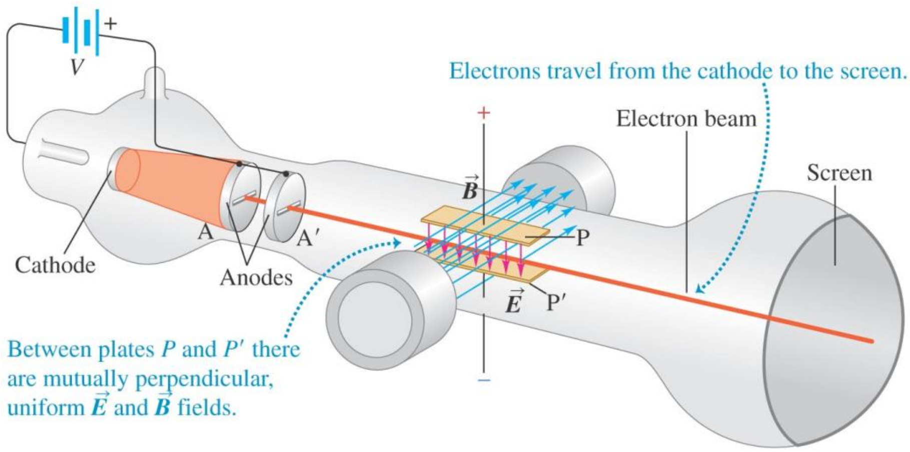
Particles of a specific speed can be selected from the beam using an arrangement of E and B fields.

- F_m (magnetic) for + charge towards right (q v B).
- F_E (electric) for + charge to left (q E).
- $F_{net} = 0$ if $F_m = F_E \Rightarrow -qE + q\,v\,B = 0 \Rightarrow v = E/B$
- Only particles with speed E/B can pass through without being deflected by the fields.



v = E/B ; we get:-

$$\frac{E}{B} = \sqrt{\frac{2eV}{m}} \qquad\qquad So\ \frac{e}{m} = \frac{E^2}{2VB^2}$$



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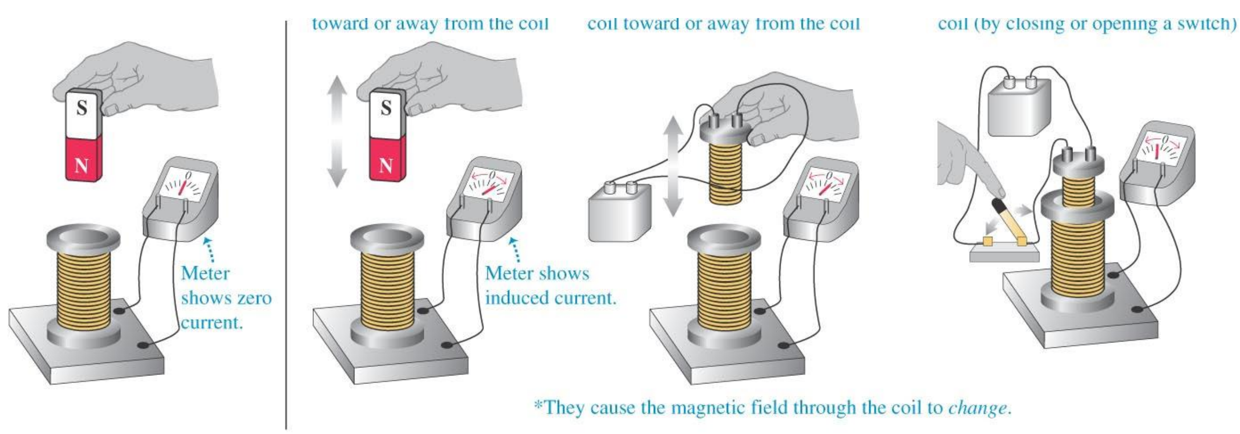
Chapter Two - Electromagnetic Induction

Induction Experiments

- An induced current (and emf) is generated when: (a) we move a magnet around a coil, (b) move a second coil toward/away another coil, (c) change the current in the second coil by opening/closing a switch.



- Magnetically induced emfs are always the result of the action of nonelectrostatic forces. The electric fields caused by those forces are E_n (nonCoulomb, non conservative).

Electromagnetic Induction

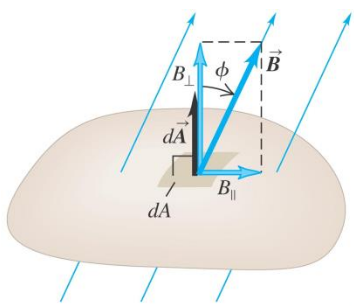
The central principle of electromagnetic inducts is Faraday's Law. This low relates induced emf to changing magnetic flux in any loop, including a closes circuit.

Faraday's Law

The Common element in all induction effects is changing magnetic flux through a circuit.

For an infinitesimal- area element $d\vec{A}$ in magnetic field B, the magnetic flux $d\emptyset_B$ through the area is:-

$$d\emptyset_B = \vec{B}\,.d\vec{A} = B_\perp\, dA = BdA\, Cos\,\emptyset$$



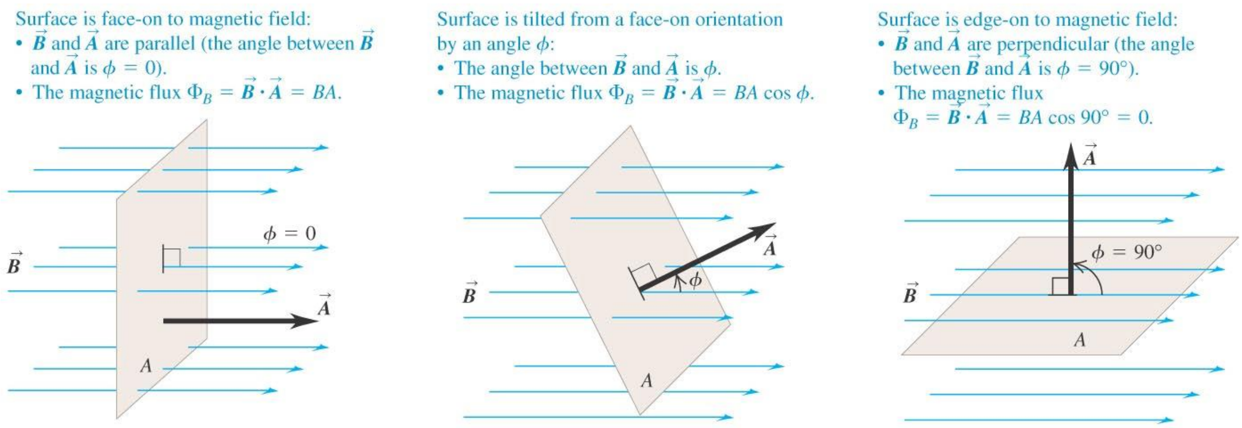
Where $B_\perp$ is the component to $\vec{B}$ perpendicular to the surface of the area element and $\emptyset$ is the angle between $\vec{B}$ and $d\vec{A}$.

The total magnetic flux $\emptyset_B$ through a finite area is the integral of this expression over the area.

$$\Phi_B = \int \vec{B}\cdot d\vec{A} = \int B\cos\varphi\cdot dA$$

If $\vec{B}$ is uniform over a flat area $\vec{A}$, then:

$$\Phi_B = \vec{B}\cdot\vec{A} = B\cdot A\cdot\cos\varphi$$



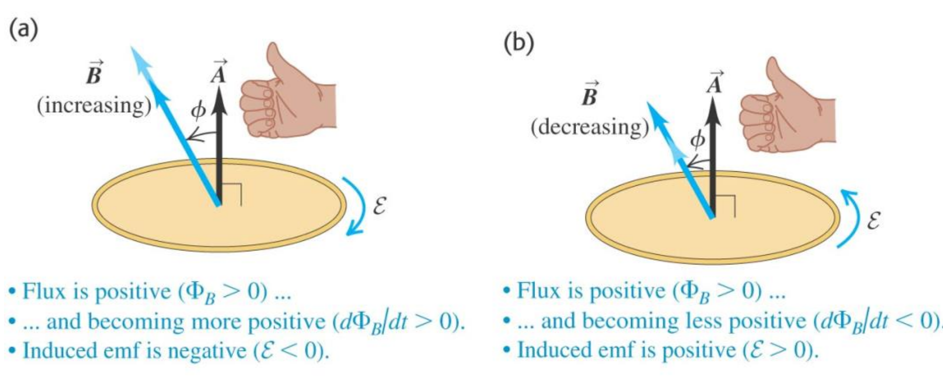
Faraday’s Law of Induction states:

“The induced emf in a closed loop equals the negative of the time rate of Change of the magnetic flux through the loop.

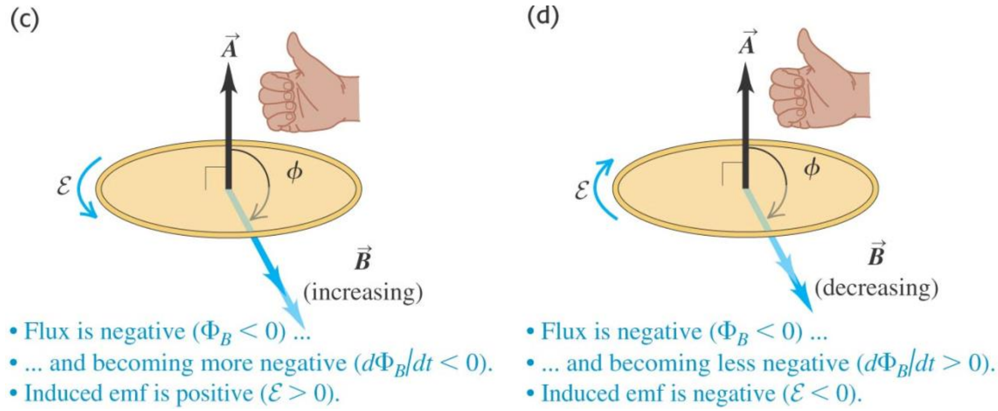
$$\varepsilon = -\frac{d\Phi_B}{dt}$$

- Increasing flux → $\varepsilon < 0$; Decreasing flux → $\varepsilon > 0$

- Direction: curl fingers of right hand around A, if $\varepsilon > 0$ is in same direction of fingers (counter-clockwise), if $\varepsilon < 0$ contrary direction (clockwise).



- Only a change in the flux through a circuit (not flux itself) can induce emf. If flux is constant → no induced emf.



Coil: $$\varepsilon = -N\frac{d\Phi_B}{dt}$$

N = number of turns

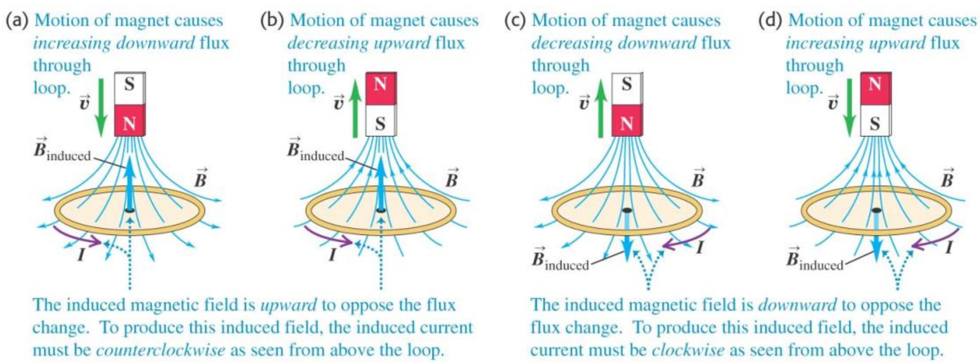
- If the loop is a conductor, an induced current results from emf. This current produces an additional magnetic field through loop. From right hand rule, that field is opposite in direction to the increasing field produced by electromagnet.

Lenz's Law

- Alternative method for determining the direction of induced current or emf.

"The direction of any magnetic induction effect is such as to oppose the cause of the effect".

-The "cause" can be changing the flux through a stationary circuit due to varying B, changing flux due to motion of conductors, or both.

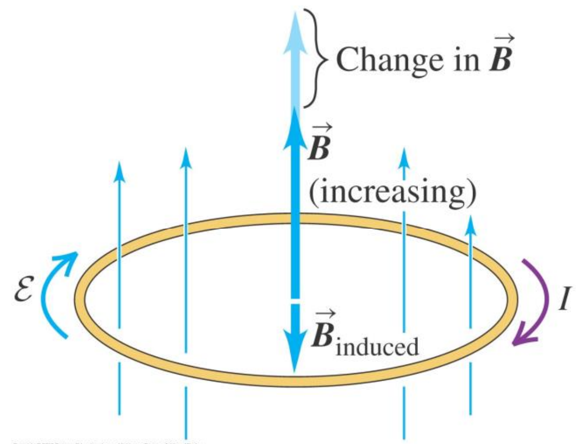


- If the flux in an stationary circuit changes, the induced current sets up a magnetic field opposite to the original field if original B increases, but in the same direction as original B if B decreases.

- The induced current opposes the change in the flux through a circuit (not the flux itself).

- If the change in flux is due to the motion of a conductor, the direction of the induced current in the moving conductor is such that the direction of the magnetic force on the conductor is opposite in direction to its motion (e.g. slide-wire generator). The induced current tries to preserve the "status quo" by opposing motion or a change of flux.

B induced downward opposing the change in flux ($d\Phi/dt$). This leads to induced current clockwise.



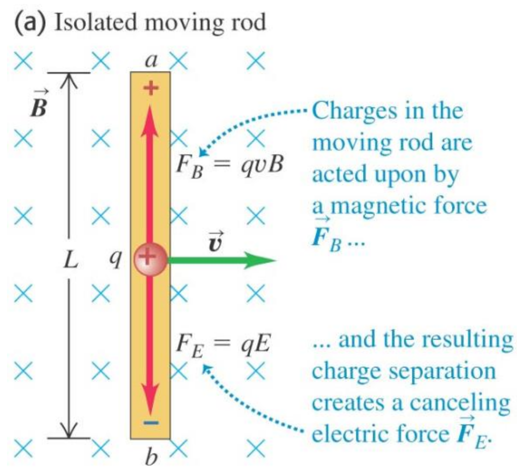
Lenz's Law and the Response to Flux Changes

- Lenz's Law gives only the direction of an induced current. The magnitude depends on the circuit's resistance. Large R → small induced I → easier to change flux through circuit.

- If loop is a good conductor → I induced present as long as magnet moves with respect to loop. When relative motion stops → I = 0 quickly (due to circuit's resistance).

- If R = 0 (superconductor) → I induced (persistent current) flows even after induced emf has disappeared (after magnet stopped moving relative to loop). The flux through loop is the same as before the magnet started to move → flux through loop of R =0 does not change.

Motional Electromotive Force



- A charged particle in rod experiences a magnetic force $\vec{F} = q\vec{v} \times \vec{B}$ that causes free charges in rod to move, creating excess charges at opposite ends.

- The excess charges generate an electric field (from a to b) and electric force ($F = q\,E$) opposite to magnetic force.