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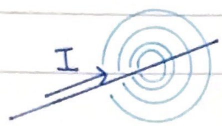
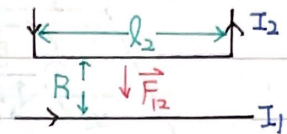
# Magnetic Field and Magnetic Forces

## Magnetic Field

**Ørsted**




**Ampère**




$$\vec{F}_{12} = C\frac{I_1 I_2}{R} l_2 = |\vec{B}_1| I_2 |\vec{l}_2|$$
$$= I_2 \vec{l}_2 \times \vec{B}_1$$

$$[B_1] = \frac{[\vec{F}_{12}]}{[I \cdot l]} = \frac{N}{A \cdot m} = \text{Tesla}$$

$$1 \text{ Telsa} = 10^4 \text{ Gauss}$$

if we perform an experiment by placing a particle with charge $q$ in the magnetic field, we find the following results that are similar to those for experiment on electric forces

* the magnetic force is proportional to the charge $q$ of the particle
* the magnetic force on a negative charge is directed opposite to the force on a positive charge moving in the same direction
* the magnetic force is proportional to the magnitude of the magnetic field vector $\vec{B}$

we also find the following results, which are totally different from those for experiments on electric forces

* the magnetic forces is proportional to the speed $v$ of the particle
* if the velocity vector makes an angle $\theta$ with the magnetic field, the magnitude of the magnetic force is proportional to $\sin\theta$
* when a charged particle moves in a direction not parallel to the magnetic field vector, the magnetic force acts in a direction perpendicular to both $\vec{v}$ and $\vec{B}$; that is, the magnetic force is perpendicular to the plane formed by $\vec{v}$ and $\vec{B}$
* when a charged particle moves parallel to the magnetic field vector, the magnetic force on the charge is zero

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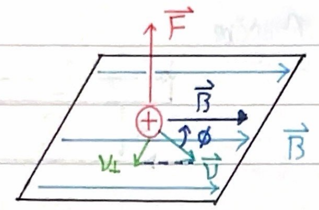
$\vec{F} = q\,\vec{v} \times \vec{B}$ , $F = |q| v_\perp B = |q| vB \sin\phi$

is an observation based on experiment



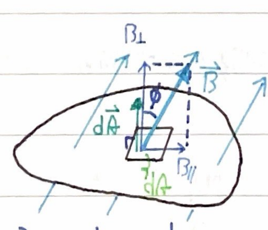

let's compare the important differences between the electric and magnetic versions of the particle in a field model

* the electric force vector is along the direction of the electric field, whereas the magnetic force vector is perpendicular to the magnetic field
* the electric force acts on a charged particle regardless of whether the particle is moving, whereas the magnetic force acts on a charged particle only when the particle is in motion
* the electric force does work in displacing a charged particle, whereas the magnetic force associated with a steady magnetic field does no work when a particle is displaced because the force is perpendicular to the displacement of its point of application

if a charge moving with a velocity $\vec{v}$ in the presence of both an electric field $\vec{E}$ and a magnetic field $\vec{B}$ is described by two particle in a field models

the total force (called the Lorentz force) acting on the charge is $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$

## Magnetic Flux




$d\Phi_B = B_\perp dA = B\cos\phi\, dA = \vec{B}\cdot d\vec{A}$

$\Phi_B = \int B_\perp dA = \int B\cos\phi\, dA = \int \vec{B}\cdot d\vec{A} = T\cdot m^2 =$ weber, wb

the total magnetic flux through a closed surface is always zero

$\oint \vec{B}\cdot d\vec{A} = 0$ Gauss's law for magnetism

magnetic flux density $B = \dfrac{d\Phi_B}{dA_\perp}$

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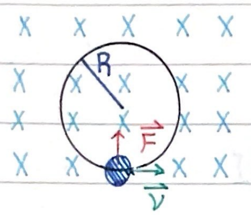
# Motion of Charged Particles in a Magnetic Field

the magnetic force never has a component parallel to the particle's motion, so the magnetic force can never do work on the particle

motion of a charged particle under the action of a magnetic field along is always motion with constant speed



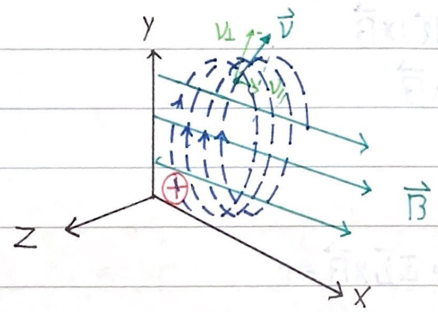

$$F_B = qvB = \frac{mv^2}{R} \quad , \quad R = \frac{mv}{qB} = \frac{P}{qB}$$

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

$$T = \frac{2\pi r}{v} = \frac{2\pi}{\omega} = \frac{2\pi m}{qB}$$

the frequence f is independent of the radius R of the path, it is called the cyclotron frequency in a particle accelerator called a cyclotron

if the direction of the initial velocity is not perpendicular to the field



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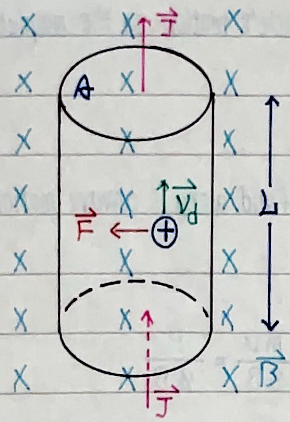
# Magnetic Force on a Current-Carrying Conductor

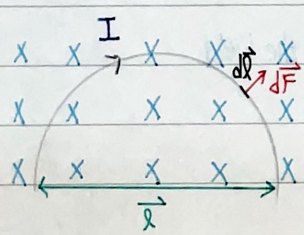



the number of charges per unit volume is $n$

$$\vec{F} = (nAL)(q v_d B) = n q v_d A L B \qquad \text{since } J = n q v_d \text{ , } JA = I$$

$$= I \ell B \qquad = I \ell B \sin\phi$$

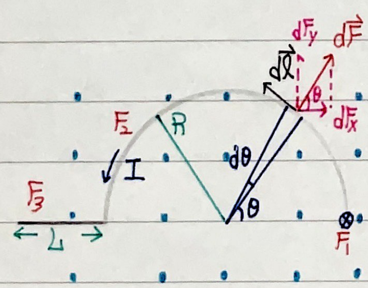
$$\Rightarrow \vec{F} = I \vec{\ell} \times \vec{B}$$




$$\vec{F} = \int d\vec{F} = \int I \, d\vec{\ell} \times \vec{B} \quad \text{if } \vec{B} \text{ is regular}$$

$$= I \left( \int d\vec{\ell} \right) \times \vec{B}$$

$$= I \vec{\ell} \times \vec{B}$$




$$\vec{F}_1 = I \vec{L} \times \vec{B} = 0$$

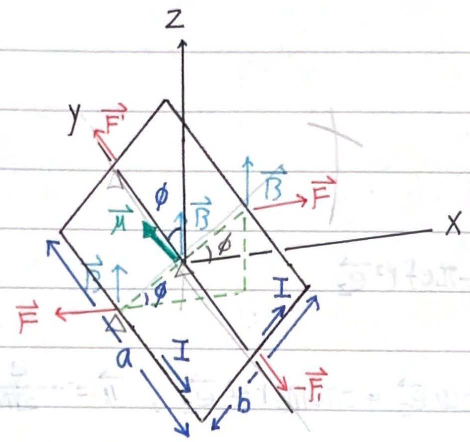
$$\vec{F}_3 = I \vec{L} \times \vec{B} = I(-L \vec{e}_x) \times B \vec{e}_z = I L B \vec{e}_y$$

$$dF_{2x} = I(R\,d\theta) B \cos\theta \text{ , } F_{2x} = IRB \int_0^{\pi} \cos\theta \, d\theta = 0$$

$$dF_{2y} = I R \, d\theta \, B \sin\theta \text{ , } F_{2y} = IRB \int_0^{\pi} \sin\theta \, d\theta = 2IRB$$

$$\vec{F}_1 + \vec{F}_2 + \vec{F}_3 = IB(2R + L) \vec{e}_y$$

Force and Torque on a Current Loop



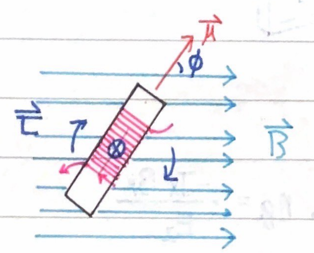

$\vec{F} = I a B \qquad F' = Ib\sin(90° - \phi) = IbB\cos\phi$

$\tau = 2F\frac{b}{2}\sin\phi$

$= IabB\sin\phi = IBA\sin\phi$ and magnetic dipole moment $\vec{\mu} = I\vec{A}$

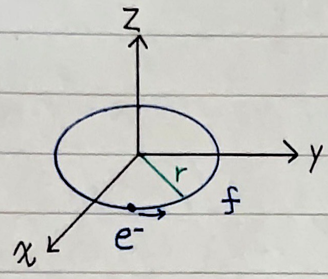
$= \mu B \sin\phi = \vec{\mu}\times\vec{B}$

$U = -\vec{\mu}\cdot\vec{B} = -\mu B\cos\phi$




$\tau = NIAB\sin\phi$

$= \vec{\mu}\times\vec{B}$

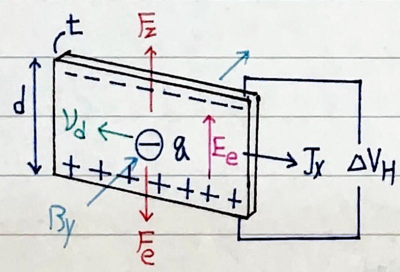


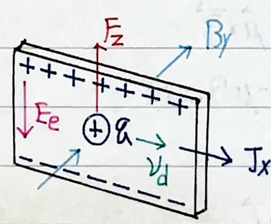

$I = f(-e)$

$\vec{\mu} = I\vec{A} = (-ef)(\pi r^2 \vec{e_z}) = -\pi e f r^2 \vec{e_z}$

$\vec{L} = \vec{r} \times \vec{P} = \vec{r} \times m_e \vec{v} = m_e r^2 \omega \vec{e_z} = 2\pi m_e r^2 f \vec{e_z}$ , $\vec{\mu} = -\frac{e}{2m_e}\vec{L}$

## The Hall Effect




$F_z = |q| v_d B \quad J_x = n_q v_d$

$q E_z + q v_d B_y = 0$ , $E_z = -v_d B_y$ , $v_d = \frac{I}{n q A}$ , $n_q = \frac{-J_x B_y}{E_z}$

$\Delta V_H = Ed = v_d B d = \frac{IBd}{n q A}$

$= \frac{IB}{n q t} \quad = R_H \frac{IB}{t}$ , $R_H$, Hall coefficient $= \frac{1}{n q}$