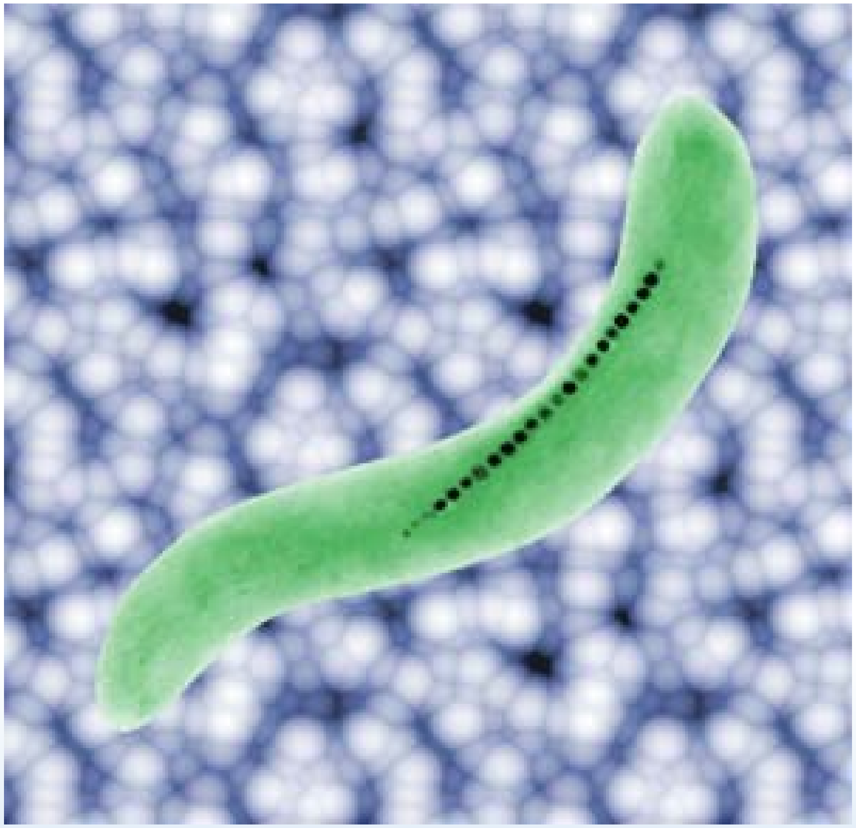


Phys 102 – Lecture 11

Magnetic dipoles & current loops

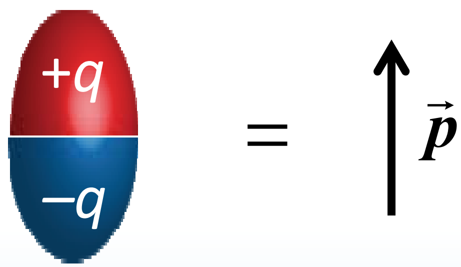
Today we will...

- Learn how magnetic fields act on
  - Magnetic dipoles
  - Current loops
- Apply these concepts!
  - Magnetotactic bacteria
  - Principles behind NMR/MRI, EPR/ESR
  - Magnetic materials (paramagnets and ferromagnets)

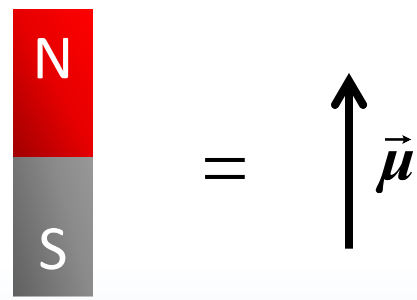
Magnetic dipole & dipole moment

A magnetic N and S pole make up a *magnetic dipole*

Recall: electric dipole



Magnetic dipole



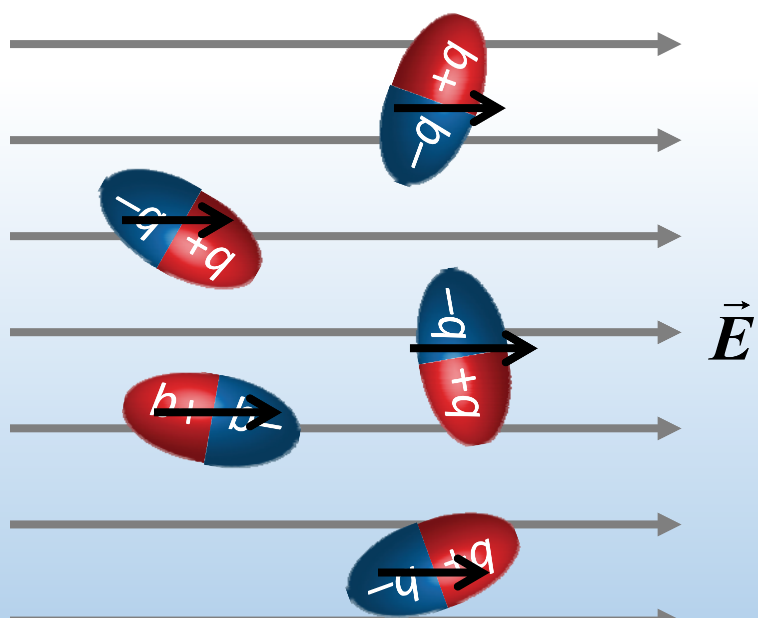
Magnetic dipole moment is analogous to electric dipole moment

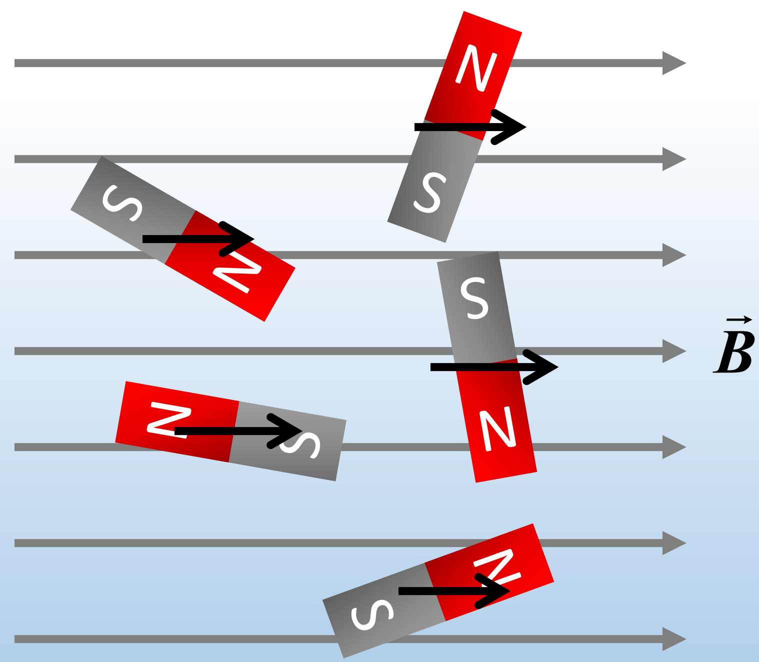
Direction: Vector from S to N pole (by convention)

Dipole in uniform field

Electric & magnetic dipole moments align parallel to field

Torque:	$\tau = pE\sin\theta$	Lect. 3	$\tau = \mu B\sin\theta$
Energy:	$U_{dip} = -pE\cos\theta$	Lect. 4	$U_{dip} = -\mu B\cos\theta$

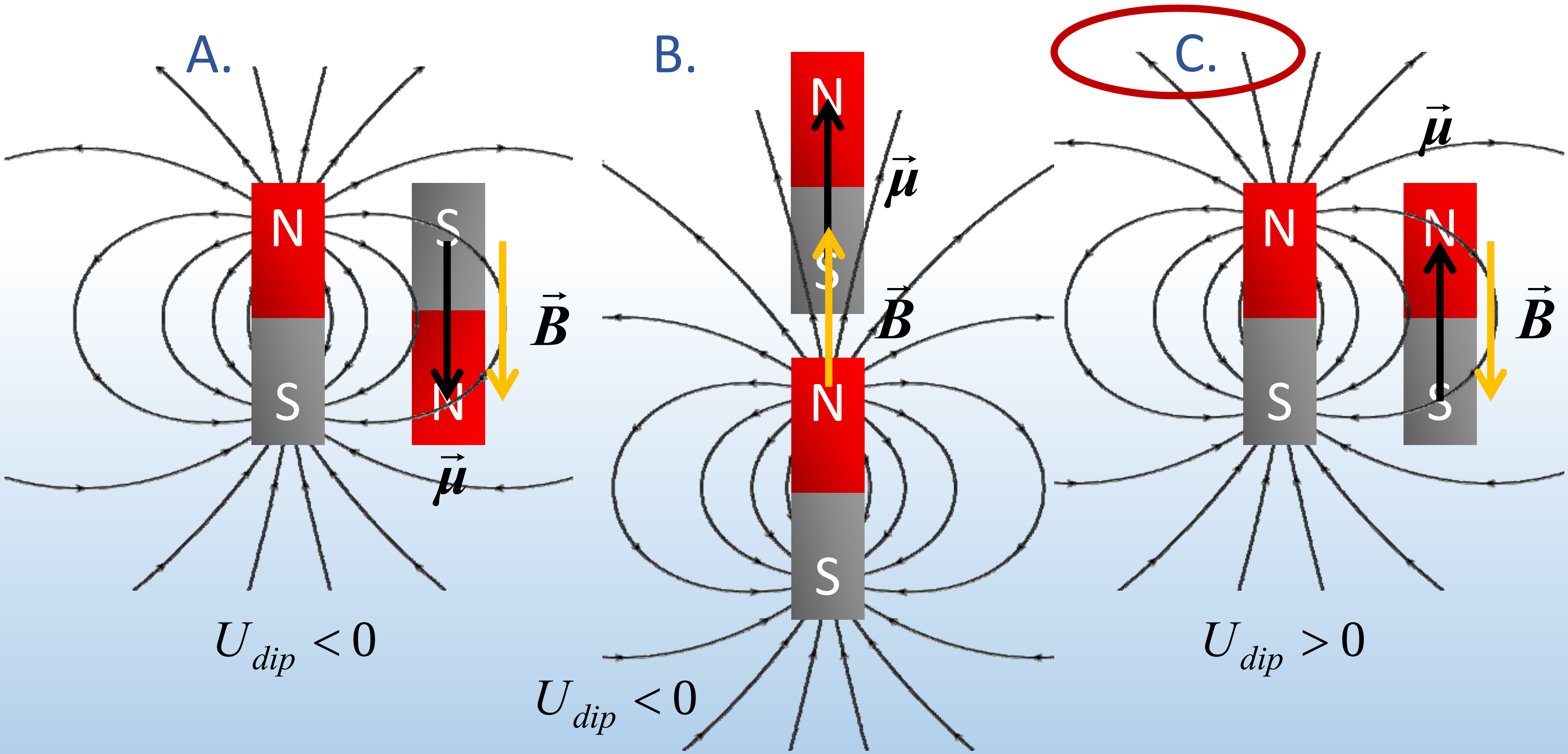




DEMO

ACT: CheckPoint 1.1

Which of the three configurations of magnetic dipoles show below has the highest potential energy?



A. $U_{dip} < 0$

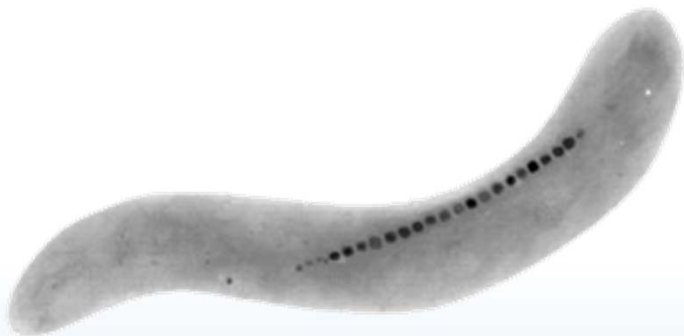
B. $U_{dip} < 0$

C. $U_{dip} > 0$

$$U_{dip} = -\mu B \cos\theta$$

Calculation: magnetic bacteria

Magnetotactic bacteria grow a chain of magnets to align to the Earth's *B* field



Magnetospirillum magnetotacticum

Room temperature kinetic energy tends to randomizes orientation

$$K_{dip.} = 4\times10^{-21} J$$

$K_{dip.} + U_{dip.} \geq 0$ Dipoles are randomized

$K_{dip.} + U_{dip.} < 0$ Dipoles tend to be aligned

Find minimum value of μ such that cells align to the Earth's field

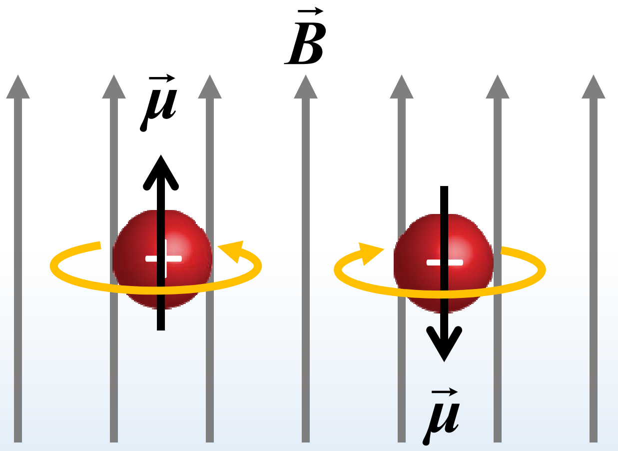
$$U_{dip.} = -\mu B_{earth} \qquad \mu = \frac{K_{dip.}}{B_{earth}} = \frac{4\times10^{-21}}{5\times10^{-5}} = 8\times10^{-17}\ \text{J/T}$$

$$\mu_{actual} = 2-8\times10^{-16}\ \text{J/T}$$

Cells make just enough magnets to align to Earth's field

Spin & magnetic fields

Electrons, protons, & neutrons (and many others) have an intrinsic property called "*spin*" which gives them a *magnetic dipole moment*



$U_{dip} = -\mu_{prot} B \quad U_{dip} = +\mu_{prot} B$

Nuclear magnetic resonance (NMR) / *magnetic resonance imaging* (MRI)

Detects energy difference between nuclear spins (ex: ^{1}H) parallel and anti-parallel to *B* field

$$\mu_{prot} = 1.4 \times 10^{-26}\ \mathrm{J/T}$$

Electron paramagnetic resonance (EPR) / *electron spin resonance* (ESR) applies same principle with electron spin

$$\mu_{elec} = 9.3 \times 10^{-24}\ \mathrm{J/T}$$

Note big difference in dipole moment!
EPR/ESR require smaller *B* field than NMR/MRI

We'll revisit this in Lect. 25

Magnetic force on current

Recall: *B* field exerts a force on a *moving* charge *q*

Current *I* is flow of + charge

Magnitude

$$\boxed{F = |q| vB \sin\theta} = ILB\sin\theta$$

Current

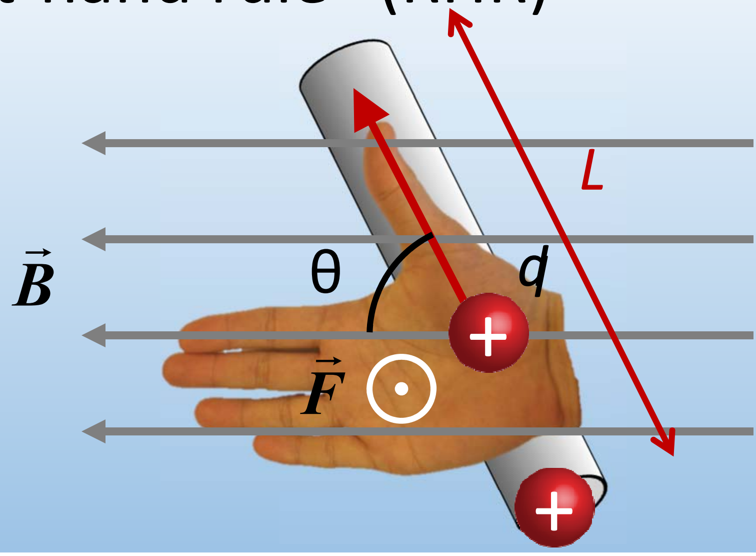
Length of wire

B field strength

Angle between *I* and *B*

Direction

"Right-hand rule" (RHR)



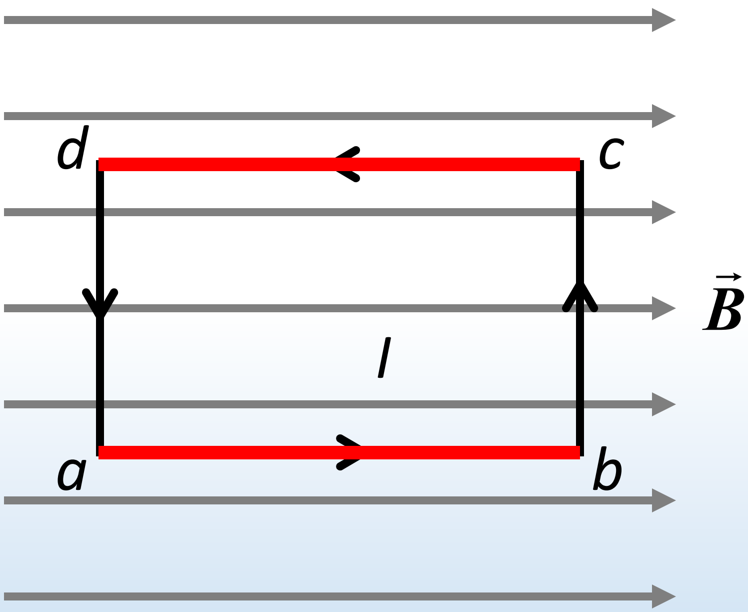
Thumb along *I*

Fingers along $\vec{B}$

$\vec{F}$ on *I* is *out of palm*

CheckPoint 2.1

A rectangular loop of wire is carrying current *I* as shown. There is a uniform magnetic field parallel to the sides *a–b* and *c–d*.



$F = ILB\sin\theta$

θ = 0, so $F_{a-b} = 0$

θ = 180°, so $F_{c-d} = 0$

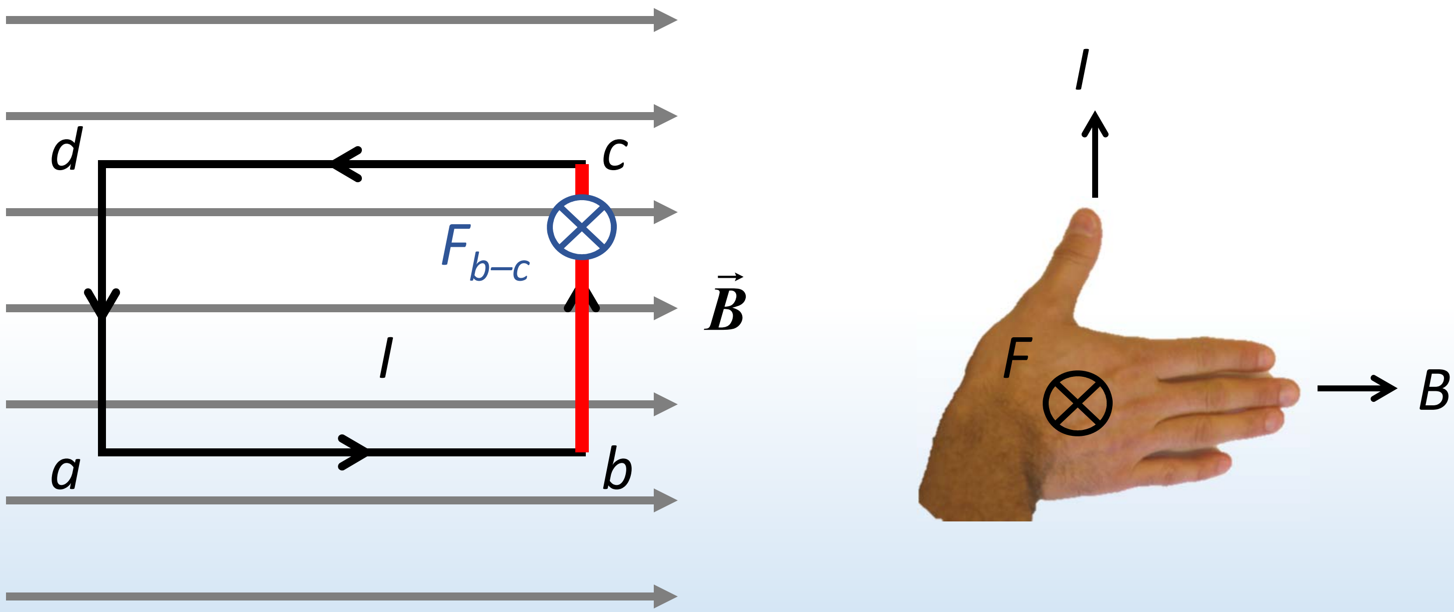
What is the direction of the force on section *a–b* of the wire?

A. force is zero
B. out of the page
C. into the page

...on section *c–d* of the wire?

ACT: CheckPoint 2.2

A rectangular loop of wire is carrying current *I* as shown. There is a uniform magnetic field parallel to the sides *a*–*b* and *c*–*d*.

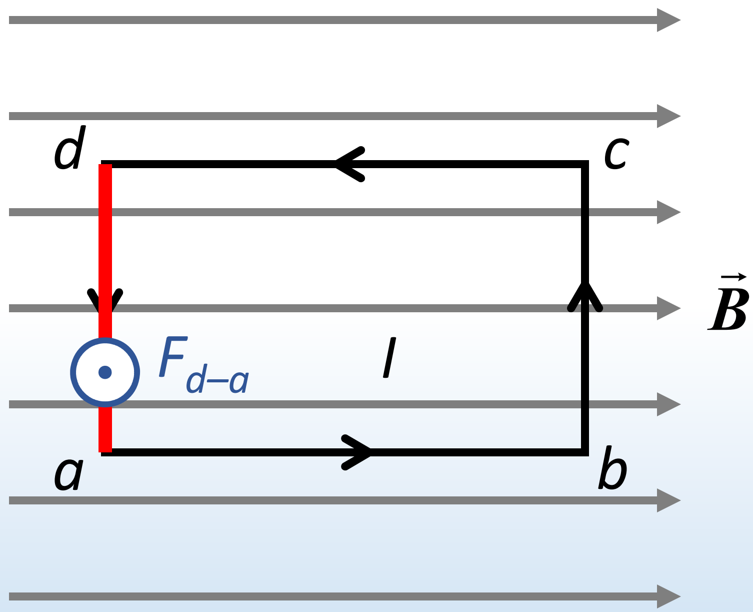


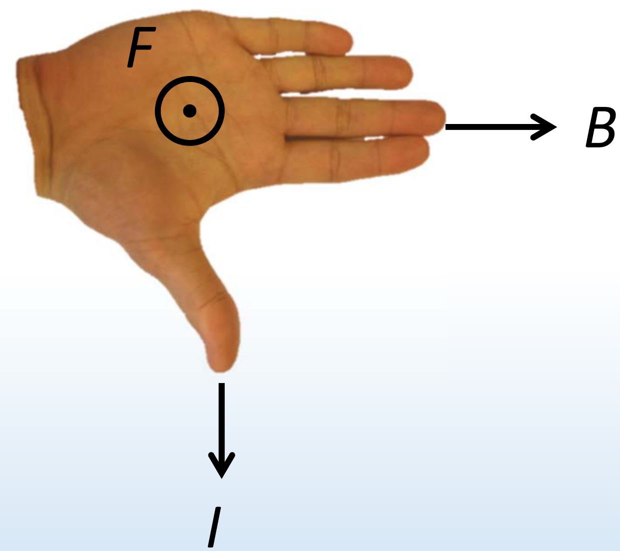
What is the direction of the force on section *b*–*c* of the wire?

A. force is zero
B. out of the page
C. into the page

ACT: Force on loop

A rectangular loop of wire is carrying current *I* as shown. There is a uniform magnetic field parallel to the sides *a*–*b* and *c*–*d*.



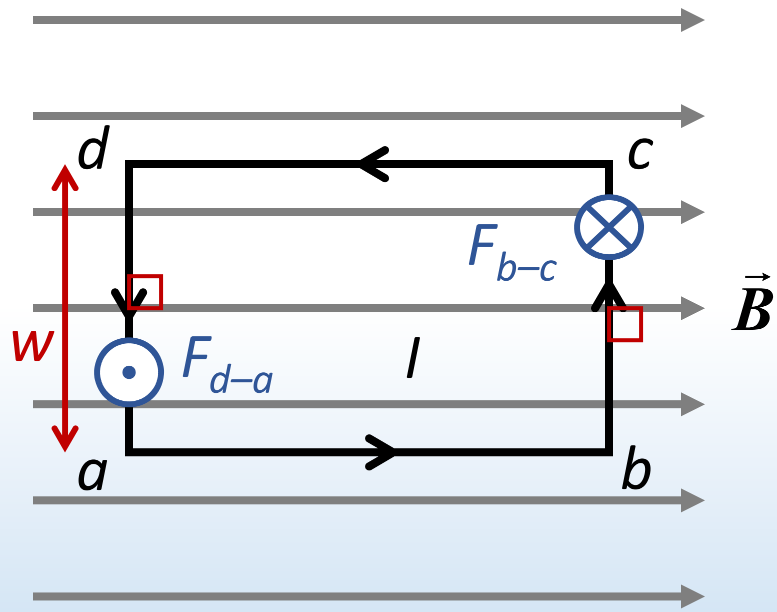


What is the direction of the force on section *d*–*a* of the wire?

A. force is zero
B. out of the page
C. into the page

CheckPoints 2.3 & 2.4

So, does the loop move?



Compare magnitudes of forces:

$$F_{b-c} = F_{d-a} = IBw\sin\theta$$

θ = 90°

Net force is 0, so the loop does not *translate*

$$\vec{F}_{loop} = 0$$

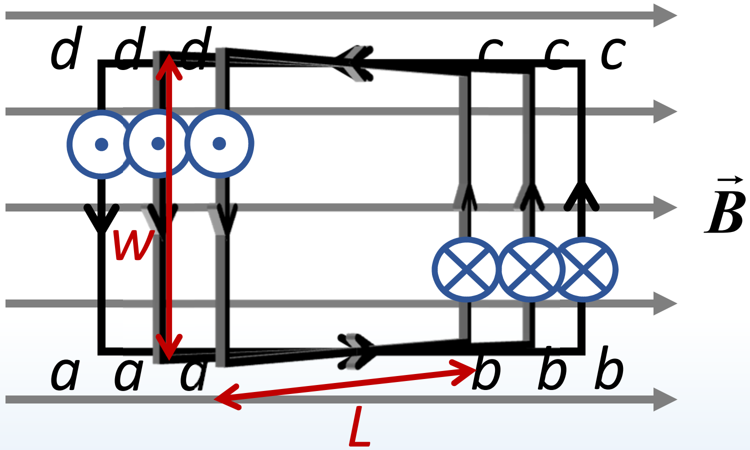
However, there is a net non-zero *torque* on the loop!

Loop *rotates* $\vec{\tau}_{loop} \neq 0$

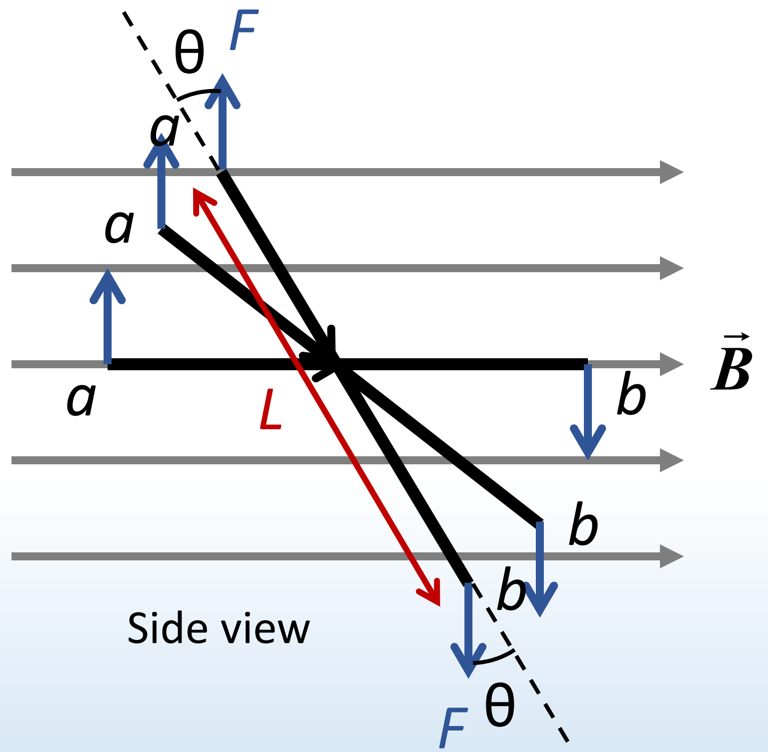
DEMO

Torque on current loop

Loop spins in *B* field



Top view



Side view

B field generates a torque on the loop

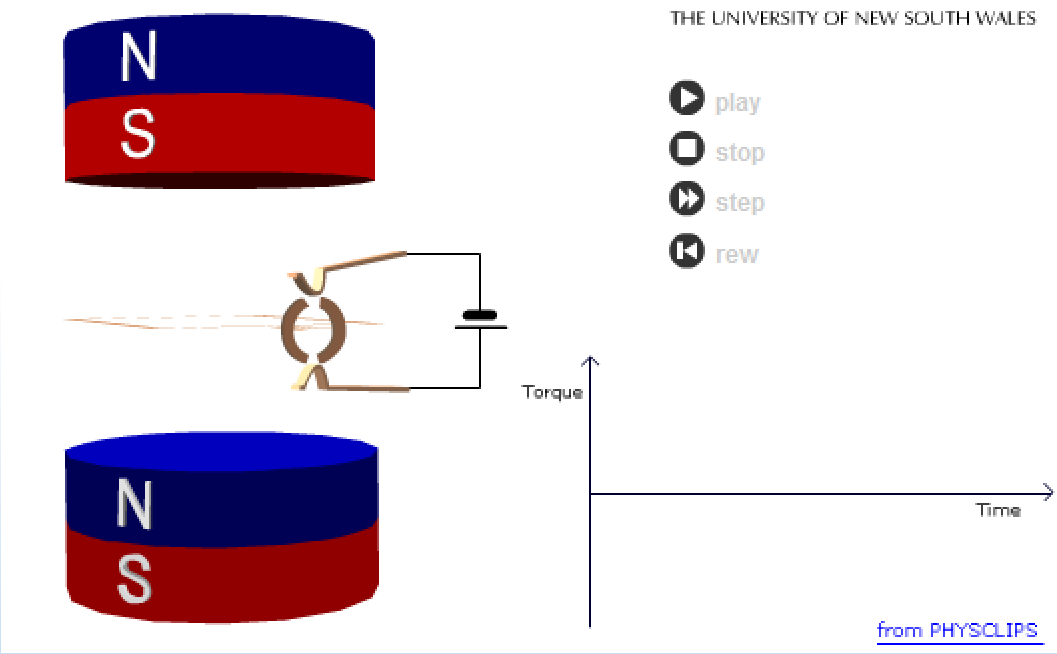
$$\tau_{loop} = 2F\frac{L}{2}\sin\theta = IBwL\sin\theta$$

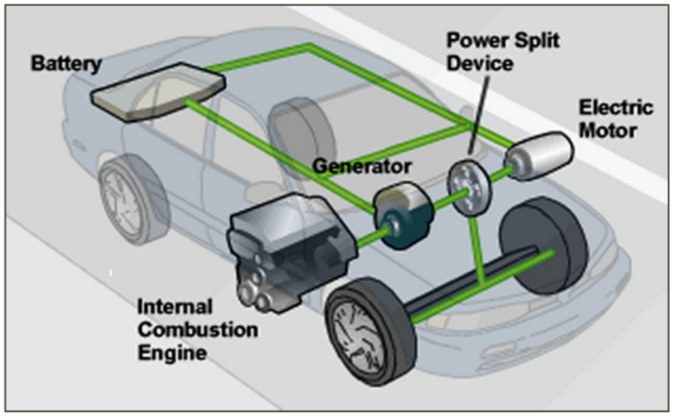
Loop area

$$\boxed{\tau_{loop} = IAB\sin\theta}$$

Electric motors

DC motors use a clever arrangement of current carrying coils and permanent magnets to turn a shaft:

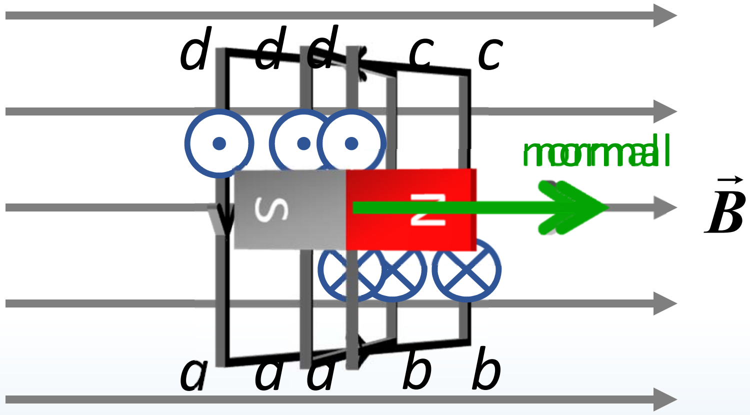




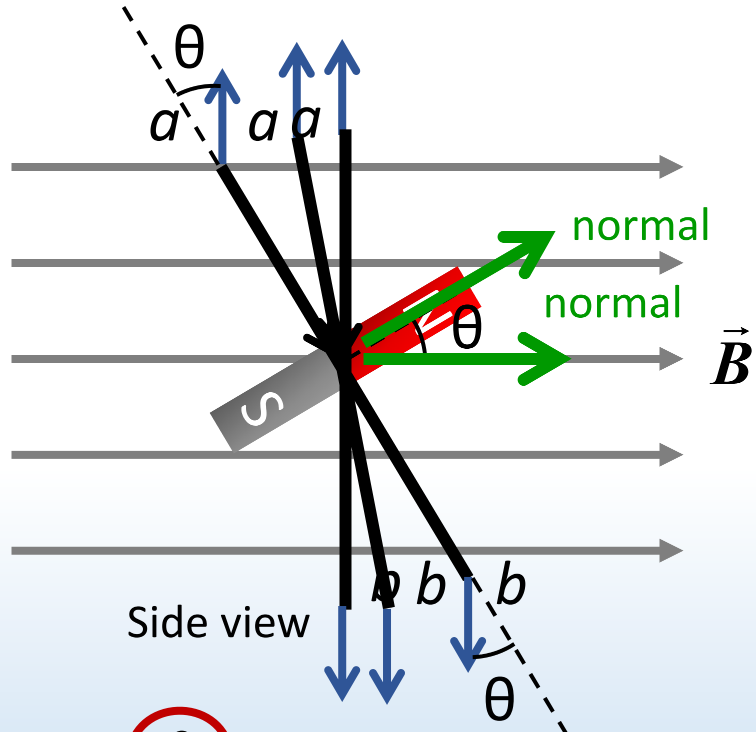
DEMO

Current loop & magnetic dipole

B field exerts torque on loop



Top view



Side view

$$\tau_{loop} = IAB\sin\theta = \mu B\sin\theta$$

Same angle

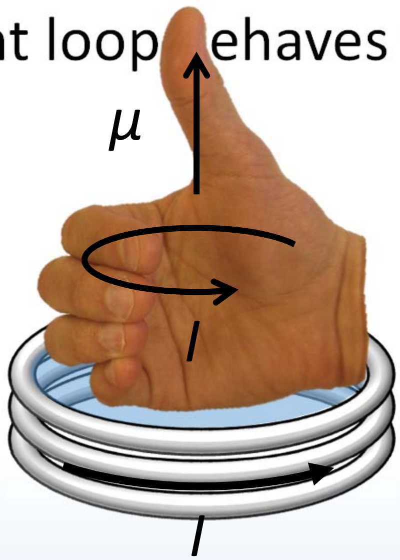
Current loop behaves the same as magnetic dipole ⊥ to loop plane

Convenient to define a *normal vector* ⊥ to loop plane, || to dipole moment

Torque aligns *normal vector* || to *B* field

Magnetic dipole & current loop

A current loop behaves the same as a *magnetic dipole*



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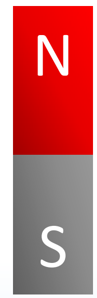

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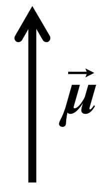


Equivalent *<u>magnetic dipole moment</u>*:

Magnitude

$$\mu = NIA$$

True for *flat* loop of *any* shape

For a loop with *N* turns of wire

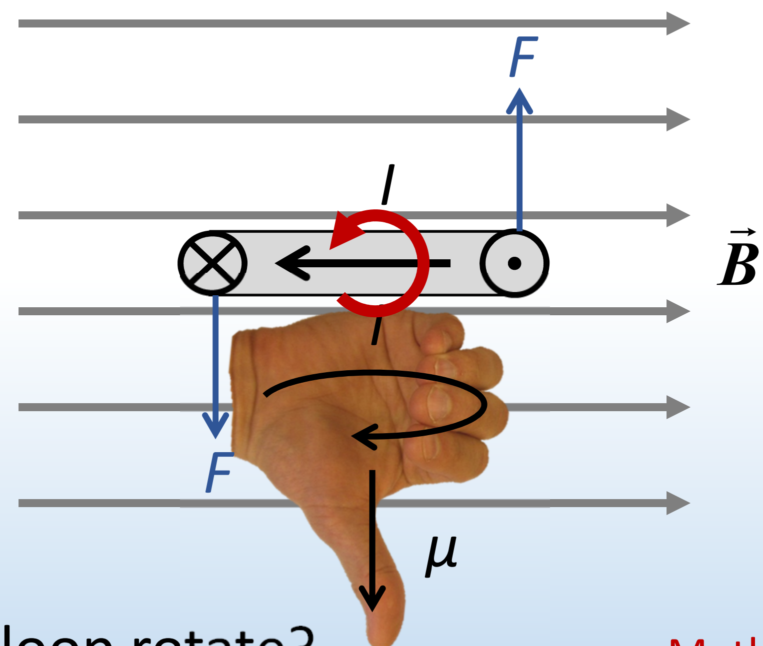
Direction

Another “right hand rule”: Curl fingers along *I*

$\vec{\mu}$ along thumb

ACT: *Current loop practice*

A loop is placed in a uniform *B* field. A current *I* flows around the loop as shown.



Which way does loop rotate?

A. Clockwise
B. Counterclockwise
C. The loop does not rotate

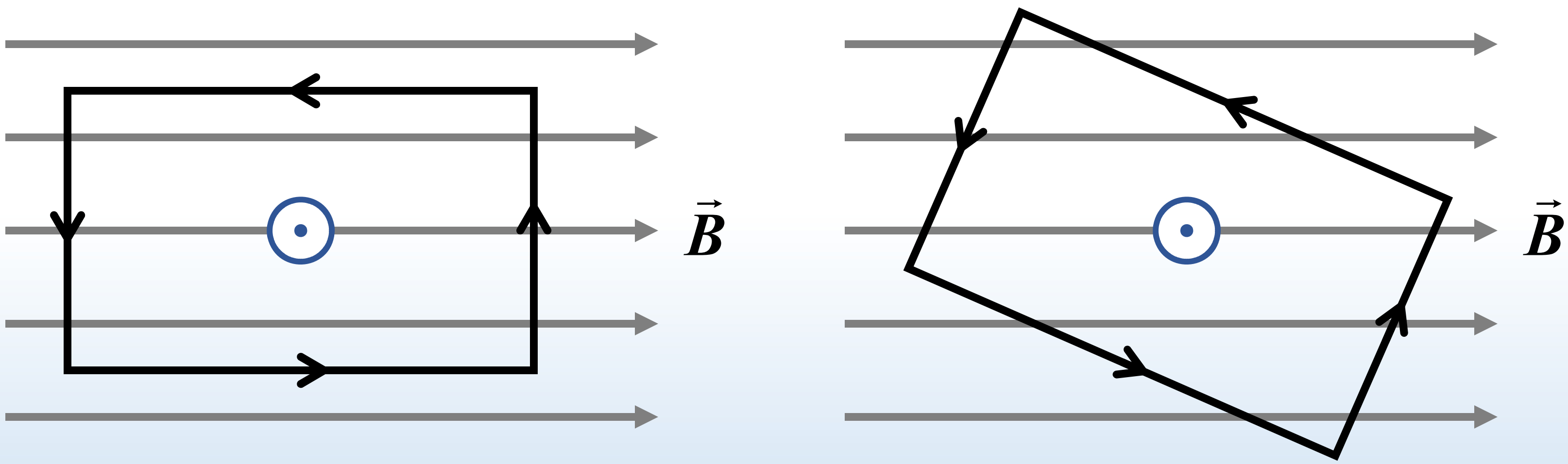
Method 1: determine torque

Method 2: determine moment

Same answer!

ACT: Torque on a loop

Compare the torque on loop 1 and 2, which have identical area *A*, and current *I*.



A. $\tau_1 > \tau_2$

B. $\tau_1 = \tau_2$

C. $\tau_1 < \tau_2$

$$\tau = IAB\sin\theta$$

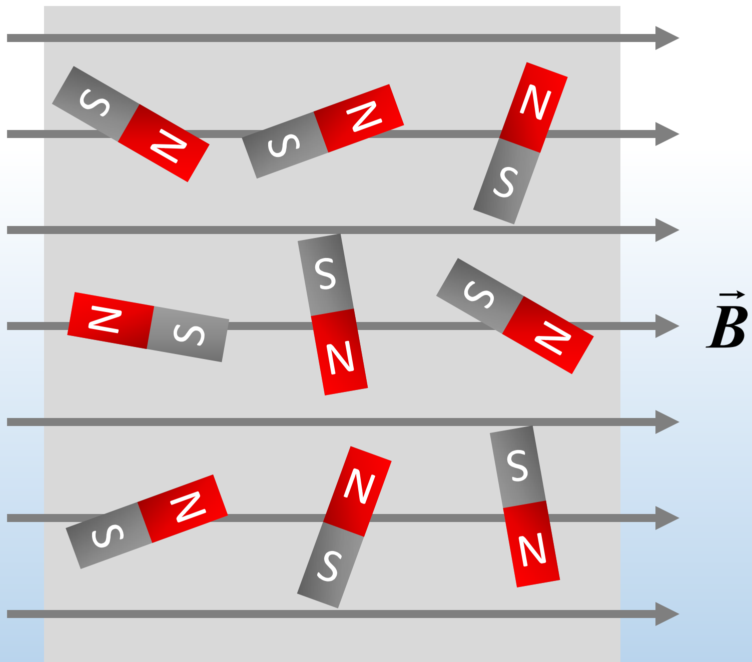
I, *A*, *B* are the same

Normal vectors or equivalent dipole moment & θ are the same

Para- & ferromagnetism

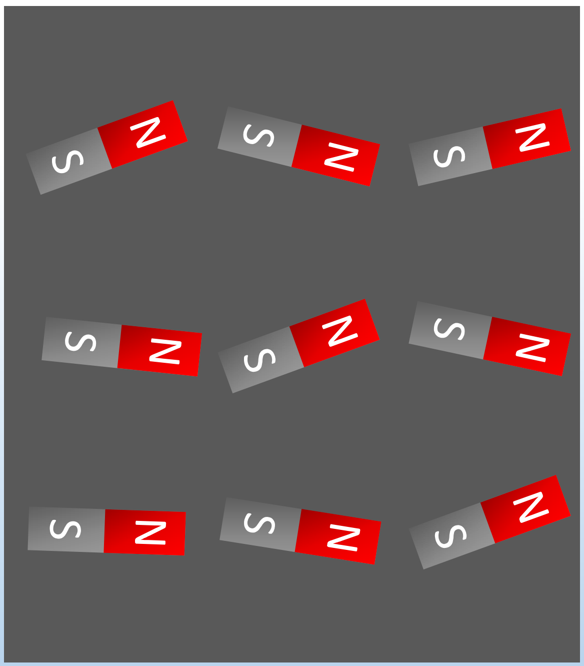
In some materials, unpaired electron (spin & orbit) give atoms net magnetic moment

In *paramagnets*, atomic dipoles are randomly oriented



Apply a *B* field and dipoles align!
Material now behaves as a magnet

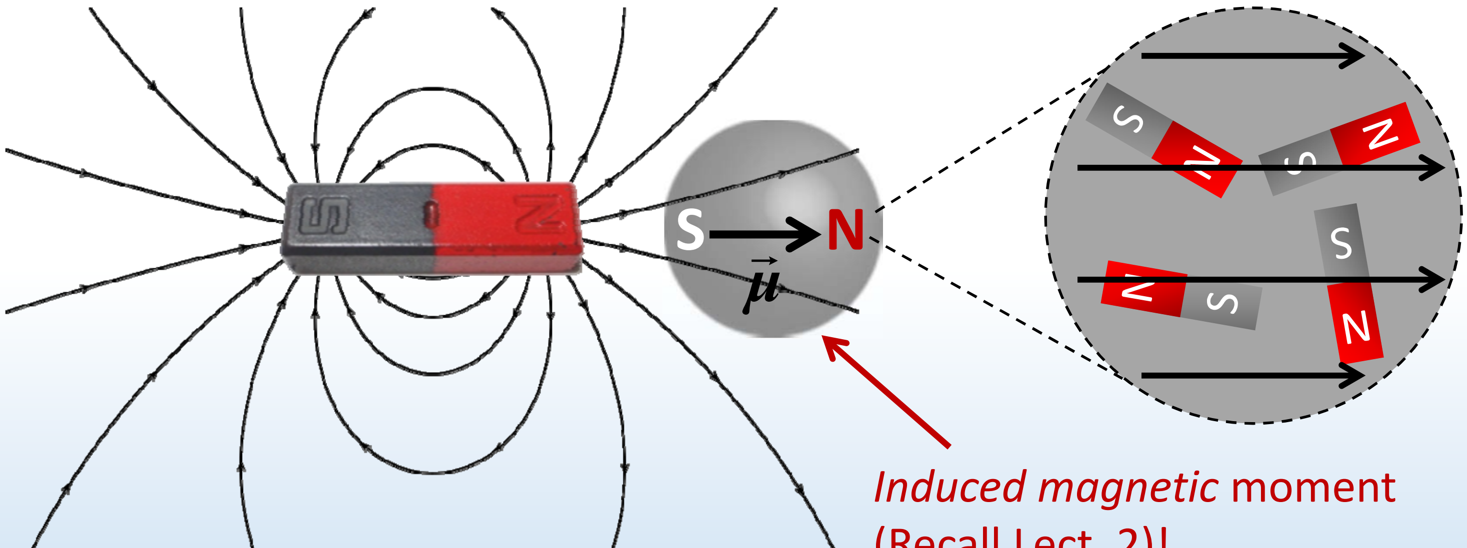
In *ferromagnets*, atomic dipoles interact and align together



Material is a permanent magnet

ACT: Magnetic materials

The N pole of a permanent magnet is brought near a *paramagnetic* ball bearing. What happens next?



Induced magnetic moment (Recall Lect. 2)!

A. The ball moves toward the magnet
B. The ball moves away from the magnet
C. The ball does not move

DEMO

Summary of today's lecture

- *B* fields exert torque on magnetic dipoles

$$\tau_{dip} = \mu B \sin\theta \quad U_{dip} = -\mu B \cos\theta$$

- *B* fields exert force on current-carrying wire

$$F_{wire} = ILB \sin\theta$$

- Current loops are equivalent to magnetic dipole

$$\mu = NIA$$