PH 102, Electromagnetism,

Post Mid Semester

Lecture 3.

Magnetostatics:

Multipole expansion of vector potential

and

Torque on magnetic dipole

D. J. Griffiths: 5.4 to 6.1

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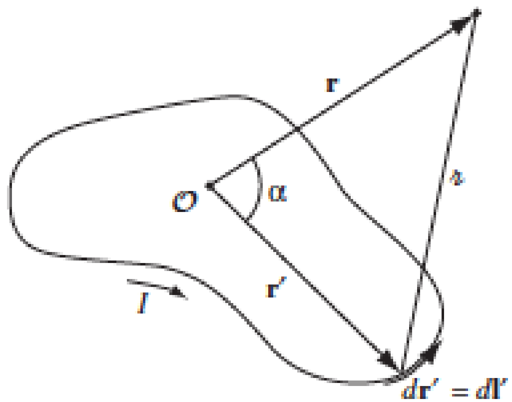
Multipole expansion of vector potential

Multipole expansion gives approximate vector potential of localized current



Potential in form of a power series in **1/*r***

$$\frac{1}{\imath} = \frac{1}{\sqrt{r^2 + (r')^2 - 2rr'\cos\alpha}} = \frac{1}{r}\sum_{n=0}^{\infty}\left(\frac{r'}{r}\right)^n P_n(\cos\alpha),$$

$$\mathbf{A}(\mathbf{r}) = \frac{\mu_0 I}{4\pi}\oint \frac{1}{\imath}\, d\mathbf{l}' = \frac{\mu_0 I}{4\pi}\sum_{n=0}^{\infty}\frac{1}{r^{n+1}}\oint (r')^n P_n(\cos\alpha)\, d\mathbf{l}',$$

Monopole ~ 1/r;

Dipole ~ $1/r^2$

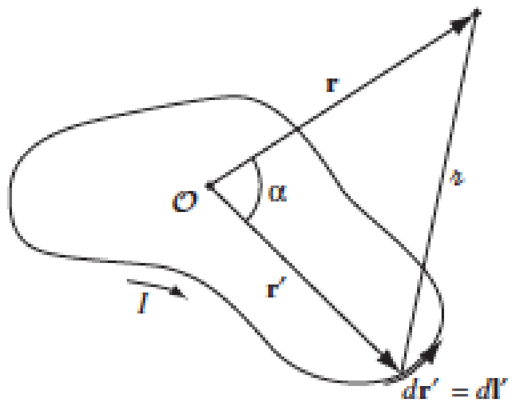
Quadruple ~ $1/r^3$

$$\mathbf{A}(\mathbf{r}) = \frac{\mu_0 I}{4\pi}\left[\frac{1}{r}\oint d\mathbf{l}' + \frac{1}{r^2}\oint r'\cos\alpha\, d\mathbf{l}' + \frac{1}{r^3}\oint (r')^2\left(\frac{3}{2}\cos^2\alpha - \frac{1}{2}\right) d\mathbf{l}' + \cdots\right].$$

Multipole expansion of vector potential

Multipole expansion gives approximate vector potential of localized current

Potential in form of a power series in ***1/r***



$$\frac{1}{\mathscr{r}} = \frac{1}{\sqrt{r^2 + (r')^2 - 2rr'\cos\alpha}} = \frac{1}{r}\sum_{n=0}^{\infty}\left(\frac{r'}{r}\right)^n P_n(\cos\alpha),$$

$$\mathscr{r}^2 = r^2 + (r')^2 - 2rr'\cos\alpha = r^2\left[1 + \left(\frac{r'}{r}\right)^2 - 2\left(\frac{r'}{r}\right)\cos\alpha\right],$$

$$\mathscr{r} = r\sqrt{1+\epsilon},$$

$$\epsilon \equiv \left(\frac{r'}{r}\right)\left(\frac{r'}{r} - 2\cos\alpha\right).$$

$$\frac{1}{\mathscr{r}} = \frac{1}{r}(1+\epsilon)^{-1/2} = \frac{1}{r}\left(1 - \frac{1}{2}\epsilon + \frac{3}{8}\epsilon^2 - \frac{5}{16}\epsilon^3 + \ldots\right),$$

$$= \frac{1}{r}\left[1 + \left(\frac{r'}{r}\right)\cos\alpha + \left(\frac{r'}{r}\right)^2 (3\cos^2\alpha - 1)/2 + \left(\frac{r'}{r}\right)^3 (5\cos^3\alpha - 3\cos\alpha)/2 + \ldots\right]$$

Multipole expansion of vector potential

$$\mathbf{A}(\mathbf{r}) = \frac{\mu_0 I}{4\pi}\left[\frac{1}{r}\oint d\mathbf{l}' + \frac{1}{r^2}\oint r' \cos\alpha \, d\mathbf{l}' + \frac{1}{r^3}\oint (r')^2 \left(\frac{3}{2}\cos^2\alpha - \frac{1}{2}\right) d\mathbf{l}' + \cdots\right].$$

Magnetic Monopole :

$$\boxed{\nabla \cdot \mathbf{B} = 0.} \qquad \mathbf{B} = \nabla \times \mathbf{A}.$$

No magnetic monopoles in nature : No point source for ***B***

The magnetic monopole term (~ 1/r) in the previous expansion is always Zero!!

$\oint d\mathbf{l}' = \mathbf{0}.$ Total vector displacement around a closed loop

The total structure of vector potential depends on this fact!

Multipole expansion of vector potential

Magnetic Dipole : In absence of monopoles dipole is the dominant term

$$\mathbf{A}_{\text{dip}}(\mathbf{r}) = \frac{\mu_0 I}{4\pi r^2} \oint r' \cos\alpha \, d\mathbf{l}' = \frac{\mu_0 I}{4\pi r^2} \oint (\hat{\mathbf{r}} \cdot \mathbf{r}') \, d\mathbf{l}'.$$

$$= \frac{\mu_0}{4\pi} \frac{\mathbf{m} \times \hat{\mathbf{r}}}{r^2},$$

$$\oint (\vec{c} \cdot \vec{r}) d\vec{l} = \vec{a} \times \vec{c}$$

$$\vec{a} = \frac{1}{2} \oint \vec{r} \times d\vec{l}$$

with $\mathbf{c} = \hat{\mathbf{r}}$

$$\oint (\hat{\mathbf{r}} \cdot \mathbf{r}') \, d\mathbf{l}' = -\hat{\mathbf{r}} \times \int d\mathbf{a}'.$$

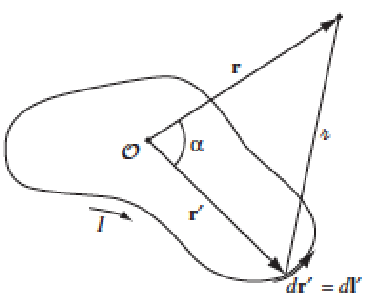
$$\hat{r} \times \oint (\vec{r}' \times d\vec{r}') = \oint \vec{r}' (\hat{r} \cdot d\vec{r}') - \oint d\vec{r}' (\hat{r} \cdot \vec{r}')$$

$$= \oint d\left[(\vec{r}'(\hat{r} \cdot \vec{r}') \right] - \oint (\hat{r} \cdot \vec{r}') d\vec{r}' - \oint d\vec{r}' (\hat{r} \cdot \vec{r}')$$

$$= -2 \oint (\hat{r} \cdot \vec{r}') d\vec{r}'$$

Here, $\boldsymbol{m}$ is the magnetic dipole moment

$$\mathbf{m} \equiv I \int d\mathbf{a} = I \mathbf{a}.$$



Magnetic dipole moment is independent of choice of origin!
No Magnetic monopole

Remember, Electric dipole moment was independent of origin only when the total charge vanished

Multipole expansion of vector potential

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Example 5.13. Find the magnetic dipole moment of the "bookend-shaped" loop shown in Fig. 5.52. All sides have length w, and it carries a current I.

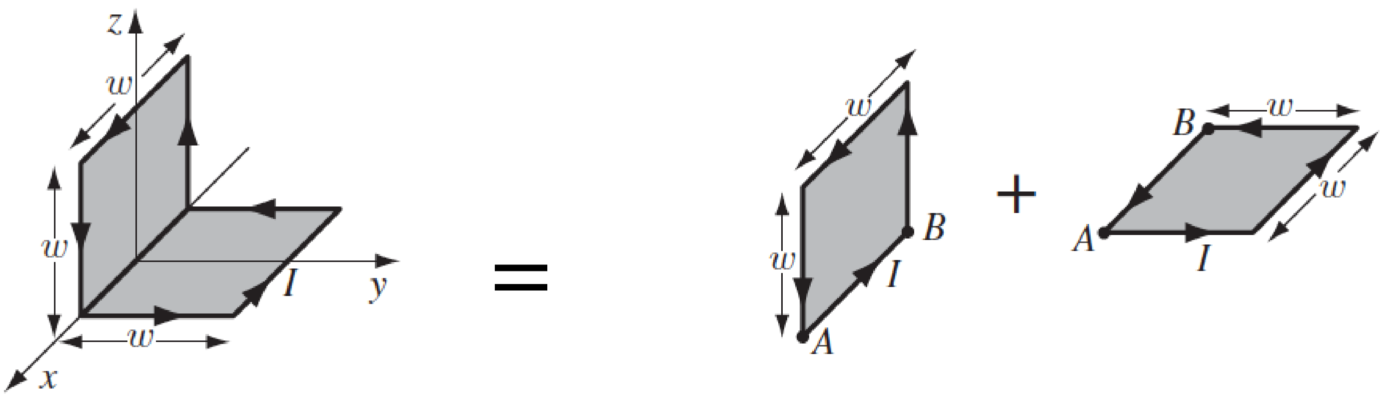


FIGURE 5.52

Extra side 'AB' cancel when two are put together as currents flow in opposite direction

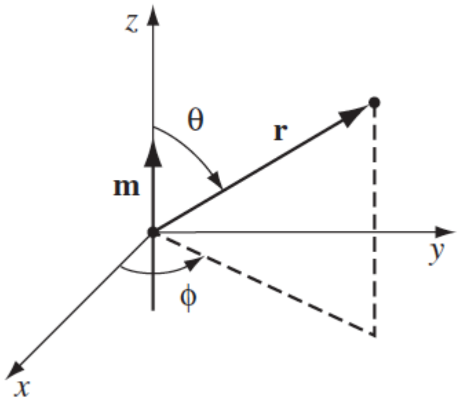
The net magnetic dipole moment, $\mathbf{m} = I w^2 \,\hat{\mathbf{y}} + I w^2 \,\hat{\mathbf{z}};$

Magnitude = $\sqrt{2} I w^2$, points along the line, $z = y$.

Multipole expansion of vector potential

Magnetic Field of a 'perfect' dipole :

'***m***' is at the origin and points in the z-direction



$$\mathbf{A}_{\text{dip}}(\mathbf{r}) = \frac{\mu_0}{4\pi}\frac{\mathbf{m}\times\hat{\mathbf{r}}}{r^2},$$

$$= \boxed{\frac{\mu_0}{4\pi}\frac{m\sin\theta}{r^2}\hat{\boldsymbol{\phi}},}$$

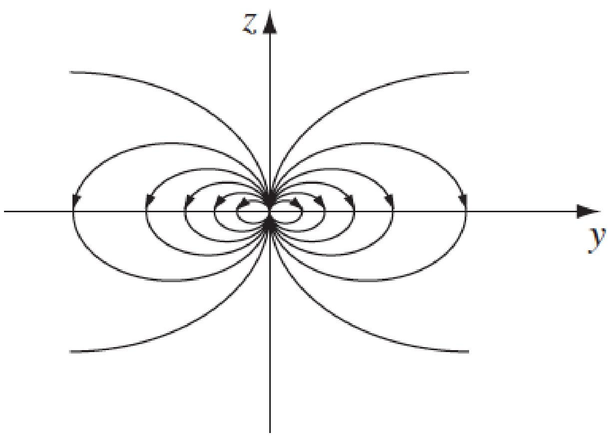
Potential @ ($\boldsymbol{r}$, $\boldsymbol{\theta}$, $\boldsymbol{\phi}$)

Hence, field

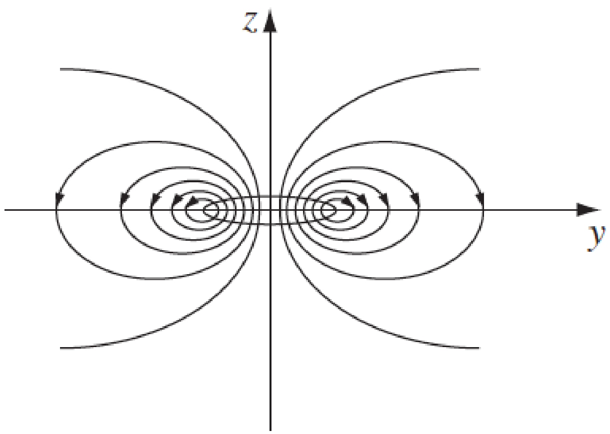
$$\mathbf{B}_{\text{dip}}(\mathbf{r}) = \nabla\times\mathbf{A} = \frac{\mu_0 m}{4\pi r^3}(2\cos\theta\,\hat{\mathbf{r}} + \sin\theta\,\hat{\boldsymbol{\theta}}).$$

Identical structure to the field of an *electric* dipole!

However,



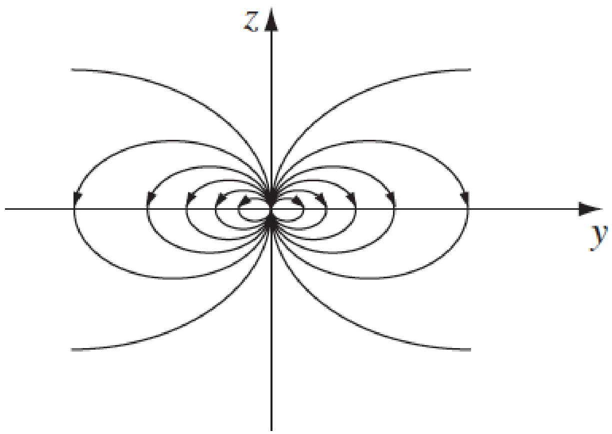
(a) Field of a "pure" dipole



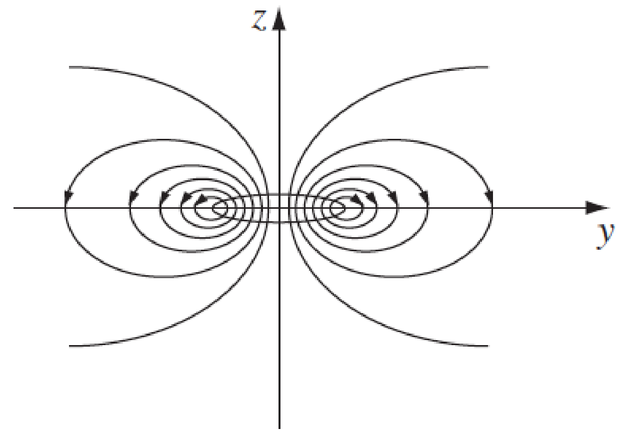
(b) Field of a "physical" dipole

Multipole expansion of vector potential

Magnetic Field of a 'perfect' dipole :



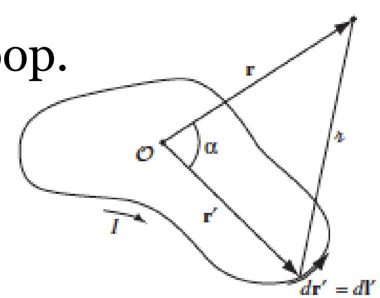
(a) Field of a "pure" dipole



(b) Field of a "physical" dipole

What about higher order terms?

Dipole moment is suitable approximation
whenever distance 'r' greatly exceeds size of the loop.



Multipole expansion of vector potential

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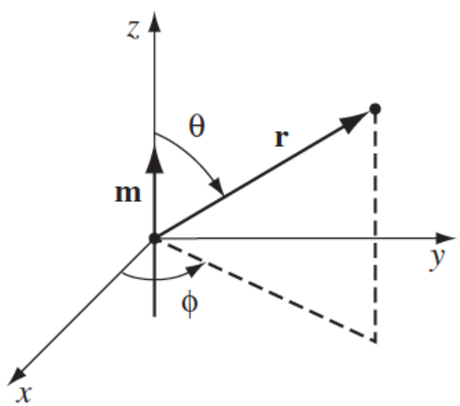
Problem 5.34 Show that the magnetic field of a dipole can be written in coordinate-free form:

$$\mathbf{B}_{\text{dip}}(\mathbf{r}) = \frac{\mu_0}{4\pi}\frac{1}{r^3}\left[3(\mathbf{m}\cdot\hat{\mathbf{r}})\hat{\mathbf{r}} - \mathbf{m}\right].$$



$$\vec{m} = m\cos\theta\hat{r} - m\sin\theta\hat{\theta}$$

$$3(\vec{m}\cdot\hat{r})\hat{r} - \vec{m} = 2m\cos\theta\hat{r} + m\sin\theta\hat{\theta}$$

$$\frac{\mu_0}{4\pi}\frac{1}{r^3}\left[3(\mathbf{m}\cdot\hat{\mathbf{r}})\hat{\mathbf{r}} - \mathbf{m}\right] = \frac{\mu_0 m}{4\pi r^3}(2\cos\theta\,\hat{\mathbf{r}} + \sin\theta\,\hat{\boldsymbol{\theta}})$$

We already found,

$$\mathbf{B}_{\text{dip}}(\mathbf{r}) = \nabla\times\mathbf{A} = \frac{\mu_0 m}{4\pi r^3}(2\cos\theta\,\hat{\mathbf{r}} + \sin\theta\,\hat{\boldsymbol{\theta}}).$$

Thus, $$\frac{\mu_0}{4\pi}\frac{1}{r^3}\left[3(\mathbf{m}\cdot\hat{\mathbf{r}})\hat{\mathbf{r}} - \mathbf{m}\right] = \mathbf{B}_{\text{dip}}(\mathbf{r})$$

Multipole expansion of vector potential

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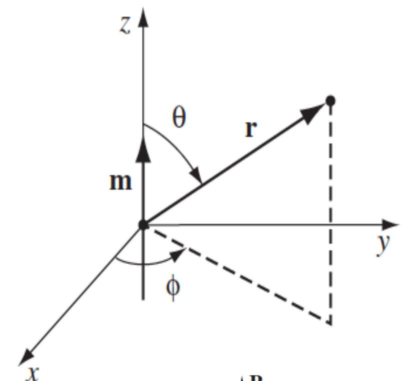
Problem 5.35 A circular loop of wire, with radius R, lies in the xy plane (centered at the origin) and carries a current I running counterclockwise as viewed from the positive z axis.

(a) What is its magnetic dipole moment?

(b) What is the (approximate) magnetic field at points far from the origin?

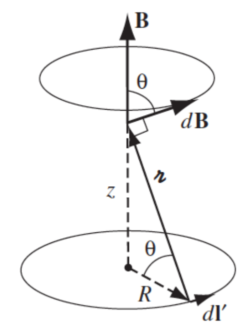
(c) Show that, for points on the z axis, your answer is consistent with the *exact* field (Ex. 5.6), when $z \gg R$.



(a) $\vec{m} = I\pi R^2 \hat{k}, \qquad \hat{k} = \left(\cos\theta\, \hat{r} - \sin\theta\, \hat{\theta}\right)$

(b) $\mathbf{B}_{\text{dip}}(\mathbf{r}) = \dfrac{\mu_0}{4\pi} \dfrac{1}{r^3} [3(\mathbf{m} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} - \mathbf{m}] = \dfrac{\mu_0 I \pi R^2}{4\pi r^3} \left(2\cos\theta\, \hat{r} + \sin\theta\, \hat{\theta}\right)$

(c) z axis, $r = z$; $\theta = 0, \pi$ and $\hat{\mathbf{r}} = \pm\hat{k}$. Thus, $\mathbf{B}_{\text{dip}}(\mathbf{r}) = \pm \dfrac{\mu_0 I R^2}{2z^3} \hat{\mathrm{k}}$.



The Biot-Savart Law :

Example 5.6, D J. G

Example 5.6. Find the magnetic field a distance z above the center of a circular loop of radius R, which carries a steady current I (Fig. 5.21).

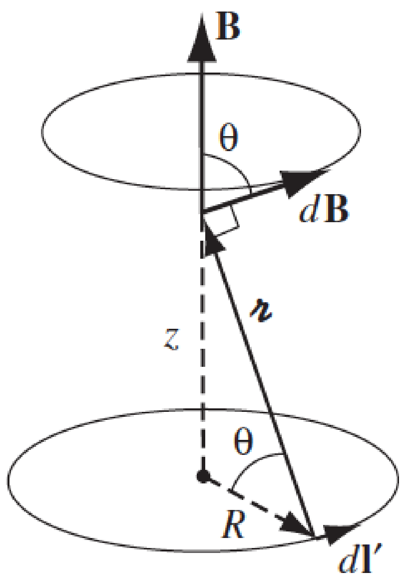


FIGURE 5.21

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} I \int \frac{d\mathbf{l}' \times \hat{\boldsymbol{\mathscr{r}}}}{\mathscr{r}^2}$$

$$\begin{aligned} B(z) &= \frac{\mu_0}{4\pi} I \int \frac{dl'}{\mathscr{r}^2} \cos\theta. \\ &= \frac{\mu_0 I}{4\pi} \left(\frac{\cos\theta}{\mathscr{r}^2} \right) \int dl' \\ &= \frac{\mu_0 I}{4\pi} \left(\frac{\cos\theta}{\mathscr{r}^2} \right) 2\pi R \\ &= \frac{\mu_0 I}{2} \frac{R^2}{(R^2 + z^2)^{3/2}}. \end{aligned}$$

Multipole expansion of vector potential

D.J.G, edition 4.

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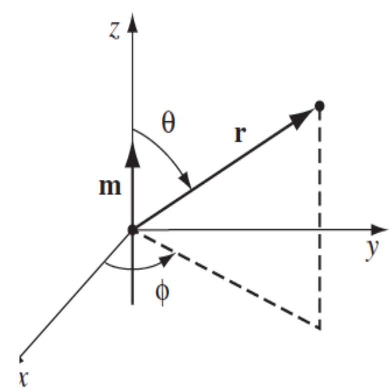


Solutions:

(a) $\vec{m} = I\pi R^2 \hat{k}, \qquad \hat{k} = \left(\cos\theta\,\hat{r} - \sin\theta\,\hat{\theta}\right)$

(b) $\mathbf{B}_{\text{dip}}(\mathbf{r}) = \dfrac{\mu_0}{4\pi}\dfrac{1}{r^3}\left[3(\mathbf{m}\cdot\hat{\mathbf{r}})\hat{\mathbf{r}} - \mathbf{m}\right] = \dfrac{\mu_0 I\pi R^2}{4\pi r^3}\left(2\cos\theta\,\hat{r} + \sin\theta\,\hat{\theta}\right)$

(c) z axis, $r = z$; $\theta = 0, \pi$ and $\hat{\mathbf{r}} = \pm\hat{k}$. Thus, $\mathbf{B}_{\text{dip}}(\mathbf{r}) = \pm\dfrac{\mu_0 I R^2}{2z^3}\hat{\text{k}}$.

From Ex. 5.6 Z >> R, $\vec{B}_{dip} \approx \dfrac{\mu_0 I R^2}{2|z|^3}\hat{\text{k}}$

Dipole term is reasonable approximation

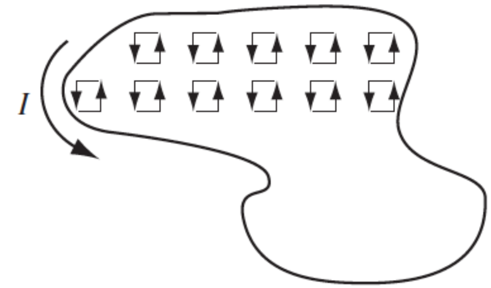
Torque and forces on magnetic dipole

Magnetic dipole experience torque in a magnetic field.

Rectangular current loop in a uniform field in the $\boldsymbol{z}$ direction.

Any current loop can be built from infinitesimal rectangles !

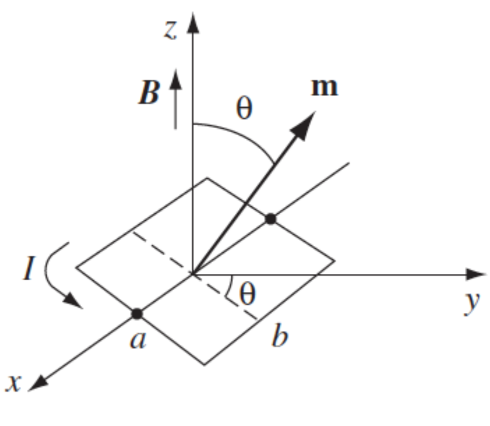
Loop is tilted at an angle θ from the $\boldsymbol{z}$ axis towards the y axis.



Forces on the slopping sides (a) cancels, they tend to stretch no torque

The net force on the loop is zero, as the forces on the 'horizontal sides' (b) are also equal.

However, the forces on 'horizontal sides' generate a torque!

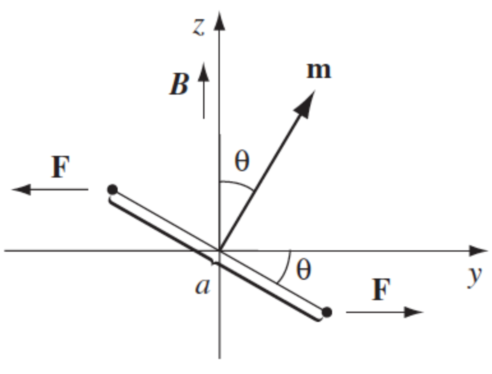


(a)

$$\mathbf{N} = aF\sin\theta\,\hat{\mathbf{x}}.$$

The force acting on the loops,

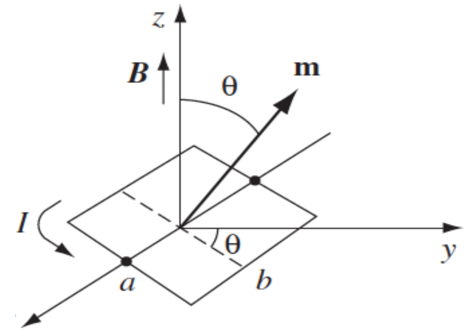
$$F = IbB,$$



(b)

Torque and forces on magnetic dipole

However, the forces on 'horizontal sides' generate a torque!



(a)

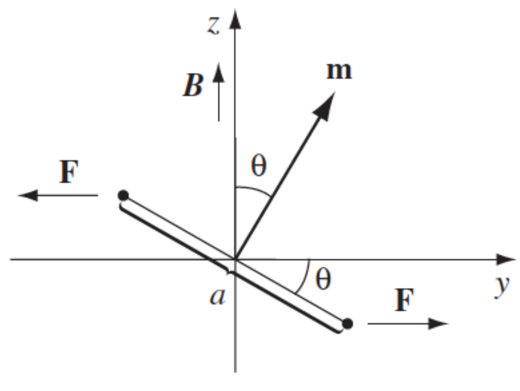
$$\mathbf{N} = aF\sin\theta\,\hat{\mathbf{x}}.$$

The force acting on the loops,

$$F = IbB,$$

Thus,

$$\mathbf{N} = IabB\sin\theta\,\hat{\mathbf{x}} = mB\sin\theta\,\hat{\mathbf{x}} = \mathbf{m}\times\mathbf{B},$$



(b)

Magnetic dipole moment of the loop

$$m = Iab$$

Note: In case of non uniform field the eq. gives the exact torque for a perfect dipole about the center.

Torque and forces on magnetic dipole

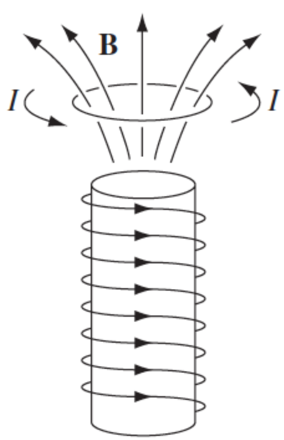
In the uniform field the net force on a current loop is zero!

$$\mathbf{F} = I \oint (d\mathbf{l} \times \mathbf{B}) = I \left(\oint d\mathbf{l} \right) \times \mathbf{B} = \mathbf{0};$$

B being constant comes outside integral and the net displacement around a closed loop also vanishes,

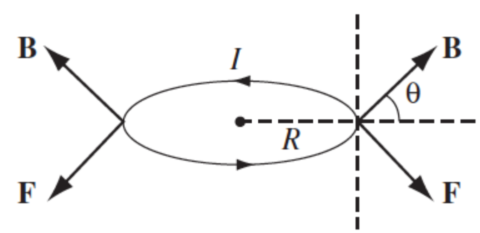
Not true for non uniform field,

Circular wire ($\boldsymbol{R}$) carrying current $\boldsymbol{I}$ is suspended over a short solenoid over the fringing region.



Here B has a radial component, hence net downward force on loop.

$$F = 2\pi I R B \cos\theta.$$



Torque and forces on magnetic dipole

For an infinitesimal loop, with dipole moment $\boldsymbol{m}$, in a magnetic field $\boldsymbol{B}$, the force is

$$\mathbf{F} = \nabla(\mathbf{m} \cdot \mathbf{B})$$

Problem 6.4 Derive Eq. 6.3. [Here's one way to do it: Assume the dipole is an infinitesimal square, of side ϵ (if it's not, chop it up into squares, and apply the argument to each one). Choose axes as shown in Fig. 6.8, and calculate $\mathbf{F} = I \int (d\mathbf{l} \times \mathbf{B})$ along each of the four sides. Expand $\mathbf{B}$ in a Taylor series—on the right side, for instance,

$$\mathbf{B} = \mathbf{B}(0, \epsilon, z) \cong \mathbf{B}(0, 0, z) + \epsilon \left.\frac{\partial \mathbf{B}}{\partial y}\right|_{(0,0,z)} .$$

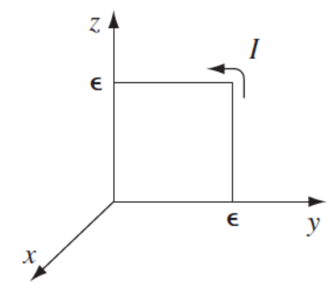


FIGURE 6.8

Force on the elemental square loop is,

$$d\vec{F} = I\left[(dy\hat{y}) \times \vec{B}(0,y,0) + (dz\hat{z}) \times \vec{B}(0,\epsilon,z) - (dy\hat{y}) \times \vec{B}(0,y,\epsilon) - (dz\hat{z}) \times \vec{B}(0,0,z)\right]$$

$$= I\left[-(dy\hat{y}) \times \{\vec{B}(0,y,\epsilon) - \vec{B}(0,y,0)\} + (dz\hat{z}) \times \{\vec{B}(0,\epsilon,z) - \vec{B}(0,0,z)\}\right]$$

Torque and forces on magnetic dipole

Force on the elemental square loop is,

$$d\vec{F} = I\Big[(dy\hat{y}) \times \vec{B}(0,y,0) + (dz\hat{z}) \times \vec{B}(0,\epsilon,z) - (dy\hat{y}) \times \vec{B}(0,y,\epsilon) - (dz\hat{z}) \times \vec{B}(0,0,z)\Big]$$

$$= I\Big[-(dy\hat{y}) \times \{\vec{B}(0,y,\epsilon) - \vec{B}(0,y,0)\} + (dz\hat{z}) \times \{\vec{B}(0,\epsilon,z) - \vec{B}(0,0,z)\}\Big]$$

Using, $\vec{B}(0,\epsilon,z) \approx \vec{B}(0,0,z) + \epsilon \frac{\partial \vec{B}}{\partial y}\Big|_{(0,0,z)}$, $\vec{B}(0,y,\epsilon) \approx \vec{B}(0,y,0) + \epsilon \frac{\partial \vec{B}}{\partial z}\Big|_{(0,y,0)}$

and $\boxed{\int dy \frac{\partial \vec{B}}{\partial z}\Big|_{(0,y,0)} \approx \epsilon \frac{\partial \vec{B}}{\partial z}\Big|_{(0,0,0)}, \int dz \frac{\partial \vec{B}}{\partial y}\Big|_{(0,0,z)} \approx \epsilon \frac{\partial \vec{B}}{\partial y}\Big|_{(0,0,0)}}$

The total force,

$$\vec{F} = \int d\vec{F} = I\epsilon^2\left[\hat{z} \times \frac{\partial \vec{B}}{\partial y} - \hat{y} \times \frac{\partial \vec{B}}{\partial z}\right]$$

$$= I\epsilon^2\left[\hat{y}\frac{\partial B_x}{\partial y} - \hat{x}\frac{\partial B_y}{\partial y} - \hat{x}\frac{\partial B_z}{\partial z} + \hat{z}\frac{\partial B_x}{\partial z}\right]$$

$$\vec{\nabla} \cdot \vec{B} = \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0 \implies \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = -\frac{\partial B_x}{\partial x}$$

$$\vec{F} = m\left[\hat{y}\frac{\partial B_x}{\partial y} + \hat{x}\frac{\partial B_x}{\partial x} + \hat{z}\frac{\partial B_x}{\partial z}\right]$$

$$\vec{m} = m\hat{x} = I\epsilon^2\hat{x}$$

$$\implies \vec{F} = \vec{\nabla}(\vec{m} \cdot \vec{B})$$

Torque and forces on magnetic dipole

Torque on a general current loop :

$$d\overline{F} = I d\overline{l} \times \overline{B}, \quad \overline{T} = I \oint \overline{r} \times (d\overline{l} \times \overline{B})$$

$$\overline{A} \times (\overline{B} \times \overline{C}) \equiv (\overline{A} \cdot \overline{C})\overline{B} - (\overline{A} \cdot \overline{B})\overline{C}.$$

Constant magnetic field : ***B*** out of the integral

zero

$$\overline{T} = I \oint (\overline{r} \cdot \overline{B}) d\overline{l} - I \oint (\overline{r} \cdot d\overline{l}) \overline{B}$$

$$\oint \nabla u \cdot d\overline{l} \equiv \oint du \equiv 0 \qquad \overline{r} = \tfrac{1}{2}\nabla(r^2)$$

$$\oint f d\overline{l} \equiv -\iint \nabla(f) \times d\overline{S}.$$

$$\overline{T} = -I \iint \nabla(\overline{r} \cdot \overline{B}) \times d\overline{S}.$$

$$\nabla(\overline{r} \cdot \overline{B}) = \overline{B}$$

Constant magnetic field : ***B***

$$\overline{T} = -I \iint \overline{B} \times d\overline{S} = I \left(\iint d\overline{S} \right) \times \overline{B}$$

$$\overline{m} = I \iint d\overline{S}.$$

$$\overline{T} = \overline{m} \times \overline{B}.$$

Magnetisation

- **Magnetisation**: Net alignment of magnetic dipoles inside a **medium**, in the presence of an **applied magnetic field**.

  - Magnetisation: parallel (paramagnet, Al) or opposite (diamagnets, Cu) to the applied magnetic field. ($\boldsymbol{P} = \varepsilon_0 \chi_e \boldsymbol{E}$, $\chi_e > 0$ ➔ Same as $\boldsymbol{E}$)

- Ferromagnets (Fe, Ni)**:** Magnetisation retained even after removal of magnetic field.

$\mathbf{N} = \mathbf{m} \times \mathbf{B}$, Torque is in a direction that the line of dipole is parallel to the field and responsible for paramagnetism (odd no of electrons).

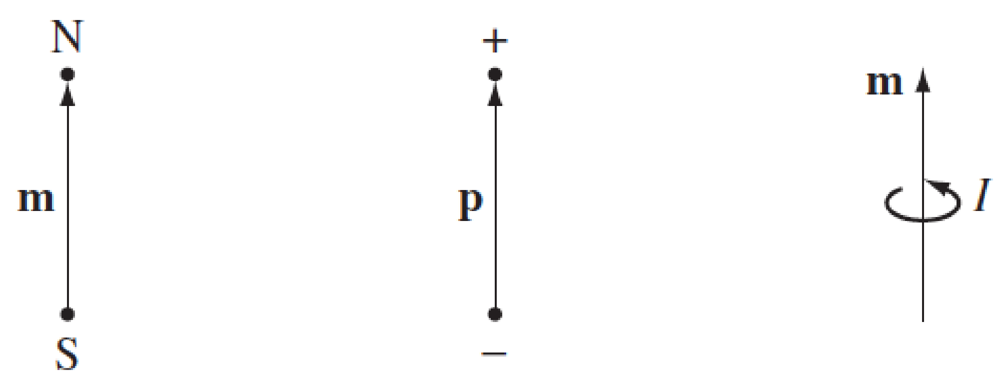
Atomic Electrons revolve around the nucleus : Effective magnetic dipole.

Even electrons neutralises the torque on the combination.

Magnetisation

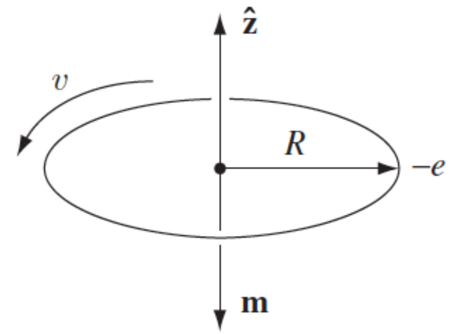
- No separated magnetic monopoles but tiny current loops!

- Magnetisation is not due to monopoles rather due to tiny current loops.



(a) Magnetic dipole (Gilbert model) (b) Electric dipole (c) Magnetic dipole (Ampère model)

Magnetic fields and Atomic Orbits



Current due to orbital motion: $I = \frac{-e}{T} = -\frac{ev}{2\pi R}.$

Is it a steady current? Time period is too small , $T = 2\pi R/v$.

-ve sign for electron.

The orbital dipole moment is, $\mathbf{m} = I\pi R^2 = -\frac{1}{2}evR\,\hat{\mathbf{z}}.$

In magnetic field, acting torque = $\mathbf{m} \times \mathbf{B}$, tries to tilt the dipole.

Difficult to tilt the entire orbit!

However,
orientation of the magnetic field can speed up or slow down the electron motion.

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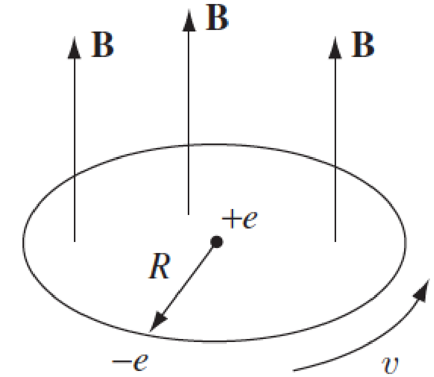

For magnetic fields perpendicular to the orbital plane,

$$\frac{1}{4\pi\epsilon_0}\frac{e^2}{R^2} + e\bar{v}B = m_e\frac{\bar{v}^2}{R}.$$

In absence of magnetic fields,

$$\frac{1}{4\pi\epsilon_0}\frac{e^2}{R^2} = m_e\frac{v^2}{R},$$

The new speed is greater than the zero magnetic field (B = 0) case,

$$e\bar{v}B = \frac{m_e}{R}(\bar{v}^2 - v^2) = \frac{m_e}{R}(\bar{v}+v)(\bar{v}-v),$$

For small change $\Delta v = \bar{v} - v$,

$$\Delta v = \frac{eRB}{2m_e}.$$

[$\bar{v} + v = 2\bar{v} - \Delta v,$
$(\Delta v)^2 \approx 0$]

B turned on and electrons speed up!

Change in orbital speed (i.e., change in current) results in change in dipole moment,

$$\Delta \mathbf{m} = -\frac{1}{2} e(\Delta v) R\, \hat{\mathbf{z}} = -\frac{e^2 R^2}{4m_e} \mathbf{B}.$$

Note: Change in dipole moment is opposite to the magnetic field direction.

However, random orientations of electron orbits cancels the orbital dipole moments.

Presence of magnetic field leads to net dipole moment (antiparallel B): Diamagnetism.

Diamagnetism:

- Universal but weaker than Paramagnetism.
- Observed in atoms with even number of electrons (no Paramagnetism)

Paramagnetism vs Diamagnetism

• Easier to tilt the spin than the entire orbit: orbital contribution
to paramagnetism is small!

• Paramagnetism: Unpaired electrons, spin dipoles experience a torque trying to align them parallel to the field.

• Diamagnetism: Orbital speed of the electrons is changed, such that the change in orbital dipole moment opposes the direction of the applied field.

Magnetisation (M): magnetic dipole moment per unit volume

(analogous to Polarisation)

- Paramagnetic: magnetisation upward hence the force is downward.
- Diamagnetic: The magnetisation (force) is downward (upward).
- Paramagnet is attracted into the field but diamagnet is repelled.
- The actual force is much smaller (4-5 order of magnitudes) than an iron sample of similar size