Electromagnetic Theory

CREDIT HOURS FIRST LEVEL(PHYSICS /PHYSICS AND COMPUTER SCIENCE PROGRAM)

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COLLECTED BY DR. FATEMA ALZAHRAA MOHAMMAD

PHYSICS DEPARTMENT-FACULTY OF SCIENCE-DAMIETTA UNIVERSITY-EGYPT)

PHYSICS FOR SCIENTISTS AND ENGINEERS

BY RAYMOND A. SERWAY , JOHN W. JEWETT

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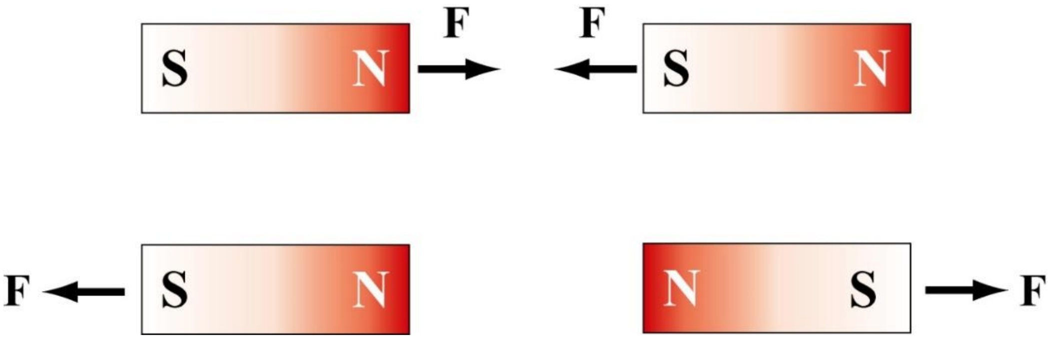
Chapter 5: Magnetic Fields

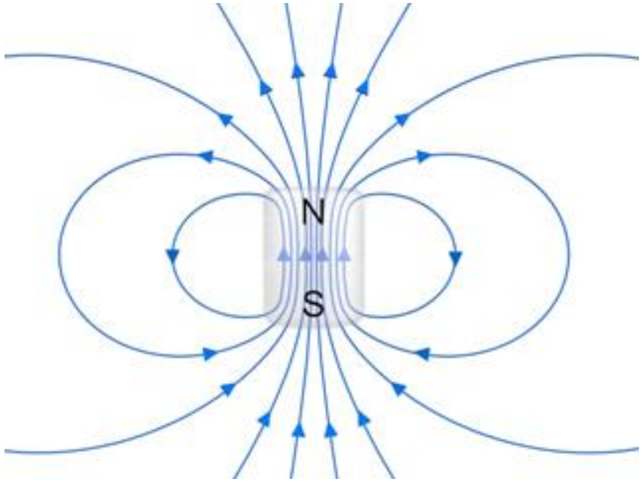
- Magnetic Fields and Forces.
- Motion of a charged Particle in a Uniform Magnetic Field.
- Magnetic Force Acting on a Current-Carrying Conductor.
- Torque on a current loop in a uniform magnetic field.

Magnetism was first discovered in the ancient world, when people noticed that lodestones, naturally magnetized pieces of the mineral magnetite, (Iron ore found near Magnesia) could attract iron.[1] The word *magnet* comes from the Greek term μαγνῆτις λίθος *magnētis lithos*,[2] "the Magnesian stone,[3] lodestone." In ancient Greece.

The magnetic force is a consequence of the electromagnetic force, one of the four fundamental forces of nature, and is caused by the **motion of charges**. Two objects containing charge with the same direction of motion have a magnetic attraction force between them. Similarly, objects with charge moving in opposite directions have a repulsive force between them.

Like Poles repel, Opposites Attract. **No** Magnetic Monopoles





They point up inside the magnet

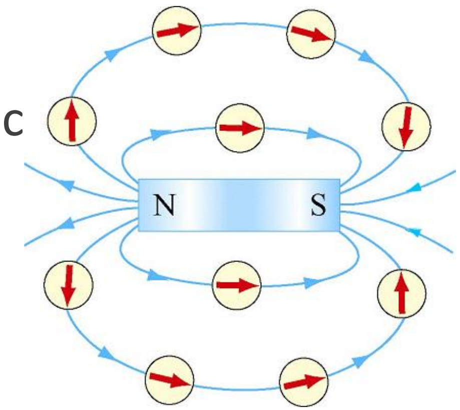
Magnetic field lines are continuous.

E field lines begin and end on charges.

There are no magnetic charges (monopoles) so B field lines ***never*** begin or end

Compass needles align N-S: magnetic Poles

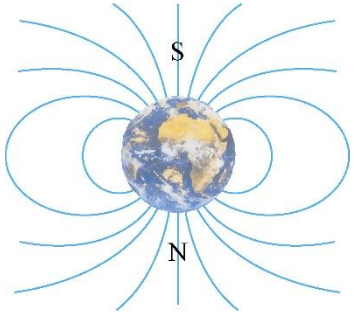
- North (geographic South) Poles attracted to geographic North (South)



Magnetic Field Lines = direction of compass deflection.

Electric Currents produce deflections in compass direction.

Magnetic field lines leave from N, end at S



Magnetic Fields in analogy with Electric Fields

Electric Field:

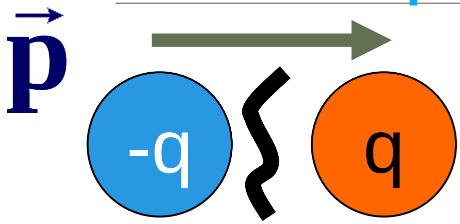
- Distribution of charge creates an electric field ***E(r)*** in the surrounding space.
- Field exerts a force ***F****=q* ***E(r)*** on a charge *q* at ***r***

Magnetic Field:

- <u>Moving</u> charge or current creates a magnetic field ***B(r)*** in the surrounding space.
- Field exerts a force ***F*** on a charge <u>moving</u> *q* at ***r***.

Magnetic Monopoles?

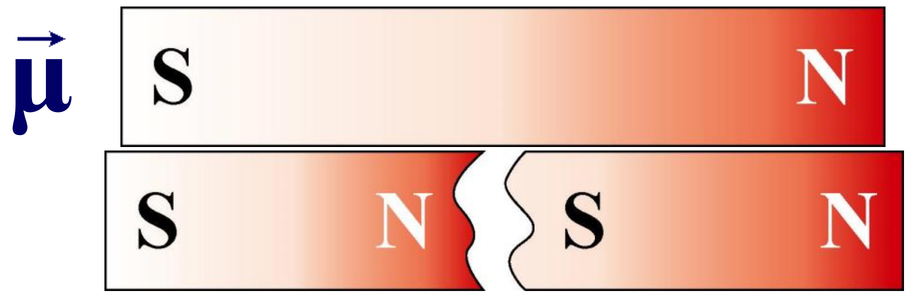
Electric Dipole



When cut:

2 monopoles (charges)

Magnetic Dipole



When cut: 2 dipoles

Magnetic monopoles do not exist in isolation

Another Maxwell’s Equation! (2 of 4)

$$\oiint_S \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{q_{in}}{\varepsilon_0}$$

Gauss’s Law

1st Maxwell’s Equation

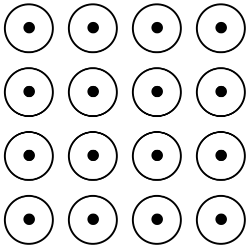
$$\oiint_S \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = 0$$

Magnetic Gauss’s Law

2nd Maxwell’s Equation

Notation Demonstration

OUT of page
"Arrow head"



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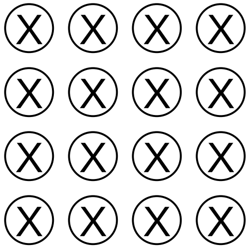
"Arrow Tail"

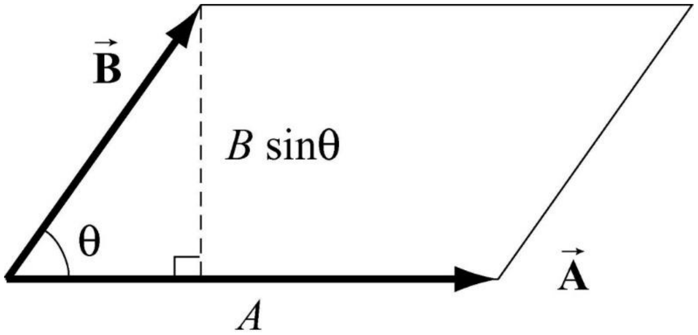


Computing magnitude of cross product A x B:

$$\left|\vec{\mathbf{C}}\right| = \left|\vec{\mathbf{A}}\right|\left|\vec{\mathbf{B}}\right|\sin\theta$$

$$\vec{\mathbf{C}} = \vec{\mathbf{A}} \text{x} \vec{\mathbf{B}}$$

$|\vec{\mathbf{C}}|$: area of parallelogram



Cross Product: Direction

For this method, keep your hand flat!

1) Put Thumb (of right hand) along **A**
2) Rotate hand so fingers point along **B**
3) Palm will point along **C**

Right Hand Rule #1:

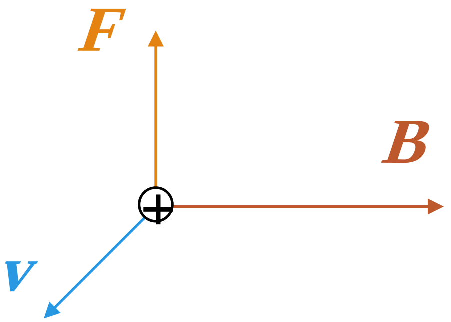
Magnetic Fields and Magnetic Forces

Magnetic Force (F) on a moving charge

- proportional to electric charge q.
- perpendicular to velocity ***v*.**
- proportional to speed *v* (for a given geometry)
- perpendicular to Magnetic Field ***B***
- proportional to field strength *B* (for a given geometry)

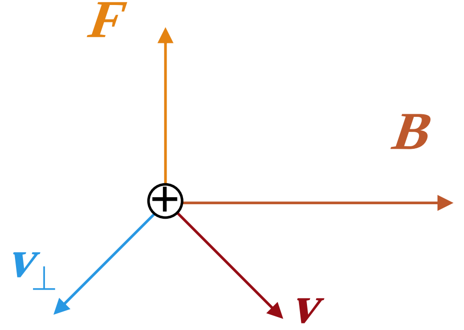
$$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$$

$$F = |q|\, v\, B \sin\theta$$
$$= |q|\, v\, B \quad (\mathbf{v} \perp B)$$



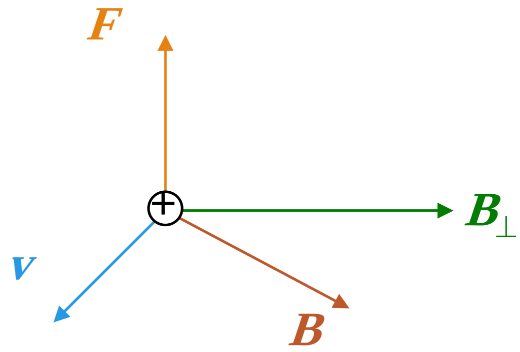
$\boldsymbol{F} = q\,\boldsymbol{v} \times \boldsymbol{B}$

$F = |q|\, v_{\perp}\, B$



$\boldsymbol{F} = q\,\boldsymbol{v} \times \boldsymbol{B}$

$F = |q|\, v\, B_{\perp}$



Units of Magnetic Flux Denisty:

[B] = [F]/([q][v])

= N/(C m s^{-1}) = Tesla=Wb/ m^2 SI unit

Defined in terms of force on standard current

CGS Unit 1 Gauss = 10^{-4} Tesla,Earth's field strength ~ 1 Gauss

Electromagnetic Force: $\boldsymbol{F} = q\,(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$

= Lorentz Force Law

Magnetic Field Lines and Magnetic Flux

Magnetic Field Lines

- Mapped out with compass
- Are not lines of force (***F*** is not parallel to ***B***)
- Field Lines never intersect

Magnetic Flux

$d\Phi_B = \mathbf{B} \cdot d\mathbf{A}$

$$d\Phi_B = \vec{B} \cdot d\vec{A}$$

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

$$\oint \vec{B} \cdot d\vec{A} = 0 \quad \text{no magnetic charge! (no monopoles)}$$

Gauss's law for magnetism(2nd equation of Maxwell's Equations.

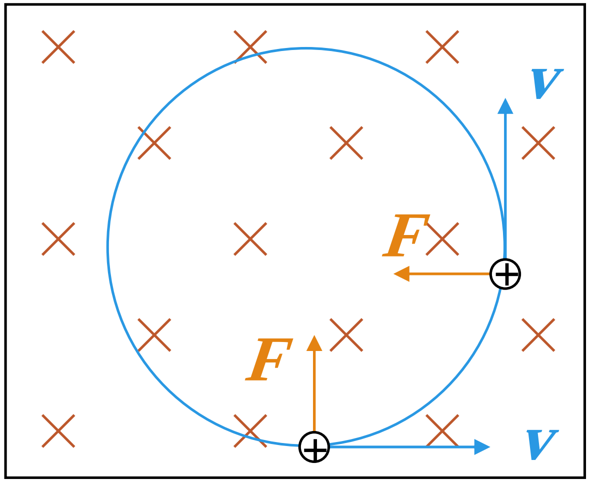
SI Unit of Flux:

- 1Weber = 1Tesla x 1 m^2
- for a small area $B = d\Phi_B / dA_\perp$
- B = “Magnetic Flux Density”

Flux through an open surface will play an important role

Motion of Charged Particles in a Magnetic Field

Charged Particle moving perpendicular to the Magnetic Field



- Circular Motion!
- (simulations)

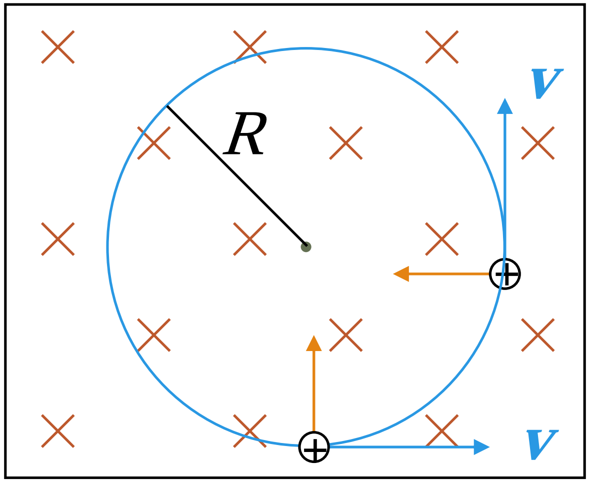
Charged Particle moving perpendicular to a uniform Magnetic Field

$$F = |q| vB = \frac{mv^2}{R}$$

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

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

$$= \text{cyclotron frequency}$$



Work done by the Magnetic Field on a free particle:

$$dW = \vec{F} \cdot d\vec{x}$$

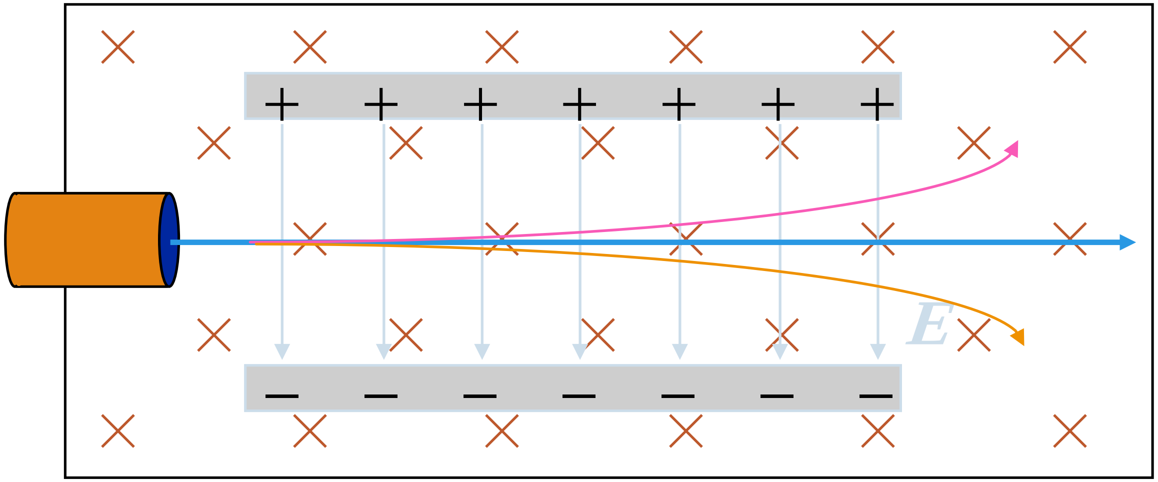
$$= \left(q\vec{v} \times \vec{B}\right) \cdot \vec{v} dt$$

$$= 0!$$

=> no change in Kinetic Energy! Motion of a free charged particle in **any** magnetic field has constant speed.

Velocity Selector

makes use of crossed **E** and **B** to provide opposing forces



upwards

$\boldsymbol{F} = q\,\boldsymbol{v} \times \boldsymbol{B}$

downwards

$\boldsymbol{F} = q\boldsymbol{E}$

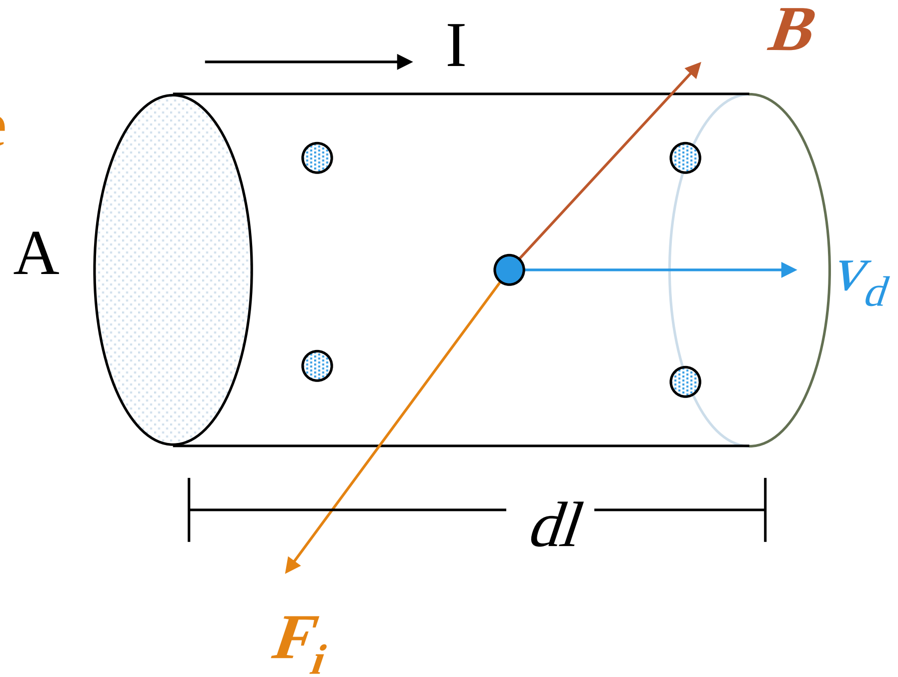
No net deflection => forces exactly cancel:

$|q|\,v\,B = |q|\,E$

$v = E/B$

Magnetic Force Acting on a Current-Carrying Conductor Wire

Consider an arbitrary shaped wire segment, its area is A as shown in given figure, the magnetic force exerted on a small segment of vector length dl



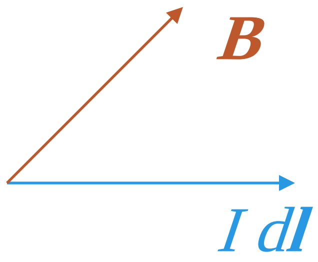
$$F = \sum F_i = \sum q_i \vec{v}_i \times \vec{B}$$

$$= Nq\vec{v}_d \times \vec{B} = n \cdot volume \cdot q\vec{v}_d \times \vec{B}$$

$$= nAdlq\vec{v}_d \times \vec{B} = \vec{J}Adl \times \vec{B}$$

$$= Id\vec{l} \times \vec{B} \quad (RHR)$$

Example: A 1-m bar carries 50 A from west to east in a 1.2 T field directed 45° North of East. What is the magnetic force on the bar?



Force will be directed upwards (out of the plane of the page)

F=I**L**x**B**

$$F = ILB\sin\theta$$

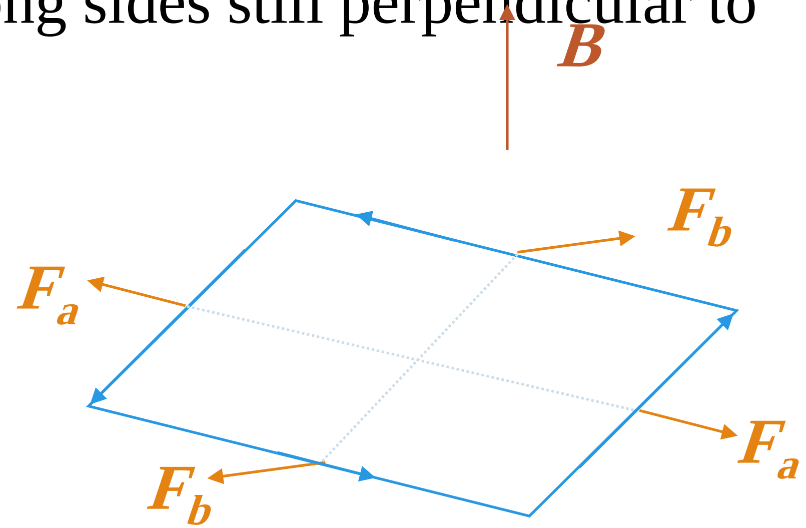
$$= 50A\,1m\,1.2T\sin 45^\circ$$

$$= 42.4N$$

Torque on a Current Loop in uniform magnetic field

(from $\boldsymbol{F} = I\, \boldsymbol{l} \times \boldsymbol{B}$)

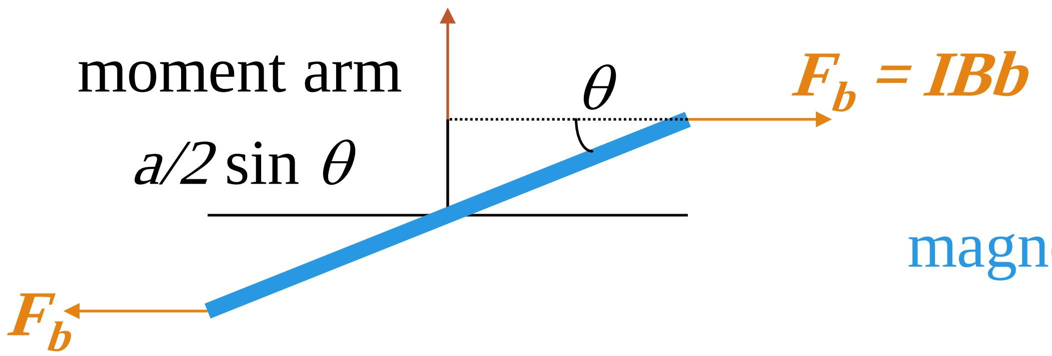
Rectangular loop in a magnetic field (directed along z axis) short side length a, long side length b, tilted with short sides at an angle with respect to ***B***, long sides still perpendicular to ***B***.

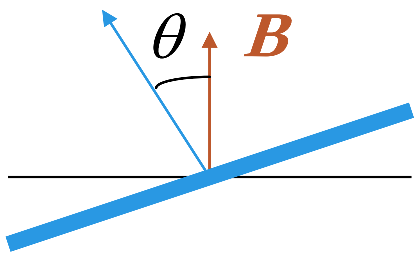


Forces on short sides cancel: no net force or torque.

Forces on long sides cancel for no net force but there is a net torque.

Torque calculation: Side view





$$\tau = F_b \, a/2 \sin\theta + F_b \, a/2 \sin\theta$$

$$= Iab\, B \sin\theta \;= I\, A\, B \sin\theta$$

$$= I\, \mathbf{A} \times \mathbf{B} = \boldsymbol{\mu} \times \mathbf{B}$$

Magnetic Dipole $\boldsymbol{\mu} = I\,\mathbf{A}$

The SI unit of the magnetic dipole is A. m^2

The potential energy $U = -\boldsymbol{\mu} \cdot \mathbf{B}$

Switch current *direction* every 1/2 rotation => DC motor