Essential Physics II

英語で物理学の

エッセンス II

Lecture 8:   16-12-15

News

Schedule change:

~~Monday 7th December (１２月７日)~~ NO CLASS!

Thursday 26th November (１１月２６日)

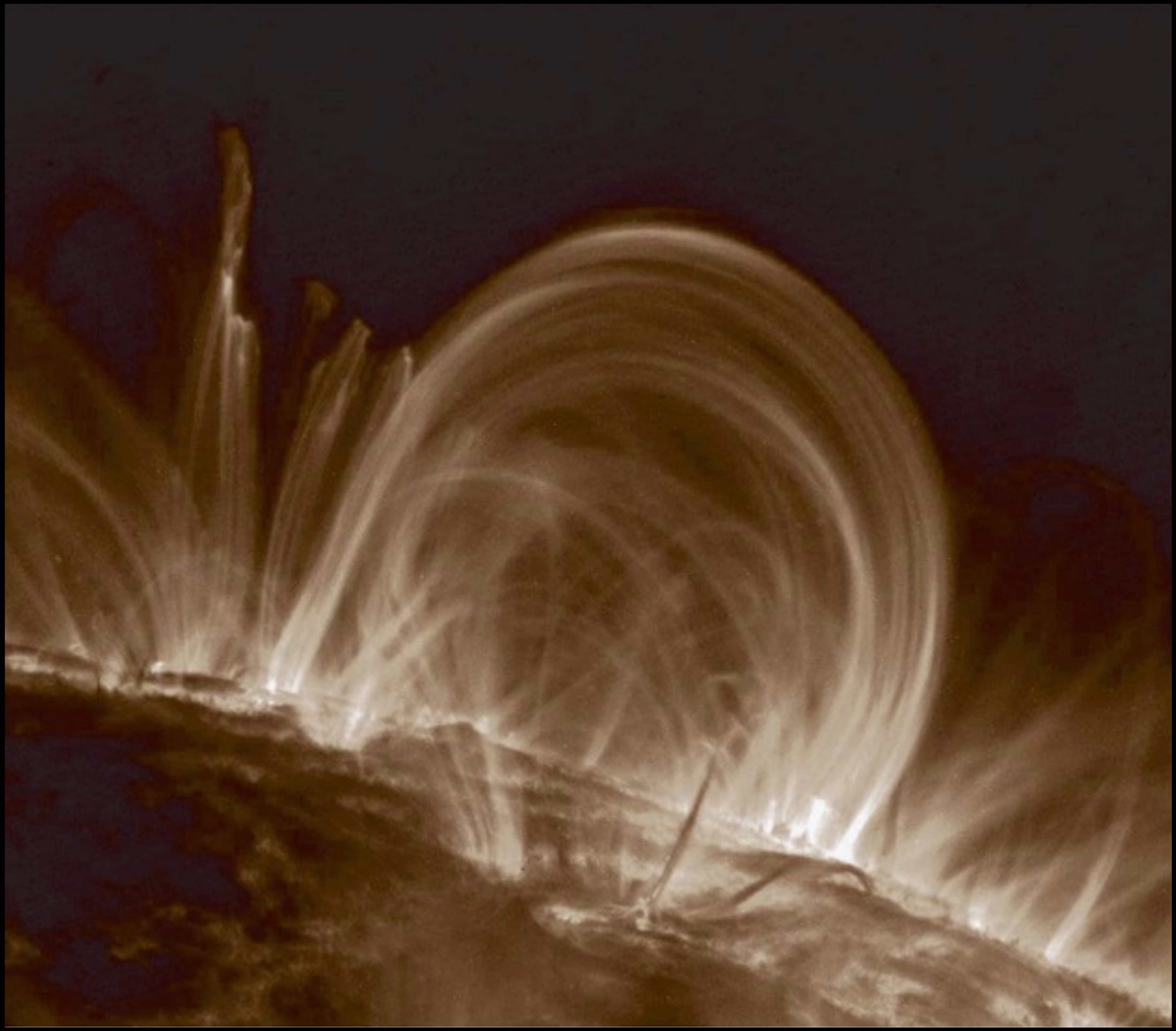
18:15 - 19:45

This week's homework: 11/26 (next lecture)

Next week's homework: 12/14
(class 11/26)

Class 11/30 homework: 12/14

What is magnetism?



What is magnetism?

Quiz

Magnetism is created by....?

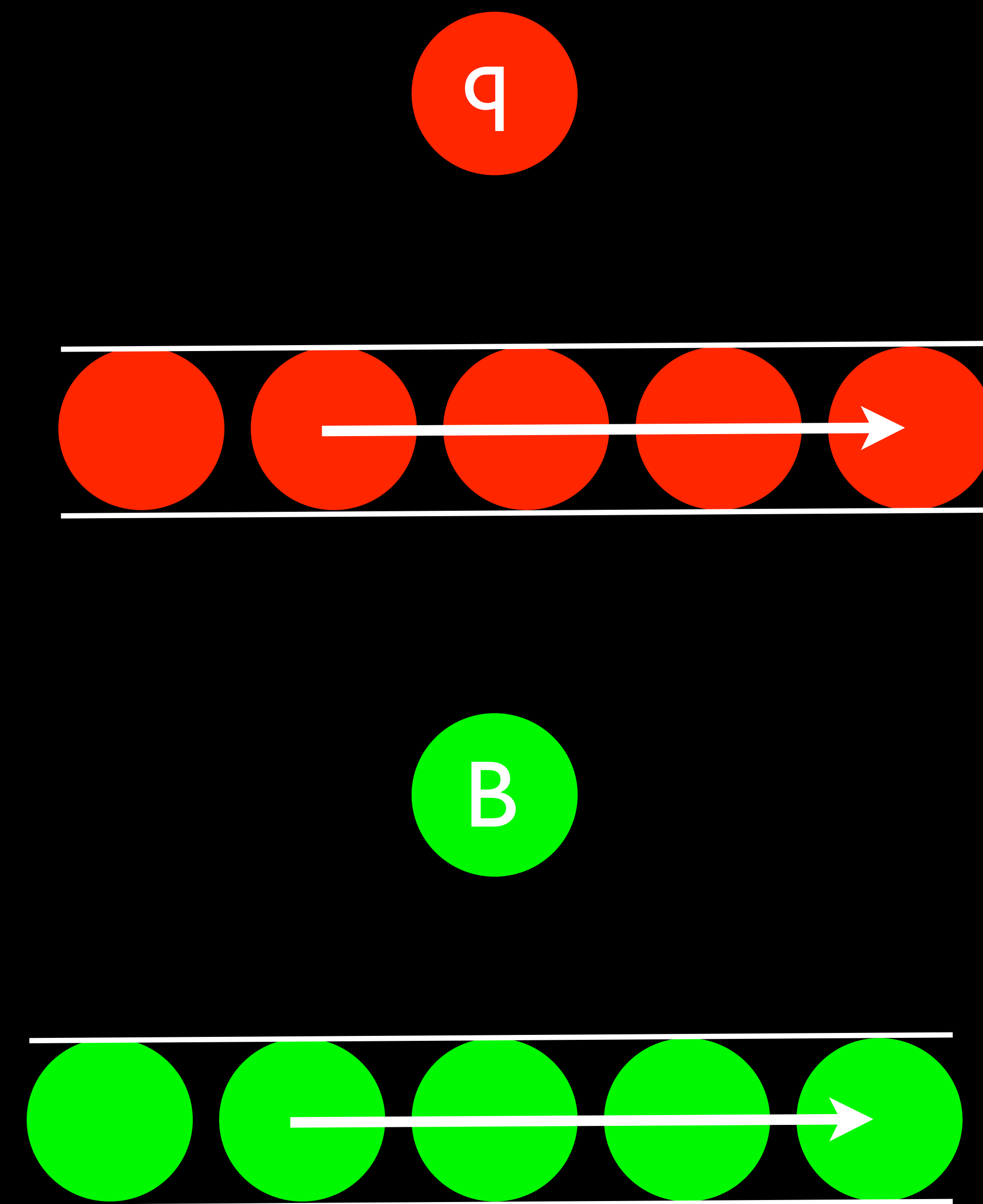
(a) electric charge

(b) electric currents

~~(c) magnetic charge~~

do not exist

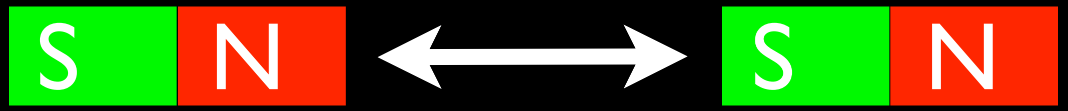
~~(d) magnetic currents~~



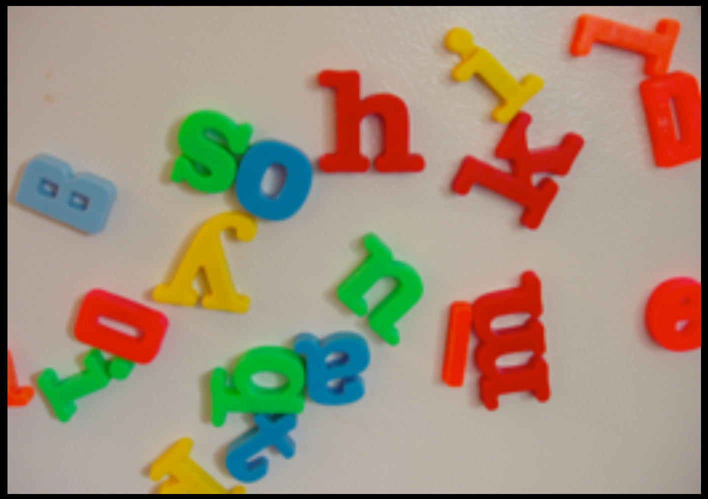
What is magnetism?

Magnetic force is seen between ...

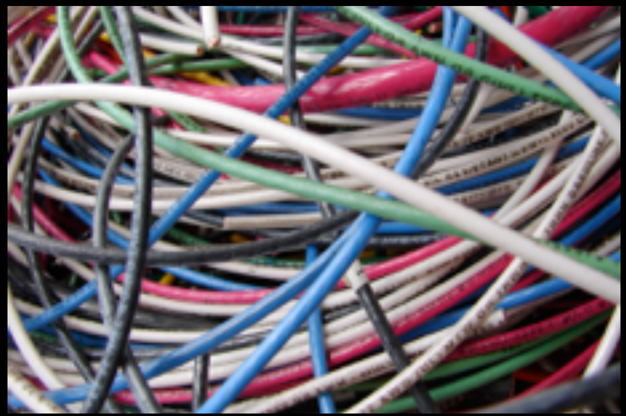
magnets

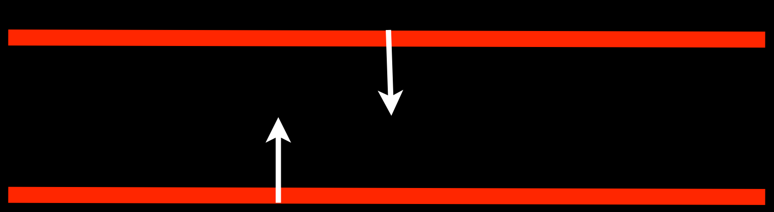


magnet and certain materials, e.g. iron



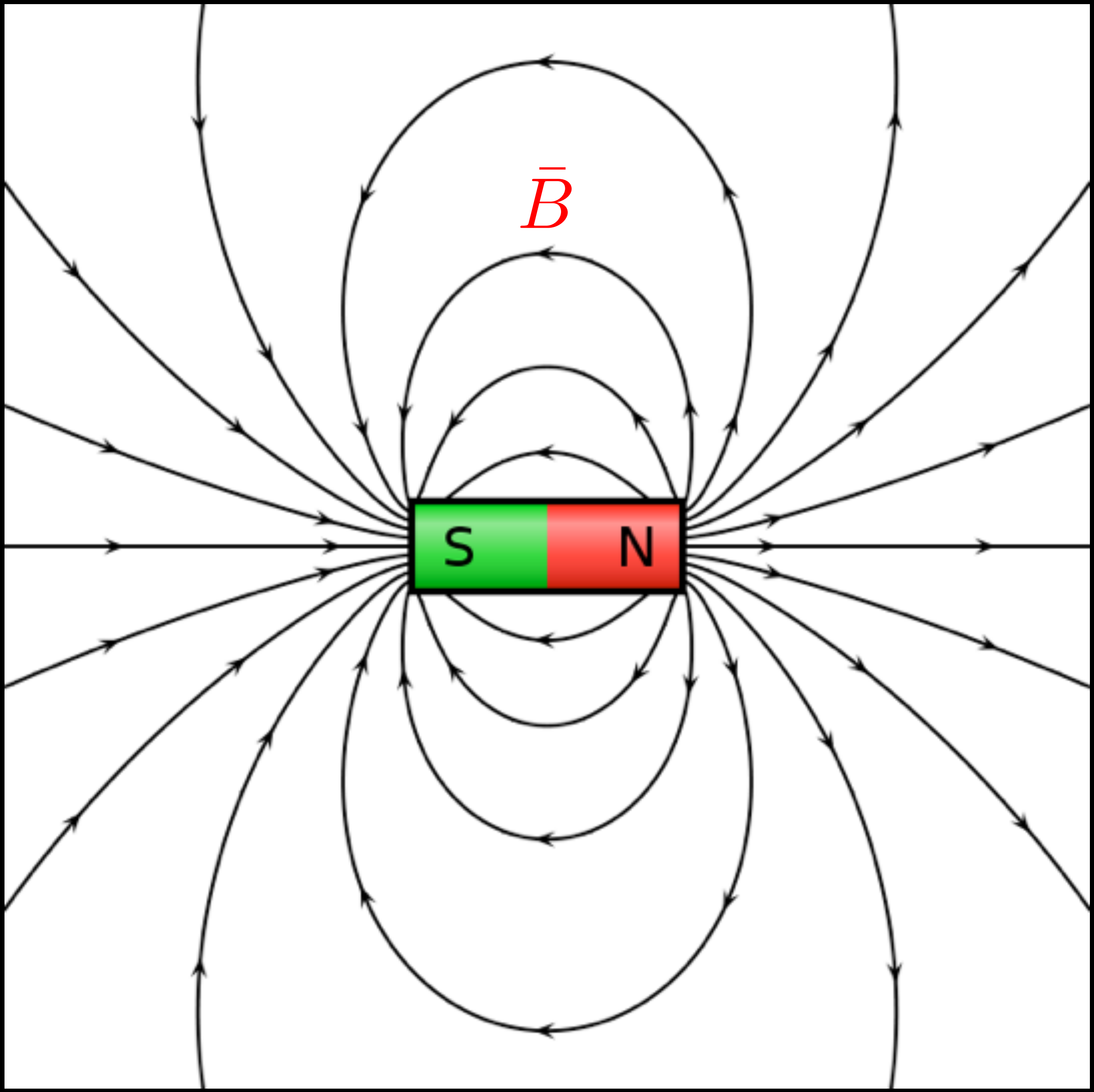
electric currents





What is magnetism?

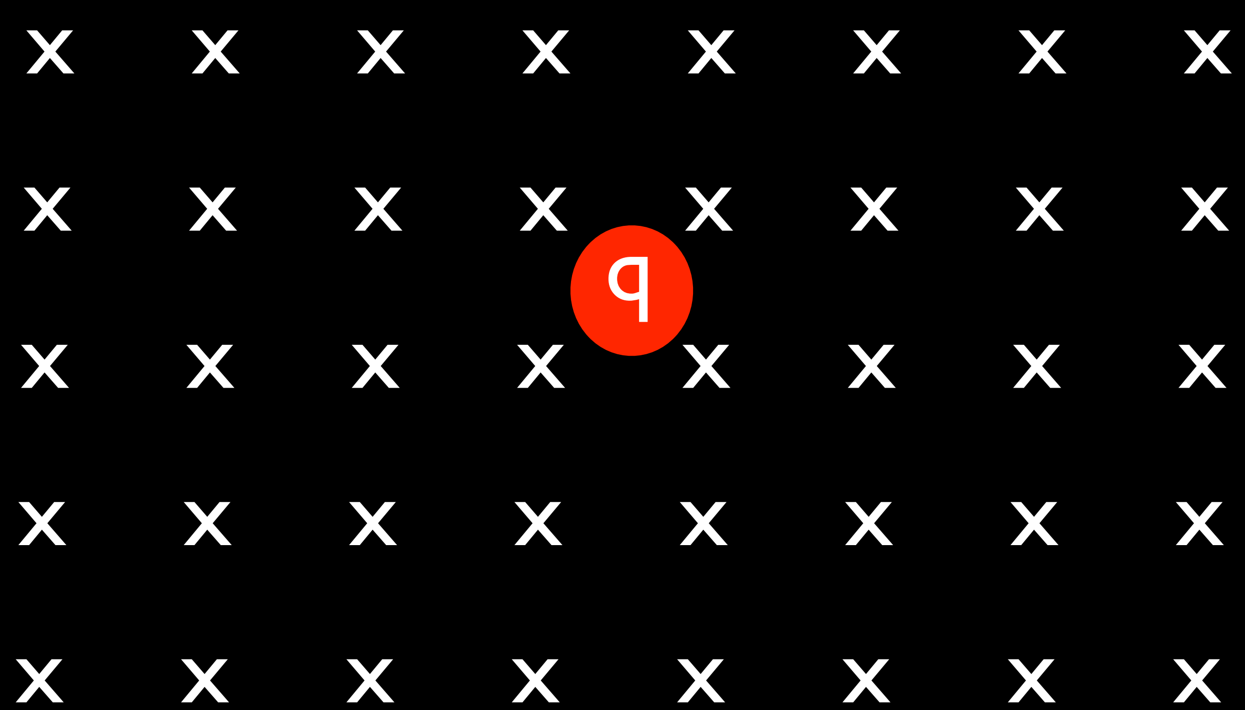
Like with electric field, $\bar{E}$, define the magnetic field, $\bar{B}$.

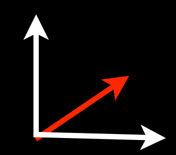


What is magnetism?

The magnetic field, $\bar{B}$, exerts a force on

***moving* electric charges**.



$\bar{B}$  into page

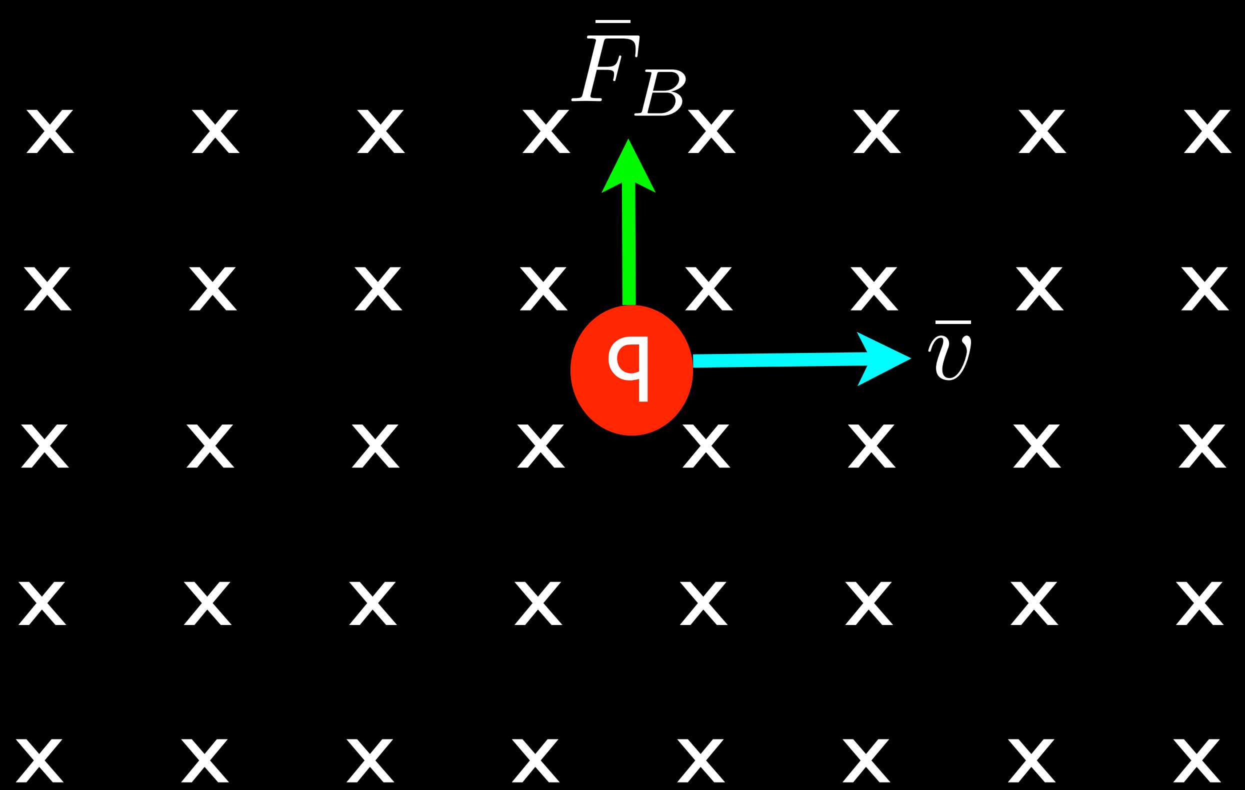
if $\bar{v} = 0$, $\bar{F}_{\rm B} = 0$

magnetic force

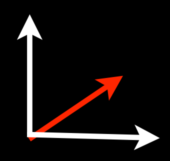
What is magnetism?

The magnetic field, $\bar{B}$, exerts a force on

moving **electric charges**.



$\bar{B}$



into page

if $\bar{v} \neq 0$, $\bar{F}_B \neq 0$

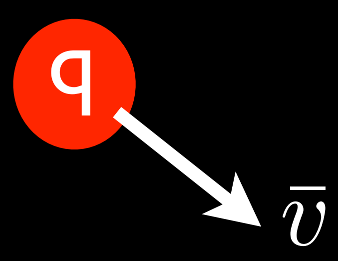
What is magnetism?

Magnetic force depends on:

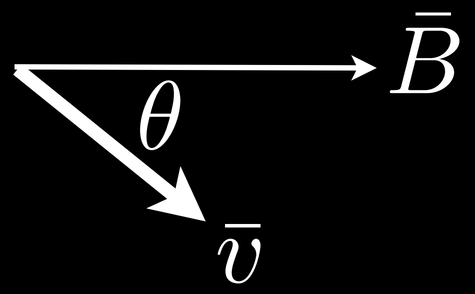
The charge, q

The magnetic field, $\bar{B}$

The charge velocity, $\bar{v}$

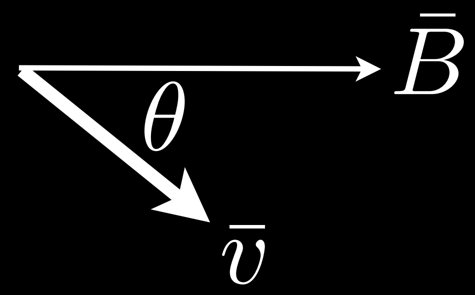


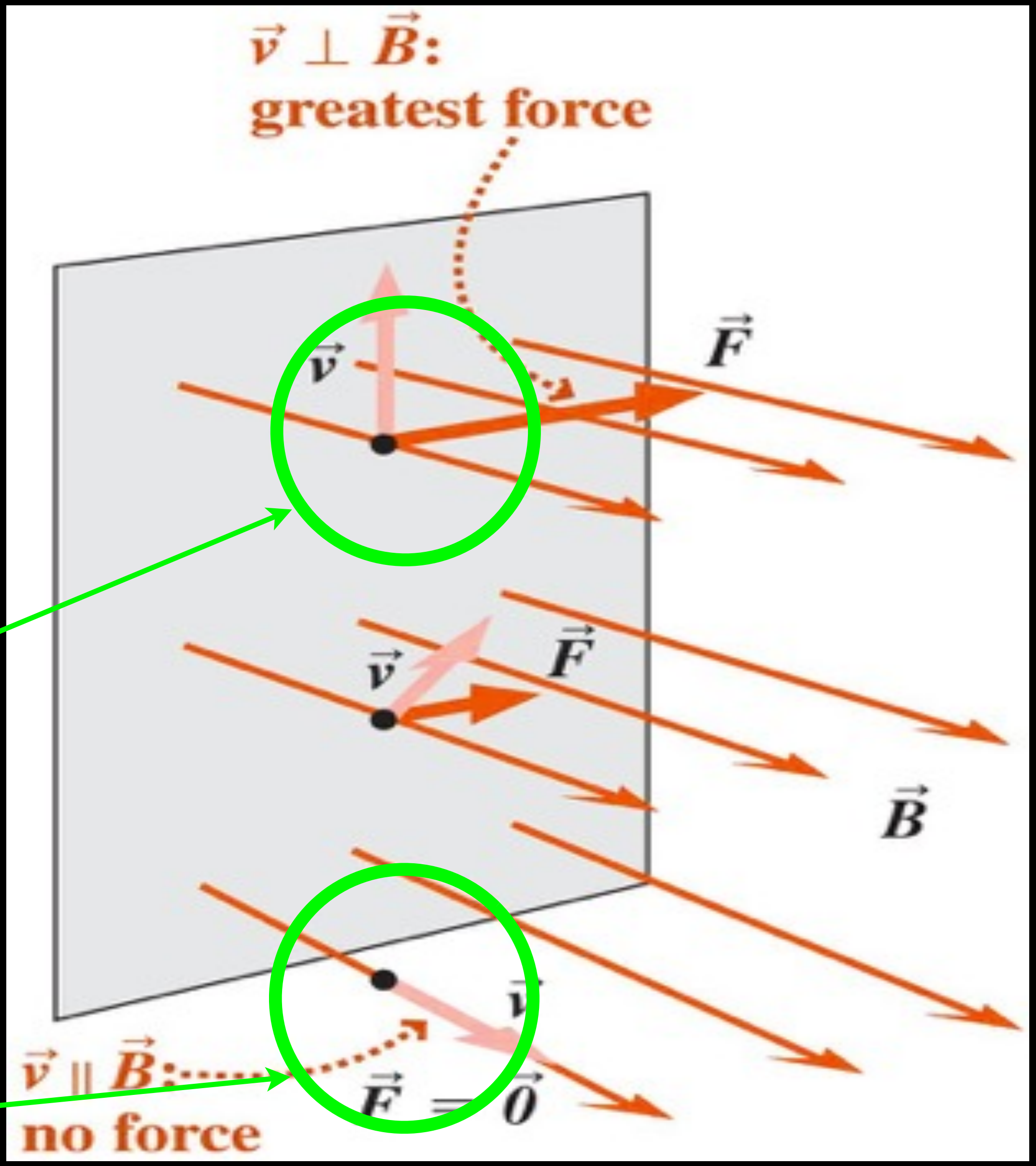
The angle, θ, between $\bar{v}$ and $\bar{B}$.



What is magnetism?

The angle, θ, between $\bar{v}$ and $\bar{B}$.



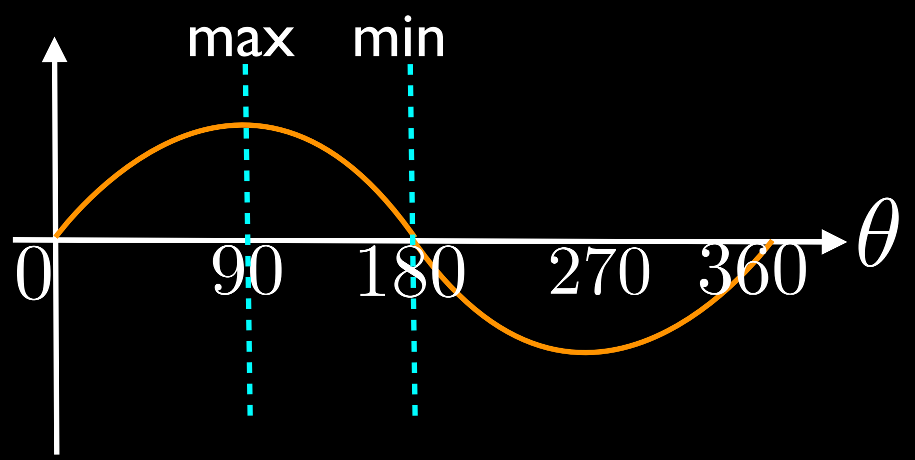


Magnetic force is max: $\theta = 90$

$\bar{v}$ perpendicular to $\bar{B}$

Magnetic force is 0: $\theta = 0$

$\bar{v}$ parallel to $\bar{B}$



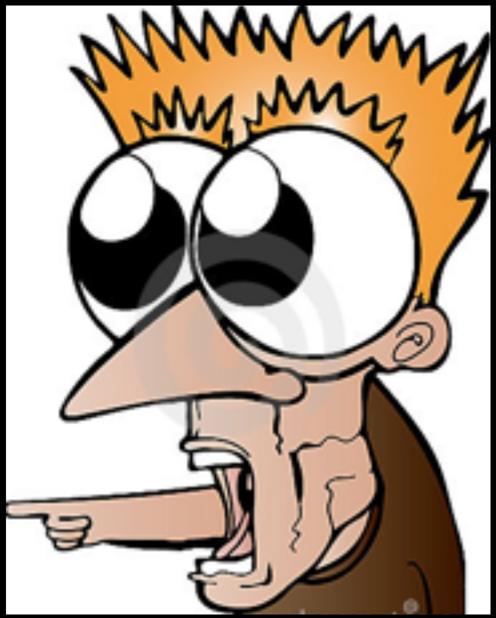
Therefore: $\bar{F}_B \propto \sin\theta$

What is magnetism?

Magnetic force magnitude:

$$|\bar{F}_{\mathrm{B}}| = |q| v B \sin\theta$$

NOT Scalar product!



|vector 1| |vector 2| $\cos\theta$ scalar product

= |vector 1| $\cdot$ |vector 2|

|vector 1| |vector 2| $\sin\theta$ vector product $0^\circ \leq \theta \leq 180^\circ$

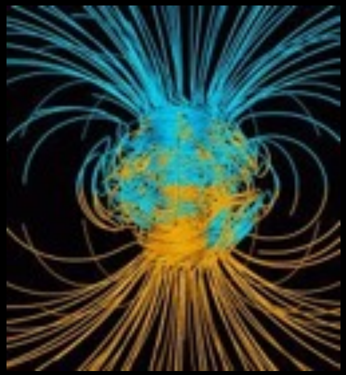
= |vector 1| x |vector 2|

$$\bar{F}_B = q\bar{v} \times \bar{B}$$

magnetic force unit: Tesla (T)

What is magnetism?

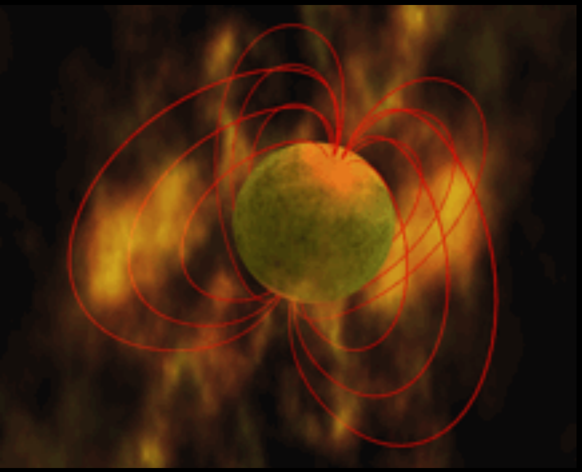
1 T is a strong magnetic field. Often use ‘Gauss’ : $1\,\mathrm{G} = 10^{-4}\,\mathrm{T}$



Earth’s magnetic field $< 1\,\mathrm{G}$

Fridge magnets $\sim 100\,\mathrm{G}$

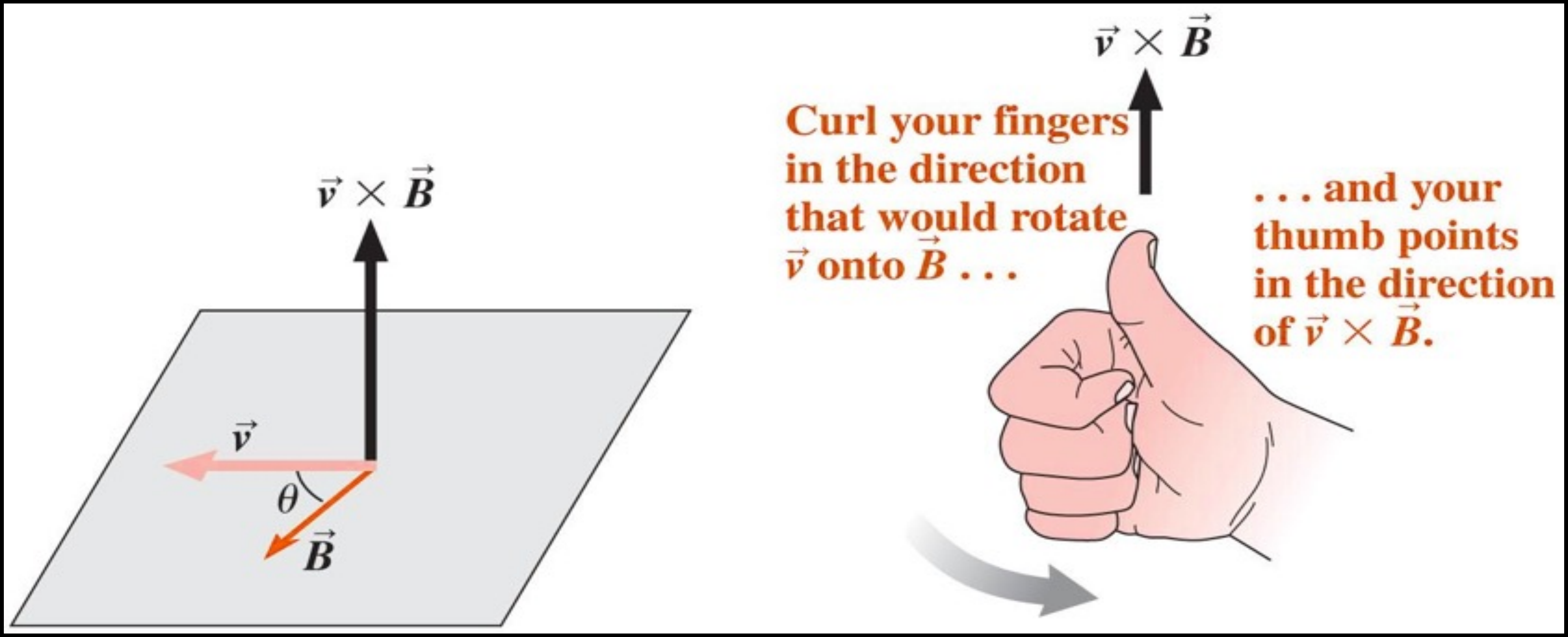
MRI $\sim 1.5\,\mathrm{T}$



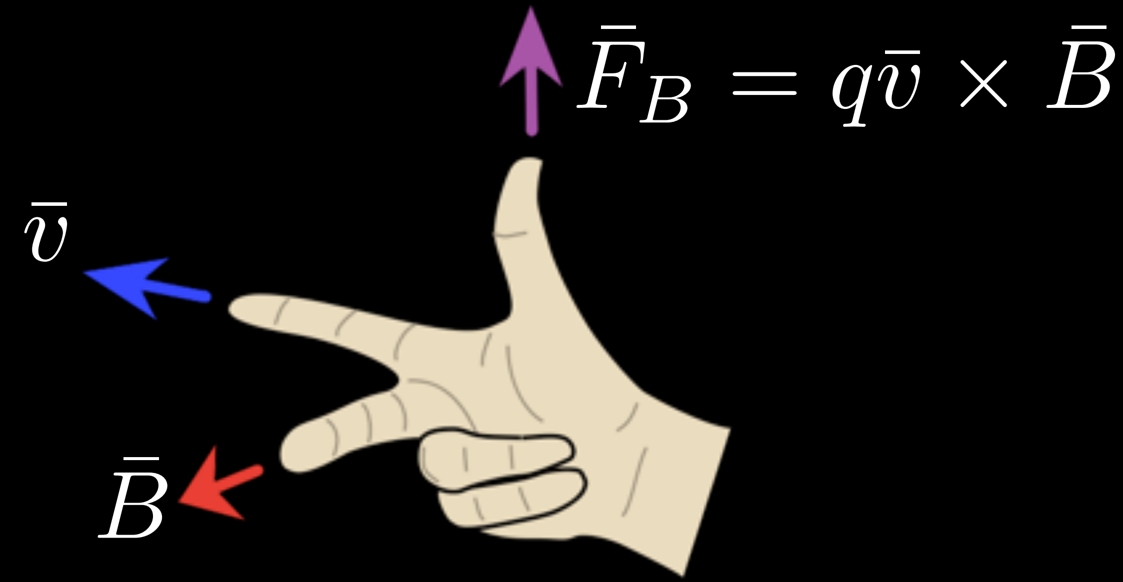
“Magnetar” $\sim 10^8 - 10^{11}\,\mathrm{T}$

What is magnetism?

Magnetic force direction: right-angles (perpendicular) to $\bar{v}$ and $\bar{B}$.



Found using right hand rule



What is magnetism?

Quiz

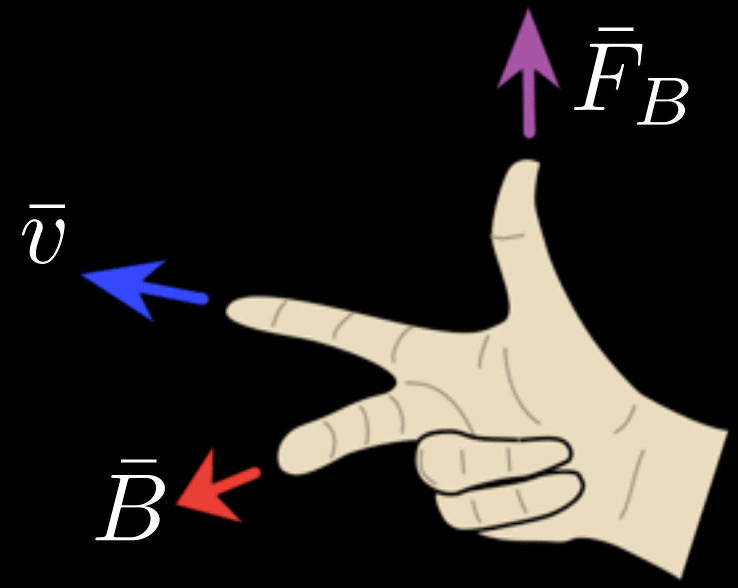
A proton moves in a magnetic field. What will the direction of the magnetic force on the proton be in cases (a)?

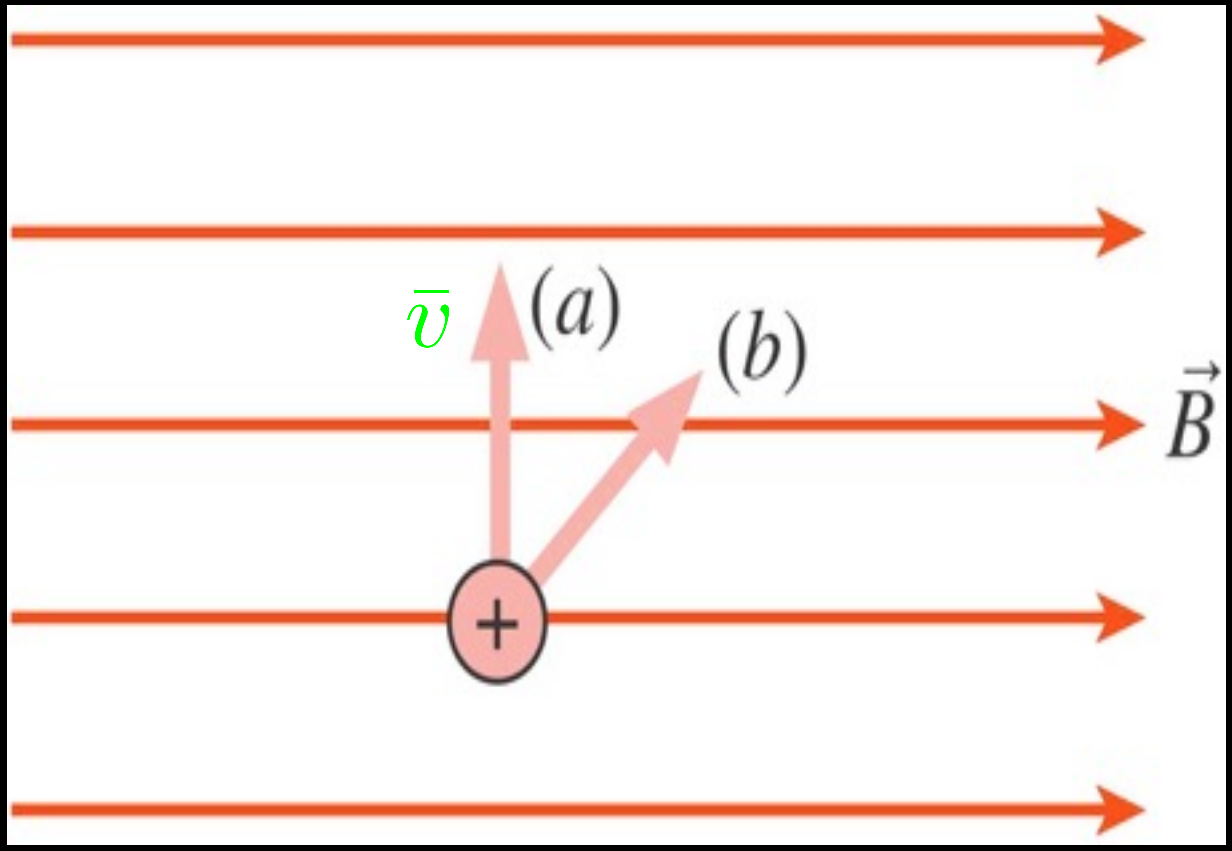
(A) parallel to $\bar{B}$

(B) out of the page

(C) into the page

(D) zero





What is magnetism?

Quiz

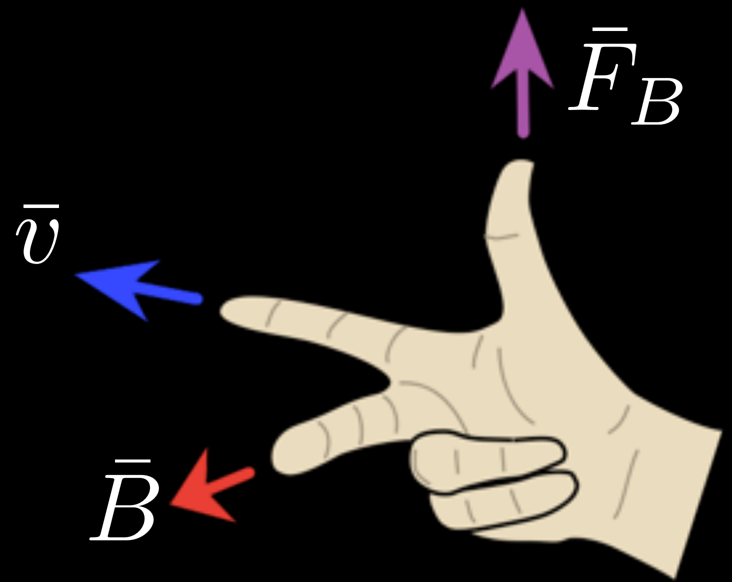
A proton moves in a magnetic field. What will the direction of the magnetic force on the proton be in cases (b)?

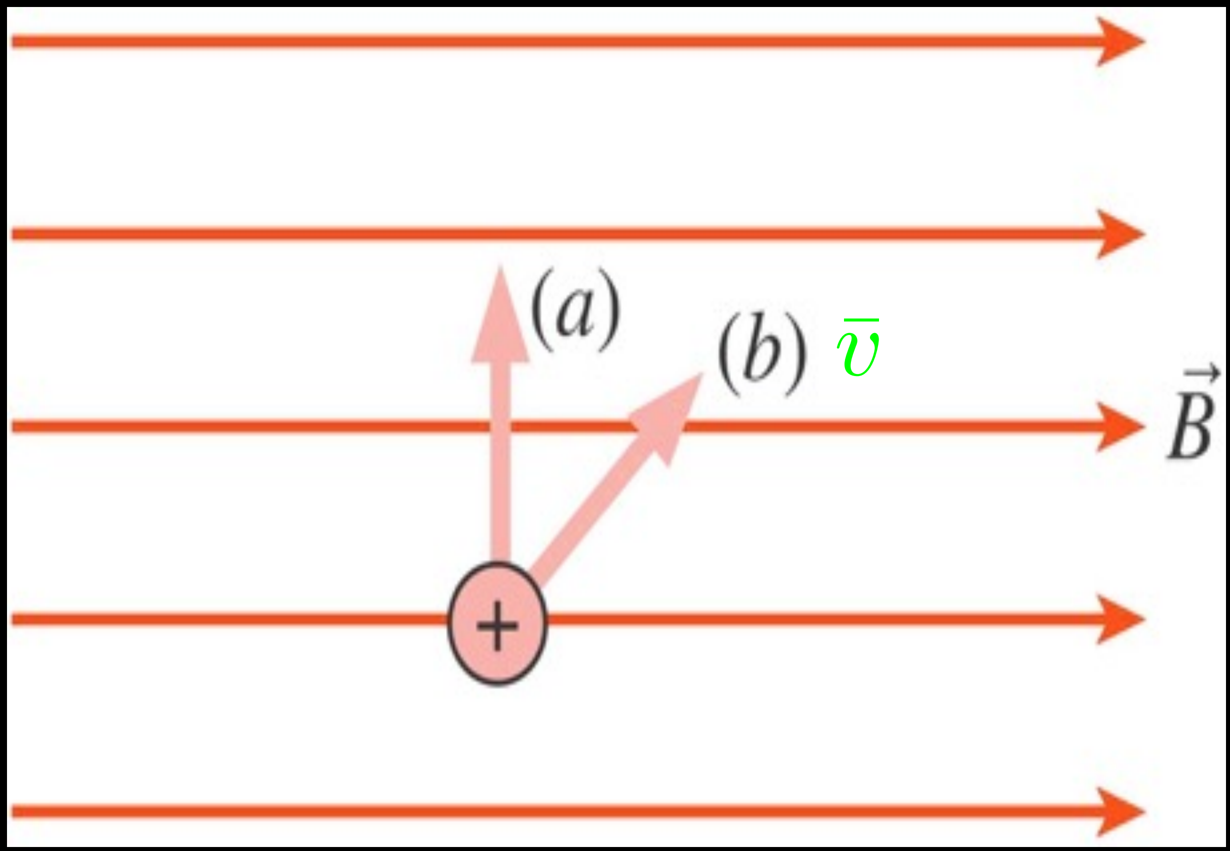
(A) parallel to $\bar{B}$

(B) out of the page

(C) into the page

(D) zero





but force is weaker

What is magnetism?

Quiz

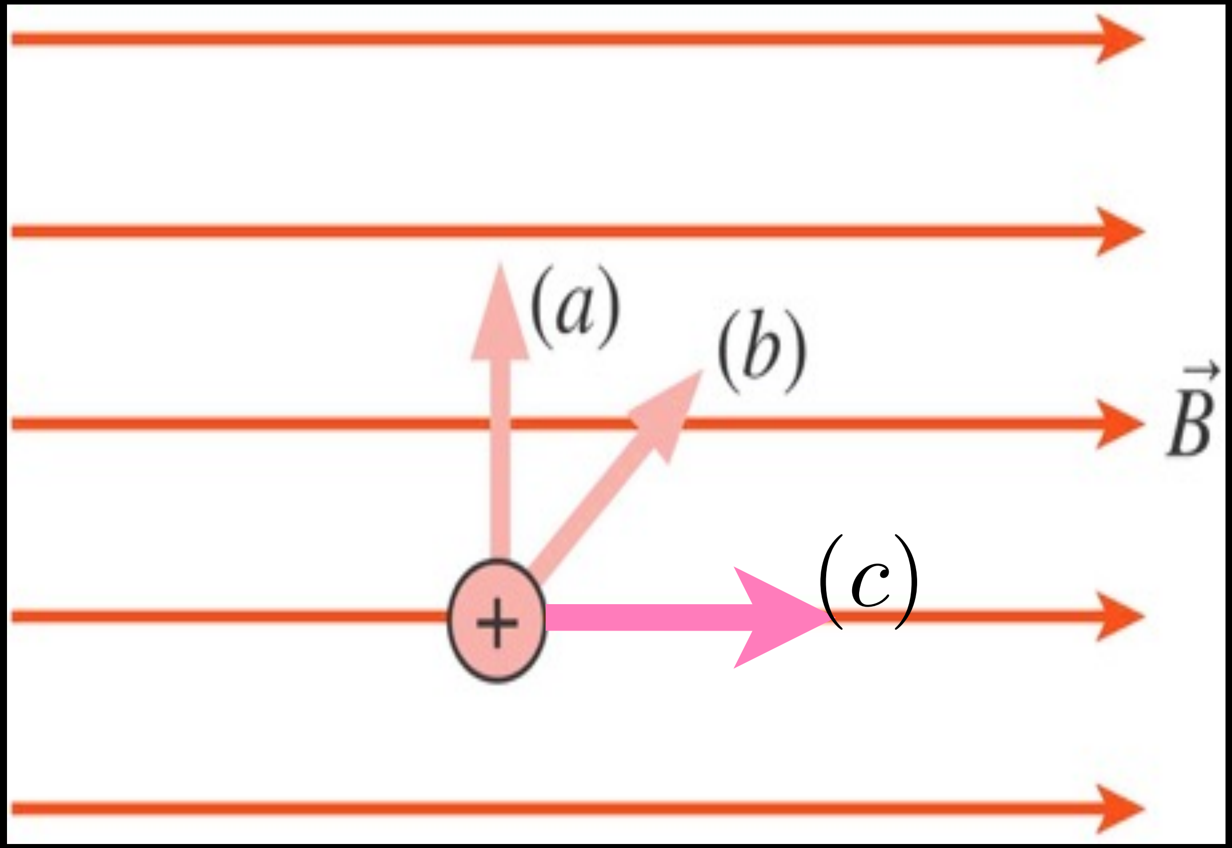
Put the magnetic forces from the 3 velocity directions in order of size, largest -> smallest

(A) a, b, c

(B) c, b, a

(C) b, a, c

(D) a, c, b



What is magnetism?

Quiz

A positive charge enters a uniform magnetic field.
What is the direction of the magnetic force?

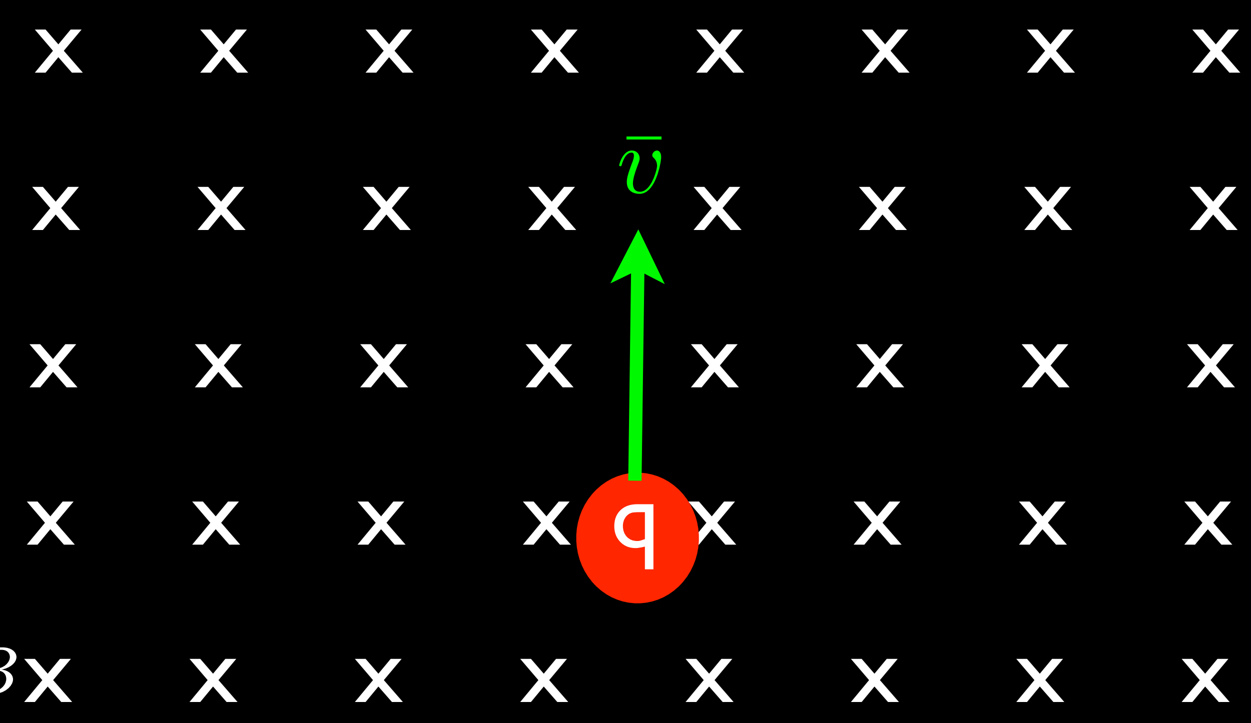
(A) down

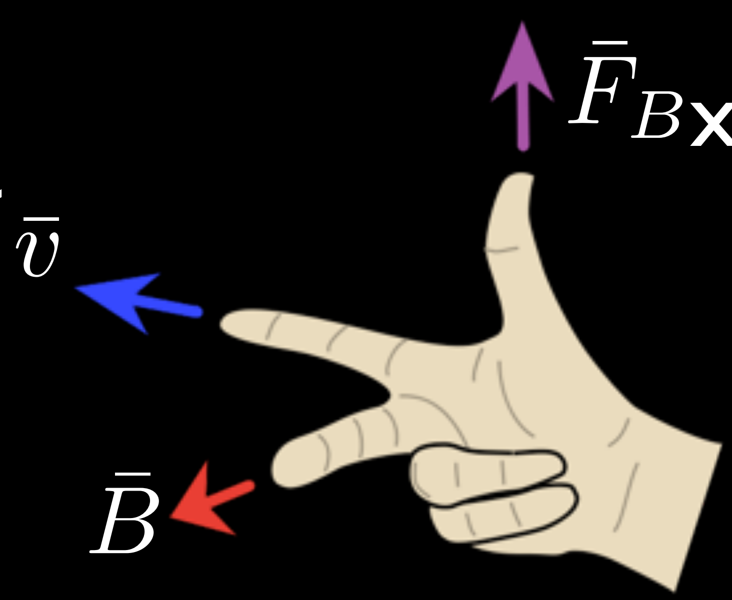
(B) out of the page

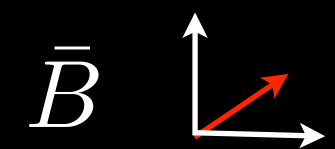
(C) into the page

(D) to the right

(E) to the left







What is magnetism?

A positive charge enters a uniform magnetic field.
What is the direction of the magnetic force?

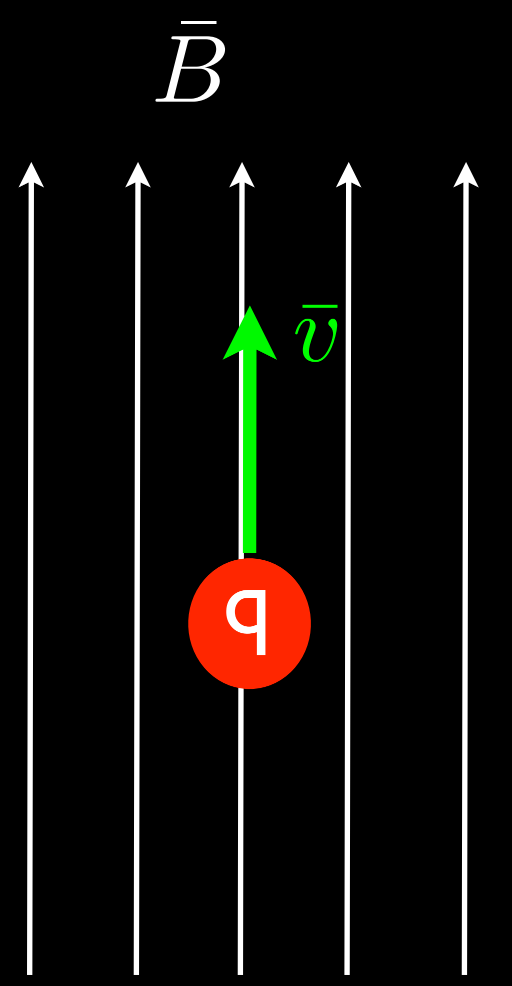
(A) zero $\sin 0 = 0$

(B) out of the page

(C) into the page

(D) to the right

(E) to the left



What is magnetism?

3 protons enter a 0.10 T magnetic field. $\bar{v} = 2.0\mathrm{Mm/s}$

Find the magnitude of the force on (1)

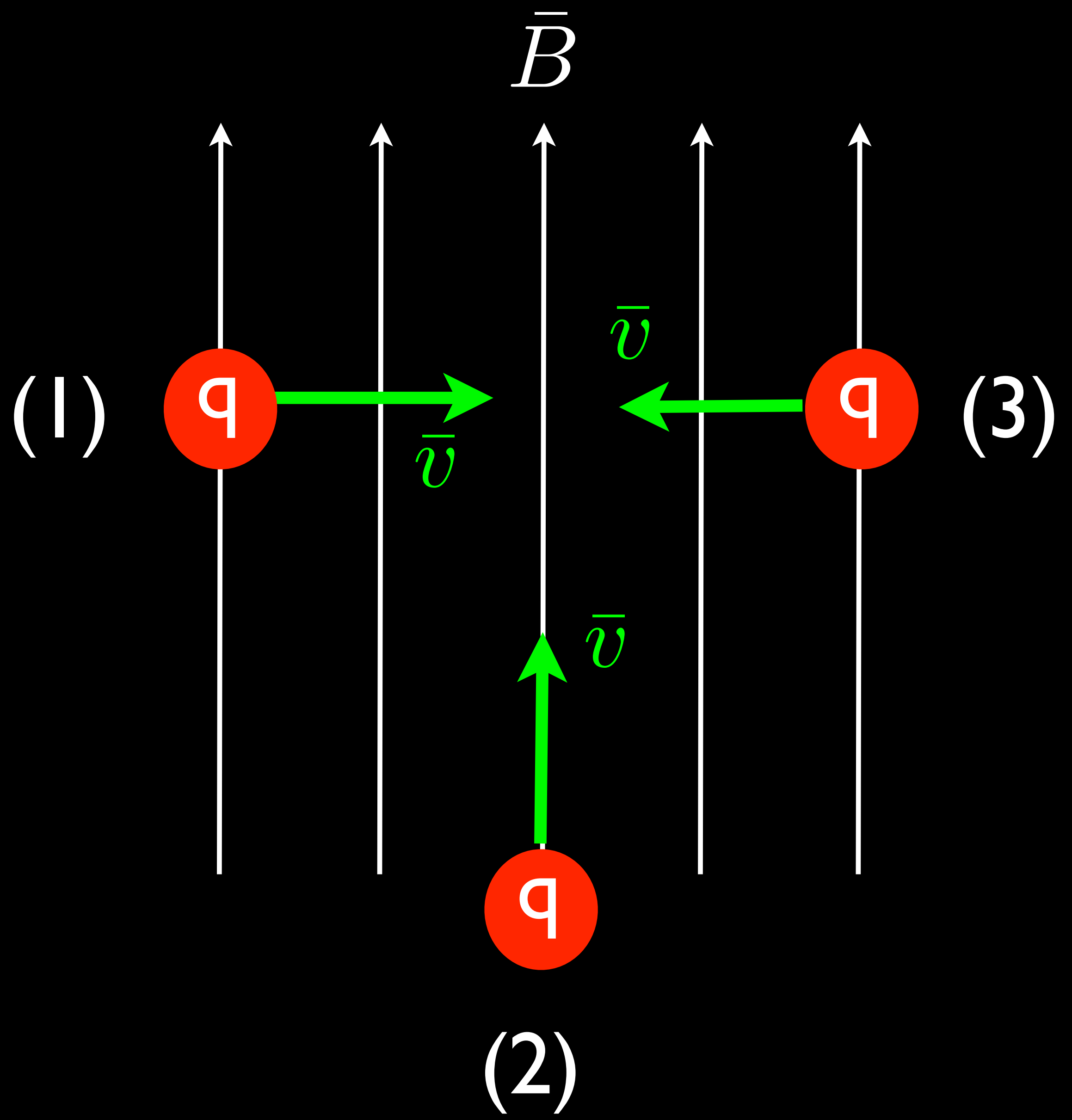
(A) 0 N

(B) $-200,000N$

(C) $200,000N$

(D) $32 \times 10^{-15}N$

(E) $-32 \times 10^{-15}N$



$e = 1.6 \times 10^{-19}\mathrm{C}$

What is magnetism?

Quiz

3 protons enter a 0.10 T magnetic field. $\bar{v} = 2.0\mathrm{Mm/s}$

Find the magnitude of the force on (1)

(A) 0 N

(B) $-200,000N$

(C) $200,000N$

(D) $32 \times 10^{-15}N$

(E) $-32 \times 10^{-15}N$

$$|\bar{F}_B| = |q||\bar{v}||\bar{B}|\sin\theta$$

$$= (1.6 \times 10^{-19})(2 \times 10^6)(0.1)\sin(90)$$

$$= 32 \times 10^{-15}\mathrm{N}$$

What is magnetism?

Quiz

3 protons enter a 0.10 T magnetic field. $\bar{v} = 2.0\mathrm{Mm/s}$

Find the magnitude of the force on (2)

(A) 0 N

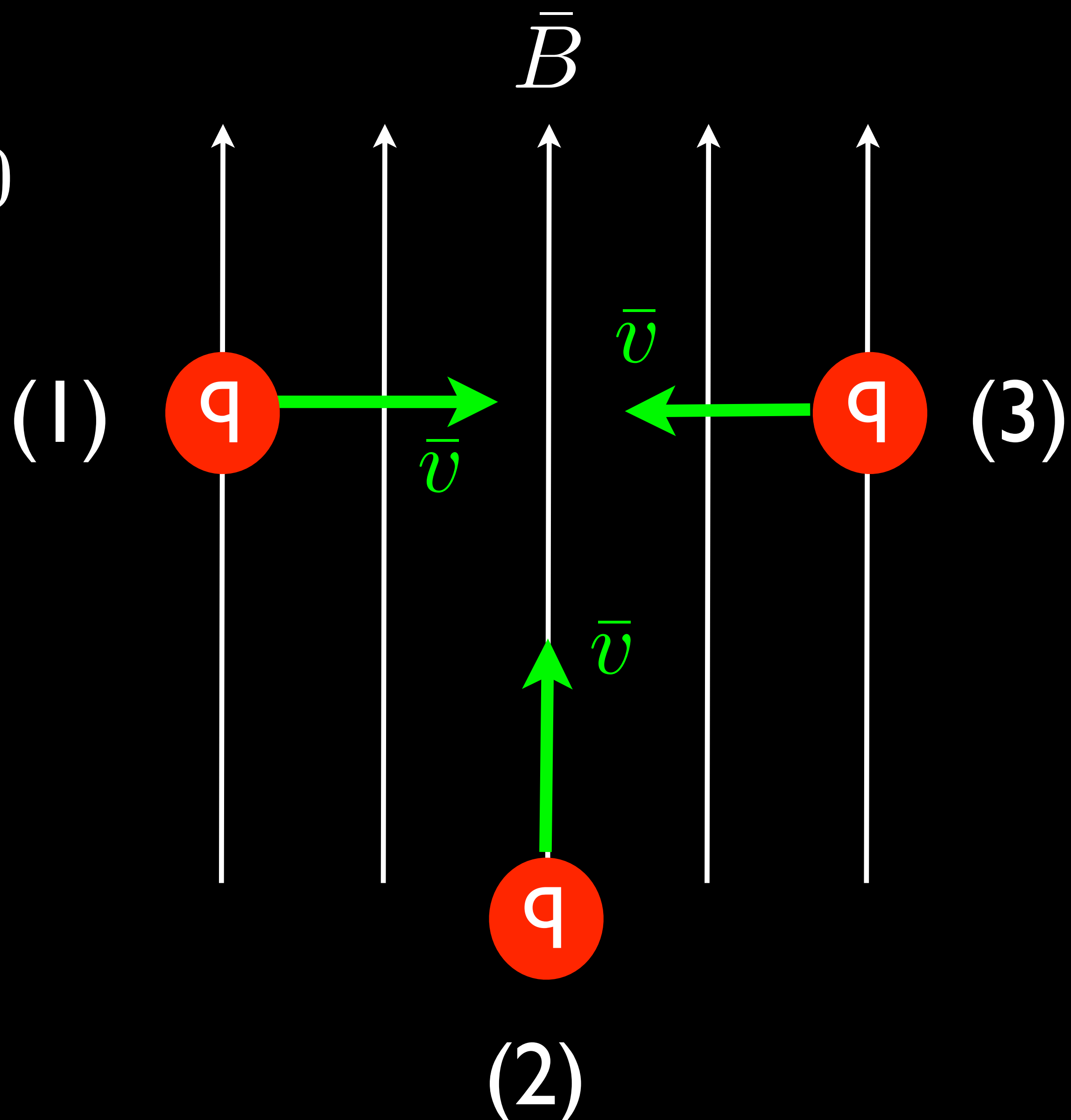
$\sin 0 = 0$

(B) $-200,000N$

(C) $200,000N$

(D) $32 \times 10^{-15}N$

(E) $-32 \times 10^{-15}N$



$e = 1.6 \times 10^{-19}\mathrm{C}$

What is magnetism?

Quiz

3 protons enter a 0.10 T magnetic field. $\bar{v} = 2.0\mathrm{Mm/s}$

Find the magnitude of the force on (3)

(A) 0 N

(B) $-200,000N$

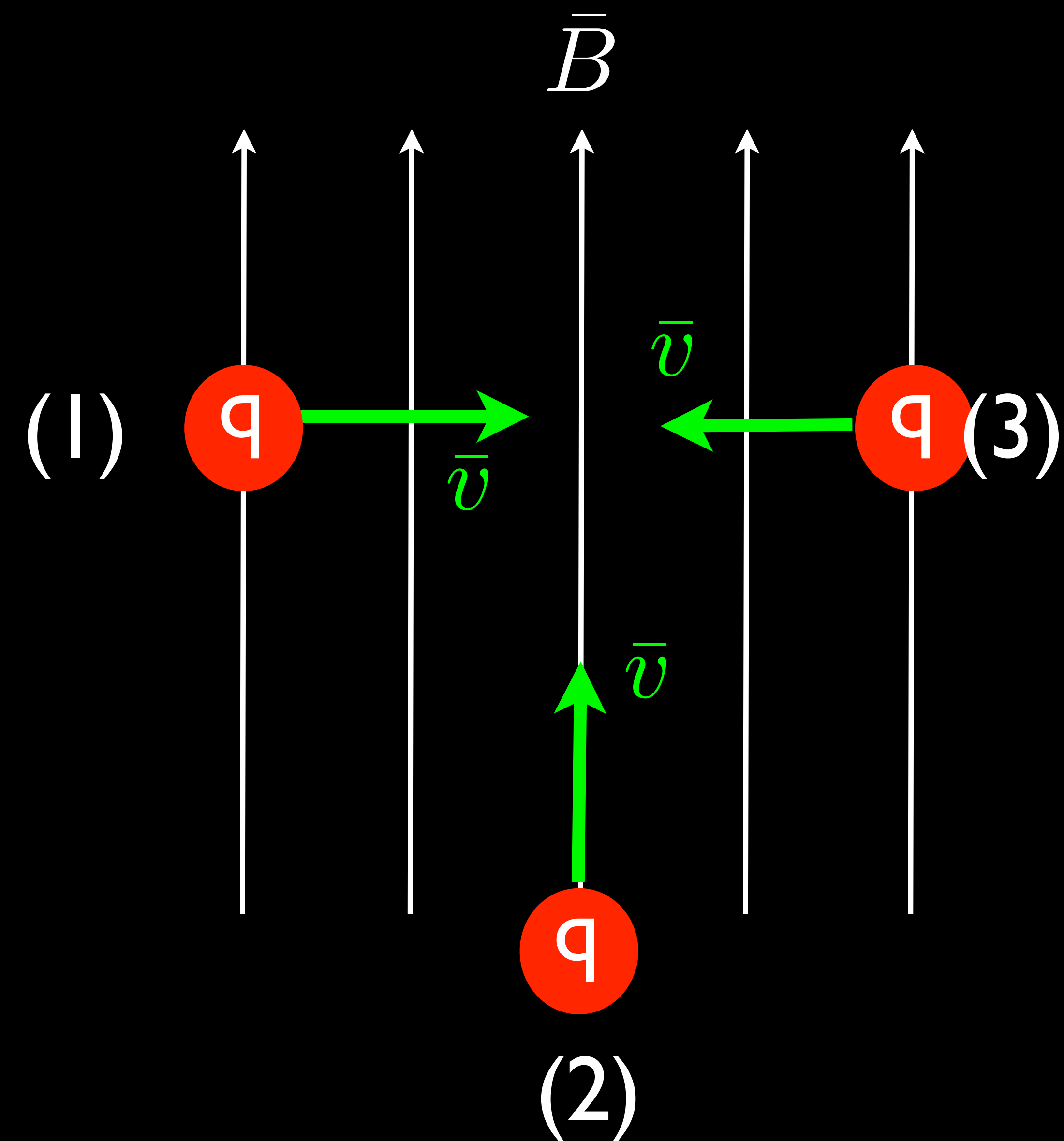
(C) $200,000N$

(D) $32 \times 10^{-15}N$

(E) $-32 \times 10^{-15}N$

$0^\circ \leq \theta \leq 180^\circ$

But! Direction is opposite



$e = 1.6 \times 10^{-19}\mathrm{C}$

What is magnetism?

The magnetic force is separate from the electric force.

Combined:

$$\bar{F} = q\bar{E} + q\bar{v} \times \bar{B}$$

electric force

magnetic force

What is magnetism?

The magnetic force is separate from the electric force.

Combined:

$$\bar{F} = q\bar{E} + q\bar{v} \times \bar{B}$$

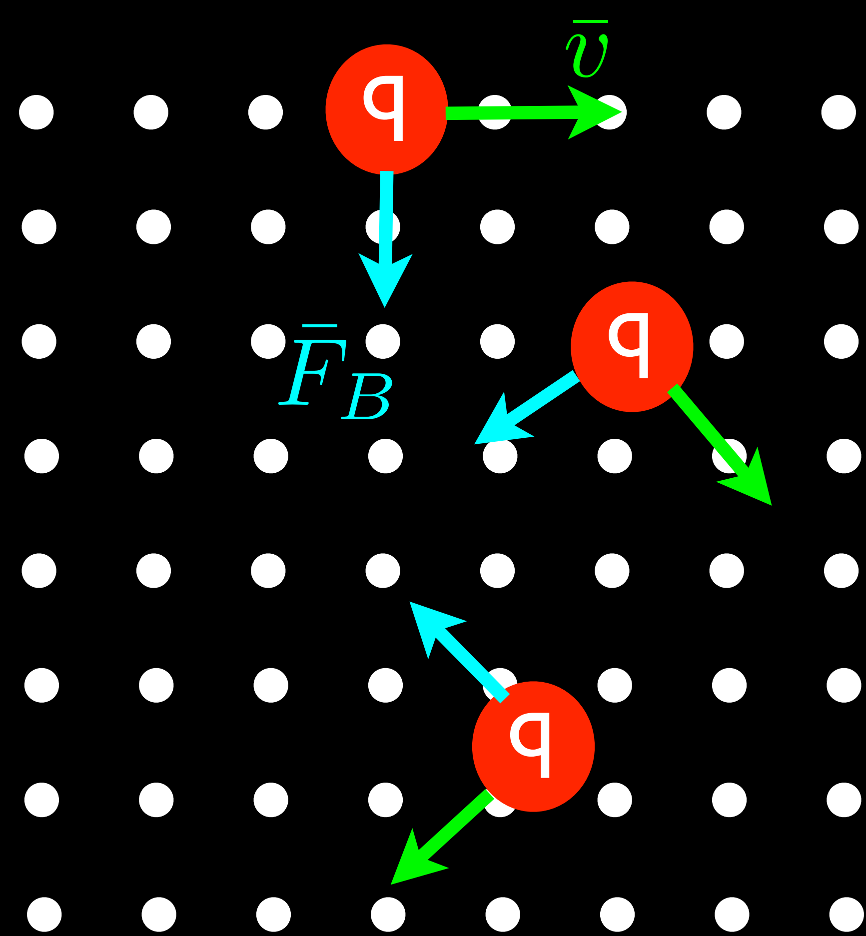
electromagnetic force

Charged particles in a magnetic field

The magnetic force is always perpendicular to the velocity.

The force changes the direction, but not the speed and it does no work.

(no component in direction of motion)



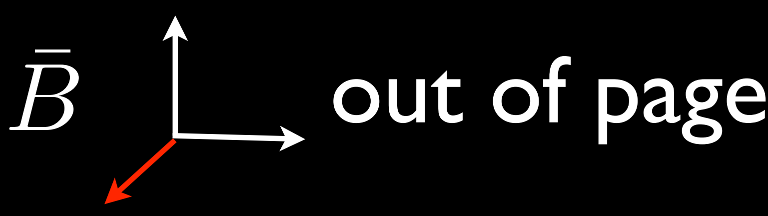
If charge moves perpendicular to the field

uniform circular motion

$F = qvB\sin 90 = qvB$ magnetic

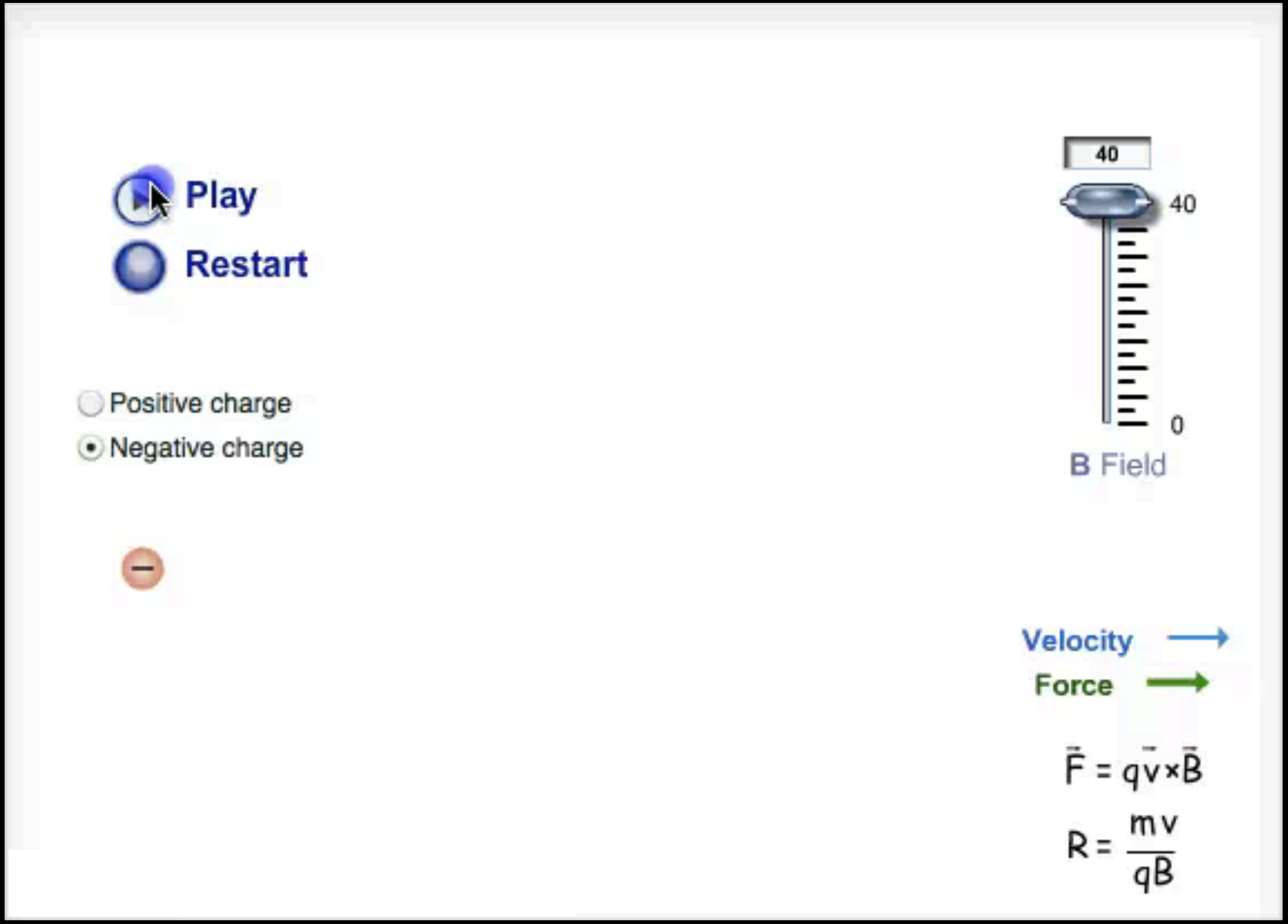
$= m\frac{v^2}{r}$ circular motion

$r = \frac{mv}{qB}$ radius of path



Charged particles in a magnetic field

$$r = \frac{mv}{qB}$$ radius of path



For constant charge (q) and momentum (p = mv)

stronger magnetic field increases the force and decreases the radius.

Charge sign reverses direction.

Charged particles in a magnetic field

$$r = \frac{mv}{qB}$$ radius of path

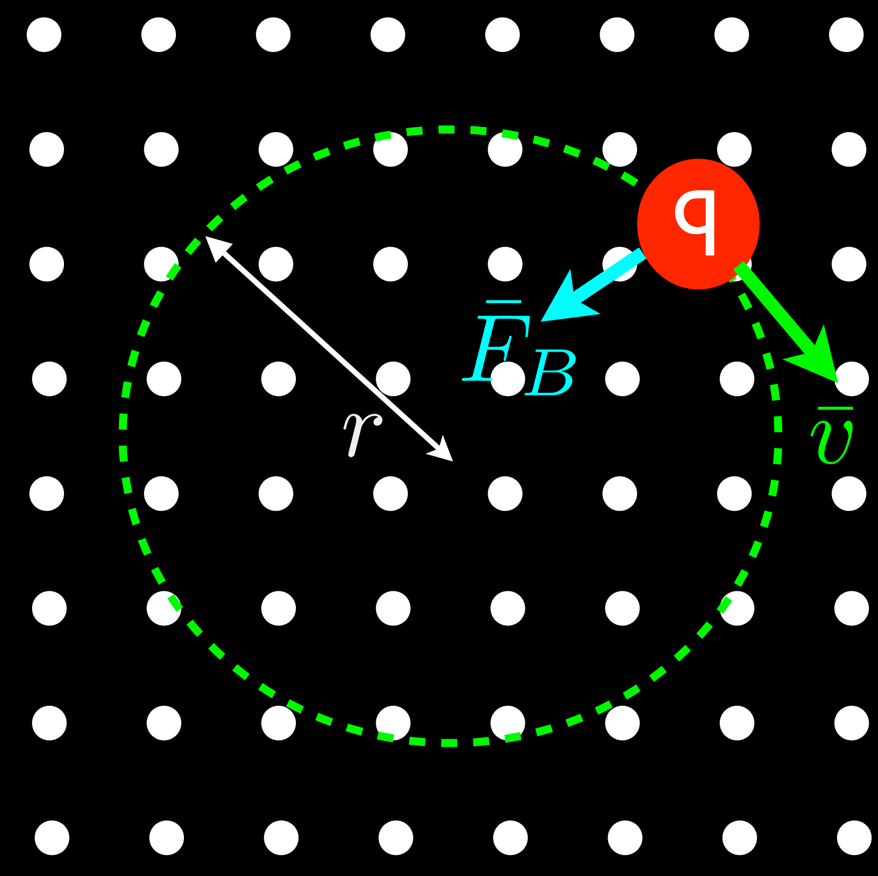
Period, T, for the circular orbit:

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

Does not depend on v or r:

$$r = \frac{mv}{qB}$$ the higher v, the larger r.

T does not change.



Charged particles in a magnetic field

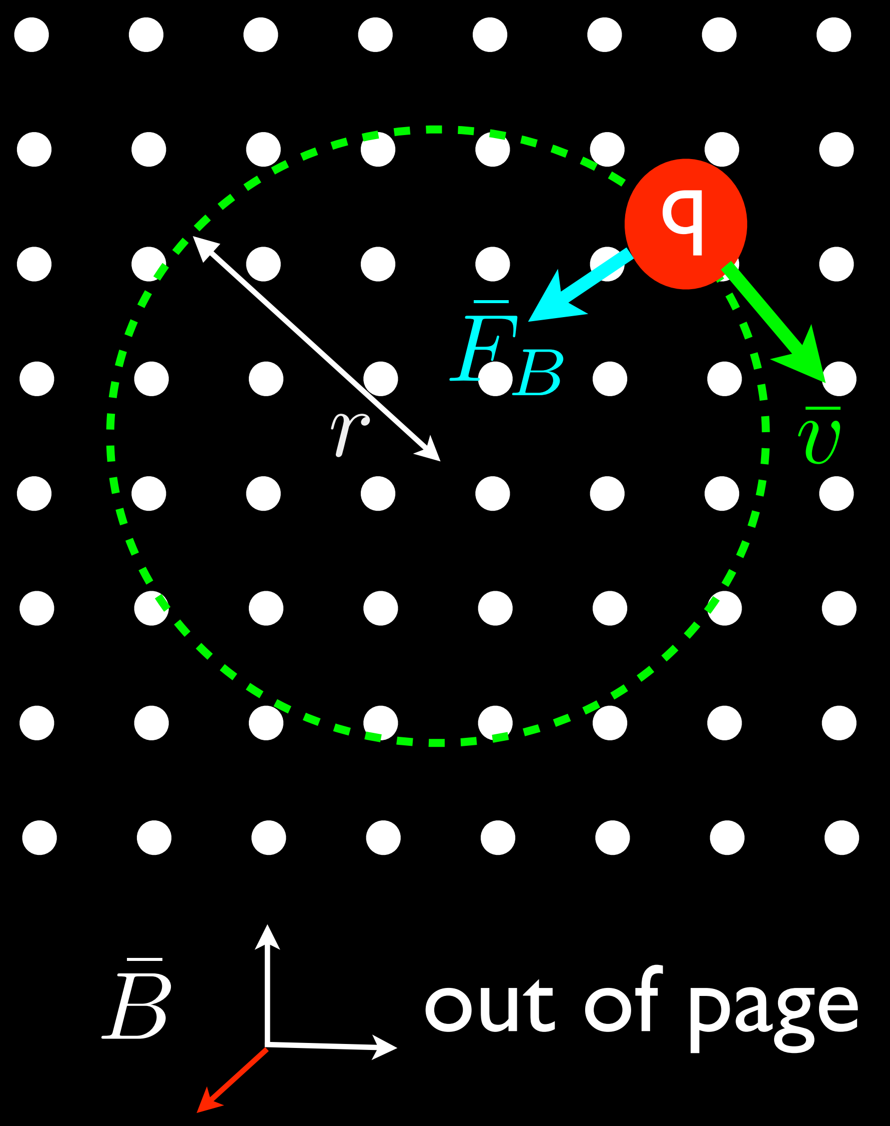
$$r = \frac{mv}{qB}$$ radius of path

Period, T, for the circular orbit:

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

and frequency:

$$f = \frac{1}{T} = \frac{qB}{2\pi m}$$ cyclotron frequency



Charged particles in a magnetic field

Quiz

2 particles of the same mass enter a magnetic field with the same speed and follow the paths shown. Which particle has the bigger charge?

(A) A

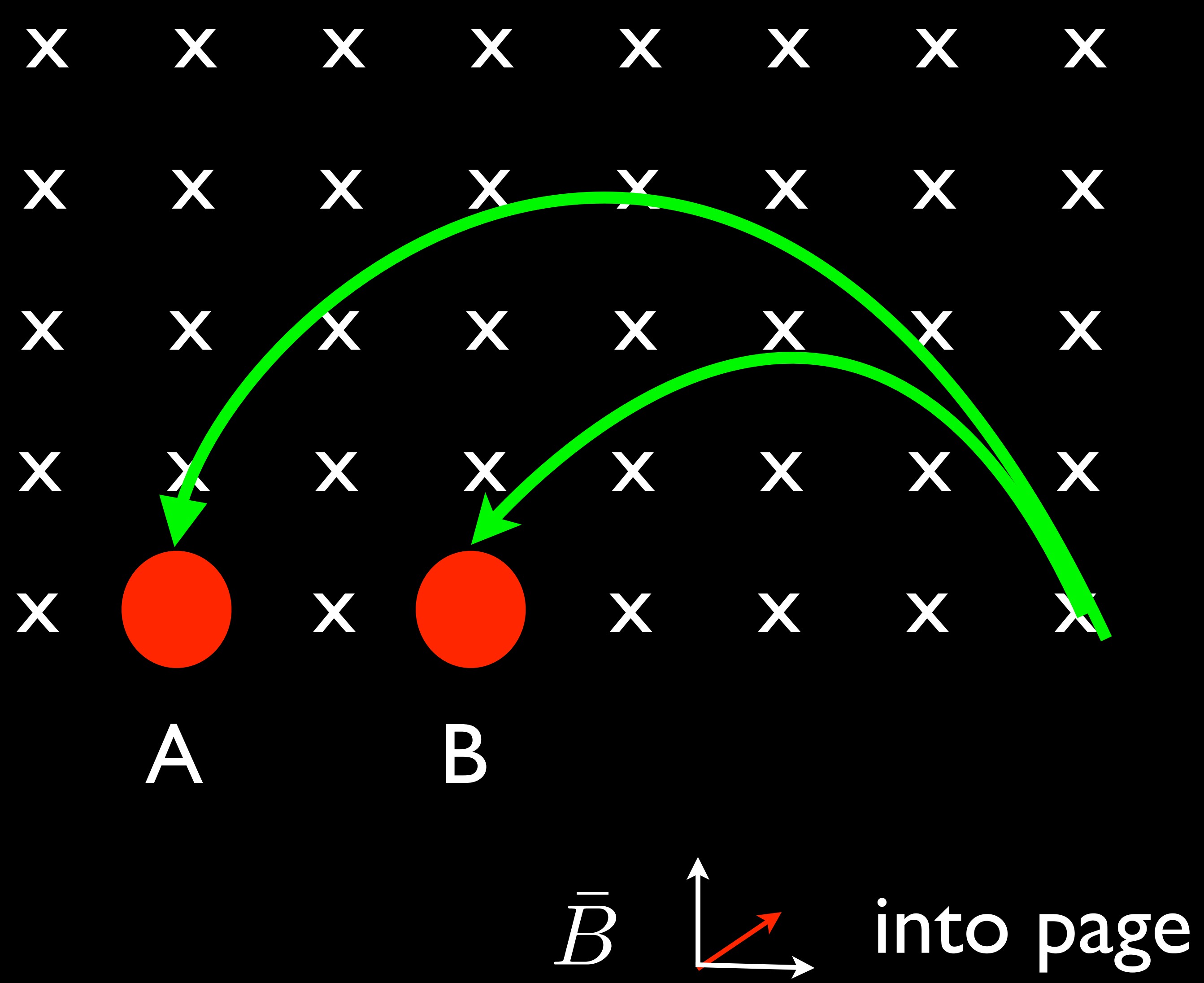
$$r = \frac{mv}{qB}$$

(B) B

bigger q = smaller r

(C) both are equal

(D) cannot tell from the picture



Charged particles in a magnetic field

If v is not perpendicular to the field:

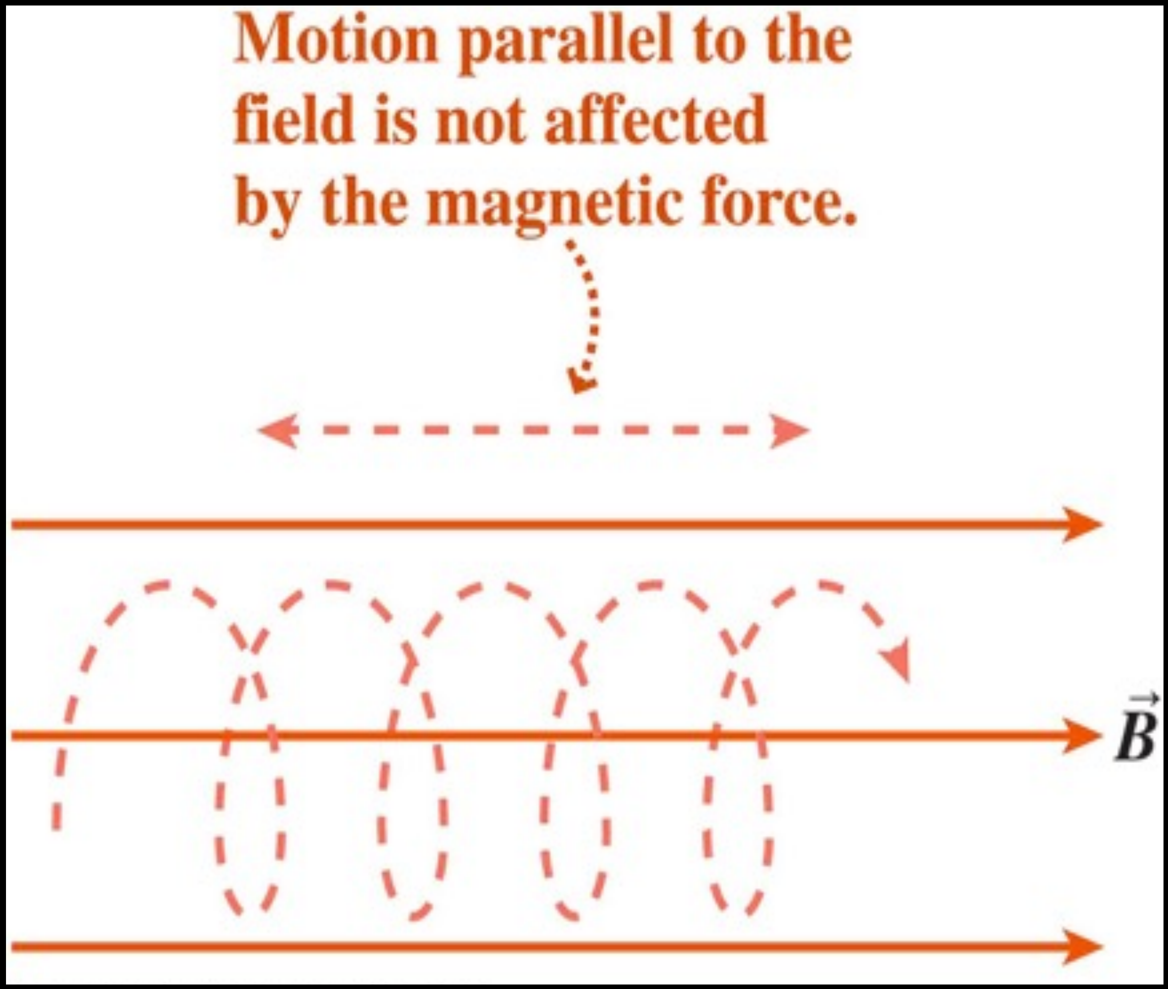
v components

perpendicular to $\bar{B}$

Gives circular motion in plane perpendicular to $\bar{B}$

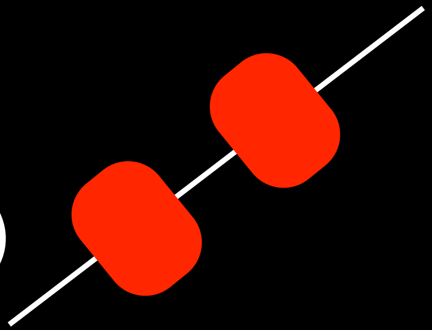
parallel to $\bar{B}$

Unaffected by field



Easy to move charge along field line.

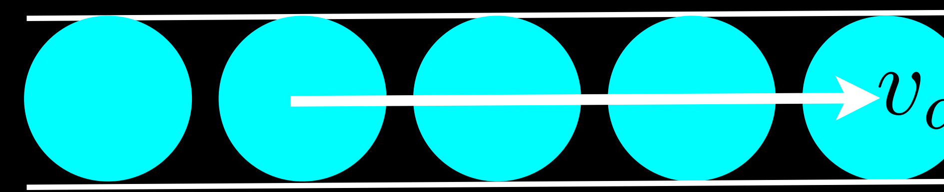
But cannot move perpendicular (→ circular motion)



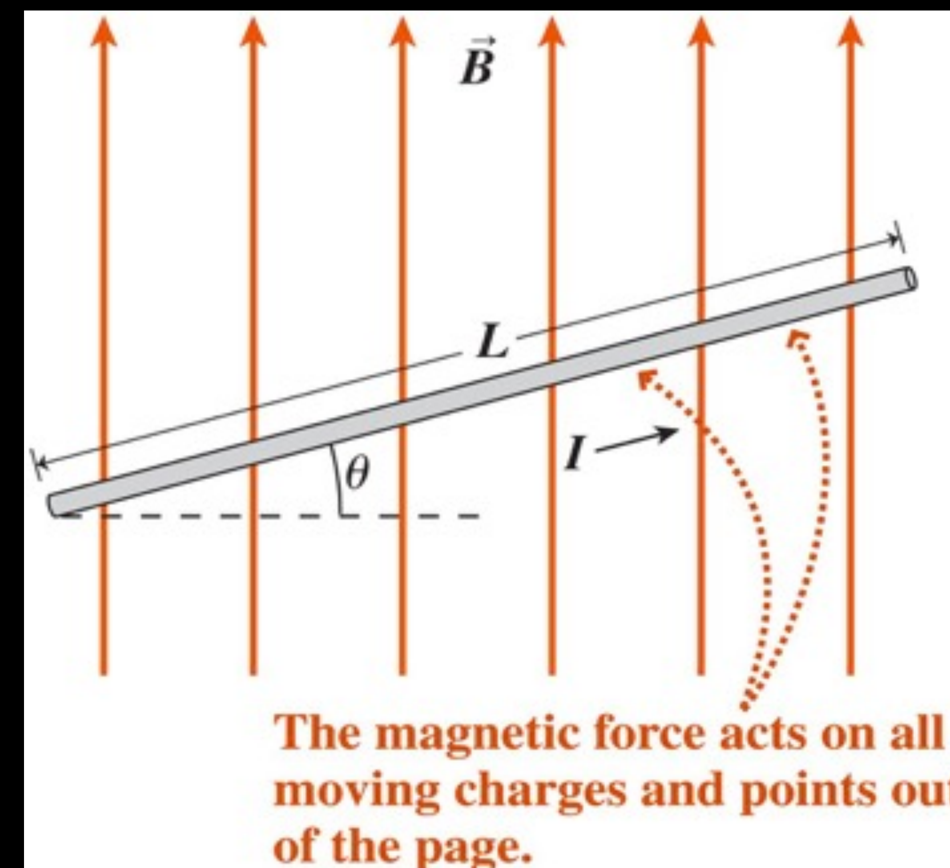
Charges are frozen to the field lines like beads on a wire.

Magnetic force on a current

An electric current is moving charges

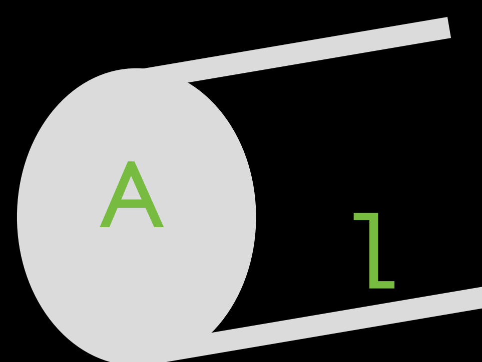


It feels a force in a magnetic field.



Each charge: $\bar{F}_q = q\bar{v}_d \times \bar{B}$

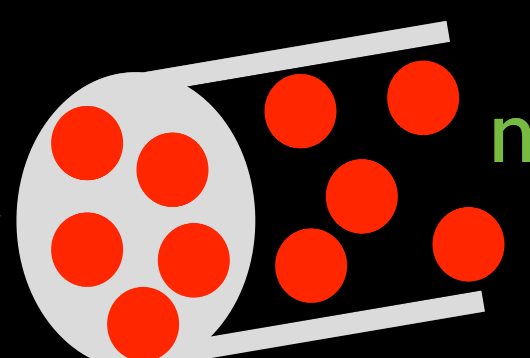
Force per length l:



$$\bar{F} = nAlq\bar{v}_d \times \bar{B}$$

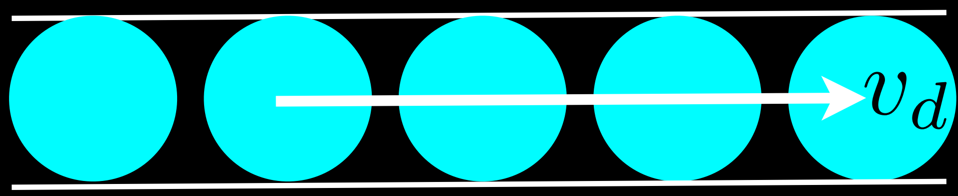
volume

charges / volume

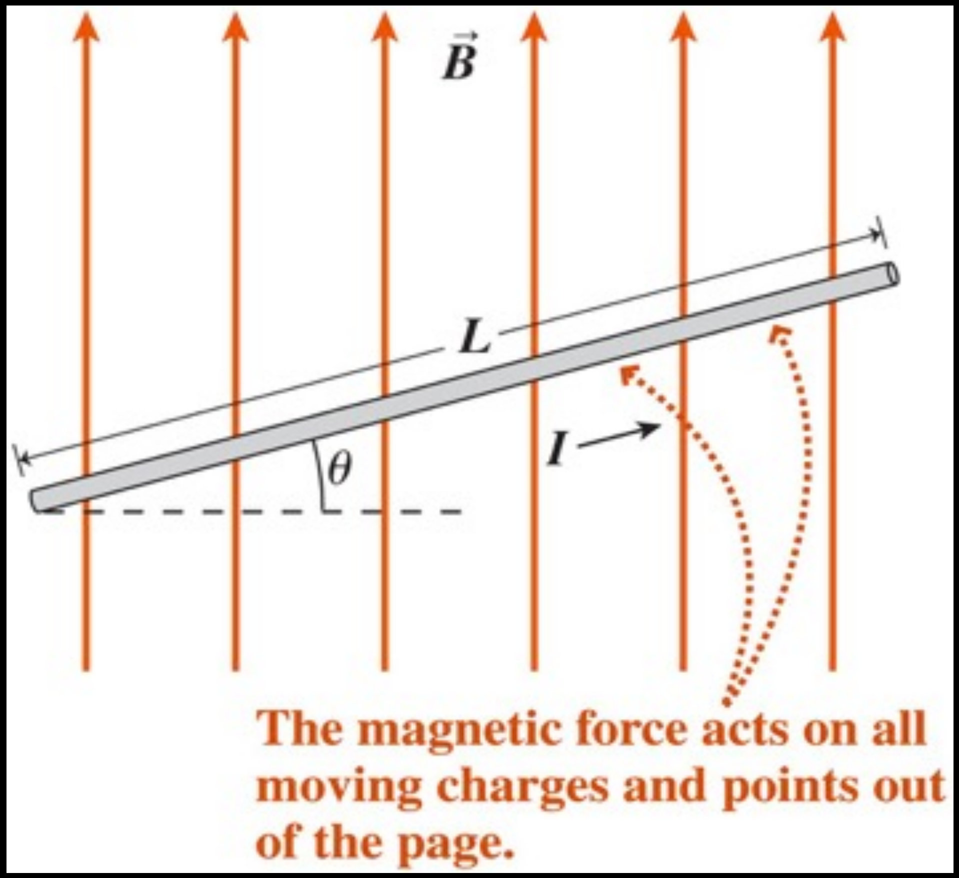


Magnetic force on a current

An electric current is moving charges



It feels a force in a magnetic field.



Each charge: $\bar{F}_q = q\bar{v}_d \times \bar{B}$

Force per length l:

$$\bar{F} = nAlq\bar{v}_d \times \bar{B}$$

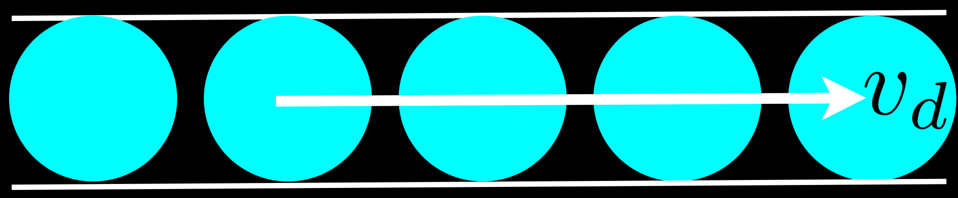
define current: $I = \dfrac{\Delta Q}{\Delta t} = \dfrac{nAlq}{l/v_d} = nAqv_d$

$$\bar{F} = I\bar{l} \times \bar{B}$$

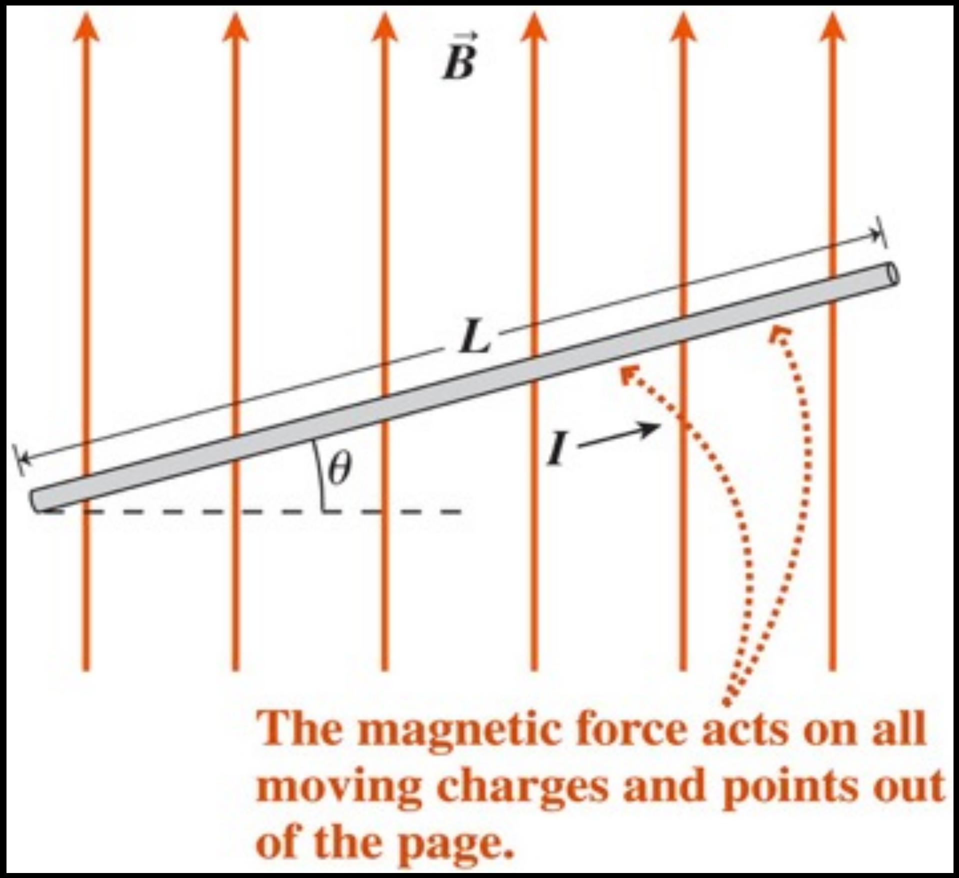
magnitude: wire length
direction: along wire

Magnetic force on a current

An electric current is moving charges



It feels a force in a magnetic field.



Each charge: $\bar{F}_q = q\bar{v}_d \times \bar{B}$

Force per length l:

$$\bar{F} = nAlq\bar{v}_d \times \bar{B}$$

define current: $I = \dfrac{\Delta Q}{\Delta t} = \dfrac{nAlq}{l/v_d} = nAqv_d$

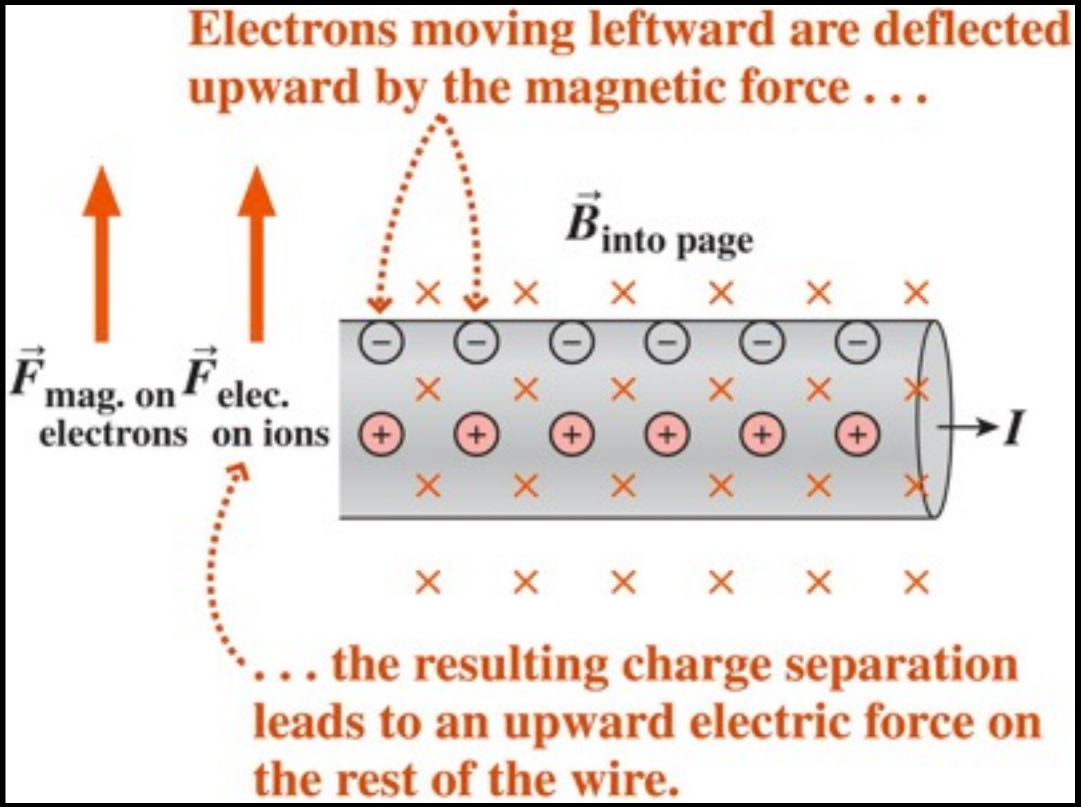
$$\bar{F} = I\bar{l} \times \bar{B}$$

magnetic force on a current

Magnetic force on a current

$\bar{F} = I\bar{l} \times \bar{B}$

magnetic force on a current



This force moves electrons to one side of the wire.

Creates electric force across wire.

Magnetic force on a current

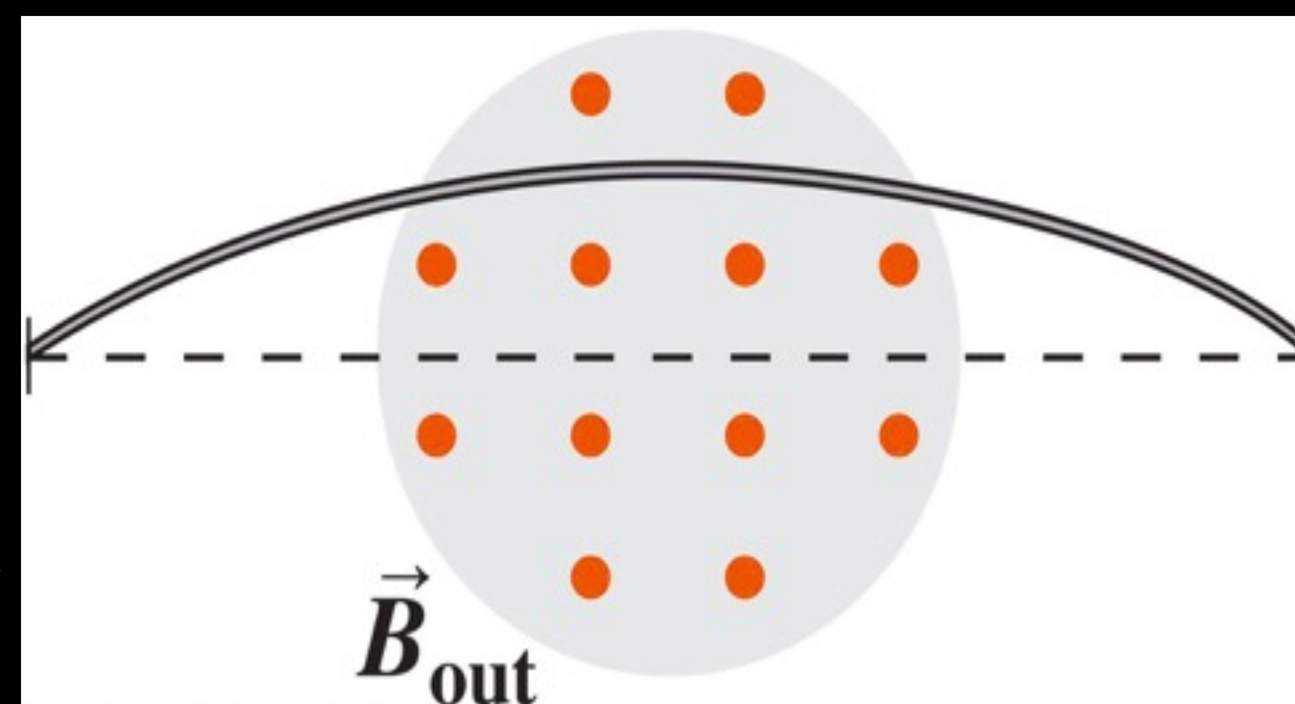
Quiz

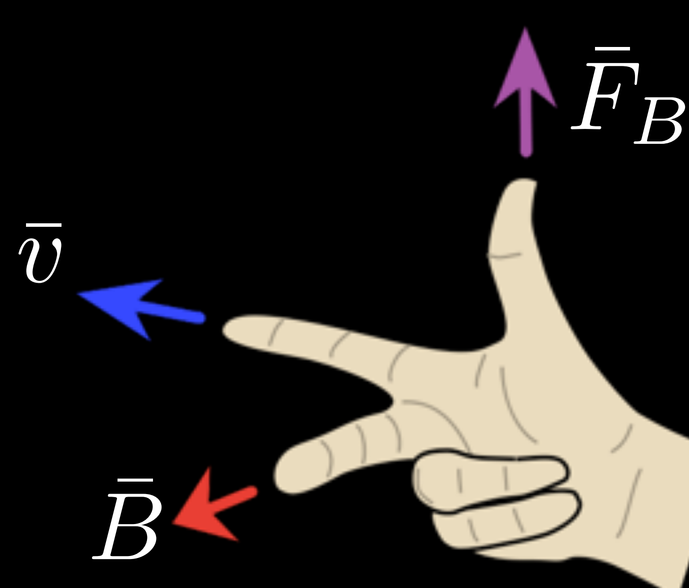
A flexible conducting wire passes through a magnetic field that points out of the page. The wire is deflected upward.

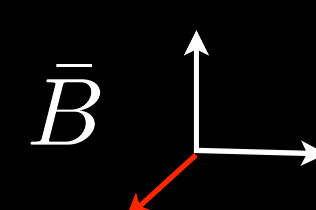
Which direction is current flowing in the wire?

(A) to the left

(B) to the right







out of page

Magnetic force on a current

Quiz

A wire carrying 15A current makes a 25 degree angle with a uniform magnetic field.

The magnetic force / unit length is 0.31 N/m.

What is the magnetic field strength?

(A) -156 mT

(B) 23 mT

(C) 49 mT

(D) 21 mT

$$\bar{F} = I\bar{l} \times \bar{B} \quad = IlB\sin\theta$$

$$B = \frac{F}{Il\sin\theta} = \frac{F}{l}\frac{1}{I\sin\theta}$$

$$= \frac{0.31\mathrm{N/m}}{(15A)\sin(25^\circ)} = 49\mathrm{mT}$$

Magnetic force on a current

Quiz

A wire carrying 15A current makes a 25 degree angle with a uniform magnetic field.

Magnetic field strength is 48.9 mT

What is the maximum force / unit length possible by *turning* the wire?

(A) 0.73 N/m

(B) 744.5 N/m

(C) 0.52 N/m

(D) 0 N/m

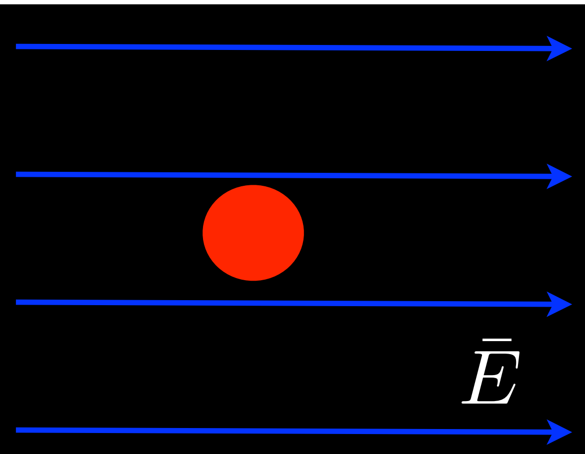
Max when $\sin\theta = 1$

$$\frac{F}{l} = IB = (15A)(48.9\mathrm{mT})$$

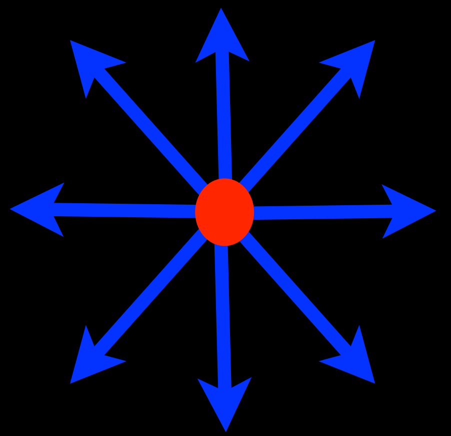
$$= 0.73\mathrm{N/m}$$

Origin of magnetic field

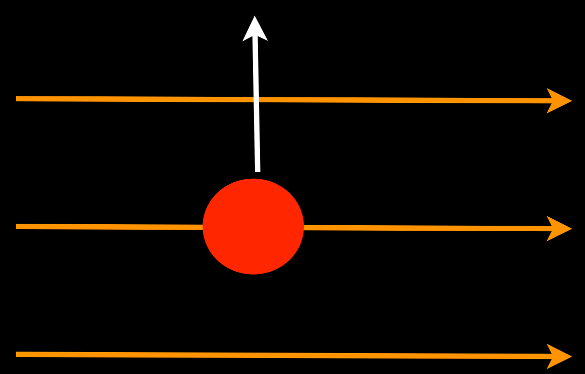
A charge feels a force in an electric field



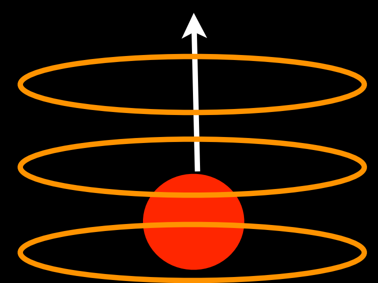
And a charge creates an electric field.



A moving charge feels a force in a magnetic field



A moving charge creates a magnetic field

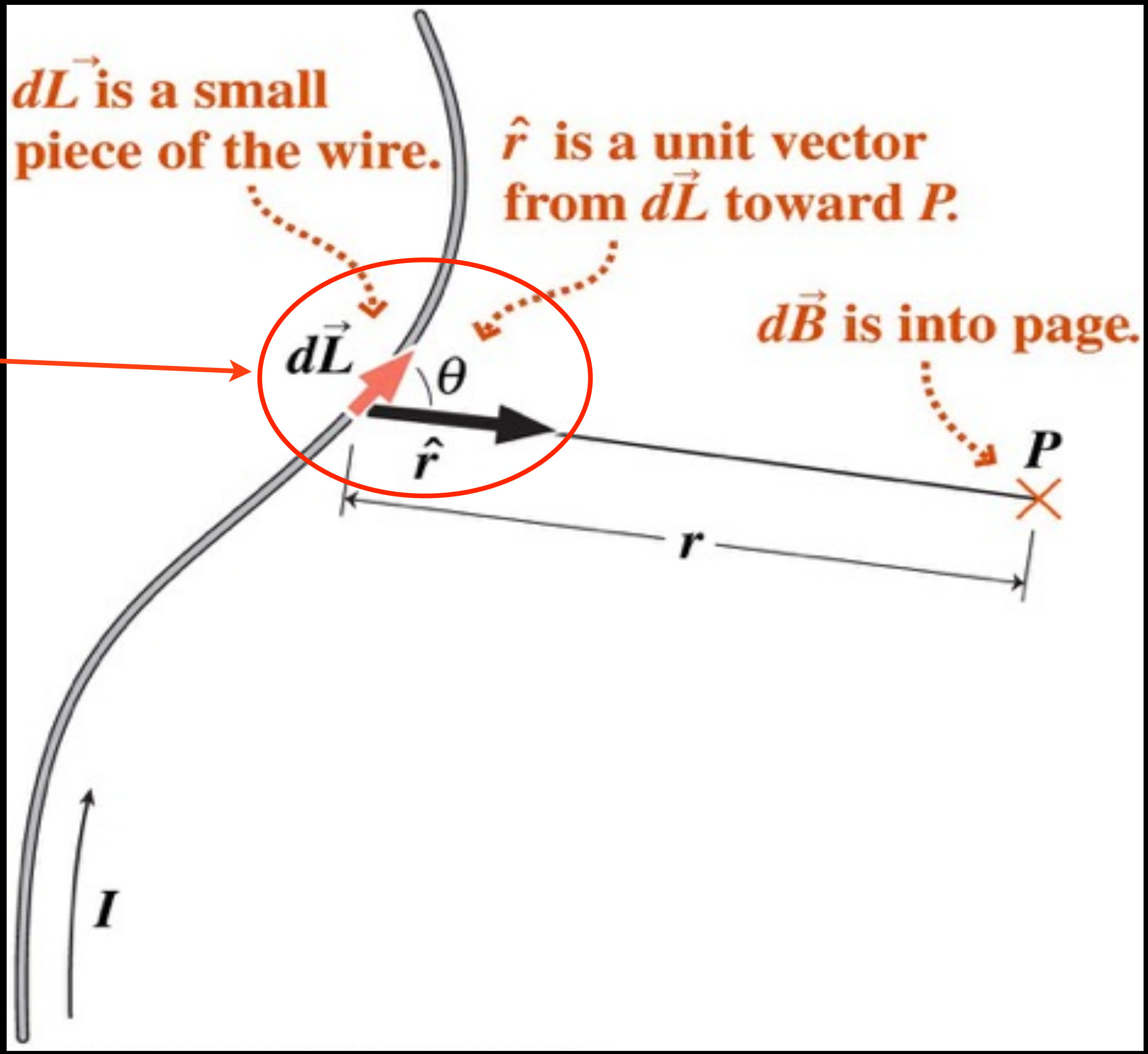


Origin of magnetic field

Biot-Savart Law

Beo-savaar

$$d\bar{B} = \frac{\mu_0}{4\pi}\frac{I d\bar{l} \times \bar{r}}{r^2}$$



Gives magnetic field, $d\bar{B}$, at point P from current element, $Id\bar{l}$

(Similar to Coulomb's law for electric field, $d\bar{E}$, from charge element, dq)

$\mu_0 = 4\pi \times 10^{-7} \mathrm{N/A^2}$ permeability constant

$$\bar{B} = \int d\bar{B} = \frac{\mu_0}{4\pi}\int \frac{I d\bar{l} \times \hat{r}}{r^2}$$

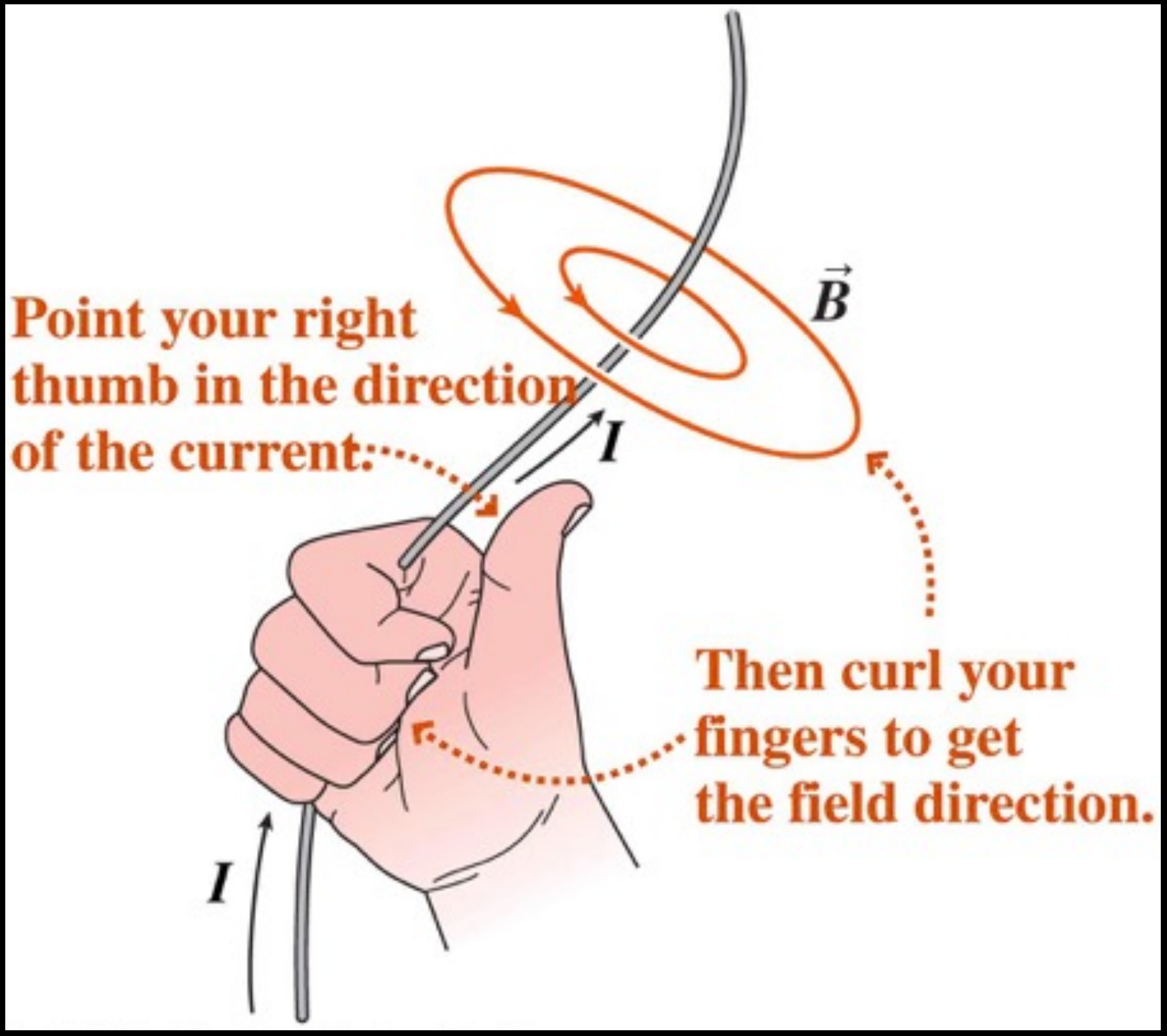
Origin of magnetic field

Electric field lines begin and end on charges.

But the magnetic field does not begin and end on moving charges

The magnetic field encircles the moving charge or current.

Magnetic field lines do not begin or end.



Direction from right-hand grip rule

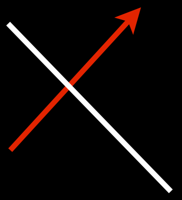
Using the Biot-Savart Law

A current loop

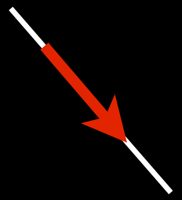
Find $\bar{B}$ at point P on axis of a circular loop carrying current I.

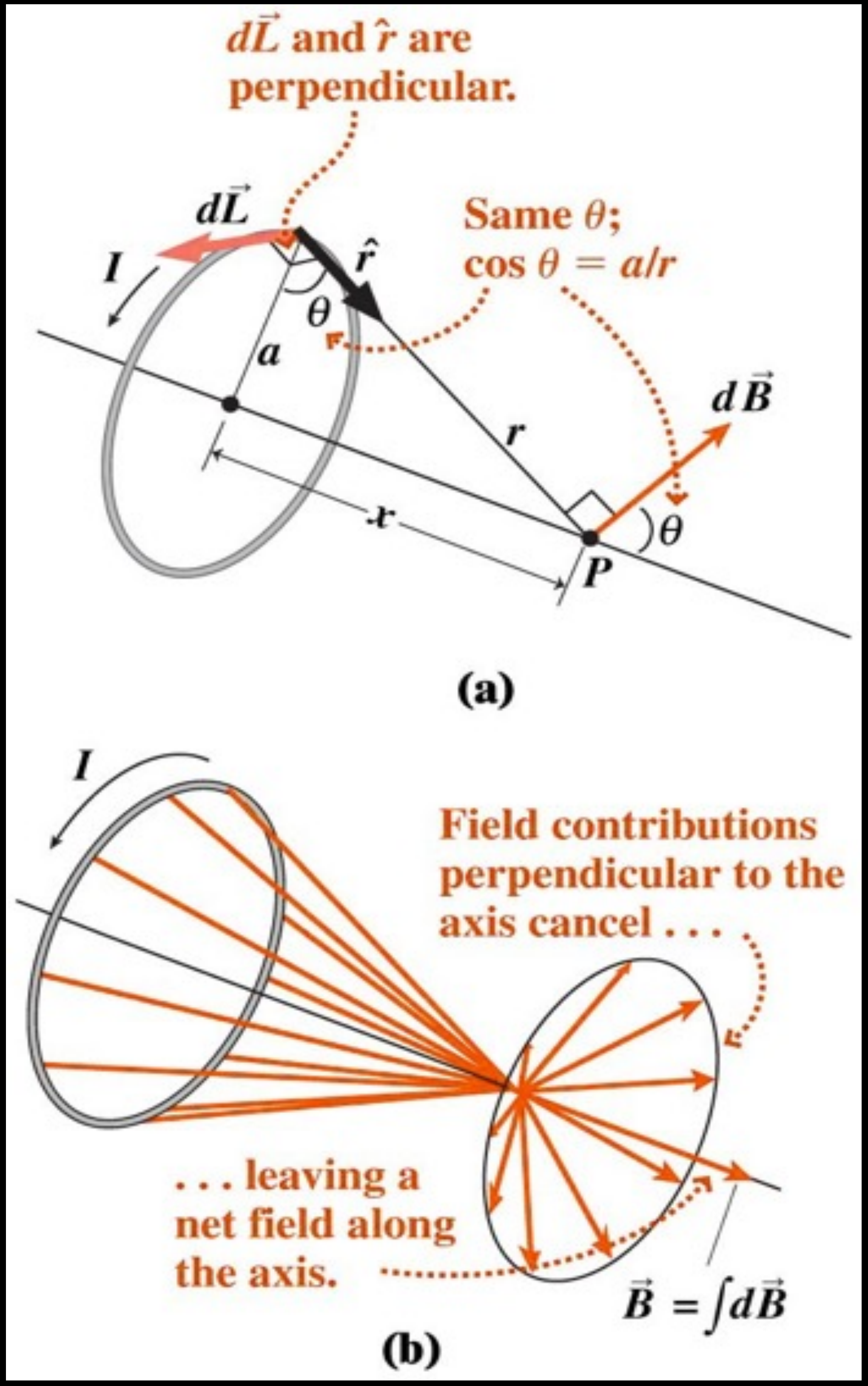
Direction of $\bar{B}$ given by right hand grip rule.

Perpendicular field components cancel.



Parallel add.





Using the Biot-Savart Law

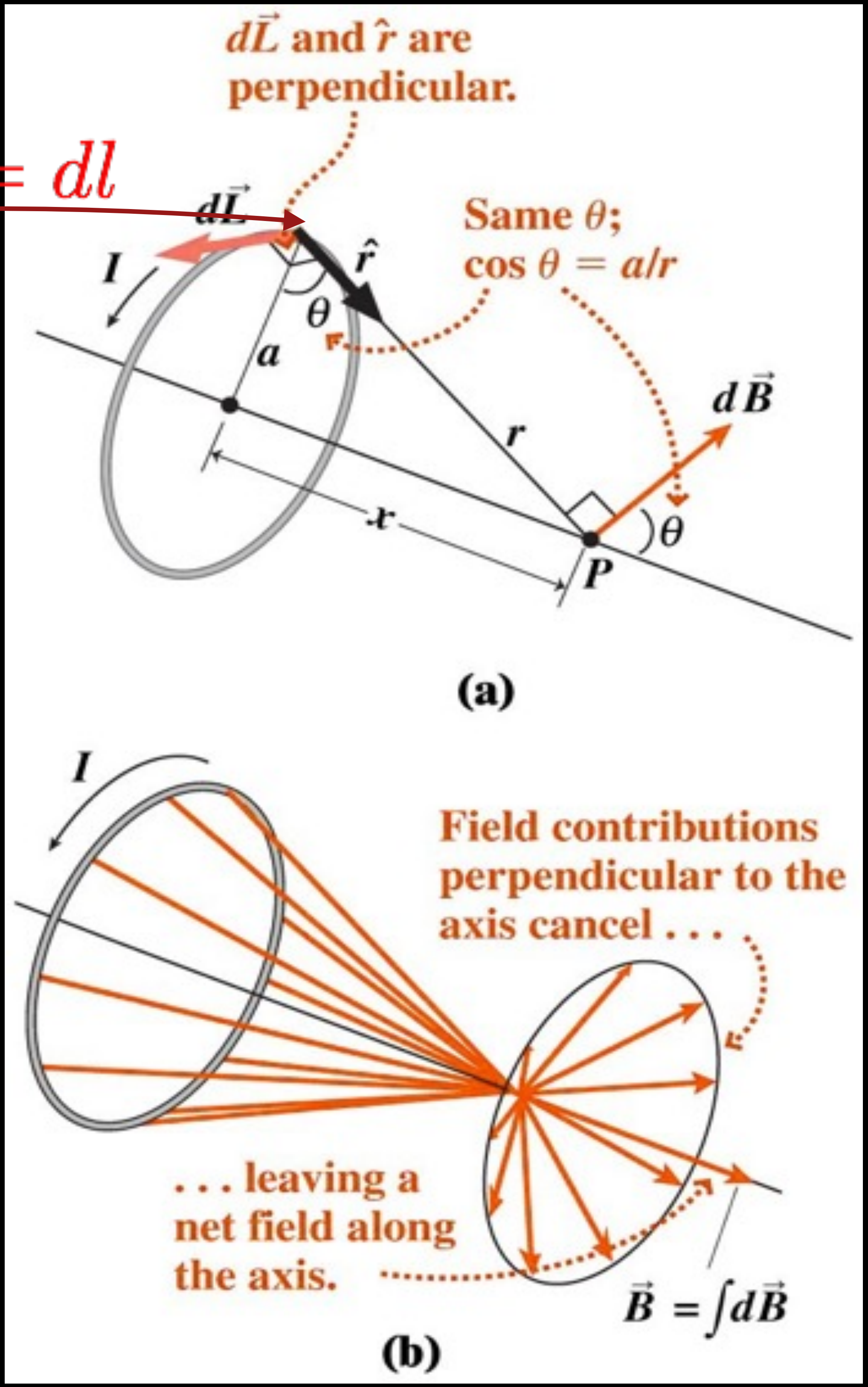
A current loop

$$\bar{B} = \int dB_x \quad = \int dB \cos\theta$$

$$d\bar{l} \times \hat{r} = dl$$

$$= \frac{\mu_0 I}{4\pi} \int_{\text{loop}} \frac{dl}{x^2 + a^2} \frac{a}{\sqrt{x^2 + a^2}}$$

r^2 $\quad$ $\cos\theta$



Using the Biot-Savart Law

A current loop

$$\bar{B} = \int dB_x \quad = \int dB \cos\theta$$

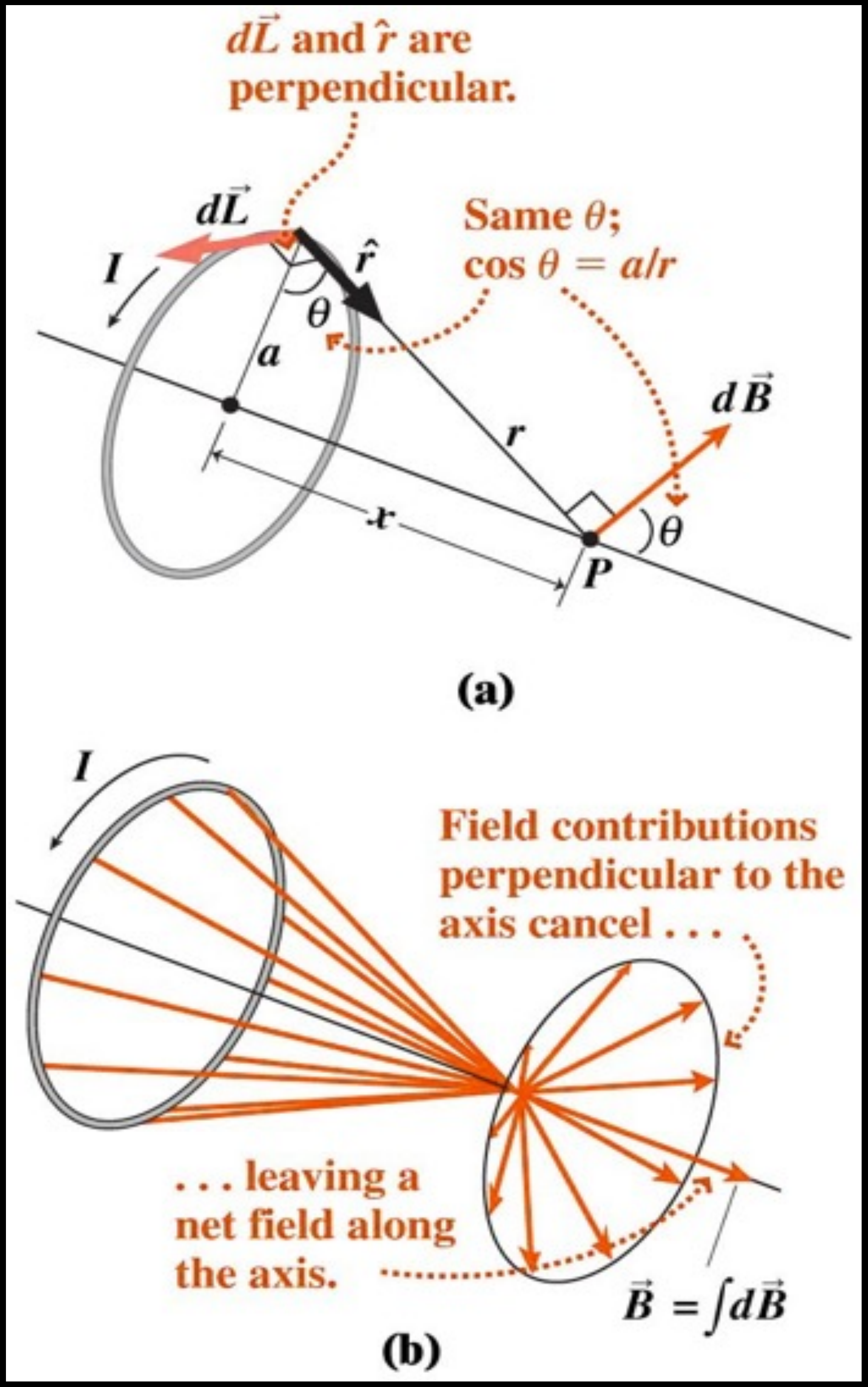
$$= \frac{\mu_0 I}{4\pi} \int_{\text{loop}} \frac{dl}{x^2 + a^2} \frac{a}{\sqrt{x^2 + a^2}}$$

$$B = \frac{\mu_0 I a}{4\pi (x^2 + a^2)^{3/2}} \int_{\text{loop}} dl$$

loop circumference: $2\pi a$

distance, x, to P is same for everywhere on loop (move outside integral)

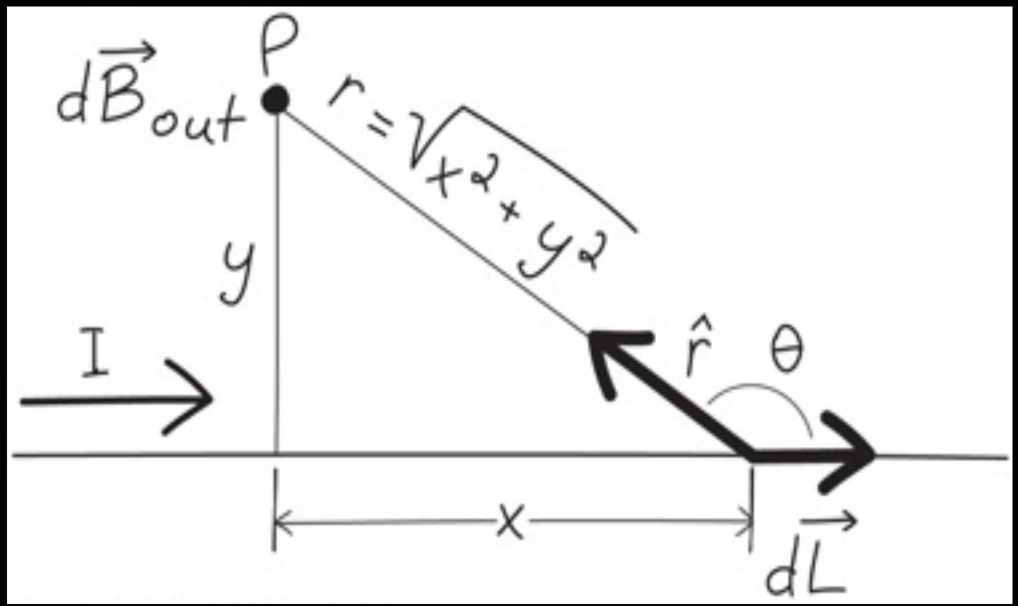
$$B = \frac{\mu_0 I a^2}{2(x^2 + a^2)^{3/2}}$$

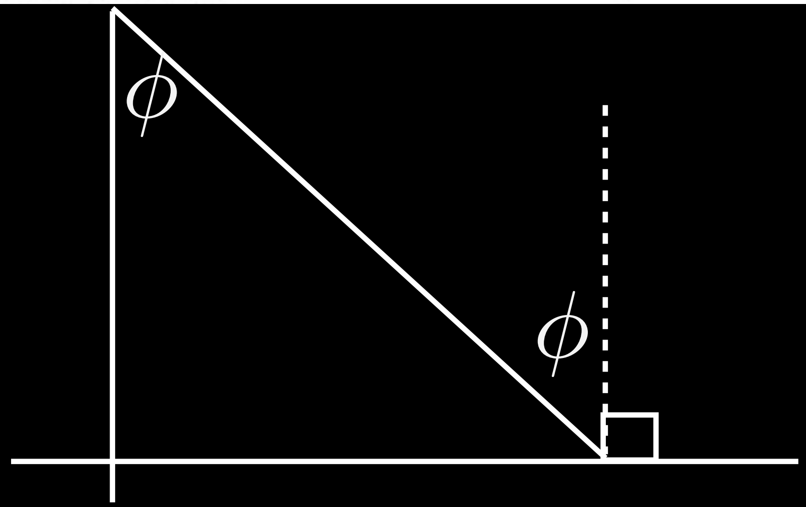


Using the Biot-Savart Law

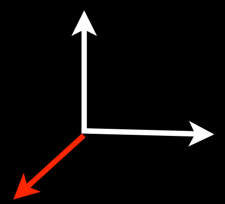
Field of a straight wire

Find $\bar{B}$ at point P from an infinitely long straight wire carrying current I.





Direction of $\bar{B}$ given by right hand grip rule.

$\bar{B}$  out of page

$$d\bar{B} = \frac{\mu_0}{4\pi}\frac{I d\bar{l} \times \bar{r}}{r^2} = \frac{\mu_0 I}{4\pi}\frac{dl \sin\theta}{r^2}$$

$$\sin\theta = \frac{y}{r} = \frac{y}{\sqrt{x^2 + y^2}}$$

$$\sin\theta = \sin(\phi + 90)$$

$$= \sin 90 \cos\phi + \cos 90 \sin\phi$$

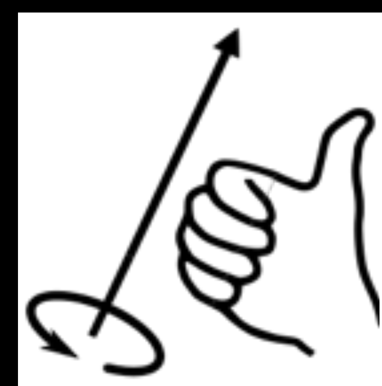
$$= \cos\phi \quad = \frac{y}{r}$$

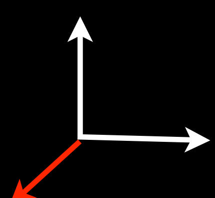
Using the Biot-Savart Law

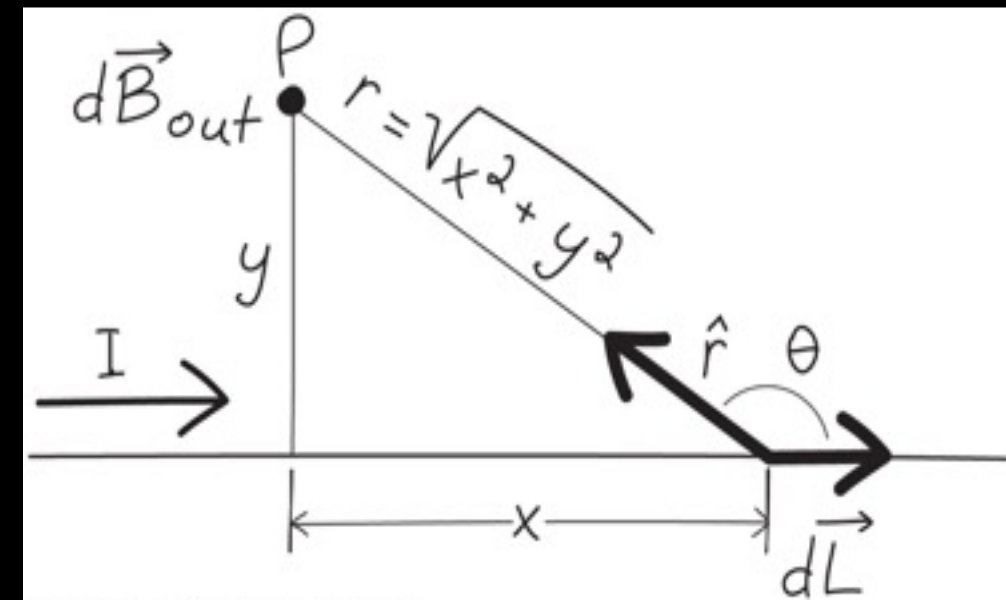
Field of a straight wire

Find $\bar{B}$ at point P from an infinitely long straight wire carrying current I.

Direction of $\bar{B}$ given by right hand grip rule.



$\bar{B}$  out of page



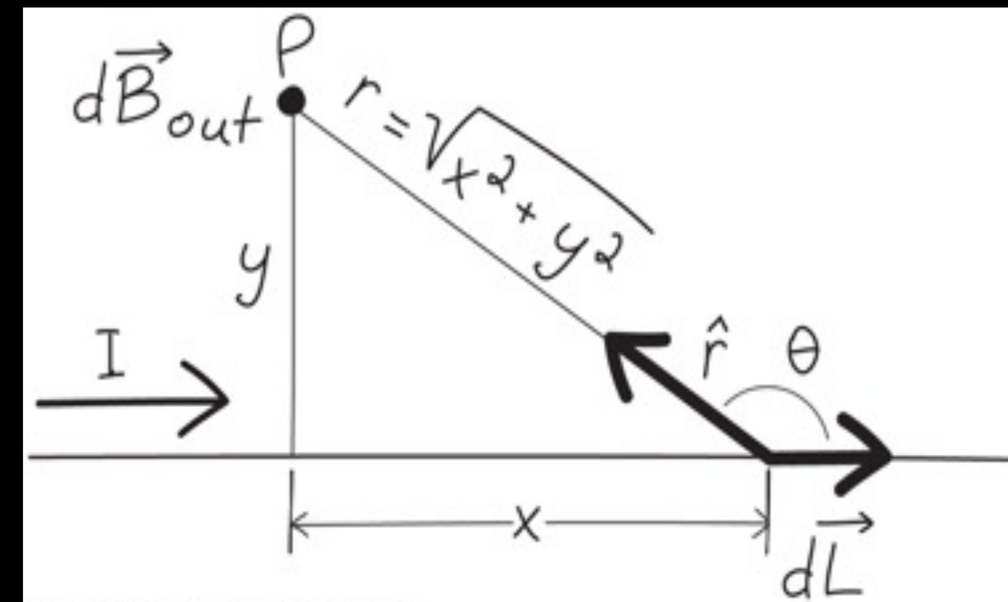
$$d\bar{B} = \frac{\mu_0}{4\pi} \frac{I d\bar{l} \times \bar{r}}{r^2} = \frac{\mu_0 I}{4\pi} \frac{dl \sin\theta}{r^2} = \frac{\mu_0 I}{4\pi} \frac{y\,dl}{(x^2 + y^2)^{3/2}}$$

on axis: $dl = dx$

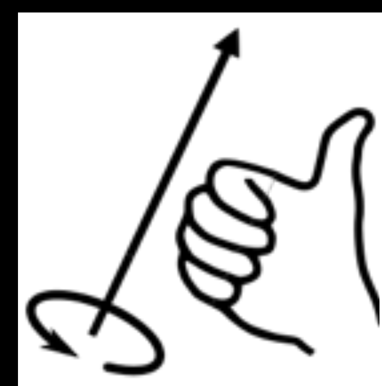
Using the Biot-Savart Law

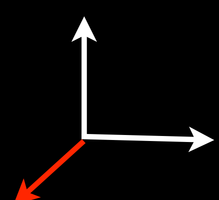
Field of a straight wire

Find $\bar{B}$ at point P from an infinitely long straight wire carrying current I.



Direction of $\bar{B}$ given by right hand grip rule.



$\bar{B}$  out of page

$$d\bar{B} = \frac{\mu_0}{4\pi}\frac{I d\bar{l} \times \bar{r}}{r^2} = \frac{\mu_0 I}{4\pi}\frac{dl \sin\theta}{r^2} = \frac{\mu_0 I}{4\pi}\frac{y dl}{(x^2+y^2)^{3/2}}$$

$$B = \int dB = \frac{\mu_0 I y}{4\pi}\int_{-\infty}^{\infty}\frac{dx}{(x^2+y^2)^{3/2}} = \frac{\mu_0 I}{2\pi y}$$

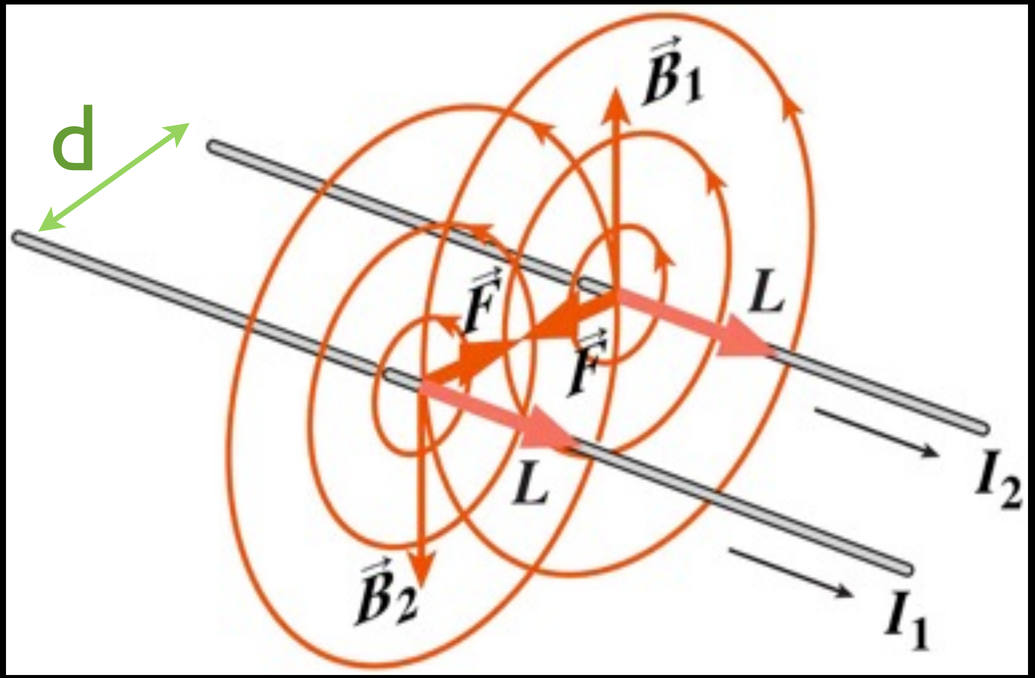
Using the Biot-Savart Law

Since magnetic fields produce a force on current-carrying wires:

$$\bar{F} = I\bar{l} \times \bar{B}$$

and current-carrying wires produce a magnetic field....

Current-carrying wires exert a force on each other.



Field from wire 1 at wire 2:

$$B_1 = \frac{\mu_0 I_1}{2\pi d}$$

This field is perpendicular to wire 2:

$$F_2 = I_2 l \times B_1 = \frac{\mu_0 I_1 I_2 l}{2\pi d}$$

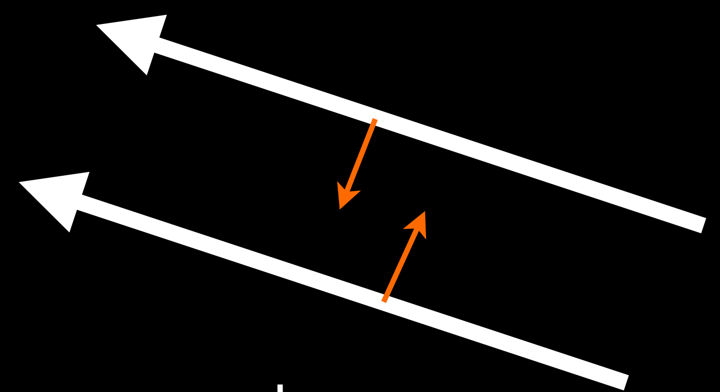
magnetic force between 2 wires

Using the Biot-Savart Law

$$F = \frac{\mu_0 I_1 I_2 l}{2\pi d}$$

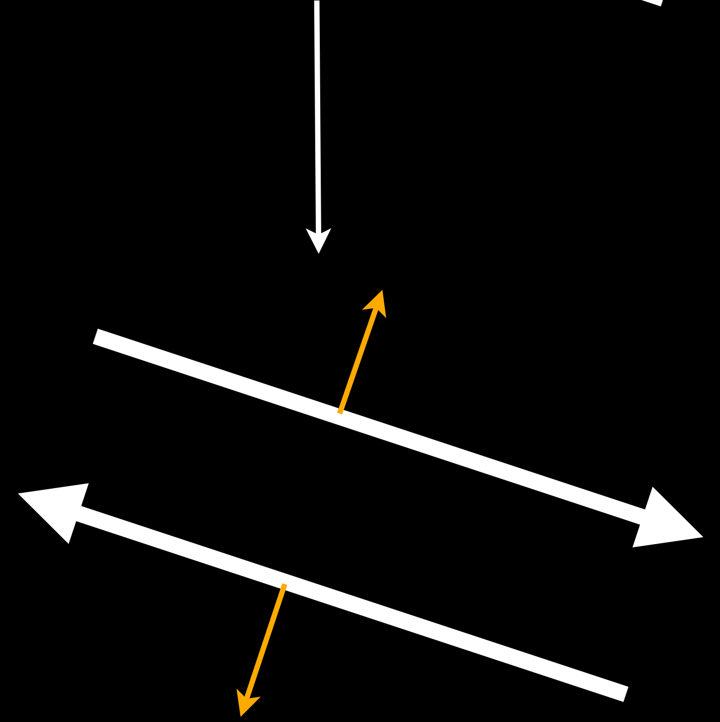
Force on each wire

Parallel currents attract.



If one current is reversed, the sign will change since: $I = nAqv_d$

$$F = \frac{\mu_0 I_1 (-I_2) l}{2\pi d} = -\frac{\mu_0 I_1 I_2 l}{2\pi d}$$



Anti-parallel currents repel

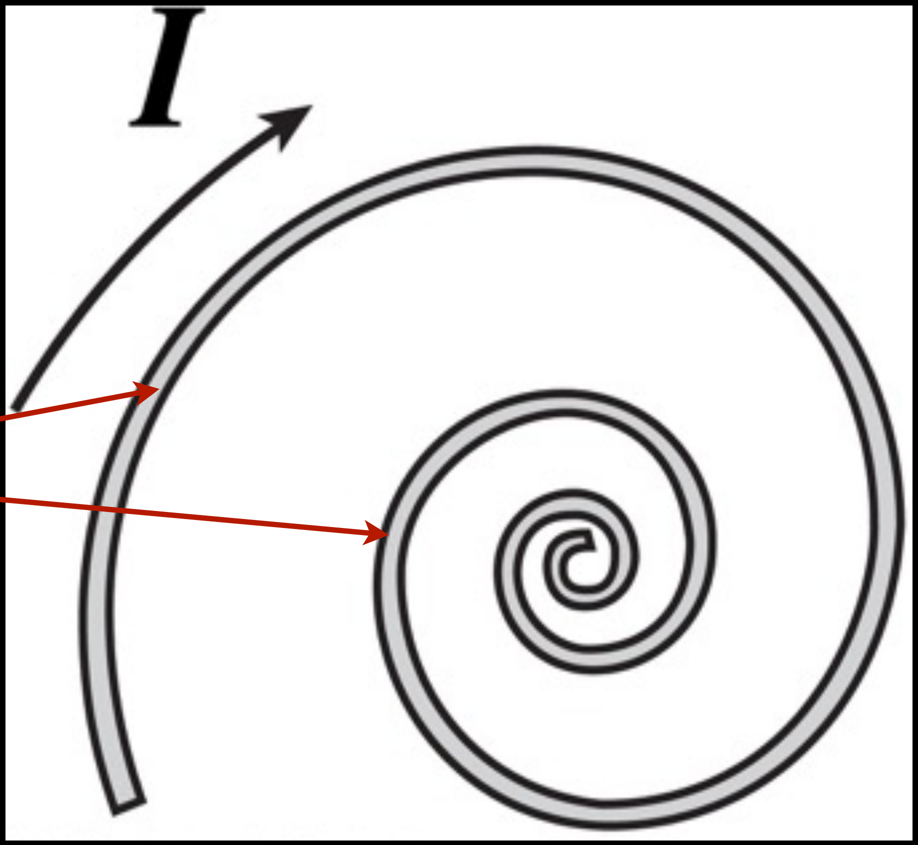
Using the Biot-Savart Law

A flexible wire is wound into a flat spiral. If a current flows in the direction shown, will the coil tighten or become looser?

(A) Tighten

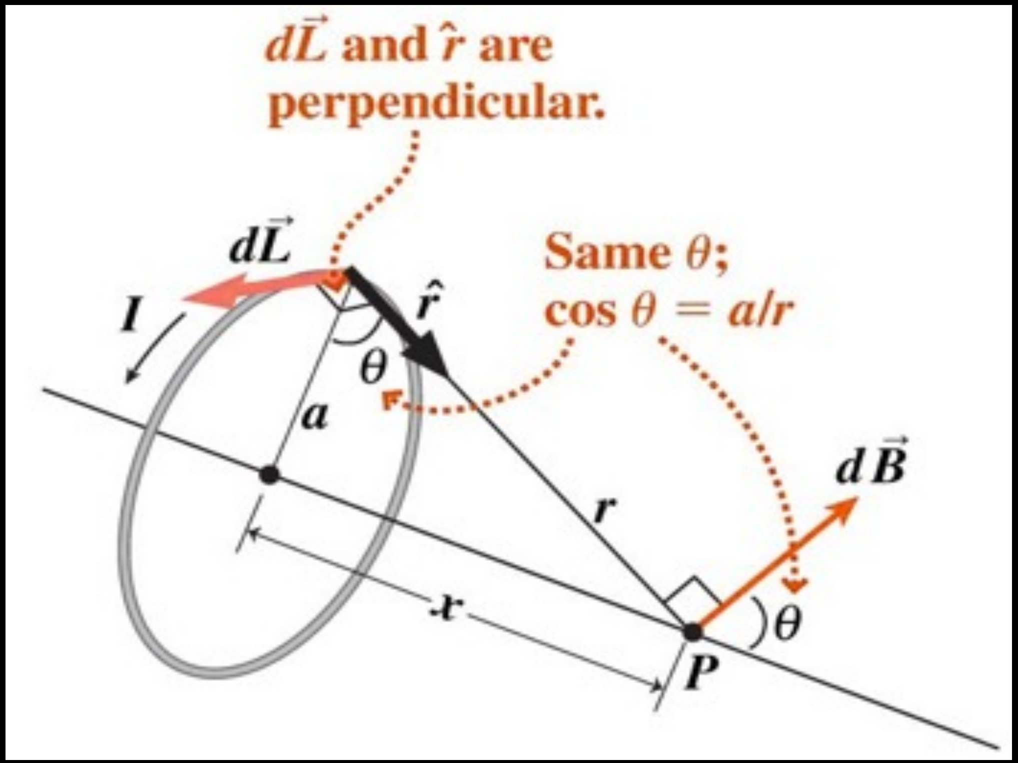
(B) Loosen

current is
parallel



Magnetic dipoles

Field from a loop: $B = \dfrac{\mu_0 I a^2}{2(x^2 + a^2)^{3/2}}$



For x >> a: $B \simeq \dfrac{\mu_0 I a^2}{2x^3} = \dfrac{2\mu_0 I A}{4\pi x^3}$

A = loop area

Compare with on-axis electric dipole: $\bar{E} = \dfrac{2kp}{x^3}\hat{i}$

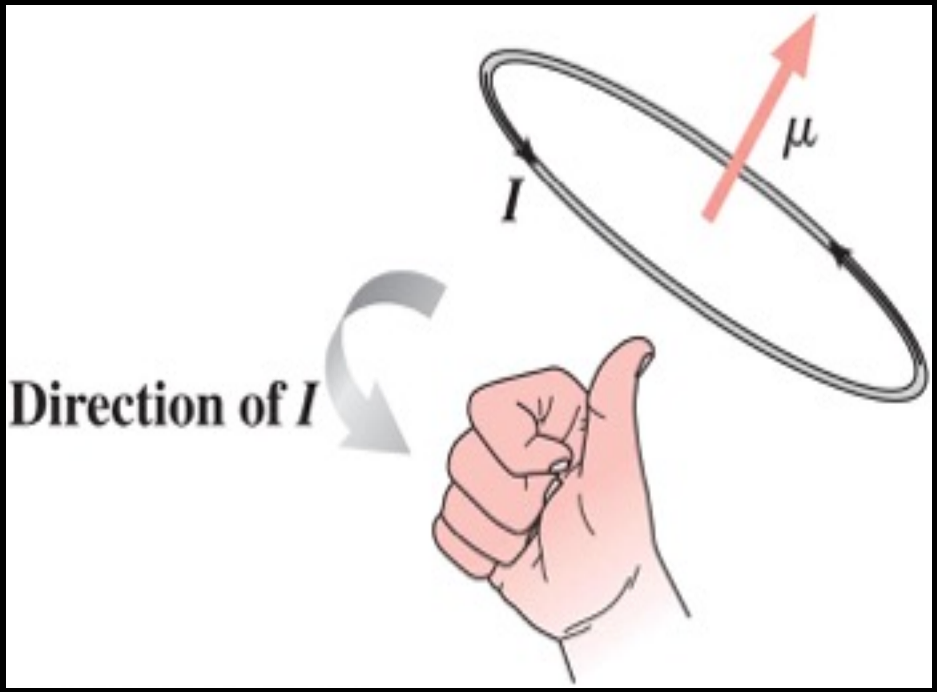
magnetic dipole moment: $\mu = IA$ ⟶ $B = \dfrac{\mu_0}{2\pi}\dfrac{\mu}{x^3}$

The current loop is a magnetic dipole.

Magnetic dipoles

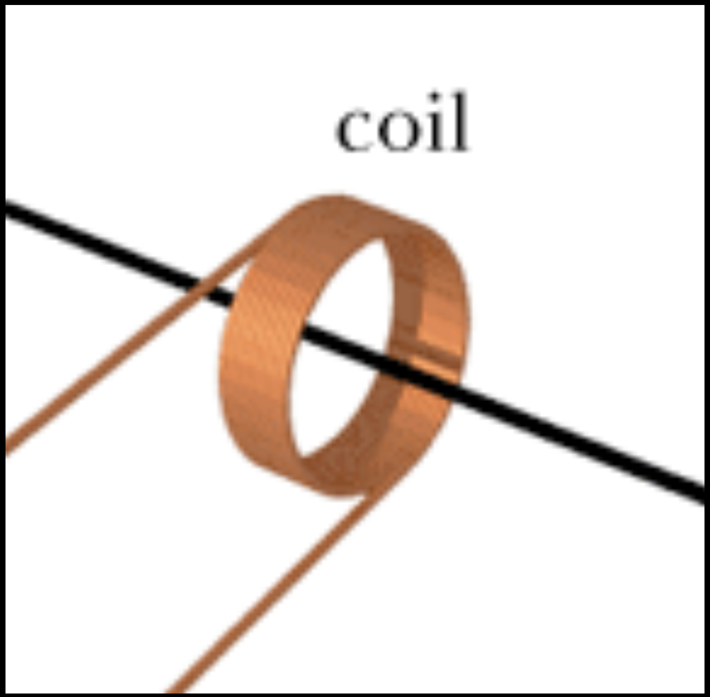
The magnetic dipole moment is a vector:

$$\bar{\mu} = I\bar{A}$$



Direction given by right hand grip rule.

Current loops normally have many turns:



$$\boxed{\bar{\mu} = NI\bar{A}}$$

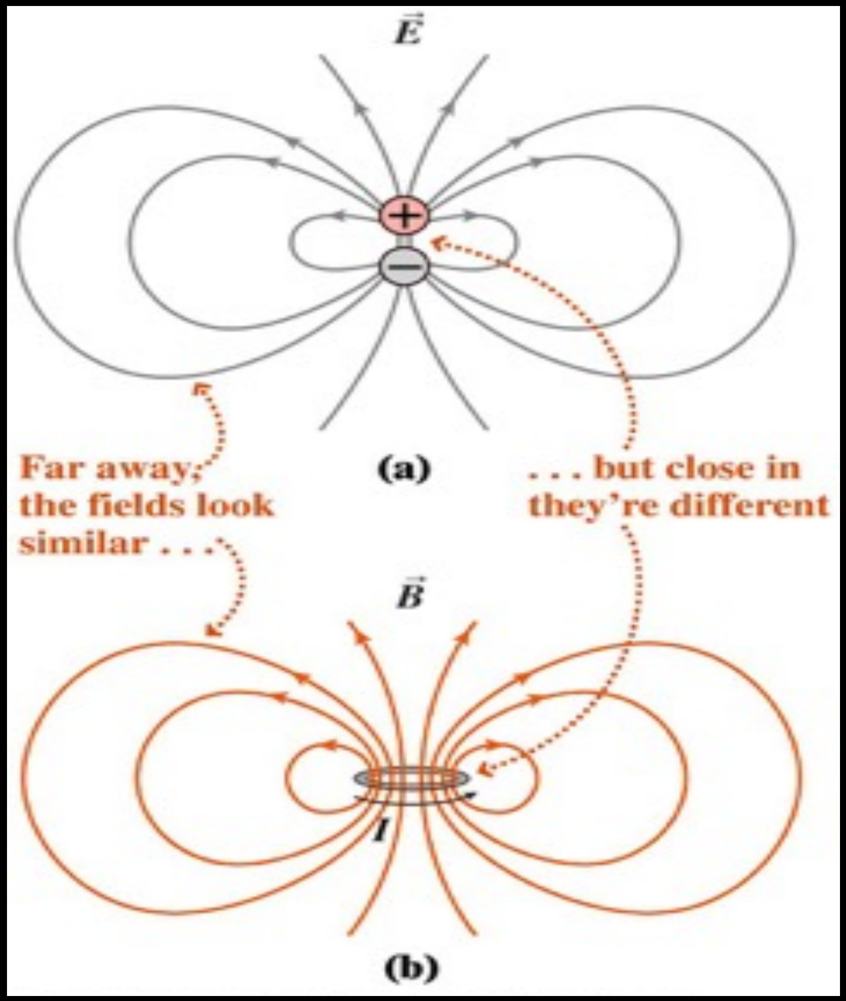
magnetic dipole moment for N-turn loop

True for any shape closed loop

Any current loop is an magnetic dipole

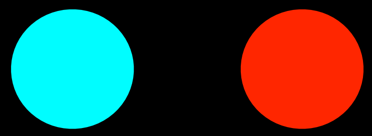
Magnetic dipoles

Far from the dipole, electric dipoles and magnetic dipoles look the same.



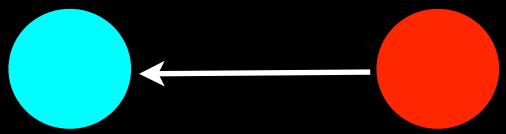
Near the dipole, they look different.

Electric dipoles can be split into positive and negative charges:

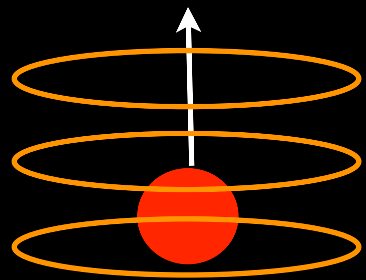


But magnetic charges or monopoles has never been found.

Electric field lines start and stop on charges.

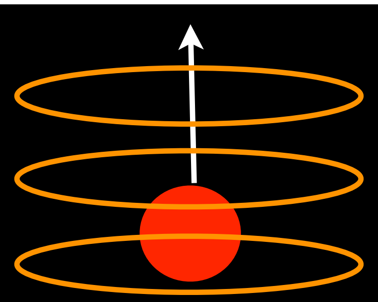


Magnetic field lines do not begin or end, but circle moving charge.



Magnetic dipoles

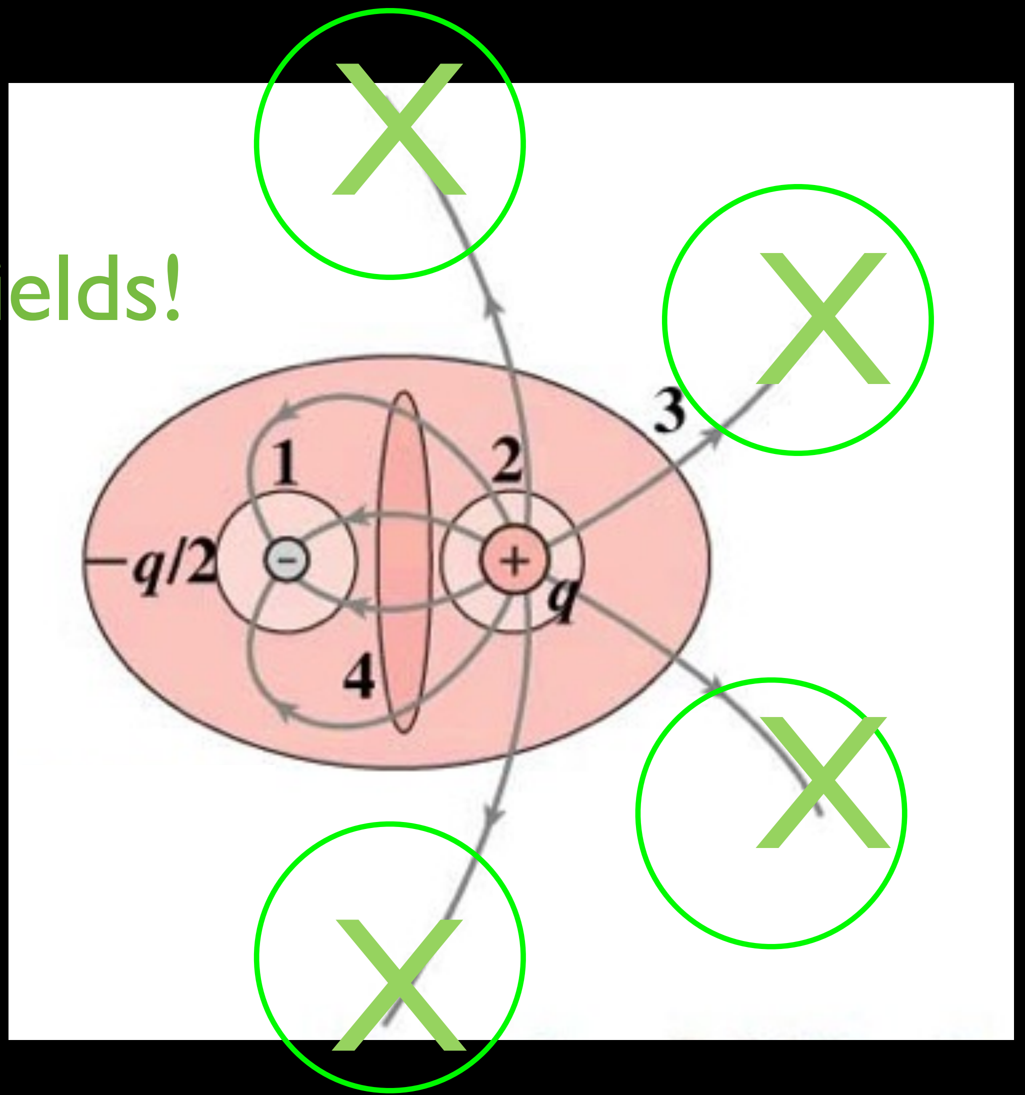
Because magnetic field lines do not begin or end....



... the magnetic flux is always zero!

$$\oint \bar{B} \cdot d\bar{A} = 0$$

Never for magnetic fields!

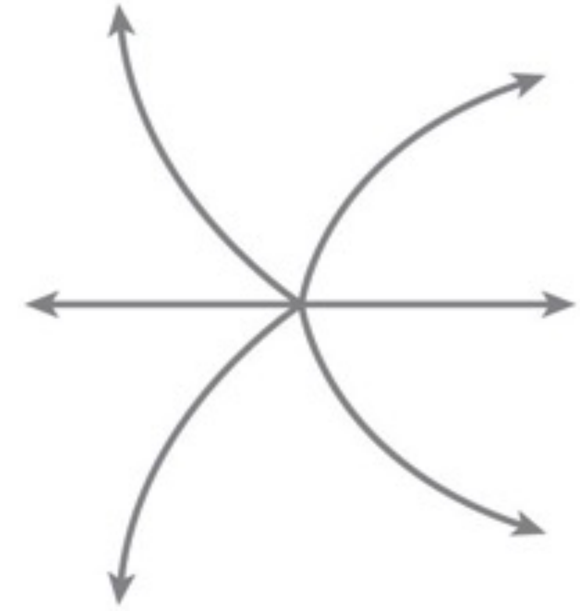


Gauss's law for magnetism

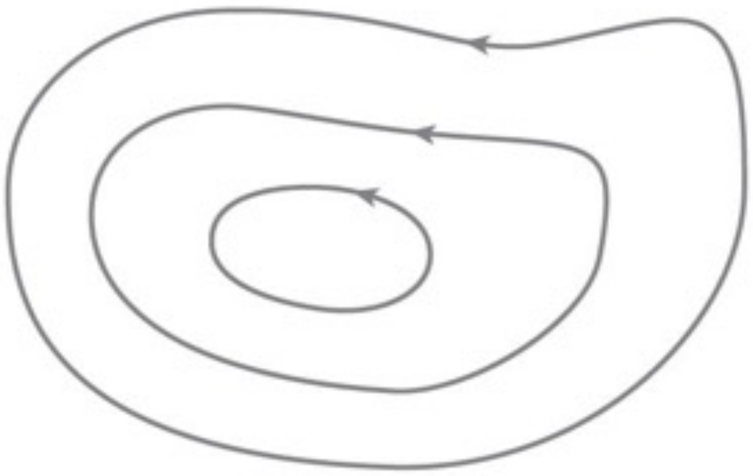
If monopoles are discovered....
Gauss's law will break!

Magnetic dipoles

Which field lines could be a magnetic field?



(a)



(b)

(A) a

(B) b

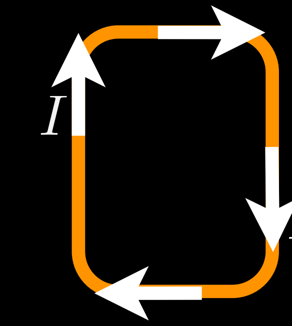
$$\oint \bar{B} \cdot d\bar{A} = 0$$

Net field lines through a closed surface = 0

Torque on a current loop

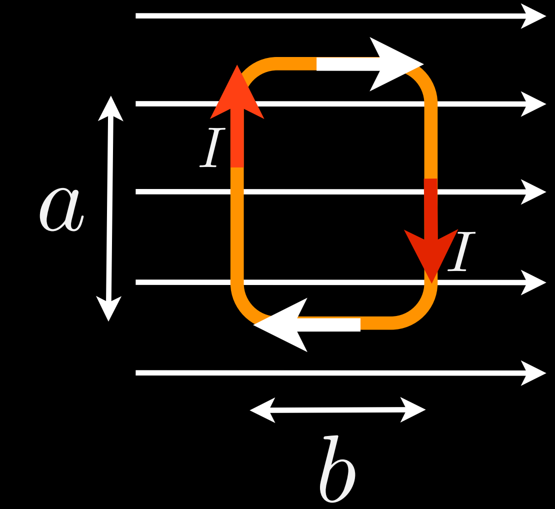
Like the electric dipole, the magnetic dipole feels a torque (turning force) in a magnetic field.

Opposite sides of loop have current in opposite directions



In uniform field, net force = 0

But component perpendicular to $\bar{B}$ creates a torque



$\bar{F} = I\bar{l} \times \bar{B} \; = IaB$ For each perpendicular side

$$\tau_{\rm side} = rF\sin\theta = \frac{1}{2}bF\sin\theta \; = \frac{1}{2}bIaB\sin\theta$$

$$\tau_{\rm net} = 2\tau_{\rm side} = IabB\sin\theta \; = IAB\sin\theta \; = \mu B\sin\theta$$

loop area

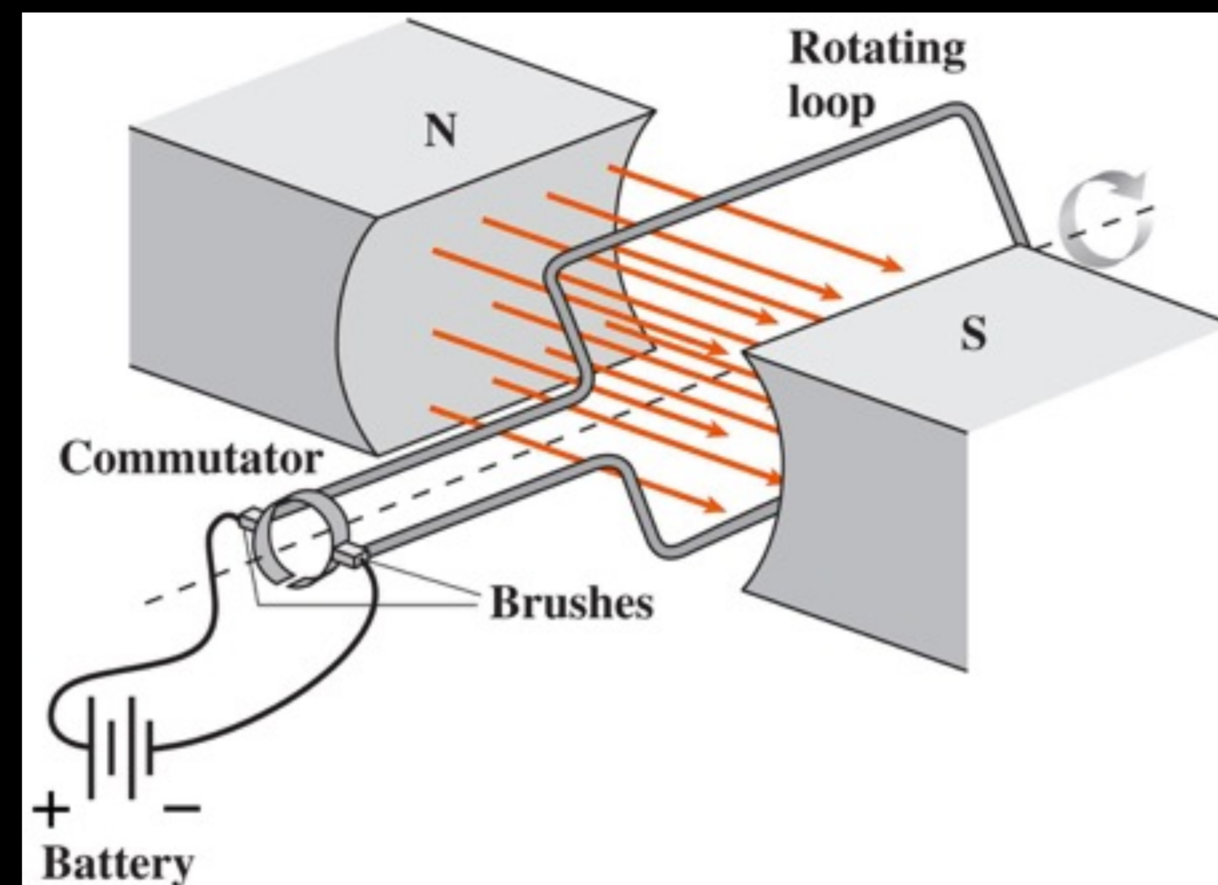
$$\bar{\tau} = \bar{\mu} \times \bar{B}$$

Torque on a current loop

The magnetic dipole turns to align with magnetic field.

If the current is reversed, the dipole will keep turning.

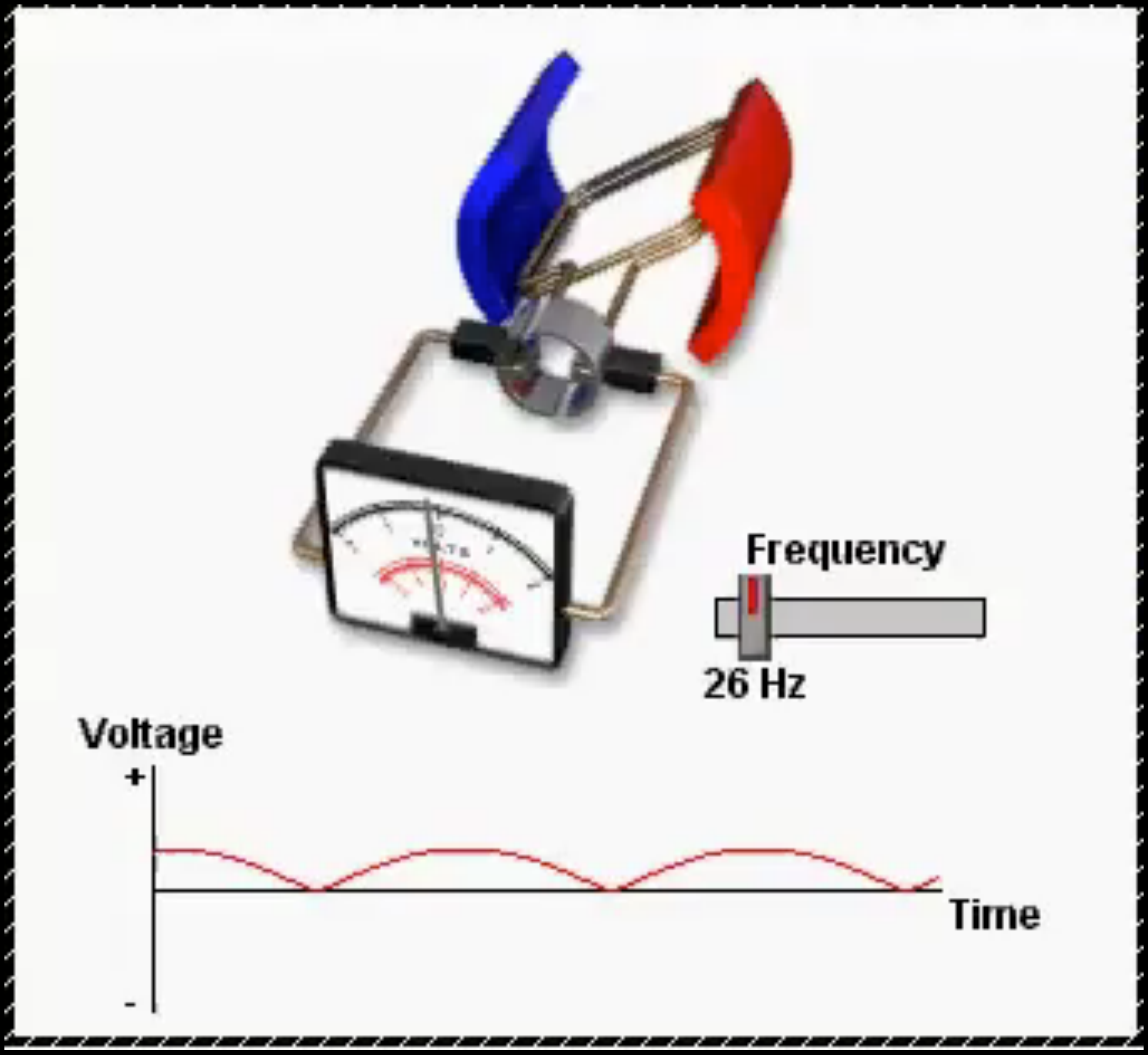
In an DC electric motor, the current loop spins between magnetic poles



Just before the dipole aligns with the field, the current direction is changed.

Loop keeps spinning in same direction.

Torque on a current loop



Torque on a current loop

Quiz

A rectangular current loop is in a uniform magnetic field.

What is the direction of the net force on the loop?

a) + x

b) + y

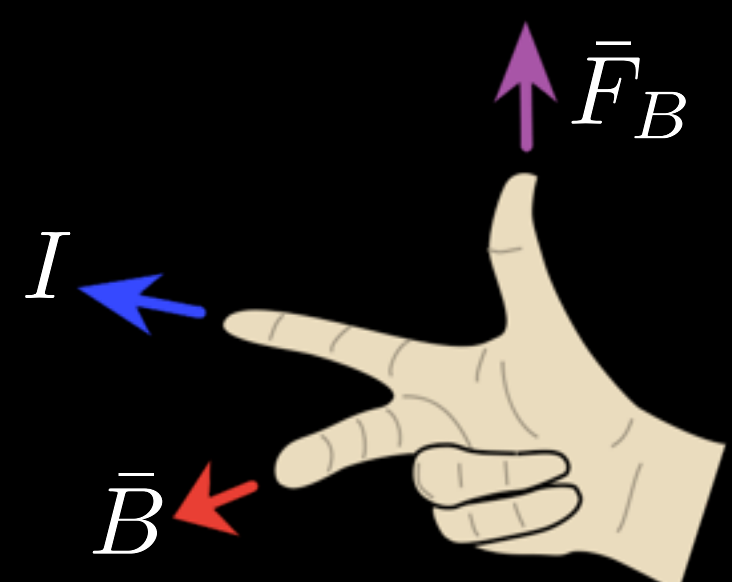
c) zero

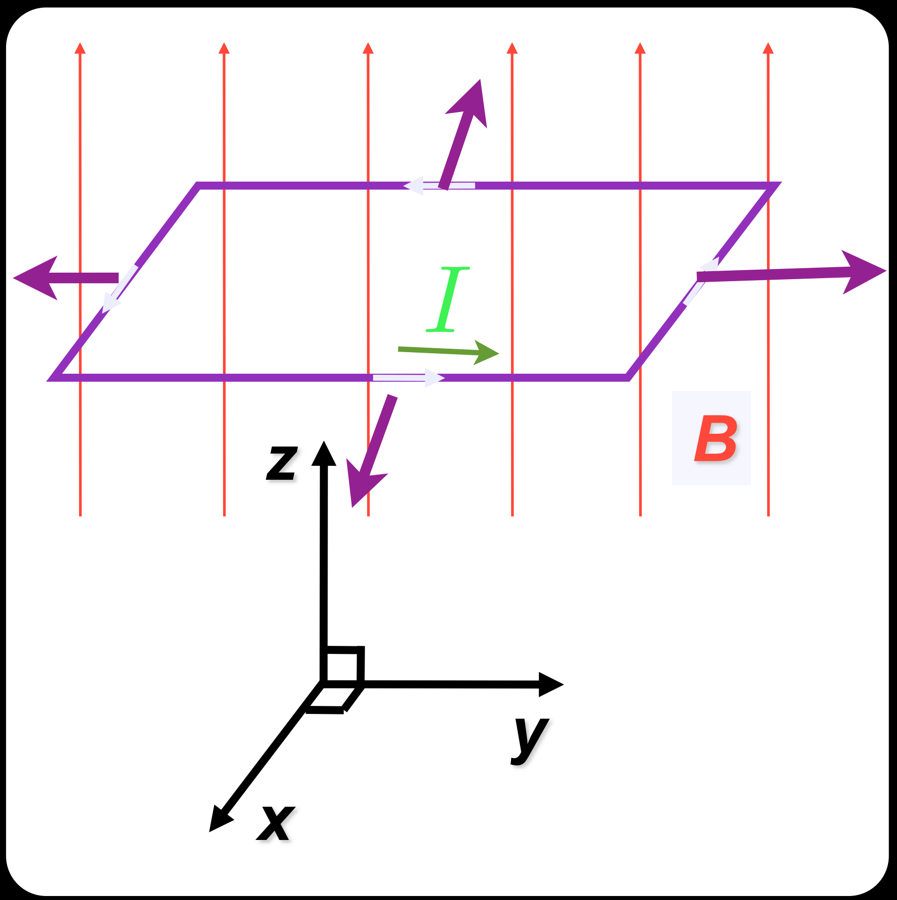
d) - x

e) - y

Forces all point out.
No torque, no net force.

$$\bar{F} = I\bar{l} \times \bar{B}$$





Torque on a current loop

Quiz

If there is a current in the loop in the direction shown, the loop will:

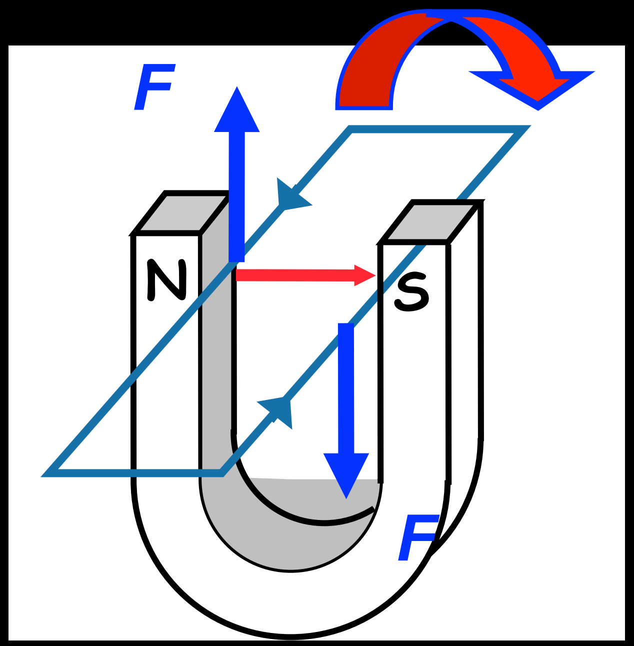
a) move up

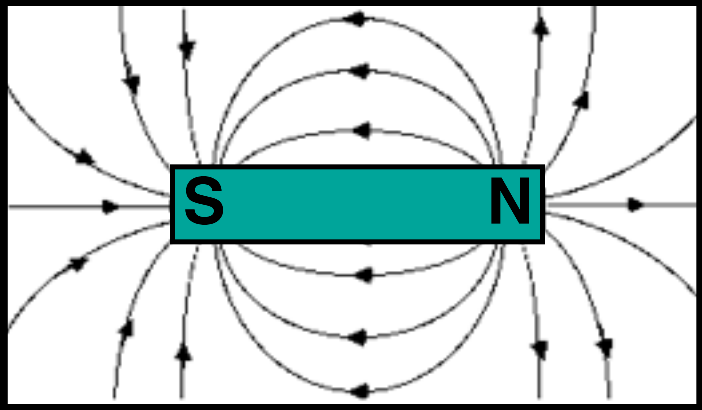
b) move down

c) rotate clockwise

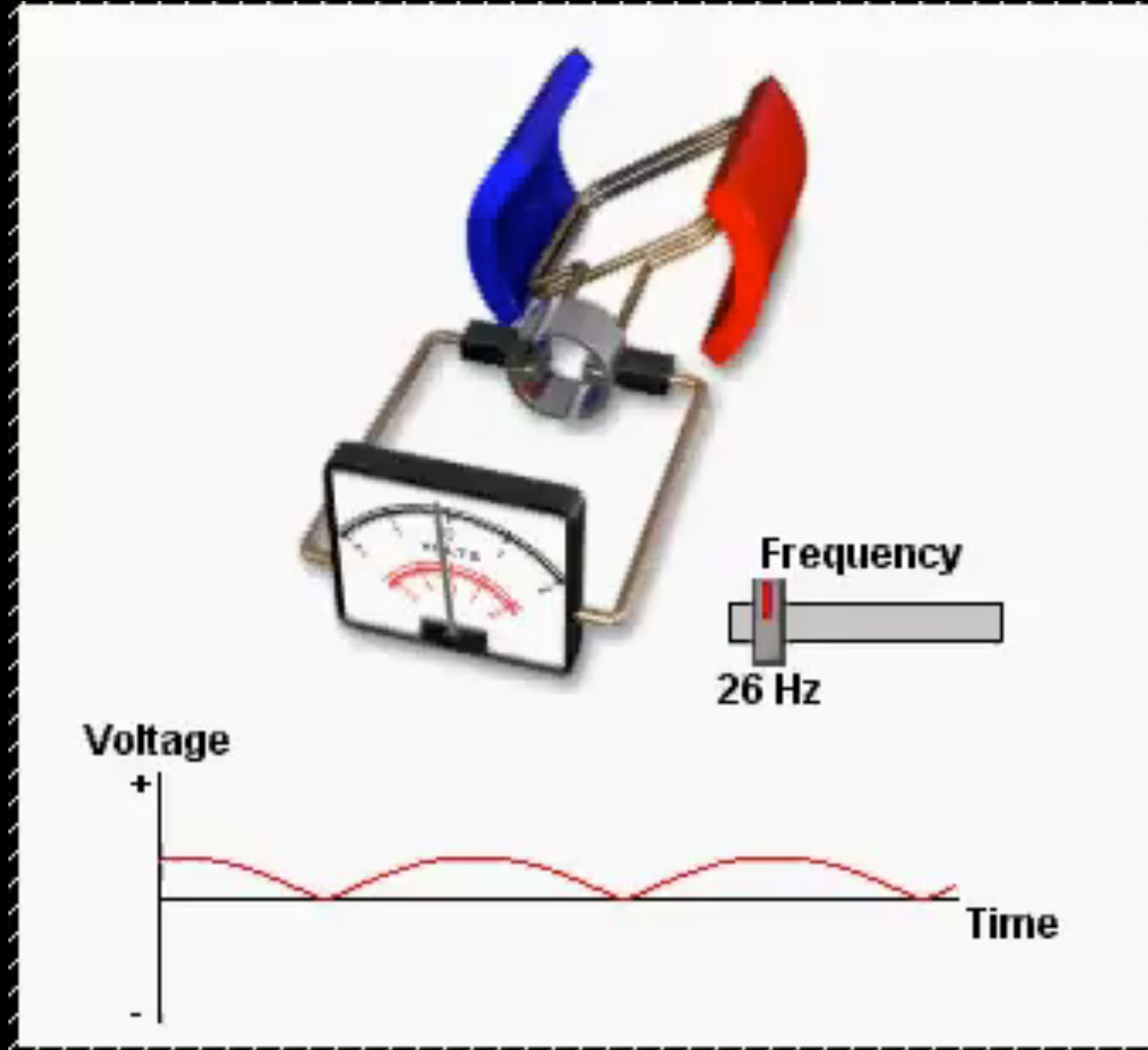
d) rotate counterclockwise

e) both rotate and move





End~



(First half of C26)

Water delivery

The Earth formed dry…

… so where did our water come from?

A likely option is after the Earth formed…

(隕石)

icy meteorites hit our planet

and delivered the water

Hayabusa2

Hayabusa2 launched December 2014

It will visit asteroid Ryugu

Take 3 samples

And return to Earth in 2020

It may bring with it the beginnings of our water