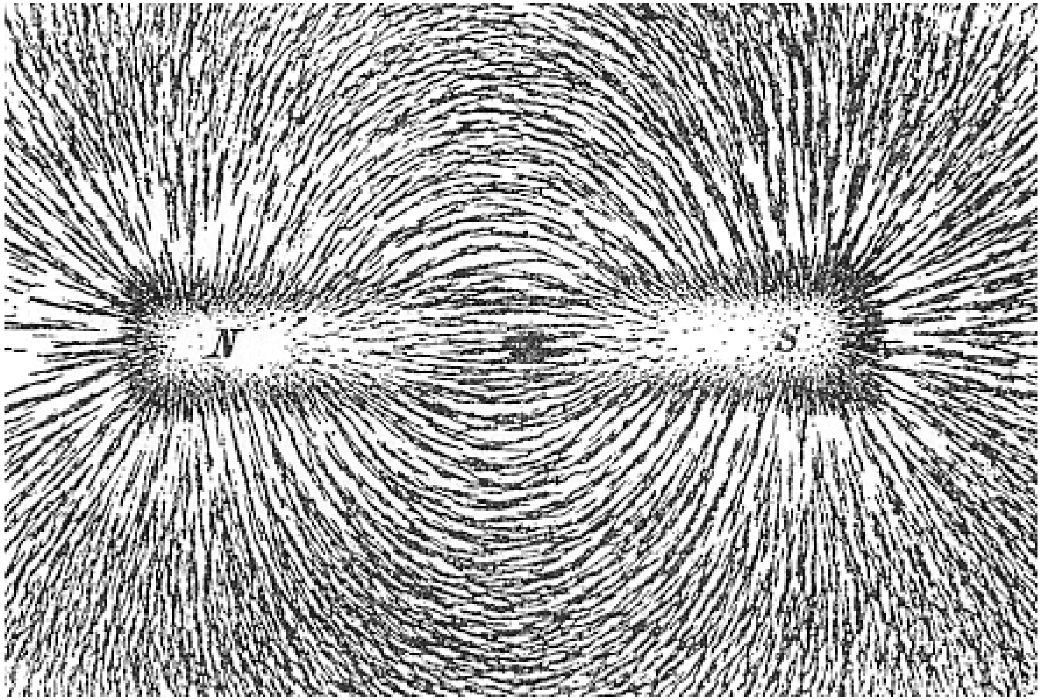
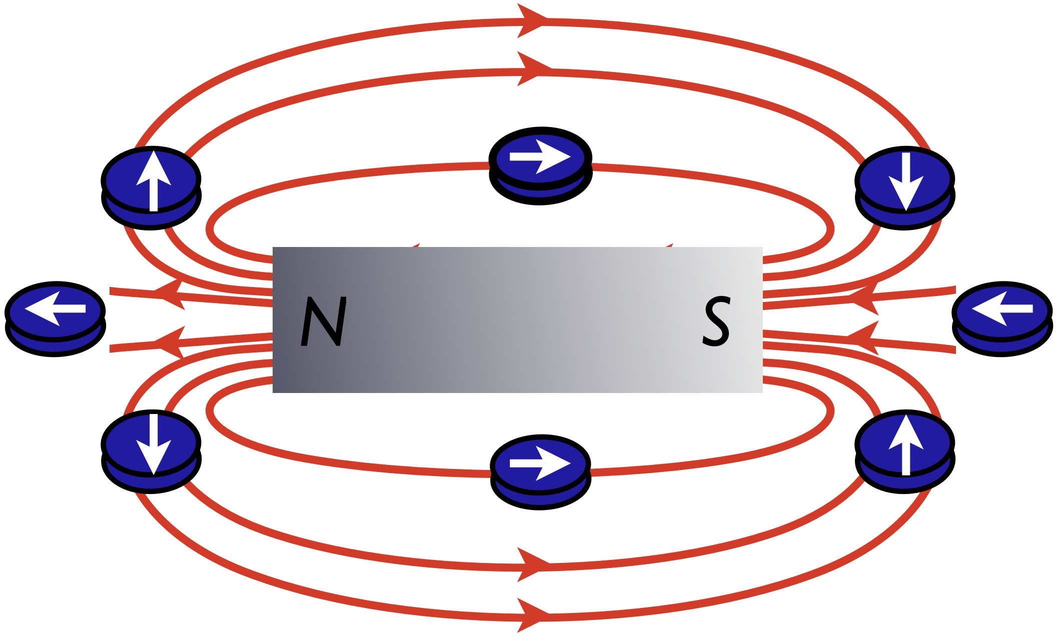
- exam 1 back tomorrow
- HW4 = solve the other 2 exam problems
  - due tonight
- short quiz tomorrow
  - magnetic forces, fields from wires

(a)



(b)

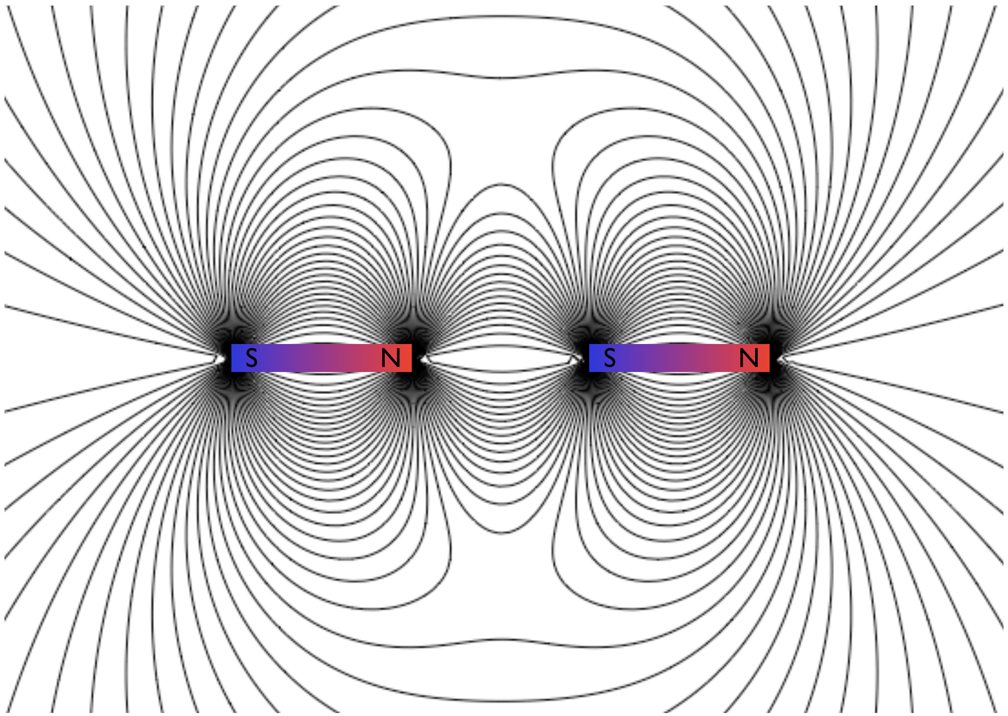


magnetism is not like electricity exactly.

magnets come only in +/- or N/S pairs

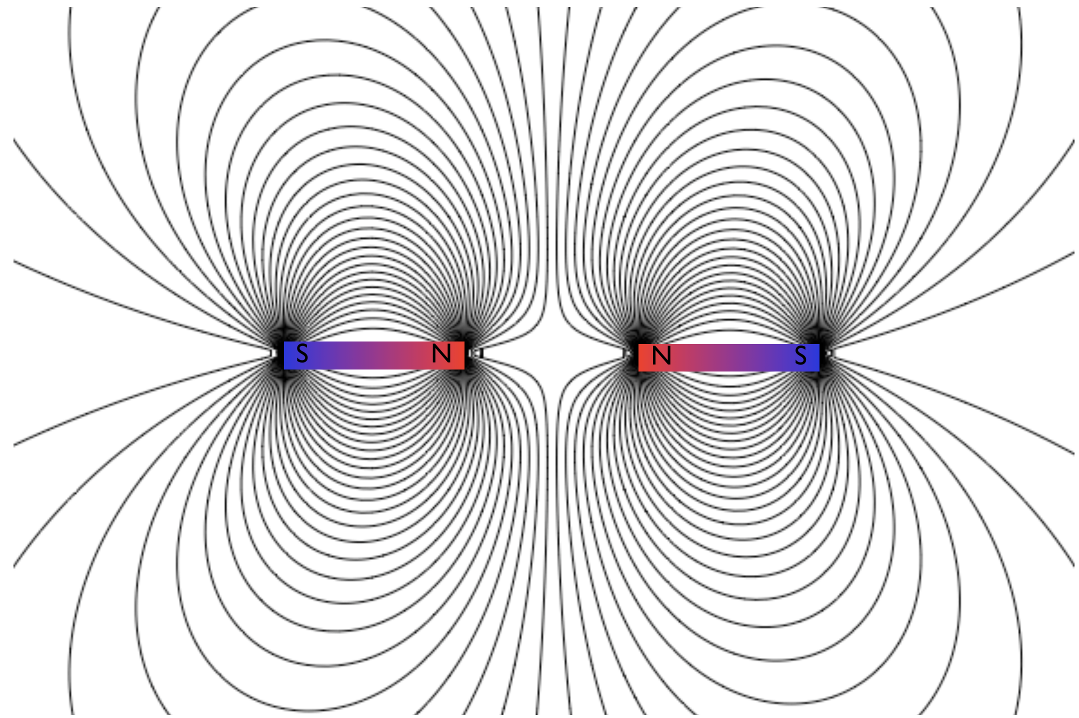
unlike poles
meet head on

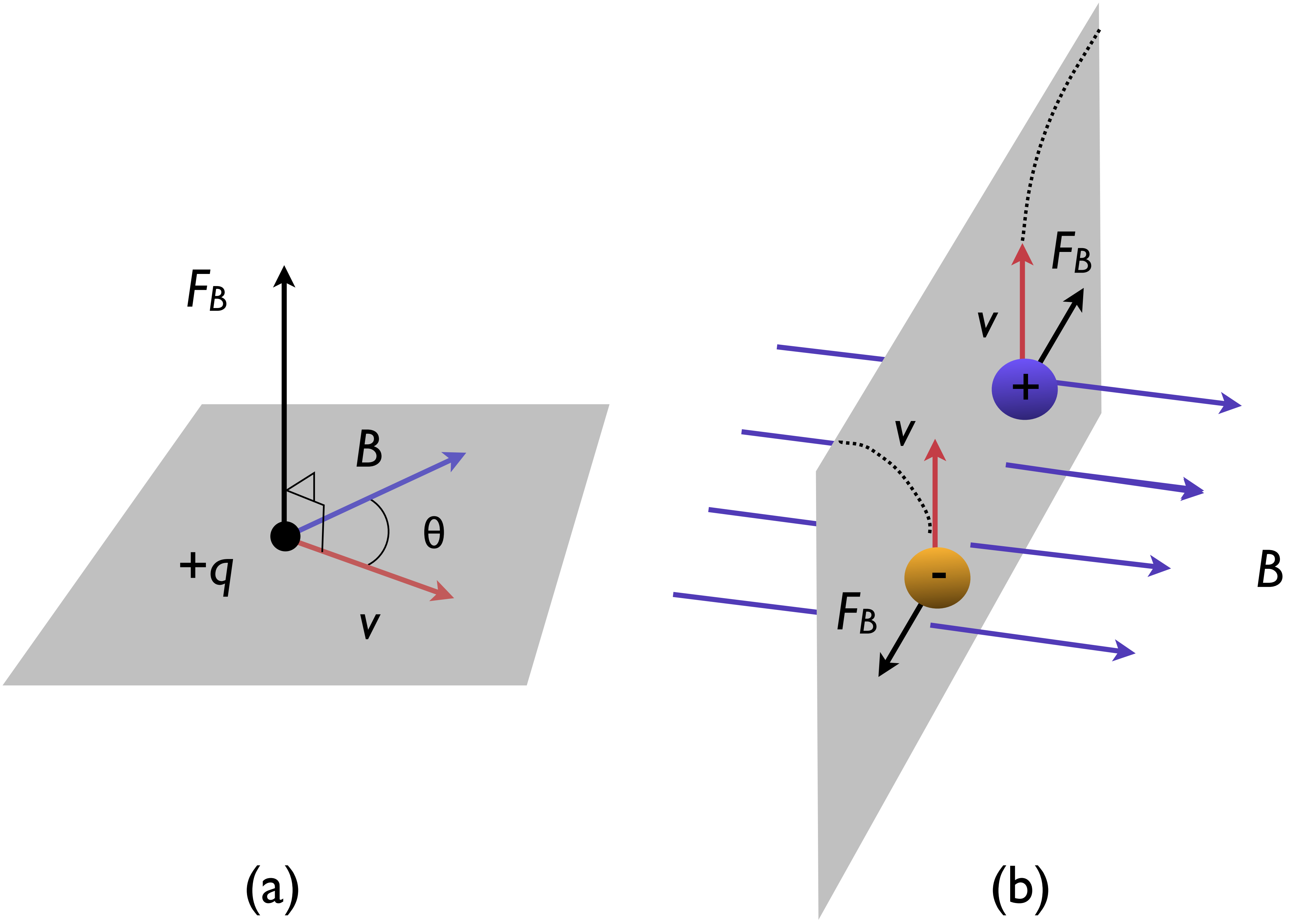
(a)



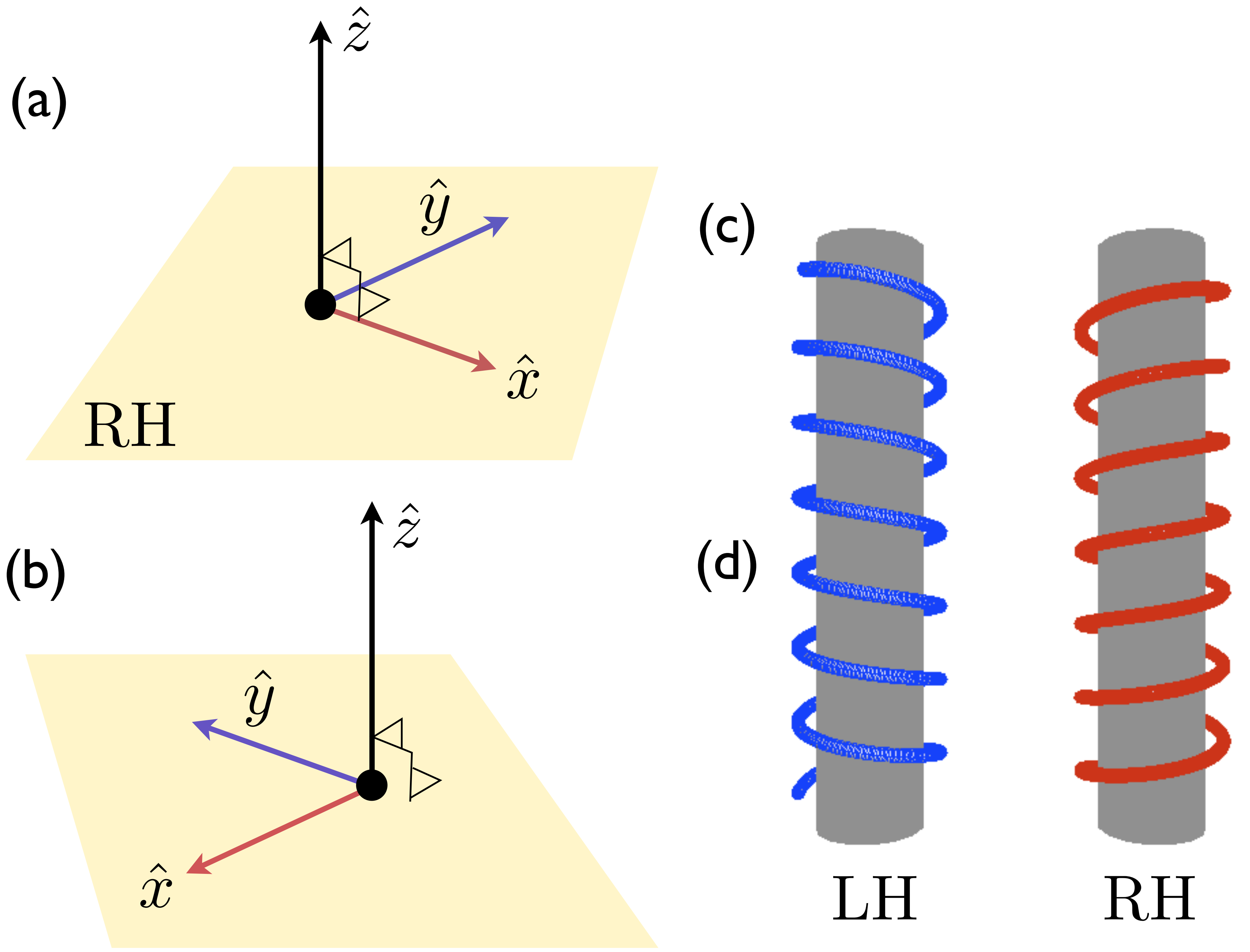
like poles
meet head on

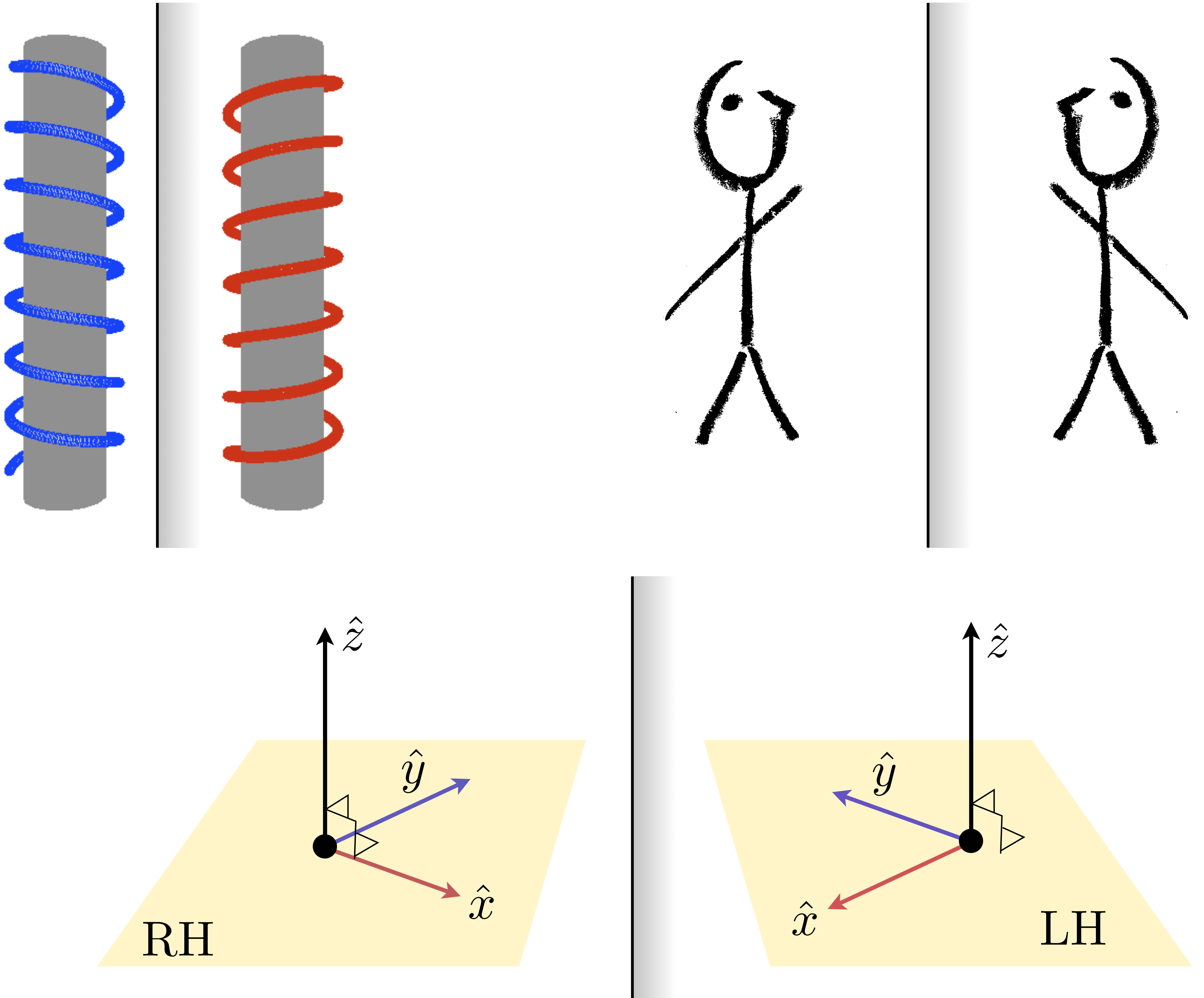
(b)



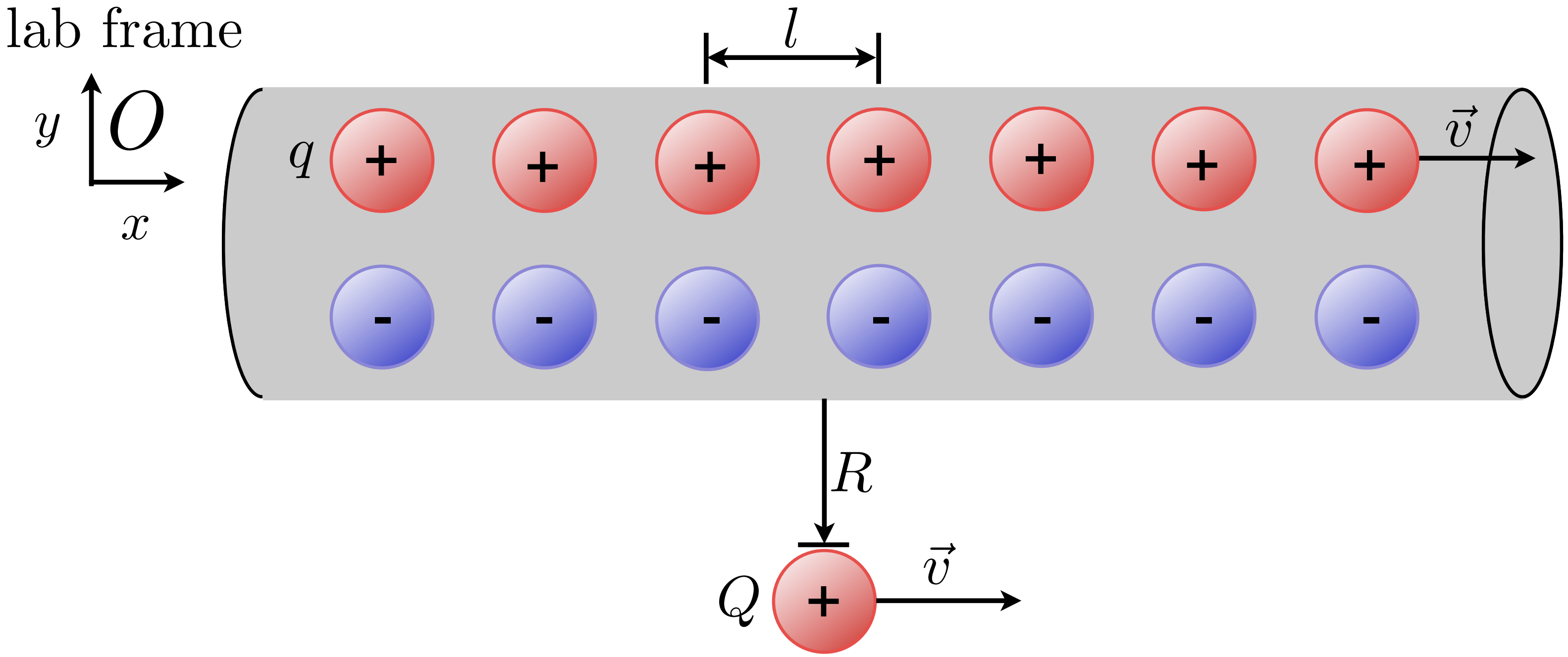


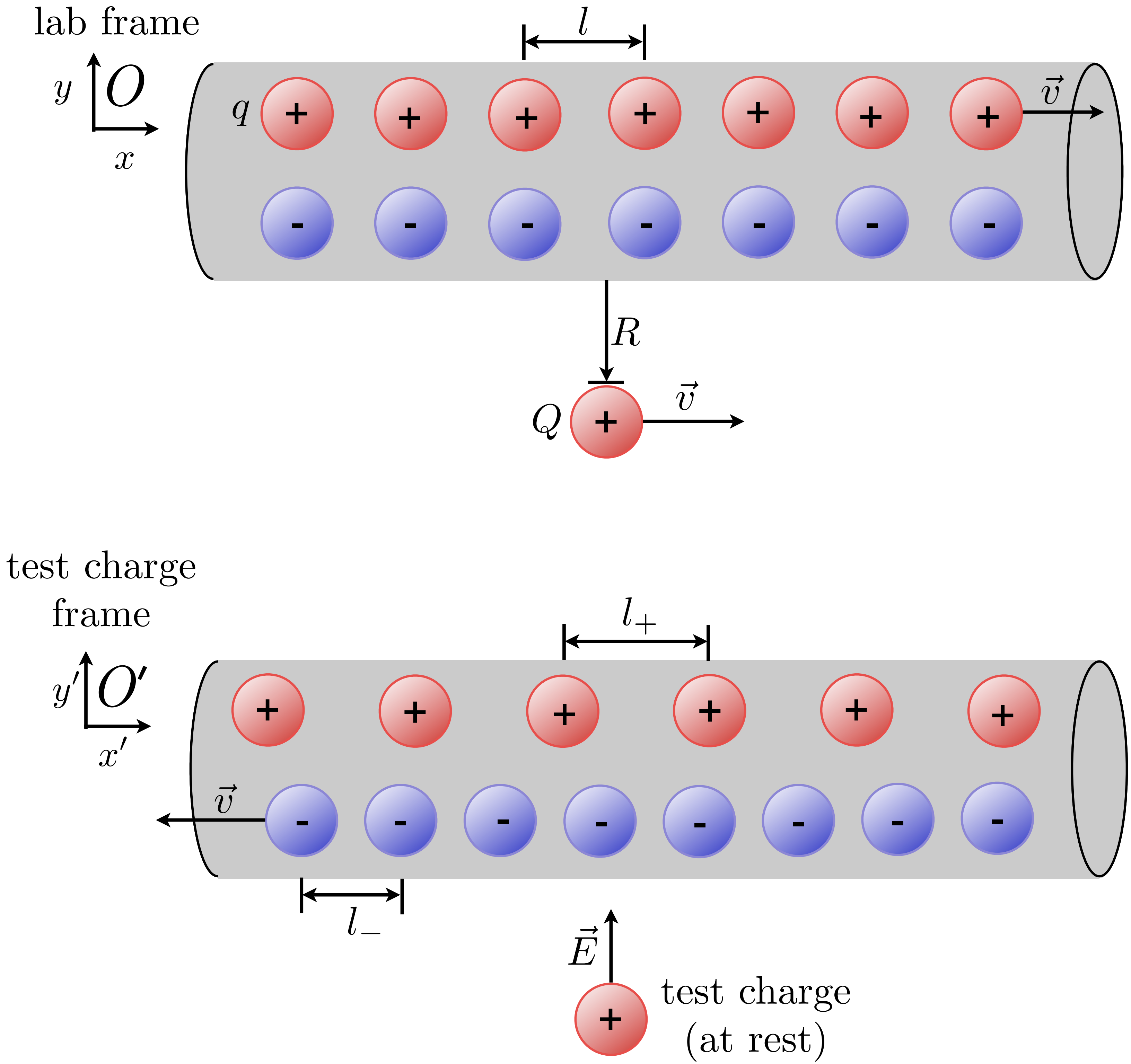
F_B
B
θ
$+q$
v
(a)
v
F_B
+
v
-
F_B
B
(b)


(a)
$\hat{z}$
$\hat{y}$
$\hat{x}$
RH
(b)
$\hat{z}$
$\hat{y}$
$\hat{x}$
(c)
(d)
LH
RH

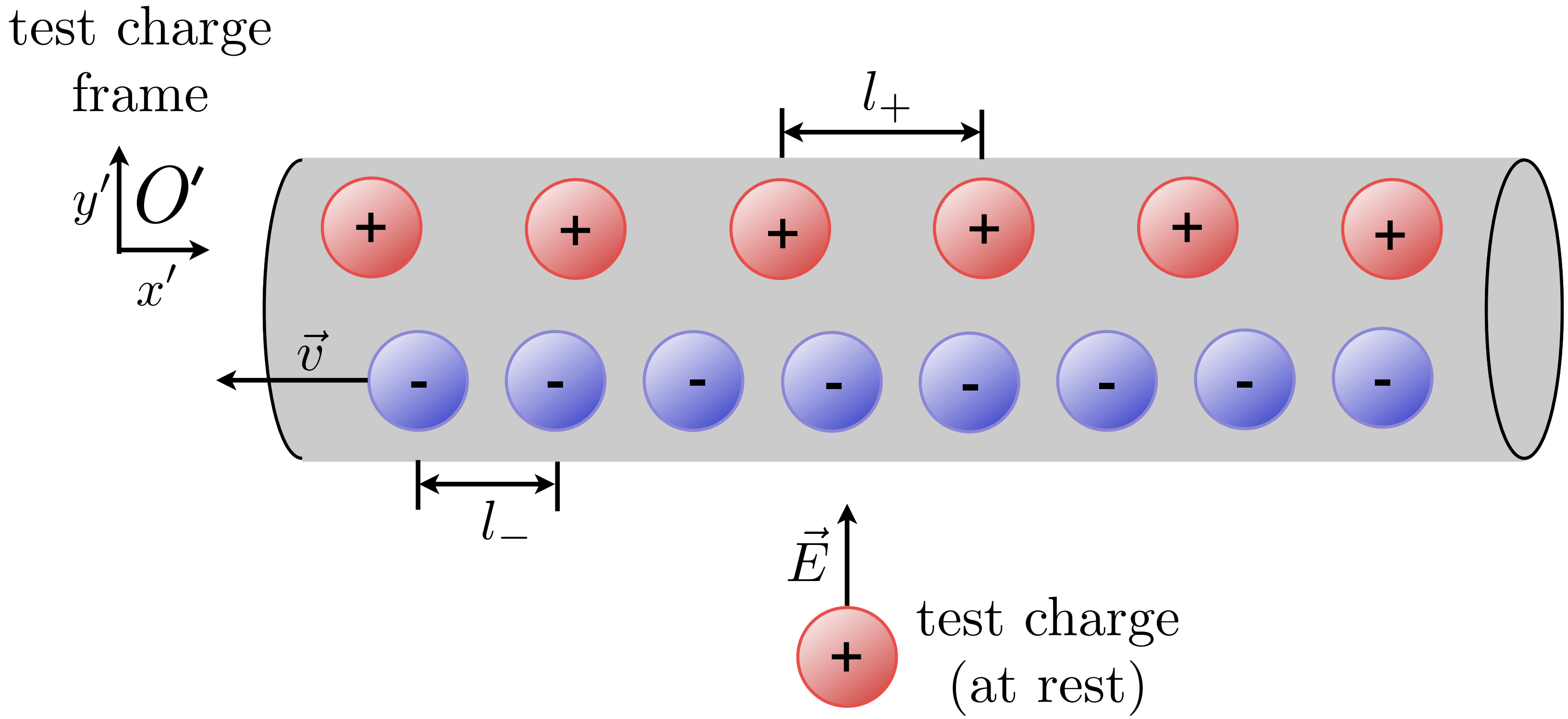


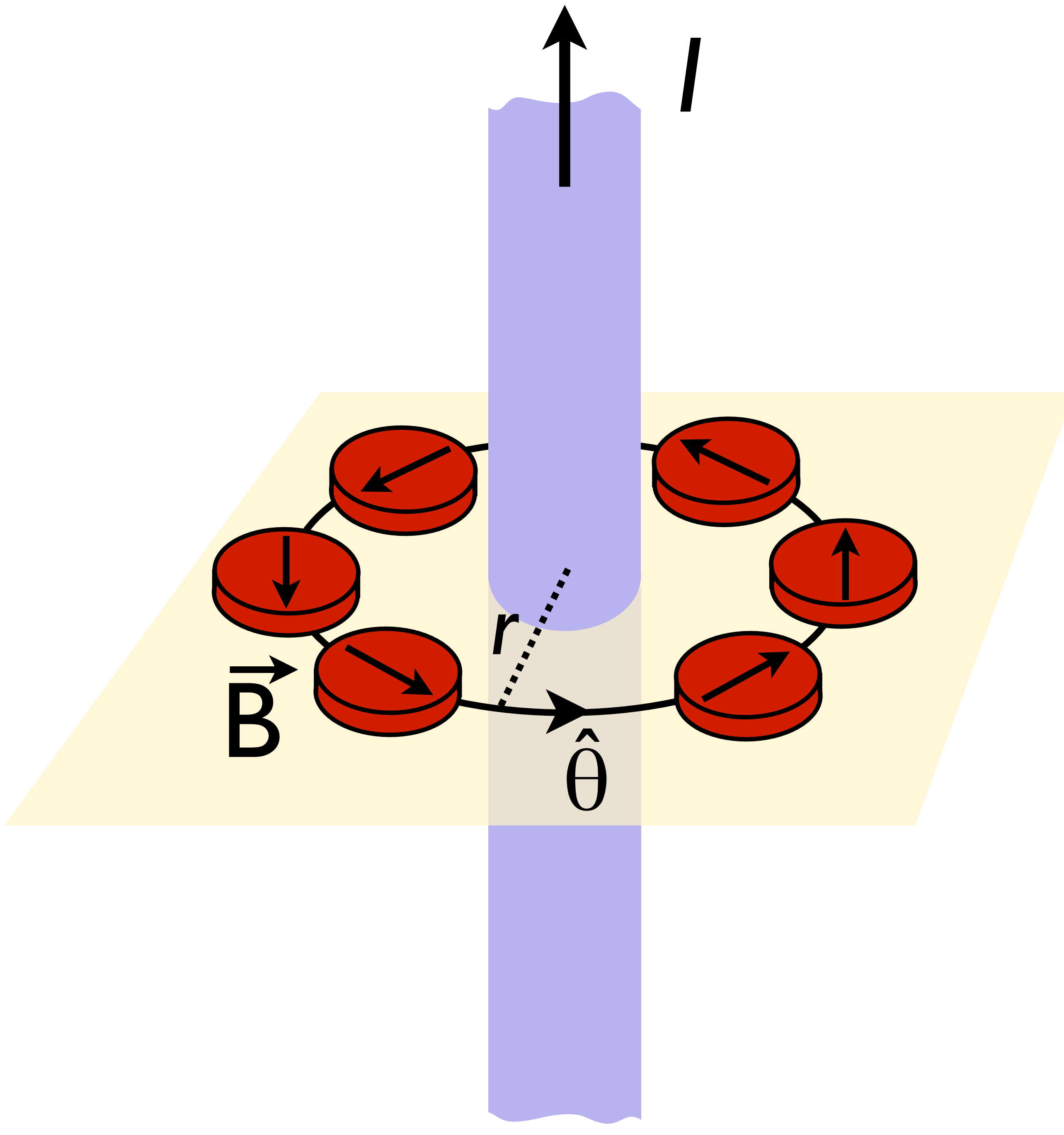
$\hat{z}$
$\hat{y}$
$\hat{x}$
RH
$\hat{z}$
$\hat{y}$
$\hat{x}$
LH


lab frame
l
y
O
x
q
$\vec{v}$
R
Q
$\vec{v}$

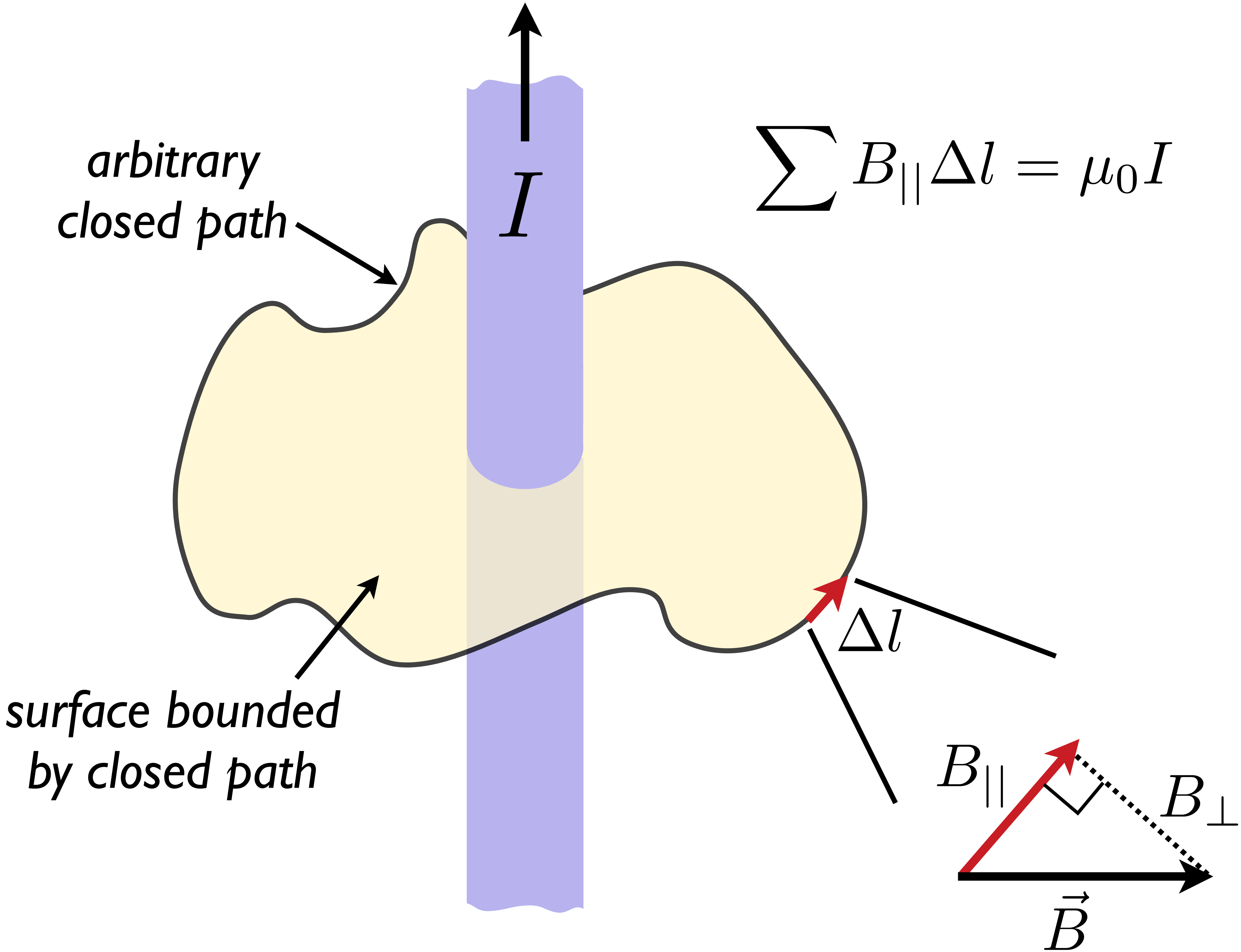


lab frame
l
y
O
x
q
$\vec{v}$
R
Q
$\vec{v}$
test charge frame
l_+
y'
O'
x'
$\vec{v}$
l_-
$\vec{E}$
test charge (at rest)

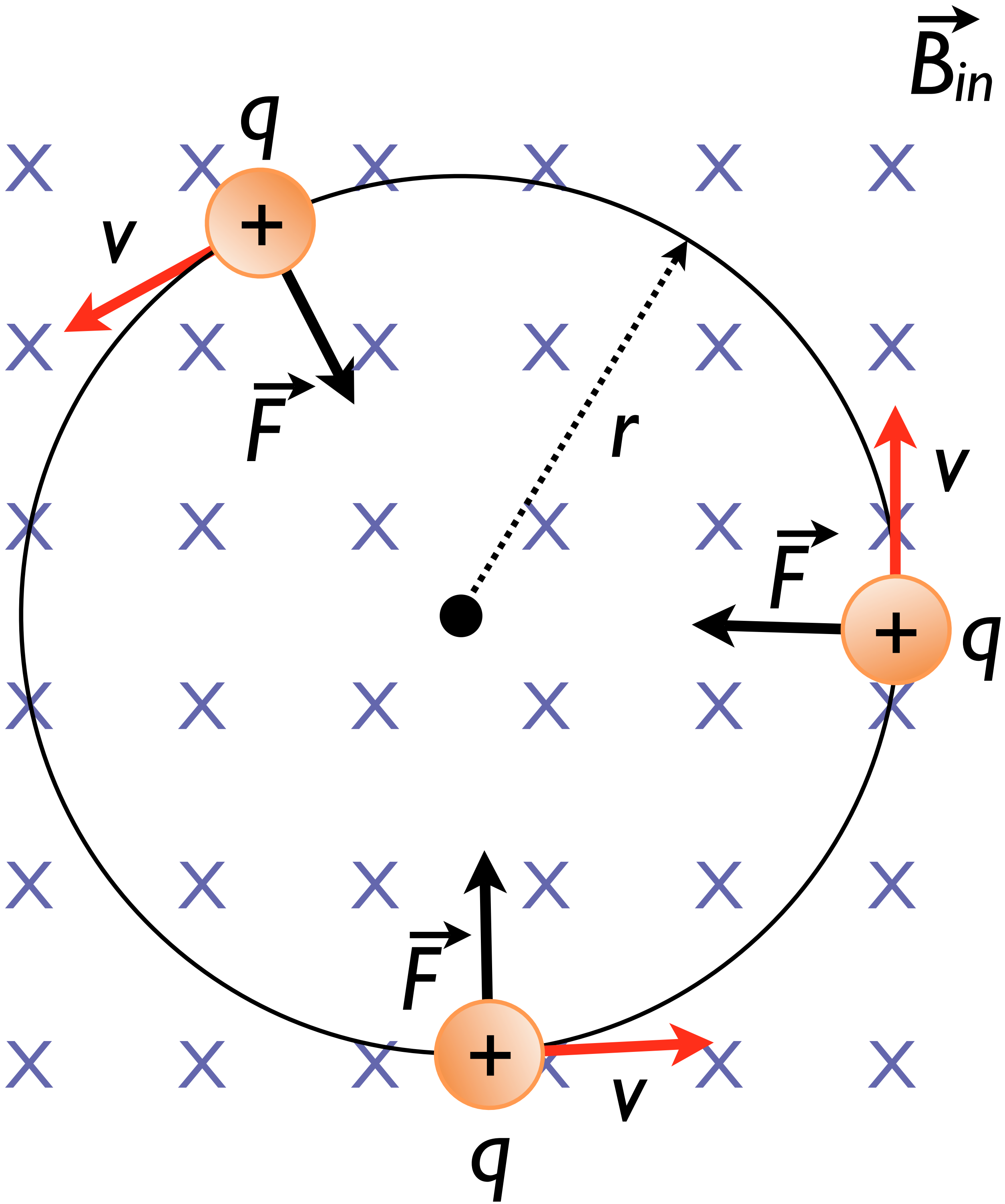

test charge
frame
y'
O'
x'
l_+
$\vec{v}$
l_-
$\vec{E}$
test charge
(at rest)

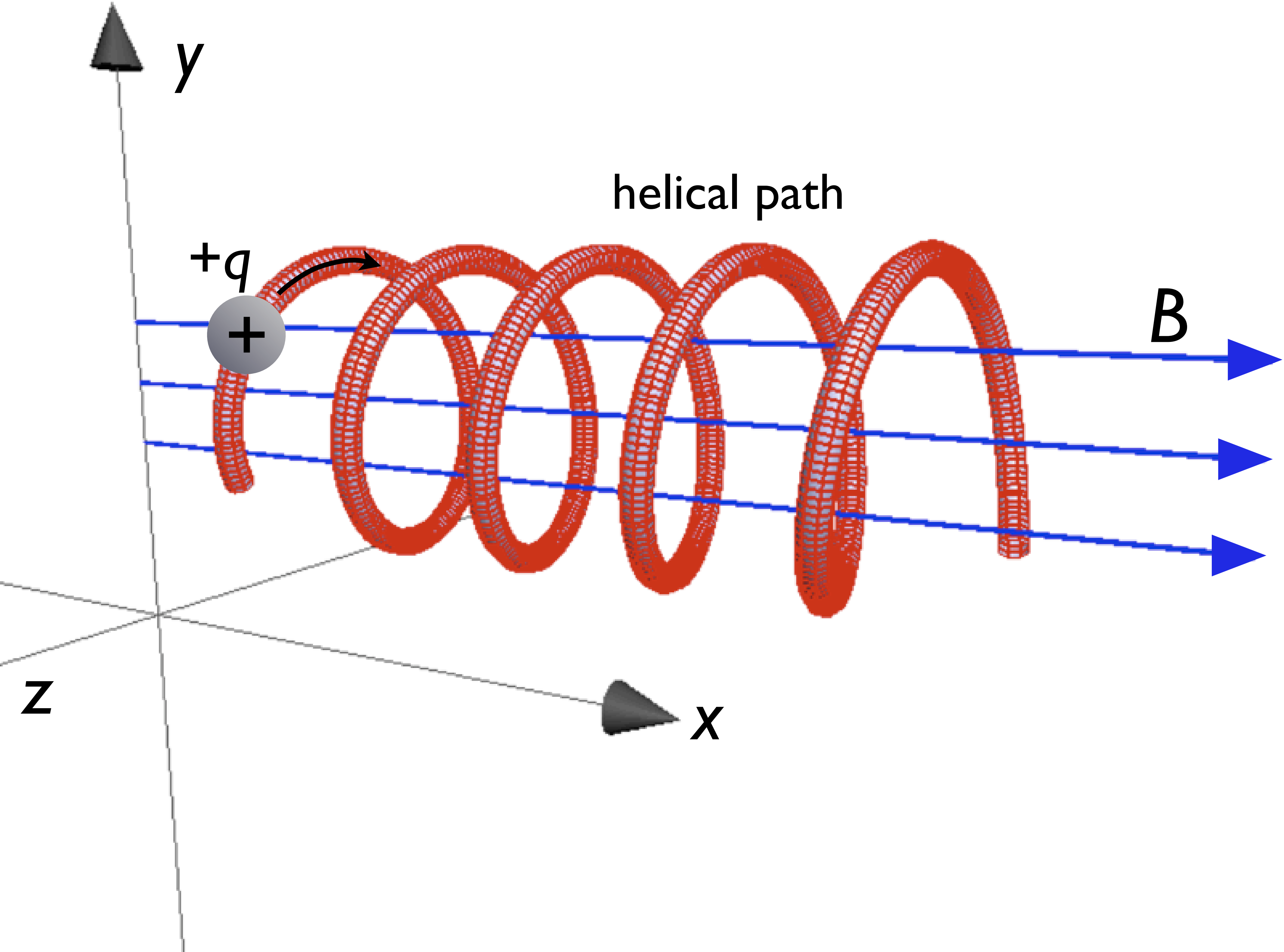


I
r
$\vec{B}$
$\hat{\theta}$

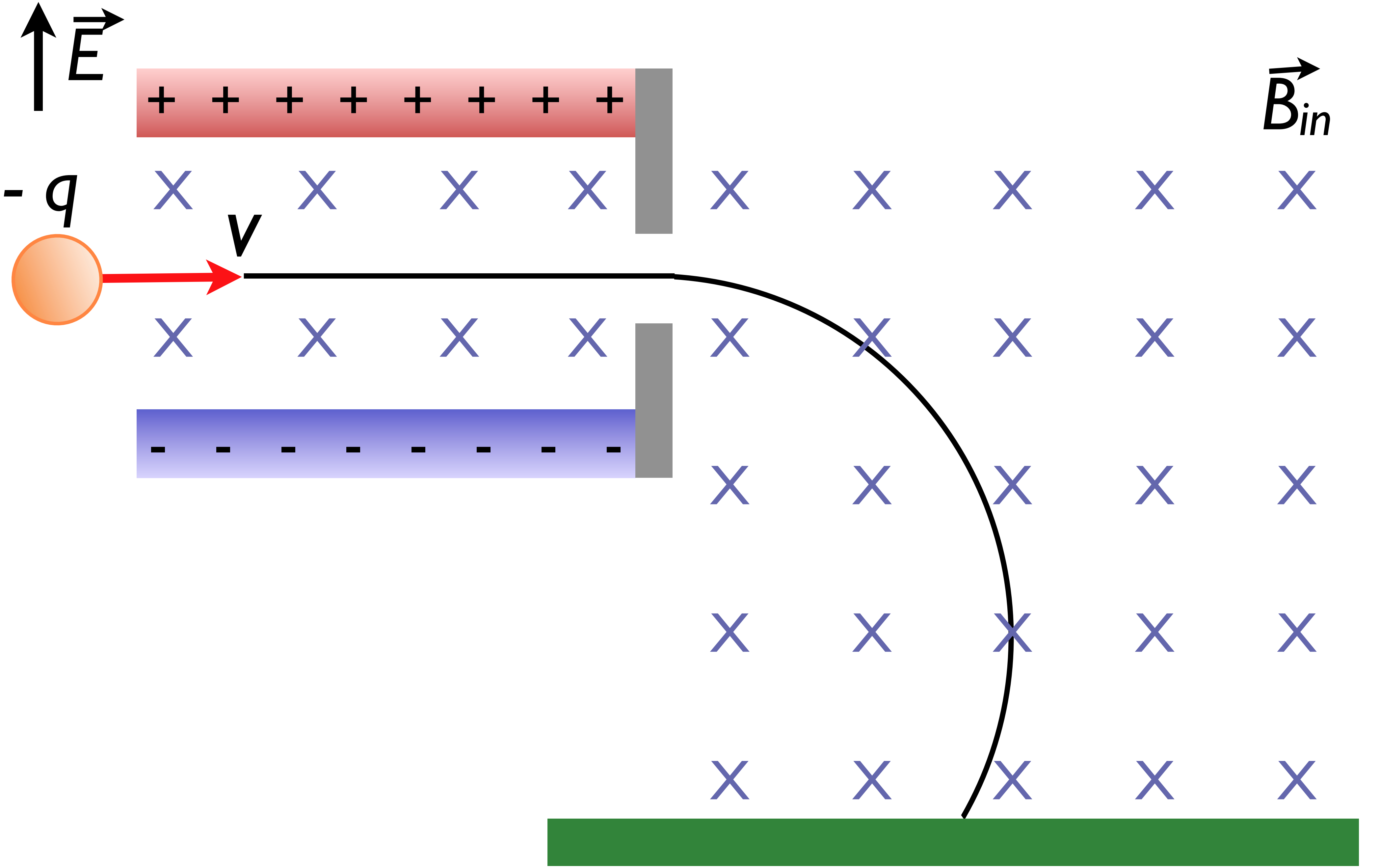


arbitrary closed path
I
$\sum B_{||}\Delta l = \mu_0 I$
surface bounded by closed path
Δl
$B_{||}$
$B_{\perp}$
$\vec{B}$

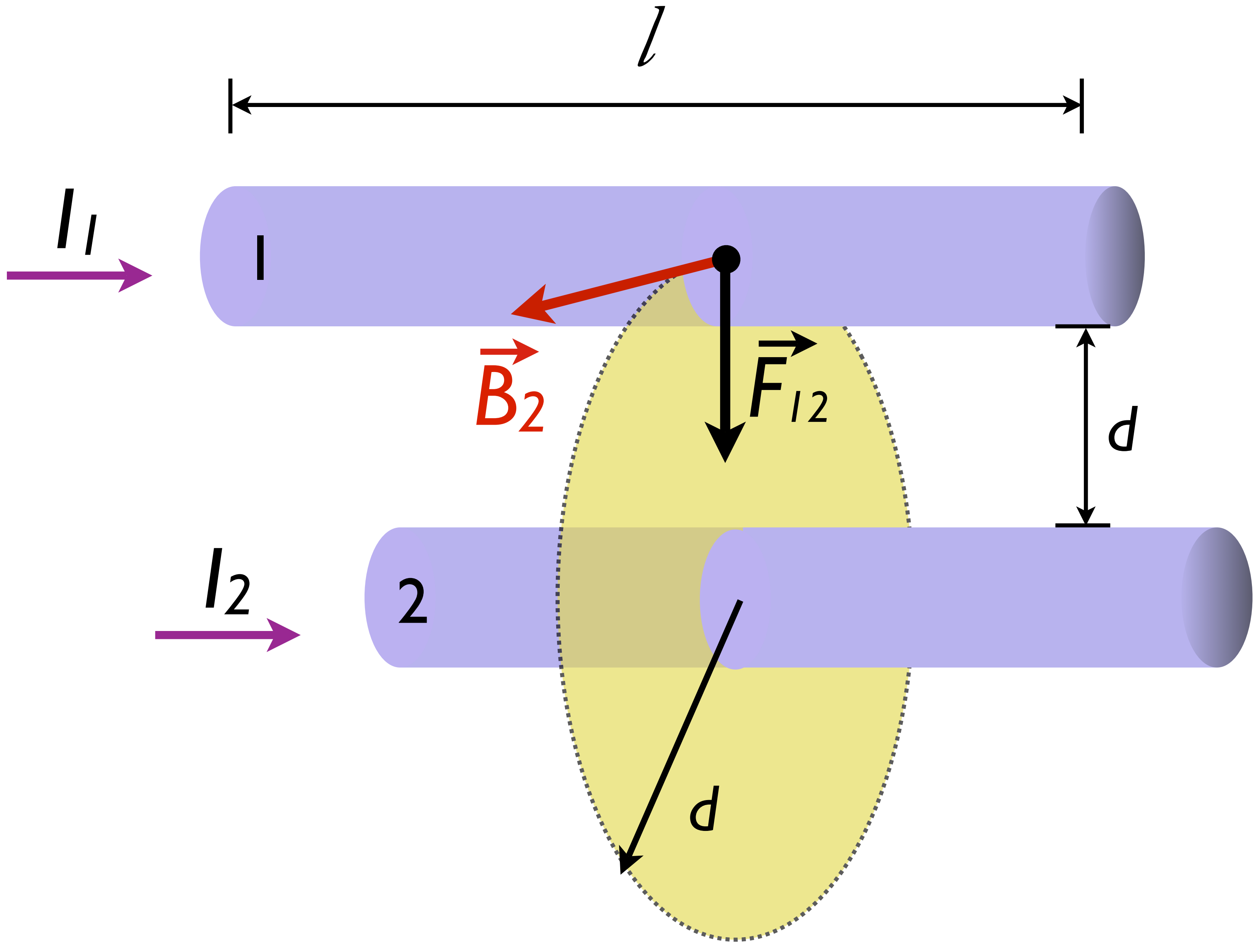

$\vec{B}_{in}$
q
v
$\vec{F}$
r
v
$\vec{F}$
q
$\vec{F}$
q
v



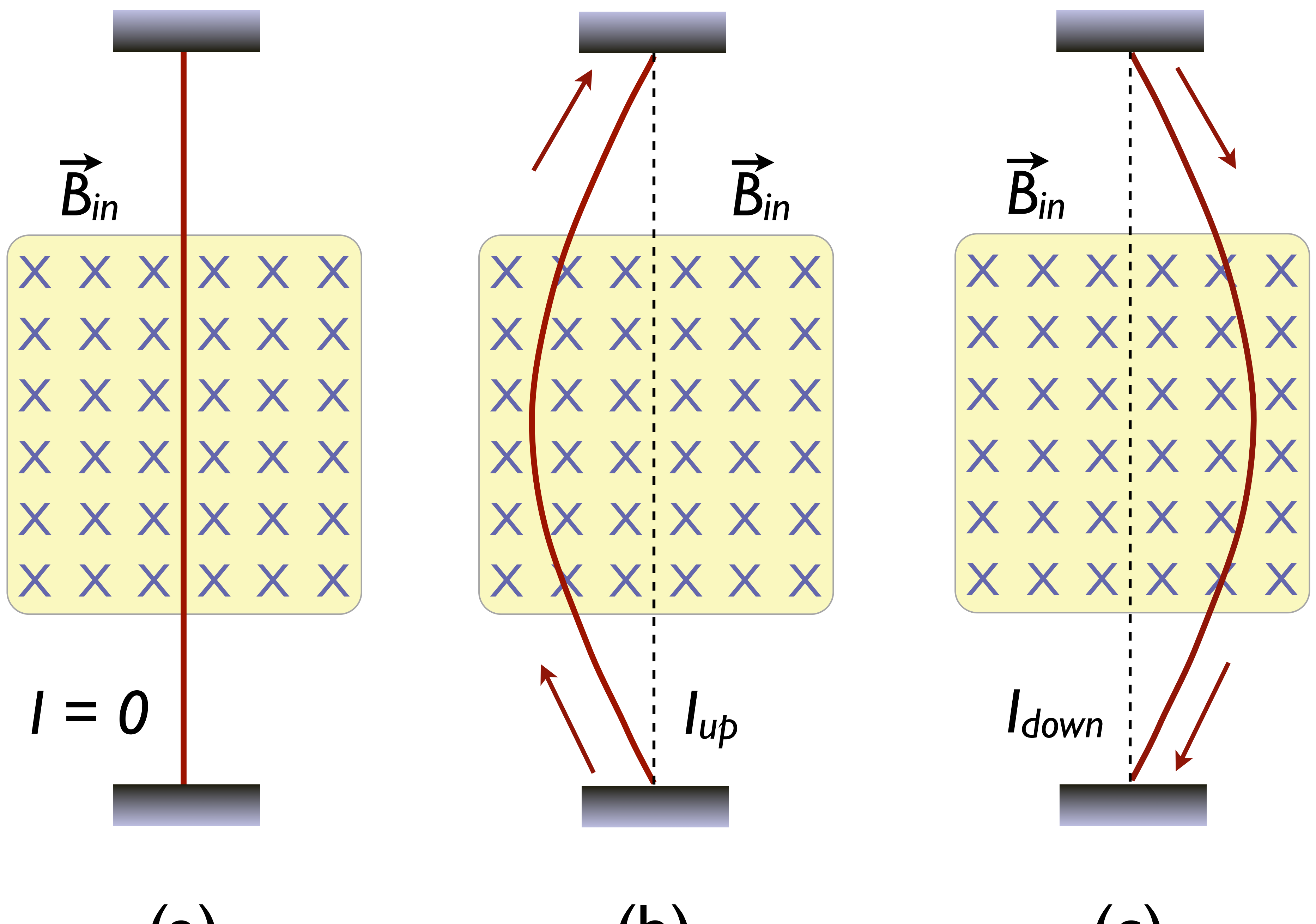
y
helical path
+q
+
B
z
x

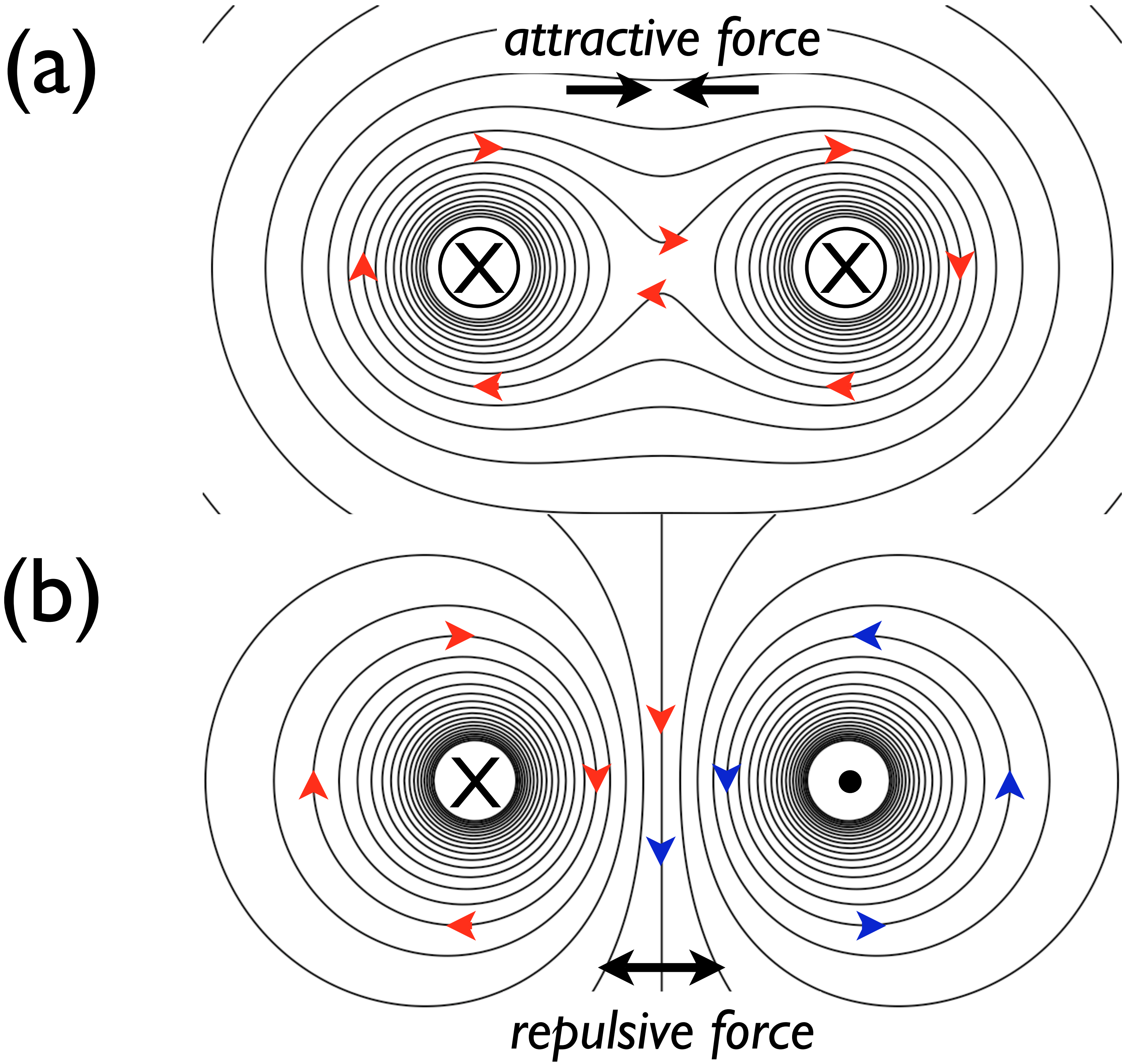


E
B_in
- q
v
+ + + + + + + +
- - - - - - - -



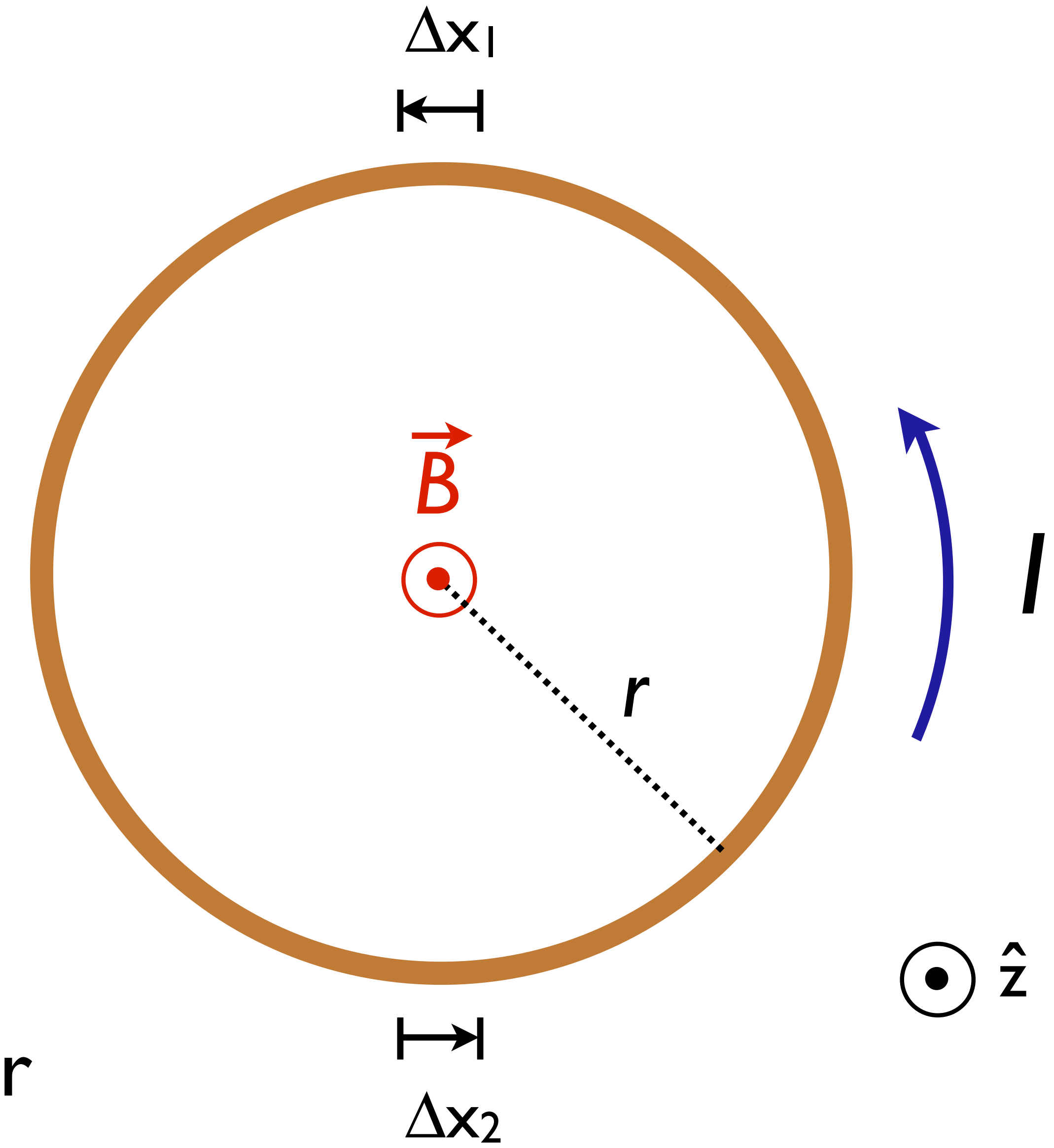
l
I_1
1
$\vec{B}_2$
$\vec{F}_{12}$
d
I_2
2
d


$\vec{B}_{in}$
$I = 0$
$\vec{B}_{in}$
I_{up}
$\vec{B}_{in}$
I_{down}
(a)
(b)
(c)


(a)
attractive force
X
X
(b)
X
repulsive force

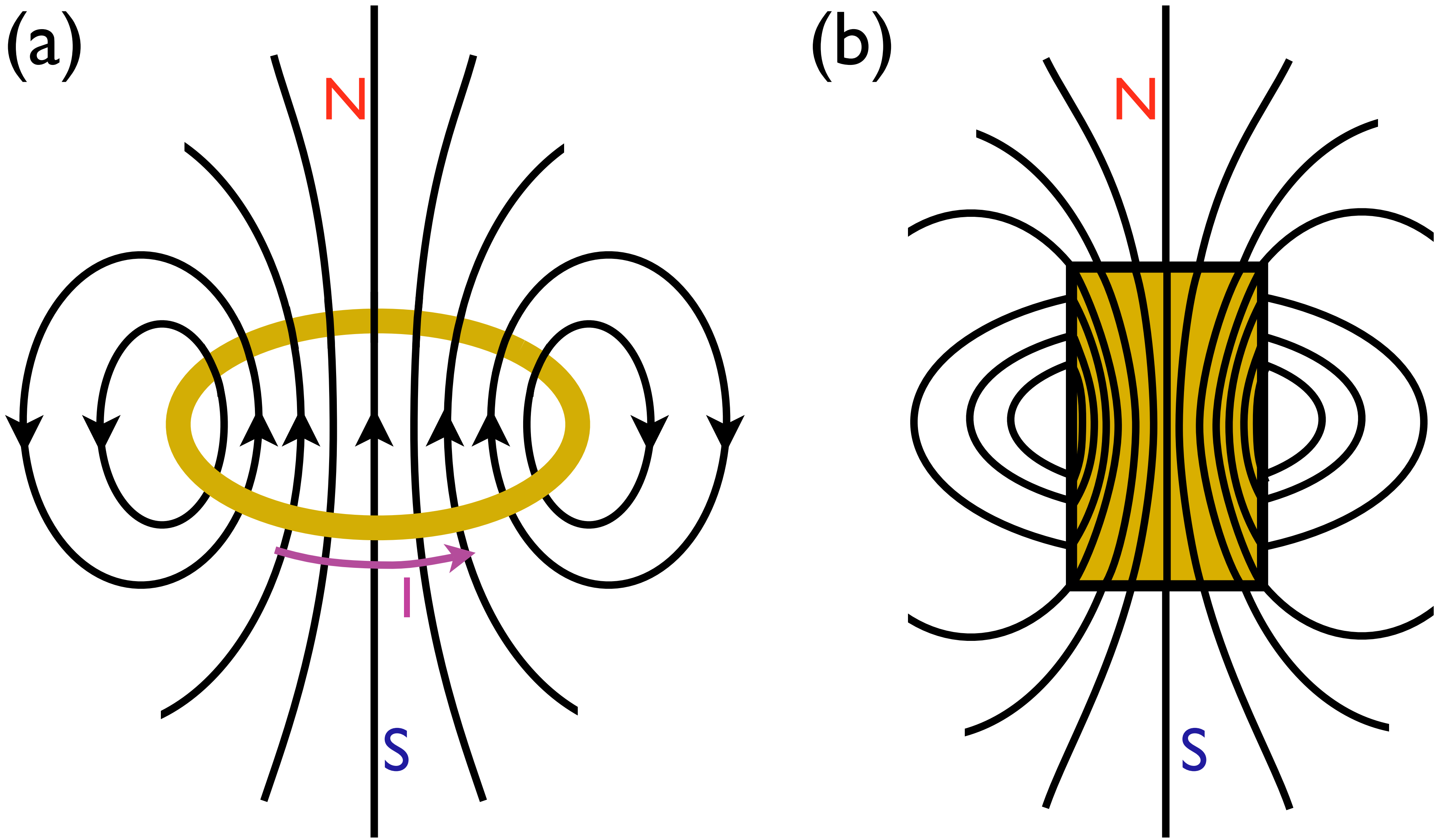
how to concentrate the magnetic field?
bend the wire in a loop

$$B = \frac{\mu_o I}{2R}$$



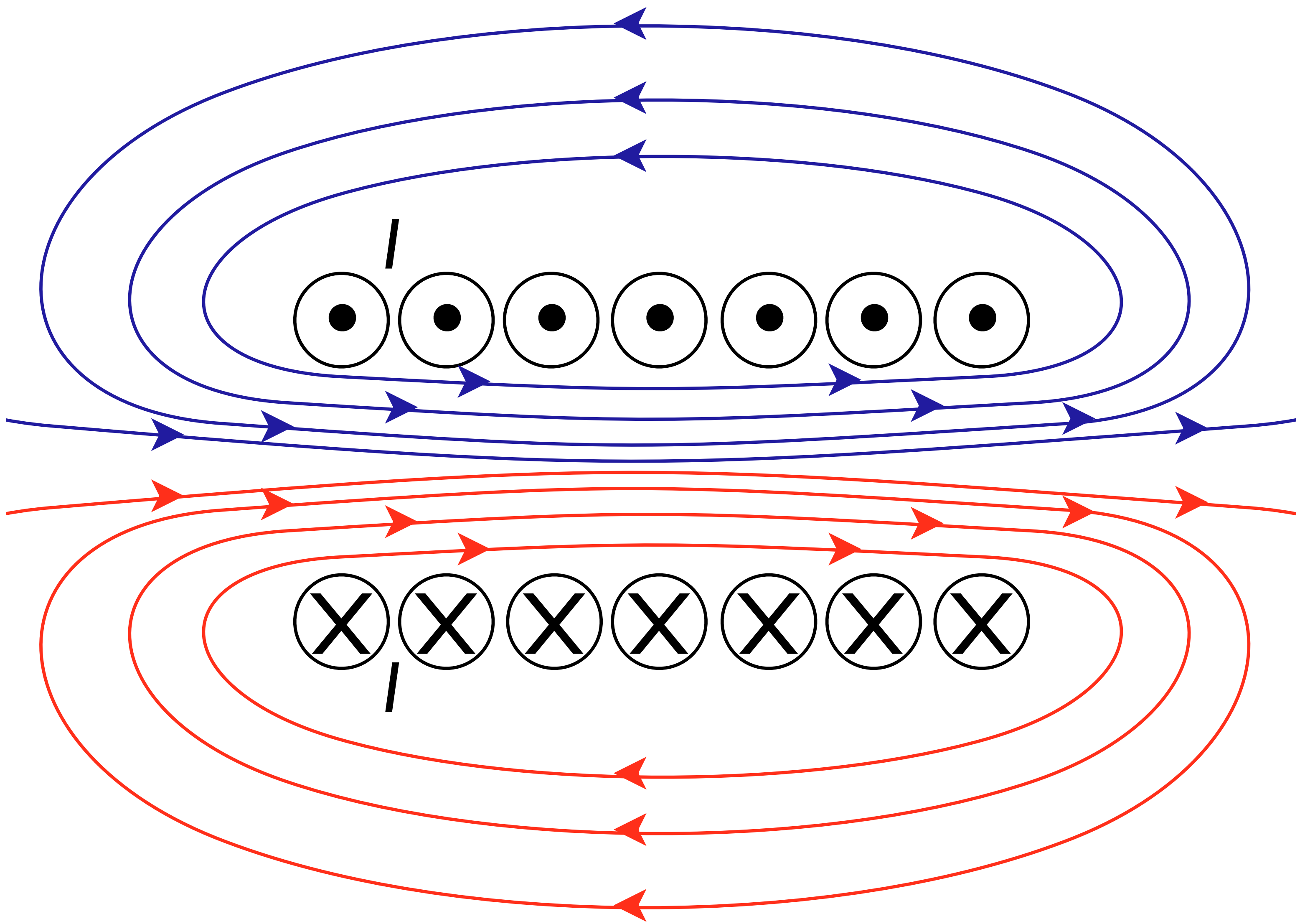
field is a factor π larger

almost like a bar magnet
(cases where they behave differently are oddballs)

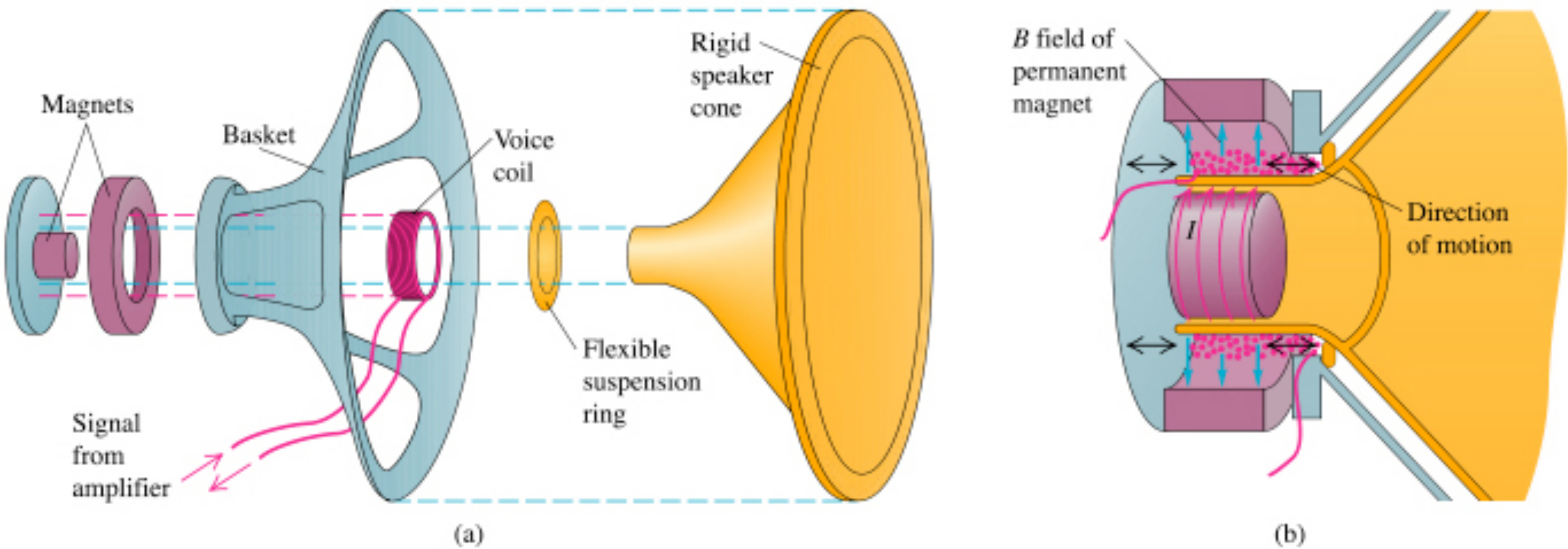


Want more? Superposition.

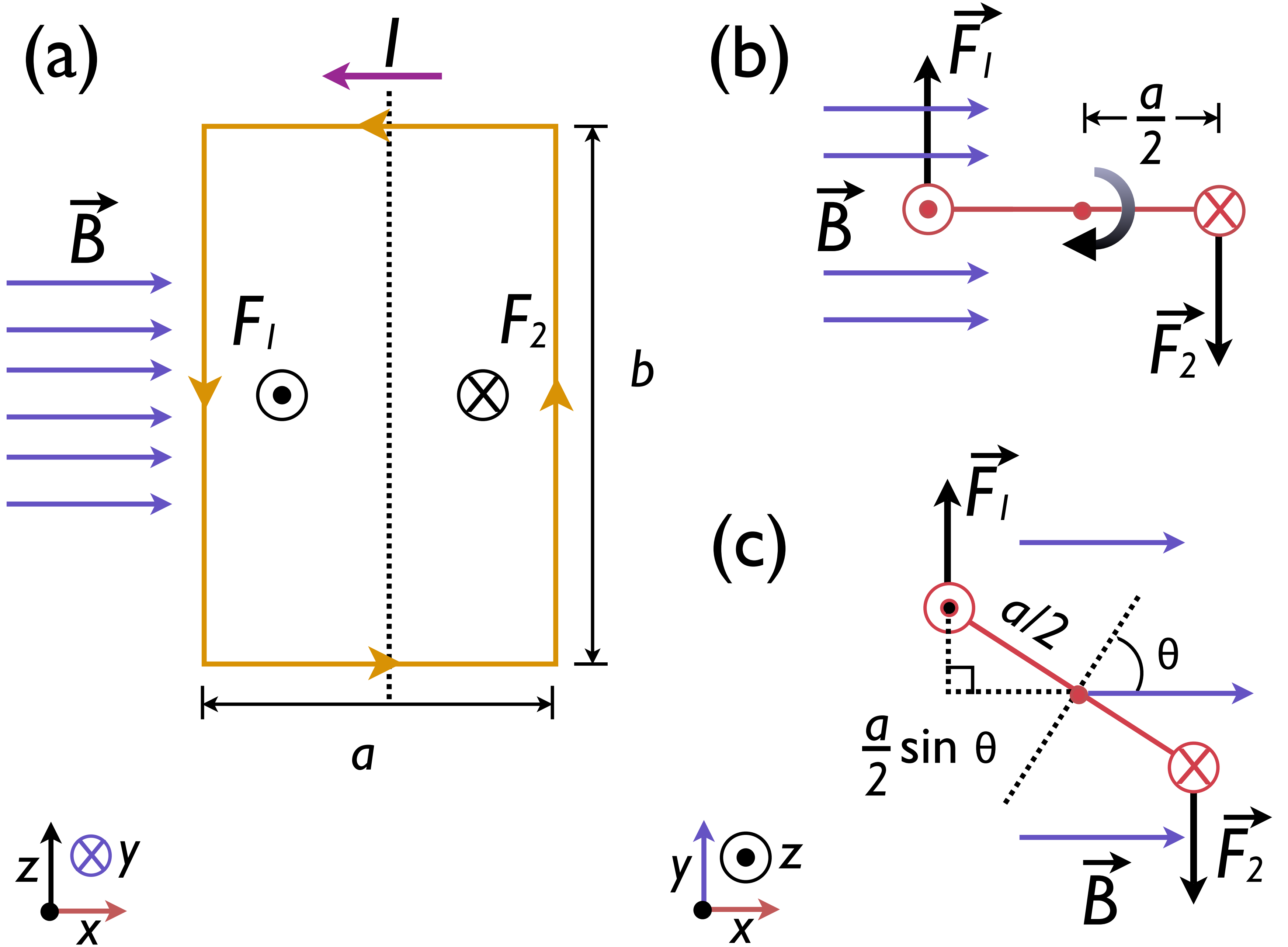
Many loops = many little B's working together.
"solenoid"



practical application: speakers

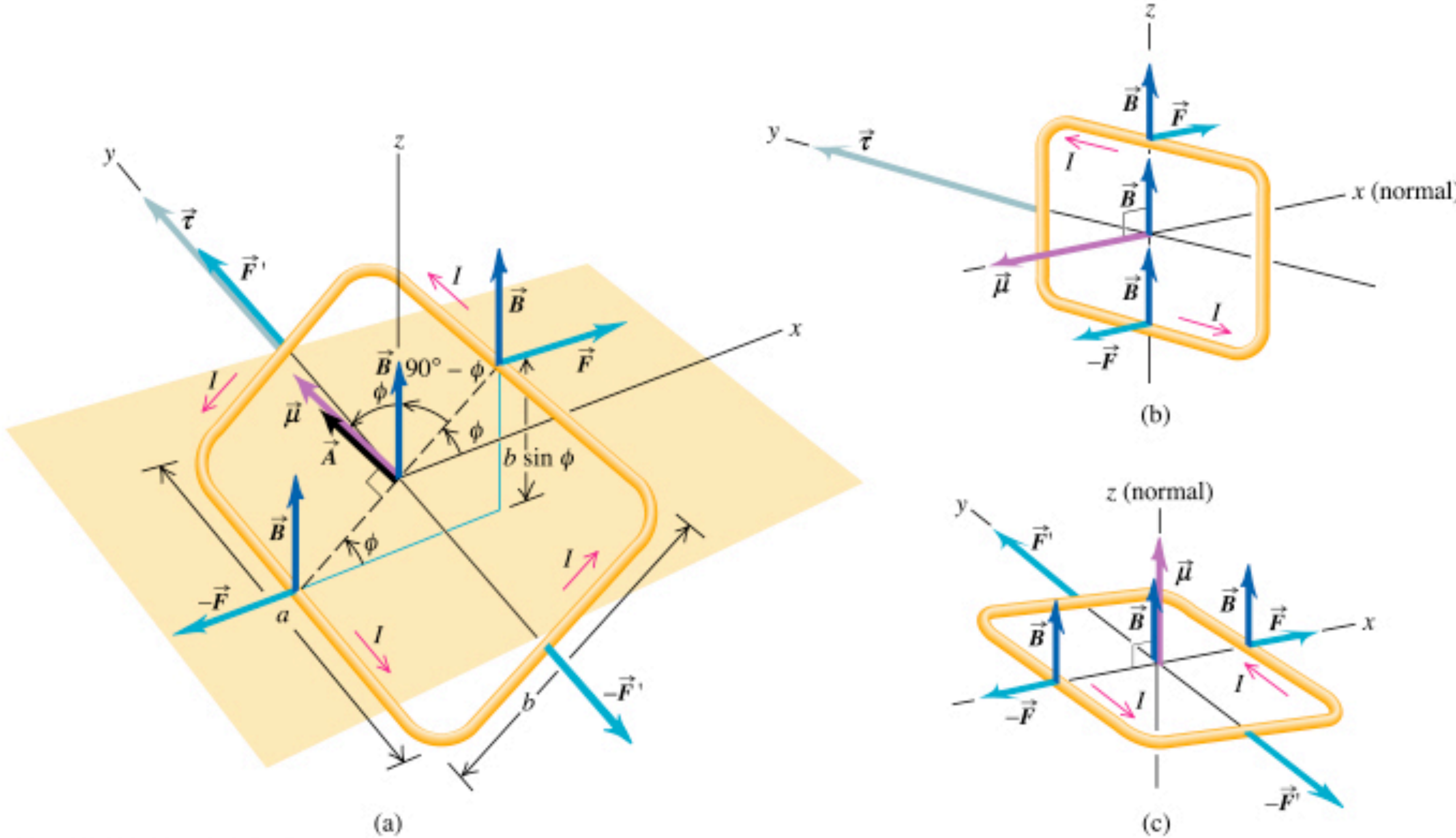


back to torque ...



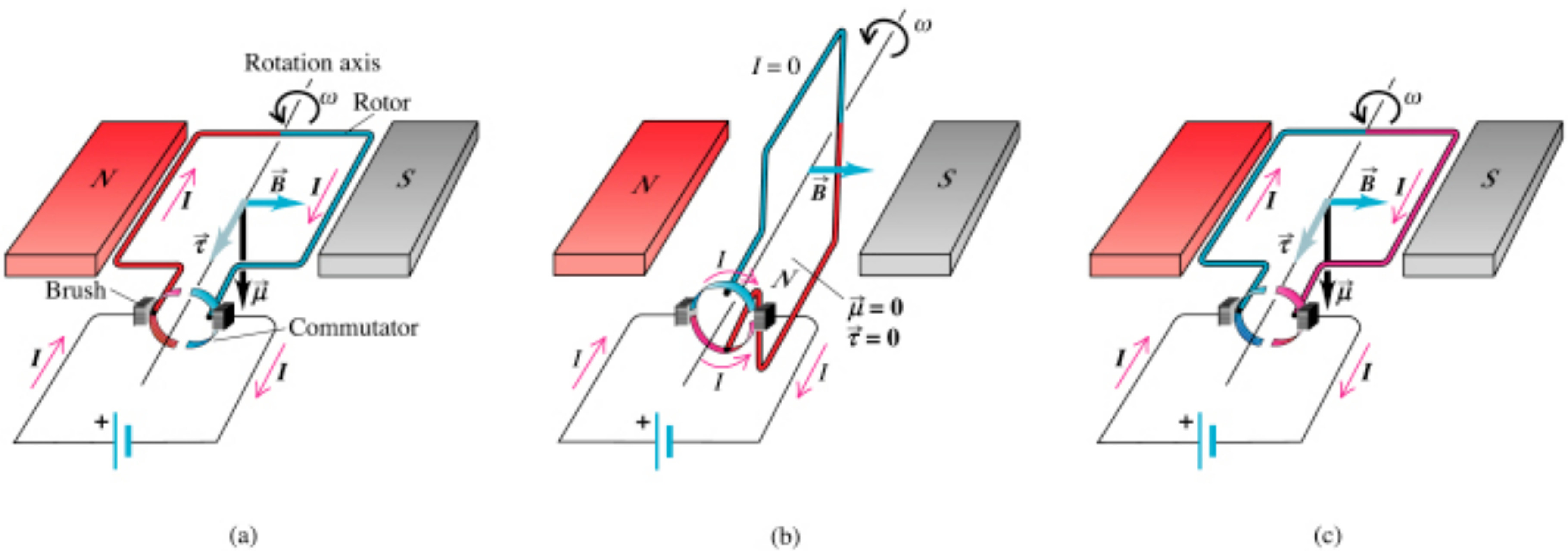
loop *plane* parallel to B - torque
loop *plane* perpendicular to B - no force or torque

or ... *magnetic moment* (perp to area) aligns with field

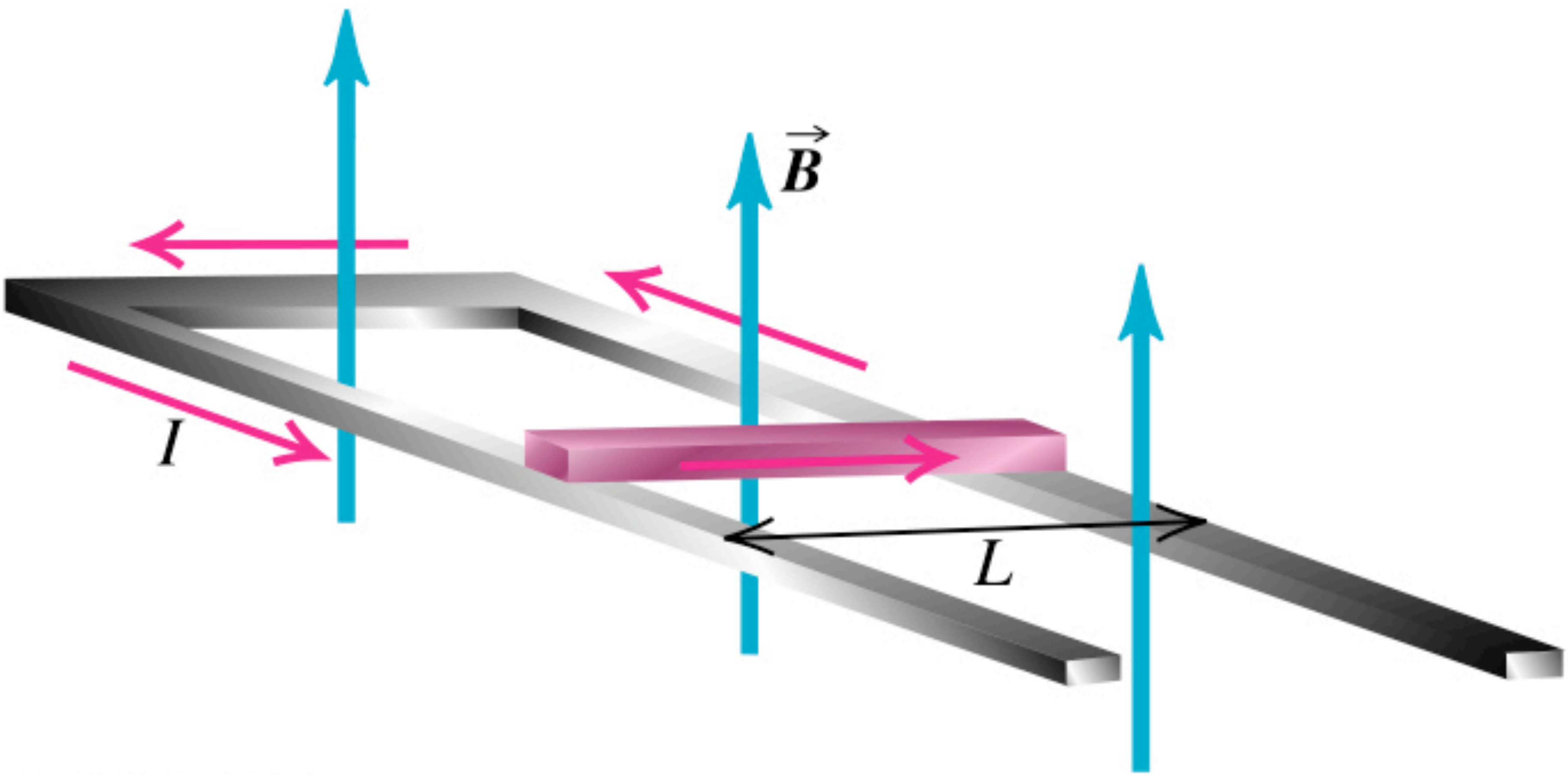


dc motor : current loop wants to rotate in field
tries to align area perpendicular along field

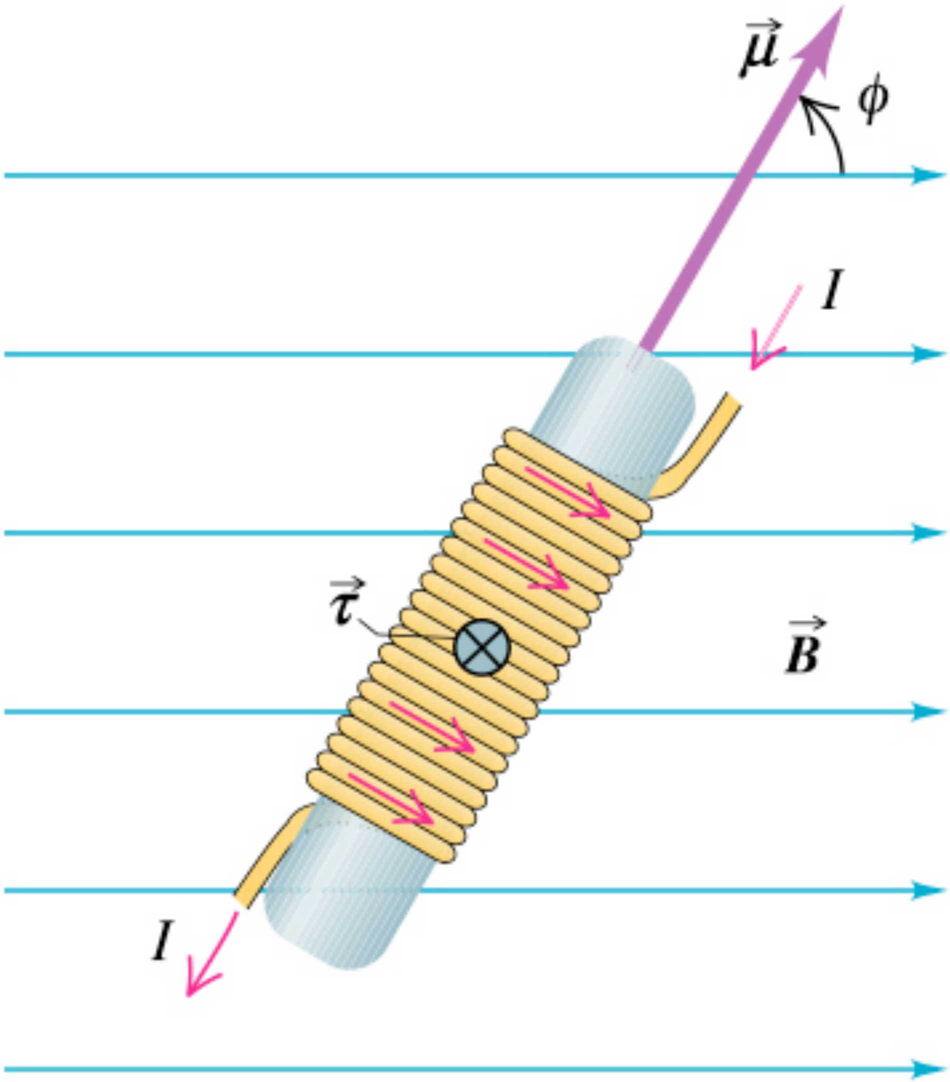
either oscillate current, or push it hard enough to "flip"

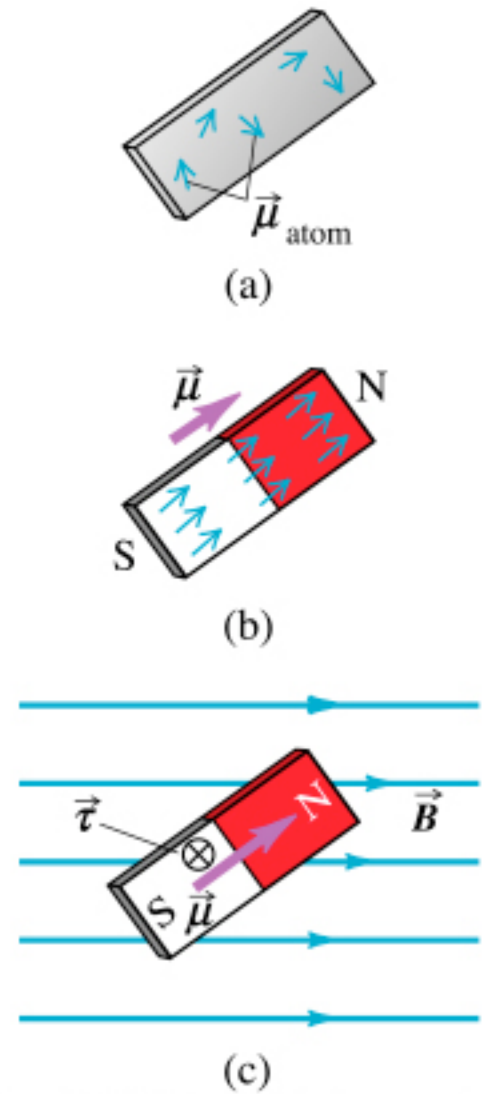


linear motor - current pushes bar out (rail gun)

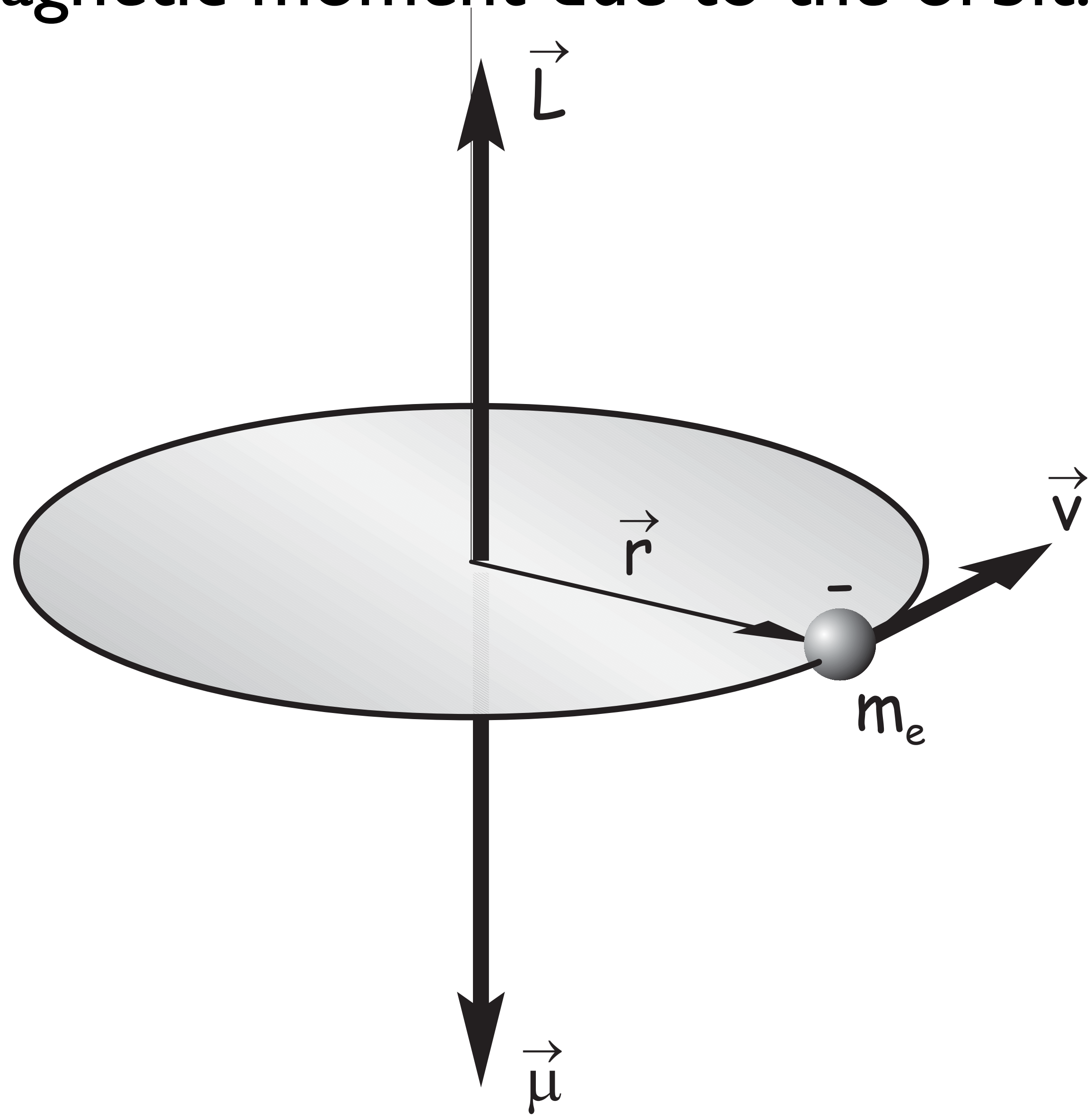


coils of wire or bar magnets - want to align with field





e- orbiting a nucleus has an orbital momentum L and a magnetic moment due to the orbit.



e- have negative charge -- current is opposite to V, and L is opposite the magnetic moment

another type of moment - spin

- *rough* analogue is a spinning ball of charge
- looks like a tiny circulating current

- really, intrinsic angular momentum of particles
- more significant than orbital effect, but moment behavior is qualitatively similar

origin of magnetic moments?

- Bohr model & orbits is not right, but a start
- orbital motion of H atom = current loop

  dipole moment generated = Bohr magneton

$$\vec{\mu}_B = -\frac{ge}{2m_e}\vec{L} \approx 9.27 \times 10^{-24}\,\mathrm{A/m^2}$$

spin of electron provides another magnetic moment

reality: magnetism does come from L

QM picture

moment comes from angular momentum

orbital momentum is important ...

... but there is also a *spin* angular momentum

Most materials of interest for us:

orbital moments are negligible

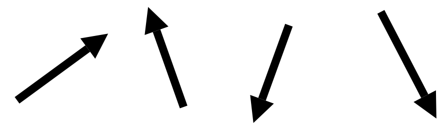
spin moments dominate

magnetism in real materials

- like dielectrics are electrically polarizable ...
- ... some materials are *magnetically* polarizable
- can be positive or negative

- B *inside* material is not the same as outside

Types of Magnetism



- Paramagnetism
  - In gases and molecular liquids and solids the individual ions, atoms, or molecules may have magnetic moments
  - the size of these moments ~ Bohr magneton
  - magnetic energy of one of these molecular magnets in a field of 1T is ~ cos θ 60ueV
  - compare to thermal energy of 25meV at RT
  - relatively weak magnetization field compared to the applied field, (M<<H) except at very low temperature

moments try to align *with* the field - your fridge

$$\mu_B \approx 60\,\mu\mathrm{eV/T} \qquad\qquad k_B \approx 86\,\mu\mathrm{eV/T}$$

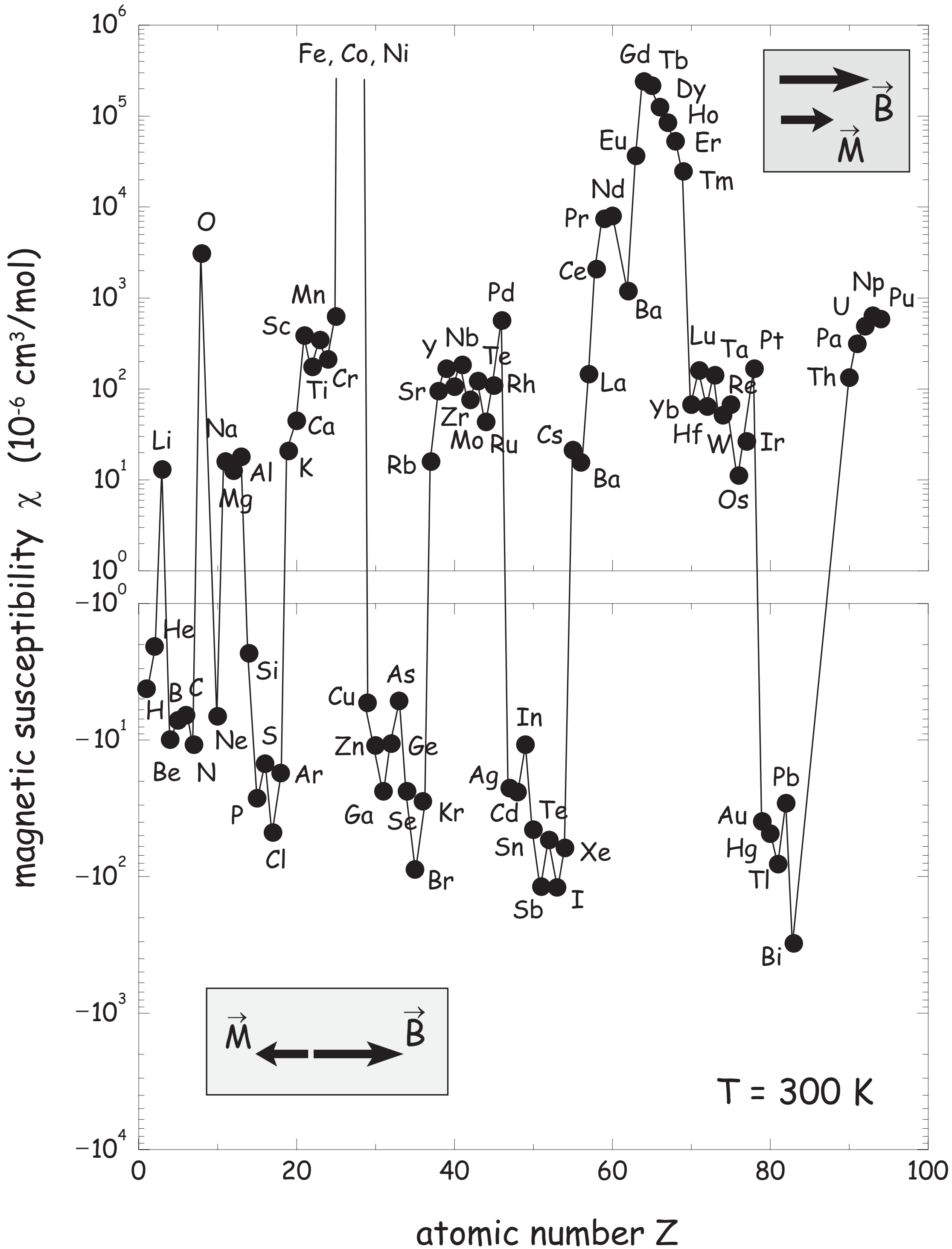
Types of Magnetism

- Diamagnetism
  - no spin magnetic moment on an atom or molecule, orbital response dominates
  - usually gives a magnetization opposite to the applied field.
  - extreme case of diamagnetism = superconductor.
    - type I superconductor - diamagnetic magnetization exactly cancels the applied field.

moments try to align *opposite* in the field

degree of alignment per applied B = susceptibility

negative for diamagnets
positive for paramagnets



- Classical Argument gives correct formula
- Some of steps are suspect
- All materials show diamagnetism,

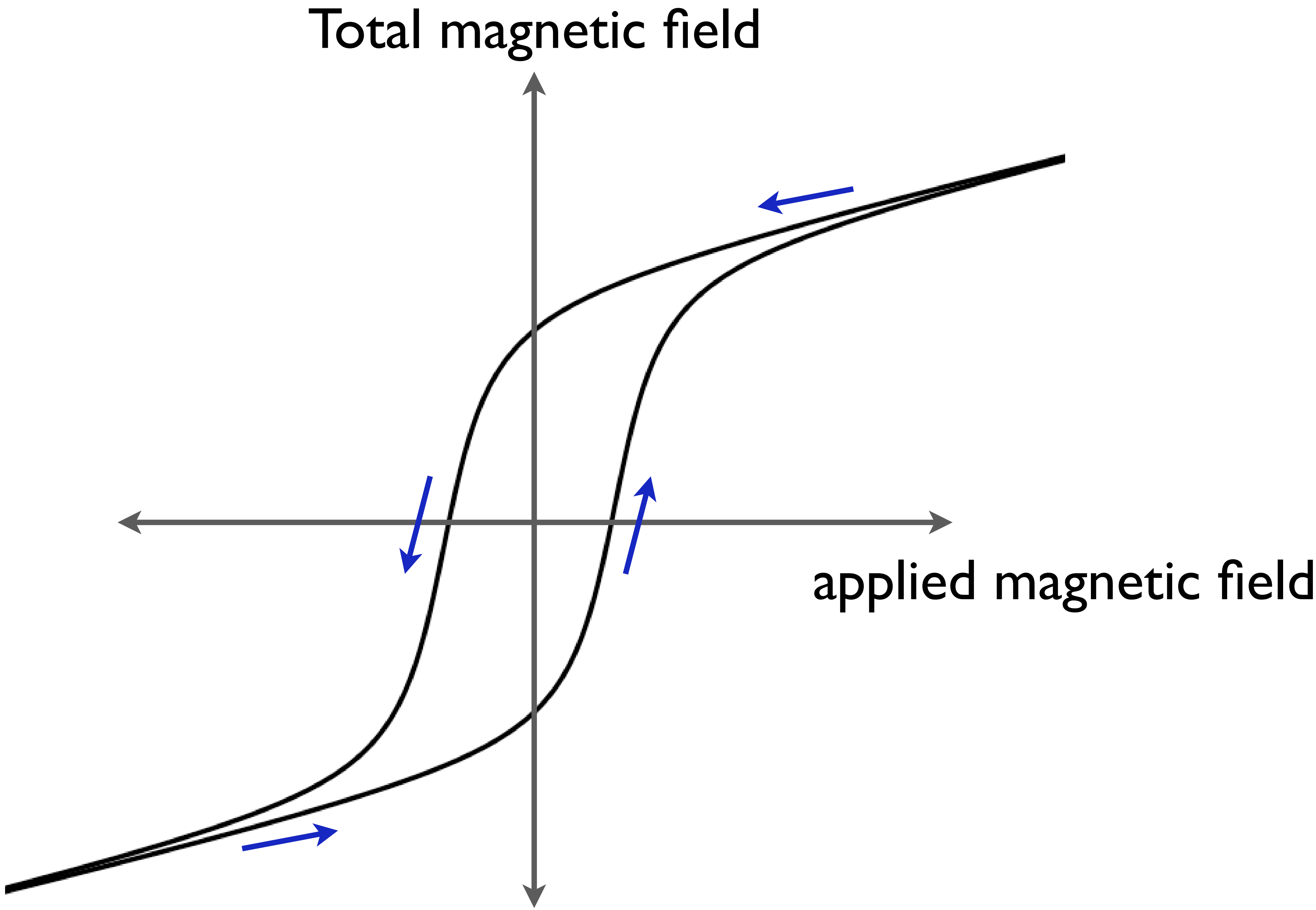
  often masked by other magnetic responses
- T independent
- All electrons contribute

- Some elements give *positive* susceptibility ... what is this?

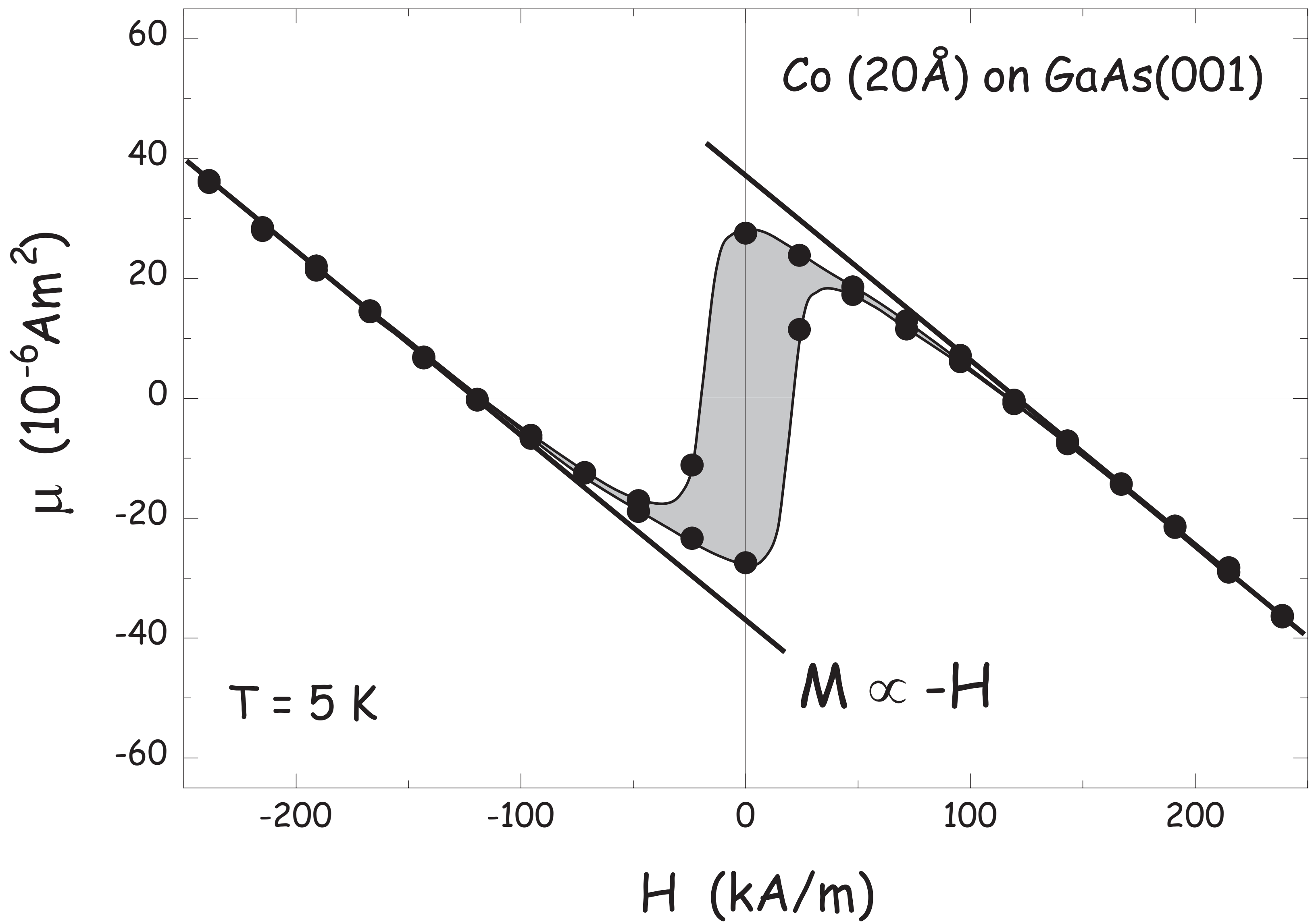
- *Paramagnetism*

Types of Magnetism

- Ferromagnetism $\uparrow \; \uparrow \; \uparrow \; \uparrow \; \uparrow \; \uparrow$
  - This type of magnetism is observed in the following metals:
    - Transition Metals Fe, Co, Ni
    - Lanthanides (rare earth) Gd, Tb, Dy, Ho, Er, Tm
    - Many alloys and compounds (some of which contain none of these atoms)
  - Ferromagnetism arises from the exchange interaction
  - quantum mechanical manifestation of the Coulomb interaction.
  - electrons can reduce their Coulomb energy by staying away from each other & increasing their spin angular momentum.
  - The exchange interaction is relatively short range.
    - mostly neighboring atoms only
  - positive interaction = neighbors parallel = FM

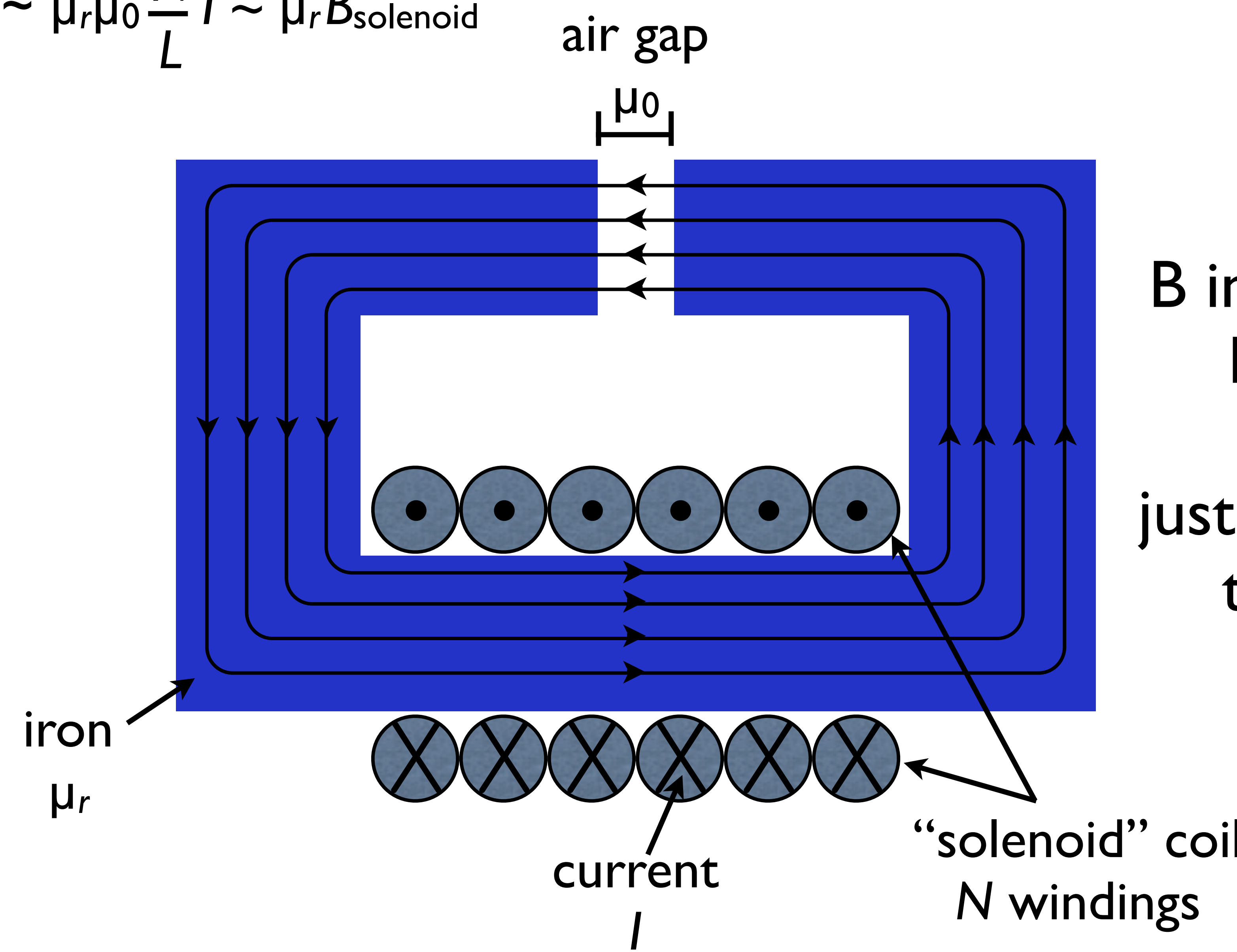

Total magnetic field
applied magnetic field

total moment = diamagnetic GaAs (huge volume) + ferromagnetic Co (small volume)



magnetic field amplifier - i.e., an electromagnet

$$B_{\text{gap}} \sim \mu_r \mu_0 \frac{N}{L} I \sim \mu_r B_{\text{solenoid}}$$

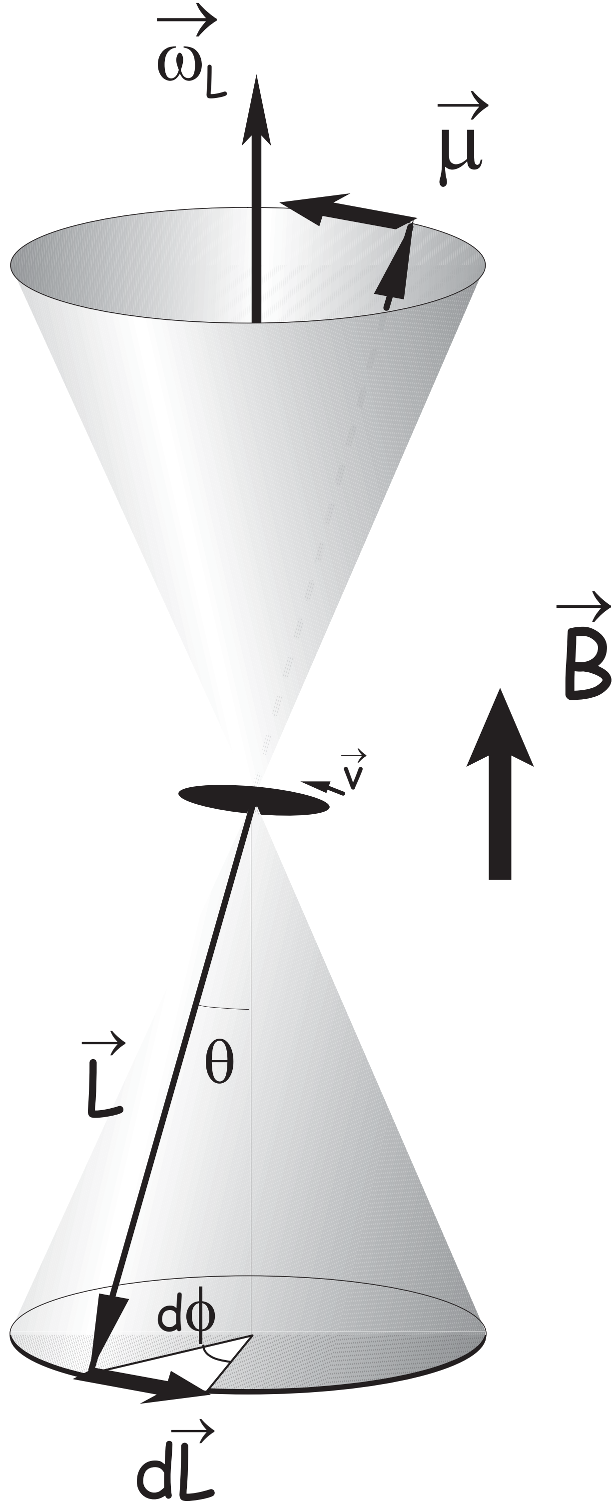


B inside iron is HUGE ...

just need tiny B to align it

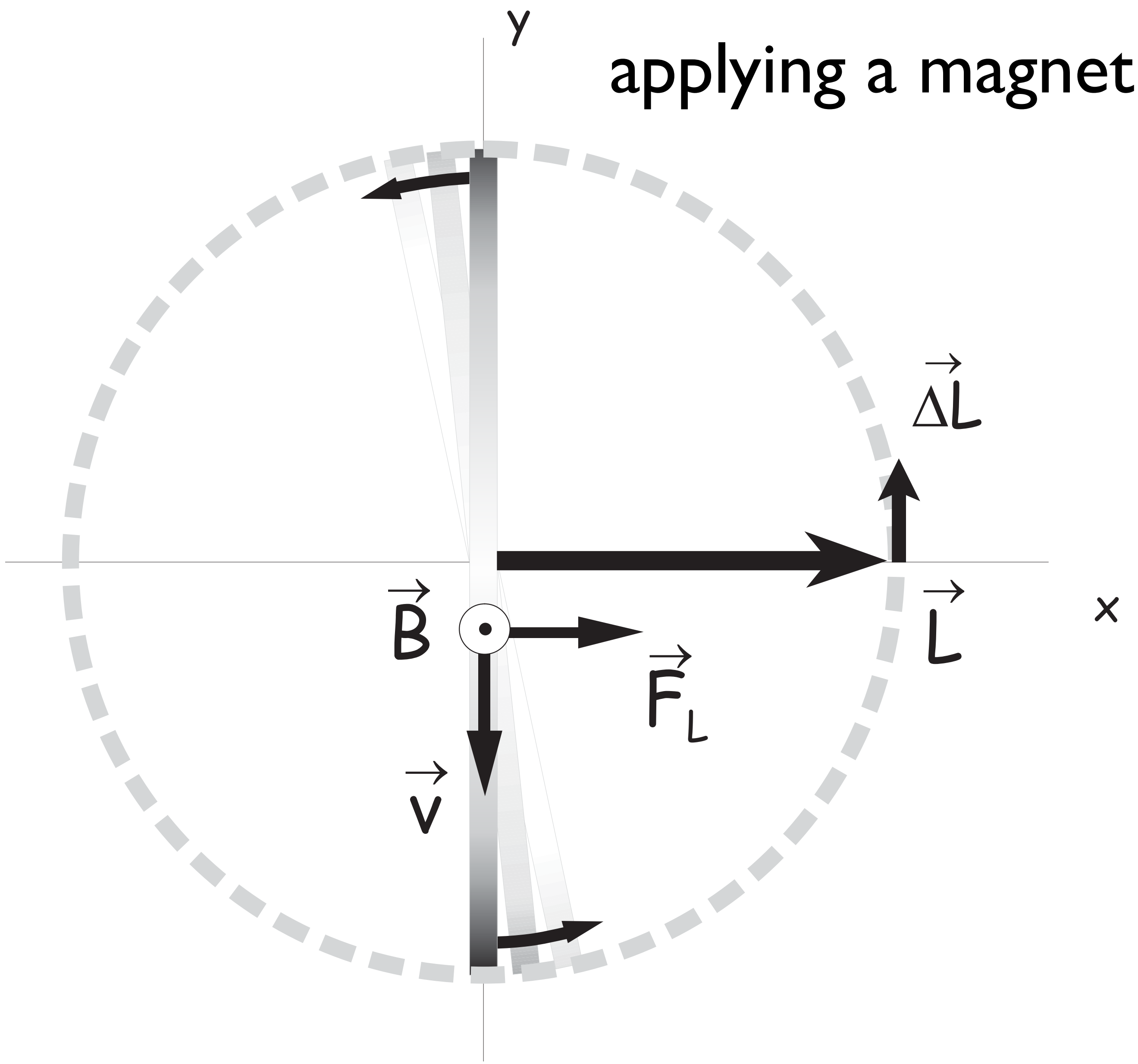
how does this relate to NMR/MRI?

what happens to a moment in B?



magnetic field
exerts a torque
on the moment
this causes
precession about
the field

applying a magnetic field: spin precession



electron orbit in the *yz* plane sets up an L
which, due to the Lorentz force, rotates in the *xy* plane

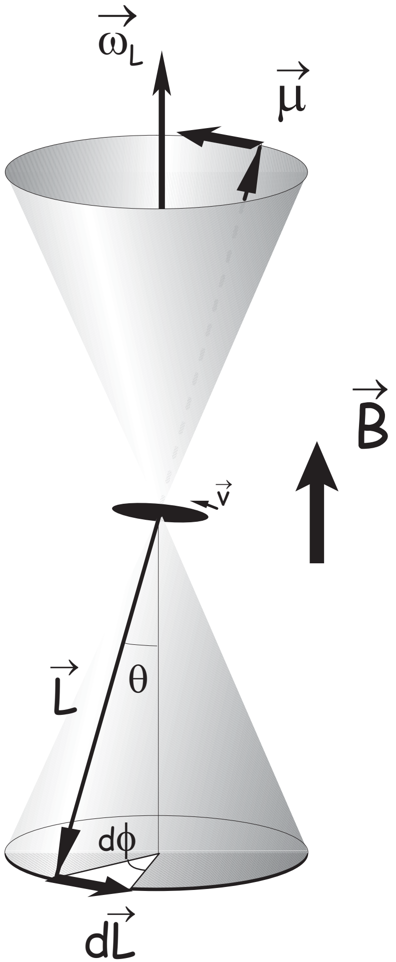
moments in a field:

energy change $$\Delta U = -\vec{\mu} \cdot \vec{B}$$

minimizing U means parallel to field

torque $$\vec{\tau} = \vec{\mu} \times \vec{B}$$

making torque zero means parallel to field



interaction with field
leads to torque ...

torque leads to
precession

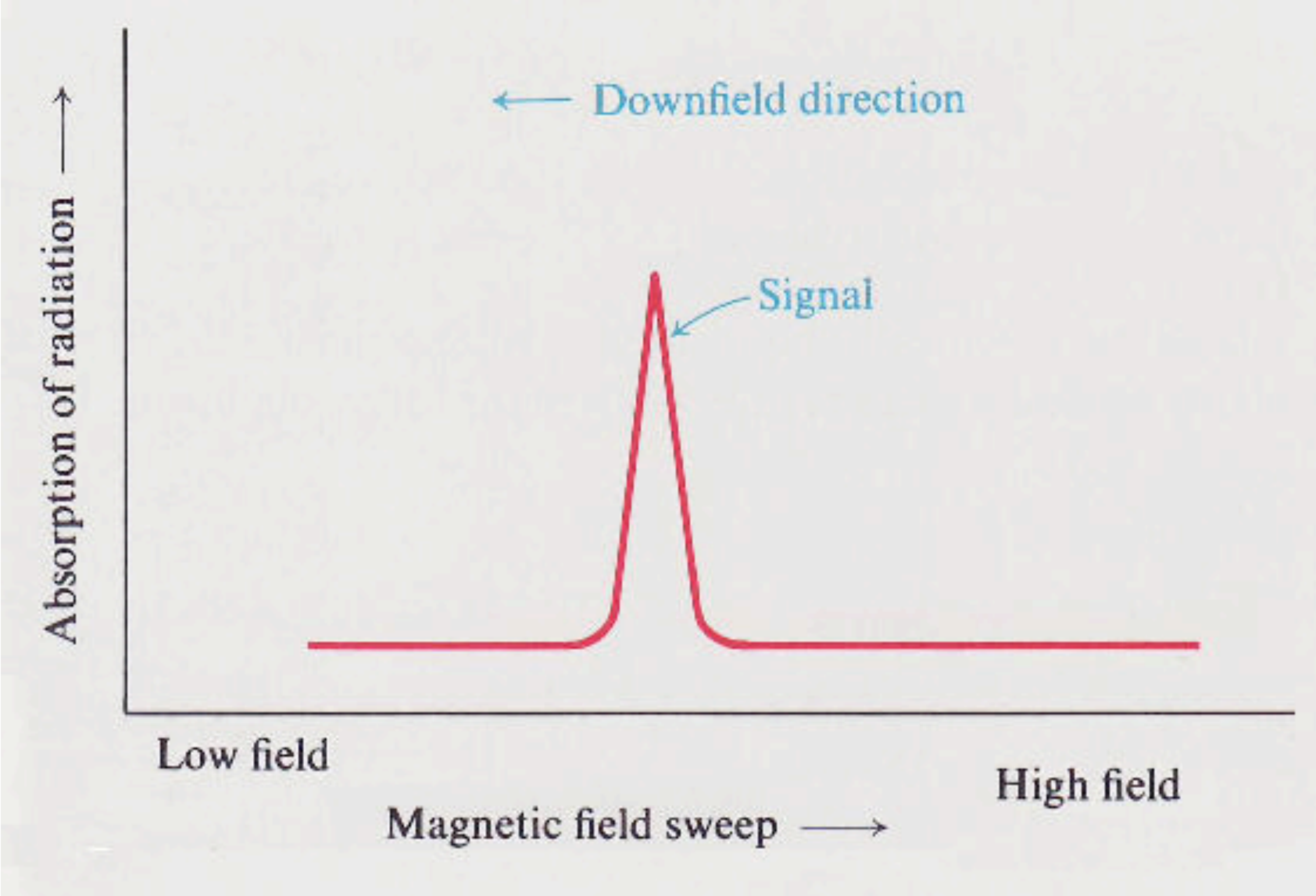
$$\Rightarrow \vec{\omega}_L = -\gamma \vec{B} = \frac{ge}{2m_e}\vec{B} \approx 14\,\mathrm{GHz/T}$$

so what?

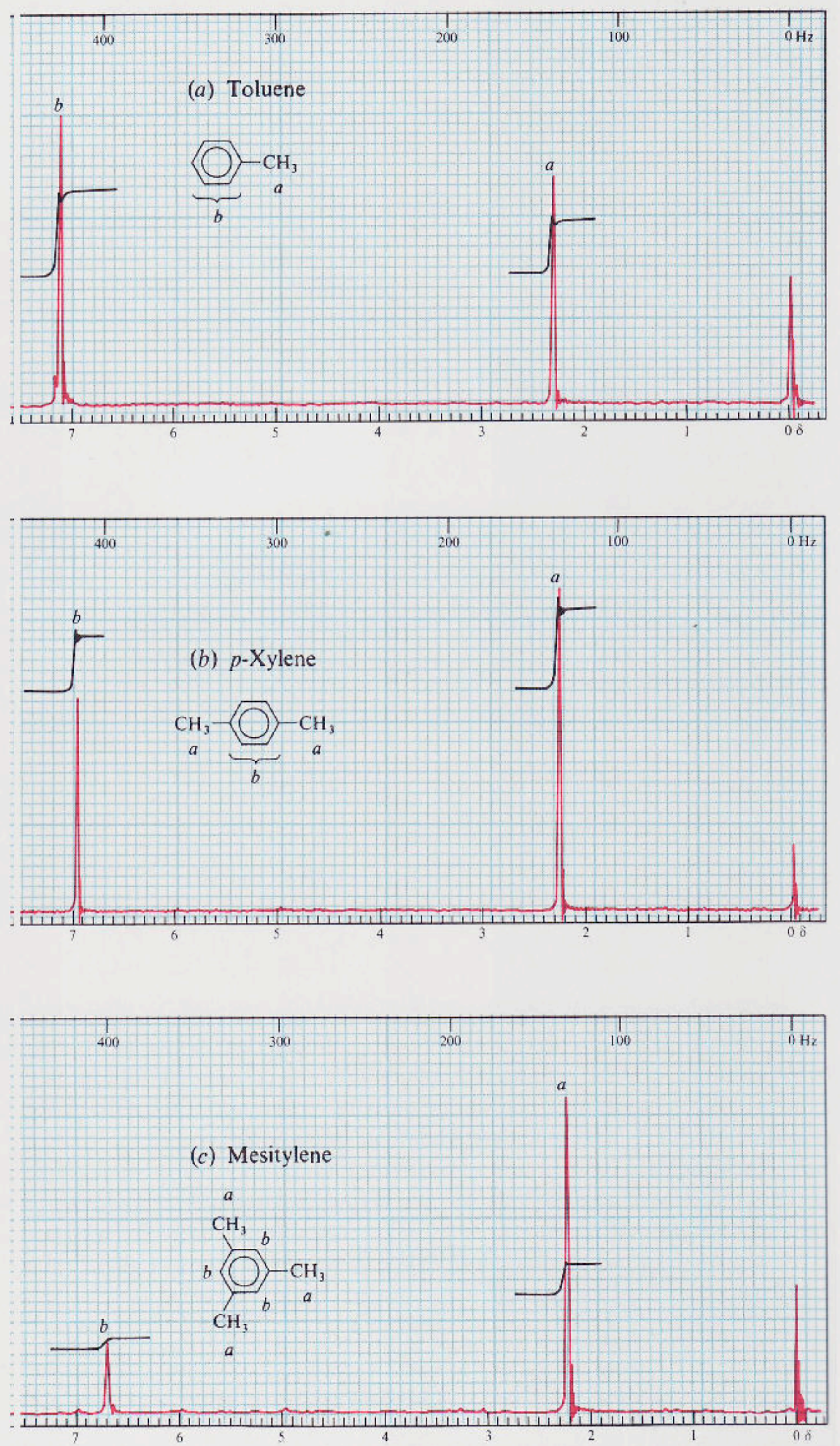
- local value of B depends on environment
- so precession frequency depends on environment
  - electron density, electronegativity, induction
- local environment is a function of bonding

- if you can measure the precession frequency, you can ID atom + environment

- (cannot really explain this without quantum)

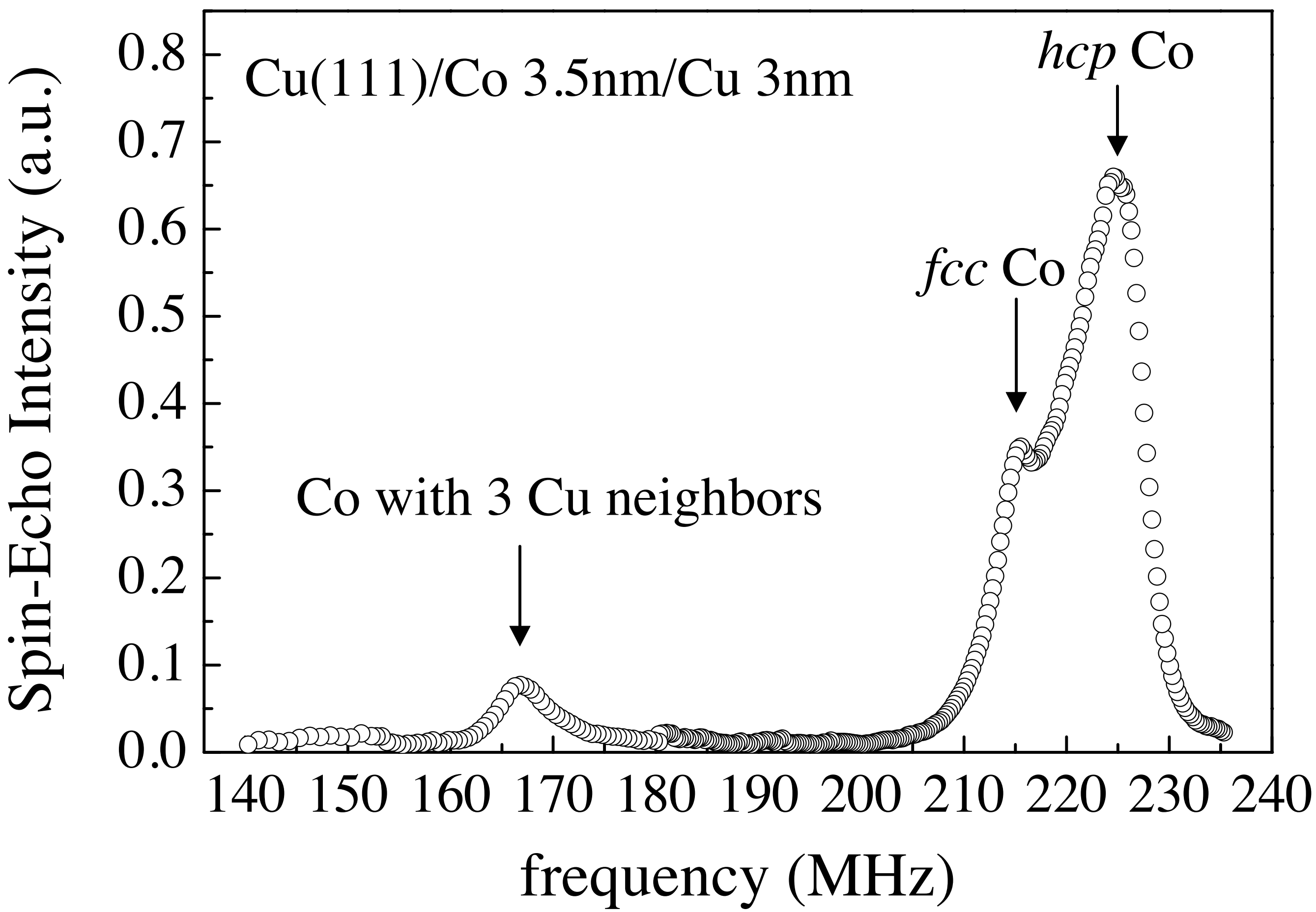


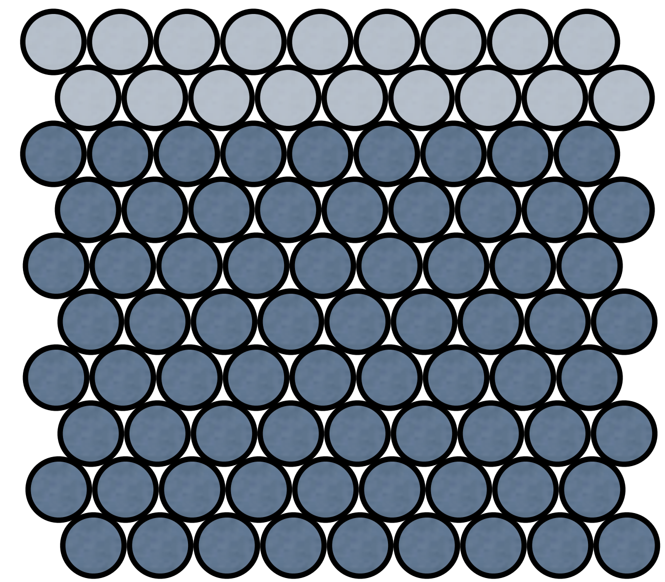
Absorption of radiation
Downfield direction
Signal
Low field
High field
Magnetic field sweep



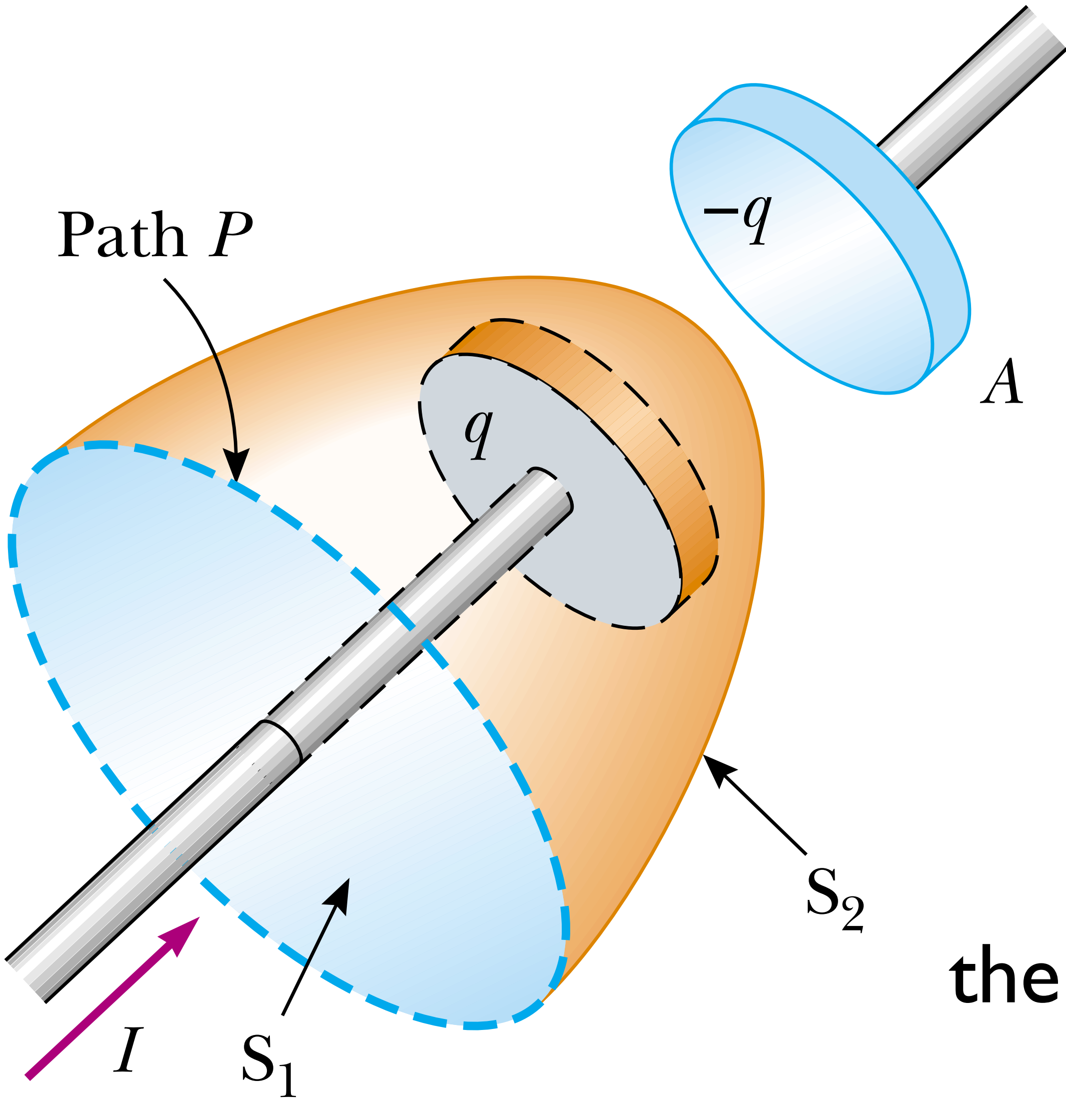
H atoms in
diff environments
give
diff frequencies

ratio of peaks ...
ratio of number of atoms





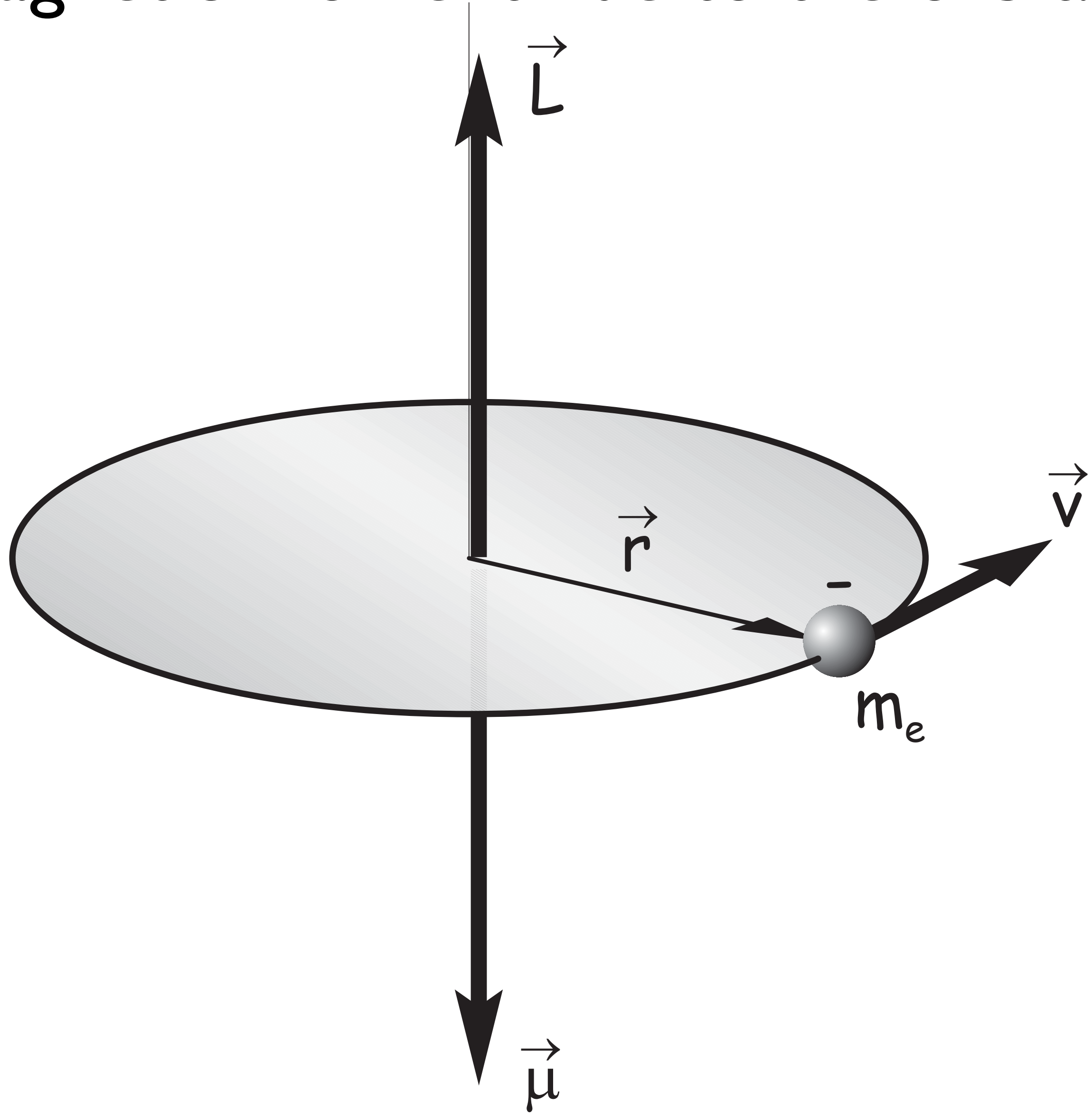
http://www.cis.rit.edu/htbooks/nmr/inside.htm



there is current through S_1, but not through S_2.

violates Ampere’s law?

e- orbiting a nucleus has an orbital momentum L and a magnetic moment due to the orbit.



e- have negative charge -- current is opposite to V, and L is opposite the magnetic moment