Magnetic Fields

Chapter
28

HW06 is up on WebAssign, due Thursday 02/29

Magnetic Fields

Reminder: If you have a charge you have an electric field.

Now: If you have a MOVING charge you ALSO have a magnetic field.

(can be thought of as relativistic effect)

A vector quantity symbolized by $\boxed{\vec{\mathbf{B}}}$

Units of Magnetic Field

The **SI** unit of magnetic field is the **tesla (T).**

$$\boxed{T = \frac{Wb}{m^2} = \frac{N}{C \cdot (m/s)} = \frac{N}{A \cdot m}}$$

- Wb is a weber = $kg \cdot m^2 \cdot s^{-2} \cdot A^{-1}$

A **non-SI** commonly used unit is a **gauss (G).**
- 1 T = 10^4 G

Definition of Magnetic Field

Recall **electric field =** space around an electrified object - a space in which electric forces act.

Now, magnetic field = the space around a magnetized object - a space in which magnetic forces act.

Electric field: defined by considering the electric force on a small test charge

Magnetic field: defined by considering the magnetic force $\vec{F}_B$ experienced by a charged particle moving with a velocity, $\vec{v}$.

- Assume (for now) there are no gravitational or electric fields present.

Magnetic Force

The magnetic field at some point in space can be defined in terms of the magnetic force, $\vec{F}_B$ experienced by a test charged particle moving with velocity $\vec{v}$.

velocity of the particle

magnetic force

$$\boxed{\vec{F} = q\vec{v} \times \vec{B}}$$

magnetic field

charge of the particle

THE CHARGED PARTICLE MUST BE MOVING.

Reminder on Cross Product

- OPERATION BETWEEN TWO VECTORS
- GIVES YOU A VECTOR

$$\vec{c} = \vec{a} \times \vec{b}$$

- NOT reversible: $\vec{a} \times \vec{b} \neq \vec{b} \times \vec{a}$

- its magnitude is given by: $|\vec{a} \times \vec{b}| = |\vec{a}||\vec{b}|sin\theta$

- its direction is given by using cartesian coordinates or by the right hand rule

- the resulting vector is always pointing in a direction perpendicular to the plane formed by $\vec{a}$ and $\vec{b}$.

Direction of cross product using Cartesian components

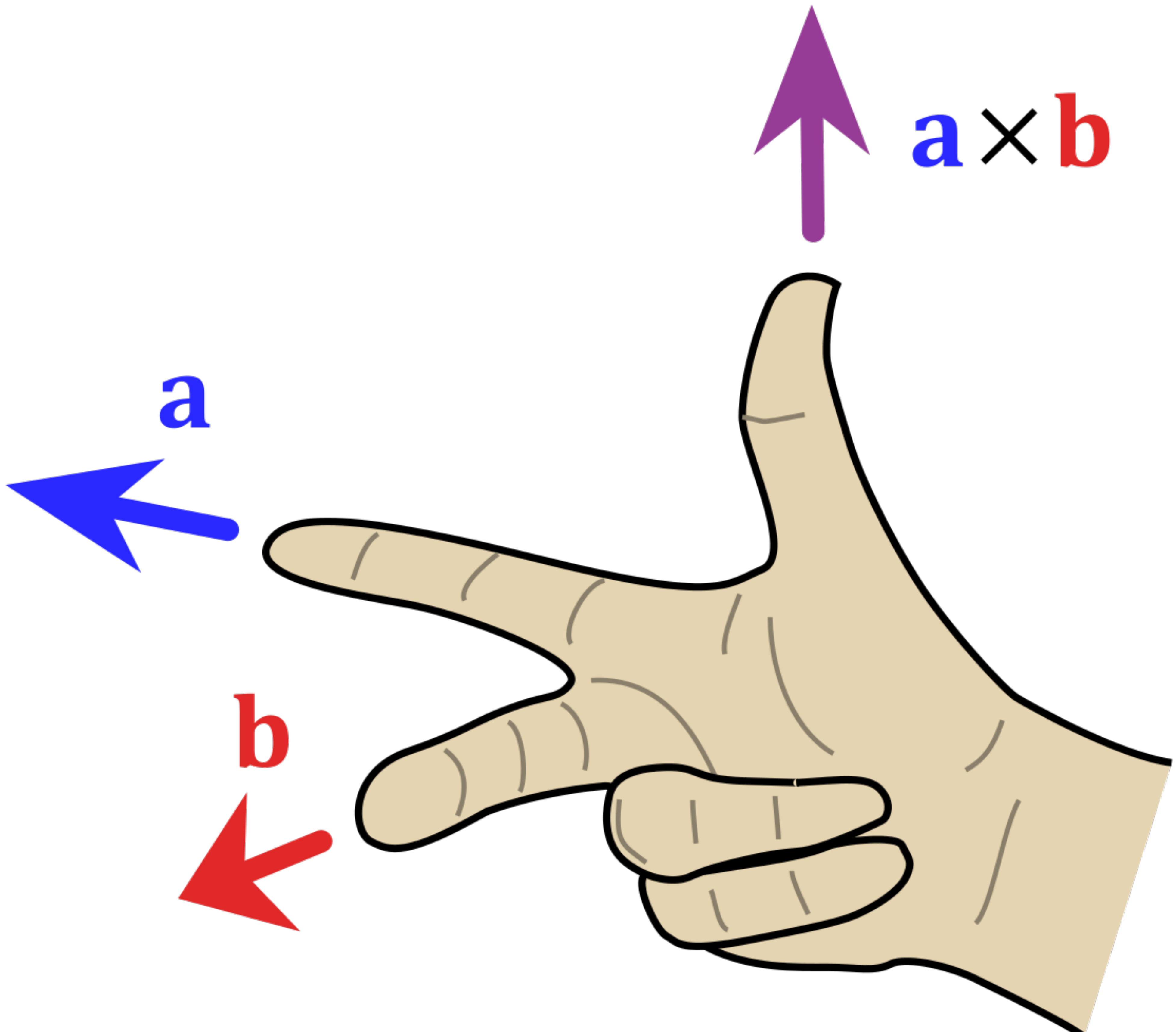
$$\vec{c} = \vec{a} \times \vec{b} = (a_x\hat{\imath} + a_y\hat{\jmath} + a_z\hat{k}) \times (b_x\hat{\imath} + b_y\hat{\jmath} + b_z\hat{k})$$
$$= a_x b_x \hat{\imath} \times \hat{\imath} + a_x b_y \hat{\imath} \times \hat{\jmath} + a_x b_z \hat{\imath} \times \hat{k} + \cdots$$

$$\boxed{\begin{array}{lll} \hat{\imath} \times \hat{\imath} = 0, & \hat{\jmath} \times \hat{\jmath} = 0, & \hat{k} \times \hat{k} = 0 \\ \hat{\imath} \times \hat{\jmath} = \hat{k}, & \hat{\jmath} \times \hat{k} = \hat{\imath}, & \hat{k} \times \hat{\imath} = \hat{\jmath} \\ \hat{\jmath} \times \hat{\imath} = -\hat{k}, & \hat{k} \times \hat{\jmath} = -\hat{\imath}, & \hat{\imath} \times \hat{k} = -\hat{\jmath} \end{array}}$$

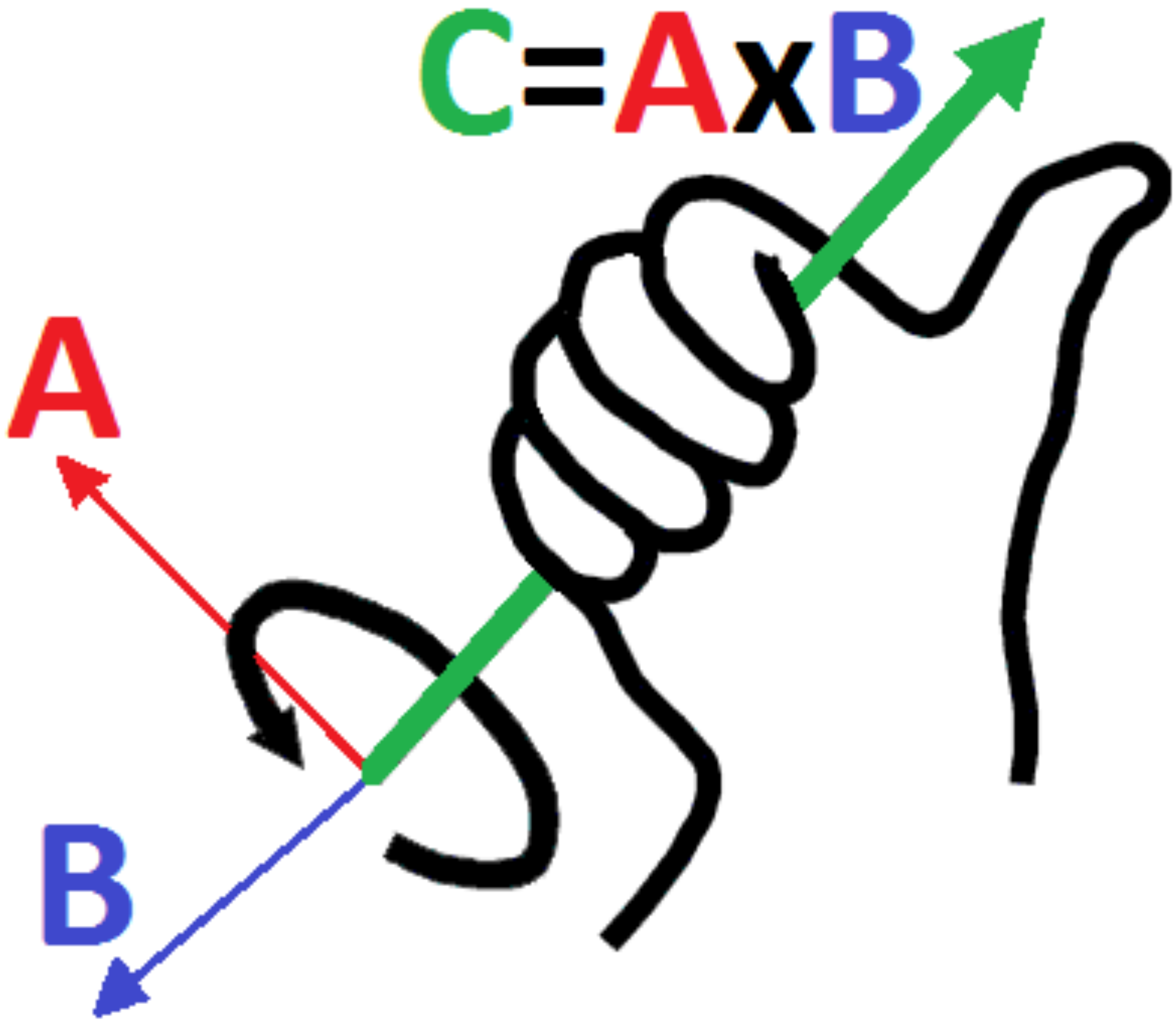
$$\boxed{\vec{c} = \vec{a} \times \vec{b} = (a_y b_z - b_y a_z)\hat{\imath} + (a_z b_x - b_z a_x)\hat{\jmath} + (a_x b_y - b_x a_y)\hat{k}}$$

this gives you the components and the direction of the cross product

Right Hand Rule: First Method

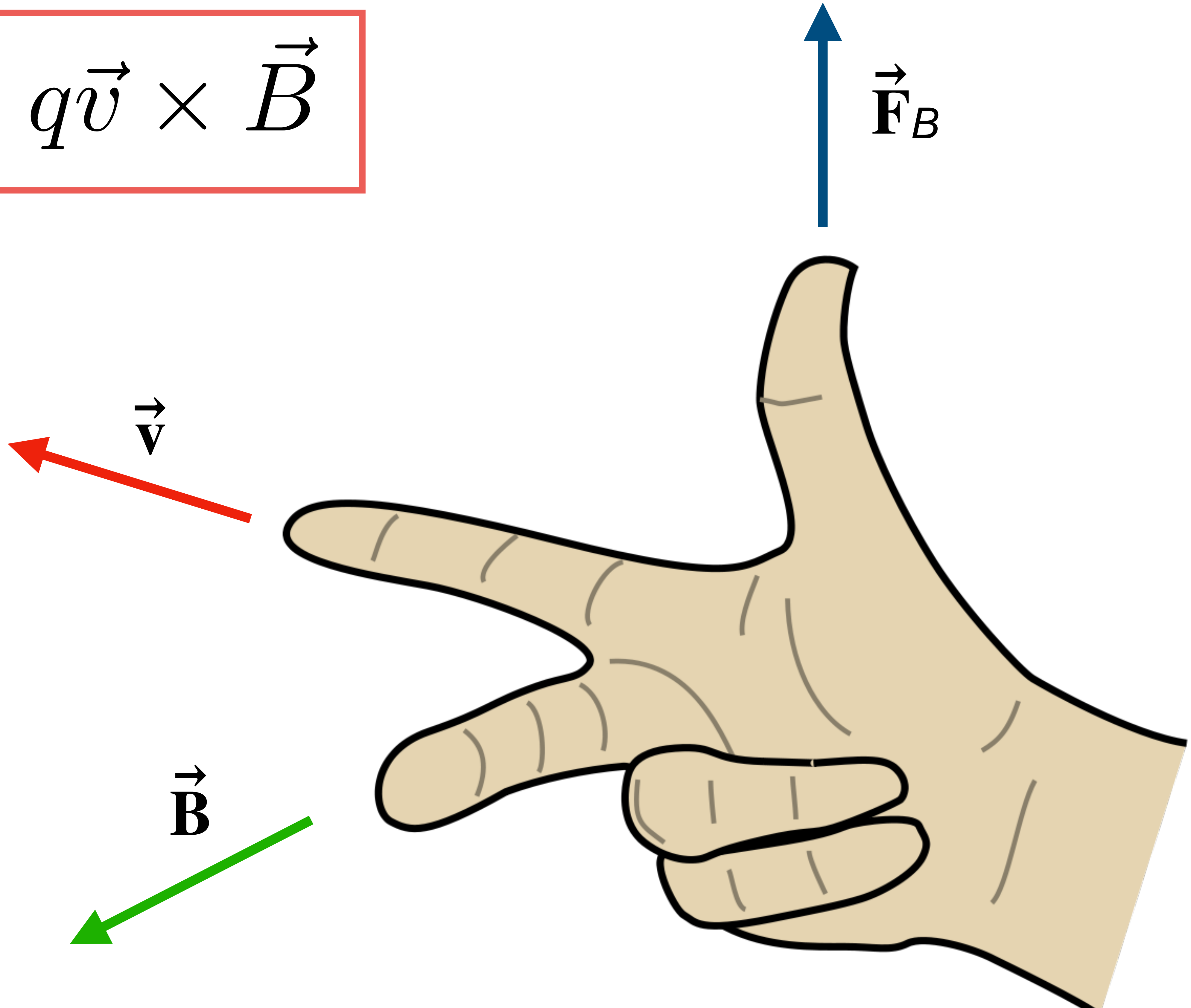


Right Hand Rule: 2nd Method



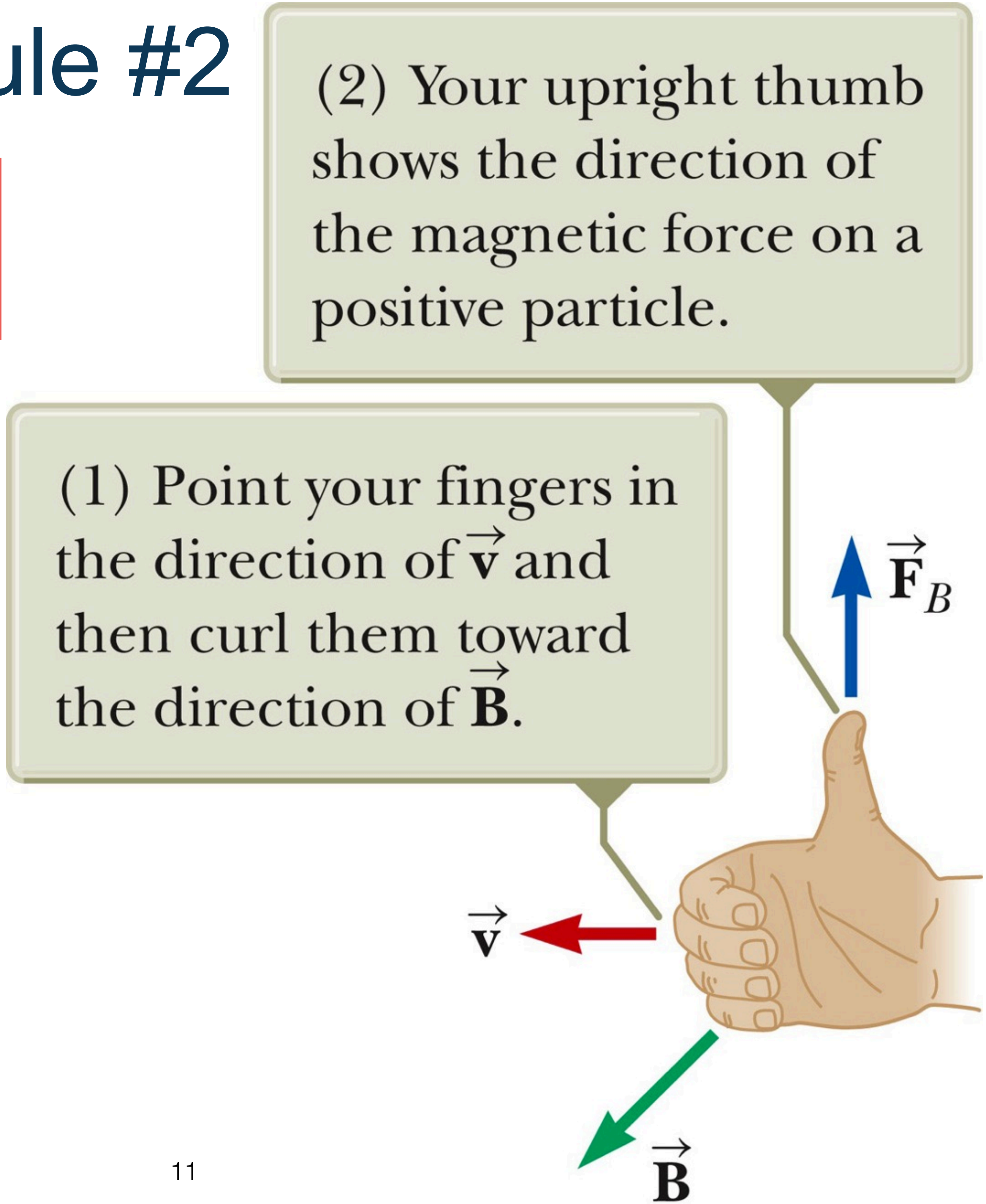
Right Hand Rule #1

$$\boxed{\vec{F} = q\vec{v} \times \vec{B}}$$



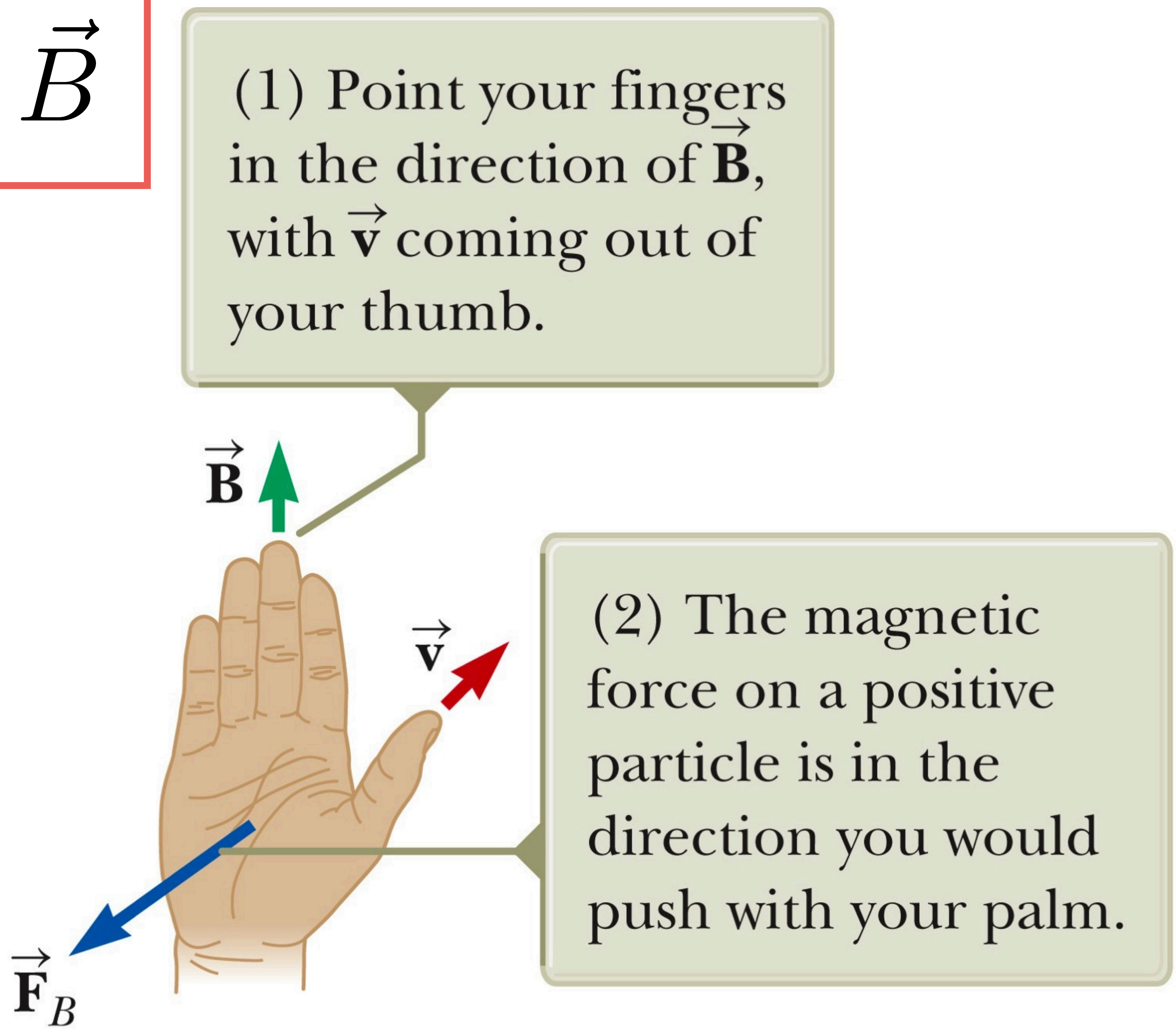
Right Hand Rule #2

$$\boxed{\vec{F} = q\vec{v} \times \vec{B}}$$



Right Hand Rule #3

$$\boxed{\vec{F} = q\vec{v} \times \vec{B}}$$



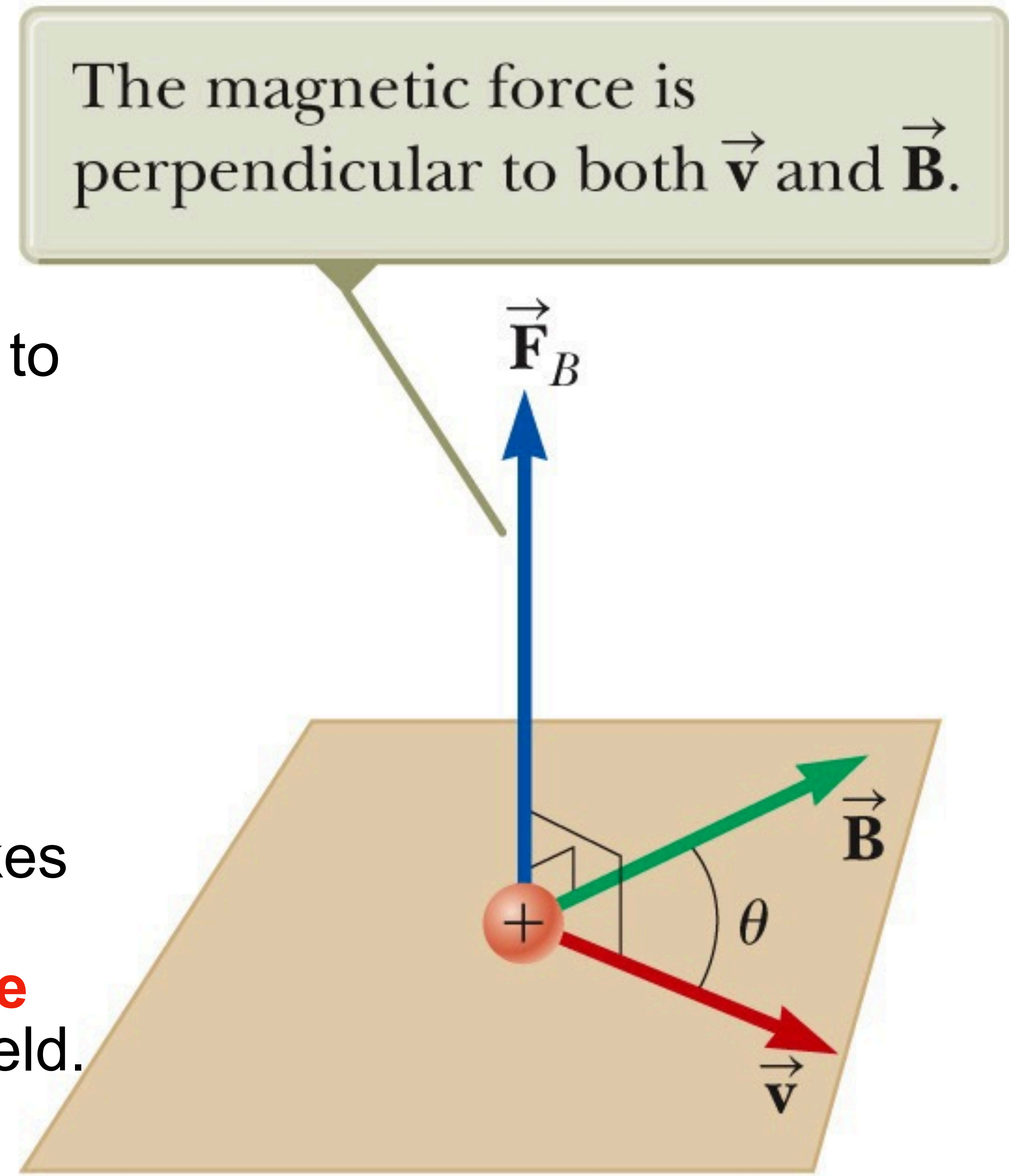
Magnetic Force

$$\boxed{\vec{F} = q\vec{v} \times \vec{B}}$$

Magnitude is given by :

$$\boxed{F = qvBsin\theta}$$

θ is the angle between $\vec{v}$ and $\vec{B}$



- When a charged particle moves parallel to the magnetic field vector, **θ = 0**

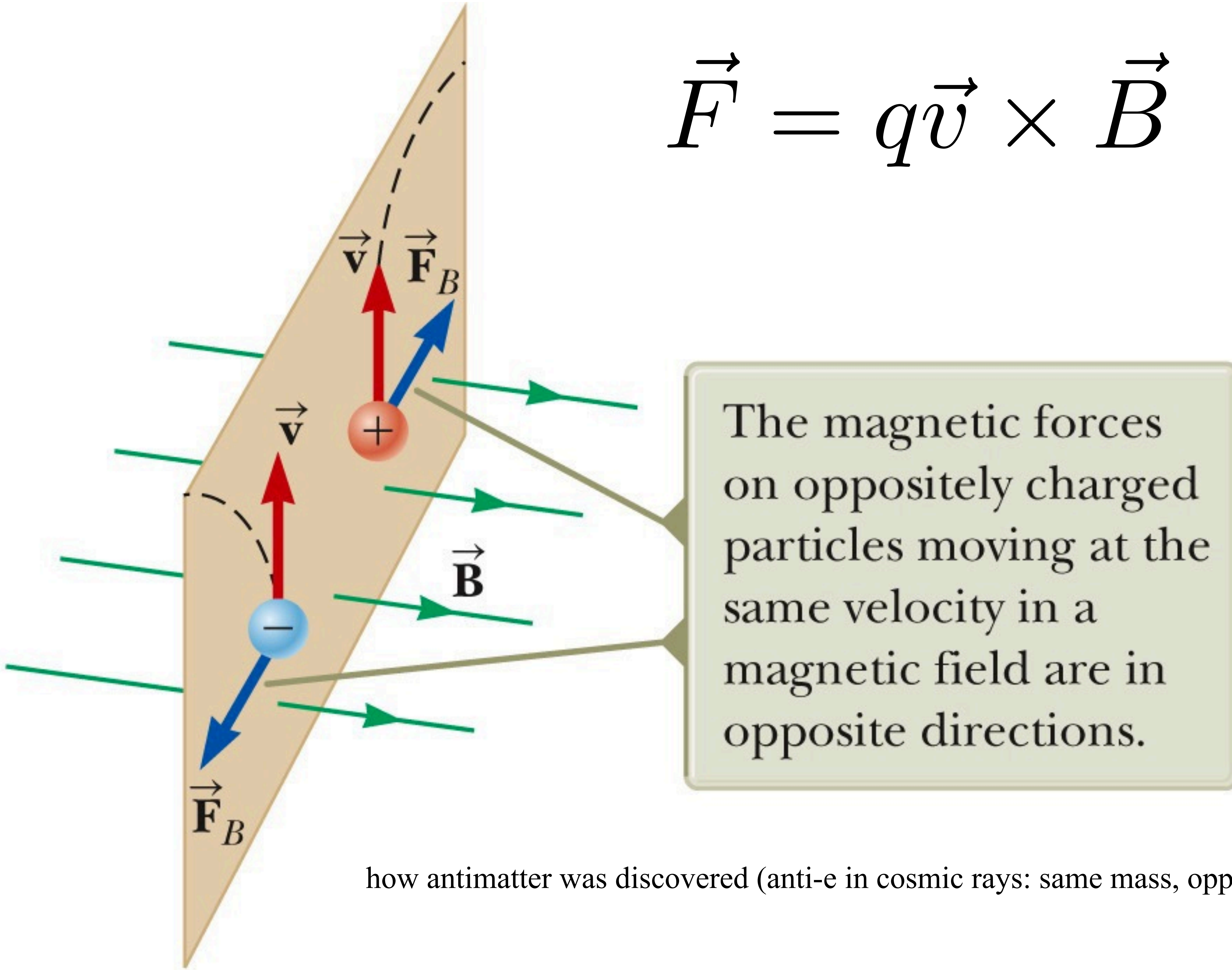
sinθ = 0 and **F = 0**

→ the magnetic force acting on the particle is zero.

- When the particle's velocity vector makes any angle **θ ≠ 0** with the field, the force acts in a direction **perpendicular to the plane** formed by the velocity and the field.

- the force is maximum when **θ = 90** degrees

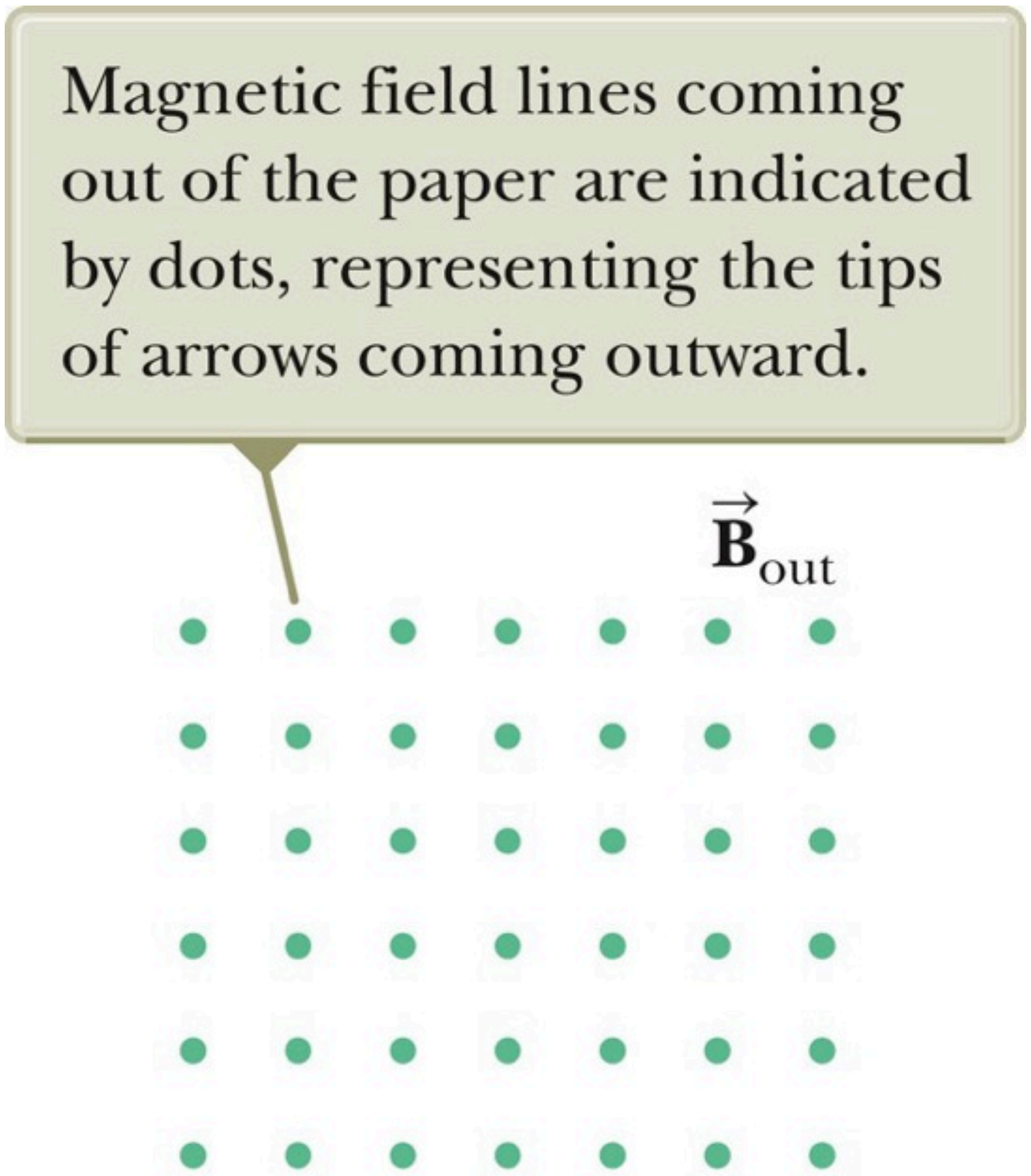
Magnetic Force due to opposite charges

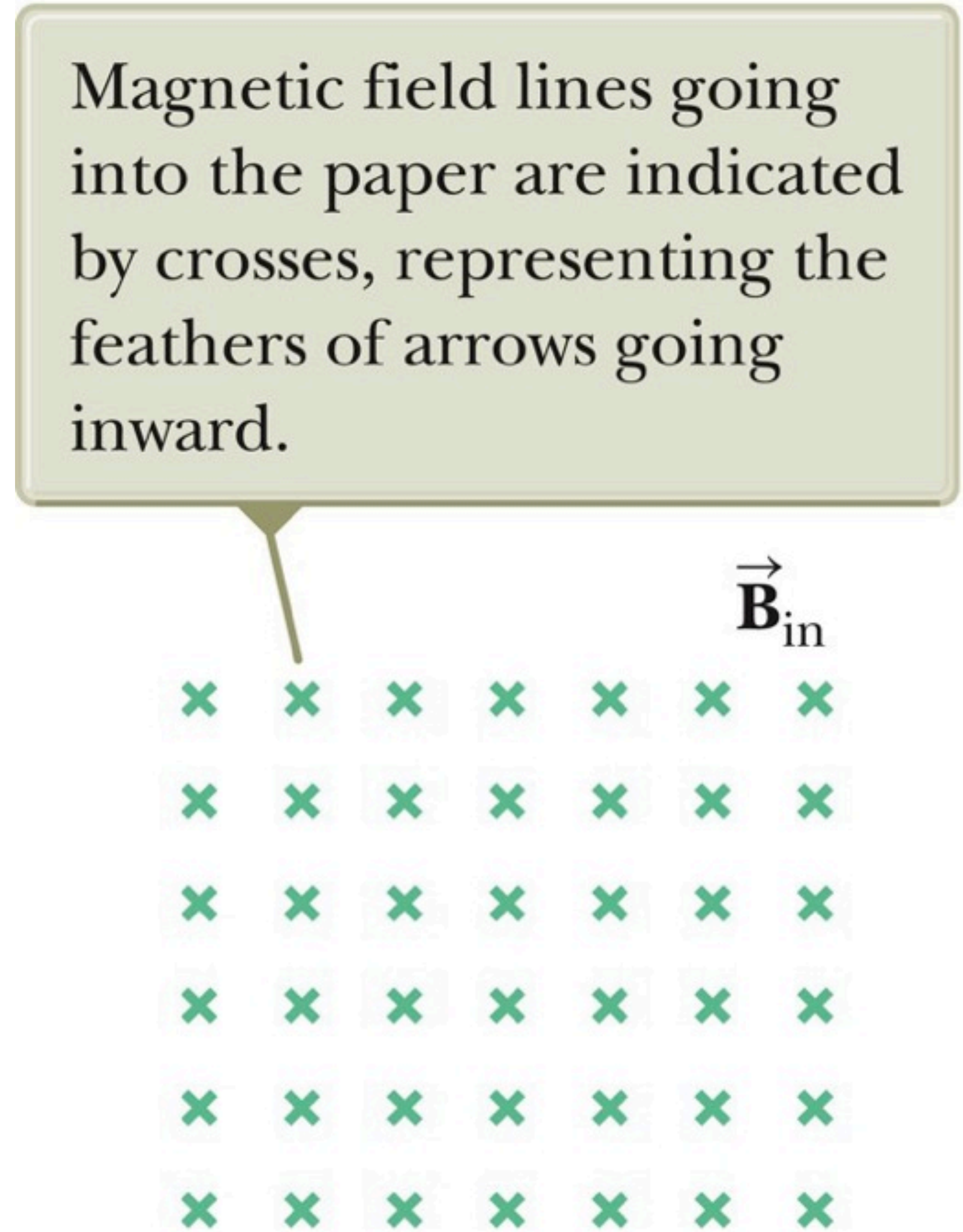


$$\vec{F} = q\vec{v} \times \vec{B}$$

how antimatter was discovered (anti-e in cosmic rays: same mass, opposite charge)

Notation Notes





dot = OUT of the page (towards you)

cross = INTO the page (away from you)

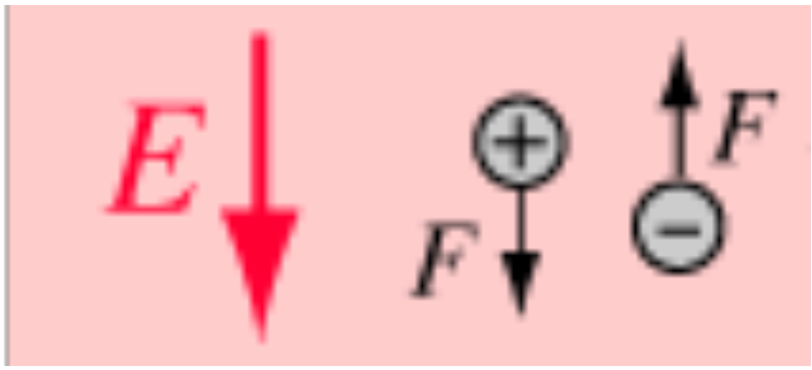
Electric and Magnetic Fields: Differences

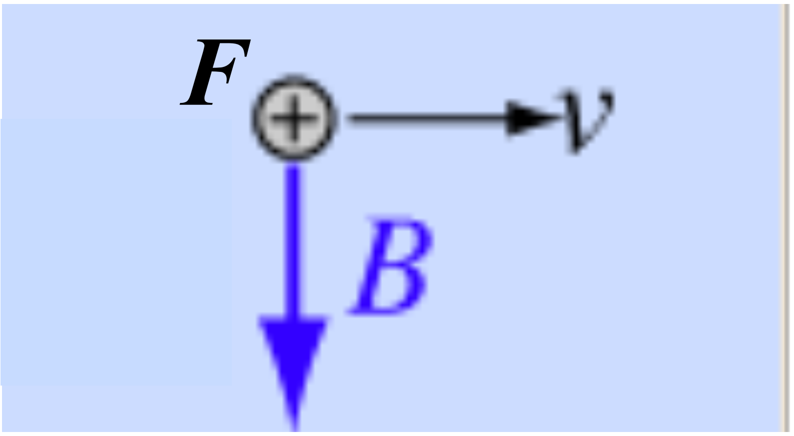
Motion

- The electric force acts on a charged particle regardless of whether the particle is moving.
- **The magnetic force acts on a charged particle only when the particle is in motion.**

Direction of force

- The electric force acts along the direction of the electric field.
- The **magnetic force acts perpendicular to the magnetic field.**





Electric and Magnetic Fields: Differences

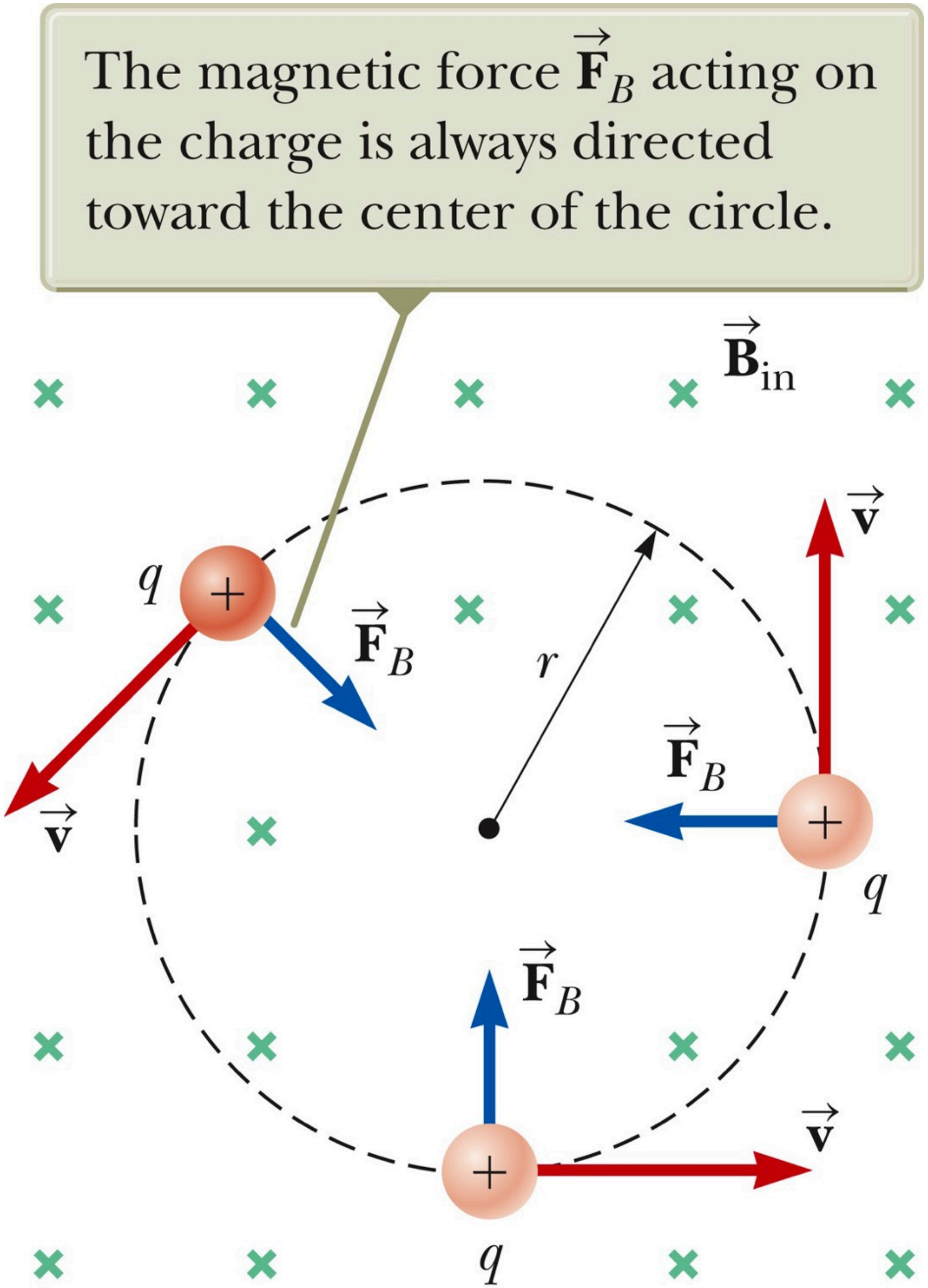
Work

- The electric force does work in displacing a charged particle.
- The **magnetic force associated with a steady magnetic field does no work when a particle is displaced.**
  - This is because the force is perpendicular to the displacement of its point of application.

Kinetic Energy

- The electric field alone can alter the kinetic energy of a charged particle.
- The magnetic field **cannot alter the kinetic energy** of a charged particle.

Charged Particle in a uniform Magnetic Field



- Take a particle moving in a B field with a velocity v perpendicular to the field
- The magnetic force causes a **centripetal acceleration**, changing the direction of the velocity of the particle.

F = ma gives :

$$F_B = qvB = \frac{mv^2}{r}$$

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

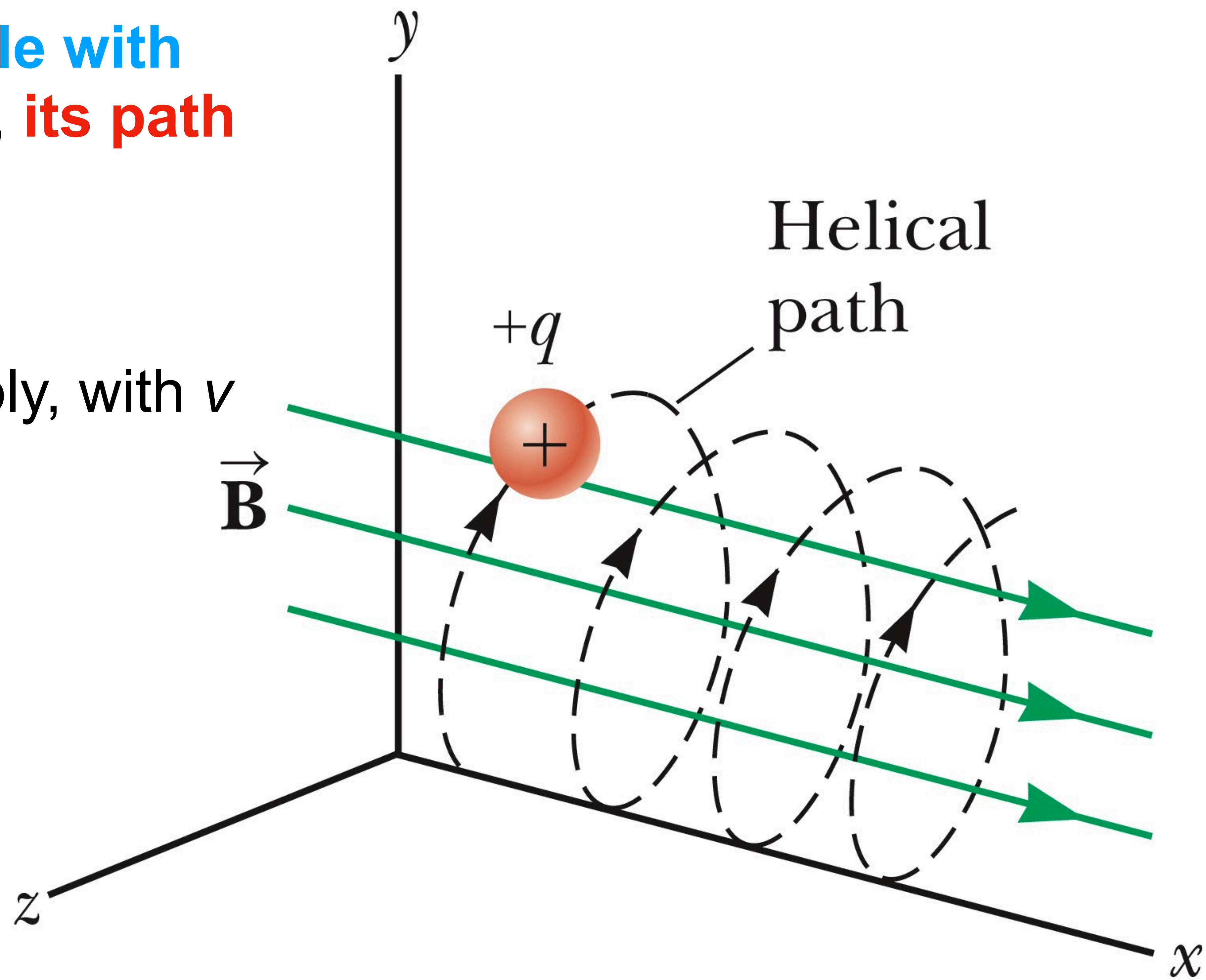
ω = angular speed T = period.

Motion of a Particle, General

If a charged particle moves in a uniform magnetic field **at some arbitrary angle with respect to the field**, **its path is a helix.**

Same equations apply, with *v* replaced by

$$v_{\perp} = \sqrt{v_y^2 + v_z^2}$$



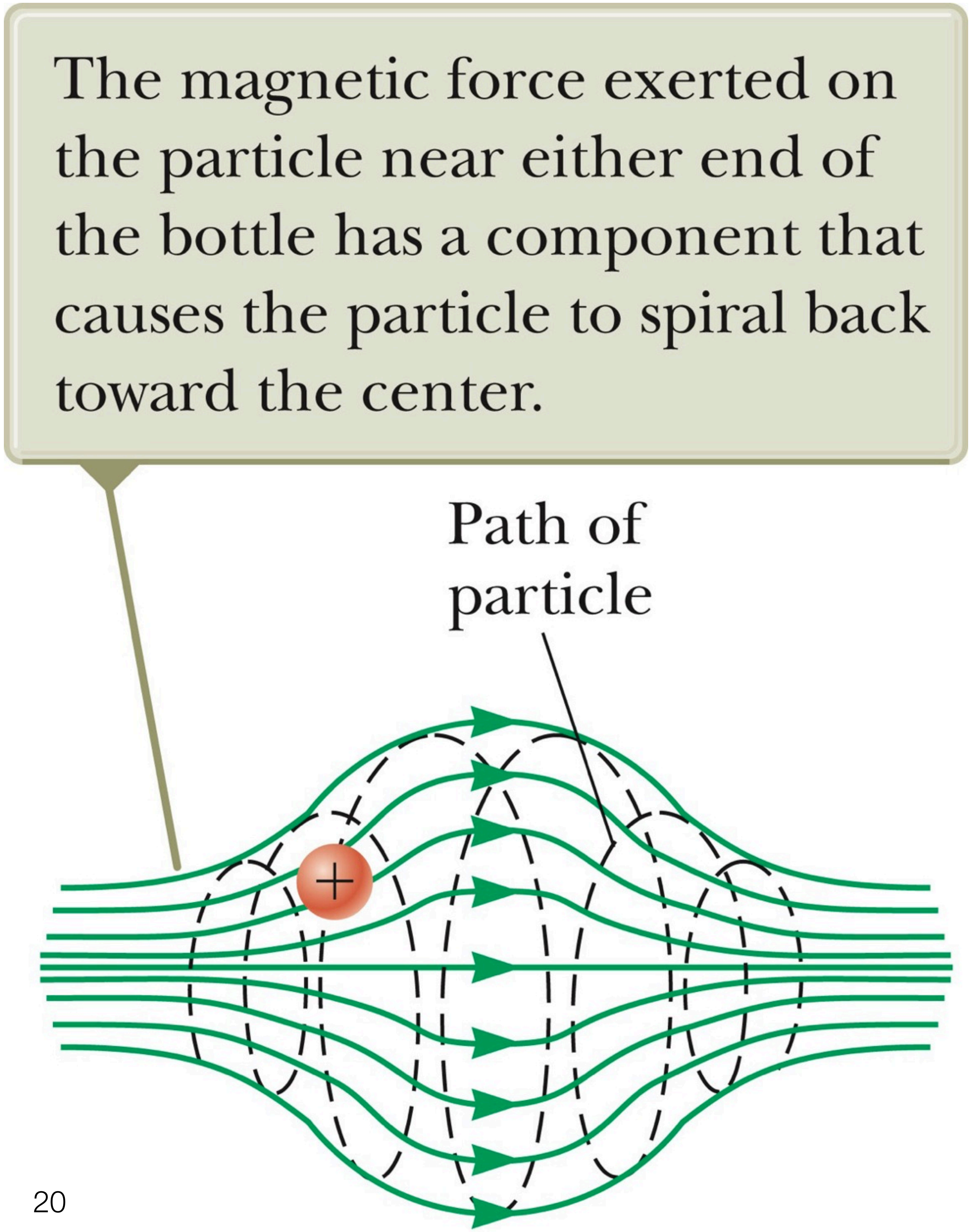
Particle in a Nonuniform Magnetic Field

The motion is complex.

For example, the particles can oscillate back and forth between two positions.

This configuration is known as a ***magnetic bottle.***

These cases get REALLY complex, really fast, that is why for the purpose of this class, **we will mostly consider uniform magnetic fields.**



Particle in a Nonuniform Magnetic Field

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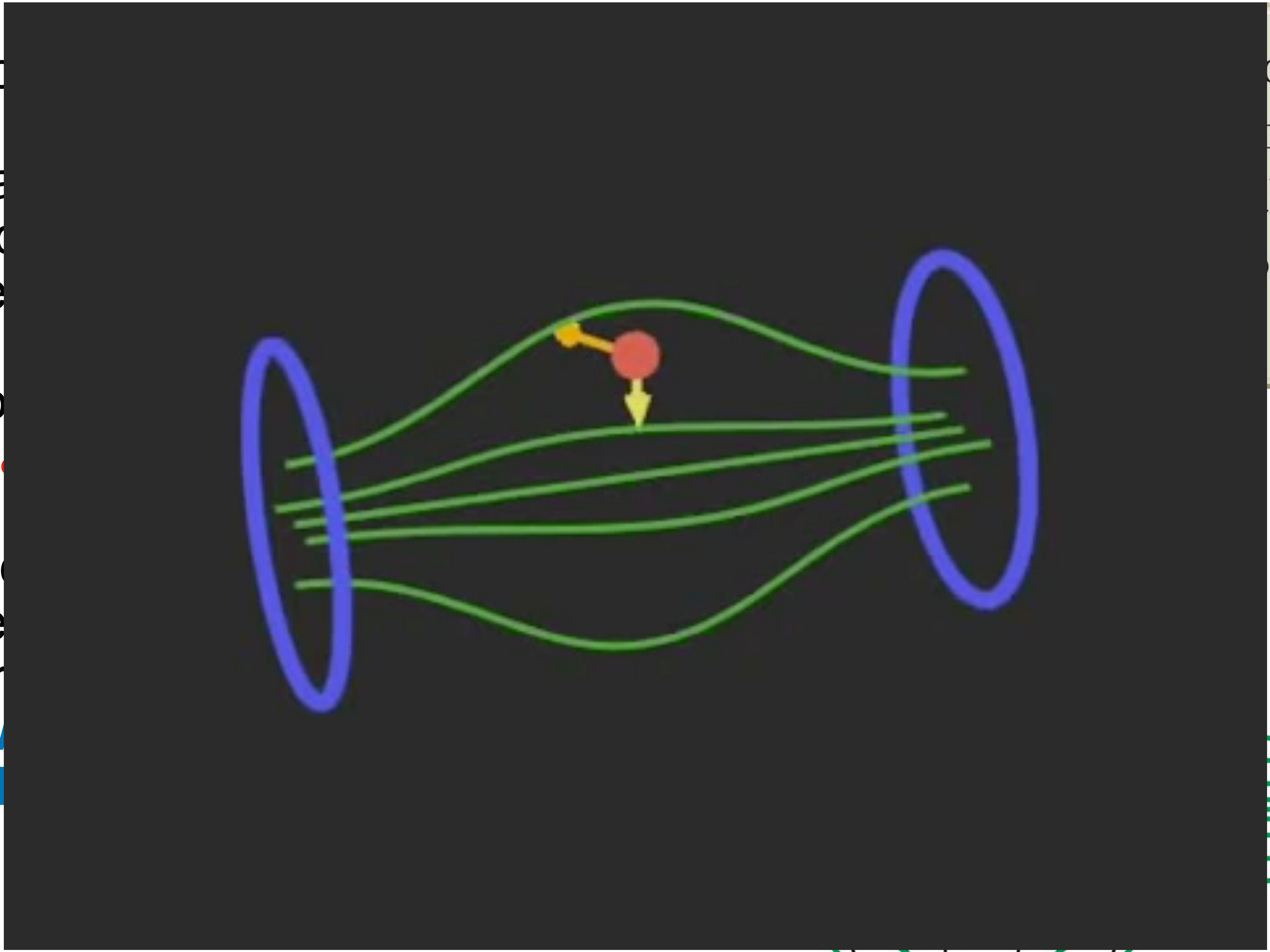

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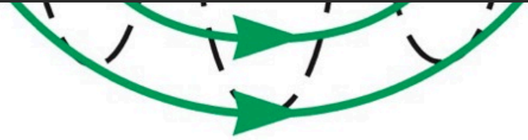


Charged Particles Moving in Electric and Magnetic Fields

In many applications, charged particles will move in the presence of both magnetic and electric fields.

In that case, the total force is the sum of the forces due to the individual fields.

- The total force is called the **Lorentz force.**

In general:

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

Magnetic Field Lines

Just like you can picture an electric field in a space through electric field lines, so it is with magnetic fields.

Just like electric field lines, magnetic fields lines:

- can never cross
- the net magnetic field at any point is the vector sum of all magnetic fields present at that point
- are a pictorial representation of the field
- are present everywhere in space
- the higher the lines' density, the higher the strength of the field

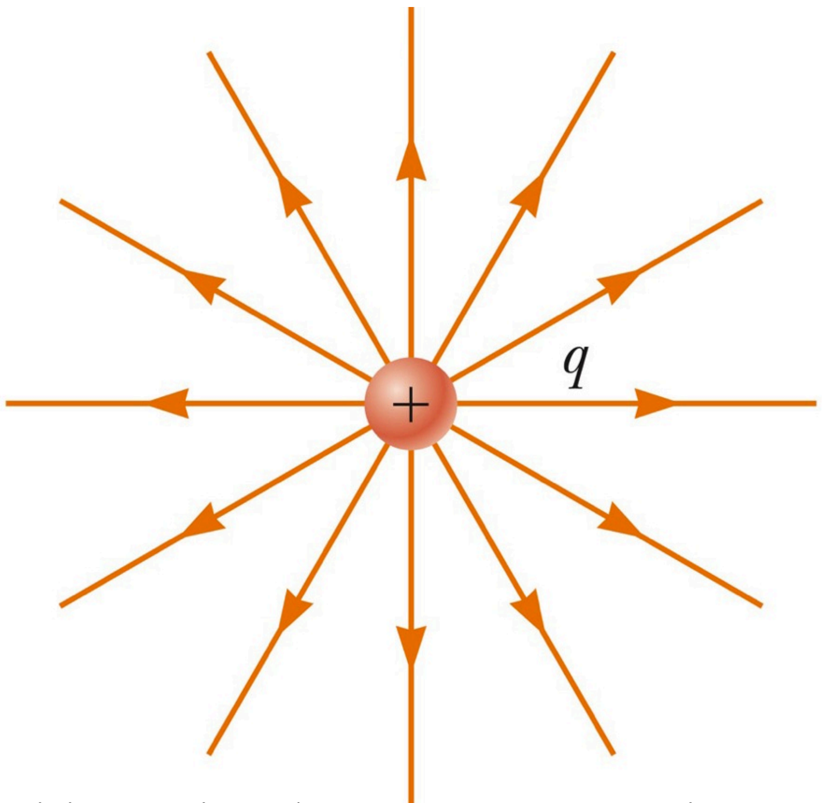
Unlike electric fields lines, magnetic field lines:

visualizable using iron filings (for instance)

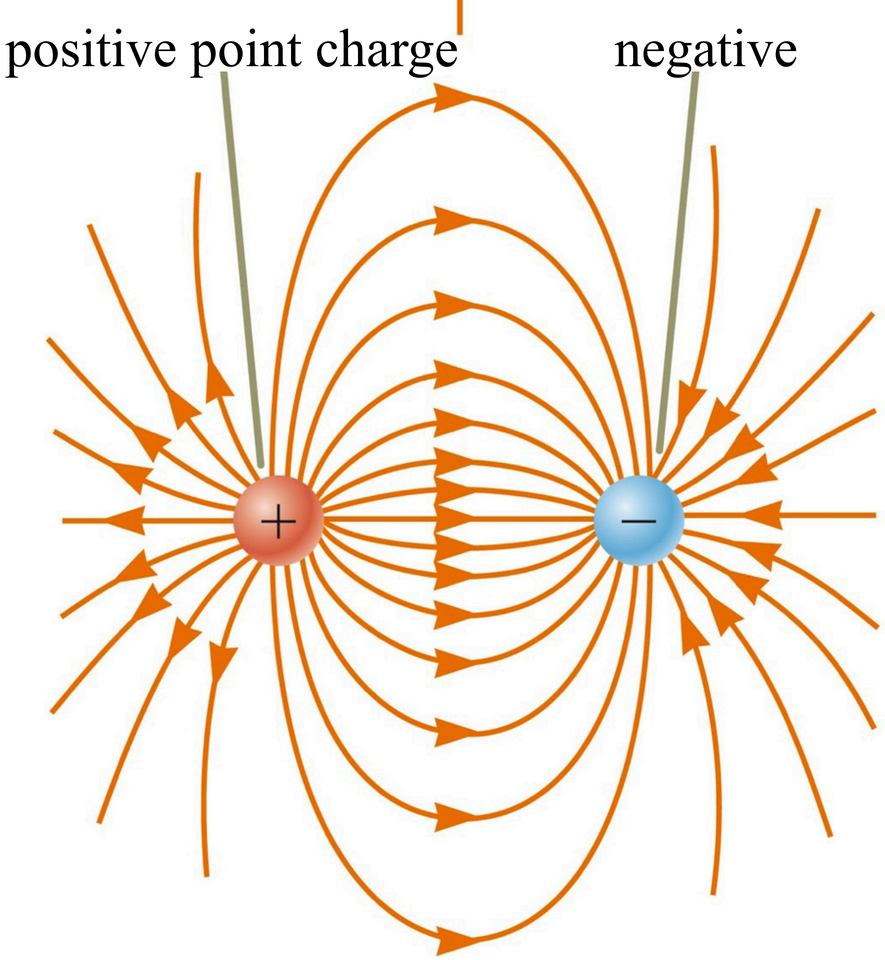
- can never be infinite, but **always form closed loops.**
- **do not represent the path of the charged particle**
- do not originate on charges, but **originate on poles**

Poles

A pole is the point where your field lines converge.



Example: **monopole** = 1 pole
A single, static + charge creates an electric field.
The + charge is the only pole.



Example: **dipole** = 2 poles
This is an electric dipole. Both charges are static (they don't move), they both produce electric field lines.
Each charge is a pole.

Magnetic Poles

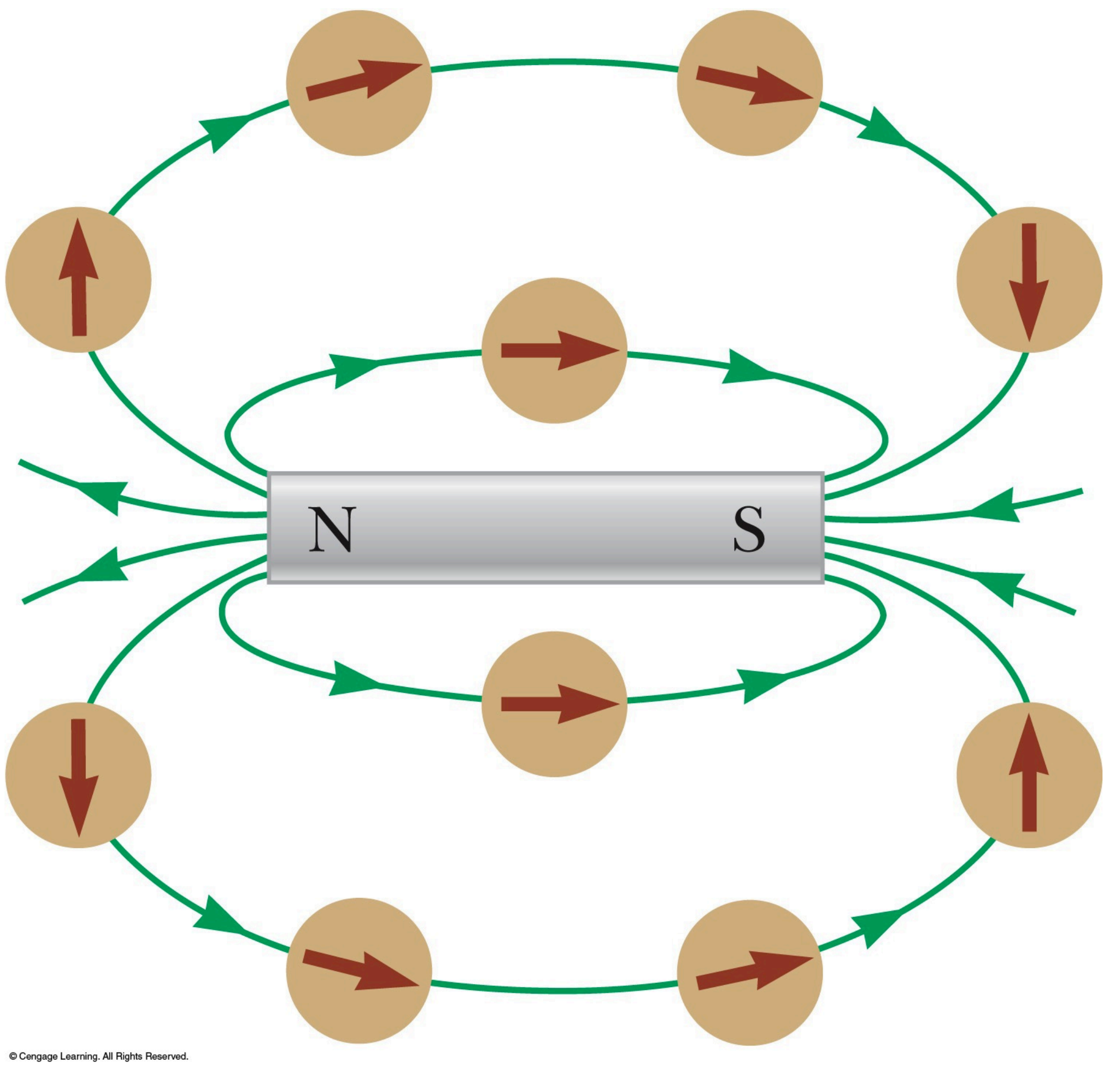
While electric monopoles exist, **THERE IS NO SUCH THING AS A MAGNETIC MONOPOLE ***

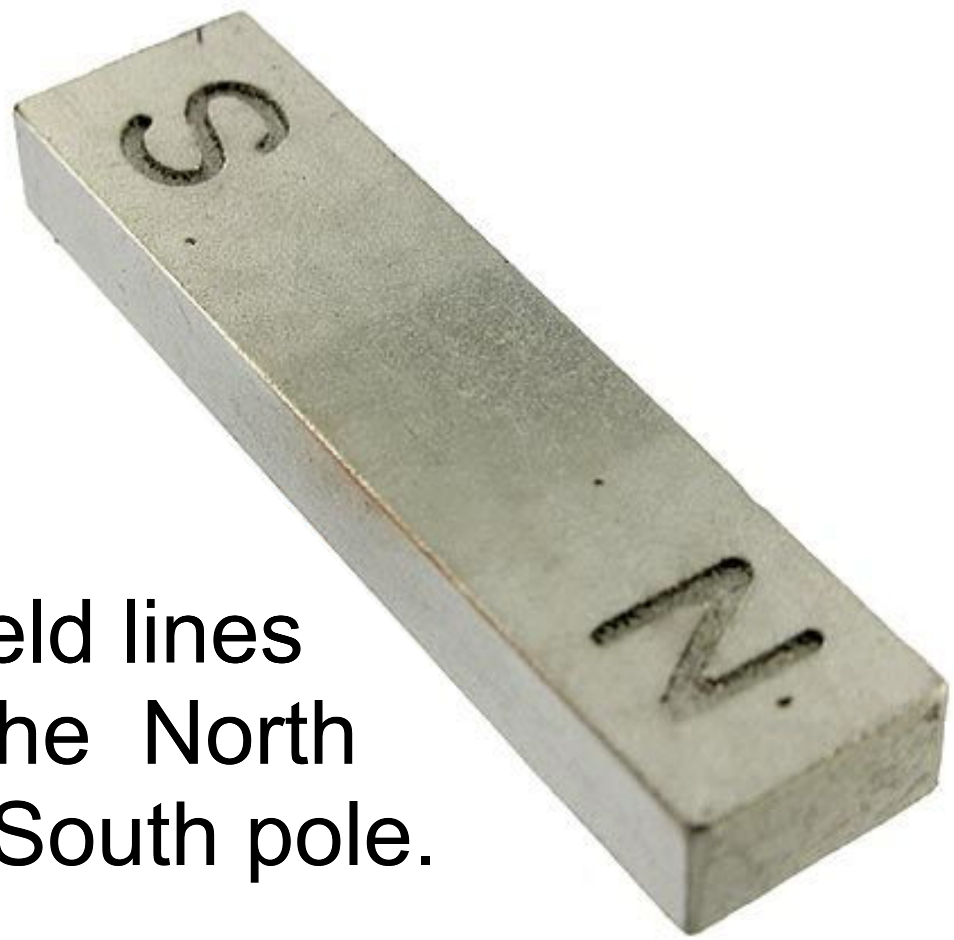
- magnetic poles always **come in pairs**.
- the simplest case is a magnetic **dipole**, which has 2 poles.
- these poles are named **North (N) and South (S)**
- these poles exert forces on each other
  - **Like poles repel** each other: N-N or S-S
  - **Unlike poles attract** each other : N-S

→ magnetic field lines originate and end on poles
→ magnetic fields are created by moving charges
→ moving charges create a dipole

* for now… GUT, String Theory says otherwise

Simplest example of a dipole: a bar magnet



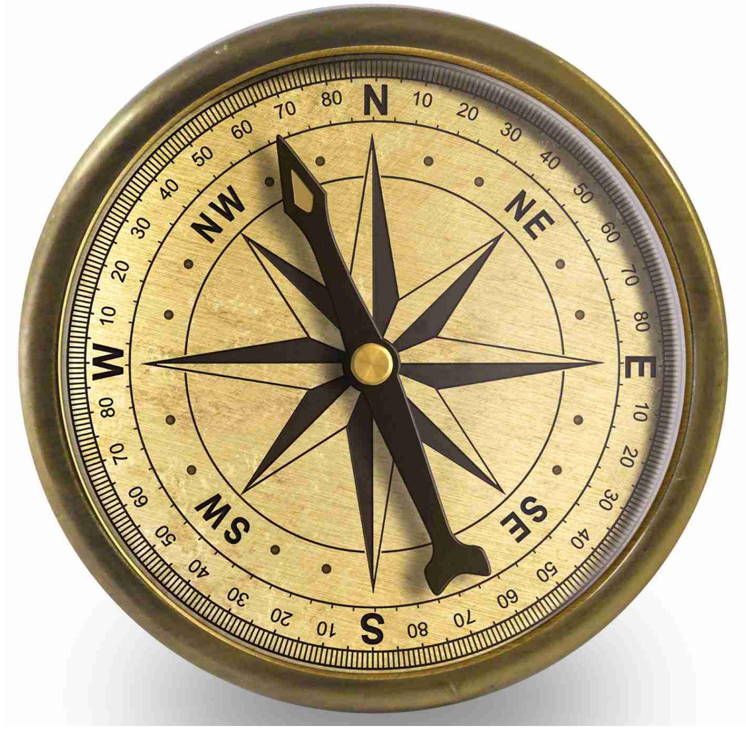


Magnetic field lines point from the North pole to the South pole.

What happens to the poles if you cut a bar magnet in 2?

If a bar magnet is suspended so that it can move freely, it will rotate. Why?

Compass : 13th century BC



A compass is a bar magnet that can move freely.

Because of **poles attraction**, **the magnet will rotate, if placed in a magnetic field, and its north pole will align with the south pole of the dipole creating the field.**

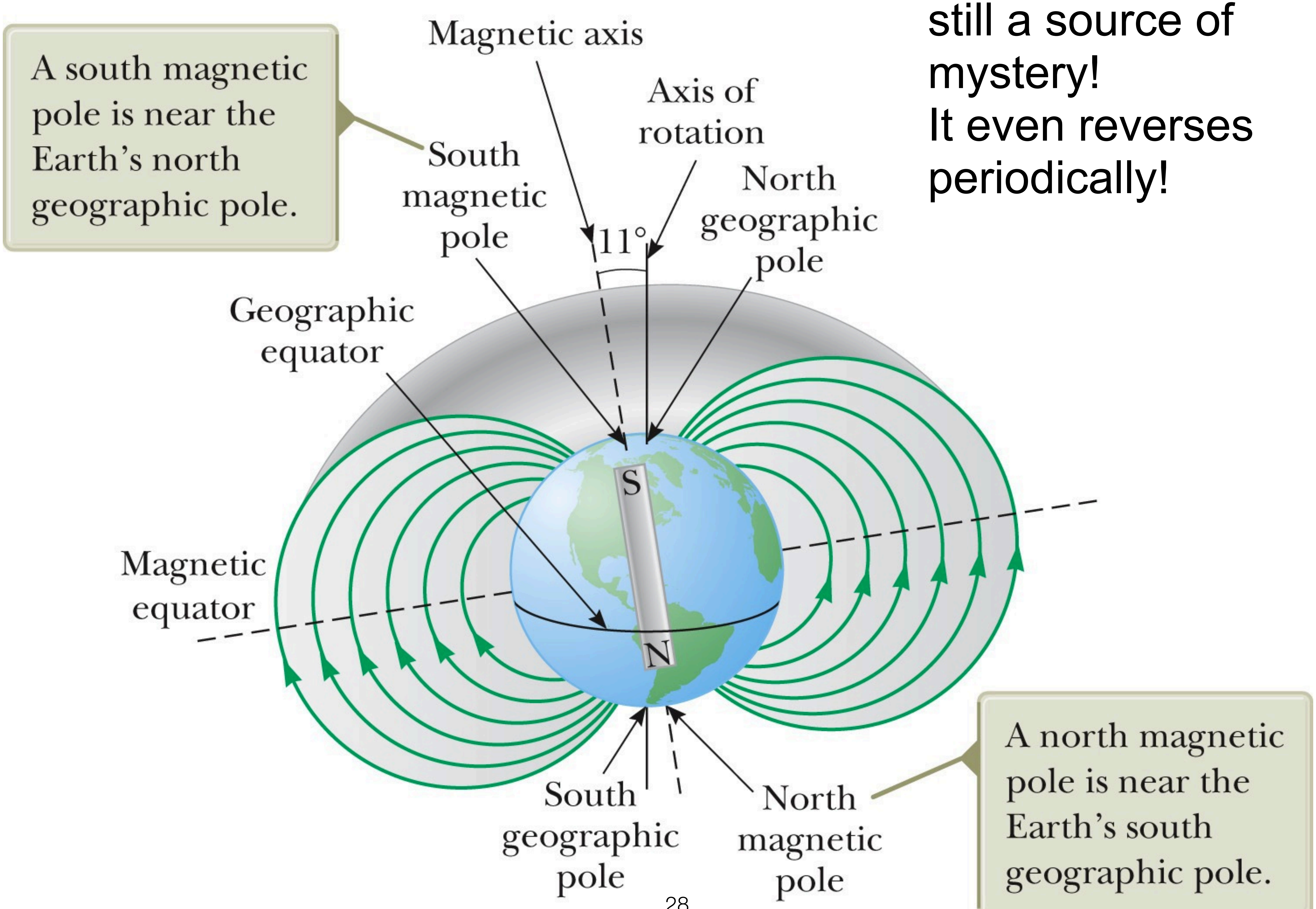
A compass works on Earth because **the Earth is a giant magnetic dipole**, therefore the Earth is the source of a magnetic field.

Fun fact: the poles received their names (N and S) due to the way a magnet behaves in the Earth's magnetic field.

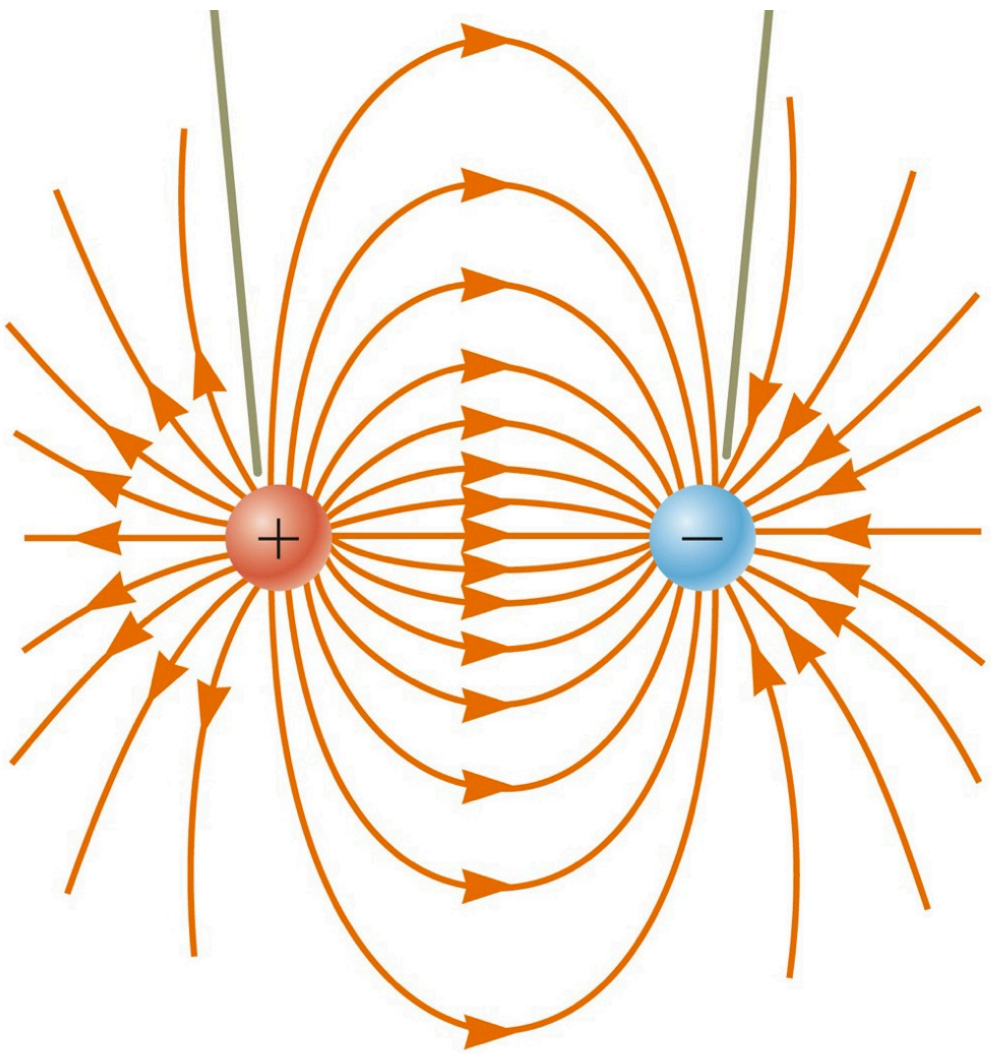
- The magnetic north pole points toward the Earth's north geographic pole.
  - This means the Earth's north geographic pole is a magnetic south pole (opposite poles attract)

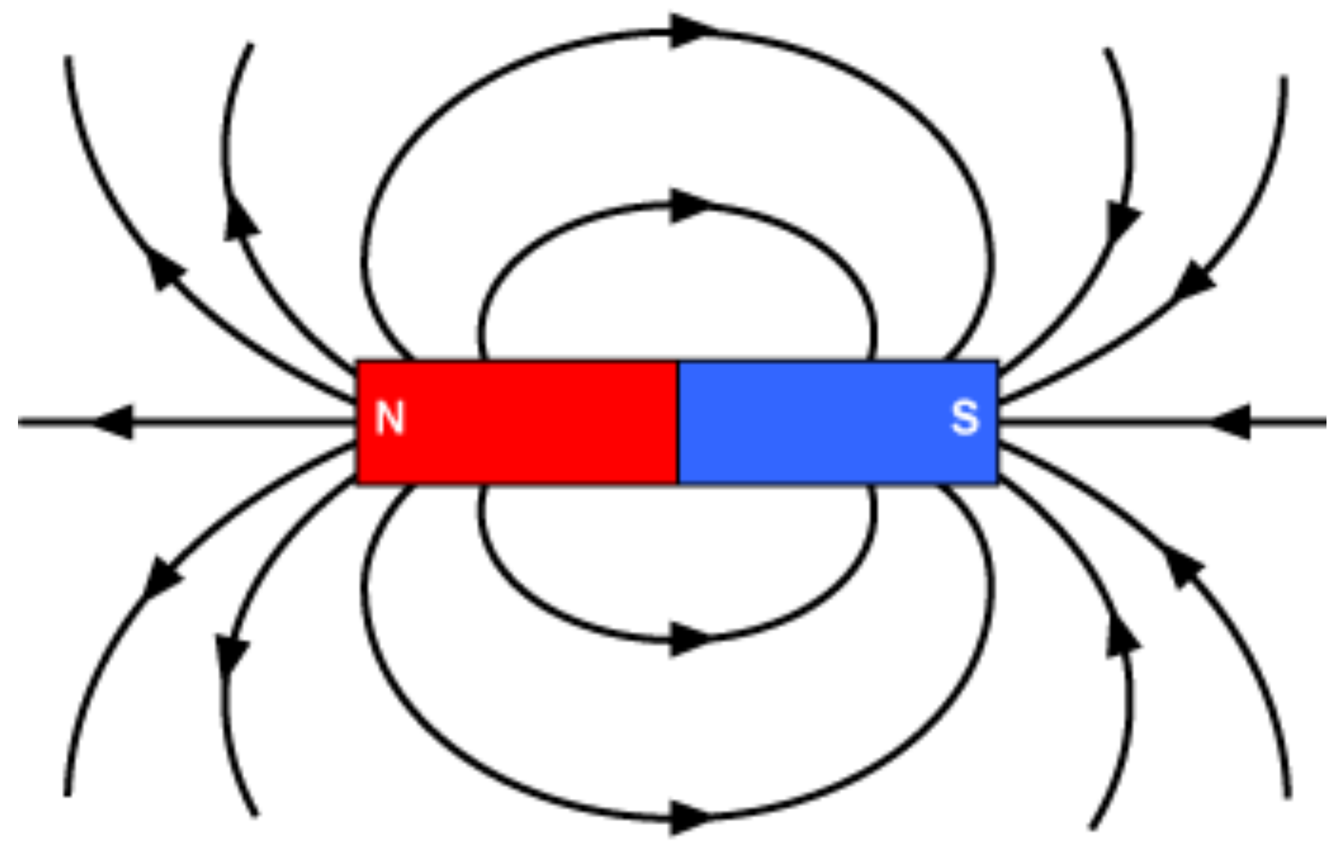
Earth's Magnetic Field

The Earth's B field is still a source of mystery!
It even reverses periodically!



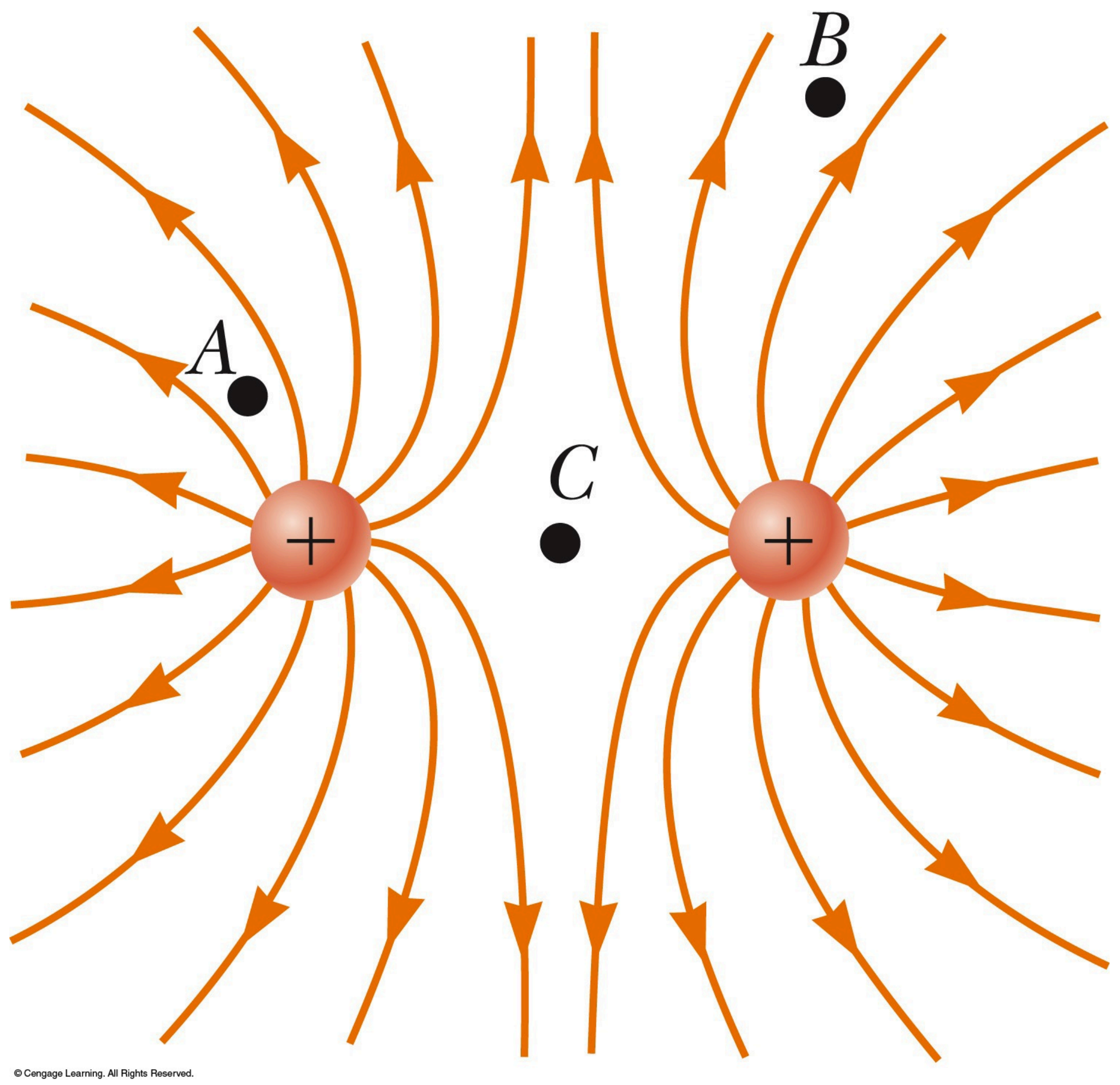
Magnetic Field Lines: Two bar magnets, opposite poles

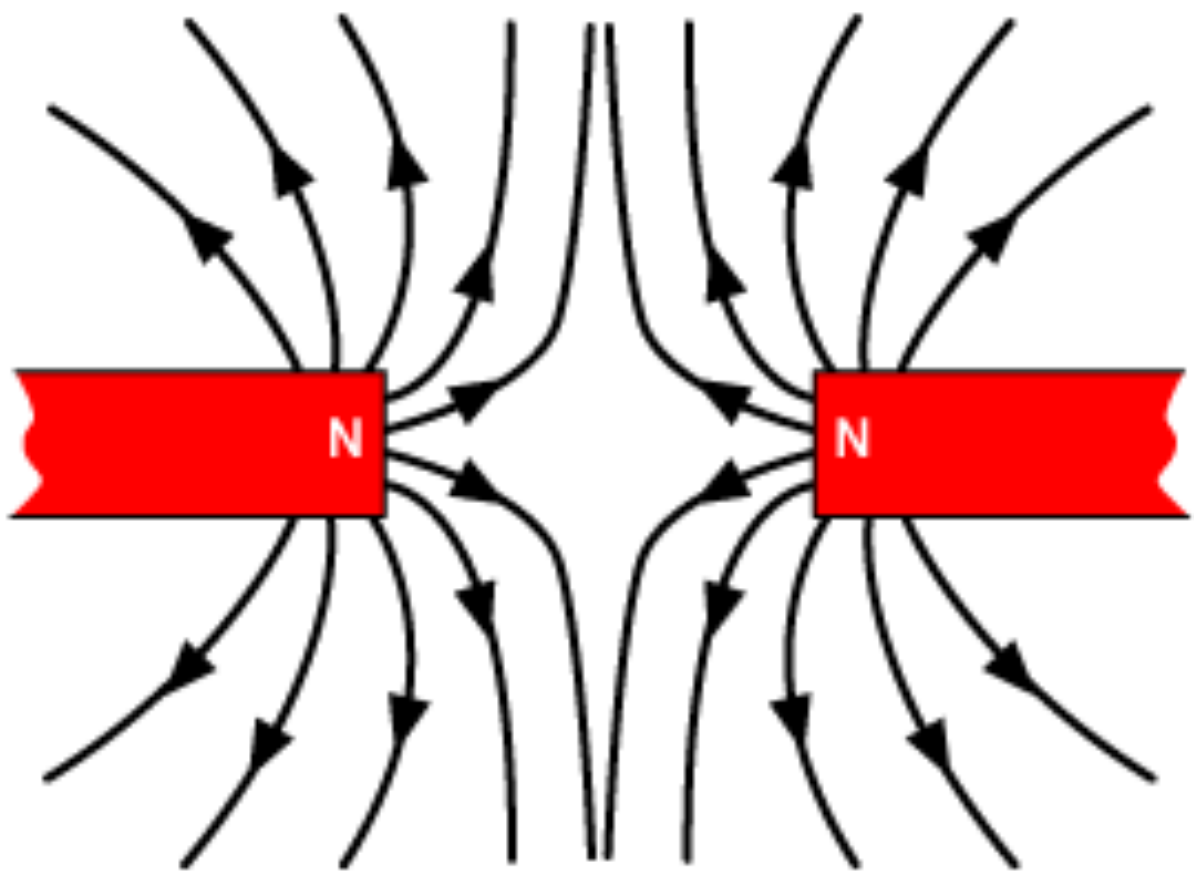




- E field produced by opposite charges
- B field produced by opposite poles

Magnetic Field Lines:
Two bar magnets, identical poles

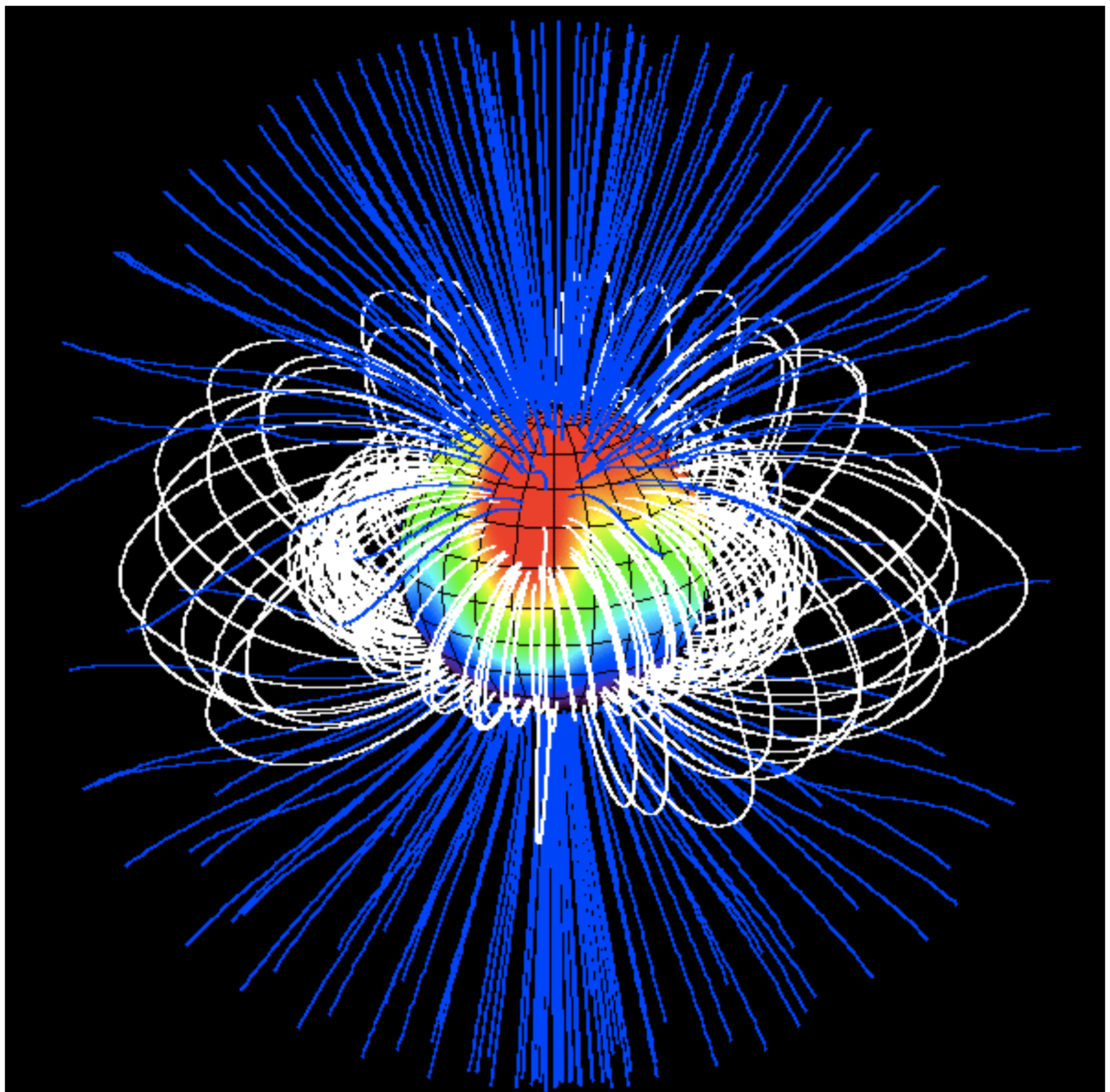




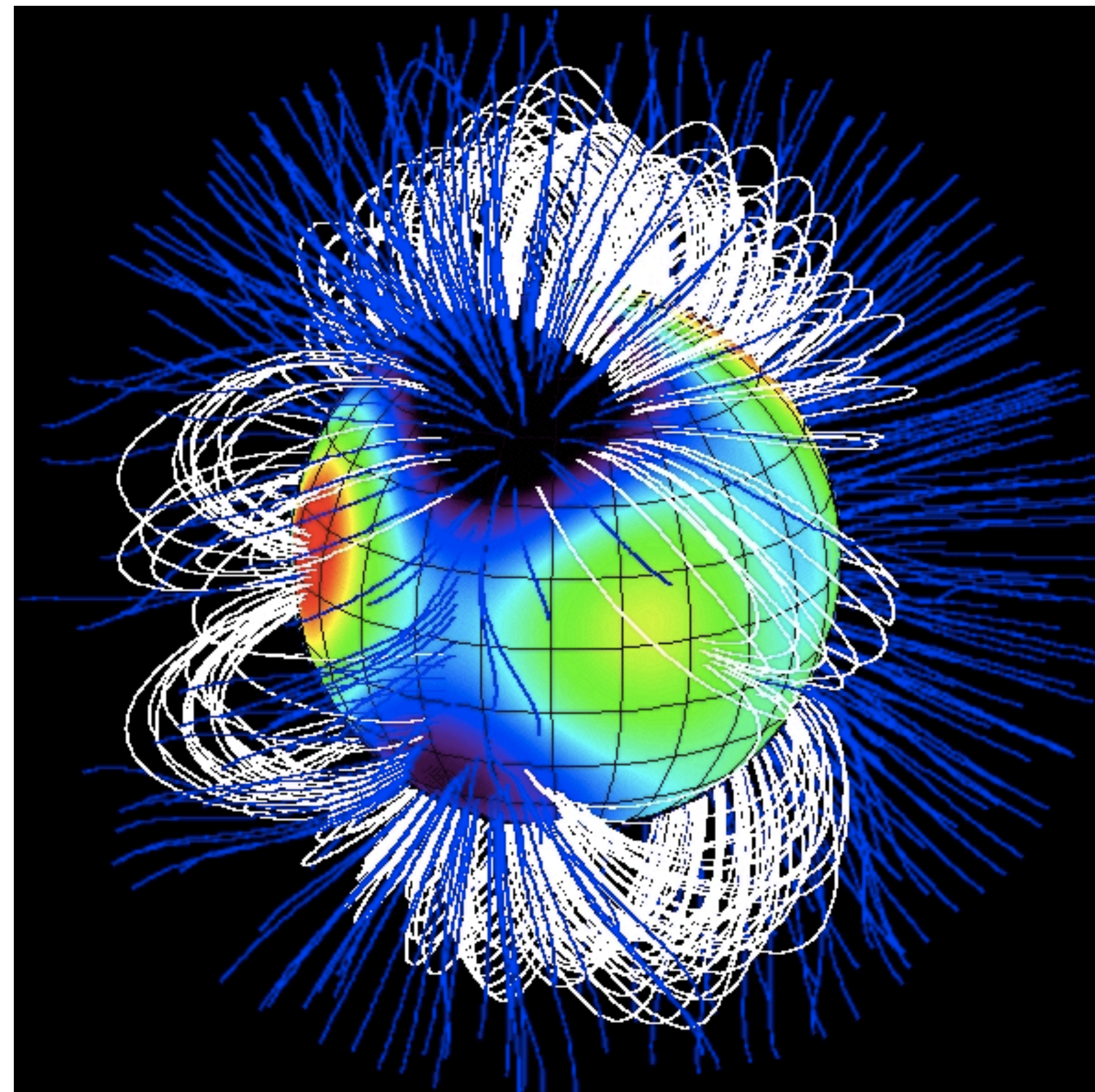
- E field produced by like charges
- B field produced by like poles

Magnetic field lines of stars

old star

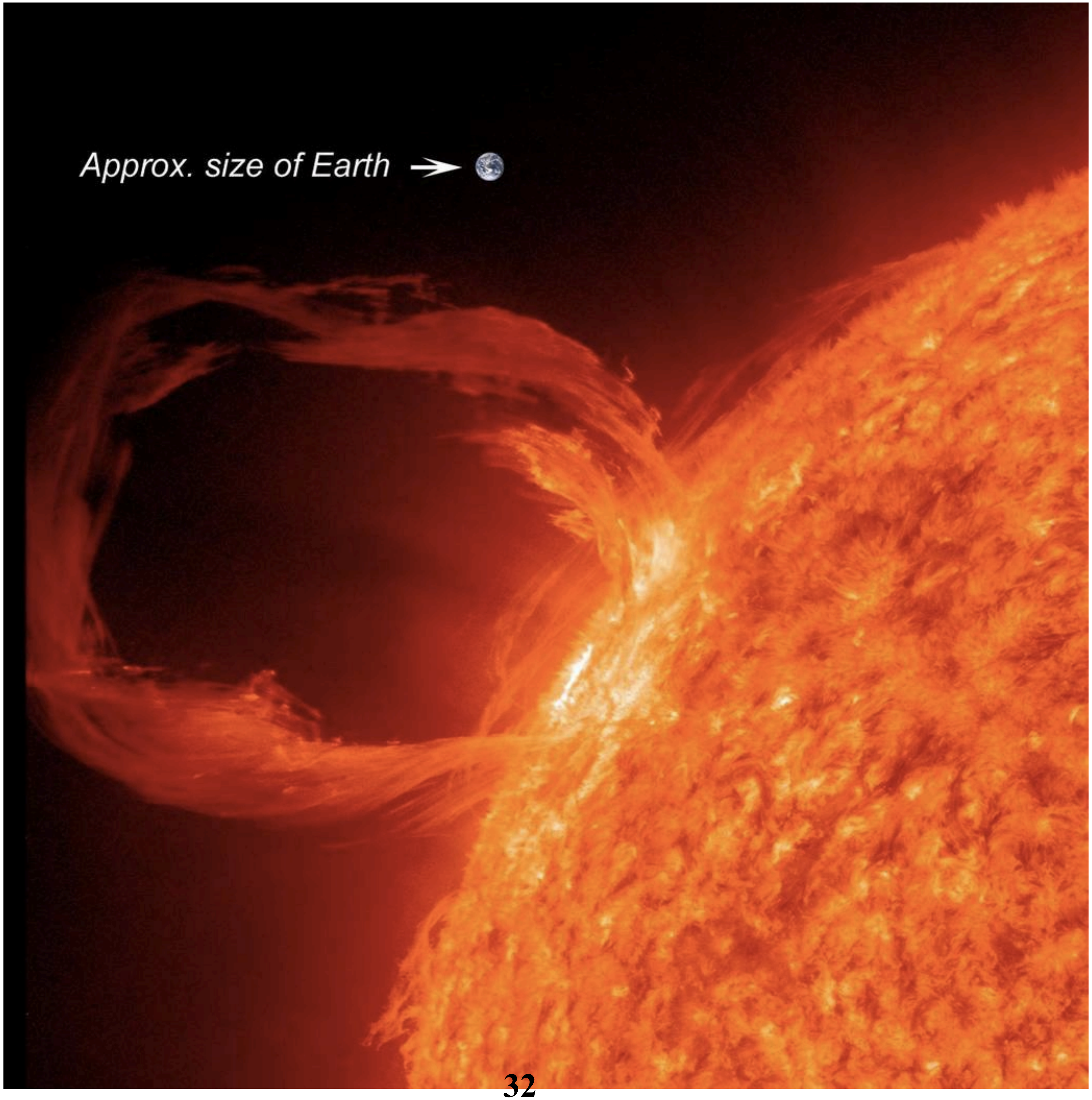


young star



images: EsPaDons

Stellar Prominence



Conceptual Questions

1. Can a **<u>constant</u>** magnetic field set into motion an electron initially at rest?

2. How can the motion of a moving particle tell you whether it is in a magnetic or in an electric field?

3. Two charged particles are projected in the same direction into a B field perpendicular to their velocities. If the particles are deflected in opposite direction, what can you say about their charges?

Conceptual Questions

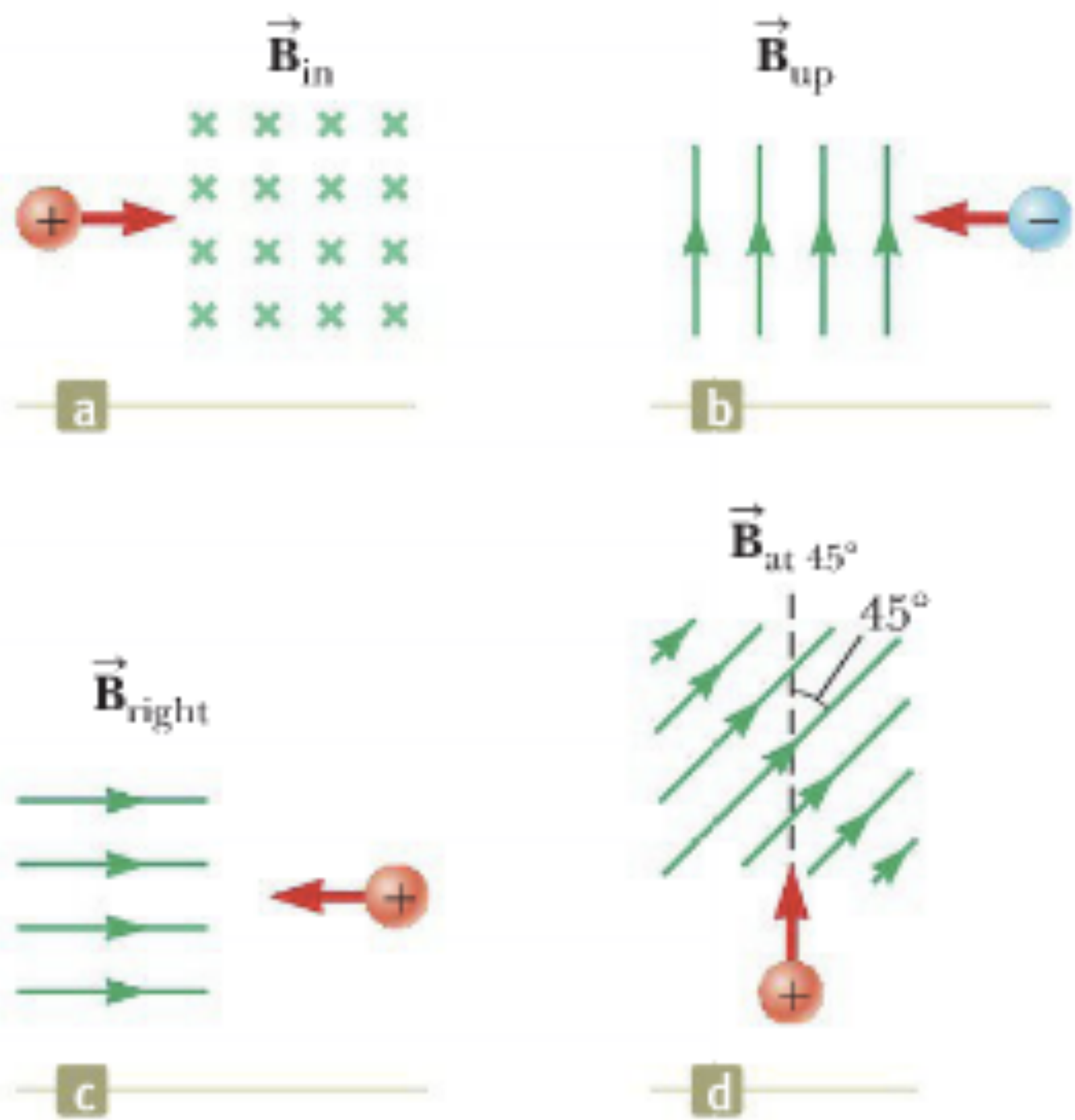
1. —> No. B field acts only on already moving charges.

2. ~~—> look at the trajectory: helix or circle is magnetic, parabola or straight line is electric.~~
   ~~—> look at the kinetic energy: constant speed is magnetic, changing speed is electric~~

3. —> opposite charges

Example Problem #1

2. W Determine the initial direction of the deflection of charged particles as they enter the magnetic fields shown in Figure P29.2.



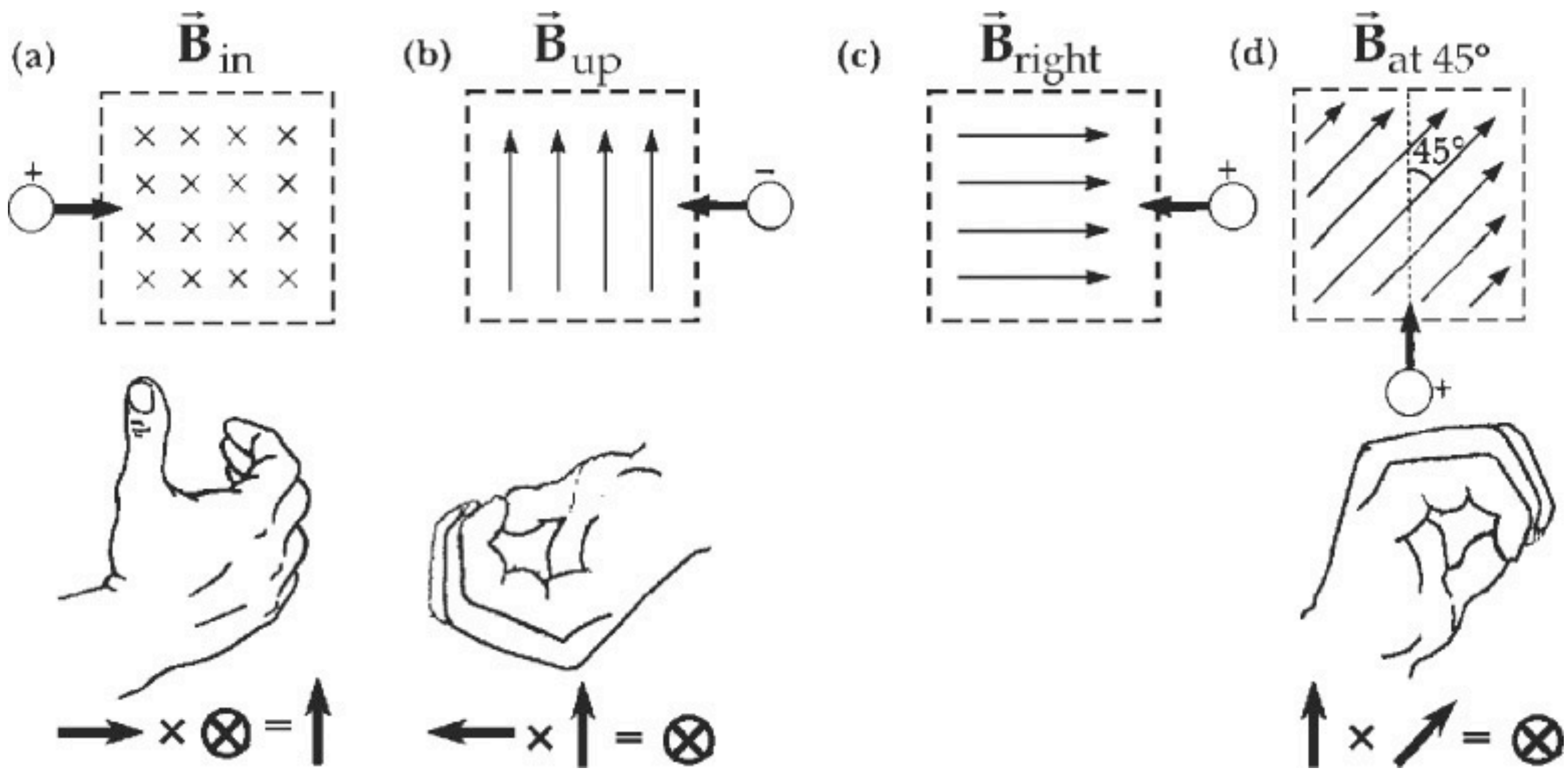
Example Problem #1: Solution

(a) up

(b) out of the page, since the charge is negative.

(c) no deflection

(d) into the page



Example Problem #2

10. A laboratory electromagnet produces a magnetic field of magnitude 1.50 T. A proton moves through this field with a speed of 6.00×10^6 m/s. (a) Find the magnitude of the maximum magnetic force that could be exerted on the proton. (b) What is the magnitude of the maximum acceleration of the proton? (c) Would the field exert the same magnetic force on an electron moving through the field with the same speed? (d) Would the electron experience the same acceleration? Explain.

Example Problem #2: Solution

(a) The proton experiences maximum force when it moves perpendicular to the magnetic field, and the magnitude of this maximum force is

$$F_{\text{max}} = qvB\sin 90^\circ$$
$$= \left(1.60\times10^{-19}\ \text{C}\right)\left(6.00\times10^{6}\ \text{m/s}\right)(1.50\ \text{T})(1)$$
$$= \boxed{1.44\times10^{-12}\ \text{N}}$$

(b) From Newton's second law,

$$a_{\text{max}} = \frac{F_{\text{max}}}{m_p} = \frac{1.44\times10^{-12}\ \text{N}}{1.67\times10^{-27}\ \text{kg}} = \boxed{8.62\times10^{14}\ \text{m/s}^2}$$

(c) Since the magnitude of the charge of an electron is the same as that of a proton, a force would be exerted on the electron that had the same magnitude as the force on a proton, but in the opposite direction because of its negative charge.

(d) The acceleration of the electron would be much greater than that of the proton because the mass of the electron is much smaller.

Example Problem #3

What good does the Earth's magnetic field do for the biosphere?

Example Problem #3: Solution

Protection from the charged-particle parts of cosmic / solar radiation

Example Problem #4

Why do magnetic monopoles not exist?

Example Problem #4: Solution

No ones knows for sure! It is a mystery!

Magnetic fields

If you have a MOVING charge you ALSO have a magnetic field.

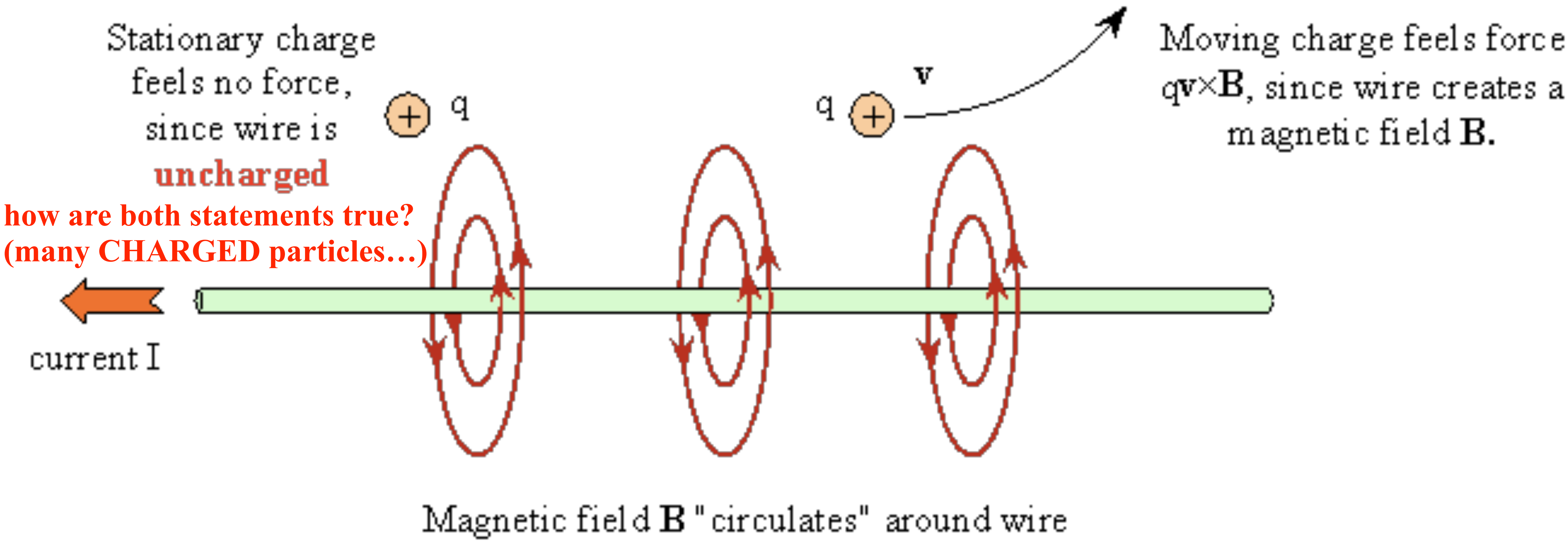
We have already encountered moving charges: we called them **currents**.

—> Currents create magnetic fields.

We no longer talk about charges, we talk about **current loops.**
The poles of a permanent magnet align with the average direction of the current loops.
A magnet generates a B field because of the movement of the electrons around each atom —> micro-currents

Magnetic Force from a current conducting wire

Take a current carrying wire.



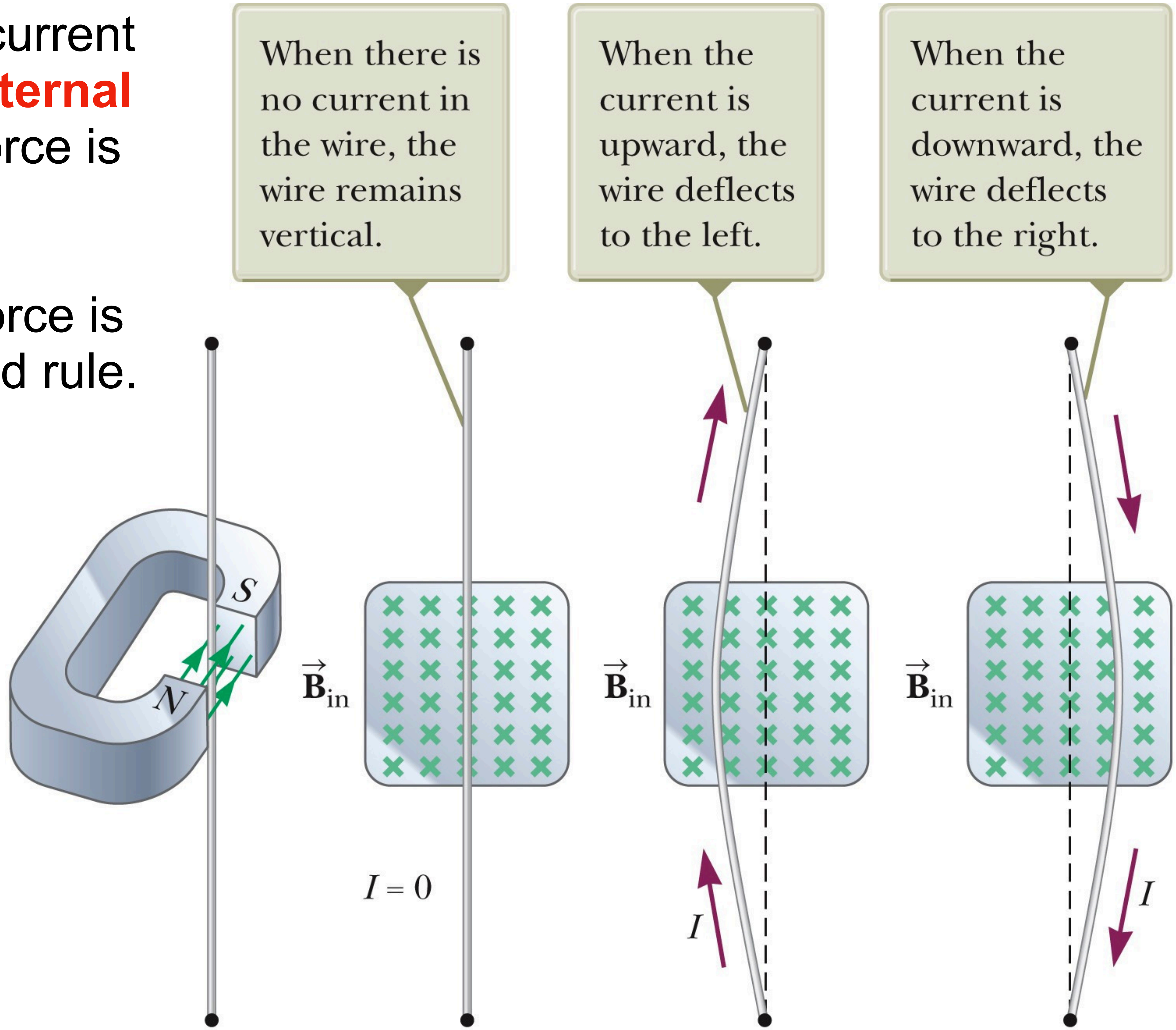
The current is a collection of many charged particles in motion —> they themselves create a B field.

Magnetic Force on a current conducting wire

If you now place the current carrying wire in an **external B field**, a magnetic force is exerted on the wire.

The direction of the force is given by the right hand rule.

$$\vec{F} = q\vec{v} \times \vec{B}$$



Magnetic Force on a current conducting wire

The magnetic force is exerted on each moving charge in the wire.

$$\vec{F} = q\vec{v} \times \vec{B}$$

The total force is the product of the force on one charge and the number of charges.

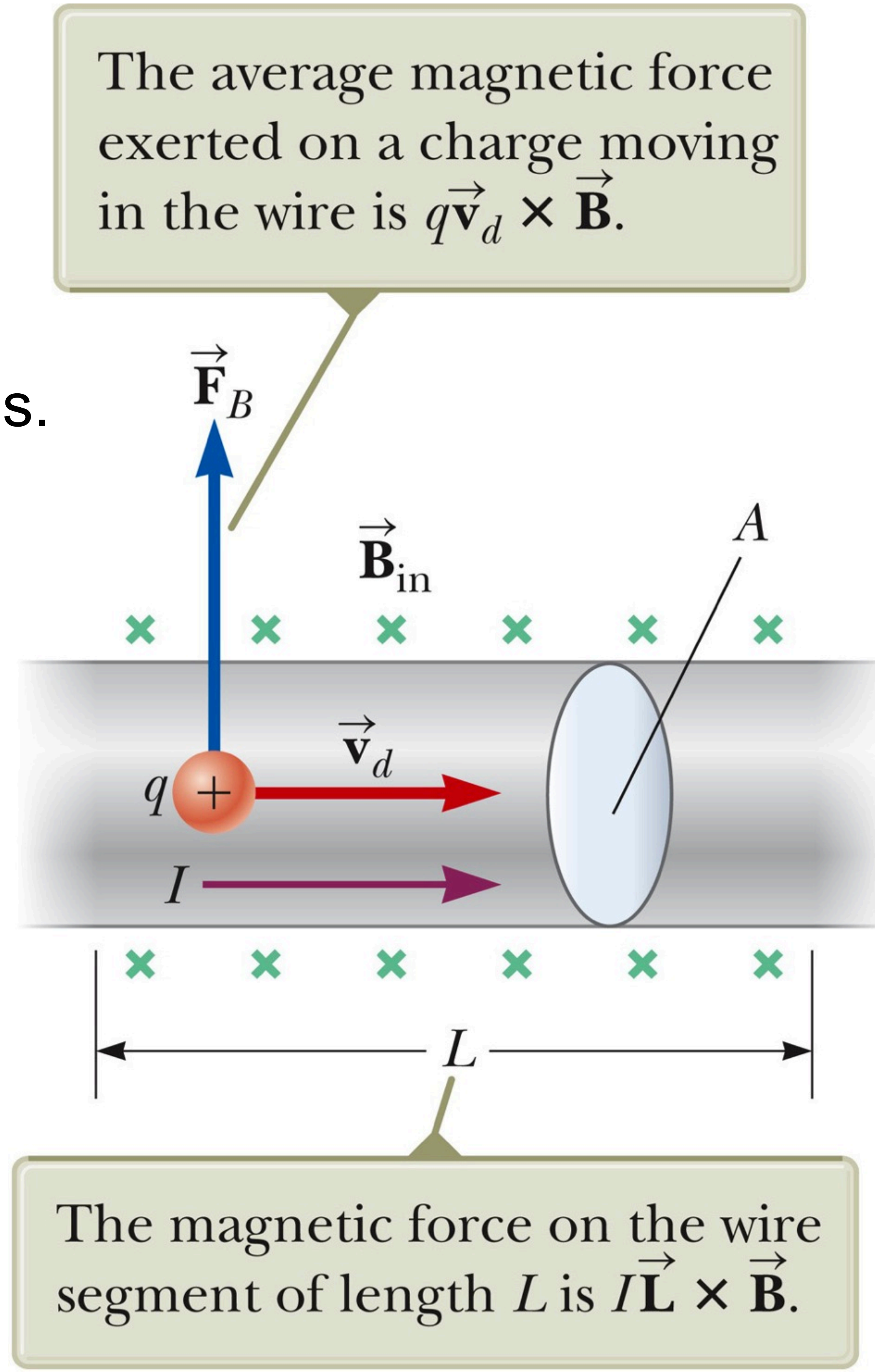
$$\vec{F} = (q\vec{v} \times \vec{B})nAL$$

n = number volume density
A = area
L = length

You know from earlier:

$$I = nqvA$$

So: $$\boxed{\vec{F} = I\vec{L} \times \vec{B}}$$

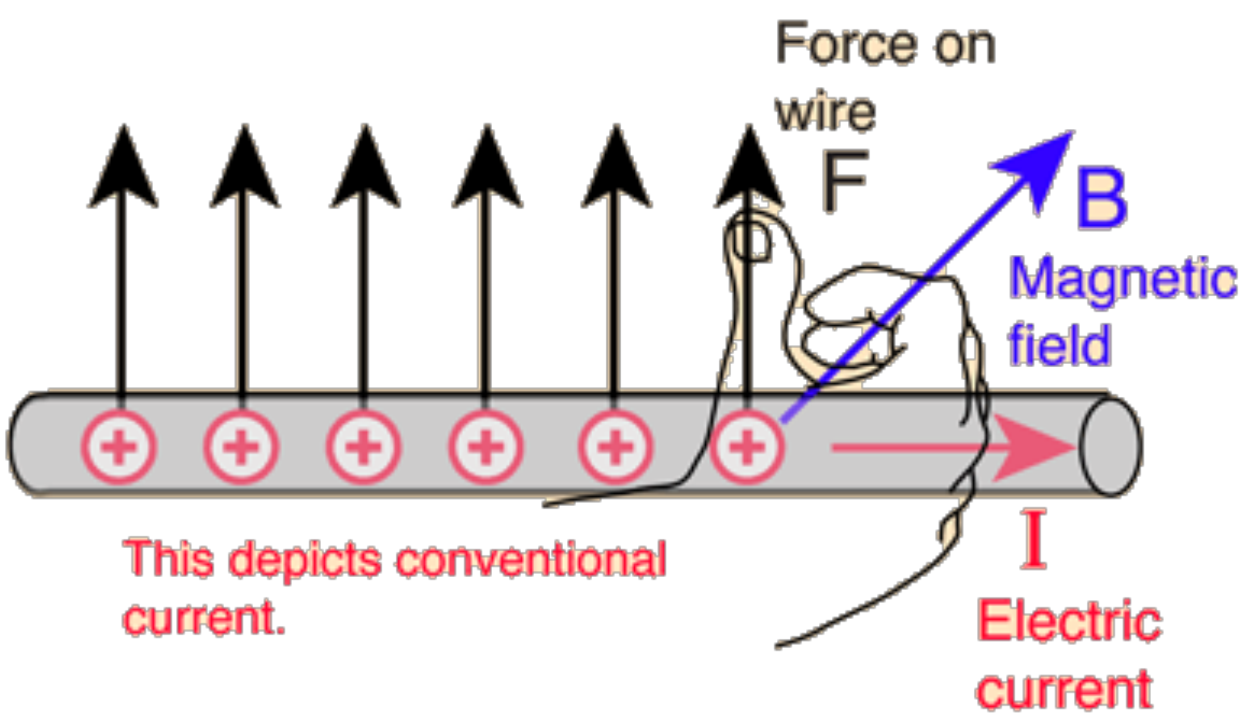


Magnetic Force on a current conducting wire

current

magnetic force $\vec{F} = I\vec{L} \times \vec{B}$ magnetic field

length vector, pointing in the direction of the current



the direction of the force is still given by the right hand rule.

This is ONLY for a straight segment of wire in a uniform magnetic field.

Force on a Wire, Arbitrary Shape

Consider a small segment of the wire:

$$d\vec{s}$$

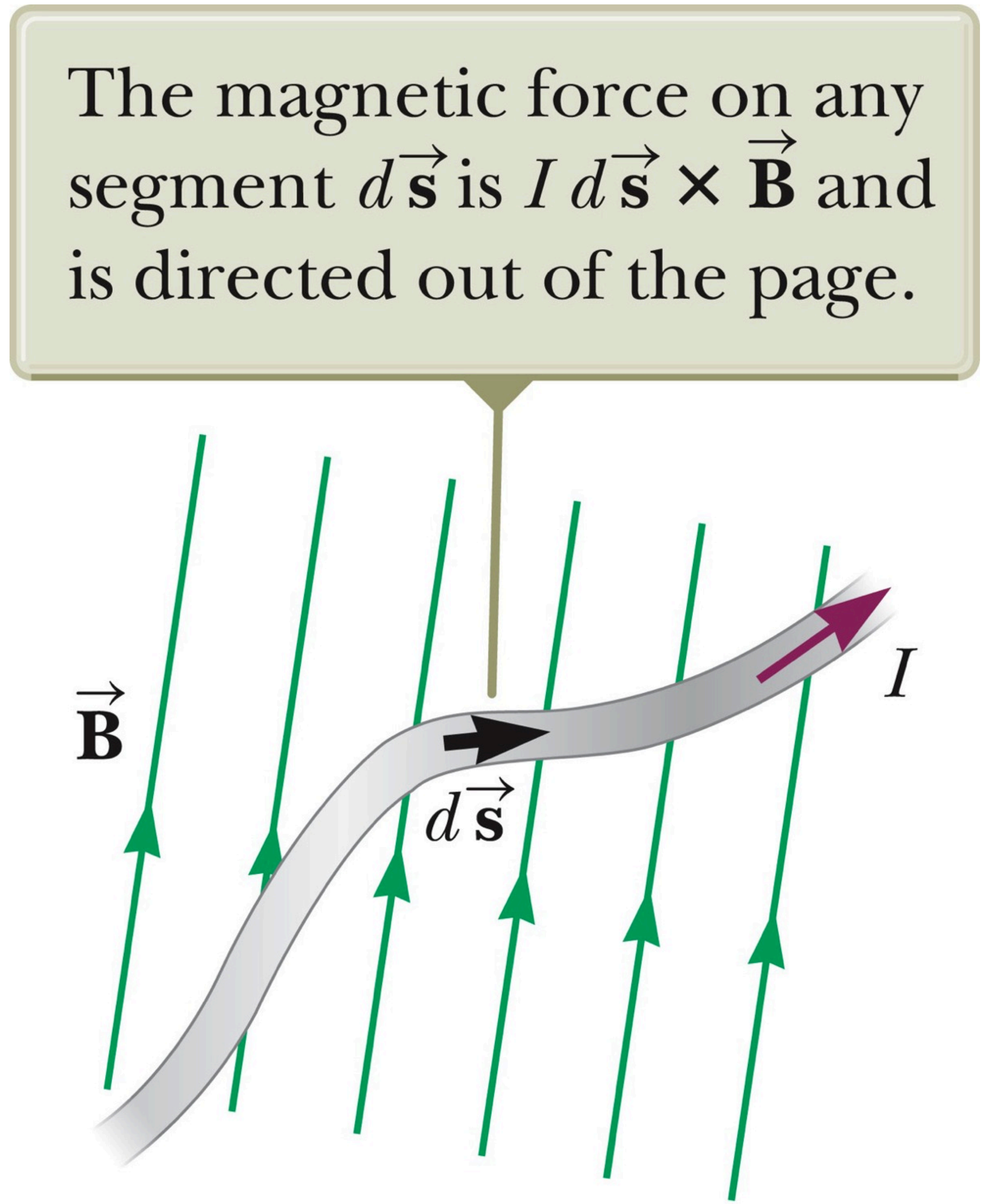
The force exerted on this segment is :

$$d\vec{F}_B = I d\vec{s} \times \vec{B}$$

STOP HERE?

The total force is

$$\boxed{\vec{F}_B = I \int_a^b d\vec{s} \times \vec{B}}$$



Current Loop

Consider a rectangular loop.
The loop carries a current I in a uniform magnetic field B.
What magnetic force act on the loop?

$$\vec{F} = I\vec{L} \times \vec{B}$$

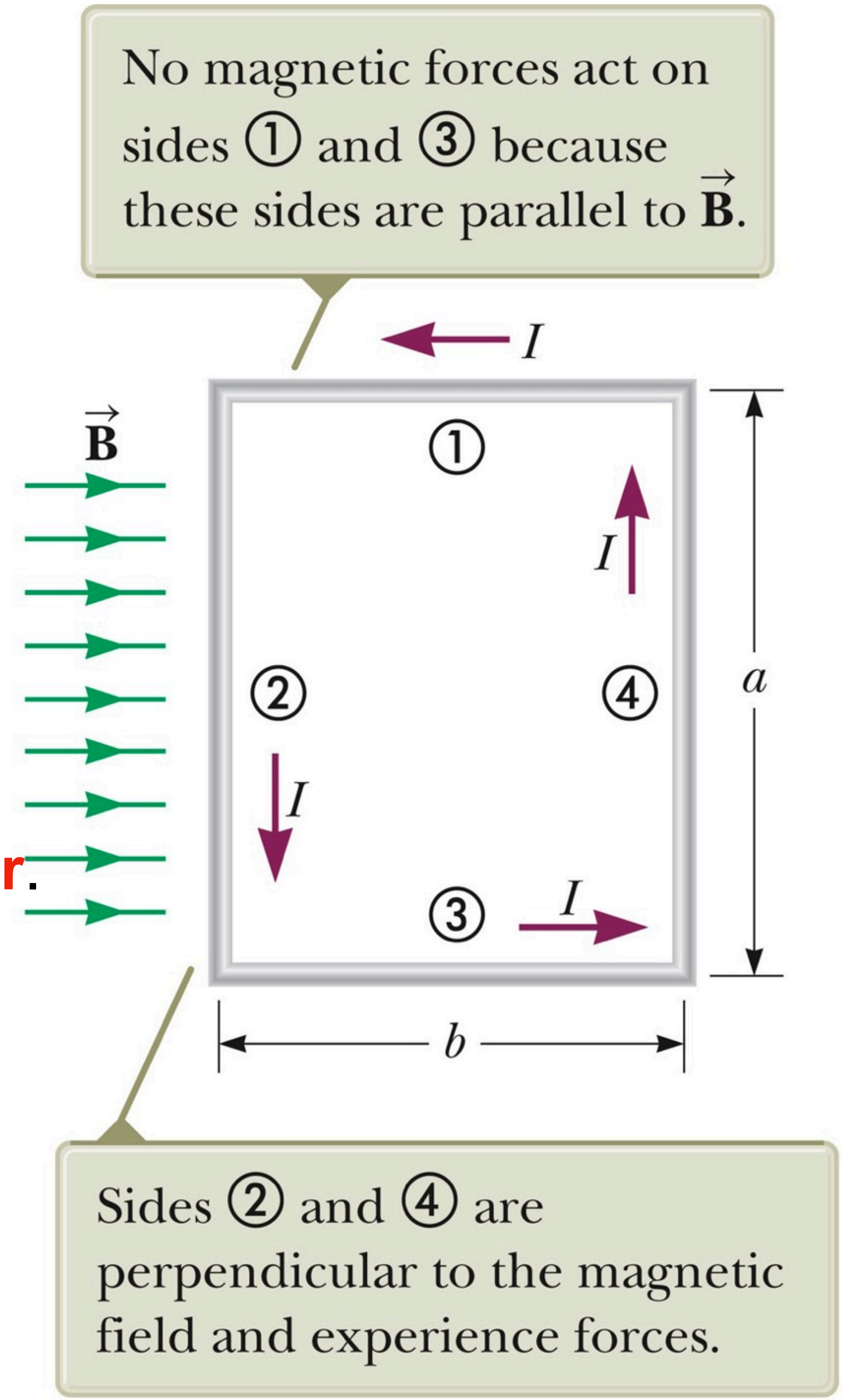
On sides 1 and 3, B and I are **parallel**.
Side 3: θ = 0 —> sin θ = 0
Side 1: θ = 180 degrees —> sin θ = 0
So:

$$\vec{L} \times B = 0 \qquad F_1 = F_3 = 0$$

On sides 2 and 4, B and I are **perpendicular**.
Side 3: θ = 90 —> sin θ = 1
Side 1: θ = 90 —> sin θ = 1
So:

$$\boxed{F_2 = F_4 = I\,a\,B}$$

The direction of F_2 is out of the page.
The direction of F_4 is into the page.



What’s a magnet?

Or rather, why do some materials exhibit magnetic properties, and others don’t?

2 things:

—> torque
—> magnetic dipole moment

Torque on a Current Loop

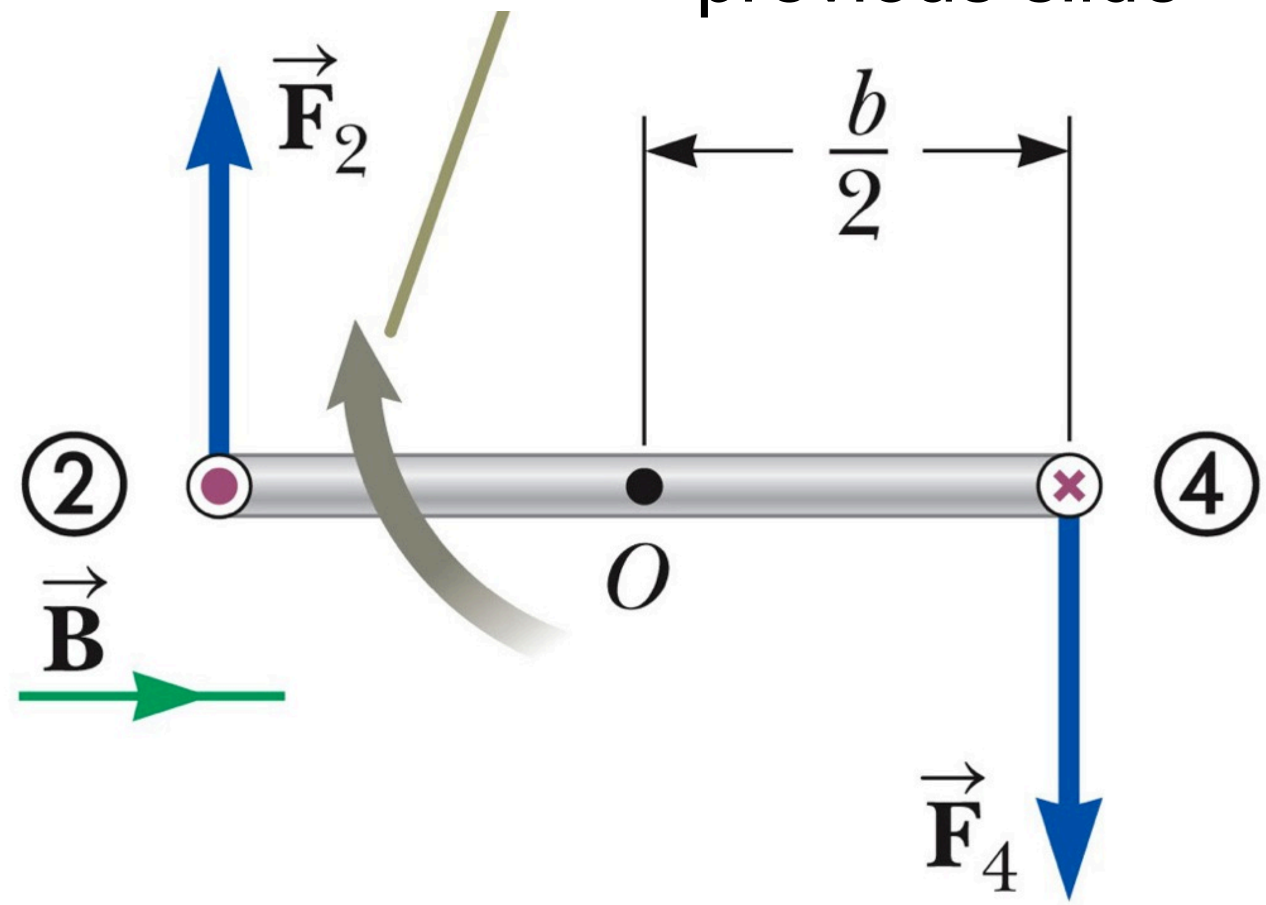
side view of the current loop in previous slide

The forces are equal and in opposite directions, but not along the same line of action.
The forces produce a torque around point *O*.

$$\boxed{\tau = \vec{r} \times F}$$

physics 1!

r is the distance to the pivot point!!



The maximum torque is found by:

$$\tau_{max} = F_2 \frac{b}{2} + F_4 \frac{b}{2} = (I\,aB)\frac{b}{2} + (I\,aB)\frac{b}{2}$$
$$= I\,abB$$

F2 and F4 create a torque. The torque makes the current loop rotate.

The area enclosed by the loop is A= *ab*, so $\tau_{max} = IAB$.

- This maximum value occurs only when the field is **parallel to the plane of the loop.**

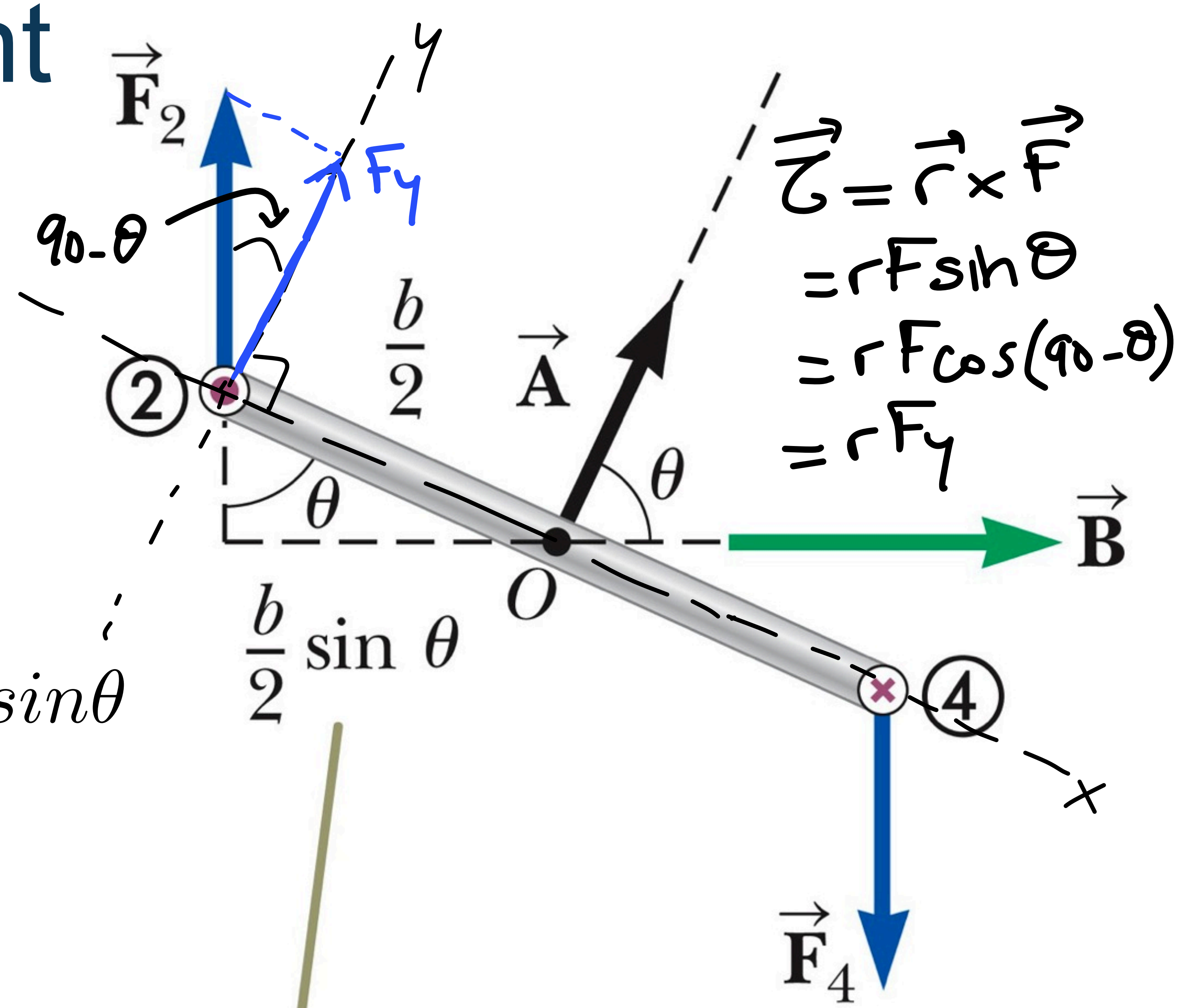
Torque on a Current Loop, General

$$\vec{\tau}_{net} = \sum \vec{\tau} = \vec{\tau}_2 + \vec{\tau}_4$$
$$= rF_2 sin\theta + rF_4 sin\theta$$
$$= \frac{b}{2} IaBsin\theta + \frac{b}{2} IaBsin\theta$$
$$= IabBsin\theta$$
$$= IABsin\theta$$

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

A= *ab : area of the loop*

$\vec{A}$ the area vector, it is perpendicular to the plane of the loop



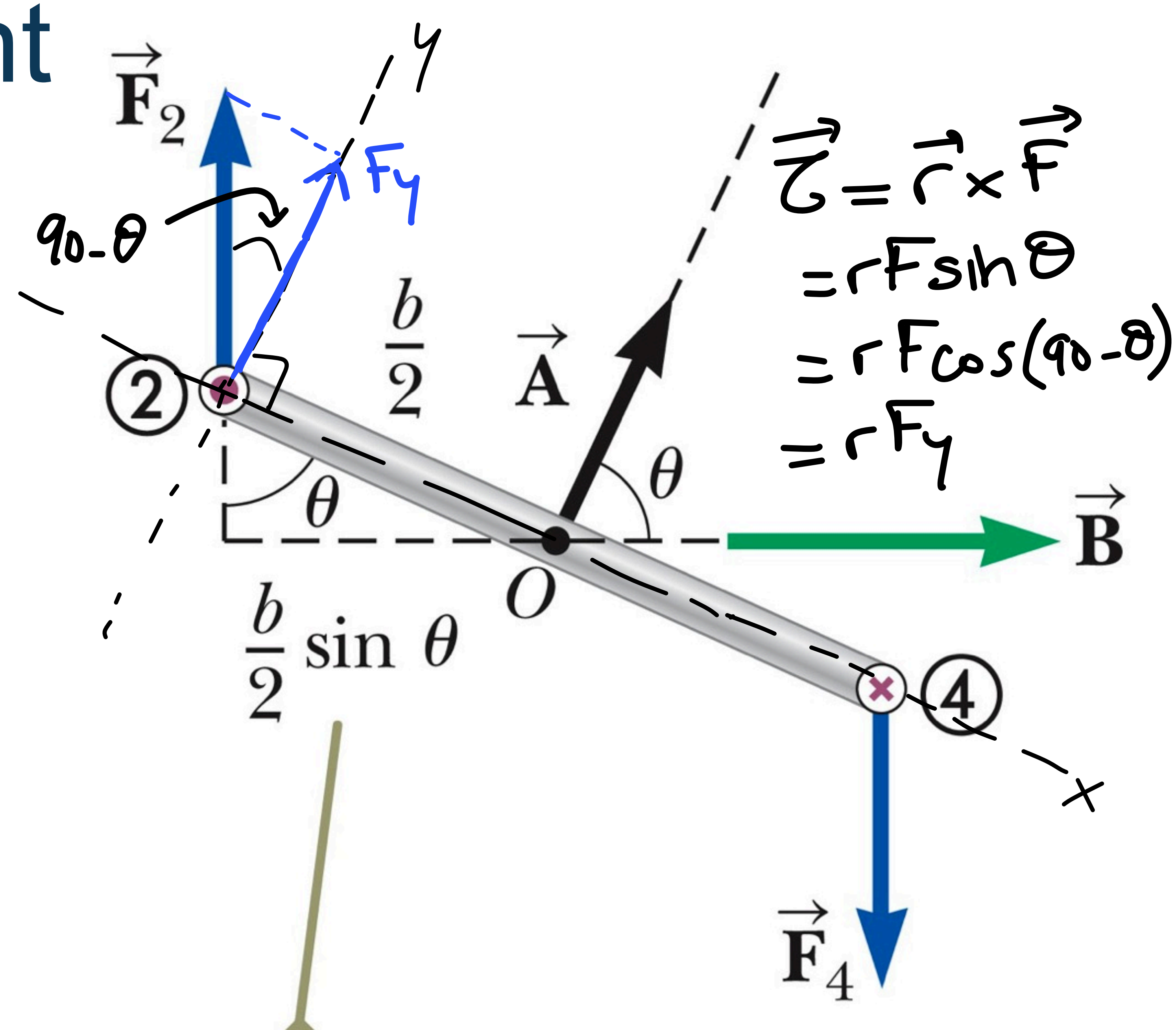
When the normal to the loop makes an angle θ with the magnetic field, the moment arm for the torque is $(b/2)\sin\theta$.

Torque on a Current Loop, General

$$\vec{\tau}_{net} = I\vec{A} \times \vec{B}$$

The torque is **maximum** when the field is perpendicular to the normal to the plane of the loop.
The torque is **zero** when the field is parallel to the normal to the plane of the loop.

The current loop will align with the field. At which point there is no more torque.
= stable equilibrium

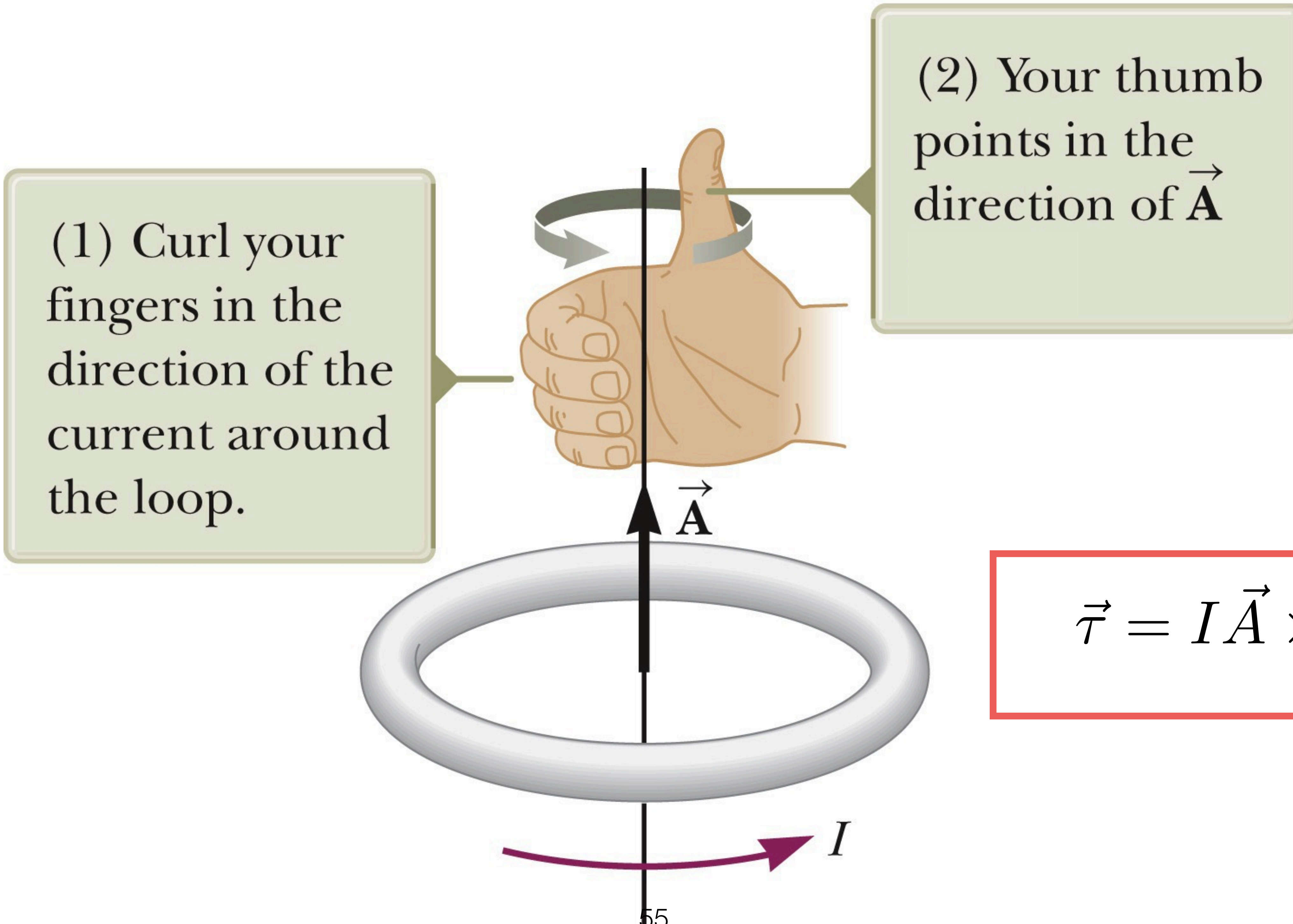


When the normal to the loop makes an angle θ with the magnetic field, the moment arm for the torque is $(b/2)\sin\theta$.

Torque makes the current loop rotate such that it aligns with the B field.

Direction

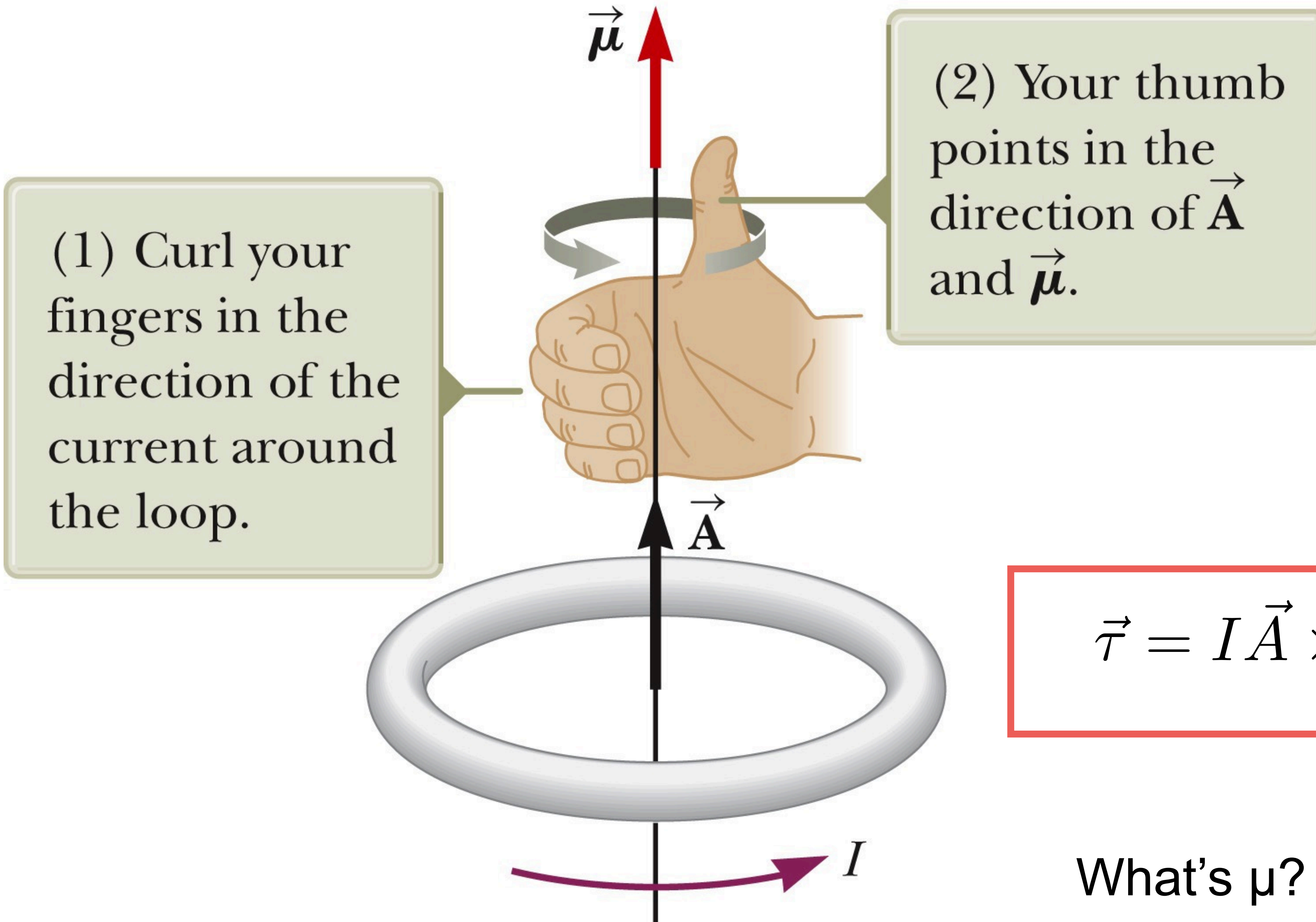
The right-hand rule can be used to determine the direction of A.
Curl your fingers in the direction of the current in the loop.
Your thumb points in the direction of A .



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

Direction

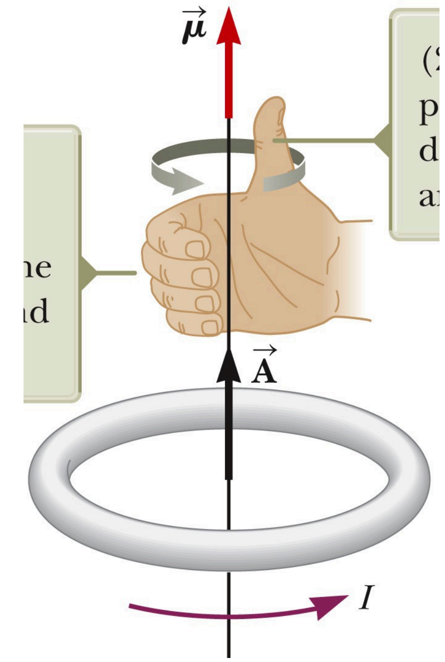
The right-hand rule can be used to determine the direction of A.
Curl your fingers in the direction of the current in the loop.
Your thumb points in the direction of A **and μ**.



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

What's μ?

Magnetic Dipole Moment



$$\vec{F}_B = I \int_a^b d\vec{s} \times \vec{B}$$

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

The product $I\vec{\mathbf{A}}$ is defined as the **magnetic dipole moment, μ**, of the loop.

SI units: A · m²

Torque in terms of magnetic moment: $\boxed{\vec{\tau} = \vec{\mu} \times \vec{B}}$

- Valid for any orientation of the field and the loop
- Valid for a loop of any shape

Any current loop has a magnetic field and thus has a magnetic dipole moment.

This includes atomic-level current loops described in some models of the atom.

Magnetic Moments – Classical Atom

The electrons move in circular orbits.

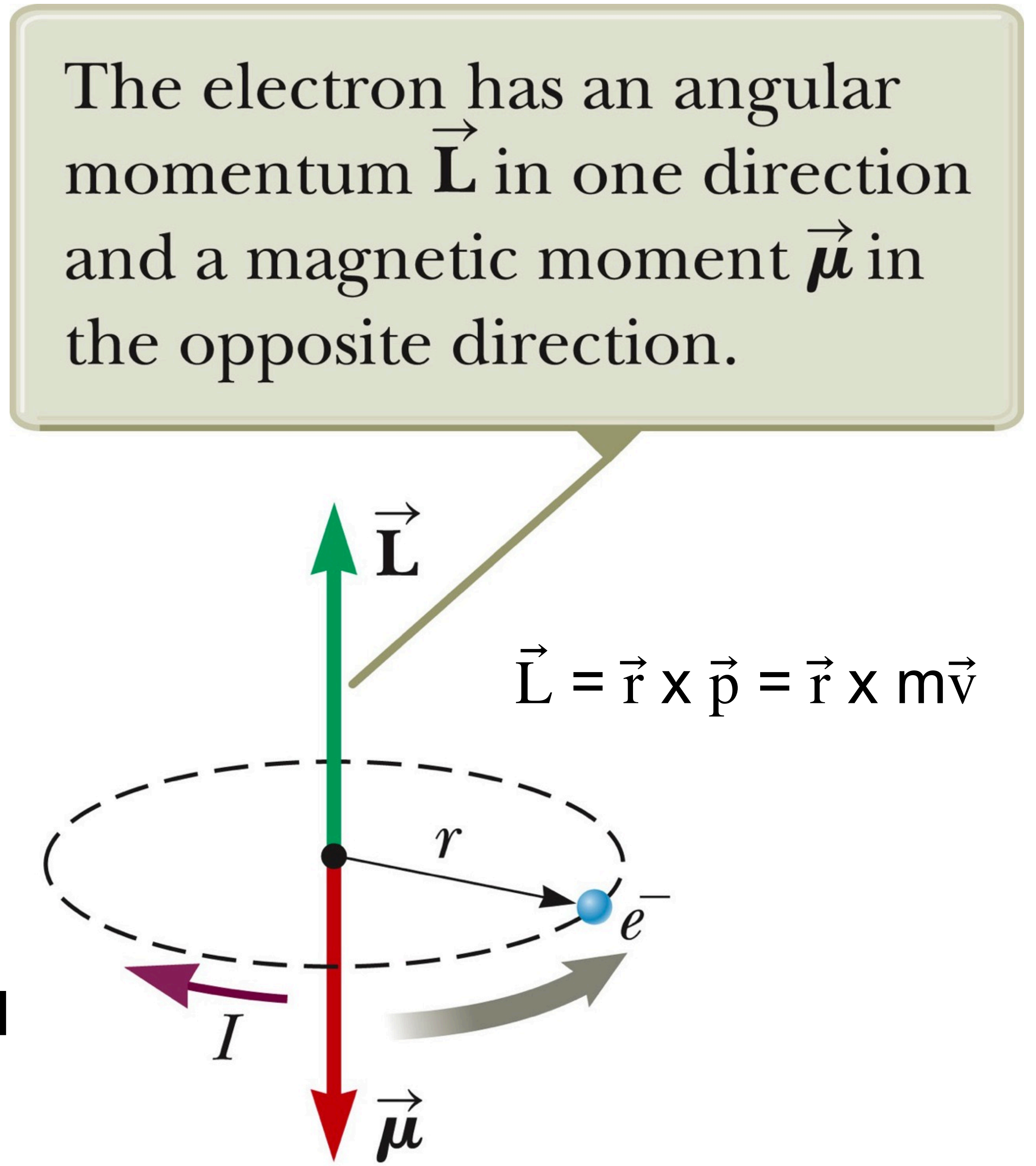
The orbiting electron constitutes a **tiny current loop**.

The magnetic moment of the electron is associated with this orbital motion.

L is the angular momentum.

μ is magnetic moment.

In most substances, the magnetic moment of one electron is canceled by that of another electron orbiting in the opposite direction.

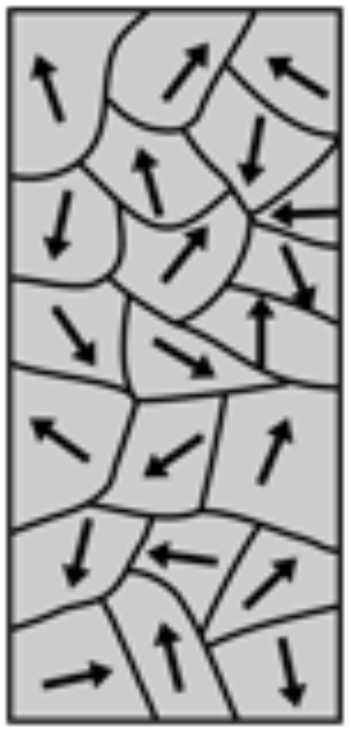


The net result is that the magnetic effect produced by the orbital motion of the electrons is either zero or very small.

Ferromagnetism

Some substances, like iron, exhibit strong magnetic effects.

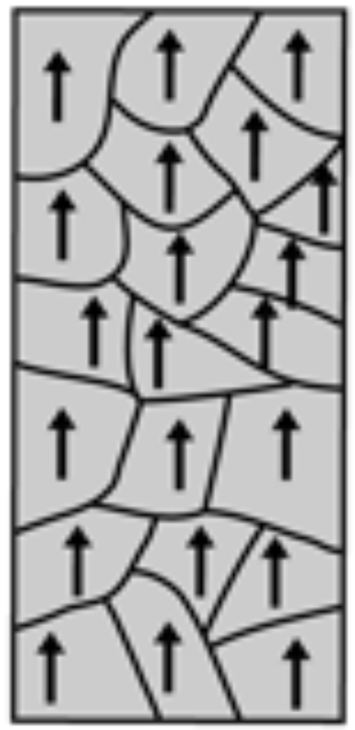
They contain permanent atomic magnetic moments that tend to align parallel to each other **even in a weak external magnetic field**.



In bulk material the domains usually cancel, leaving the material unmagnetized.

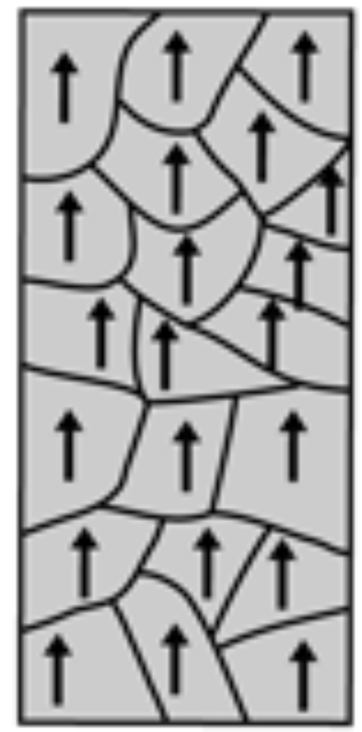
magnetic moments are randomly oriented

torque!



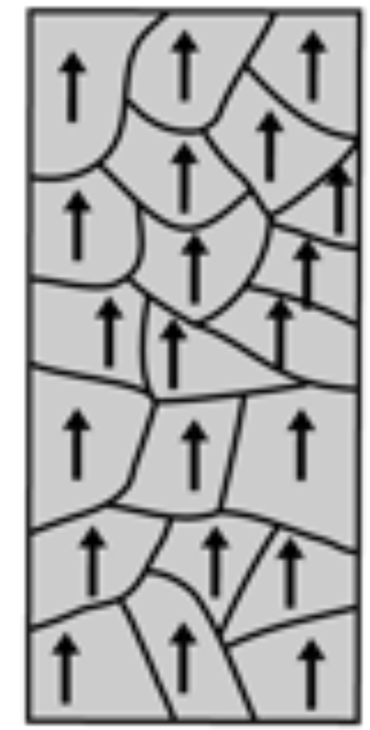
Externally applied magnetic field.

magnetic moments align with the field



remove the external field.
the magnetic moments stay aligned:
the substance is **magnetized**

N



S

you now have a magnet!

Example: a magnet on your fridge

The magnet contains iron, and is magnetized:
its magnetic moments are aligned, and stay aligned.
The magnet is permanent and is ferromagnetic.

The fridge contains some iron, but is NOT magnetized.
All the dipole moments are randomly distributed.
The fridge is also ferromagnetic —> it can be magnetized.

You bring the magnet next to the fridge, it creates a field in the fridge which magnetizes the small region of the fridge where the magnet is.

Paramagnetism

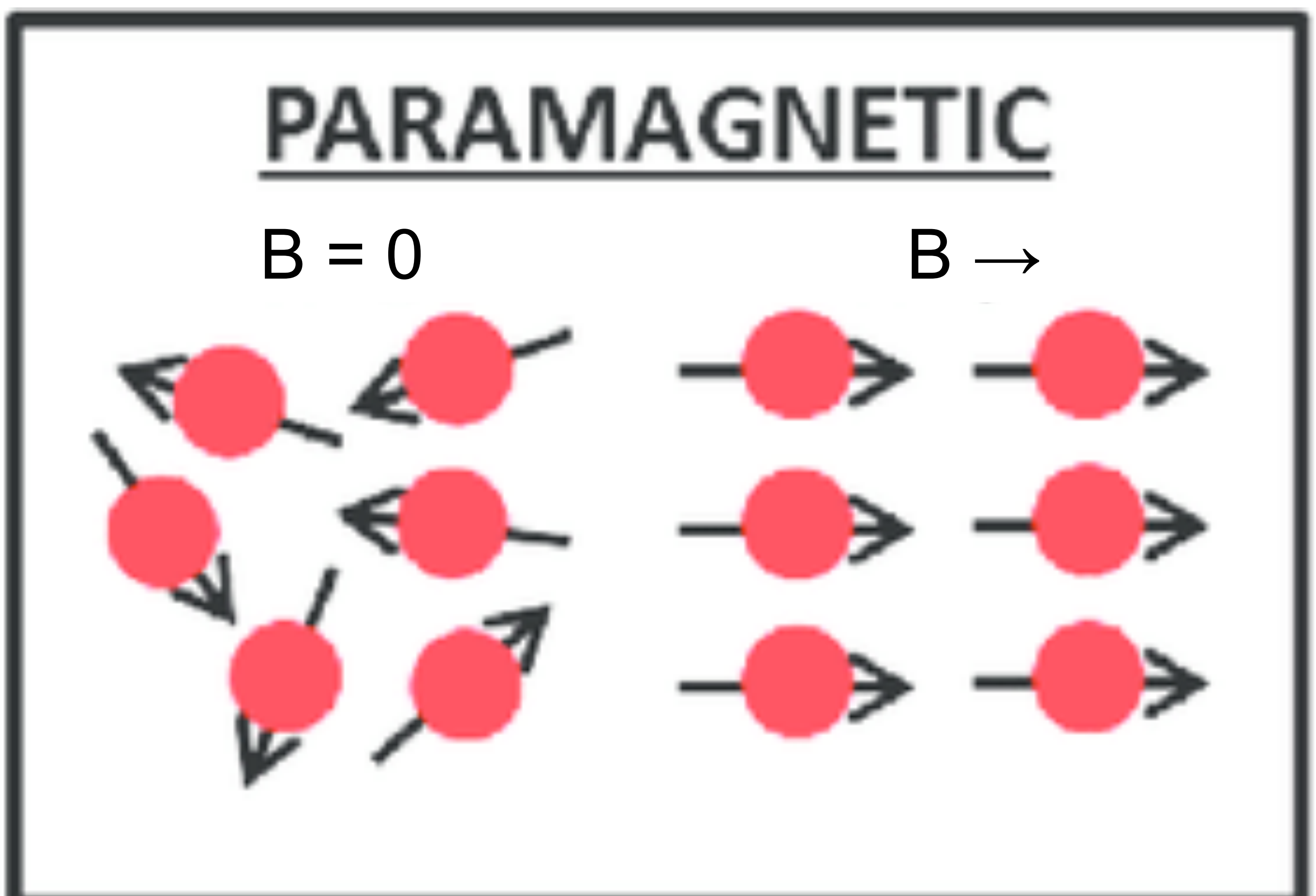
Paramagnetic substances (e.g. aluminum) have small but positive magnetism.

- The magnetic moments interact weakly with each other.

When placed in an external magnetic field, its atomic moments tend to line up with the field.

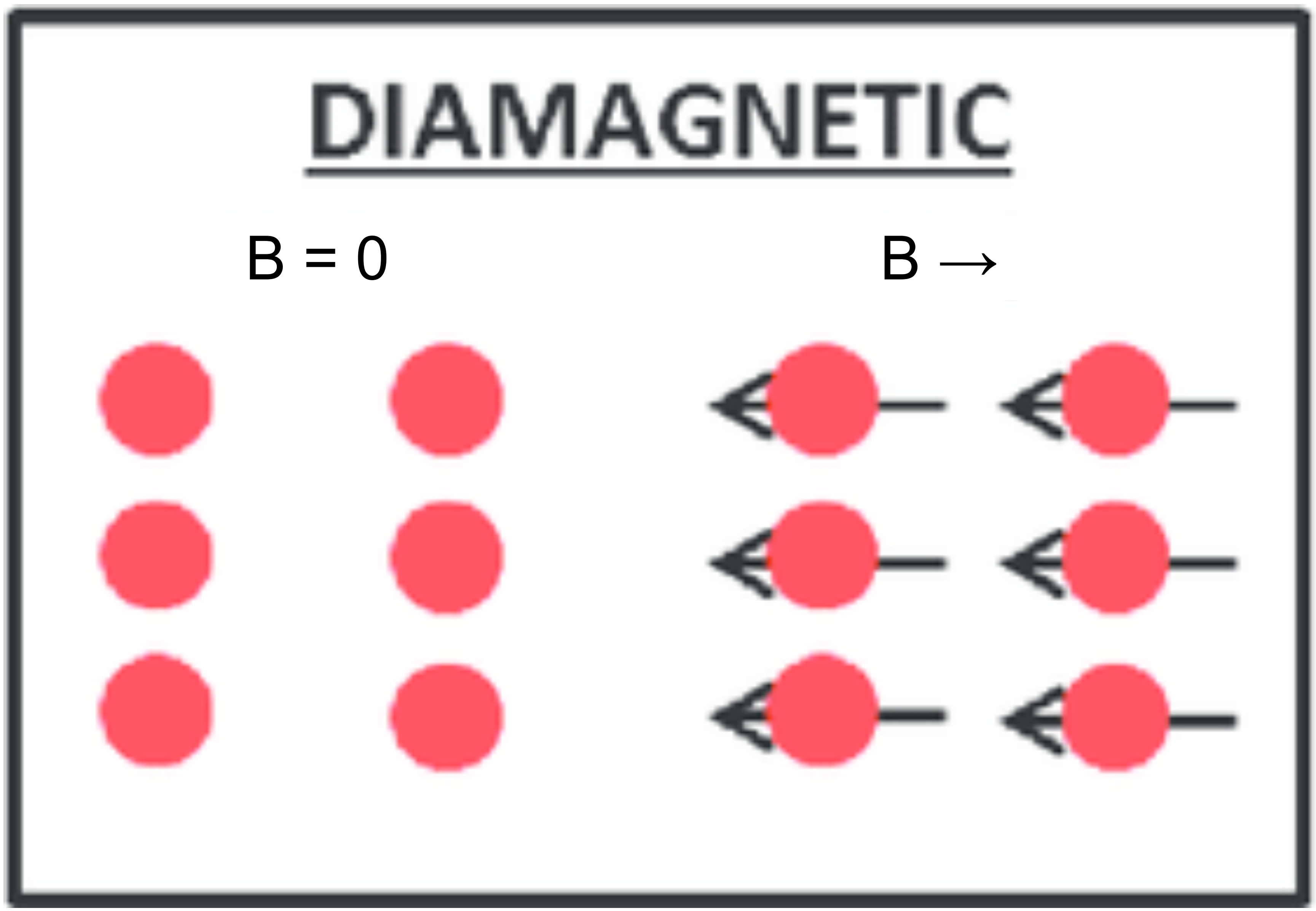
- The alignment process competes with thermal motion which randomizes the moment orientations.

When the external field is taken away, the magnetic moments randomize again.

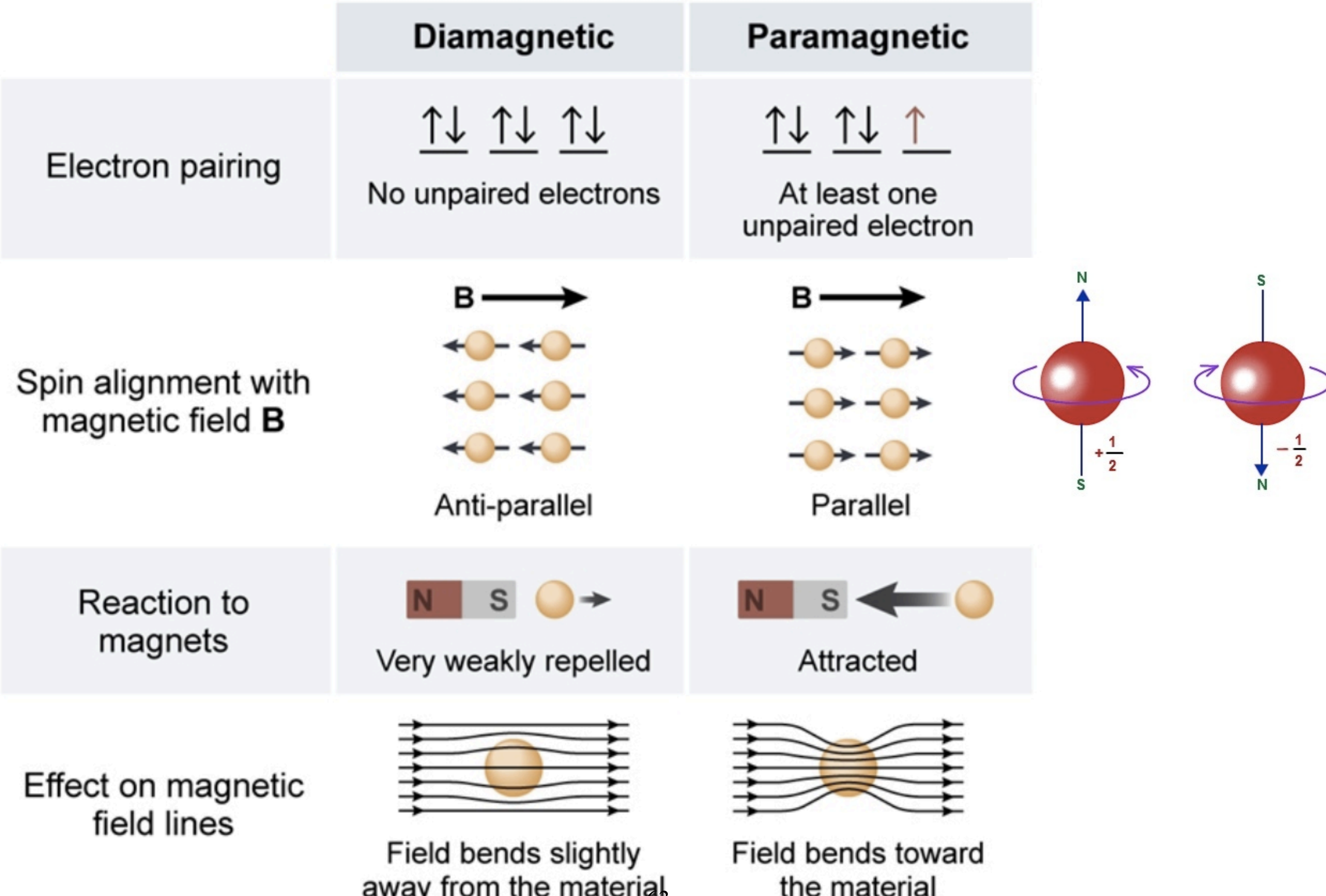


Diamagnetism

When an external magnetic field is applied to a diamagnetic substance, a **weak magnetic moment is induced in the direction opposite the applied field.**
Diamagnetic substances (e.g. silver) are weakly repelled by a magnet.



Types of magnetism



Meissner Effect

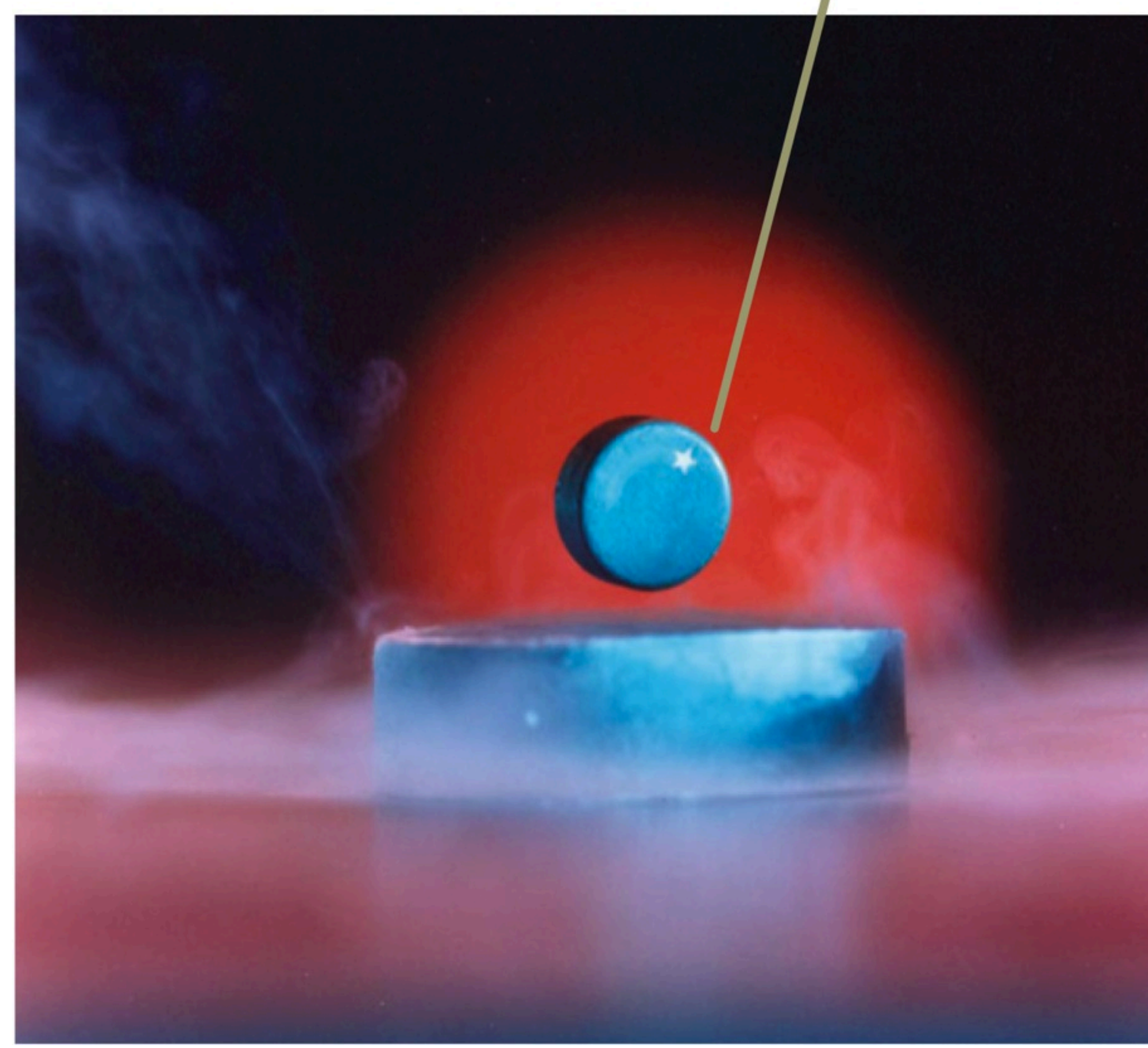
Certain types of superconductors also exhibit perfect diamagnetism in the superconducting state.

- This is called the **Meissner effect.**

If a permanent magnet is brought near a superconductor, the two objects repel each other.

The field from the magnet induces a current in the superconductor
Because superconductors have no resistance, the current goes on forever, and you have **levitation**.

In the Meissner effect, the small magnet at the top induces currents in the superconducting disk below, which is cooled to −321°F (77 K). The currents create a repulsive magnetic force on the magnet causing it to levitate above the superconducting disk.



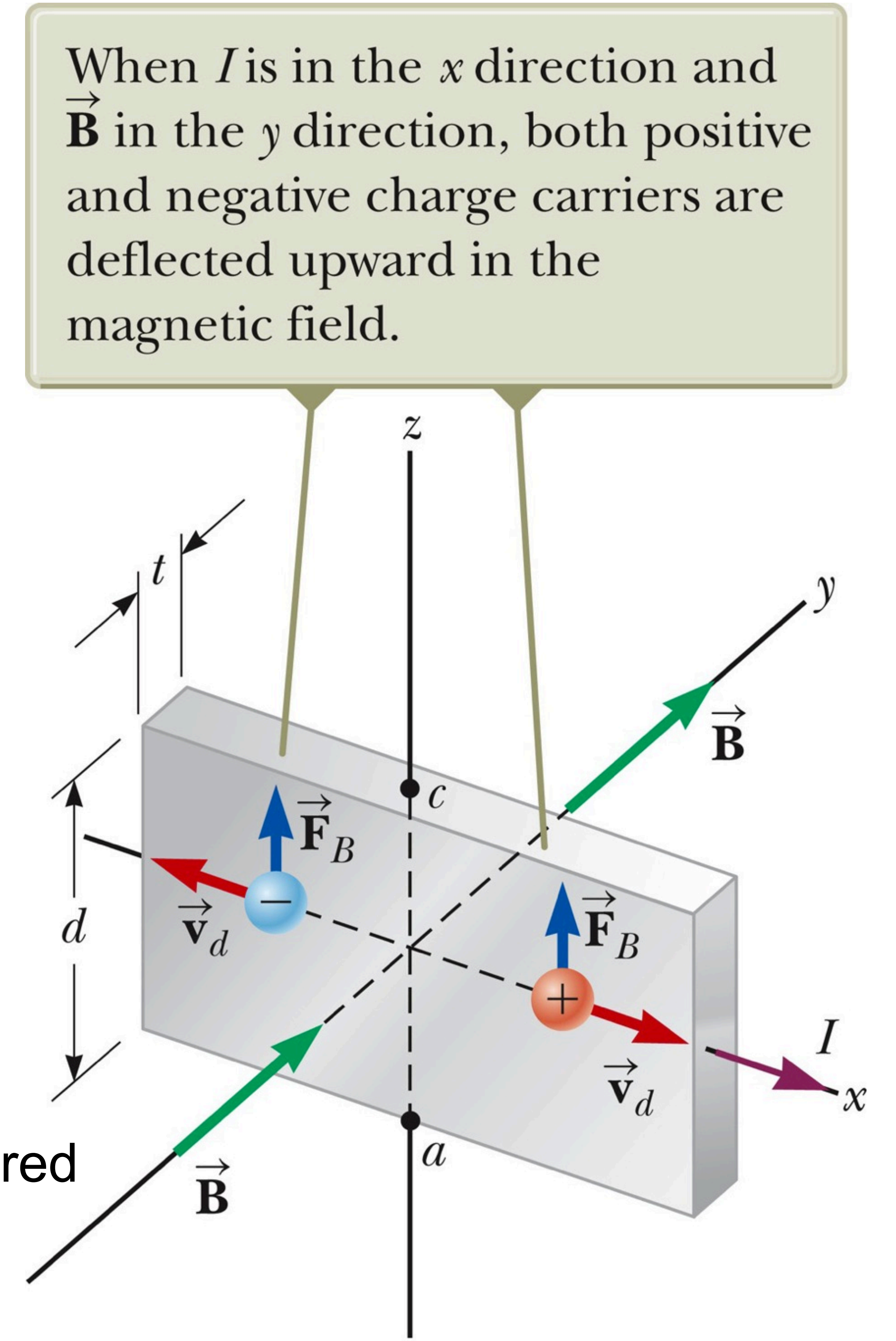
Courtesy Argonne National Laboratory

Hall Effect

When a current carrying conductor is placed in a magnetic field, **a potential difference is generated in a direction perpendicular to both the current and the magnetic field.**

It arises from the deflection of charge carriers to one side of the conductor as a result of the magnetic forces they experience.

The Hall effect gives information regarding the sign of the charge carriers and their density and can also be used to measure magnetic fields.



The Hall voltage is measured between points *a* and *c*.

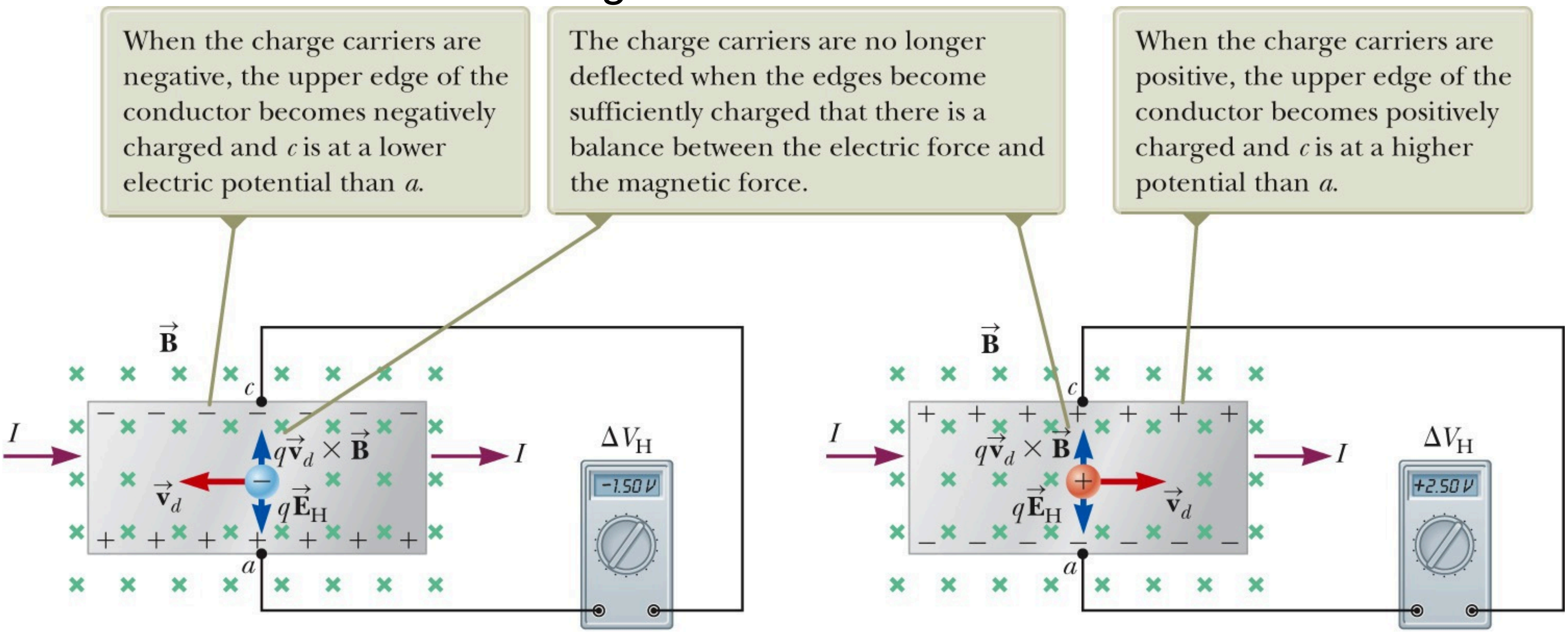
Hall Effect

When the charge carriers are negative, they experience an upward magnetic force, they are deflected upward, an excess of positive charge is left at the lower edge.

This accumulation of charge establishes an electric field in the conductor.

It increases until the electric force balances the magnetic force.

If the charge carriers are positive, an excess of negative charges accumulates on the lower edge.



Hall Voltage

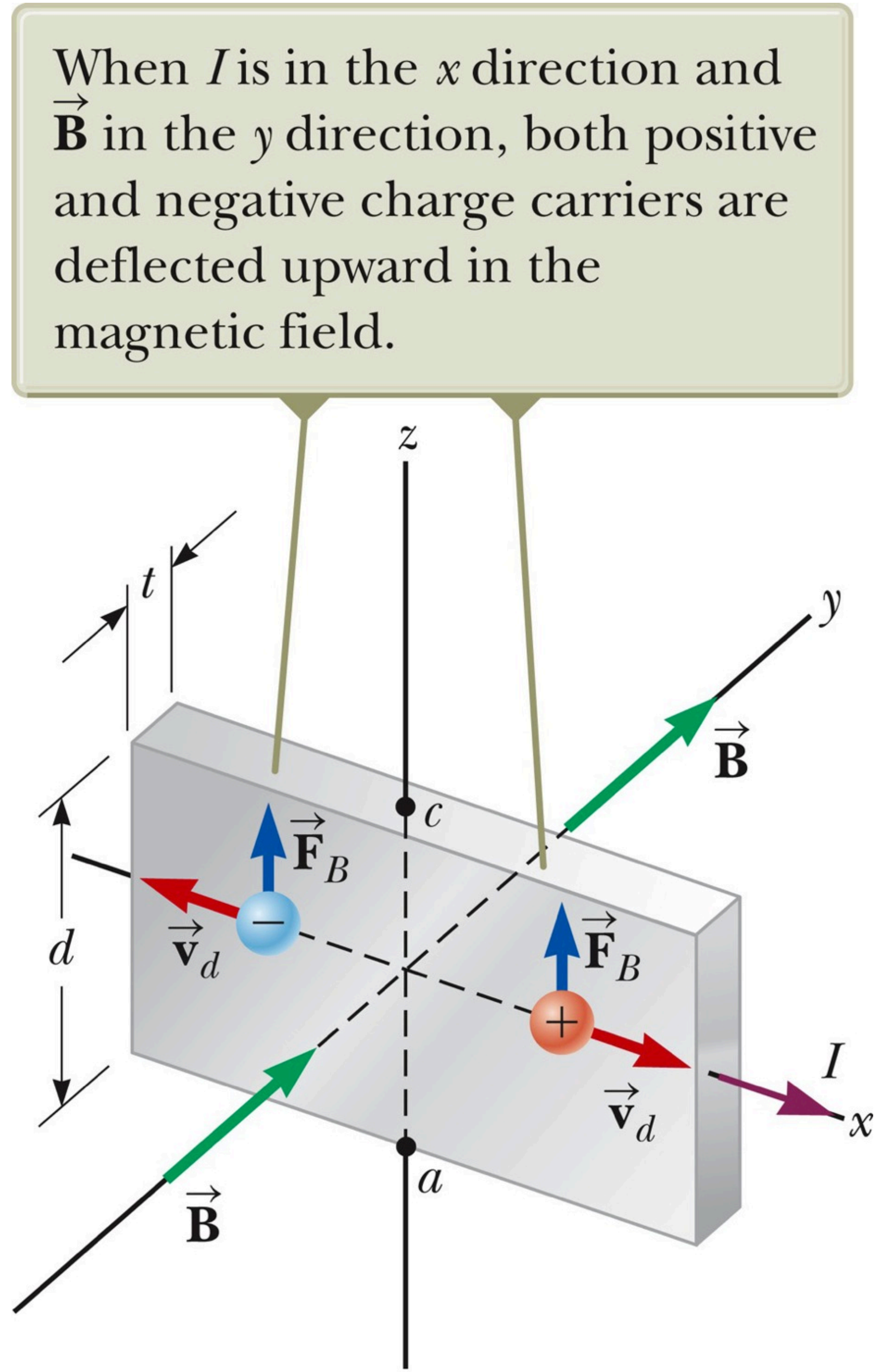
$F_E = F_B$ $qE = qvB$ $E = vB$

$\Delta V_H = E_H d = v_d\, B\, d$

- d is the width of the conductor
- v_d is the drift velocity = I/nqA
- A = td
- If B and d are known, v_d can be found

$$\Delta V_H = \frac{IB}{nqt} = \frac{R_H IB}{t}$$

- $R_H = 1 / nq$ is called the **Hall coefficient.**
- A properly calibrated conductor can be used to measure the magnitude of an unknown magnetic field.



Conceptual questions

1) Is it possible to orient a current loop in a uniform magnetic field such that the loop doesn’t tend to rotate?

2) how can a current loop be used to determine the presence of a magnetic field in a given region of space?

3) without torque, could a magnet be created?

Conceptual questions

1) Is it possible to orient a current loop in a uniform magnetic field such that the loop doesn't tend to rotate?
Yes. B field perpendicular to the loop.

2) how can a current loop be used to determine the presence of a magnetic field in a given region of space?
By looking at the torque. If the torque is zero the field is along the axis of the loop.

3) without torque, could a magnet be created?
No. the torque is the alignment process.

Example Problem #5

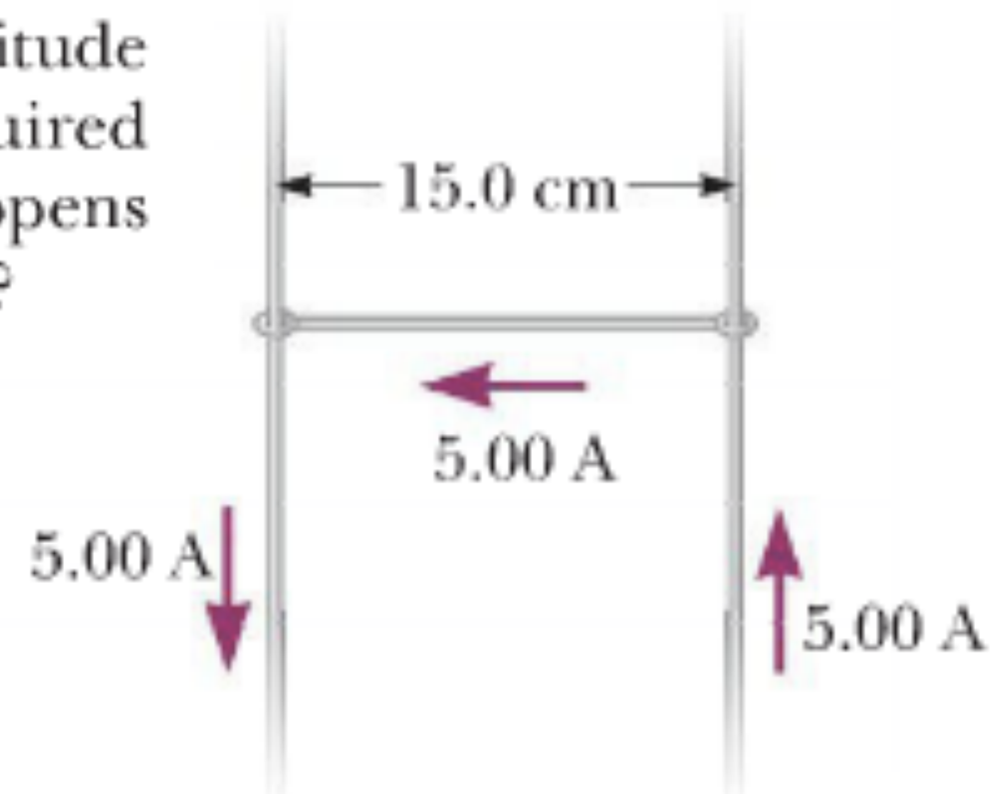
MacGyver created a magnet by hitting an iron rod hard. Realistic?

Example Problem #5: Solution

YES! But works best with pure iron, aligned with the Earth's field.

Example Problem #6

40. Consider the system pictured in Figure P29.40. A 15.0-cm horizontal wire of mass 15.0 g is placed between two thin, vertical conductors, and a uniform magnetic field acts perpendicular to the page. The wire is free to move vertically without friction on the two vertical conductors. When a 5.00-A current is directed as shown in the figure, the horizontal wire moves upward at constant velocity in the presence of gravity. (a) What forces act on the horizontal wire, and (b) under what condition is the wire able to move upward at constant velocity? (c) Find the magnitude and direction of the minimum magnetic field required to move the wire at constant speed. (d) What happens if the magnetic field exceeds this minimum value?



Example Problem #6: Solution

P29.40 (a) The magnetic force and the gravitational force both act on the wire.

(b) When the magnetic force is upward and balances the downward gravitational force, the net force on the wire is zero, and the wire can move upward at constant velocity.

field

(c) The minimum magnetic filed would be perpendicular to the current in the wire so that the magnetic force is a maximum. For the magnetic force to be directed upward when the current is toward the left, $\vec{\mathbf{B}}$ must be directed out of the page. Then,

$$F_B = ILB_{\text{min}} \sin 90° = mg$$

from which we obtain

$$B_{\text{min}} = \frac{mg}{IL} = \frac{(0.015\ 0\ \text{kg})(9.80\ \text{m/s}^2)}{(5.00\ \text{A})(0.150\ \text{m})}$$

$$= \boxed{0.196\ \text{T, out of the page}}$$

(d) If the field exceeds 0.200 T, the upward magnetic force exceeds the downward gravitational force, so the wire accelerates upward.

Example Problem #7

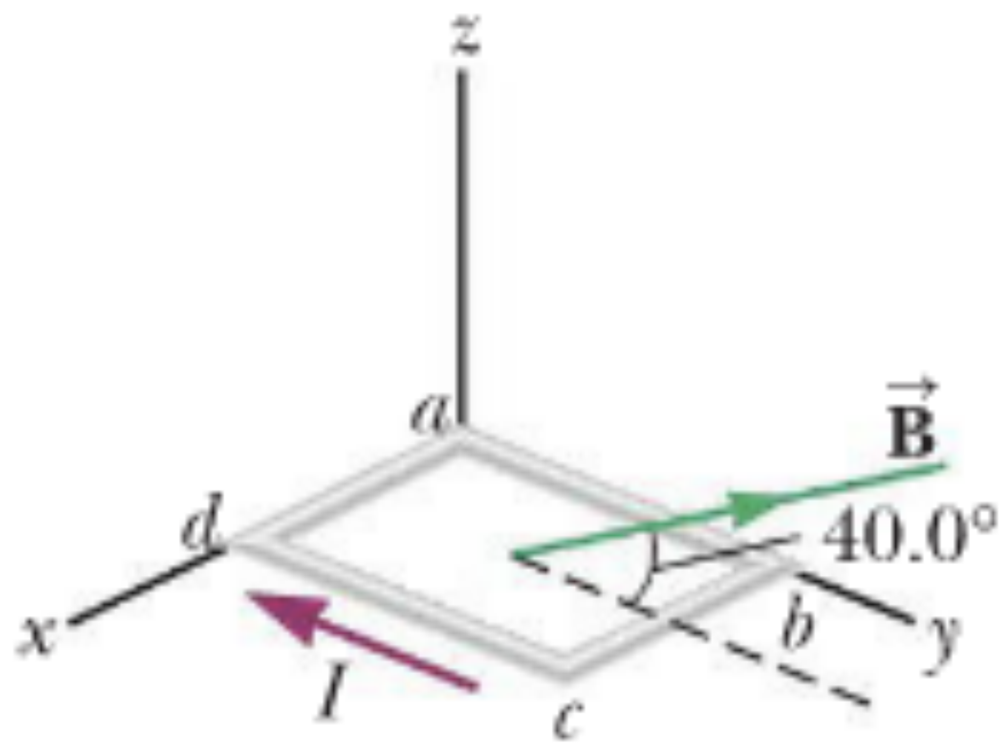
What is the strongest magnetic field that humans ever produced? (T)

Example Problem #7: Solution

Less than 100 Tesla! Less than 50 stably

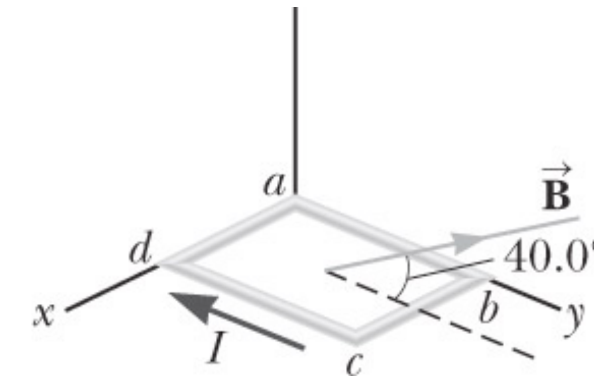
Example Problem #8

52. GP A rectangular loop of wire has dimensions 0.500 m by 0.300 m. The loop is pivoted at the x axis and lies in the xy plane as shown in Figure P29.52. A uniform magnetic field of magnitude 1.50 T is directed at an angle of 40.0° with respect to the y axis with field lines parallel to the yz plane. The loop carries a current of 0.900 A in the direction shown. (Ignore gravitation.) We wish to evaluate the torque on the current loop. (a) What is the direction of the magnetic force exerted on wire segment ab? (b) What is the direction of the torque associated with this force about an axis through the origin? (c) What is the direction of the magnetic force exerted on segment cd? (d) What is the direction of the torque associated with this force about an axis through the origin? (e) Can the forces examined in parts (a) and (c) combine to cause the loop to rotate around the x axis? (f) Can they affect the motion of the loop in any way? Explain. (g) What is the direction of the magnetic force exerted on segment bc? (h) What is the direction of the torque associated with this force about an axis through the origin? (i) What is the torque on segment ad about an axis through the origin? (j) From the point of view of Figure P29.52, once the loop is released from rest at the position shown, will it rotate clockwise or counterclockwise around the x axis? (k) Compute the magnitude of the magnetic moment of the loop. (l) What is the angle between the magnetic moment vector and the magnetic field? (m) Compute the torque on the loop using the results to parts (k) and (l).



Example Problem #8: Solution

P29.52 (a) The current in segment *ab* is in the $+y$ direction. Thus, by the right-hand rule, the magnetic force on it is in the $\boxed{+x \text{ direction}}$.



ANS. FIG. P29.52

(b) Imagine the force on segment *ab* being concentrated at its center. Then, with a pivot at point *a* (a point on the *x* axis), this force would tend to rotate segment *ab* in a clockwise direction about the *z* axis, so the direction of this $\boxed{\text{torque is in the } -z \text{ direction}}$.

(c) The current in segment *cd* is in the $-y$ direction, and the right-hand rule gives the direction of the magnetic force as the $\boxed{-x \text{ direction}}$.

(d) With a pivot at point *d* (a point on the *x* axis), the force on segment *cd* (to the left, in $-x$ direction) would tend to rotate it counterclockwise about the *z* axis, and the direction of this $\boxed{\text{torque is in the } +z \text{ direction}}$.

Example Problem #8: Solution

(e) $\boxed{\text{No.}}$

(f) $\boxed{\text{Both the forces and the torques are equal in magnitude and opposite in direction, so they sum to zero and cannot affect the motion of the loop.}}$

(g) The magnetic force is perpendicular to both the direction of the current in *bc* (the $+x$ direction) and the magnetic field. As given by the right-hand rule, this places it $\boxed{\text{in the } yz \text{ plane at } 130^\circ \text{ counterclockwise from the } +y \text{ axis.}}$

(h) The force acting on segment *bc* tends to rotate it counterclockwise about the x axis, so the torque is in $\boxed{\text{the } +x \text{ direction}}$.

(i) $\boxed{\text{Zero.}}$ There is no torque about the x axis because the lever arm of the force on segment *ad* is zero.

Example Problem #8: Solution

(j) From the answers to (b), (d), (f), and (h), the loop tends to rotate $\boxed{\text{counterclockwise}}$ about the x axis.

(k) $\mu = IAN = (0.900\ \text{A})\left[(0.500\ \text{m})(0.300\ \text{m})\right](1) = \boxed{0.135\ \text{A}\cdot\text{m}^2}$

(l) The magnetic moment vector is perpendicular to the plane of the loop (the xy plane), and is therefore parallel to the z axis. Because the current flows clockwise around the loop, the magnetic moment vector is directed downward, in the negative z direction. This means that the angle between it and the direction of the magnetic field is $\theta = 90.0° + 40.0° = \boxed{130°}$.

(m) $\tau = \mu B \sin\theta = \left(0.135\ \text{A}\cdot\text{m}^2\right)(1.50\ \text{T})\sin(130°) = \boxed{0.155\ \text{N}\cdot\text{m}}$

How high of a B-field can rotating neutron stars produce? (pulsars)

TRILLIONS of T or even MORE (But how? Neutrons are neutral!)

HW07 is up on WebAssign, due Thursday 03/07/24

Extras

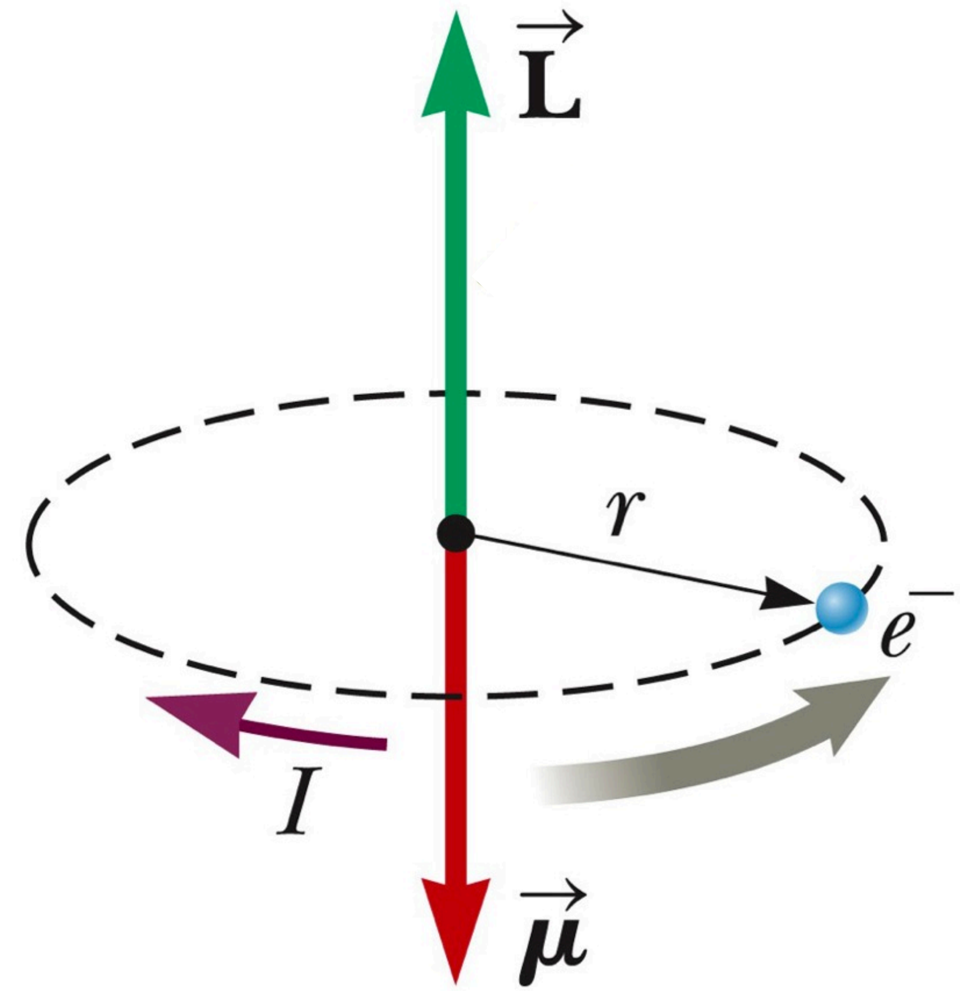
Magnetic Moments – Classical Atom

This model assumes the electron moves:

- with constant speed *v*
- in a circular orbit of radius *r*
- travels a distance $2\pi r$ in a time interval *T*

The current associated with this orbiting electron is

$$I = \frac{e}{T} = \frac{ev}{2\pi r}$$



The magnetic moment is $\mu = I A = \frac{1}{2} evr$

The magnetic moment can also be expressed in terms of the angular momentum $\vec{L} = \vec{r} \times \vec{p} = \vec{r} \times m\vec{v}$.

$$\mu = \left(\frac{e}{2m_e}\right) L$$

The vectors L and μ point in *opposite* directions. Because the electron is negatively charged

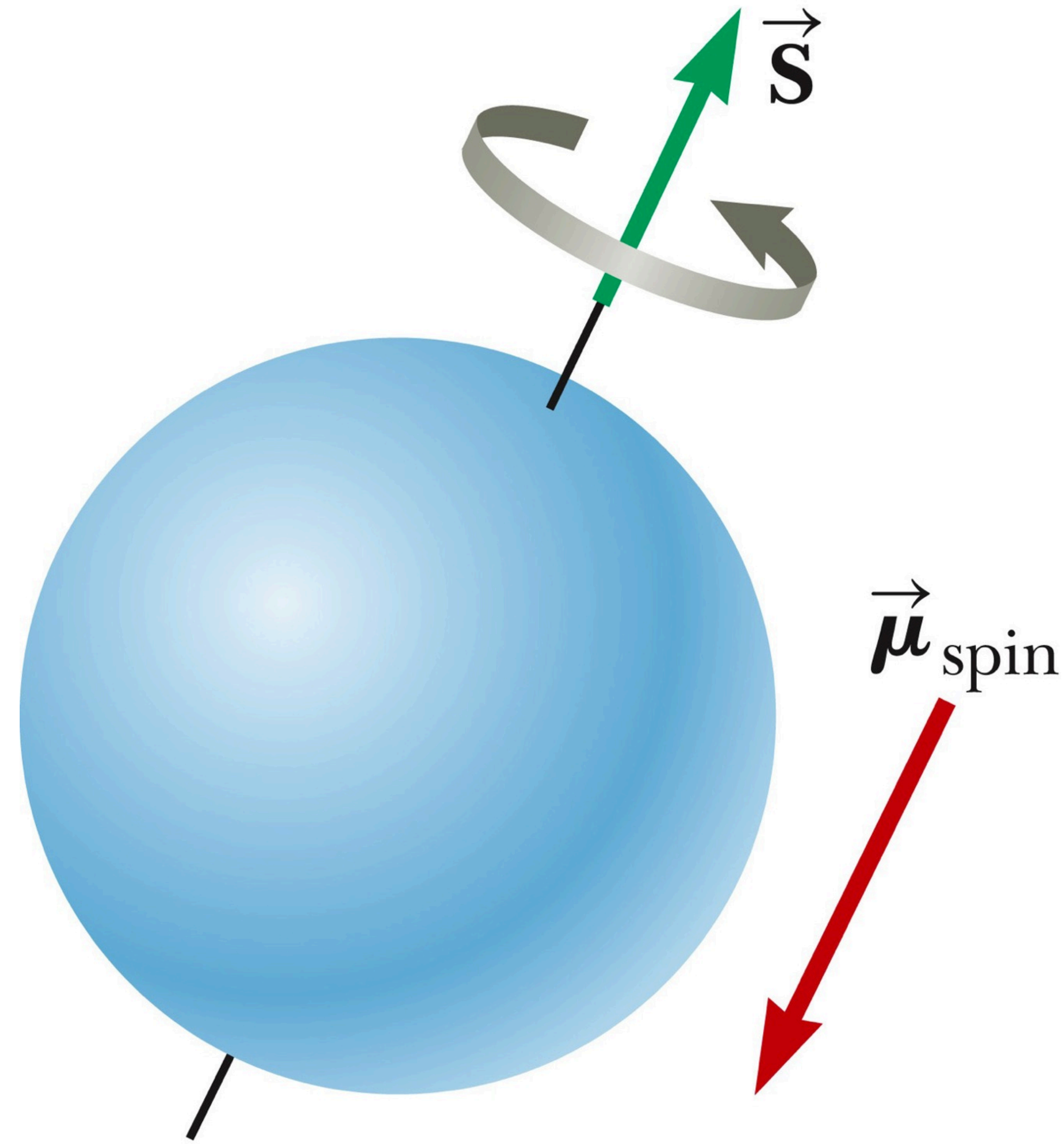
Quantum physics indicates that angular momentum is quantized.

Magnetic Moments of Multiple Electrons

In most substances, the magnetic moment of one electron is canceled by that of another electron orbiting in the same direction.
The net result is that the magnetic effect produced by the orbital motion of the electrons is either zero or very small.

Electrons (and other particles) have an intrinsic property called **spin** that also contributes to their magnetic moment.

- The electron is not physically spinning.
- It has an intrinsic angular momentum as if it were spinning.
- Spin angular momentum is actually a relativistic effect



Potential Energy

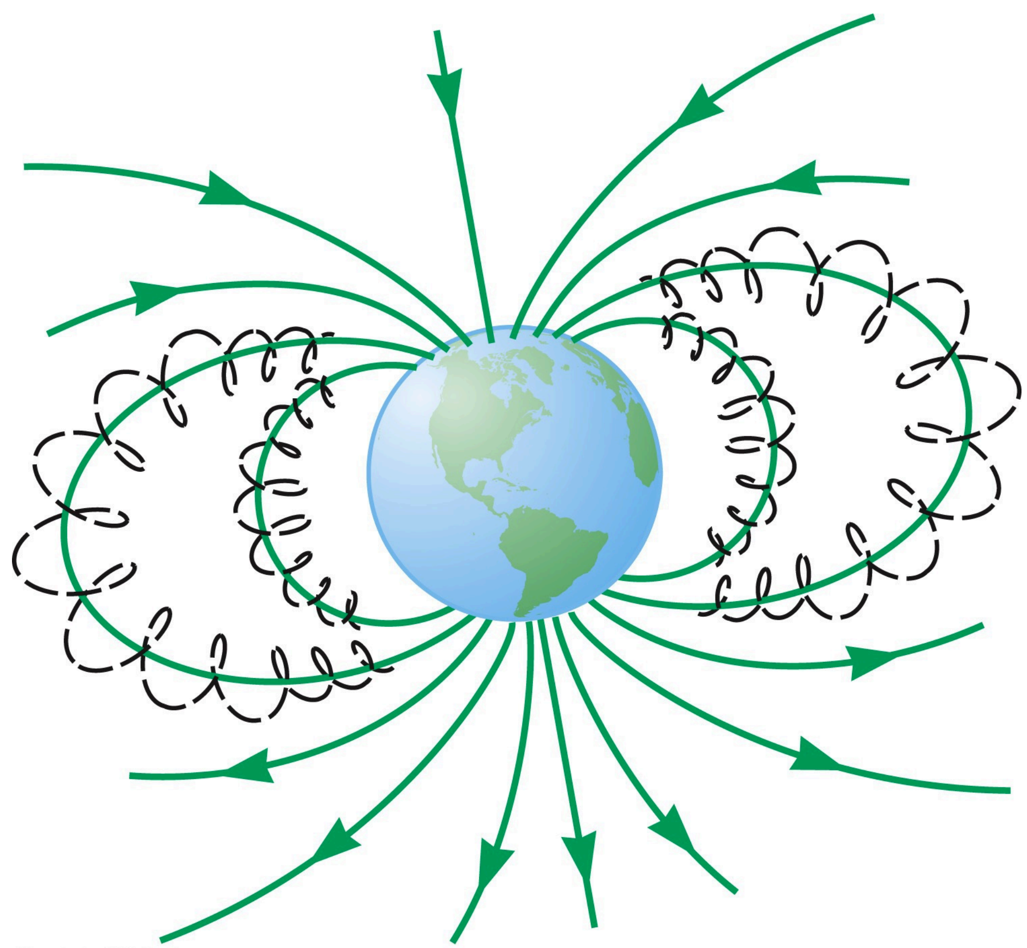
The potential energy of the system of a magnetic dipole in a magnetic field depends on the orientation of the dipole in the magnetic field given by

- U_{min} = -μB and occurs when the dipole moment is in the same direction as the field.
- U_{max} = +μB and occurs when the dipole moment is in the direction opposite the field.

U = Negative 1 times the dot product of mu and B

Van Allen Radiation Belts

The Van Allen radiation belts consist of charged particles surrounding the Earth in doughnut-shaped regions.
The particles are trapped by the Earth's nonuniform magnetic field.
The particles spiral from pole to pole.
- May result in auroras

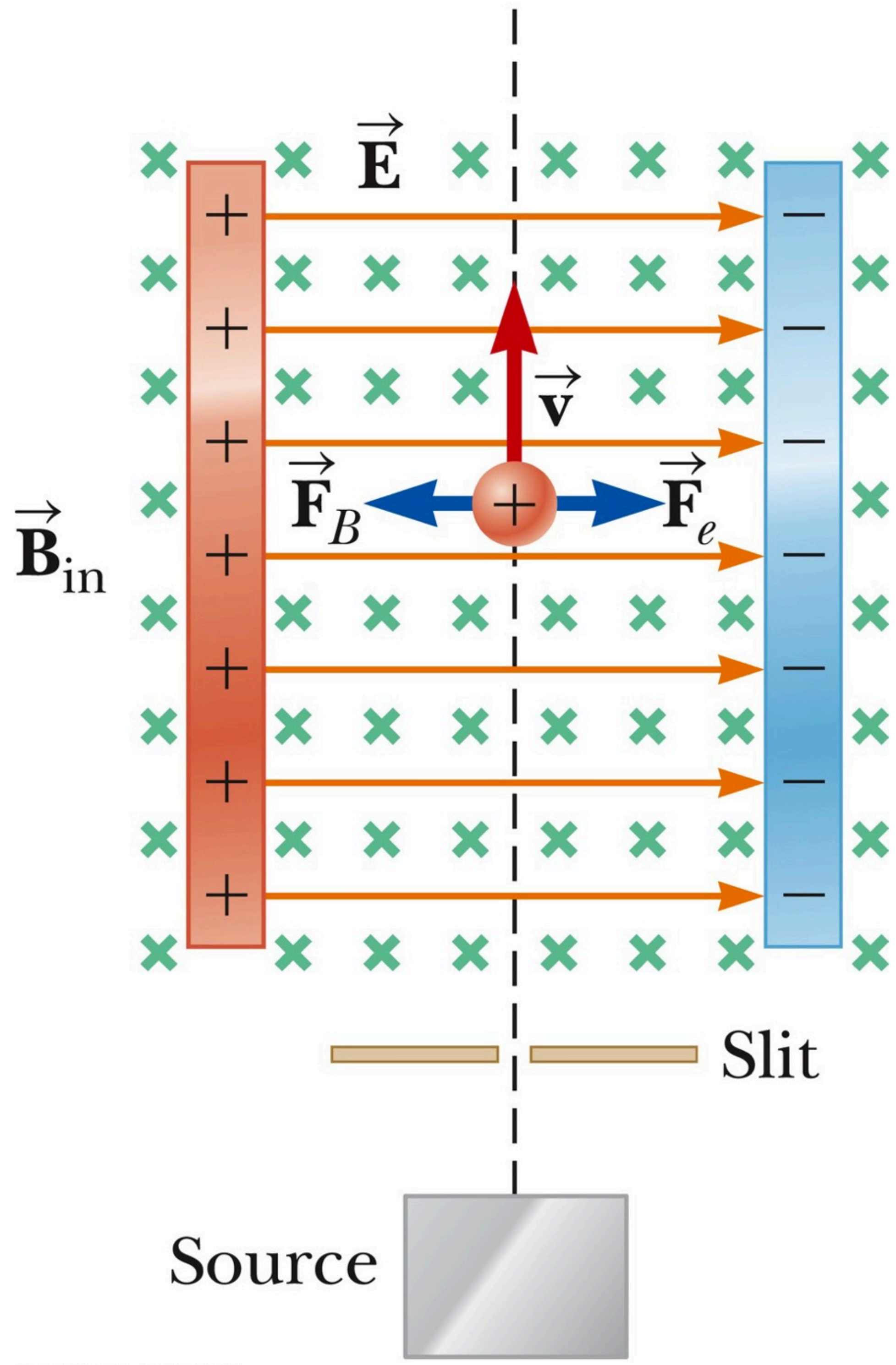


passing through is like adding a year of smoking to your life

Velocity Selector

Used when all the particles need to move with the same velocity.
A uniform electric field is perpendicular to a uniform magnetic field.
When the force due to the electric field is equal but opposite to the force due to the magnetic field, the particle moves in a straight line.
This occurs for velocities of value.

$$v = E / B$$



Velocity Selector, cont.

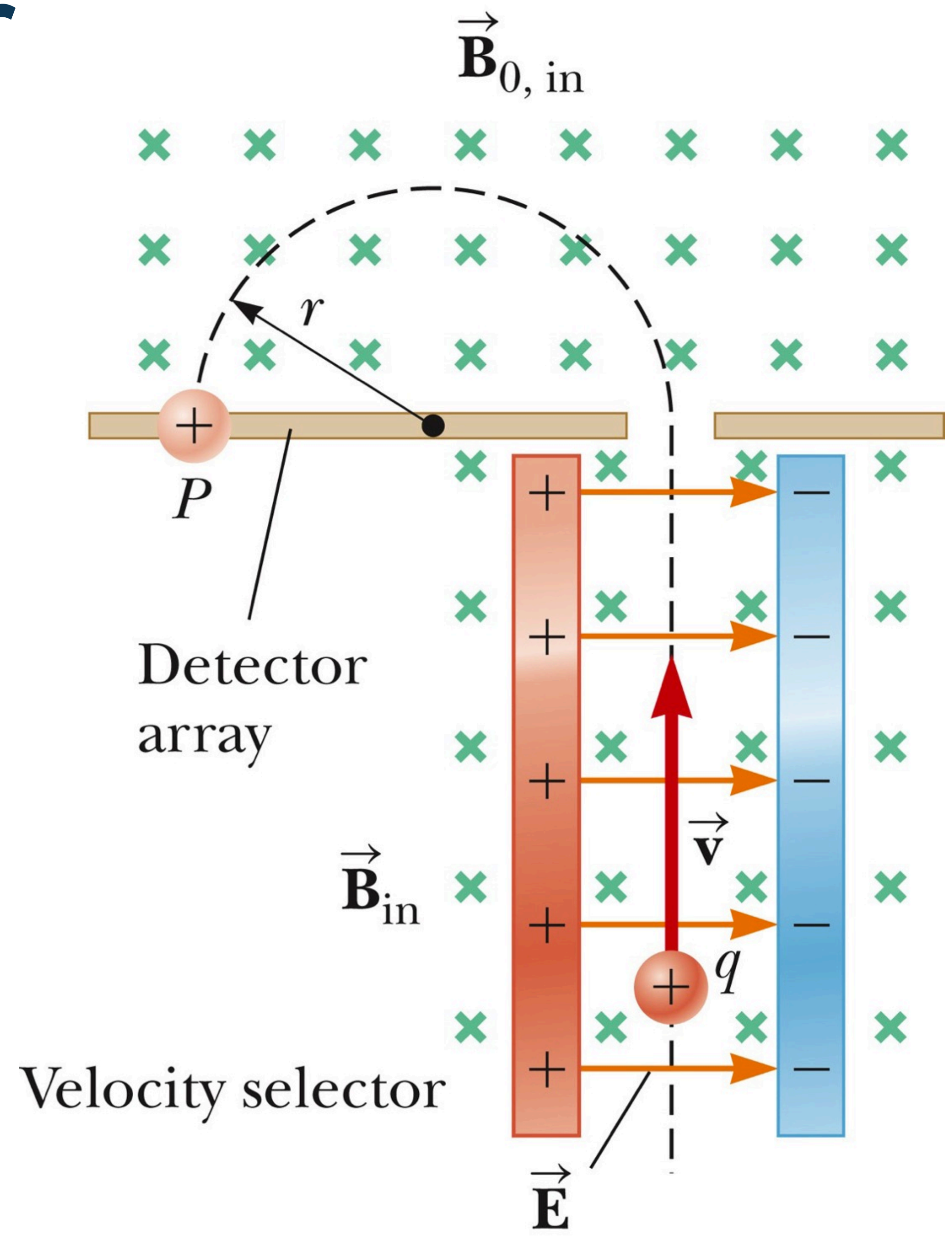
Only those particles with the given speed will pass through the two fields undeflected.

The magnetic force exerted on particles moving at a speed greater than this is stronger than the electric field and the particles will be deflected to the left.

Those moving more slowly will be deflected to the right.

Mass Spectrometer

A mass spectrometer separates ions according to their mass-to-charge ratio.
In one design, a beam of ions passes through a velocity selector and enters a second magnetic field.
After entering the second magnetic field, the ions move in a semicircle of radius r before striking a detector at P.
If the ions are positively charged, they deflect to the left.
If the ions are negatively charged, they deflect to the right.



CENGAGE Learning

Mass Spectrometer, cont.

The mass to charge (m/q) ratio can be determined by measuring the radius of curvature and knowing the magnetic and electric field magnitudes.

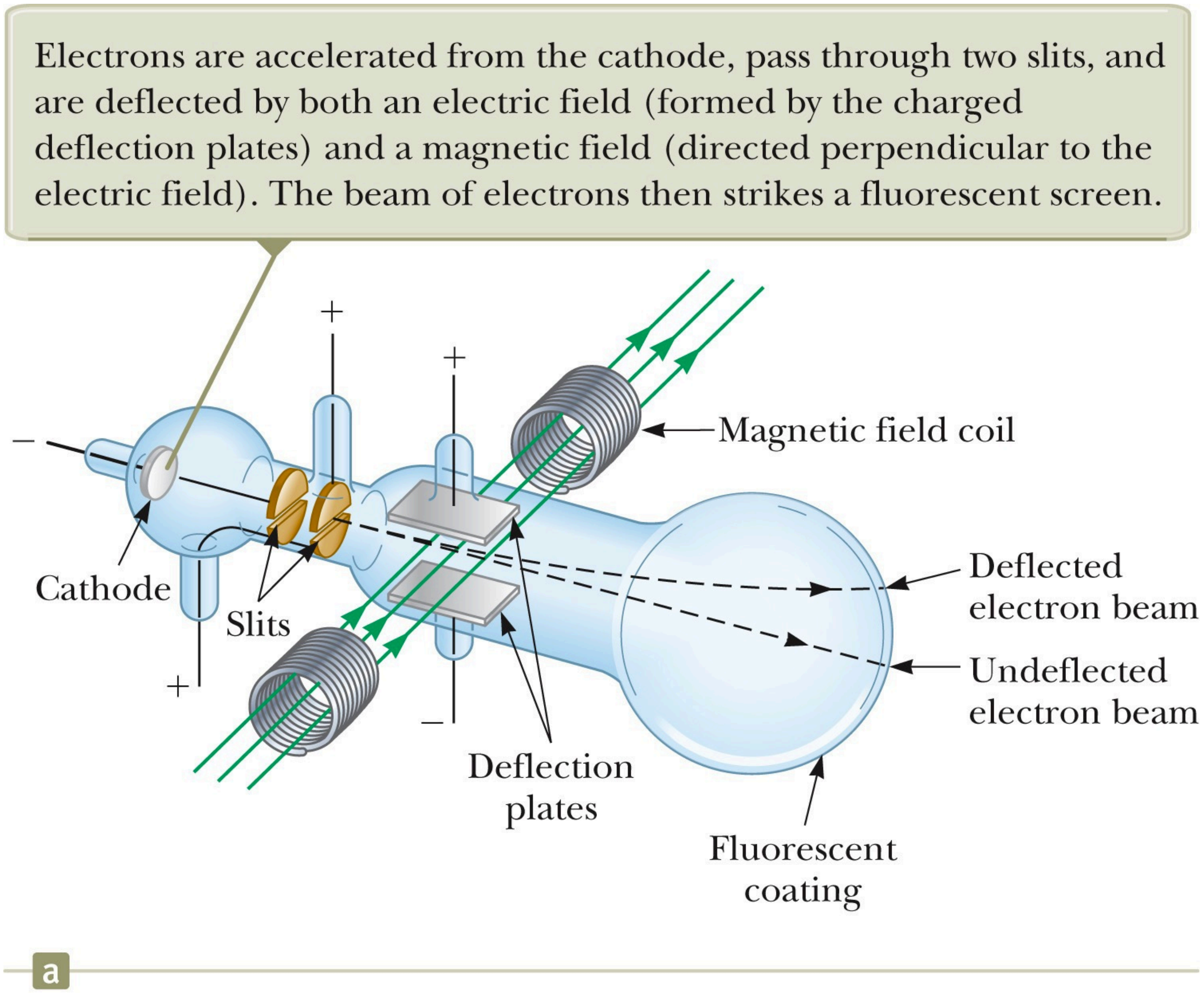
$$\frac{m}{q} = \frac{rB_o}{v} = \frac{rB_oB}{E}$$

In practice, you can measure the masses of various isotopes of a given atom, with all the ions carrying the same charge.

- The mass ratios can be determined even if the charge is unknown.

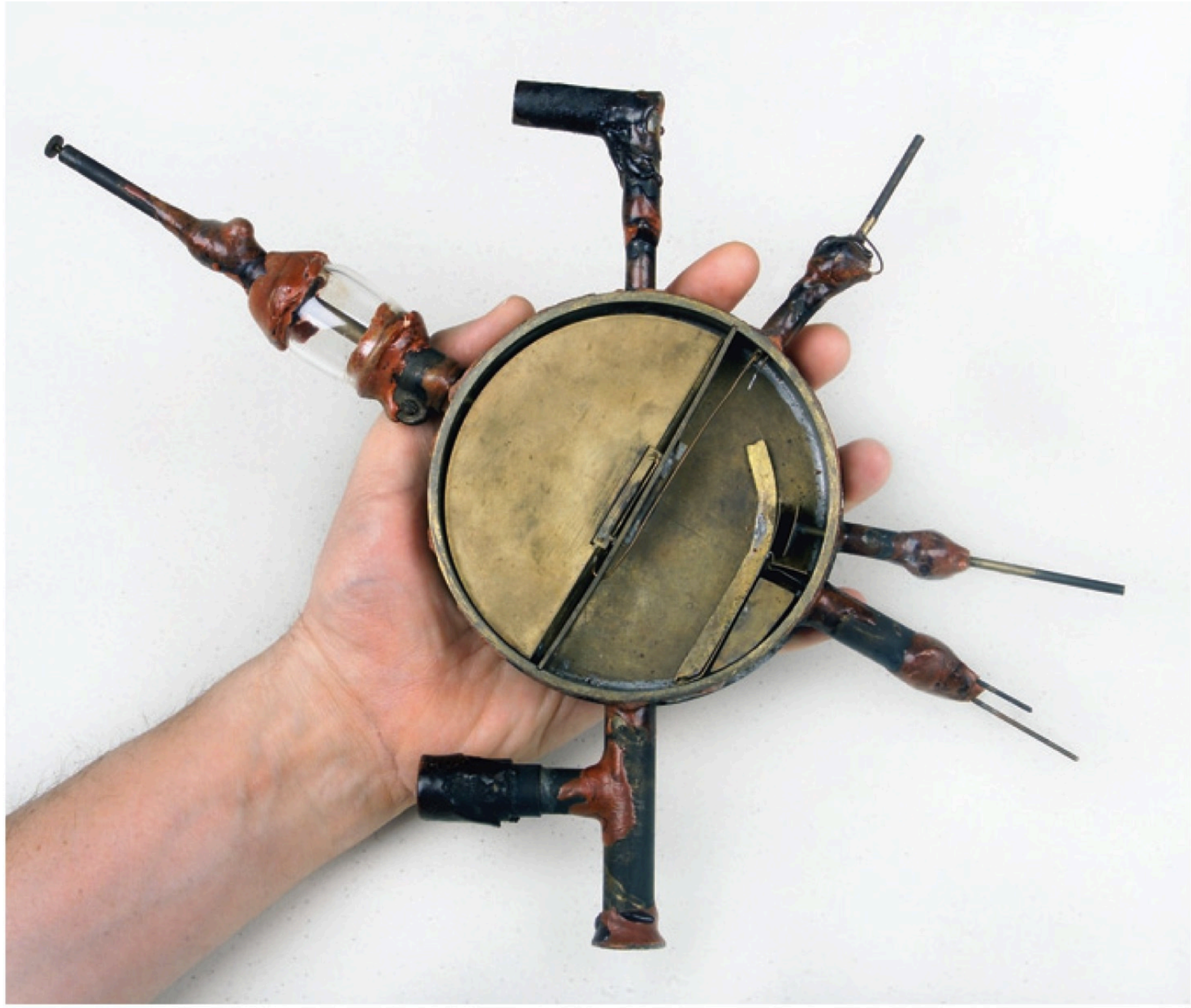
Thomson's *e/m* Experiment

Electrons are accelerated from the cathode.
They are deflected by electric and magnetic fields.
The beam of electrons strikes a fluorescent screen.
e/m was measured



Cyclotron

A **cyclotron** is a device that can accelerate charged particles to very high speeds.
The energetic particles produced are used to bombard atomic nuclei and thereby produce reactions.
These reactions can be analyzed by researchers.



Lawrence Berkeley National Lab

b

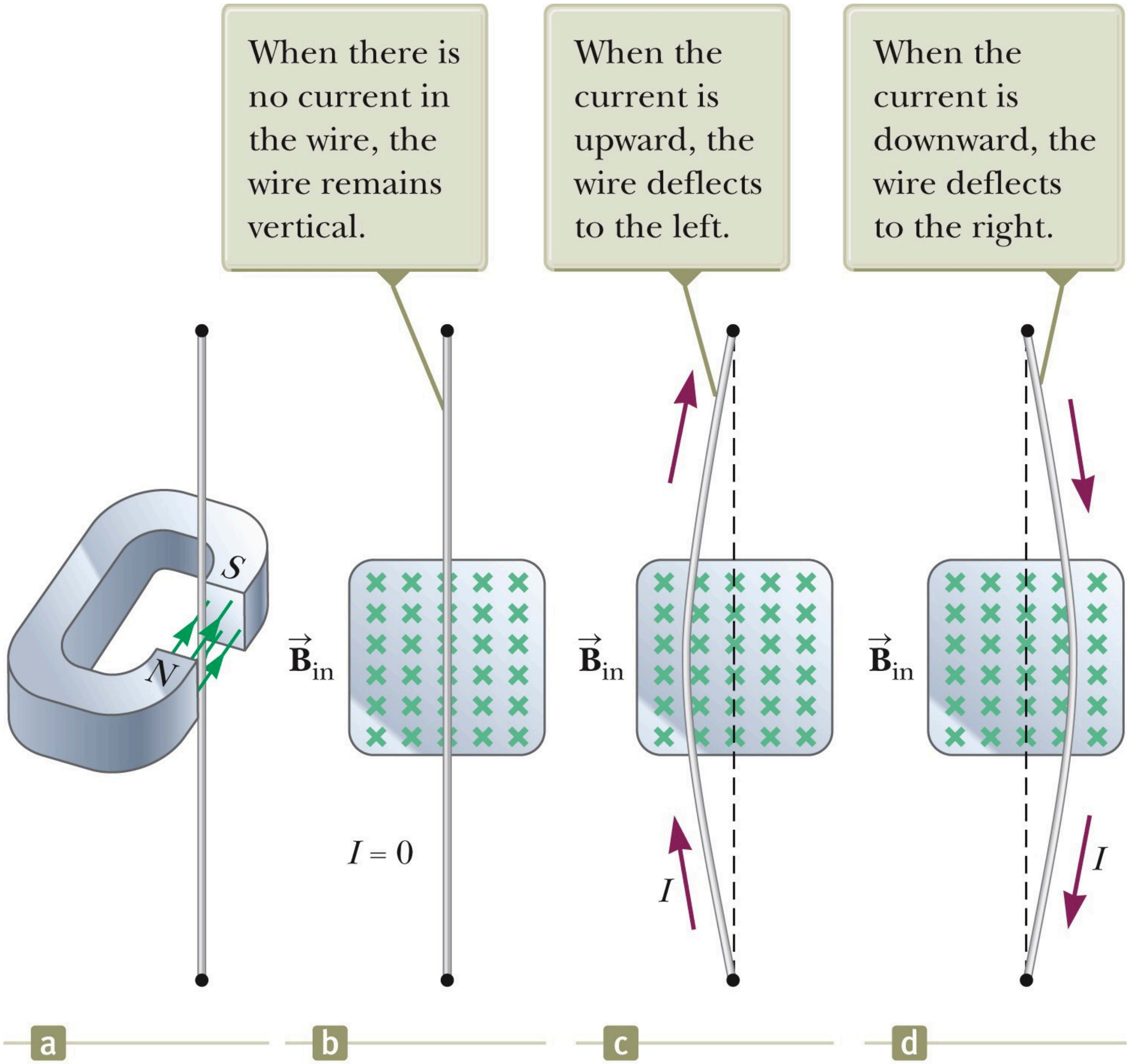
Cyclotron, cont.

D_1 and D_2 are called *dees* because of their shape.

A high frequency alternating potential is applied to the dees.

A uniform magnetic field is perpendicular to them.

A positive ion is released near the center and moves in a semicircular path.



Cyclotron, final

The potential difference is adjusted so that the polarity of the dees is reversed in the same time interval as the particle travels around one dee.

This ensures the kinetic energy of the particle increases each trip.

The cyclotron's operation is based on the fact that T is independent of the speed of the particles and of the radius of their path.

$$K = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}$$

When the energy of the ions in a cyclotron exceeds about 20 MeV, relativistic effects come into play.

Most accelerators currently used in research are *synchrotrons.*

About Synchrotrons

What is a synchrotron? And what is synchrotron light?

A synchrotron is a type of circular particle accelerator. It works by accelerating charged particles (electrons) through sequences of magnets until they reach almost the speed of light. These fast-moving electrons produce very bright light, called synchrotron light. This very intense light, predominantly in the X-ray region, is millions of times brighter than light produced from conventional sources and 10 billion times brighter than the sun. Scientists can use this light to study minute matter such as atoms and molecules.

Are all synchrotrons the same?

No. Synchrotrons fall into two major categories; high energy physics machines and sources of synchrotron light. They were first developed in the 1950's to study high energy particle collisions. These particle colliders are still used today; for example, the Large Hadron Collider at CERN. However, since the 1960s, synchrotrons have also been used, not to smash particles together, but to exploit the light produced by high energy particles undergoing acceleration.

Diamond is dedicated to the exploitation of synchrotron light. Each synchrotron is optimised to produce light with a particular energy for specific applications – Diamond produces a 3 GeV (Giga-electron-volt) electron beam, and is therefore classed as a medium energy synchrotron. Newer synchrotrons like Diamond are built on more advanced technology, and so are capable of producing more stable and brighter light.

The main difference between a cyclotron and synchrotron is: A cyclotron accelerates the particles in a spiral since the magnetic field is constant. The synchrotron adjusts the magnetic field such that the particles are kept in a circular orbit.