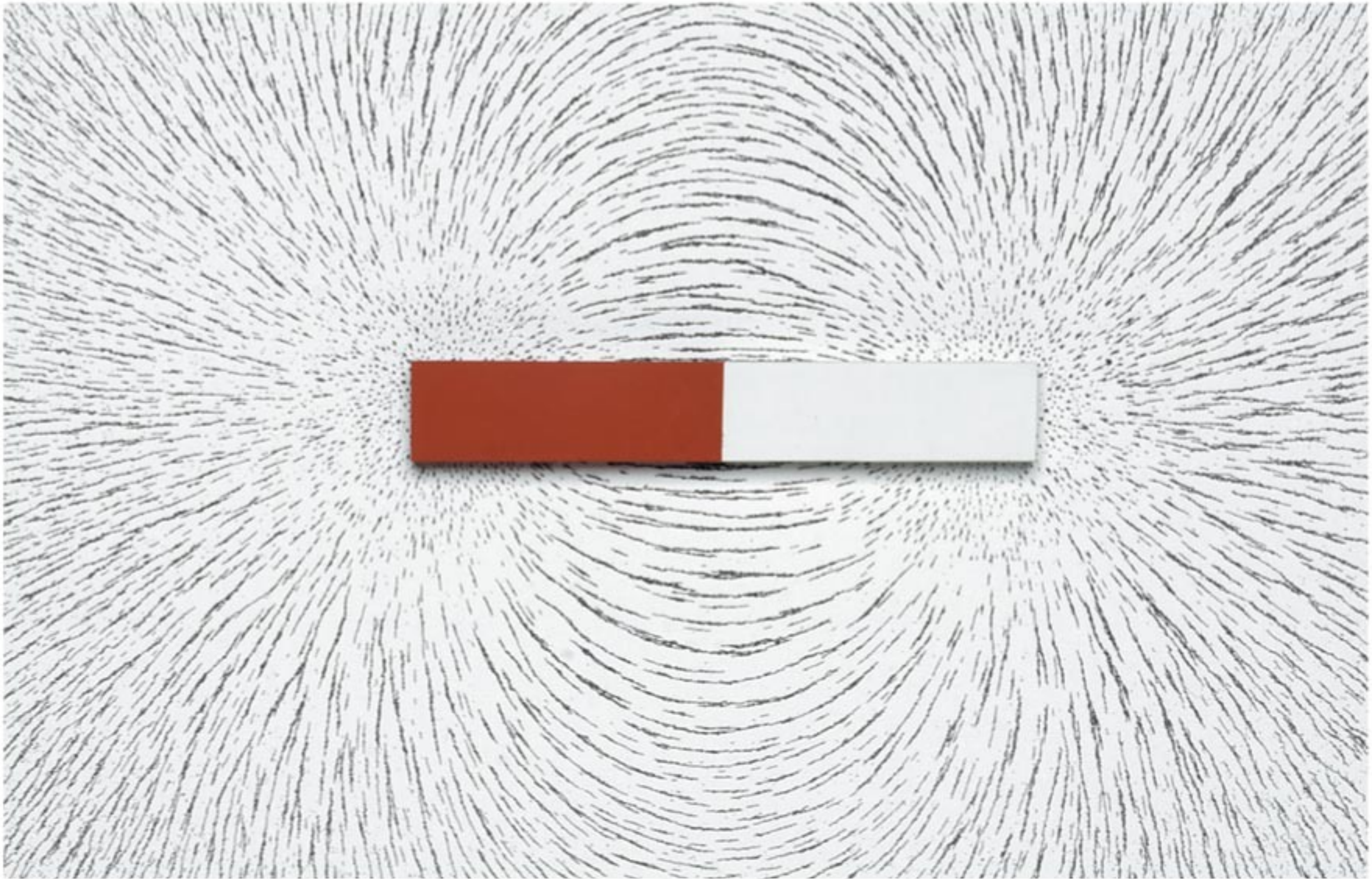
magnetic fields and forces

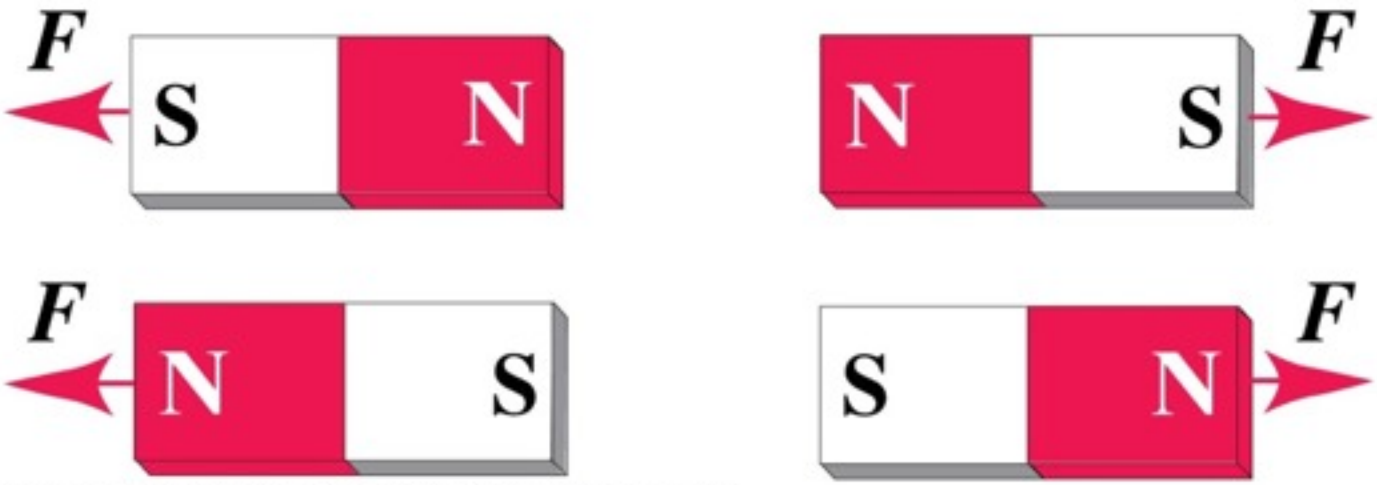
bar magnet & iron filings



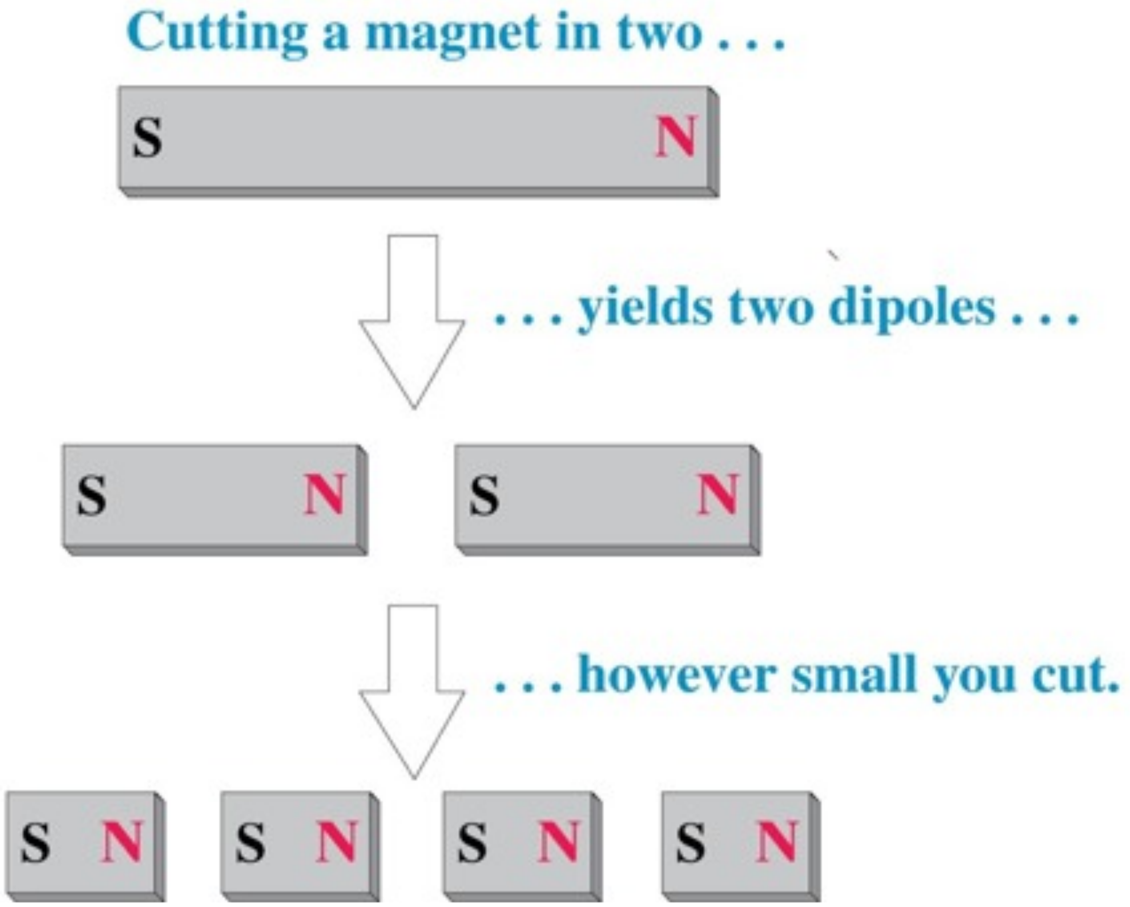
bar magnets

Unlike poles attract.

Like poles repel.



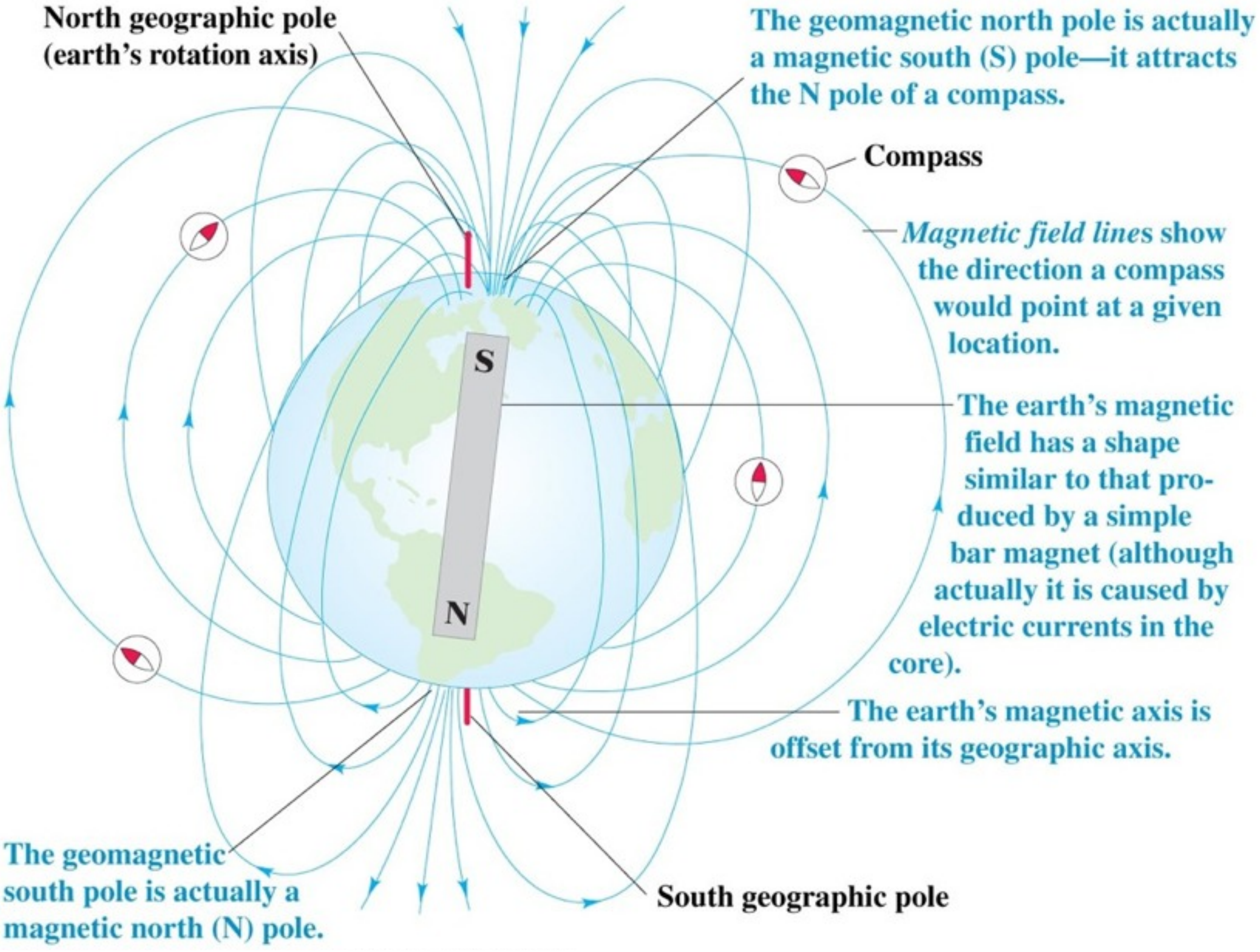
Differing from electric charges, magnetic poles always come paired and can't be isolated.


Cutting a magnet in two . . .

. . . yields two dipoles . . .

. . . however small you cut.

the Earth’s magnetic field



North geographic pole (earth’s rotation axis)

The geomagnetic north pole is actually a magnetic south (S) pole—it attracts the N pole of a compass.

Compass

Magnetic field lines show the direction a compass would point at a given location.

The earth’s magnetic field has a shape similar to that produced by a simple bar magnet (although actually it is caused by electric currents in the core).

The earth’s magnetic axis is offset from its geographic axis.

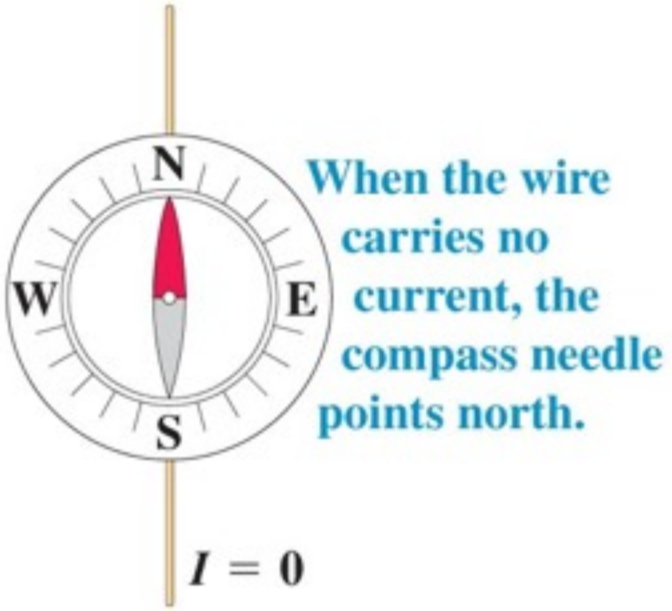
The geomagnetic south pole is actually a magnetic north (N) pole.

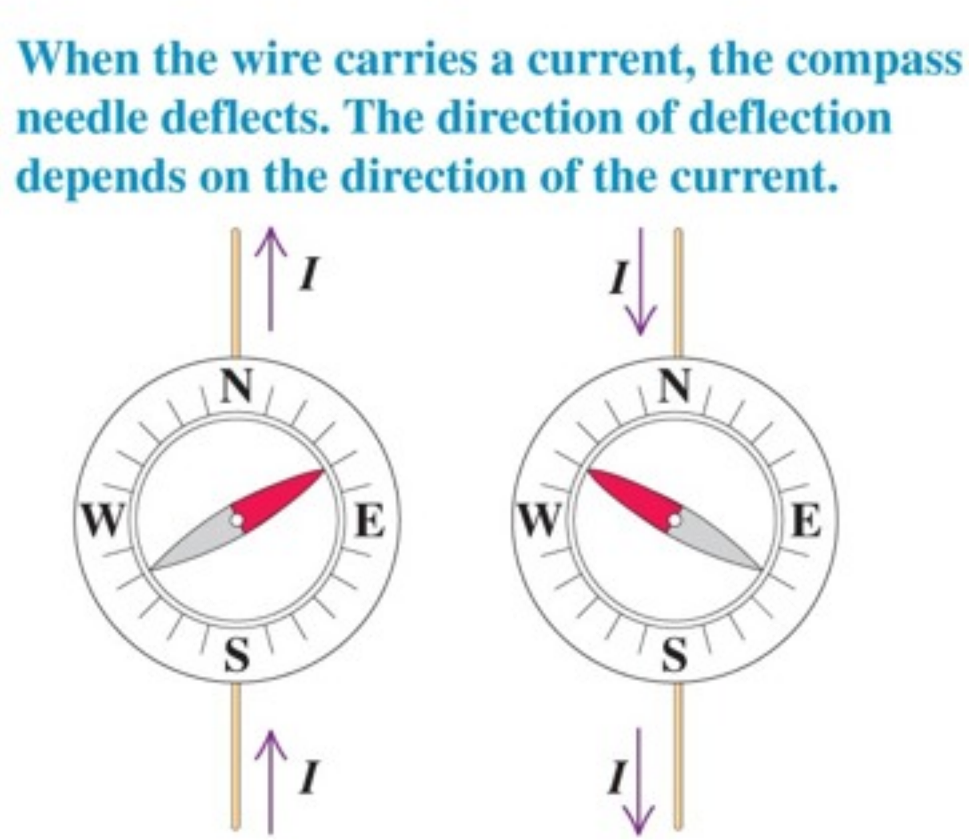
South geographic pole

‘electro’-magnetism

➜ is there a connection between electricity and magnetism ?

➜ place a compass near a current carrying wire


When the wire carries no current, the compass needle points north.


When the wire carries a current, the compass needle deflects. The direction of deflection depends on the direction of the current.

‘electro’-magnetism

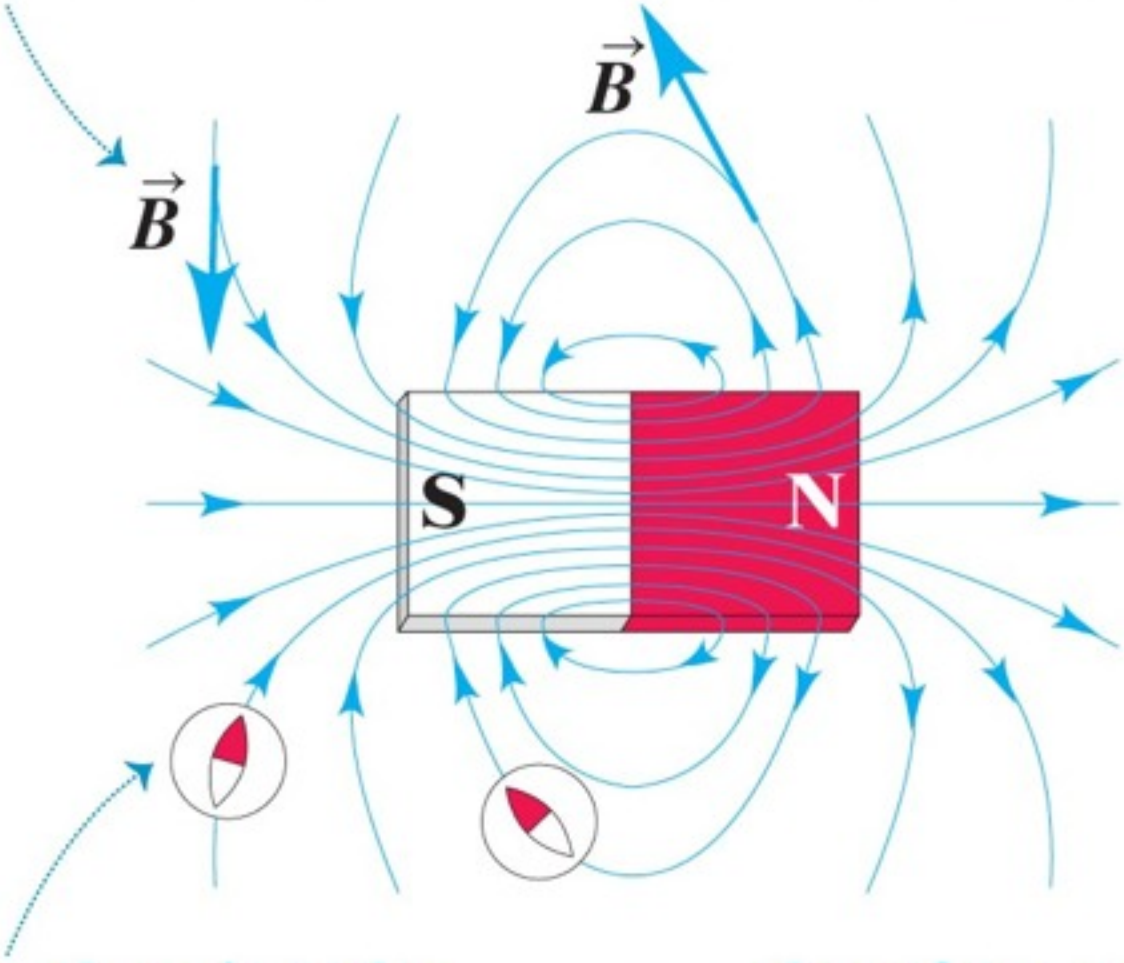
- ➜ is there a connection between electricity and magnetism ?
  - ➜ a loop carrying a large current

magnetic fields

- ➜ a vector at each point in space
- ➜ compasses line up along these vectors
- ➜ will produce a force on any moving charge (more later)

At each point, the field line is tangent to the magnetic field vector $\vec{B}$.

The more densely the field lines are packed, the stronger the field is at that point.



At each point, the field lines point in the same direction a compass would . . .

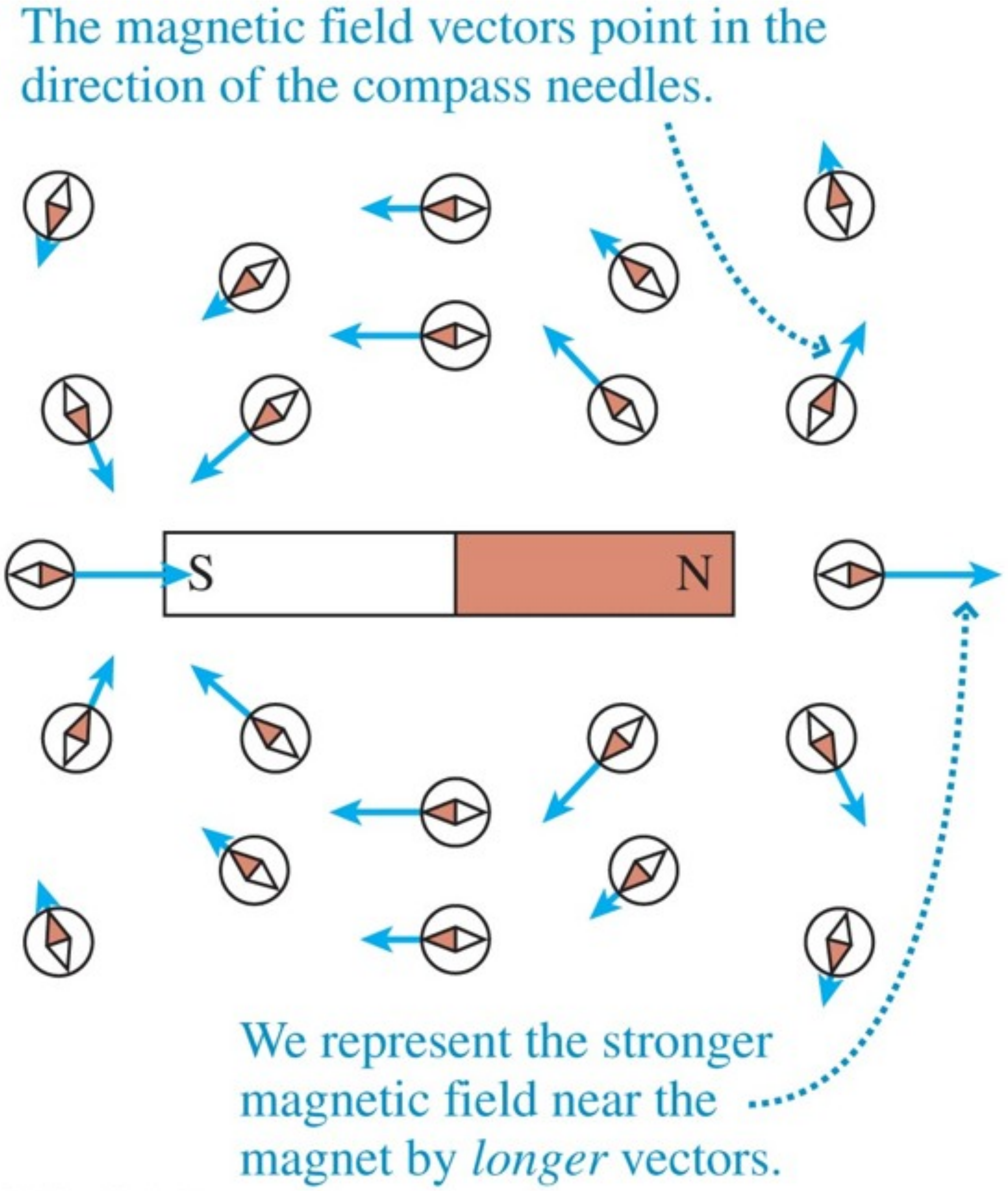
. . . therefore, magnetic field lines point *away from* N poles and *toward* S poles.

magnetic fields

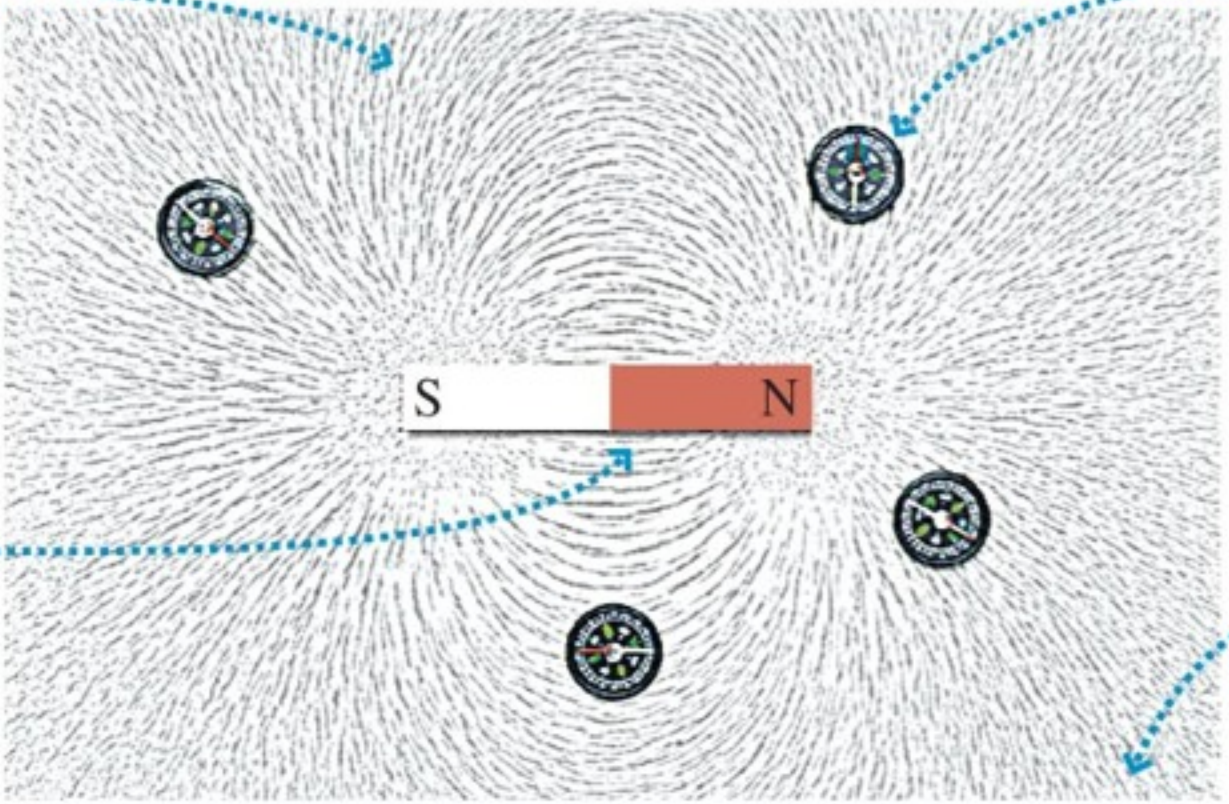
➜ a vector at each point in space

➜ compasses line up along these vectors

➜ will produce a force on any moving charge (more later)



magnetic fields



Each iron filing acts like a tiny compass needle and rotates to point in the direction of the magnetic field.

Since the poles of the iron filings are not labeled, a compass can be used to check the direction of the field.

Where the field is strong, the torque easily lines up the filings.

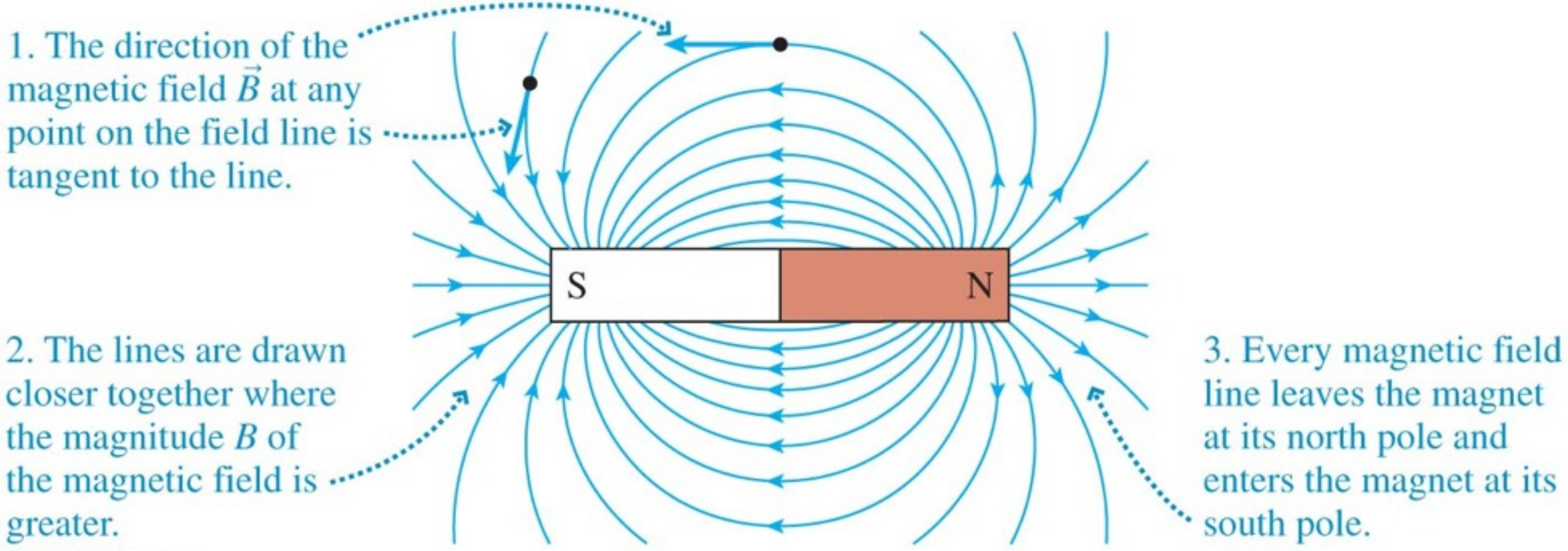
Where the field is weak, the torque barely lines up the filings.

magnetic fields

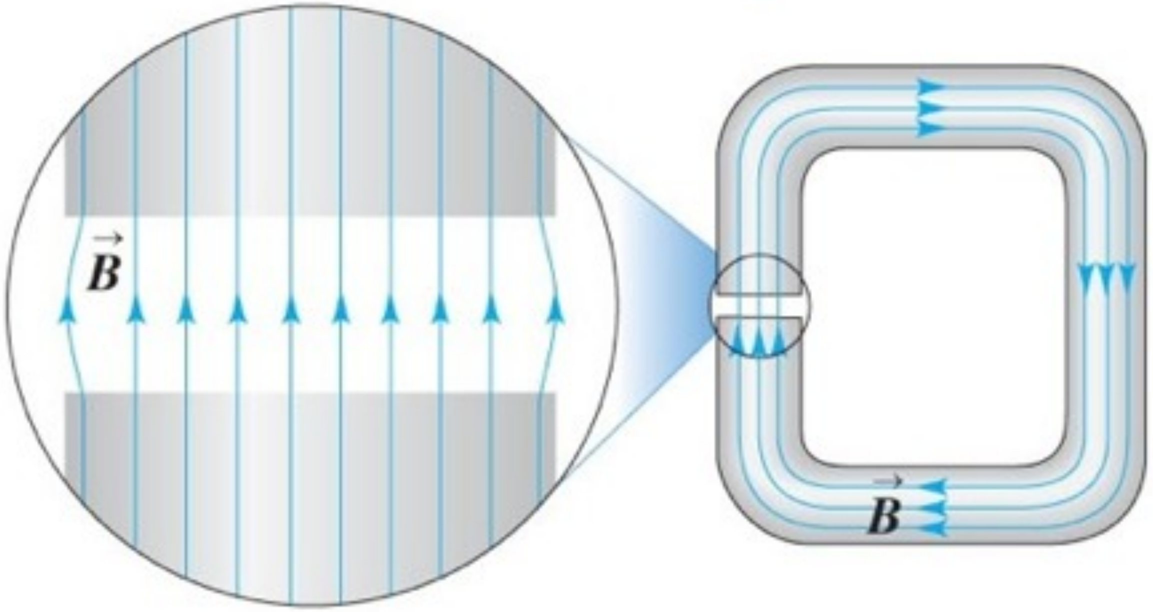
➜ a vector at each point in space

➜ compasses line up along these vectors

➜ will produce a force on any moving charge (more later)

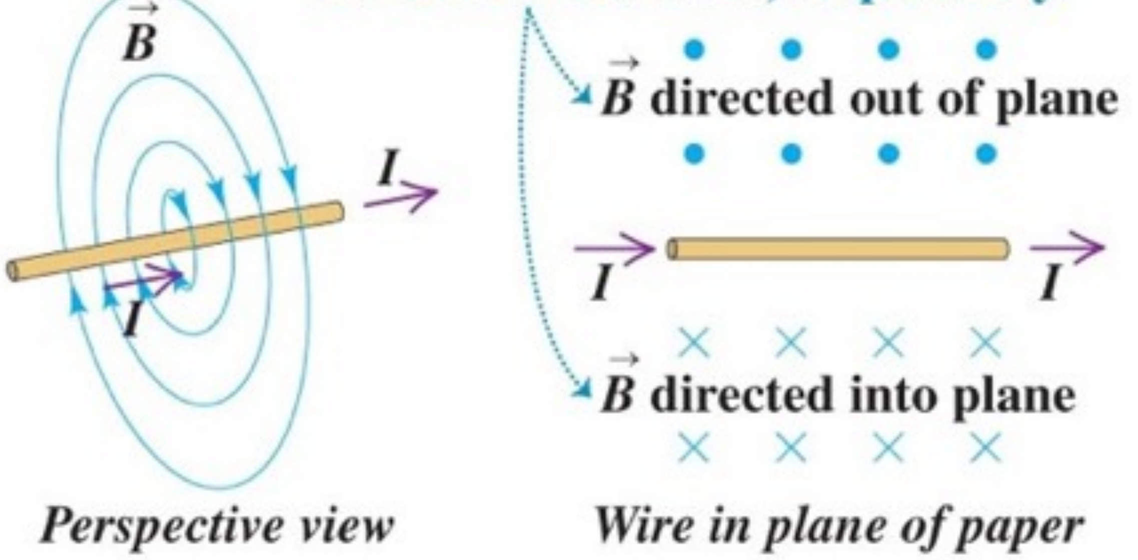


magnetic fields



Between flat, parallel magnetic poles, the magnetic field is nearly uniform.

(a) Magnetic field of a C-shaped magnet

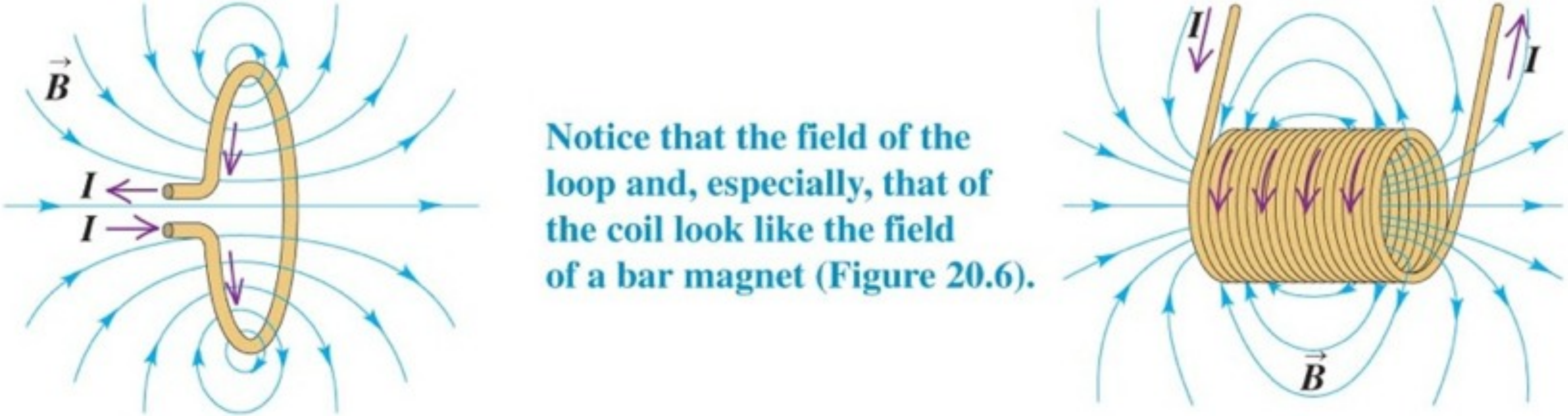


To represent a field coming out of or going into the plane of the paper, we use dots and crosses, respectively.

Perspective view

Wire in plane of paper

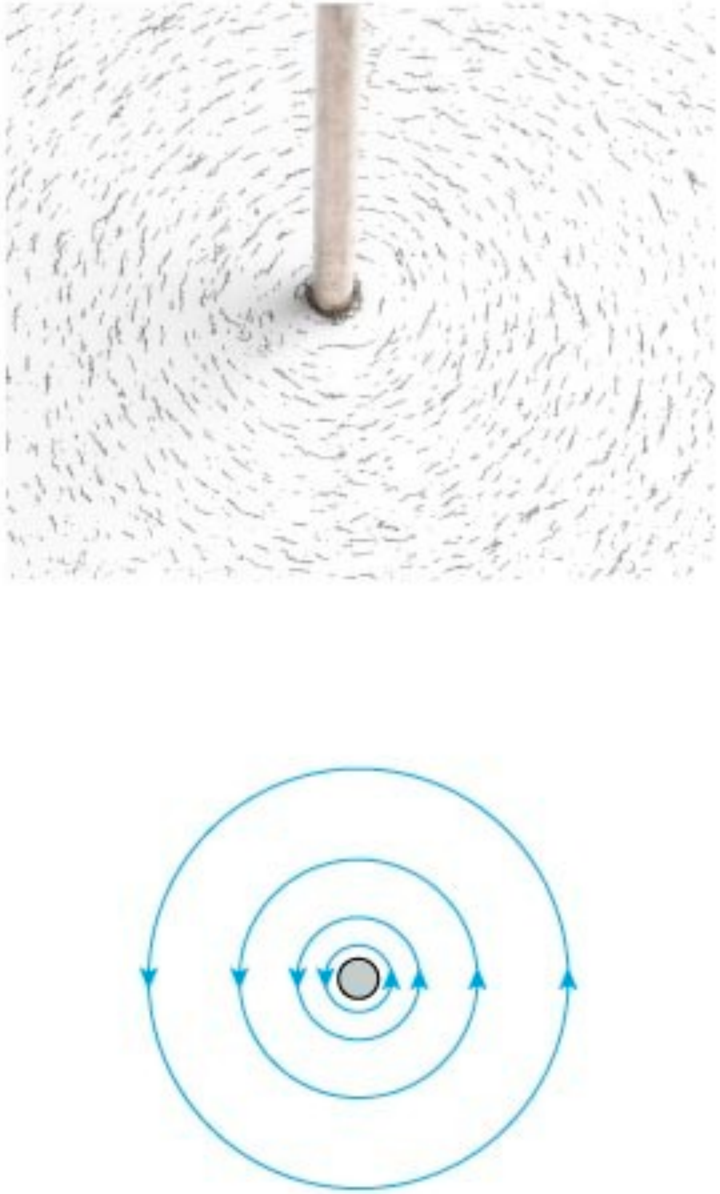
(b) Magnetic field of a straight current-carrying wire



Notice that the field of the loop and, especially, that of the coil look like the field of a bar magnet (Figure 20.6).

(c) Magnetic fields of a current-carrying loop and a current-carrying coil (solenoid)

magnetic fields



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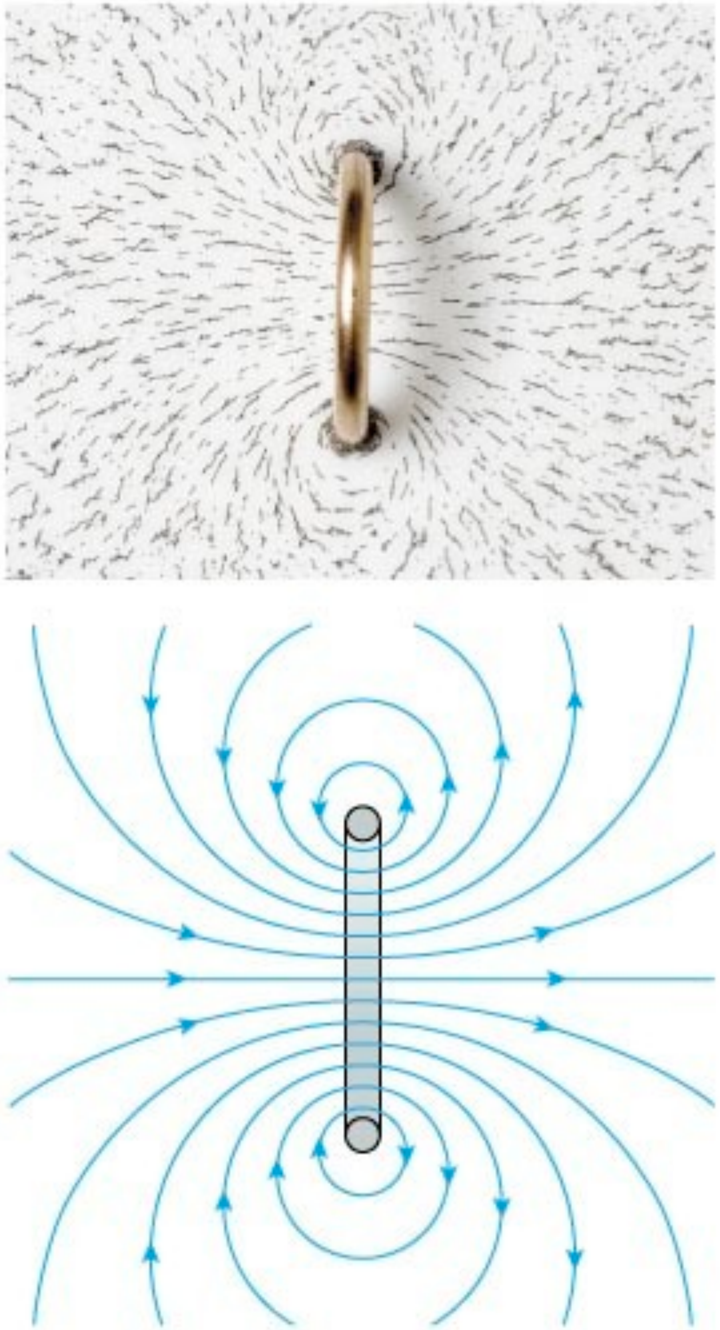

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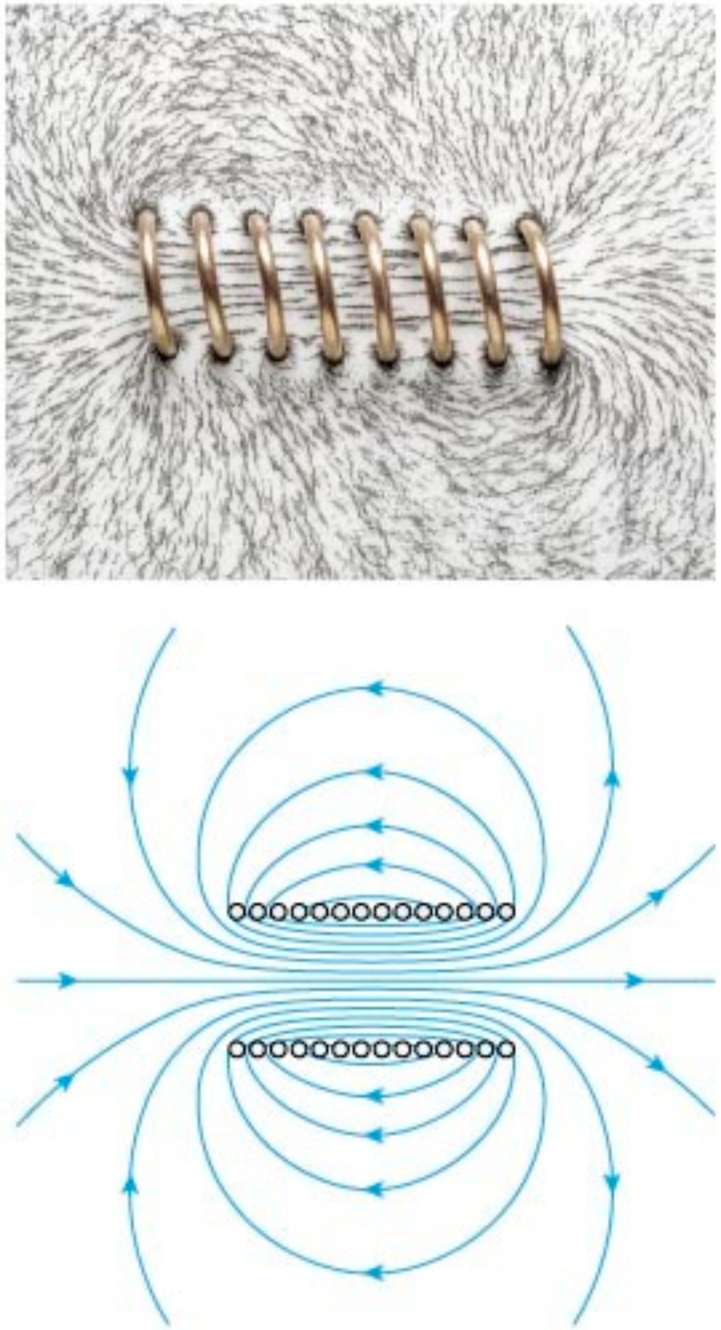

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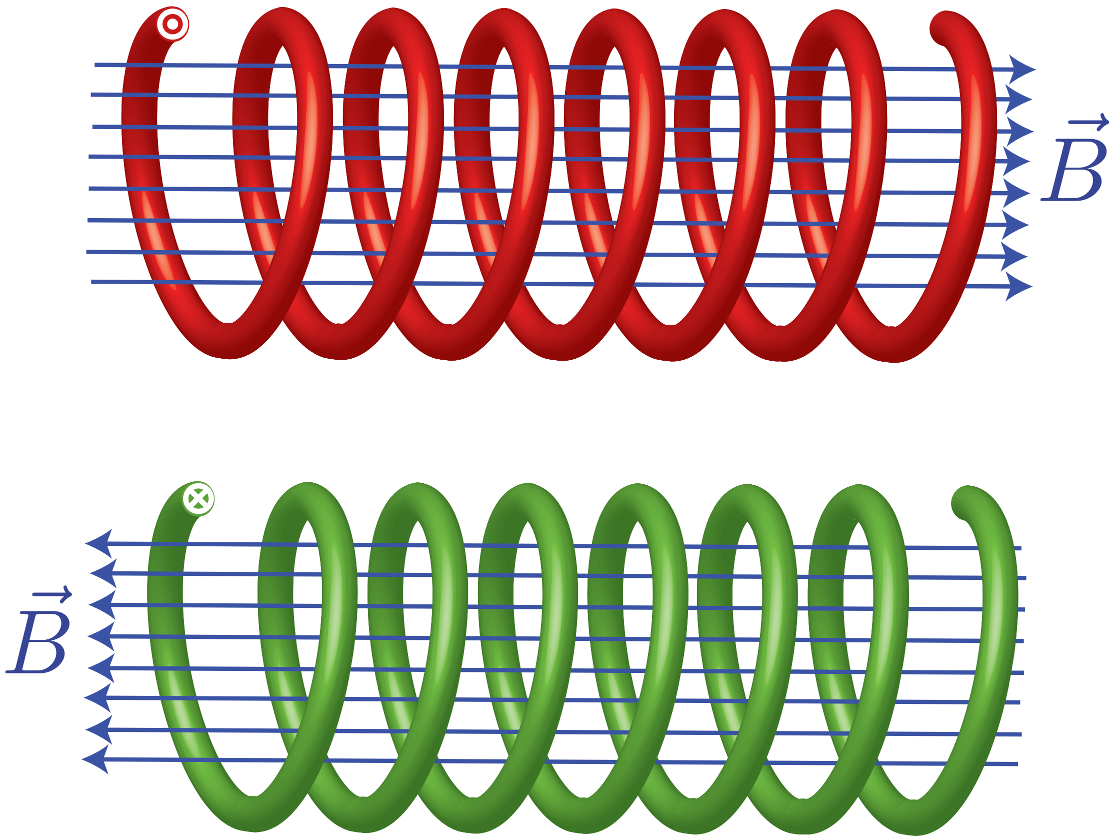
magnetic field superposition

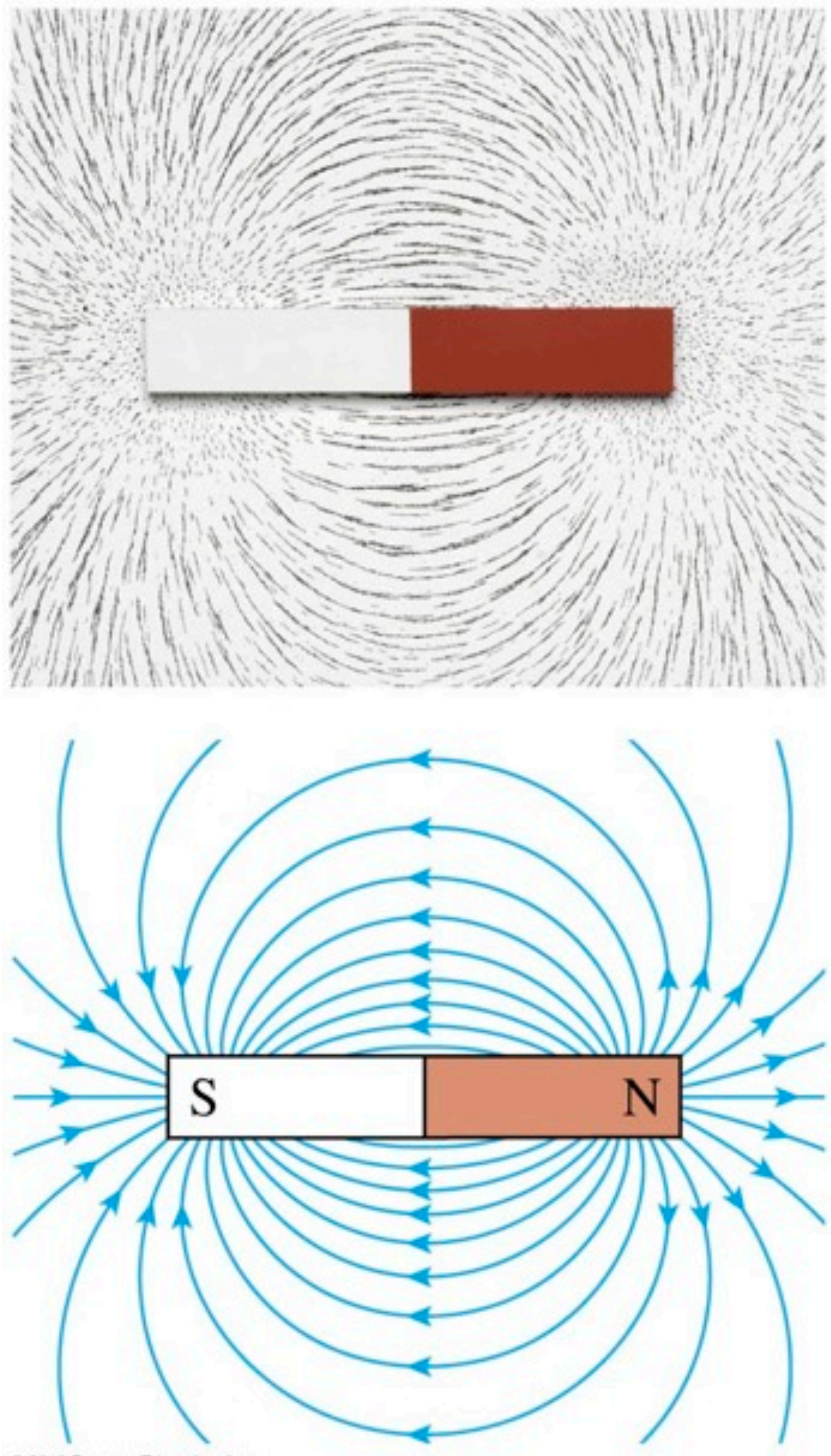
➜ just as the total electric field at any point is the vector sum of the fields from all charges nearby,

➜ so the total magnetic field is the vector sum of the fields from all magnetic sources nearby.

➜ Consider two solenoids producing nearly uniform fields:



magnetic field superposition



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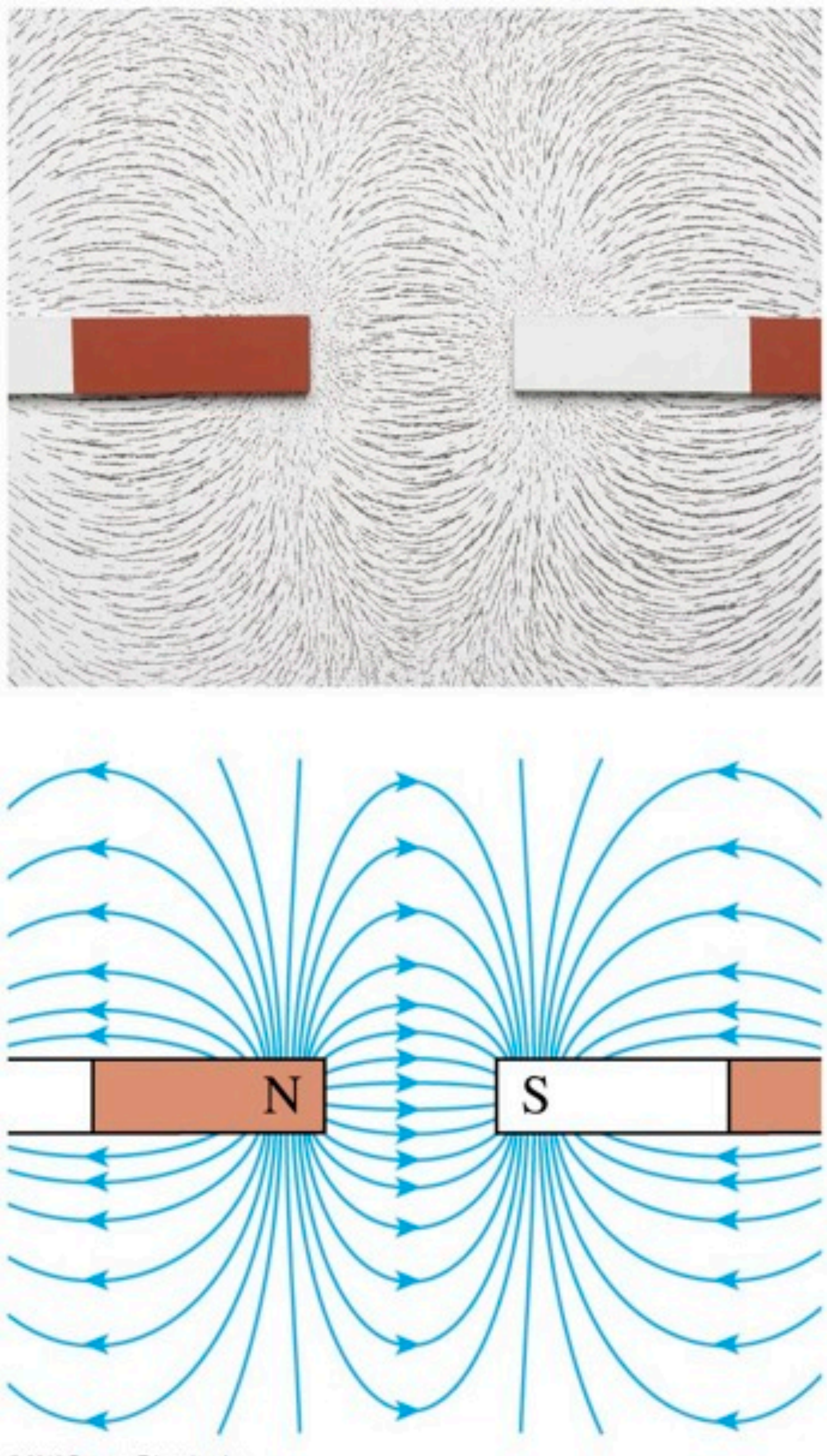

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magnetic forces

➜ magnetic fields produce a force on charged particles that are moving through them

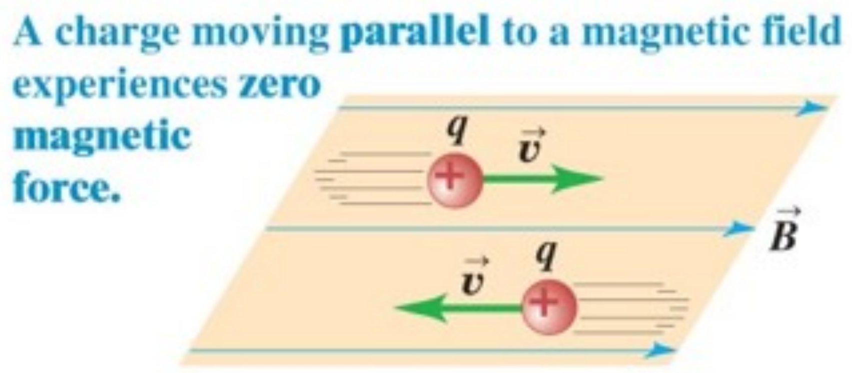
➜ experiments show that the strength of the force is proportional to

- the charge
- the speed of the particle
- the magnitude of the magnetic field

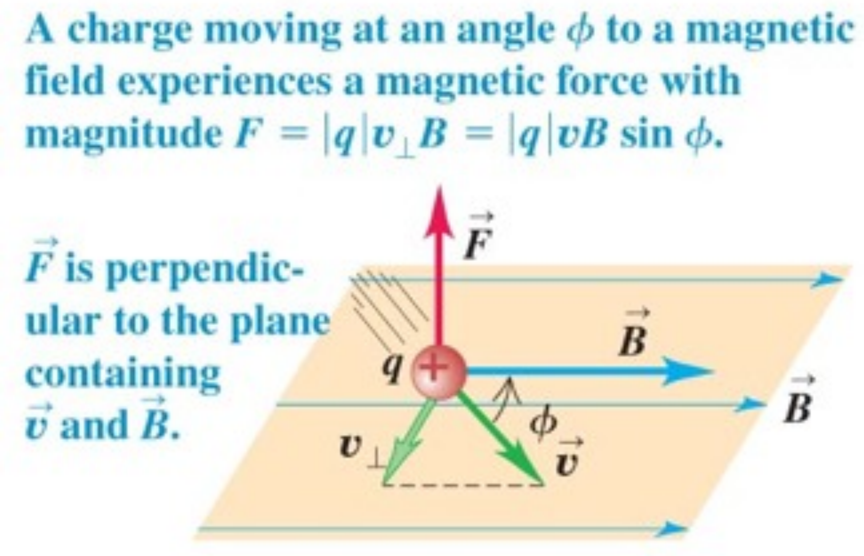
$$F = |q|vB\sin\phi$$

➜ experiments also show the direction the force acts in

- perpendicular to the velocity
- perpendicular to the magnetic field

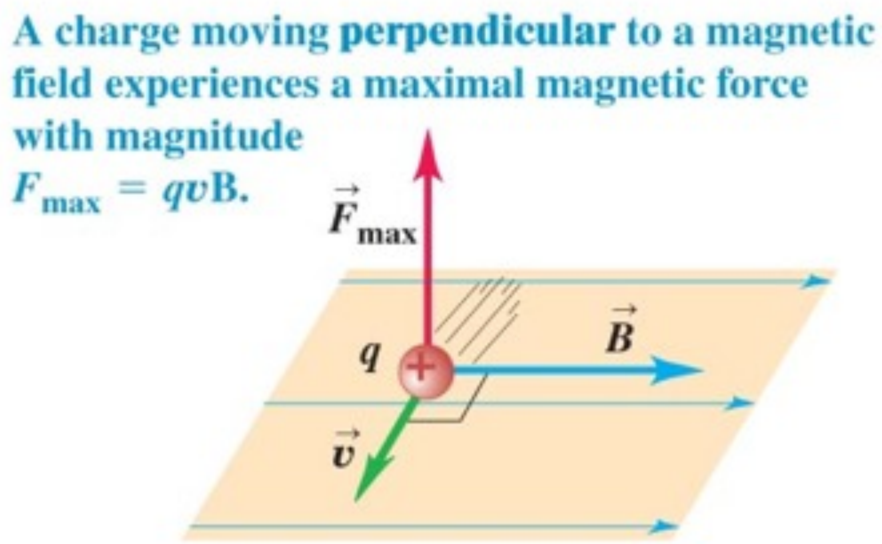


A charge moving **parallel** to a magnetic field experiences **zero magnetic force.**



A charge moving at an angle ϕ to a magnetic field experiences a magnetic force with magnitude $F = |q|v_{\perp}B = |q|vB\sin\phi$.

$\vec{F}$ is perpendicular to the plane containing $\vec{v}$ and $\vec{B}$.



A charge moving **perpendicular** to a magnetic field experiences a maximal magnetic force with magnitude $F_{\max} = qvB$.

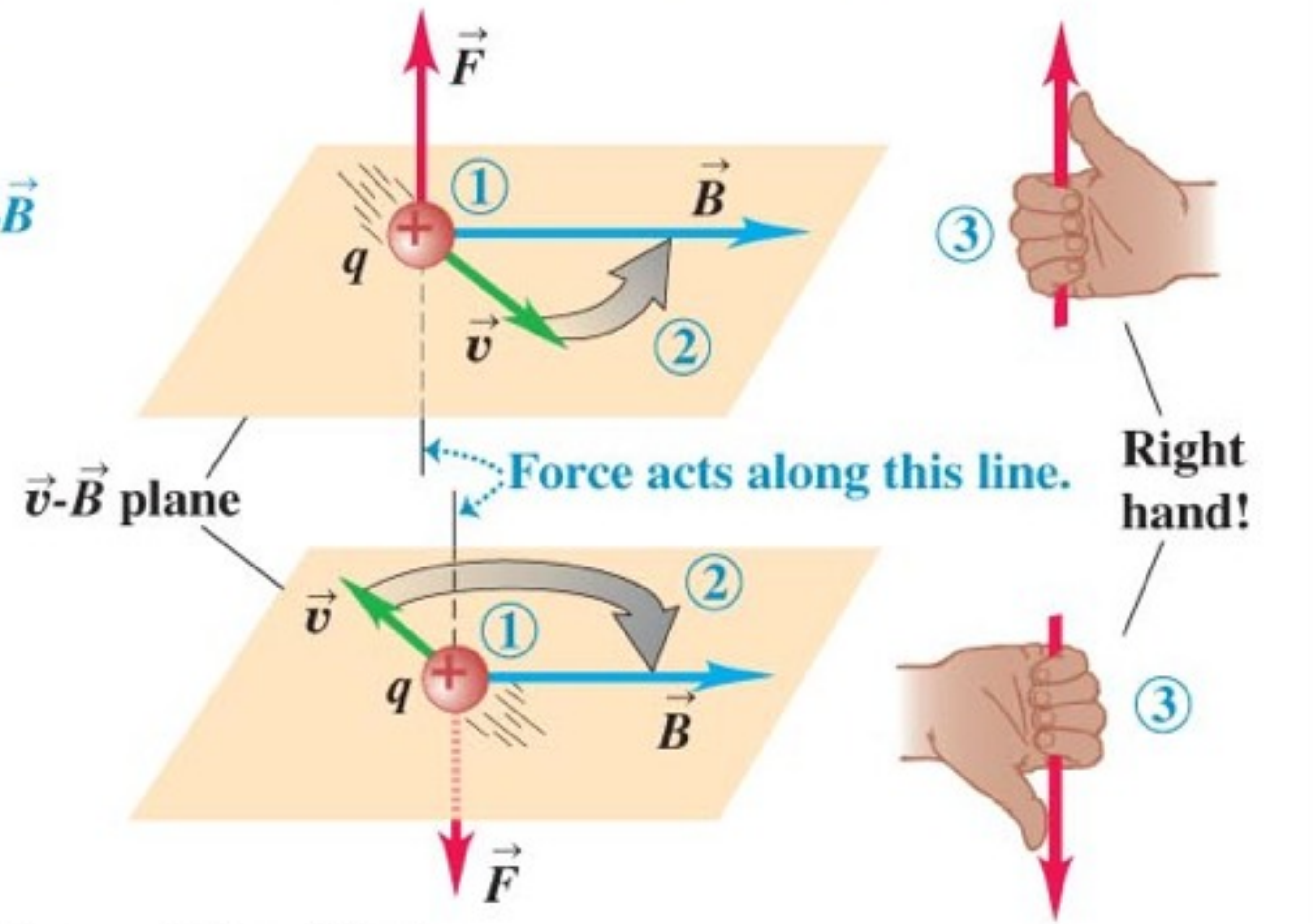
magnetic forces - the right-hand rule

Right-hand rule for the direction of magnetic force on a **positive** charge moving in a magnetic field:

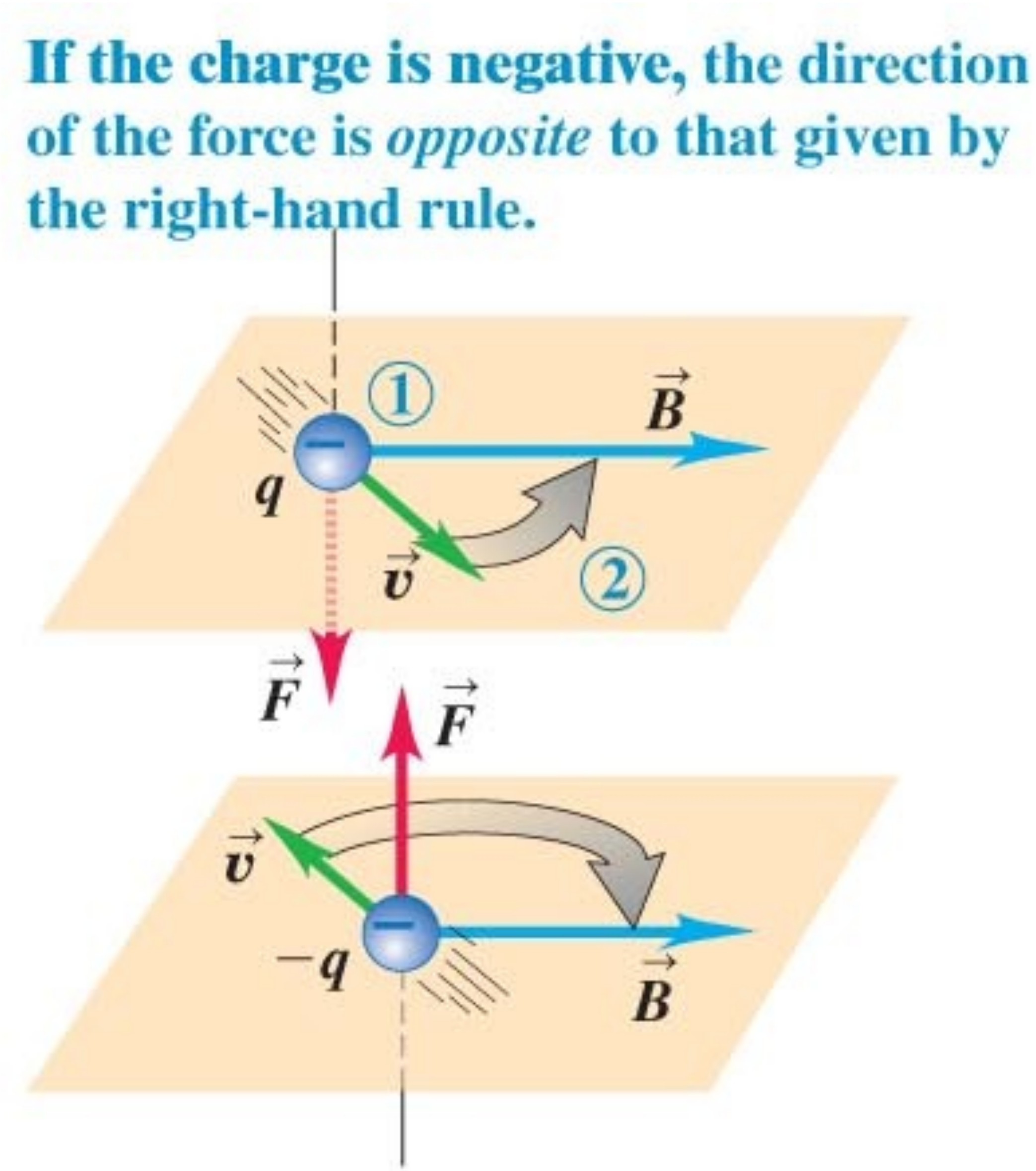
① Place the $\vec{v}$ and $\vec{B}$ vectors tail to tail.

② Imagine turning $\vec{v}$ toward $\vec{B}$ in the $\vec{v}$-$\vec{B}$ plane (through the smaller angle).

③ The force acts along a line perpendicular to the $\vec{v}$-$\vec{B}$ plane. Curl the fingers of your *right hand* around this line in the same direction you rotated $\vec{v}$. Your thumb now points in the direction the force acts.



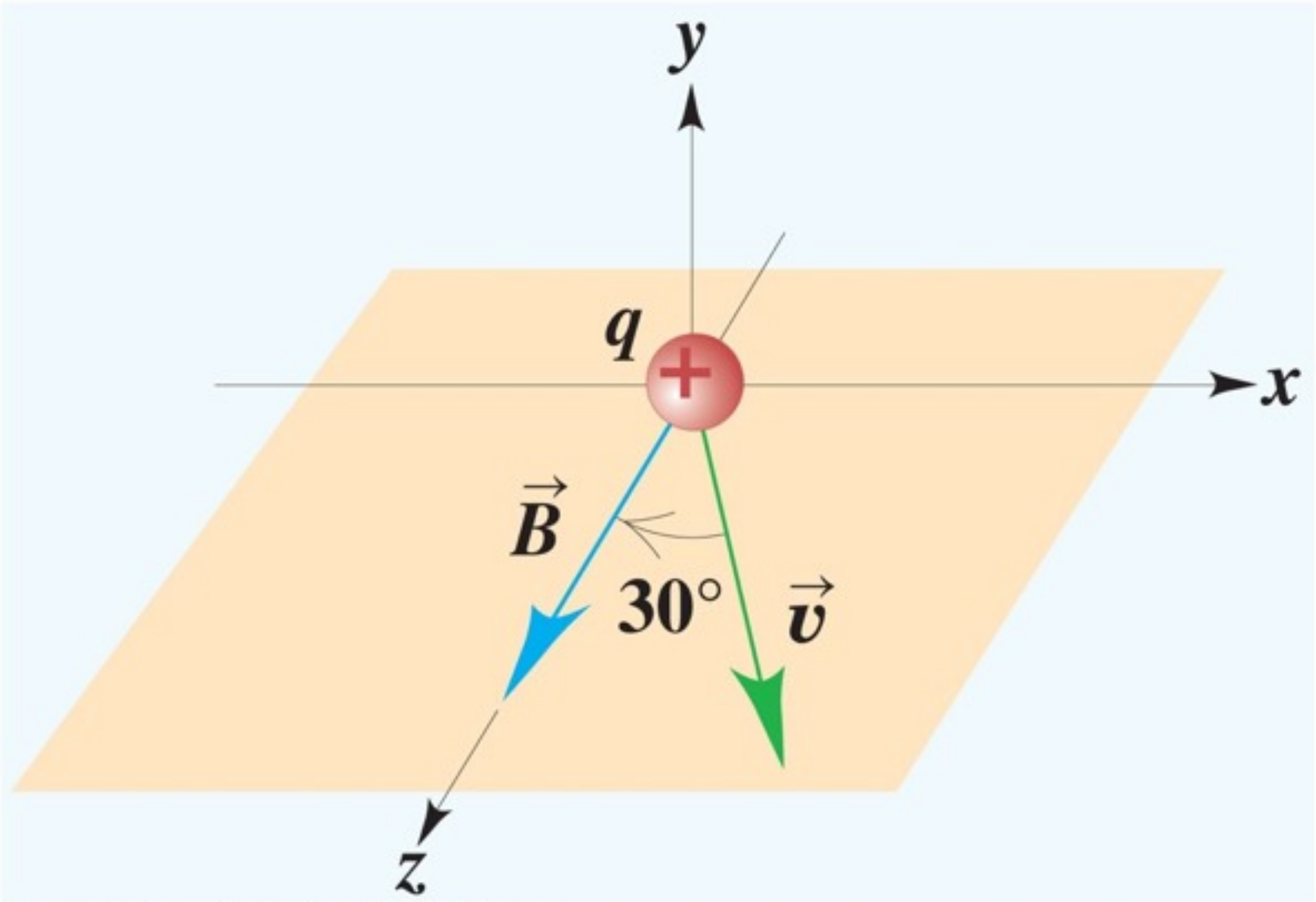
magnetic forces - the right-hand rule



If the charge is negative, the direction of the force is *opposite* to that given by the right-hand rule.

proton beam through a magnetic field

A beam of protons moves through a uniform magnetic field with magnitude 2.0 T, directed along the positive *z*-axis. The protons have a velocity of magnitude 3.0x10^5 m/s in the *xz*-plane at an angle of 30^o to the positive *z*-axis. Find the magnitude and direction of force on the proton.



motion of charged particles in a magnetic field

consider a positive charge moving in a plane perpendicular to a uniform magnetic field

force is always perpendicular to the velocity and is of constant magnitude

$$F = qvB$$

$$F = ma$$

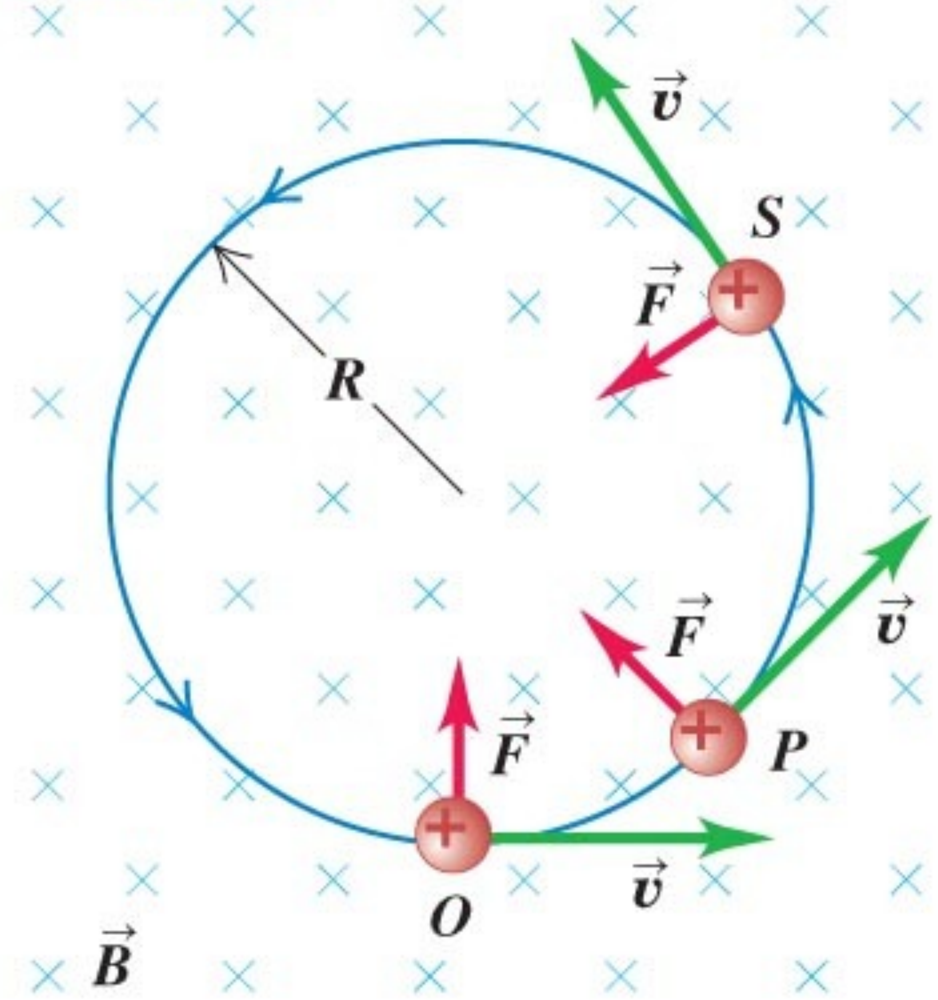
constant acceleration perpendicular to the velocity ⇒ circular motion

$$a_{\text{rad}} = \frac{v^2}{R}$$

$$m\frac{v^2}{R} = qvB$$

radius of the circle determined by

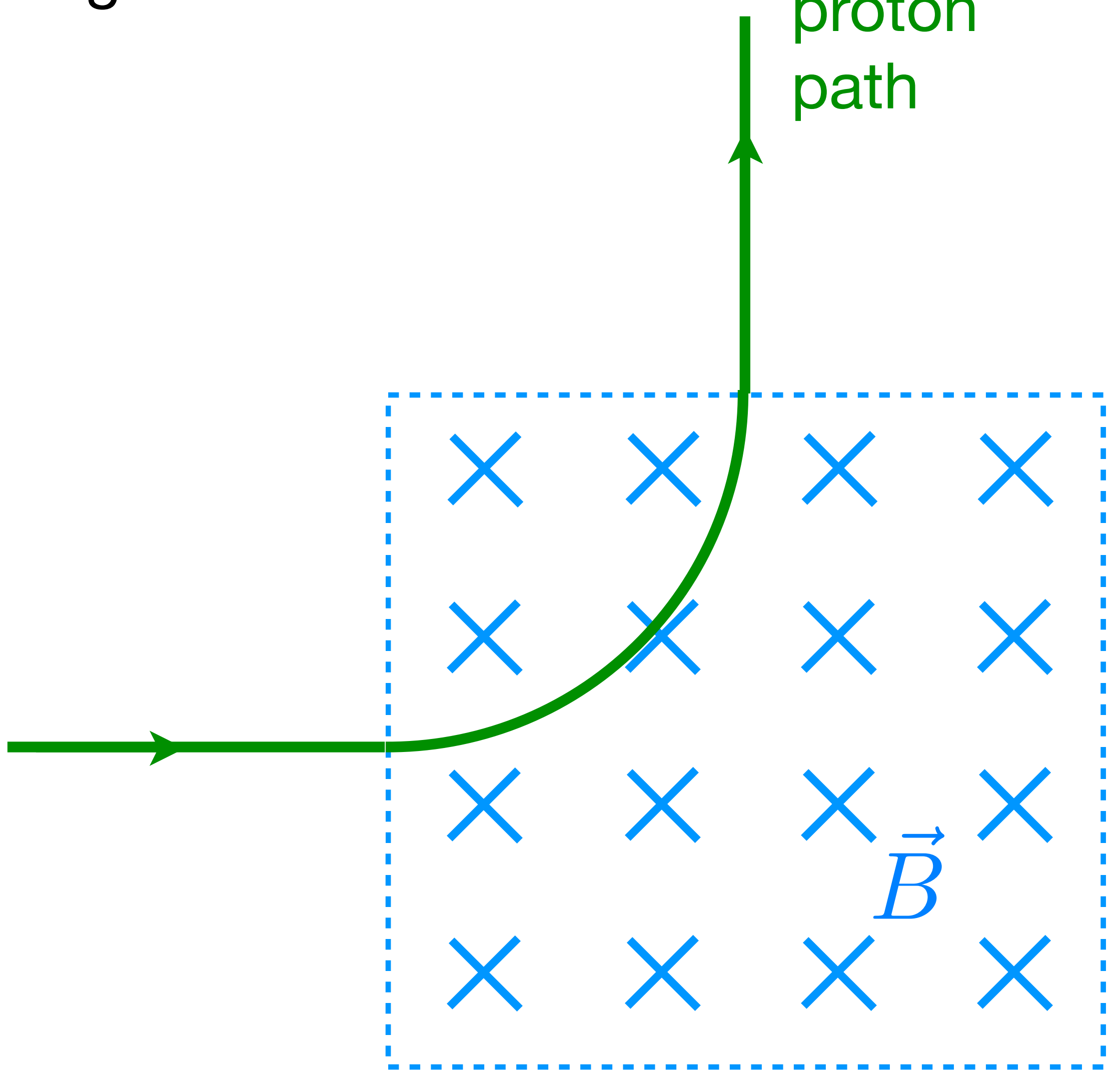
$$R = \frac{mv}{qB}$$



A charge moving at right angles to a uniform $\vec{B}$ field moves in a circle at constant speed because $\vec{F}$ and $\vec{v}$ are always perpendicular to each other.

protons in a magnetic field

A beam of protons traveling at 1.20 km/s enters a uniform magnetic field traveling perpendicular to the field. The beam exits the magnetic field in a direction perpendicular to its original direction. The beam travels a distance of 1.18 cm in the field. What is the magnitude of the magnetic field ?



$$m_p = 1.67 \times 10^{-27}\,\mathrm{kg}$$

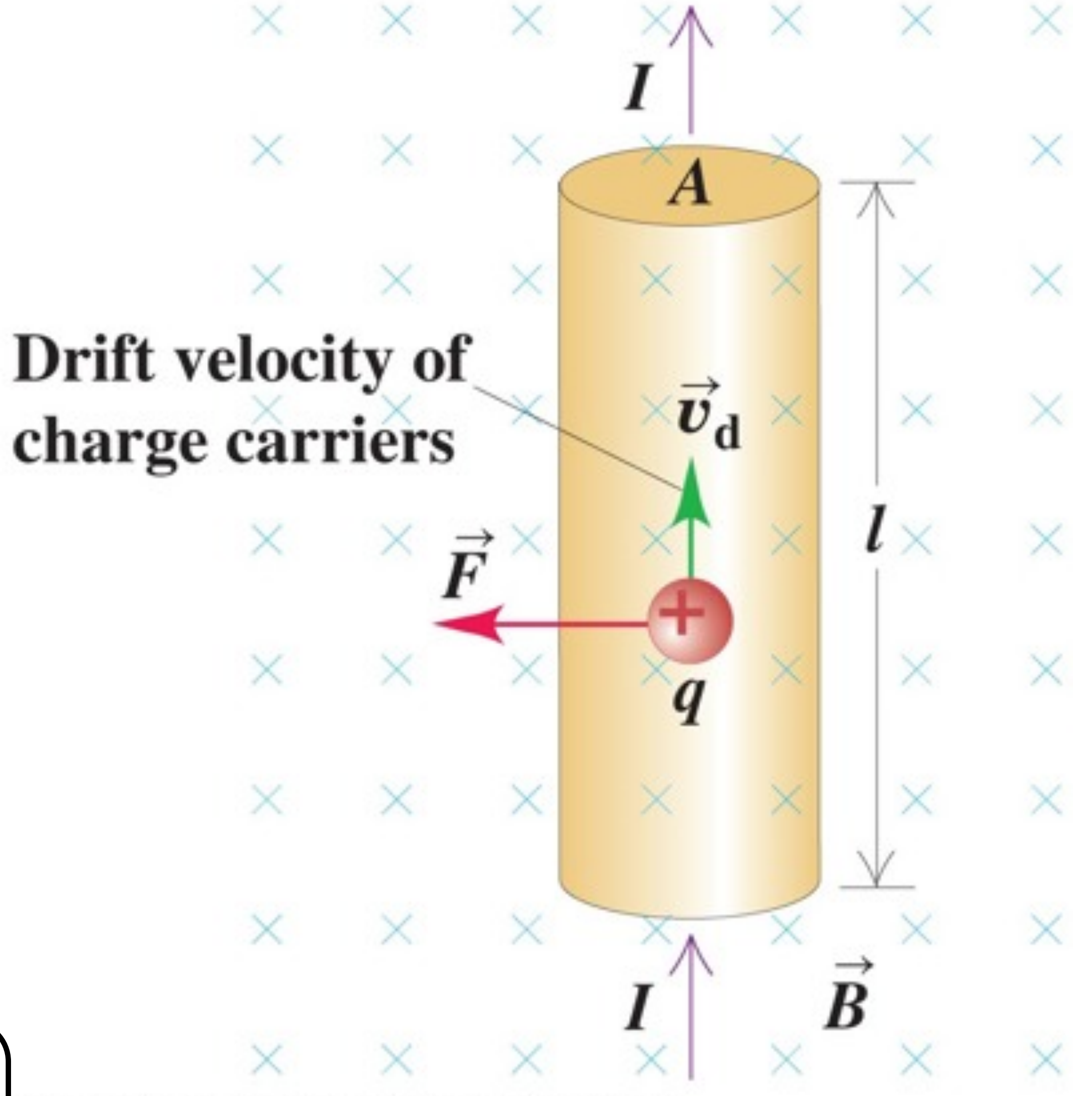
$$e = 1.60 \times 10^{-19}\,\mathrm{C}$$

force on a current carrying conductor

➜ what happens if we put a wire carrying current into a magnetic field?

➜ it contains moving charges, so we'd guess it feels a force
we can work out a formula for the force:

force on each charge $f = qv_d B$



in time Δt, a charge $Q = I\,\Delta t$ flows in

in time Δt, a charge moves $\ell = v_d \Delta t$

so the total charge in the rod is

$$Q = \frac{I\ell}{v_d}$$

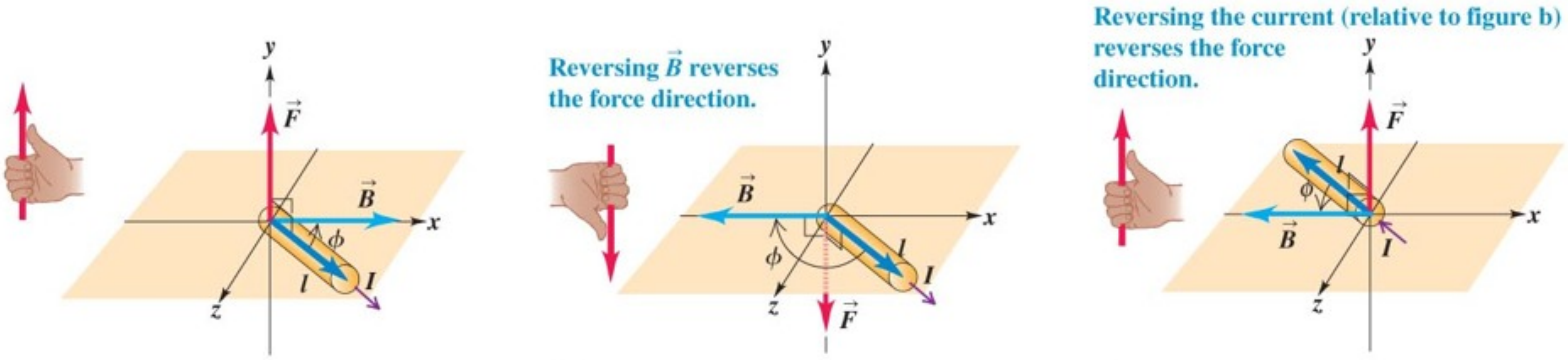
the total force on the rod is

$$F = Q v_d B$$

$$\boxed{F = I\ell B}$$

force on a current carrying conductor

- ➜ if the magnetic field is not perpendicular to the wire, then the formula is modified
- ➜ only the perpendicular component of the ***B***-field contributes to the force



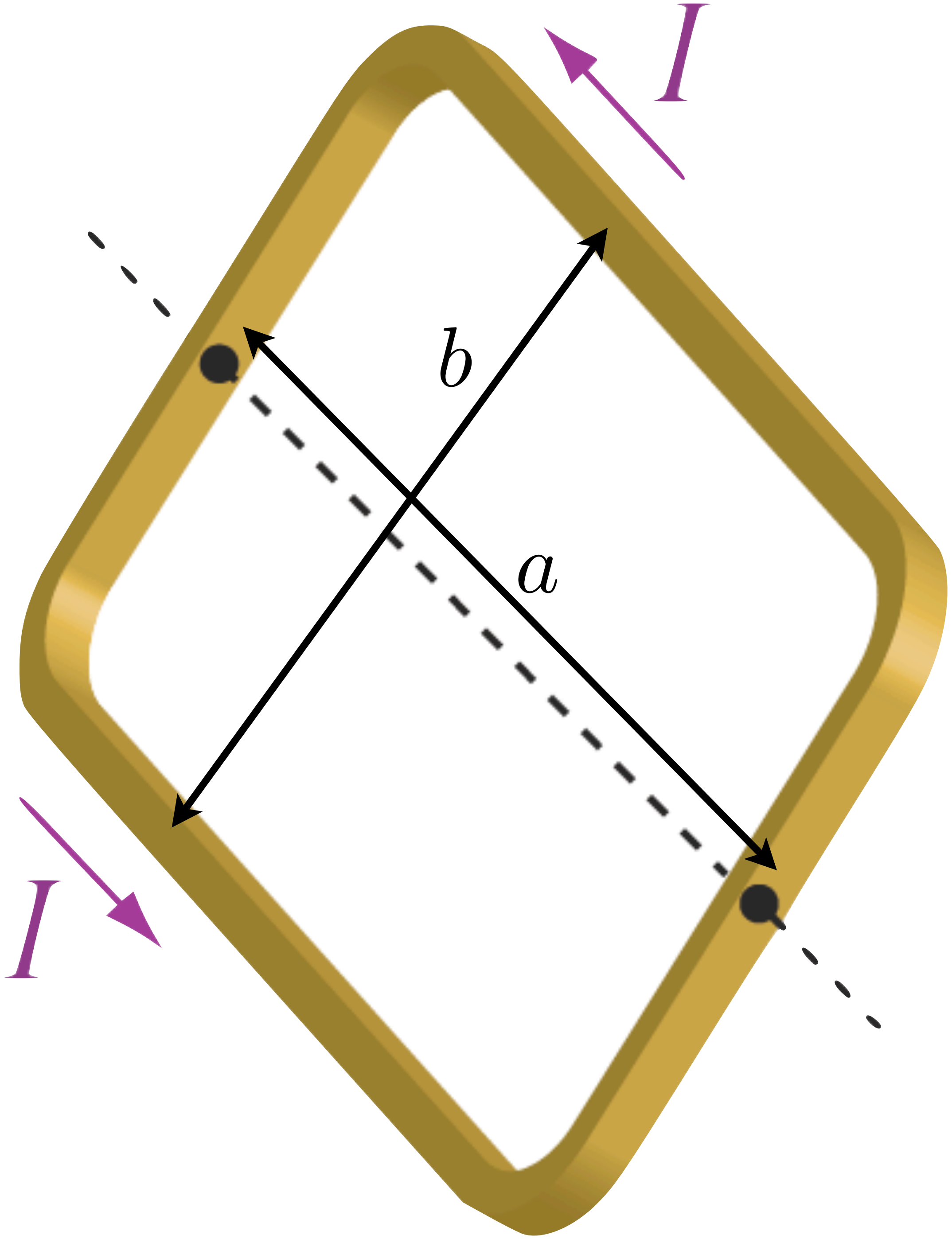
Reversing $\vec{B}$ reverses the force direction.

Reversing the current (relative to figure b) reverses the force direction.

$$\boxed{F = I\ell B\sin\phi}$$

force and torque on a current loop

➜ what happens if we put a closed current loop into a magnetic field?
e.g. consider a rectangular current carrying loop of wire in a uniform field



force and torque on a current loop

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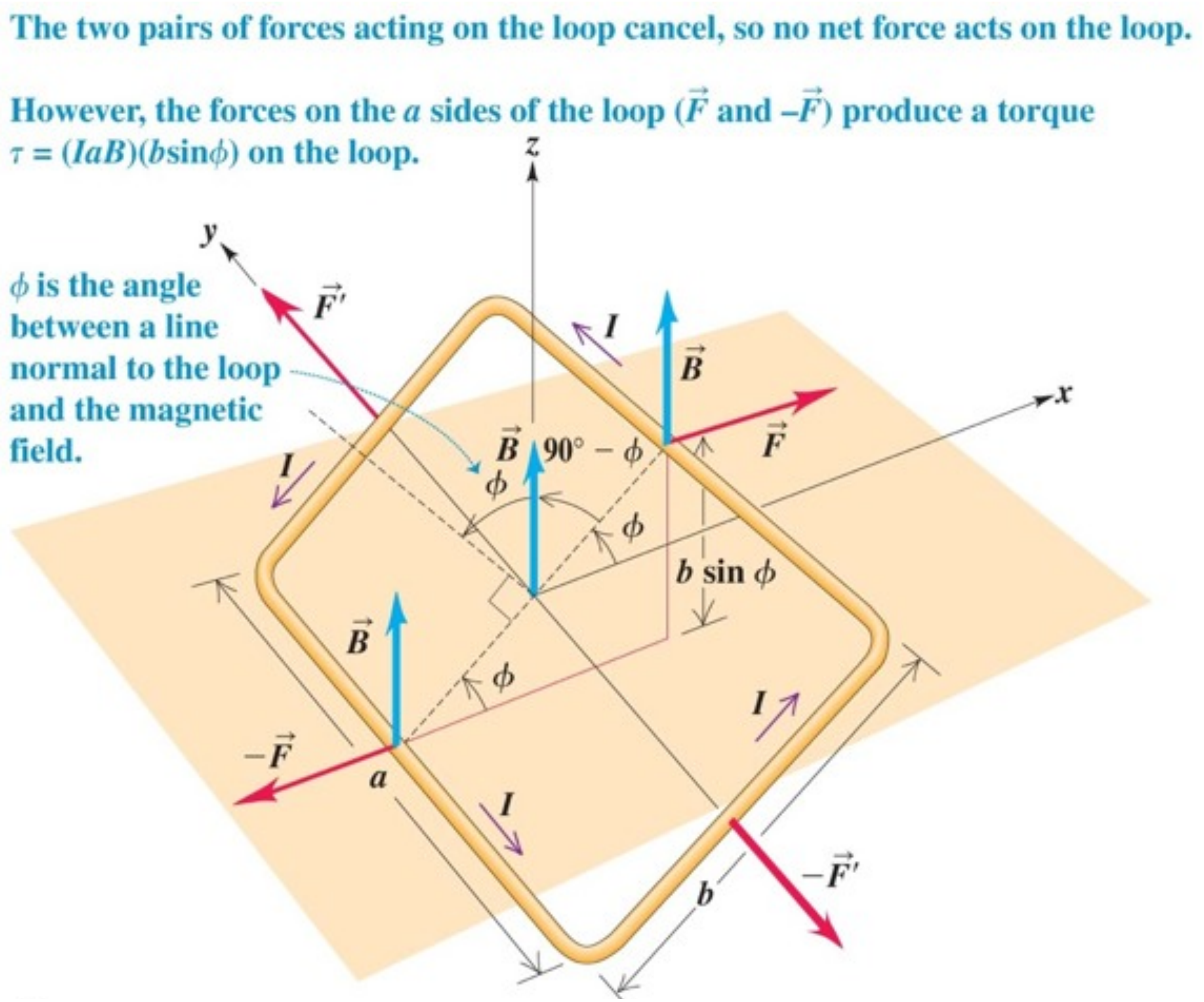
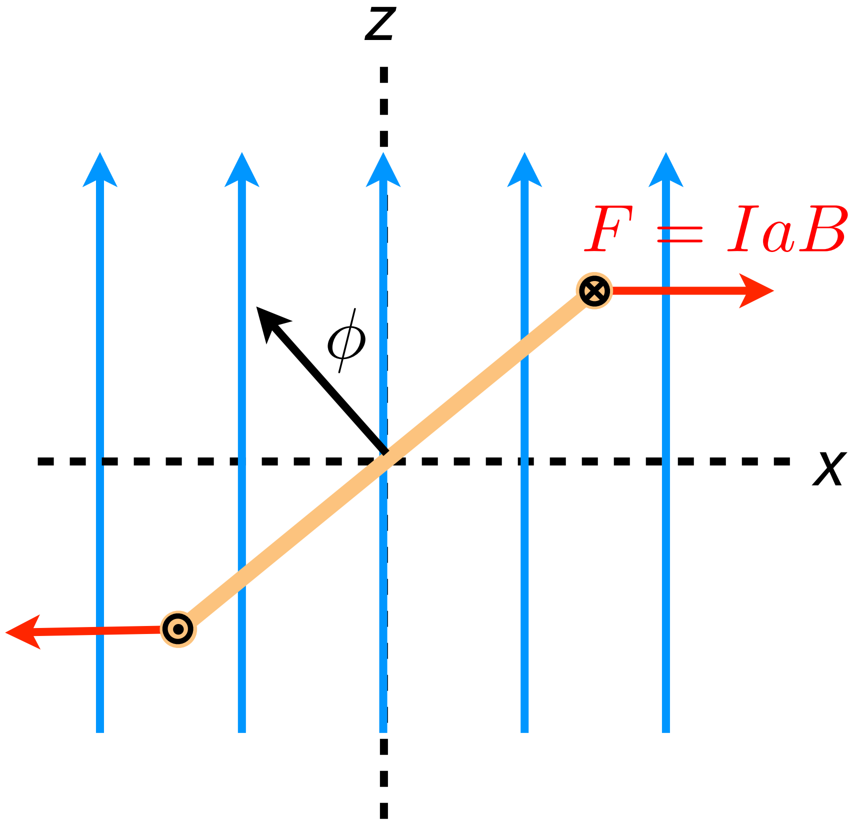


The two pairs of forces acting on the loop cancel, so no net force acts on the loop.

However, the forces on the *a* sides of the loop ($\vec{F}$ and $-\vec{F}$) produce a torque $\tau = (IaB)(b\sin\phi)$ on the loop.

ϕ is the angle between a line normal to the loop and the magnetic field.



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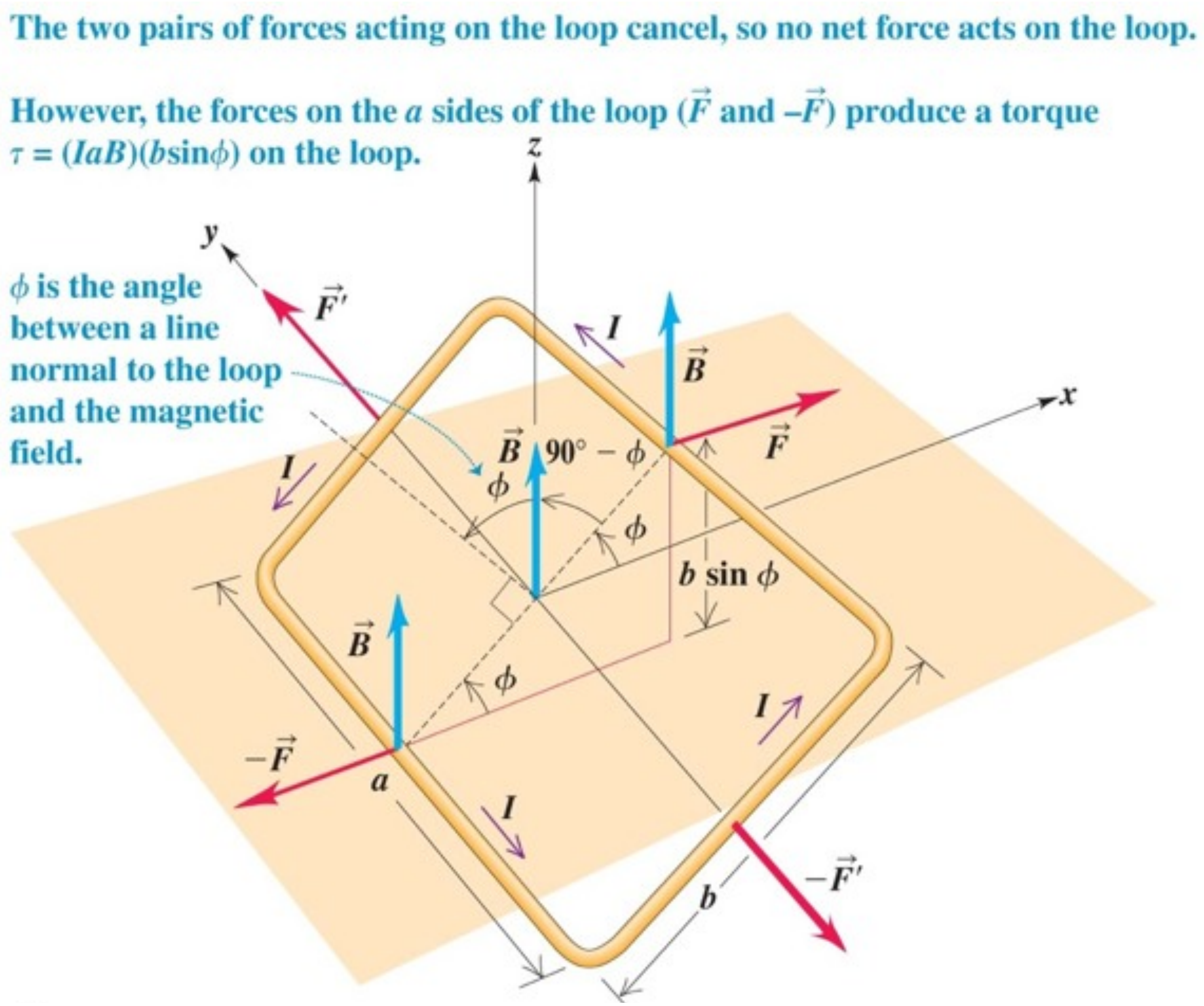

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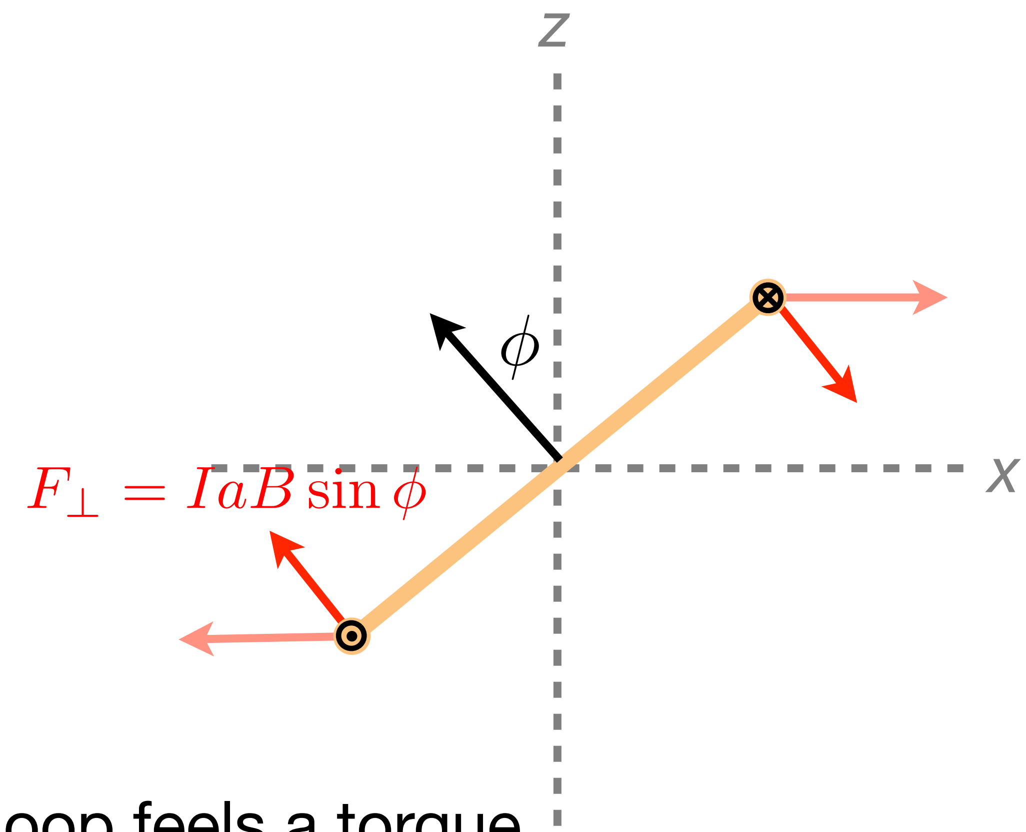


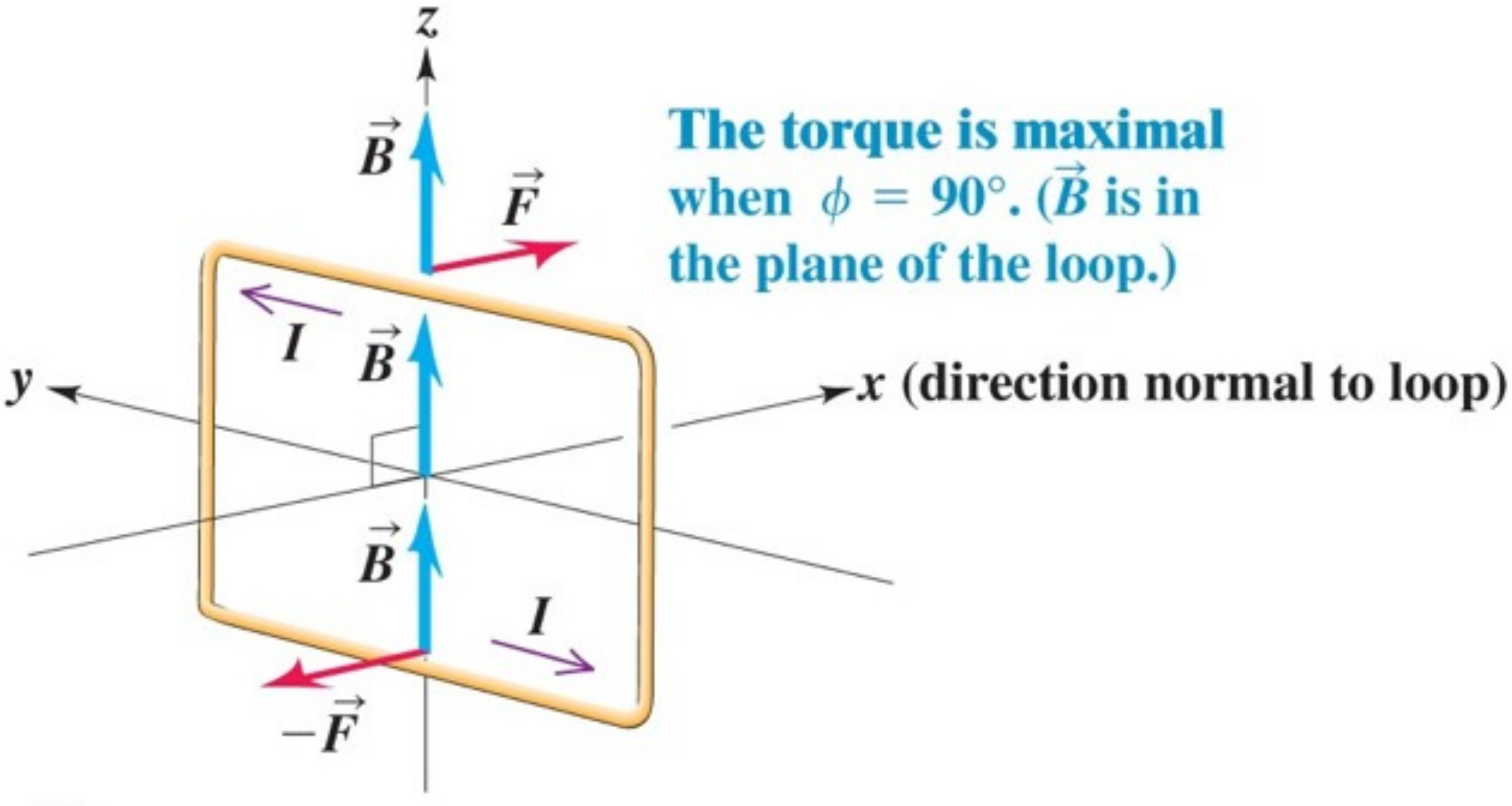
loop feels a torque

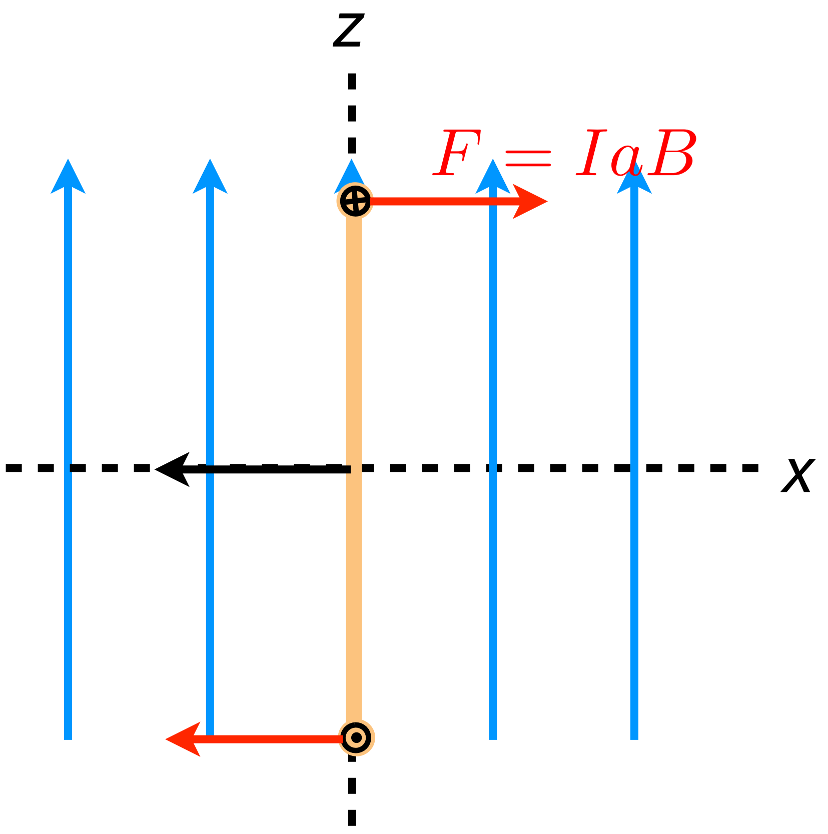
$$\tau = IaBb\sin\phi$$

$$\boxed{\tau = IAB\sin\phi}$$

force and torque on a current loop

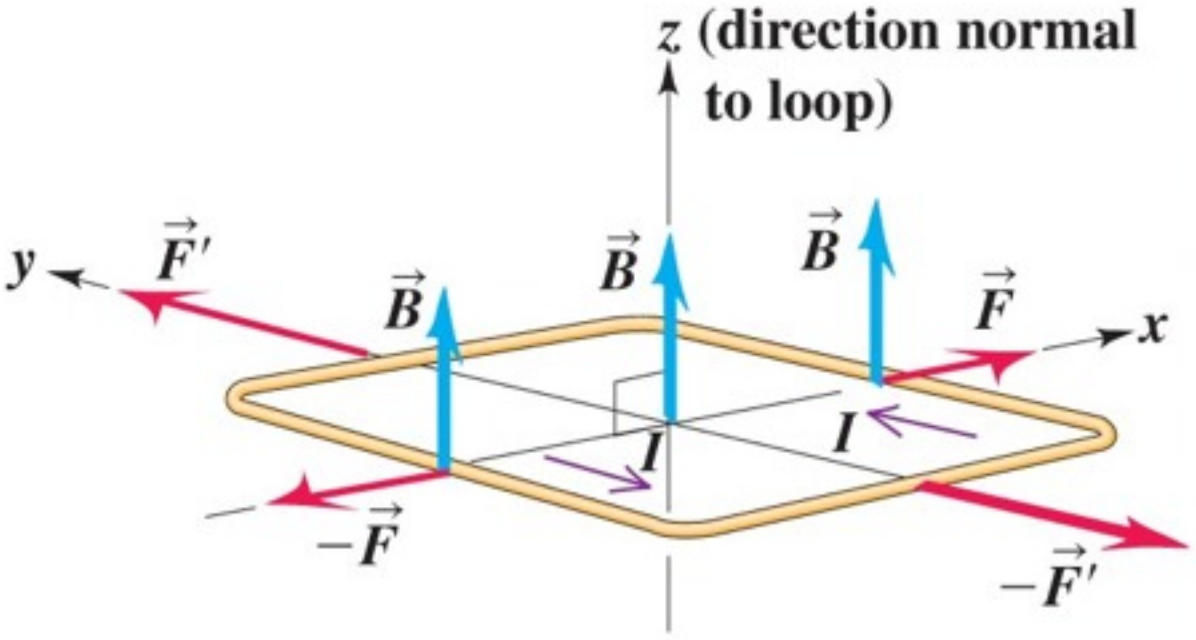
➜ what happens if we put a closed current loop into a magnetic field?
e.g. consider a rectangular current carrying loop of wire in a uniform field





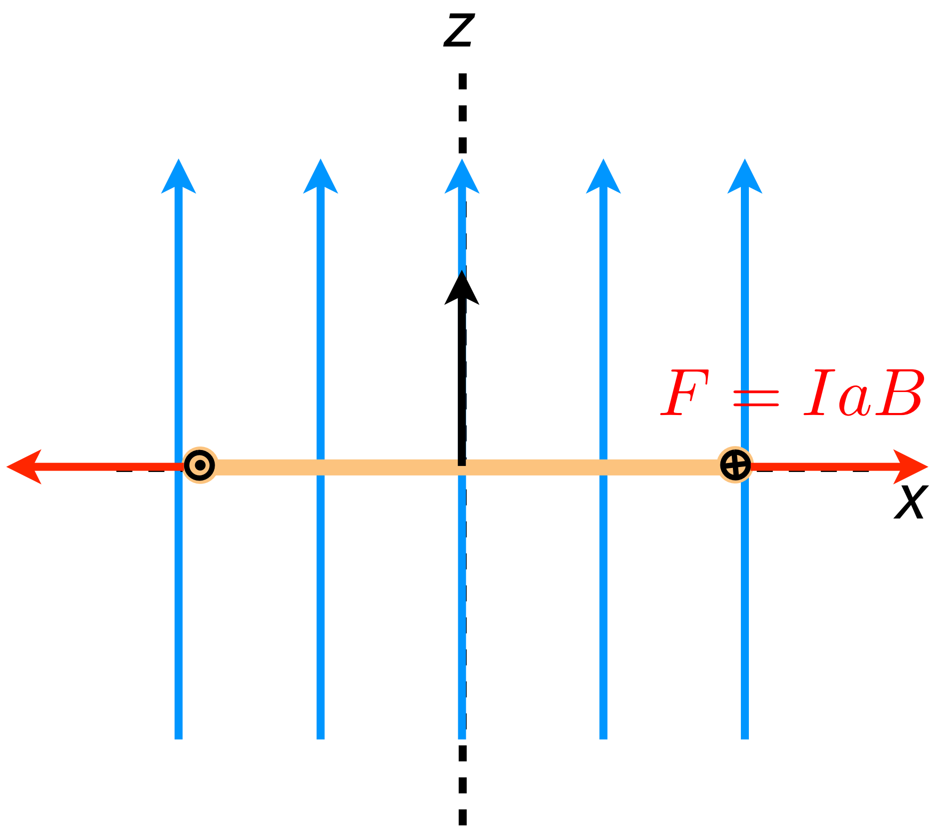
force and torque on a current loop

➜ what happens if we put a closed current loop into a magnetic field?
e.g. consider a rectangular current carrying loop of wire in a uniform field



The torque is zero when $\phi = 0$ (as shown here) or $\phi = 180°$. In both cases, $\vec{B}$ is perpendicular to the plane of the loop.

The loop is in stable equilibrium when $\phi = 0$; it is in unstable equilibrium when $\phi = 180°$.



force and torque on a current loop

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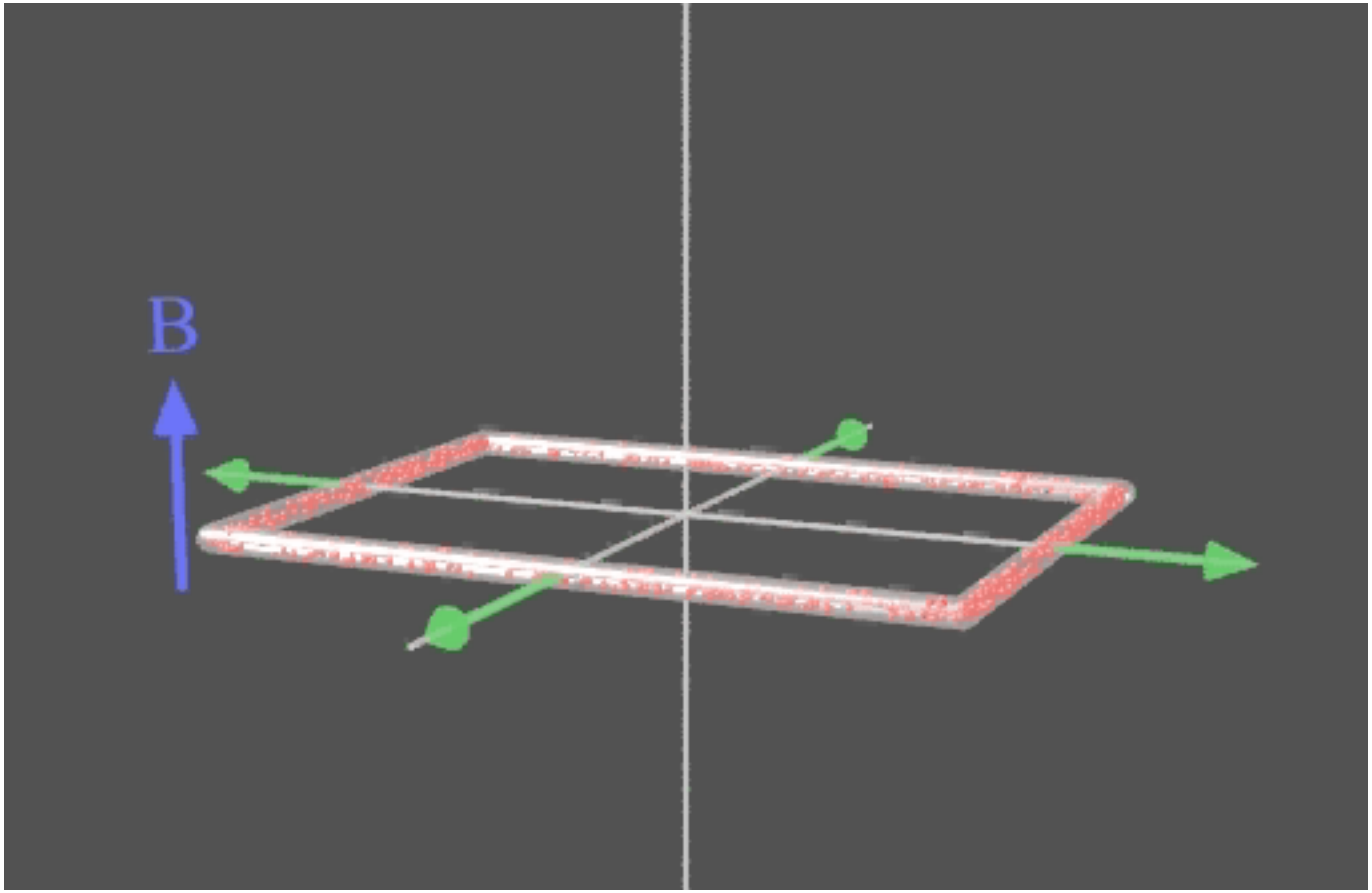
e.g. consider a rectangular current carrying loop of wire in a uniform field

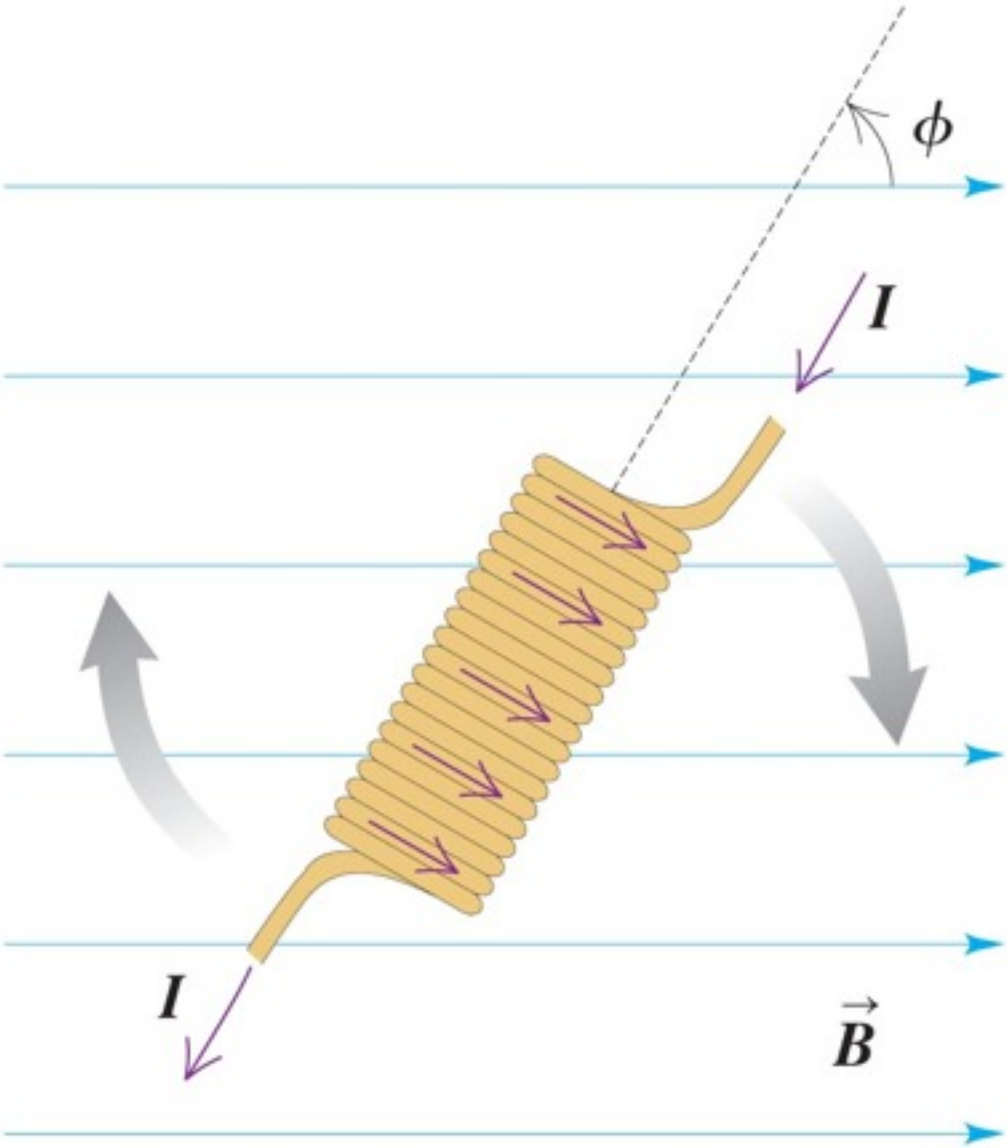


N.B. the animation isn't showing the actual motion
caused by the torque, just the variation of force with angle

solenoid in a uniform field

➜ the torque on the solenoid tends to line it up along the field

➜ same thing that a bar magnet does



The torque tends to make the solenoid rotate clockwise in the plane of the page.

magnetic field from a long straight wire

We now know what happens to moving charges and current carrying wires in magnetic fields

➜ but how do we generate a magnetic field?

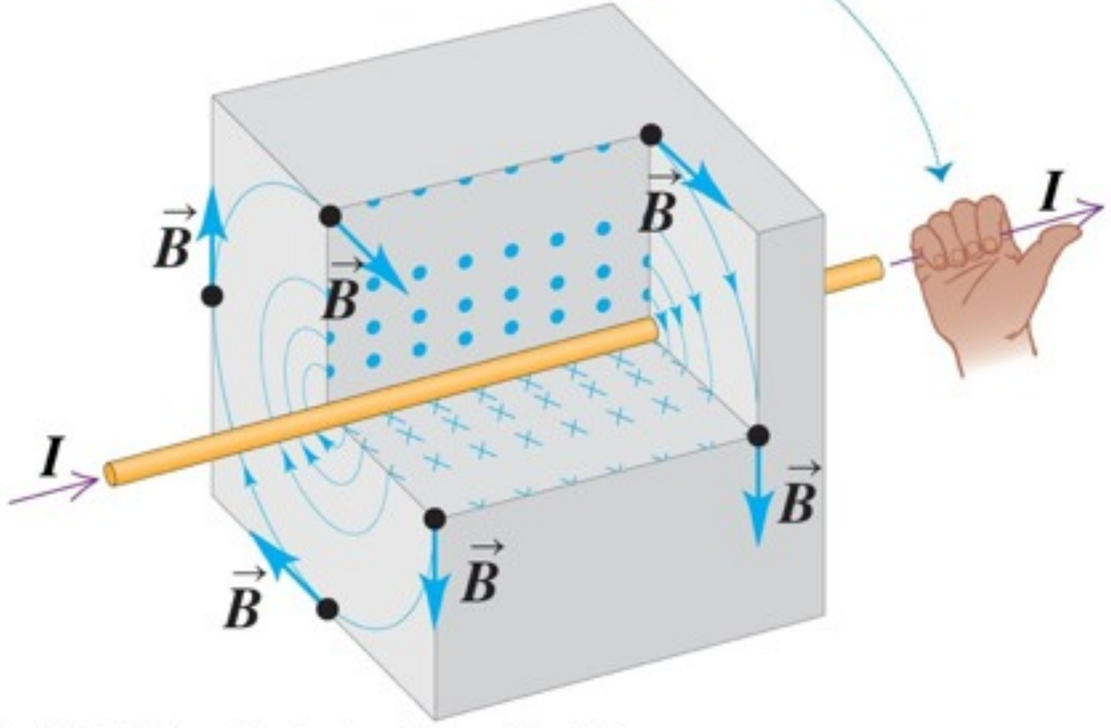
➜ turns out we can generate magnetic fields using electrical currents

➜ simplest example is a long, straight current-carrying wire

magnitude of field a perpendicular distance *r* from a wire carrying current *I*

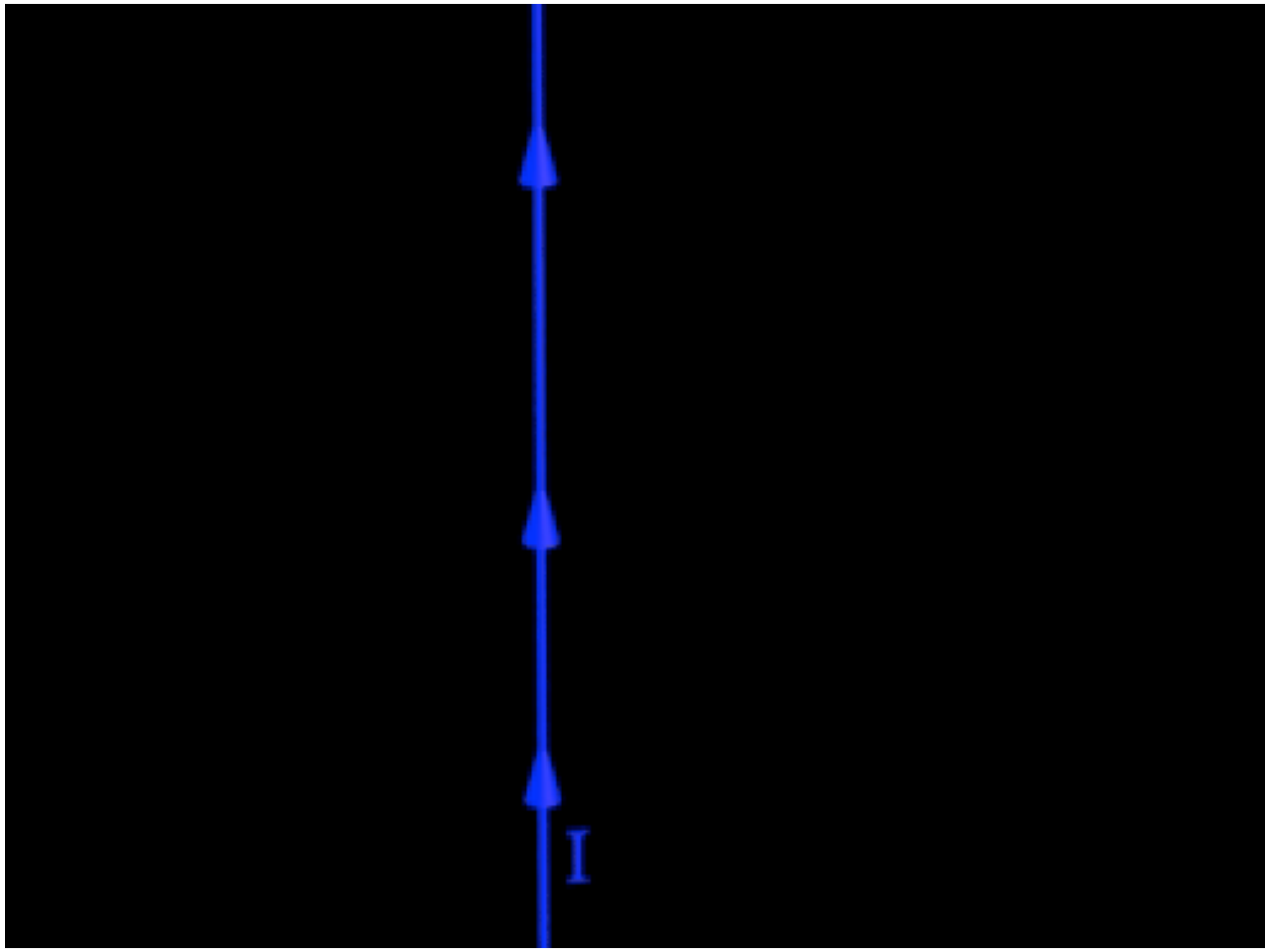
$$B = \frac{\mu_0 I}{2\pi r}$$

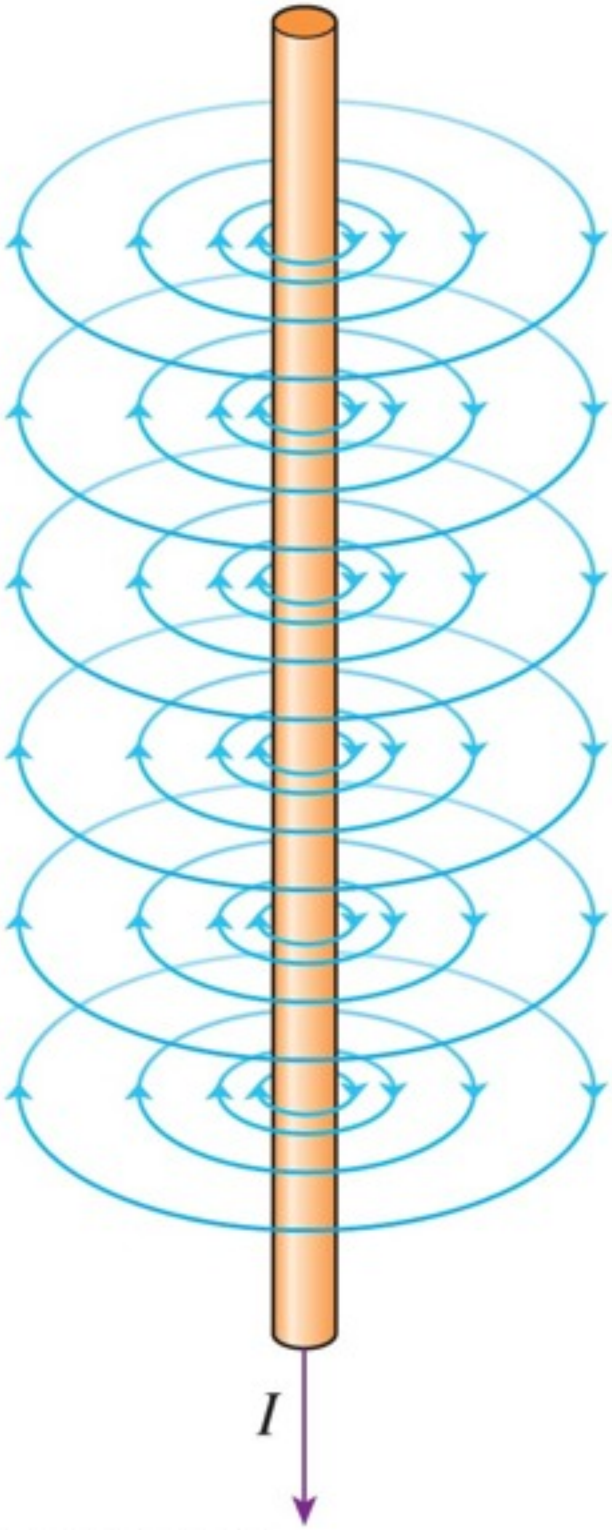
permeability of vacuum
$\mu_0 = 4\pi\times10^{-7}$ Tm/A
(*magnetic analogue of* ε_0)



Right-hand rule for the magnetic field around a current-carrying wire: Point the thumb of your right hand in the direction of the current. Your fingers now curl around the wire in the direction of the magnetic field lines.

magnetic field from a long straight wire



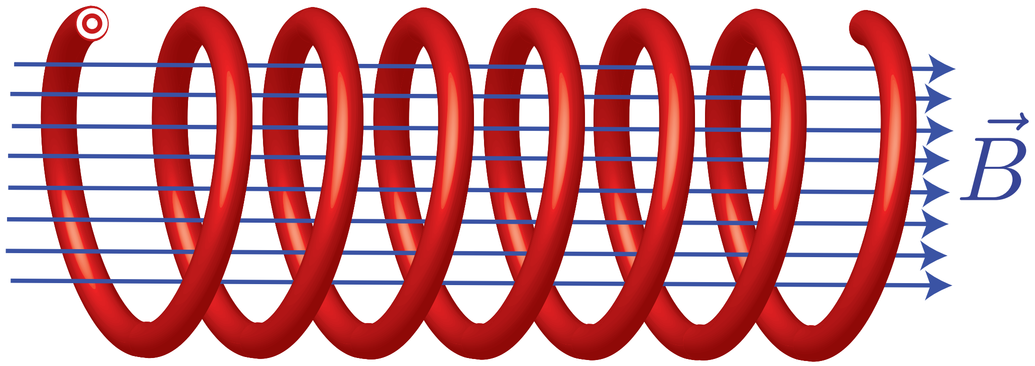


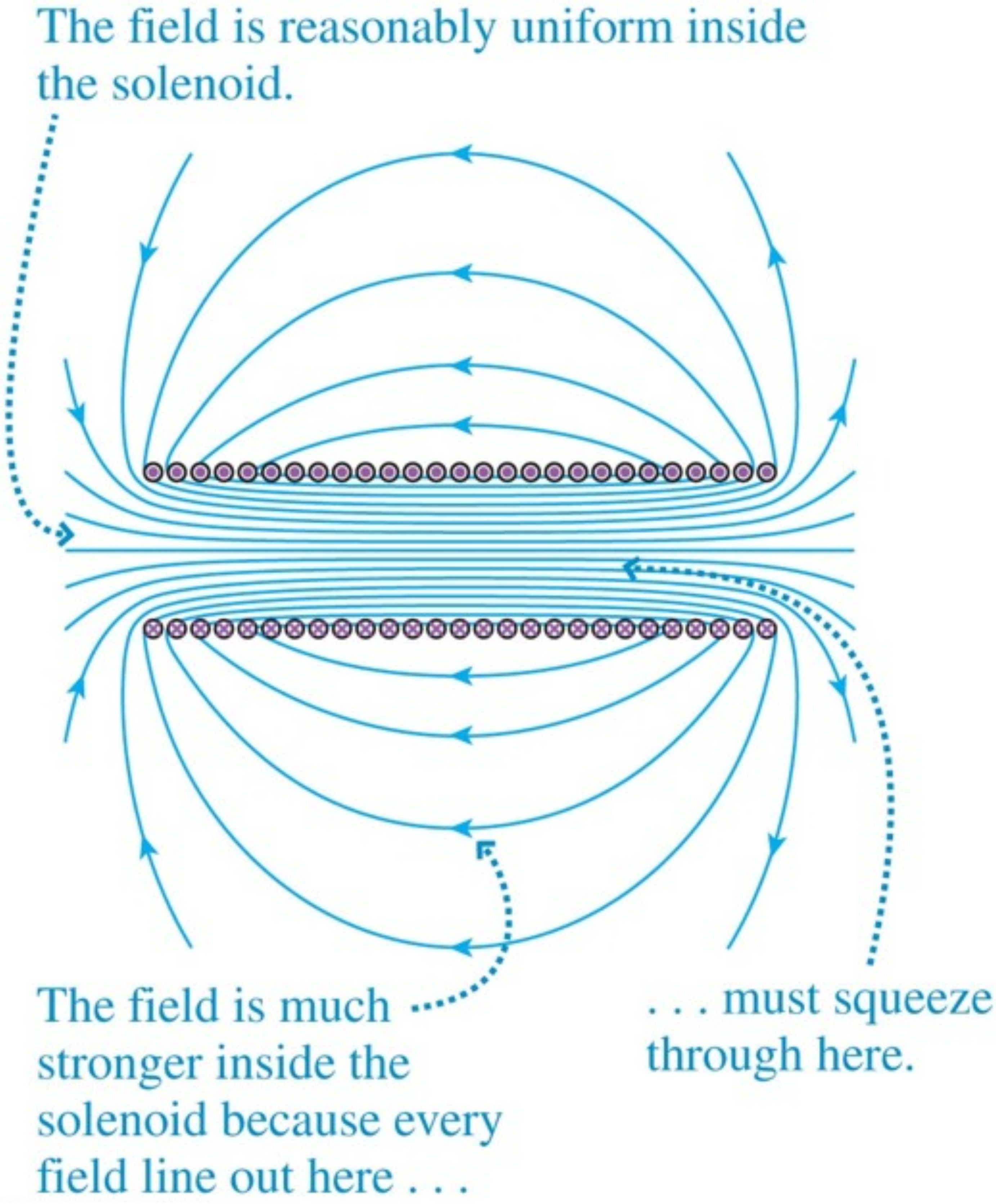
solenoid

field strength inside the coil

$$B = \mu_0 n I$$

n = turns per unit length





The field is reasonably uniform inside the solenoid.

The field is much stronger inside the solenoid because every field line out here . . .

. . . must squeeze through here.

typical field strengths

typical field strength from a wire $B = \frac{\mu_0 I}{2\pi r}$

1 cm away from a wire carrying 10 A,
$B \sim 10^{-4}$ T ~ 1 Gauss

typical field strength in a solenoid $B = \mu_0 n I$

200 turns in 10cm length carrying 10 A
$B \sim 10^{-2}$ T ~ 10 Gauss

a strong fridge magnet

close to the pole,
$B \sim 10^{-1}$ T ~ 100 Gauss

Earth's magnetic field

$B \sim 5\times10^{-5}$ T ~ 0.5 Gauss

electromagnet with an iron core

$B \sim 1$ T ~ 10^4 Gauss

superconducting electromagnets (e.g. in the LHC)

$B \sim 10$ T ~ 10^5 Gauss