W07D1 Magnetic Dipoles, Force and Torque on a Dipole, Experiment 2

W07D1 Magnetic Dipoles, Torque and Force on a Dipole, Experiment 2: Magnetic Dipole in a Helmholtz Coil
http://web.mit.edu/8.02t/www/materials/Experiments/expMagForcesDipoleHelmholtz.pdf

Reading Course Notes: Sections 8.4, 8.6.4, 8.10.4, 8.13, 9.5, 9.9

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Announcements

Exam Two Reviews:
Tuesday from 7:30-9 pm in 26-152
Tuesday from 9-10:30 pm in 26-152

PS 6 due W07 Tuesday at 9 pm in boxes outside 32-082 or 26-152

Exam 2 Thursday March 20 7:30 - 9:30 pm: See announcement pages for section room assignments

Conflict Friday March 21 8-10 am and 10-12 noon in 32-082

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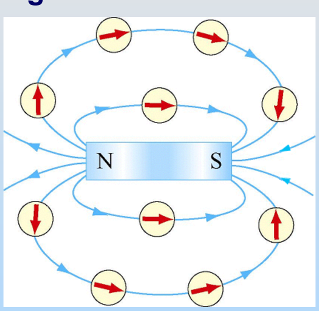
Magnetic Field of Bar Magnet



(1) A magnet has two poles, North (N) and South (S)
(2) Magnetic field lines leave from N, end at S

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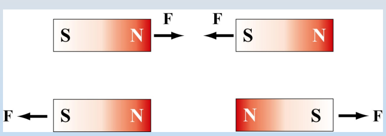
Demonstration: Magnetic Field Lines from Bar Magnet G2

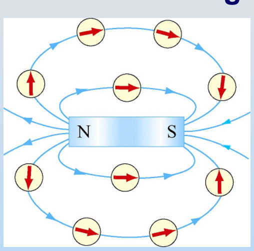
http://tsgphysics.mit.edu/front/?page=demo.php&letnum=G%202&show=0

Magnetism – Bar Magnet



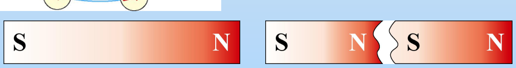
Like poles repel, opposite poles attract

Bar Magnets Are Dipoles!



- Create Dipole Field
- Rotate to orient with Field

Is there magnetic “mass” or magnetic “charge?”

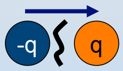


NO! Magnetic monopoles do not exist in isolation

Magnetic Monopoles?

Electric Dipole

$\vec{p}$



When cut:
2 monopoles (charges)

Magnetic Dipole

$\vec{\mu}$

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

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

Magnetic Gauss's Law

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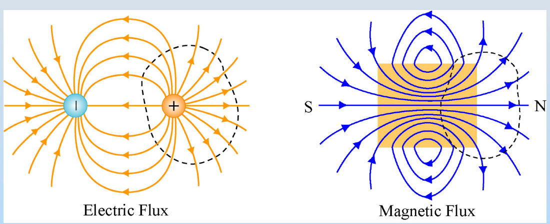
Conservation of Magnetic Flux:



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

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

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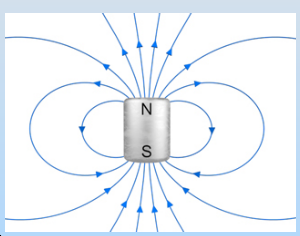
Concept Question: Magnetic Field Lines

The picture shows the field lines outside a permanent magnet The field lines inside the magnet point:



1. Up
2. Down
3. Left to right
4. Right to left
5. The field inside is zero
6. I don't know

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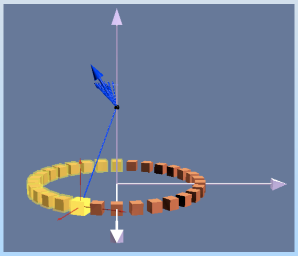
Animation: Magnetic Field Generated by a Current Loop



http://web.mit.edu/viz/EM/visualizations/magnetostatics/calculatingMagneticFields/RingMagInt/RingMagIntegration.htm

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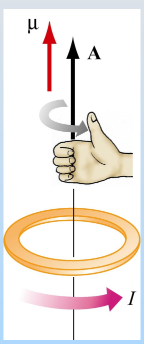
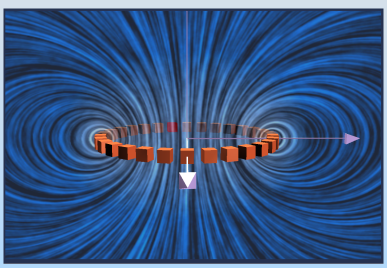
Magnetic Dipole Moment

$$\vec{\mu} \equiv IA\,\hat{\mathbf{n}} \equiv I\vec{\mathbf{A}}$$





http://web.mit.edu/viz/EM/visualizations/magnetostatics/calculatingMagneticFields/RingMagField/RingMagField.htm

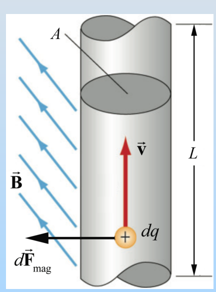
Review: Magnetic Force on Current-Carrying Wire

If the wire is a uniform magnetic field then

$$\vec{\mathbf{F}}_{\text{mag}} = \left(\int_{\text{wire}} I\, d\vec{\mathbf{s}} \right) \times \vec{\mathbf{B}}$$

If the wire is also straight then

$$\vec{\mathbf{F}}_{\text{mag}} = I(\vec{\mathbf{L}} \times \vec{\mathbf{B}})$$



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Torque on a Current Loop in a Uniform Magnetic Field

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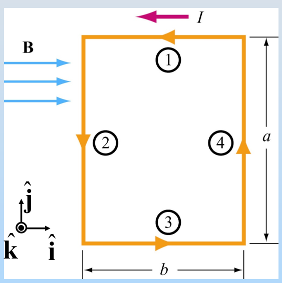
Group Problem: Current Loop

Place rectangular current loop in uniform B field



1) What is the net force on this loop?
2) What is the net torque on this loop?
3) Describe the motion the loop makes

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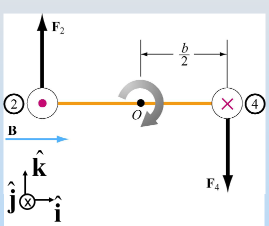
Torque on Rectangular Loop



$$\vec{\tau} = IAB\hat{\mathbf{j}}$$

Area vector

$$\vec{\mathbf{A}} = A\hat{\mathbf{n}} = ab\hat{\mathbf{n}}$$

$$\hat{\mathbf{n}} = +\hat{\mathbf{k}}, \quad \vec{\mathbf{B}} = B\hat{\mathbf{i}}$$

$$\boxed{\vec{\tau} = I\vec{\mathbf{A}} \times \vec{\mathbf{B}}}$$

No net force but there is a torque

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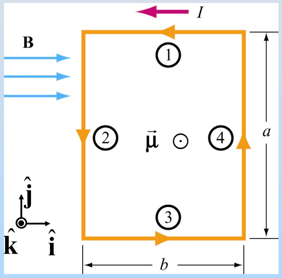
Torque on Current Loop

Place rectangular current loop in uniform B field



Magnetic moment points out of the page

$$\boxed{\vec{\tau} = \vec{\mu} \times \vec{\mathbf{B}}}$$

$$\vec{\tau} = \vec{\mu} \times \vec{\mathbf{B}} = \mu B \hat{\mathbf{j}} = IAB \hat{\mathbf{j}}$$

torque tries to align the magnetic moment vector in the direction of the magnetic field

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Demonstration: Deflection of a Compass Needle by a Magnet G1

http://tsgphysics.mit.edu/front/?page=demo.php&letnum=G%201&show=0

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Demonstration: Galvanometer principle G10

http://tsgphysics.mit.edu/front/?page=demo.php&letnum=G%2010&show=0

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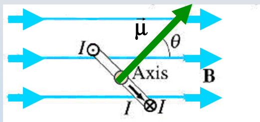
Concept Question: Dipole in Field

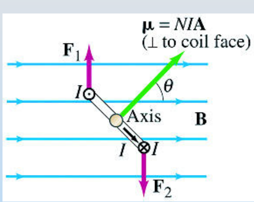


From rest, the coil above will:

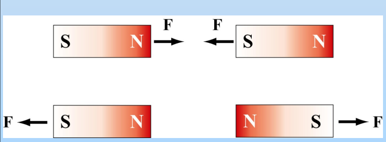
1. rotate clockwise, not move
2. rotate counterclockwise, not move
3. move to the right, not rotate
4. move to the left, not rotate
5. move in another direction, without rotating
6. both move and rotate
7. neither rotate nor move
8. I don't know

Force on a Dipole in a Non-Uniform Field

Dipoles don't move???



This dipole rotates but doesn't feel a net force in a uniform magnetic field



But dipoles can feel magnetic force.

Dipoles in Non-Uniform Fields: Magnetic Force

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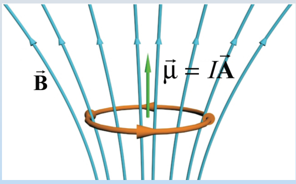
Concept Question: Dipole in Field



The current carrying coil above will feel a net force

1. upwards
2. downwards
3. of zero
4. I don't know

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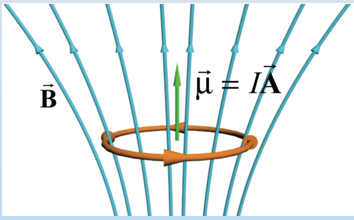
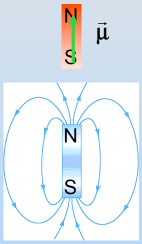
Force on Magnetic Dipole





What makes the field pictured? Bar magnet below dipole, with N pole on top. It is aligned with the dipole pictured, they attract!

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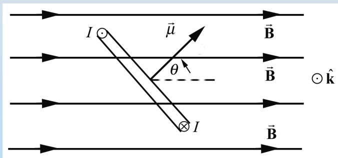
Work Done by Interaction to Anti-align Magnetic Dipole



$$\vec{\boldsymbol{\tau}} = \vec{\boldsymbol{\mu}} \times \vec{\mathbf{B}} = -\mu B \sin\theta \hat{\mathbf{k}} = \tau_z \hat{\mathbf{k}}$$

$$W = \int_0^{\pi} \tau_z \, d\theta = -\int_0^{\pi} \mu B \sin\theta \, d\theta = \mu B \cos\theta \Big|_0^{\pi} = -2\mu B$$

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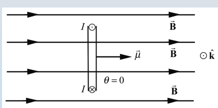
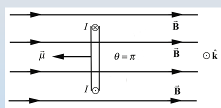
Potential Energy: Dipole in Magnetic Field





$$\Delta U = U(\theta = \pi) - U(\theta = 0) = -W = 2\mu B = -\vec{\mu}\big|_{\theta=\pi} \cdot \vec{\mathbf{B}}$$

Set zero reference point $U(\theta = \pi/2) = 0$

$$U(\theta) = -\vec{\mu} \cdot \vec{\mathbf{B}}$$

Lowest energy state (aligned) : $U(\theta = 0) = -\mu B$

Highest energy state (anti-aligned): $U(\theta = \pi) = \mu B$

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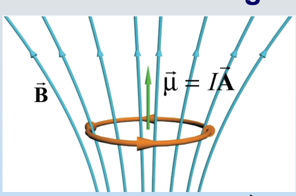
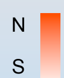
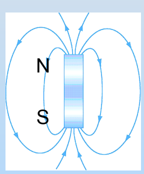
Force on Magnetic Dipole



$\vec{\boldsymbol{\mu}} \uparrow$





$$U_{Dipole} = -\vec{\boldsymbol{\mu}} \cdot \vec{\mathbf{B}}$$

$$\vec{\mathbf{F}} = -\vec{\nabla}(-\vec{\boldsymbol{\mu}} \cdot \vec{\mathbf{B}}) \Rightarrow \vec{\mathbf{F}} = \vec{\nabla}(\vec{\boldsymbol{\mu}} \cdot \vec{\mathbf{B}})$$

$$F_z(0,0,z) = \mu_z \frac{\partial B_z}{\partial z}$$

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Experiment 2: Magnetic Forces on Dipole in Fields of Helmholtz Coil

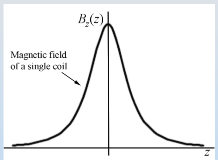
Getting Started: Set up current supply

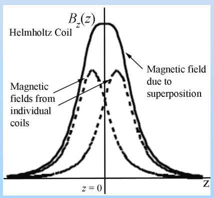
- Open circuit (disconnect a lead)
- Turn current knob full CCW (off)
- Increase voltage to ~12 V
  - This will act as a protection: V<12 V
- Reconnect leads in Helmholtz mode
- Increase current to ~1 A

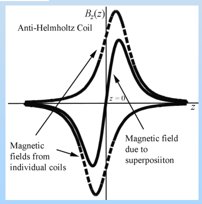
Appendix Experiment 2: Magnetic Forces on Dipole in Fields of Helmholtz Coil

Field Configurations and Concept Questions

Magnetic Field Profiles for Experiment 2

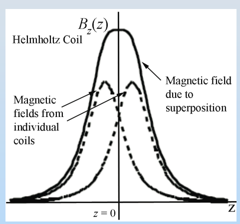






Concept Question: Dipole in Helmholtz

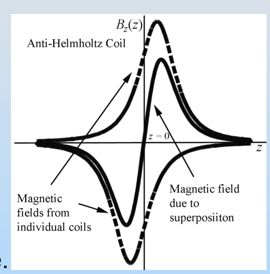
A dipole pointing along the positive x-direction and located at the center of a Helmholtz coil will feel:



1. a force but not a torque.
2. a torque but not a force.
3. both a torque and a force.
4. neither force nor torque.

Concept Question: Dipole in Anti-Helmholtz Coil

A dipole pointing along the positive z-direction and located at the center of an anti- Helmholtz coil will feel:



1. a force but not a torque.
2. a torque but not a force.
3. both a torque and a force.
4. neither force nor torque.