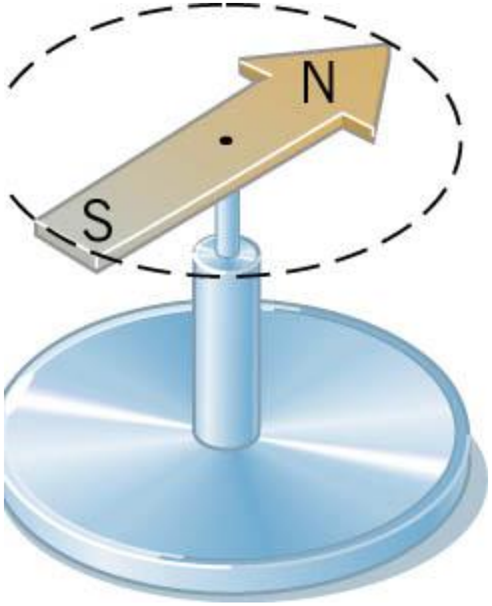
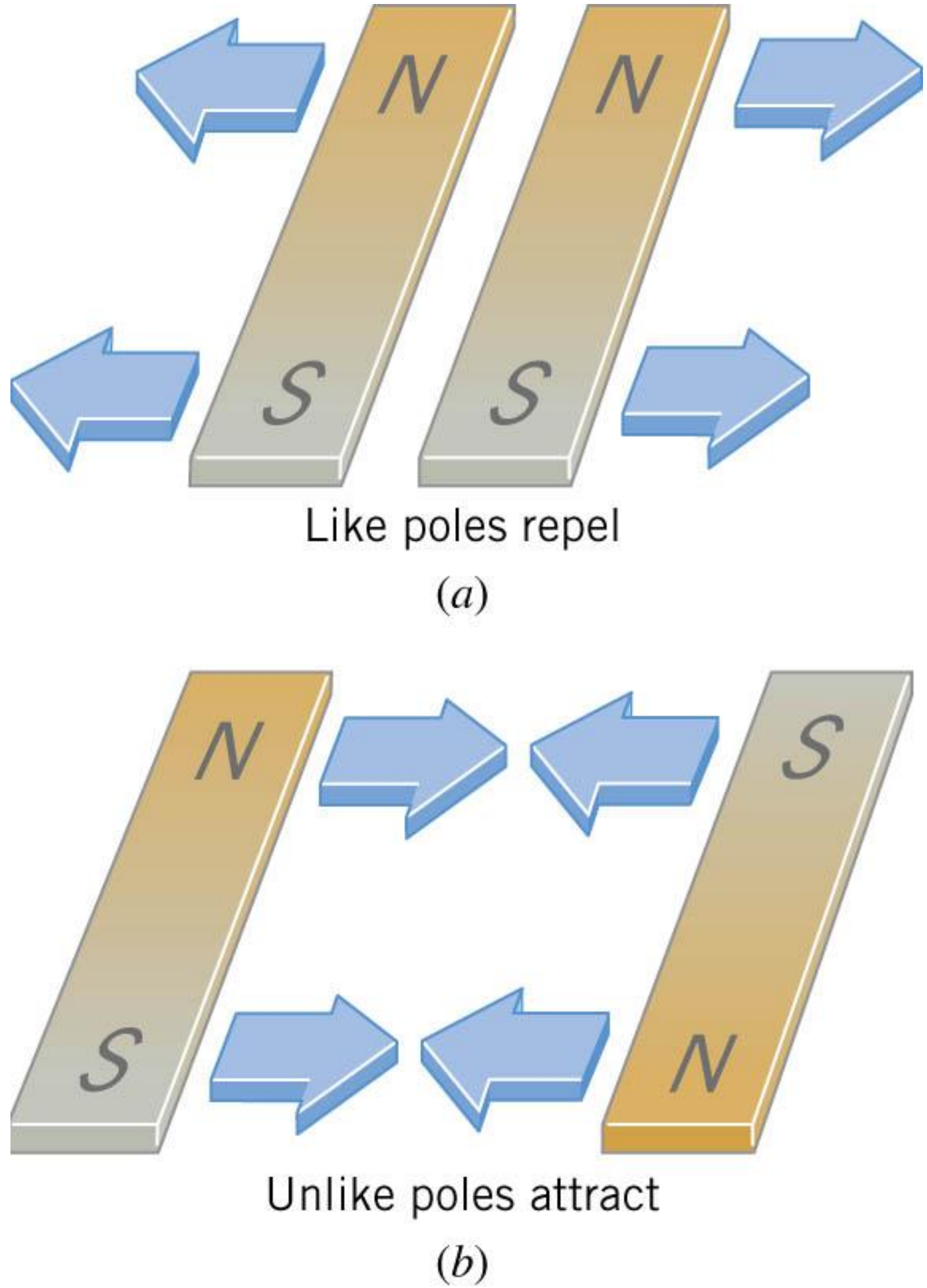
Chapter 21

Magnetic Forces and Magnetic Fields

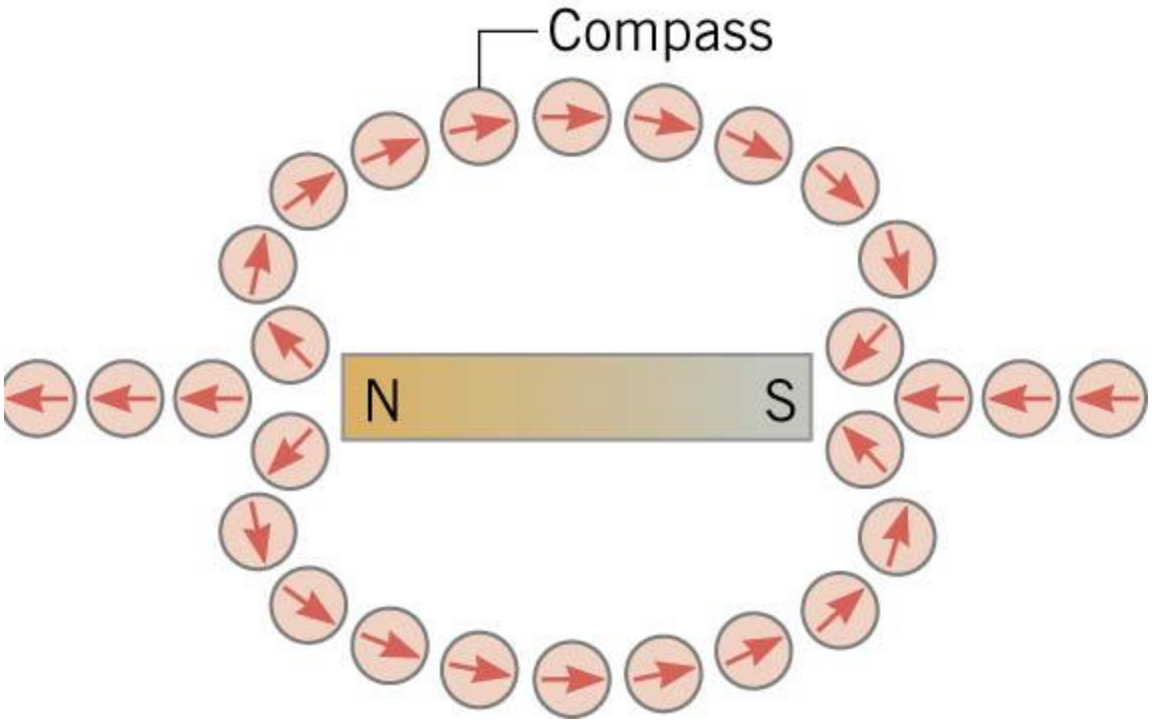


The needle of a compass is permanent magnet that has a north magnetic pole (N) at one end and a south magnetic pole (S) at the other.

The behavior of magnetic poles is similar to that of like and unlike electric charges.

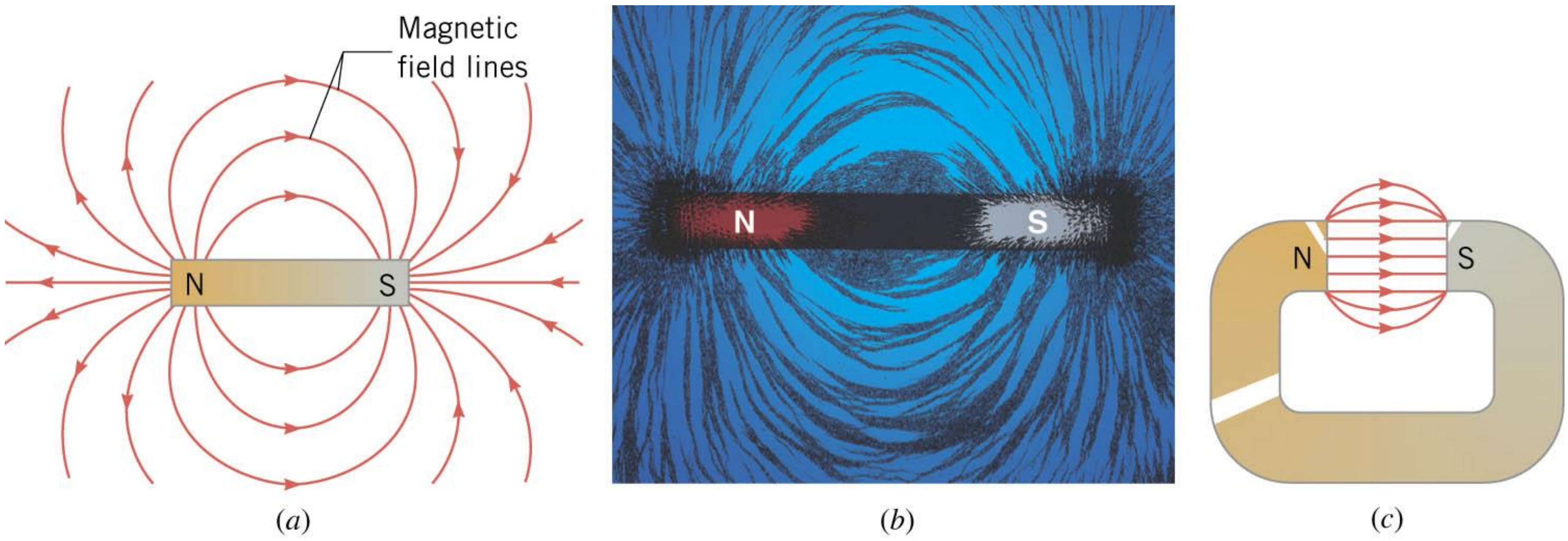


Surrounding a magnet there is a ***magnetic field***. The direction of the magnetic field at any point in space is the direction indicated by the north pole of a small compass needle placed at that point.

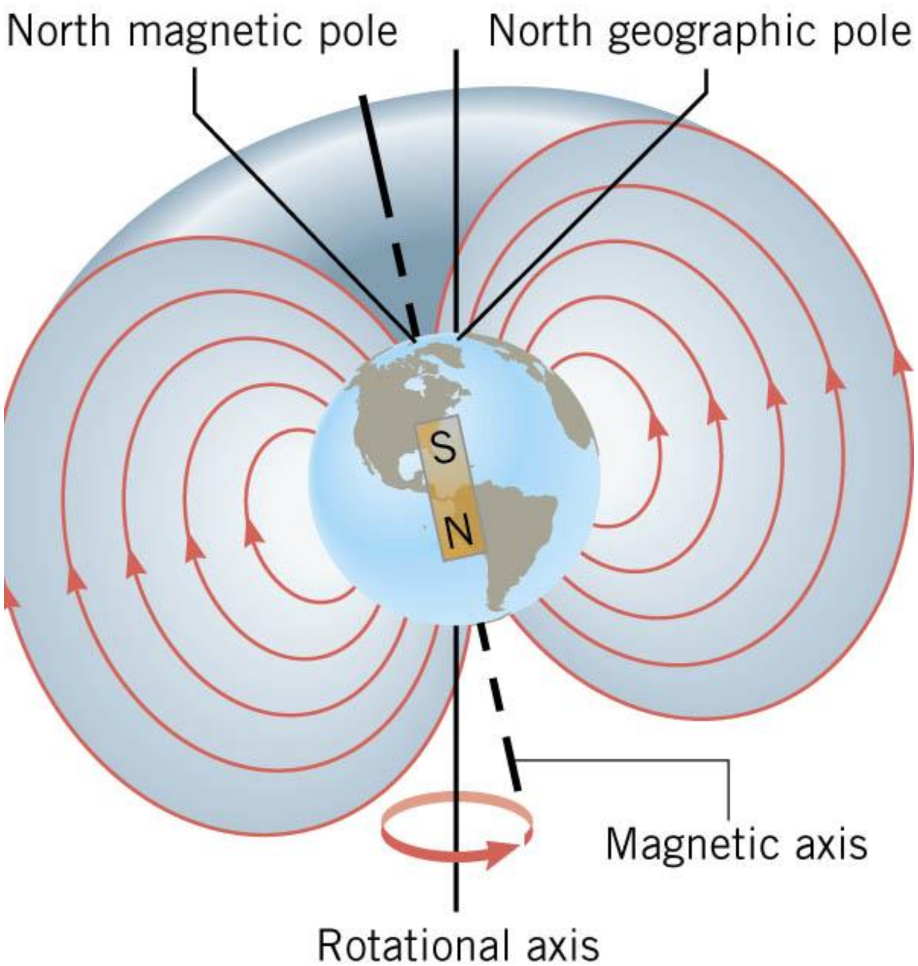


21.1 Magnetic Fields

The magnetic field lines and pattern of iron filings in the vicinity of a bar magnet and the magnetic field lines in the gap of a horseshoe magnet.

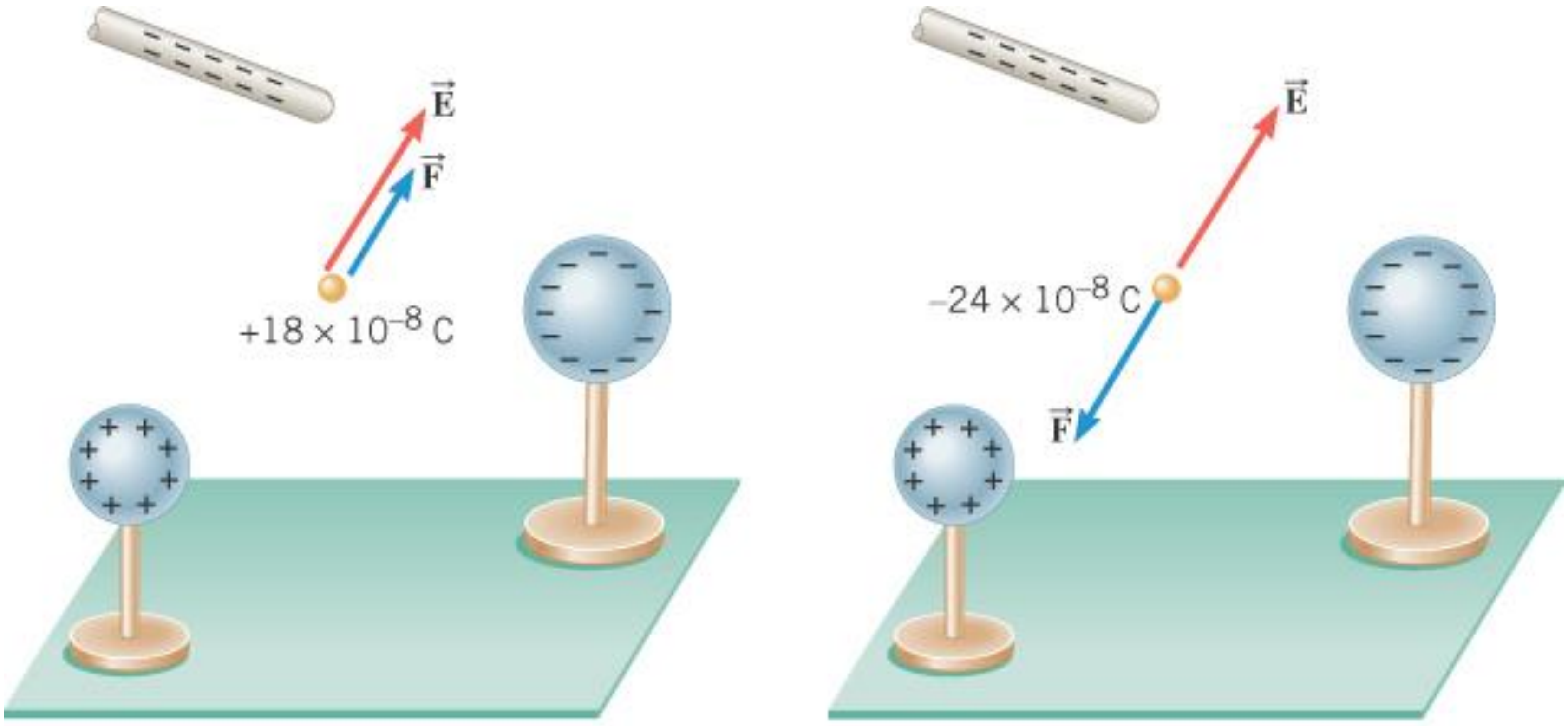


21.1 Magnetic Fields



When a charge is placed in an electric field, it experiences a force, according to

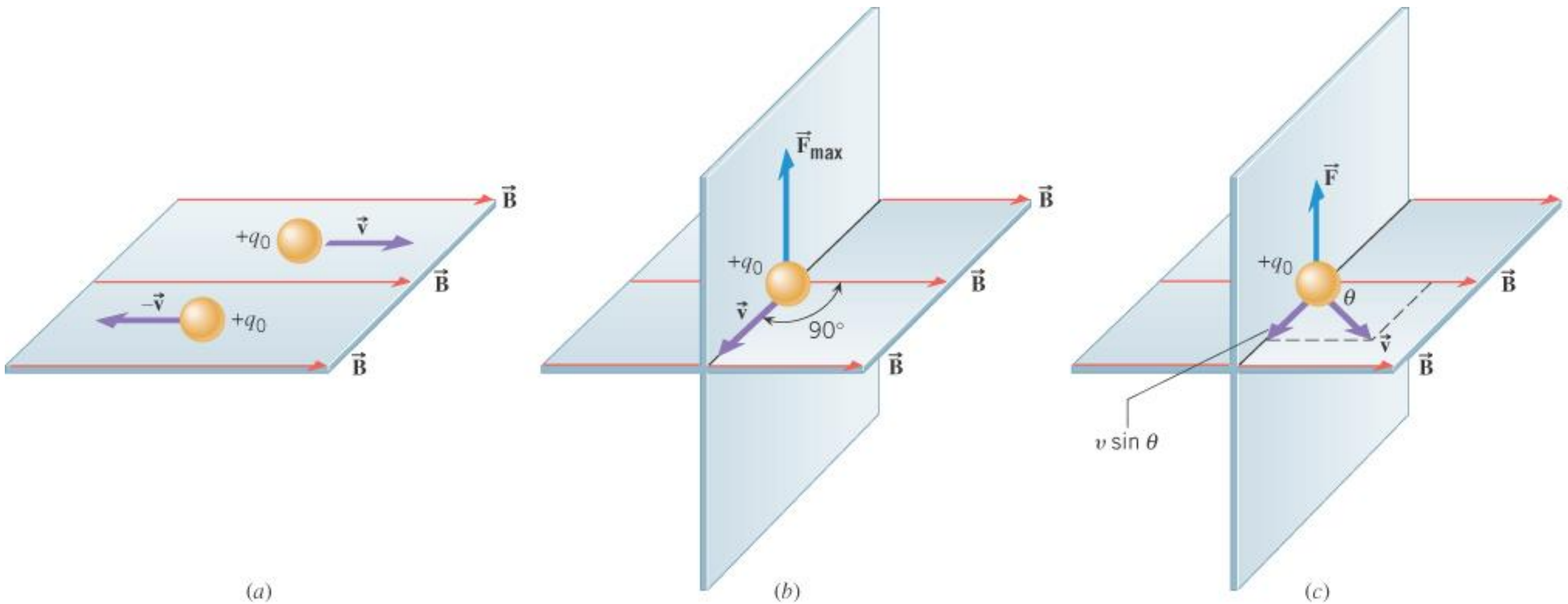
$$\vec{\mathbf{F}} = q\vec{\mathbf{E}}$$



(a) (b)

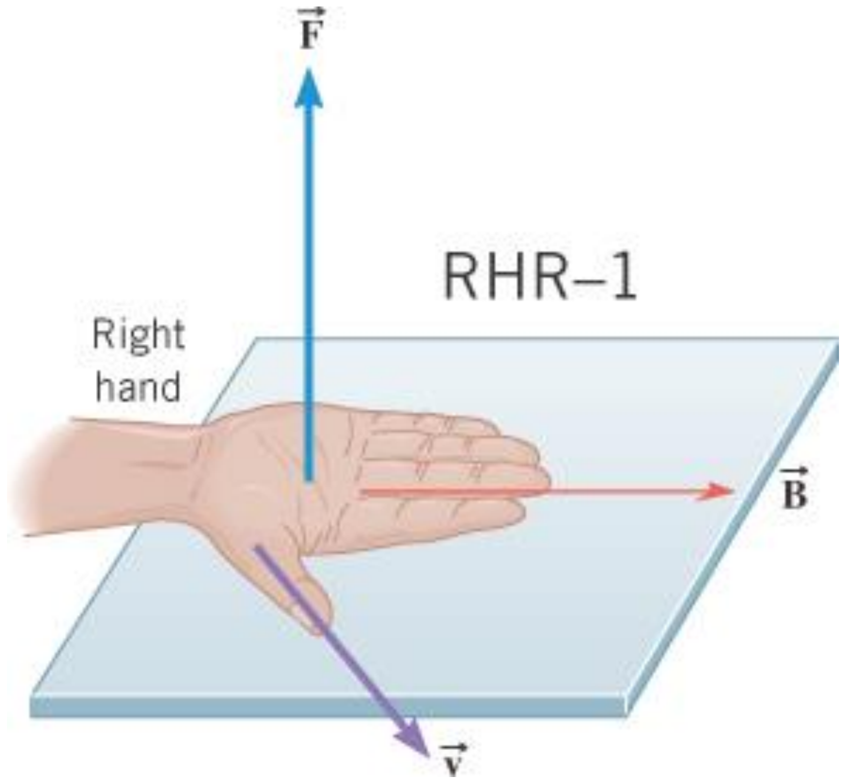
The following conditions must be met for a charge to experience a magnetic force when placed in a magnetic field:

1. The charge must be moving.
2. The velocity of the charge must have a component that is perpendicular to the direction of the magnetic field.



Right Hand Rule No. 1. Extend the right hand so the fingers point along the direction of the magnetic field and the thumb points along the velocity of the charge. The palm of the hand then faces in the direction of the magnetic force that acts on a positive charge.

If the moving charge is negative, the direction of the force is opposite to that predicted by RHR-1.



21.2 The Force That a Magnetic Field Exerts on a Charge

DEFINITION OF THE MAGNETIC FIELD

The magnitude of the magnetic field at any point in space is defined as

$$B = \frac{F}{|q_o|(v \sin\theta)}$$

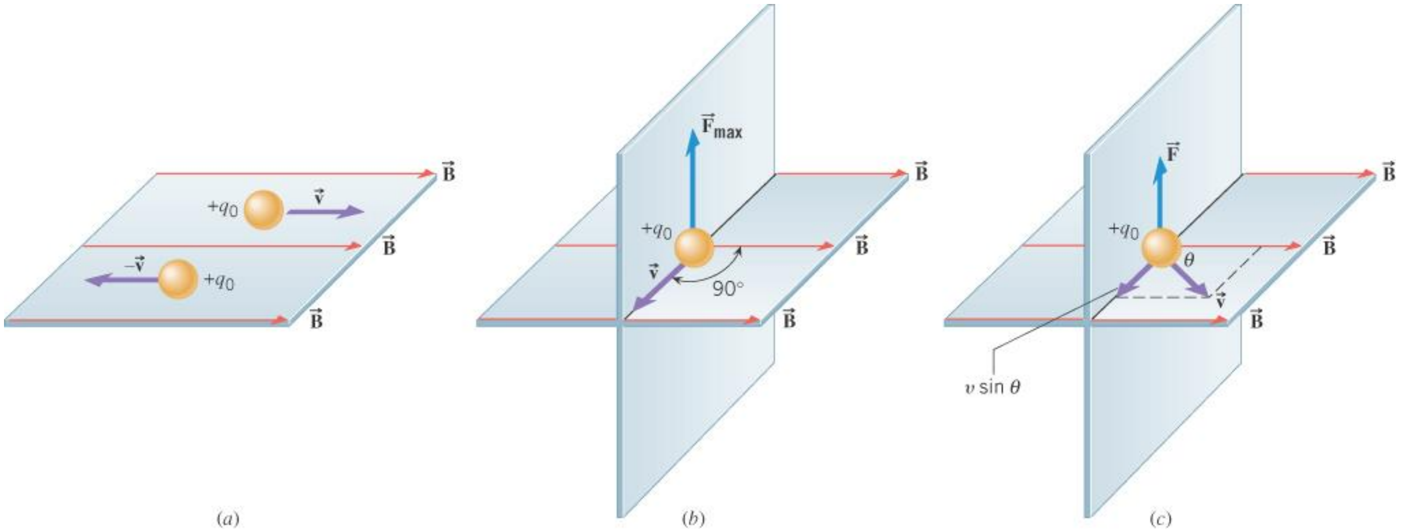
where the angle ($0 < \theta < 180^{o}$) is the angle between the velocity of the charge and the direction of the magnetic field.

SI Unit of Magnetic Field: $\frac{\text{newton} \cdot \text{second}}{\text{coulomb} \cdot \text{meter}} = 1\,\text{tesla}\,(\text{T})$

$$1\,\text{gauss} = 10^{-4}\,\text{tesla}$$

Example 1 Magnetic Forces on Charged Particles

A proton in a particle accelerator has a speed of $5.0\text{x}10^6$ m/s. The proton encounters a magnetic field whose magnitude is 0.40 T and whose direction makes and angle of 30.0 degrees with respect to the proton's velocity (see part (c) of the figure). Find (a) the magnitude and direction of the force on the proton and (b) the acceleration of the proton. (c) What would be the force and acceleration of the particle were an electron?



(a)

The acceleration is in the direction of the force.

$$F = |q_o| vB\sin\theta = \left(1.60\times10^{-19}\,\mathrm{C}\right)\left(5.0\times10^{6}\ \mathrm{m/s}\right)\left(0.40\mathrm{T}\right)\sin\left(30.0^\circ\right)$$

$$= 1.6\times10^{-13}\,\mathrm{N}$$

(b)

$$a = \frac{F}{m_\mathrm{p}} = \frac{1.6\times10^{-13}\,\mathrm{N}}{1.67\times10^{-27}\,\mathrm{kg}} = 9.6\times10^{13}\ \mathrm{m/s^2}$$

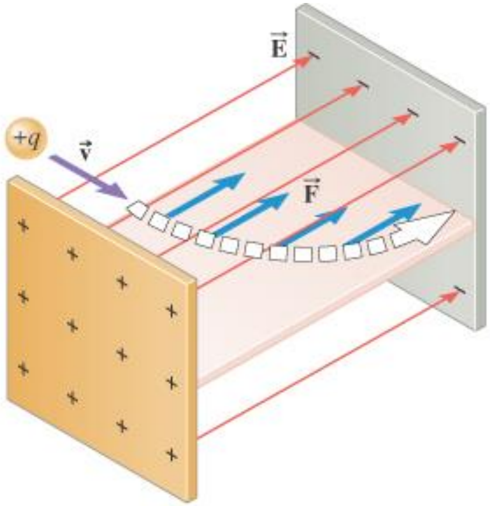
(c)

Magnitude of the force is the same, but direction is opposite.

$$a = \frac{F}{m_\mathrm{e}} = \frac{1.6\times10^{-13}\,\mathrm{N}}{9.11\times10^{-31}\,\mathrm{kg}} = 1.8\times10^{17}\ \mathrm{m/s^2}$$

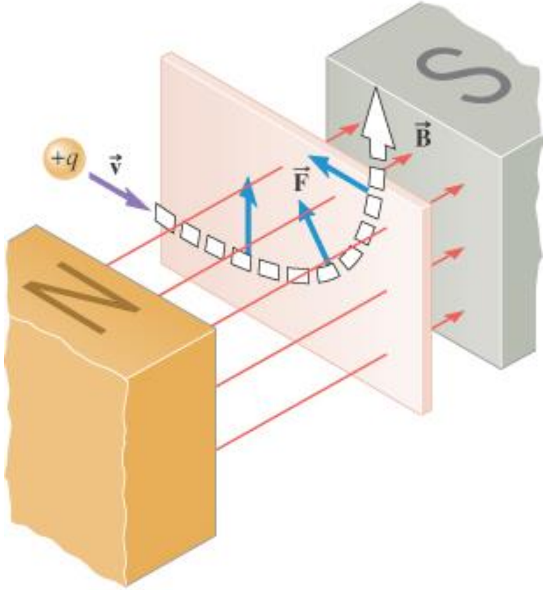
21.3 The Motion of a Charged Particle in a Magnetic Field

Charged particle in an electric field.



(a)

Charged particle in a magnetic field.

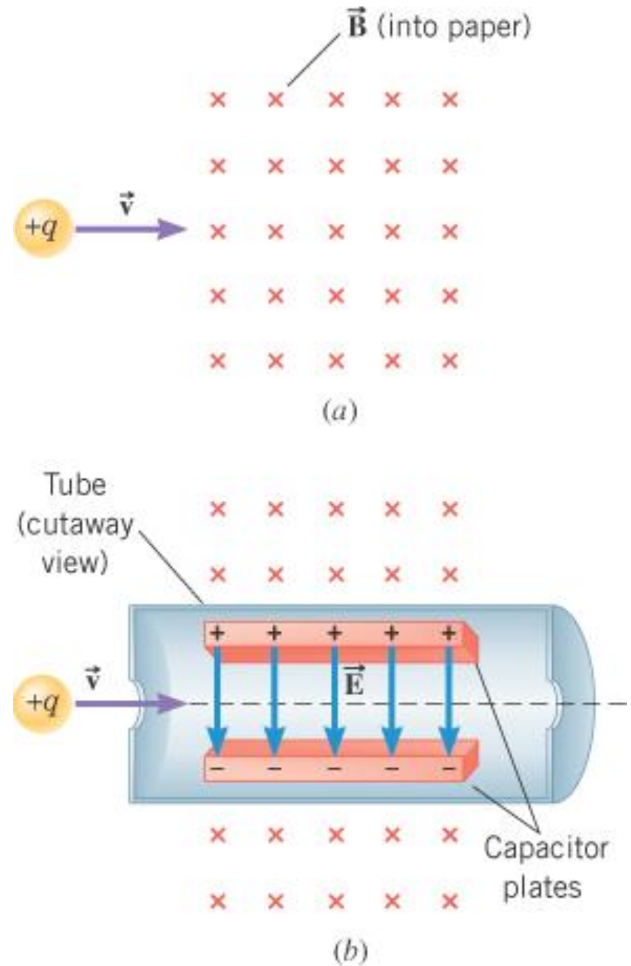


(b)

Conceptual Example 2 A Velocity Selector

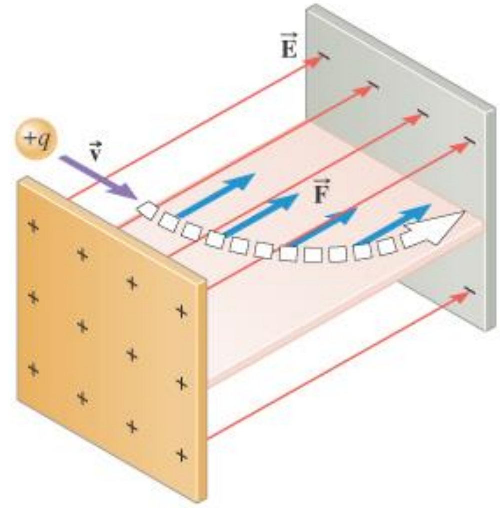
A velocity selector is a device for measuring the velocity of a charged particle. The device operates by applying electric and magnetic forces to the particle in such a way that these forces balance.

How should an electric field be applied so that the force it applies to the particle can balance the magnetic force?



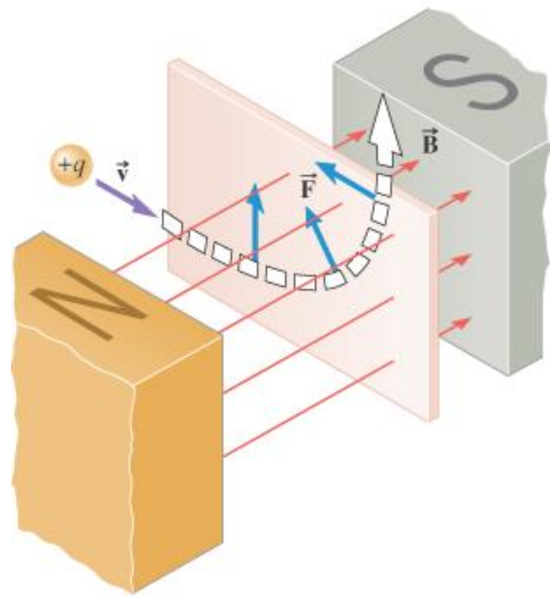
21.3 The Motion of a Charged Particle in a Magnetic Field

The electrical force *can* do work on a charged particle.



(a)

The magnetic force *cannot* do work on a charged particle.



(b)

The magnetic force always remains perpendicular to the velocity and is directed toward the center of the circular path.

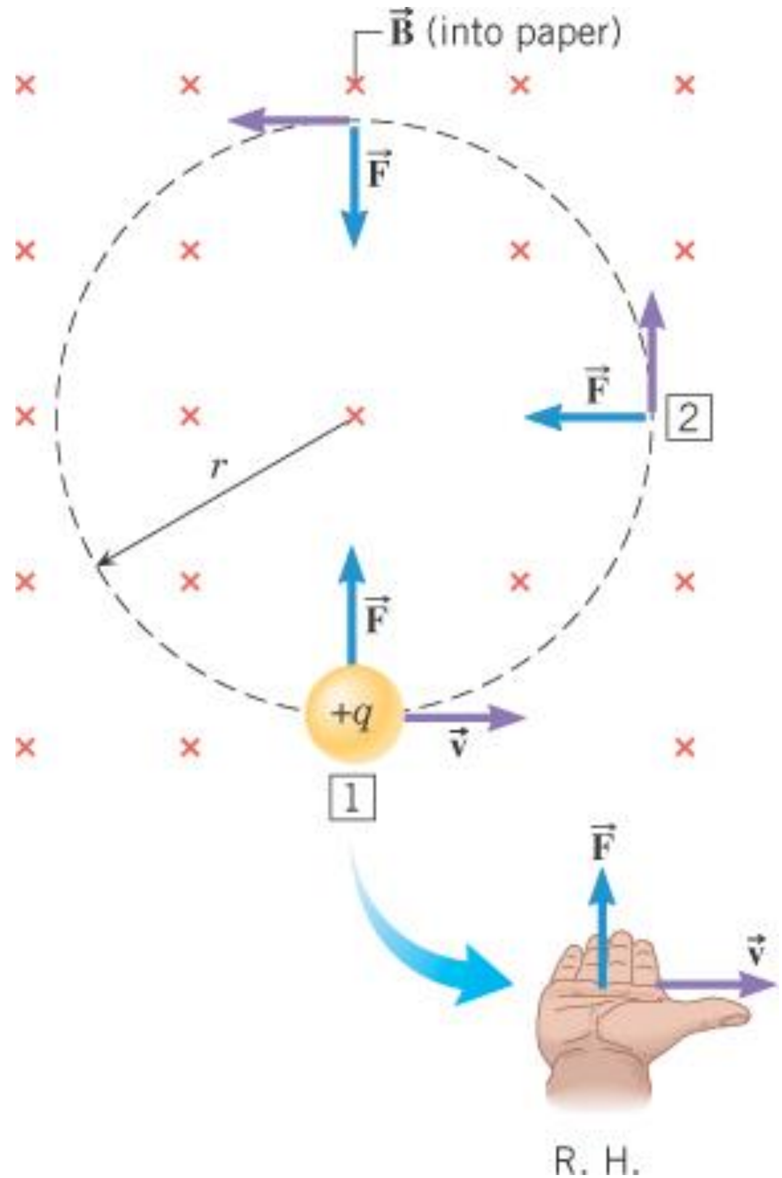
$$F_c = m\frac{v^2}{r}$$

$$\Downarrow$$

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

$$\Downarrow$$

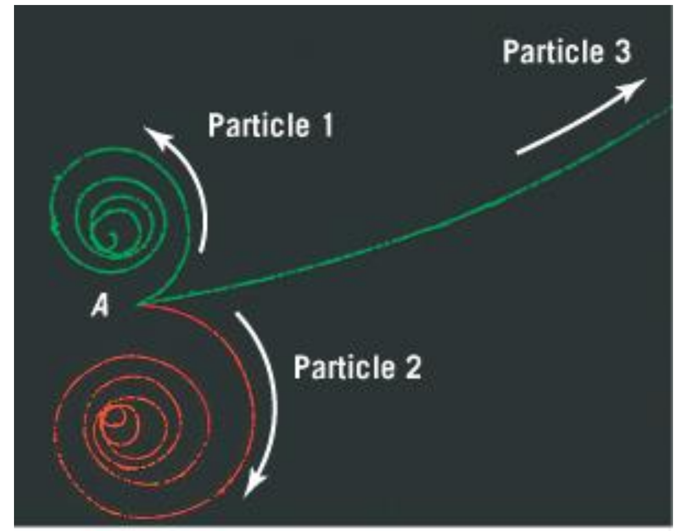
$$r = \frac{mv}{qB}$$



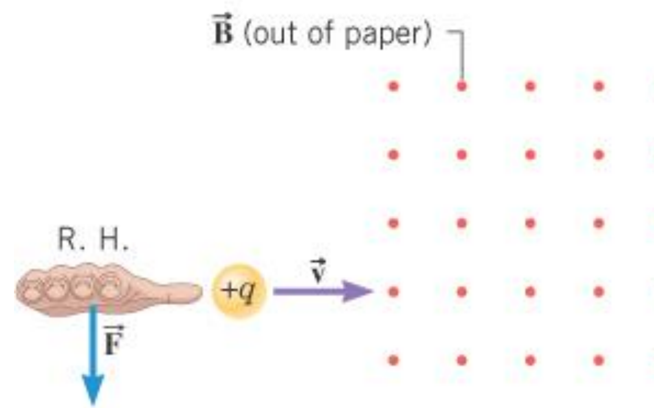
Conceptual Example 4 Particle Tracks in a Bubble Chamber

The figure shows the bubble-chamber tracks from an event that begins at point A. At this point a gamma ray travels in from the left, spontaneously transforms into two charged particles. The particles move away from point A, producing two spiral tracks. A third charged particle is knocked out of a hydrogen atom and moves forward, producing the long track.

The magnetic field is directed out of the paper. Determine the sign of each particle and which particle is moving most rapidly.



(a)



(b)

21.4 The Mass Spectrometer

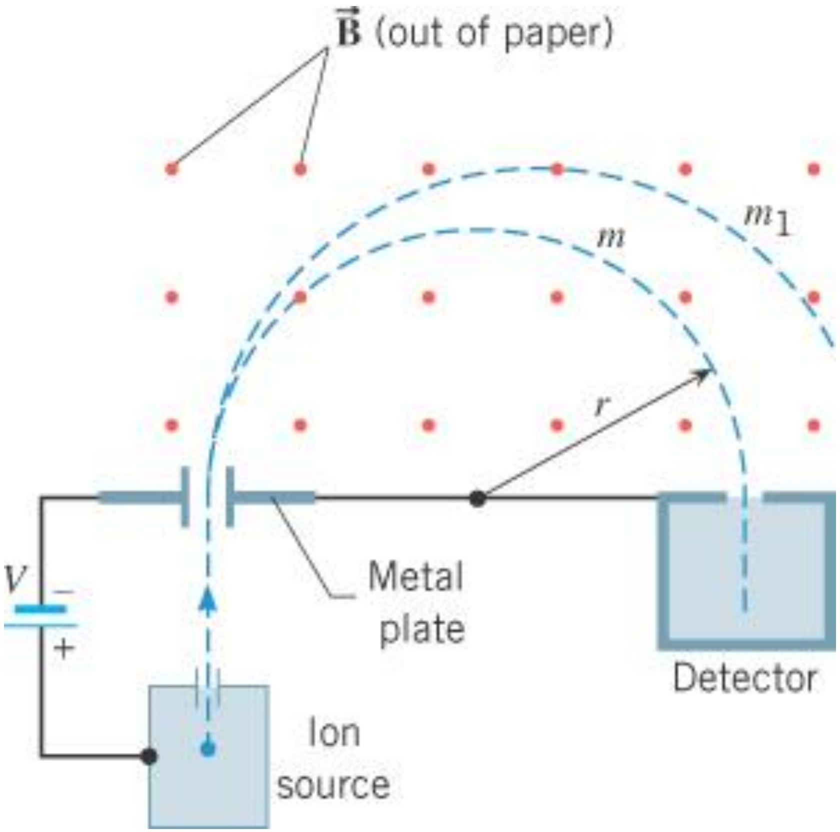
(for a singly ionized particle starting from rest)

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

magnitude of electron charge

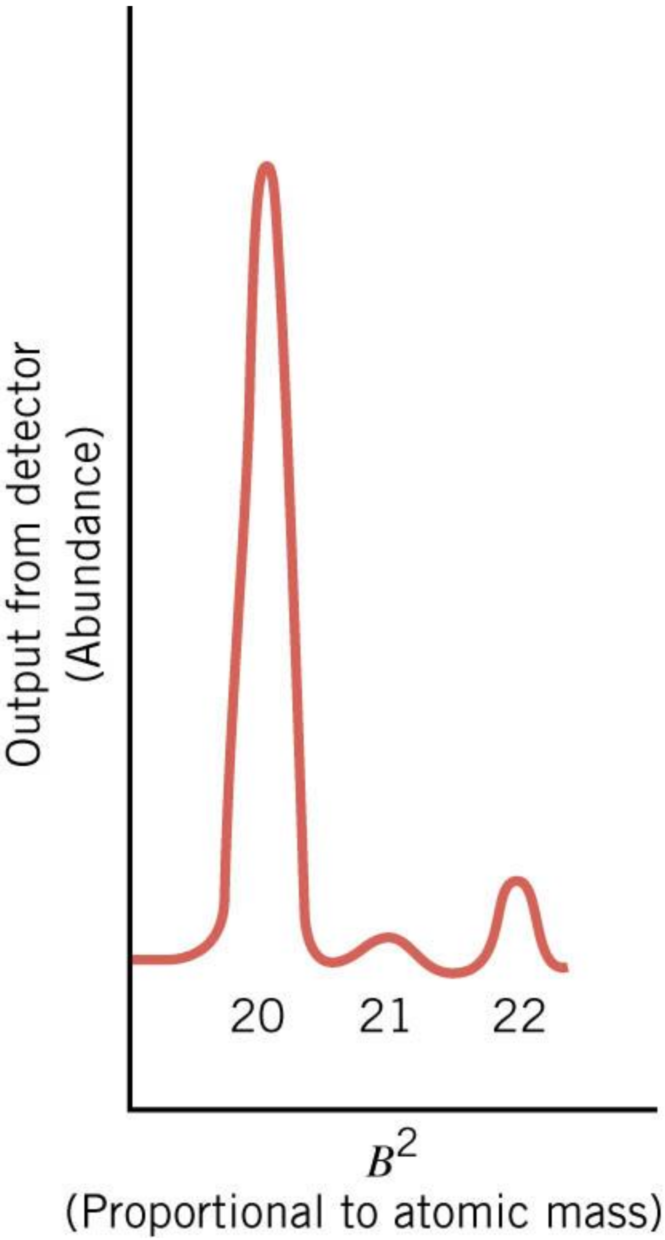
$$\tfrac{1}{2}mv^2 = eV$$

KE=PE

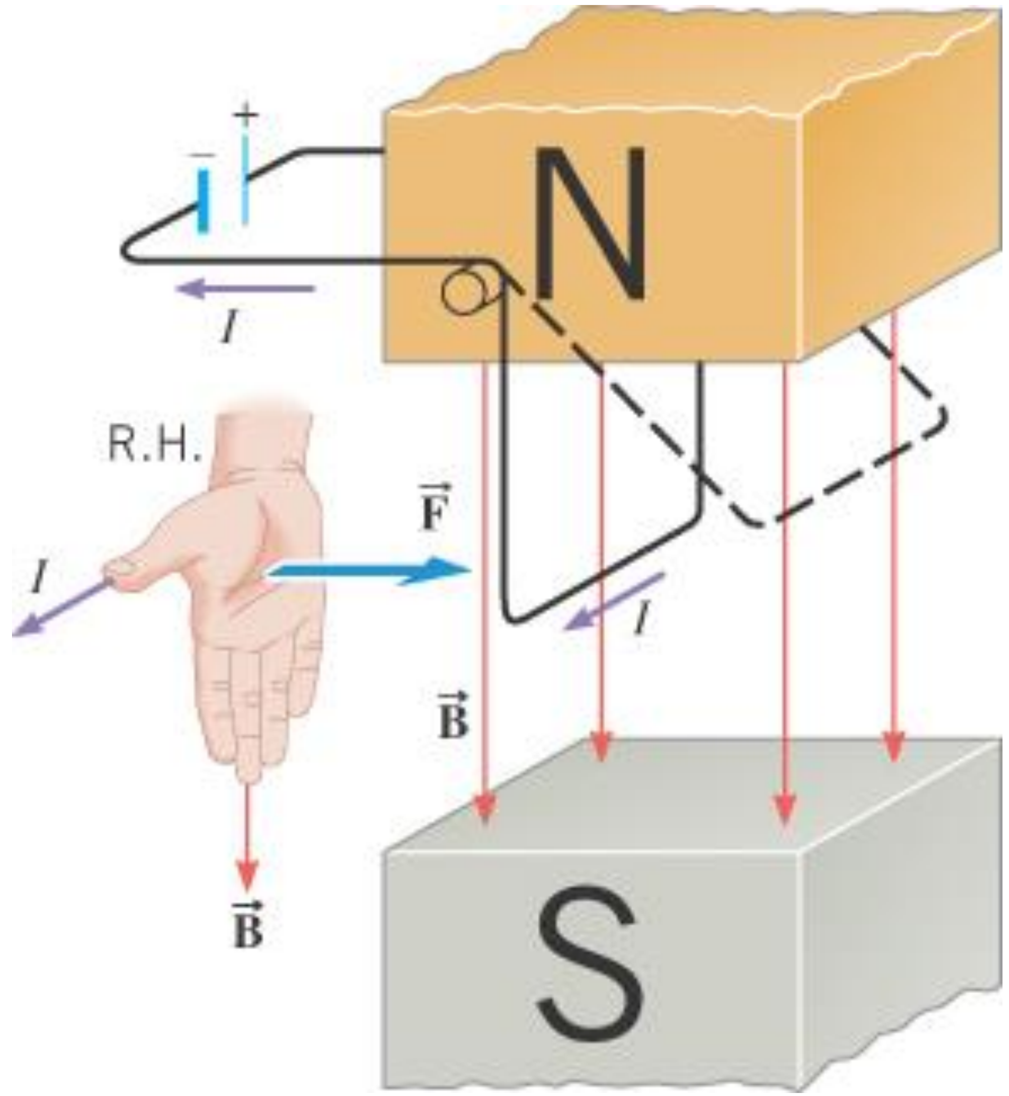


$$m = \left(\frac{er^2}{2V}\right)B^2$$

The mass spectrum of naturally occurring neon, showing three isotopes.



The magnetic force on the moving charges pushes the wire to the right.



21.5 The Force on a Current in a Magnetic Field

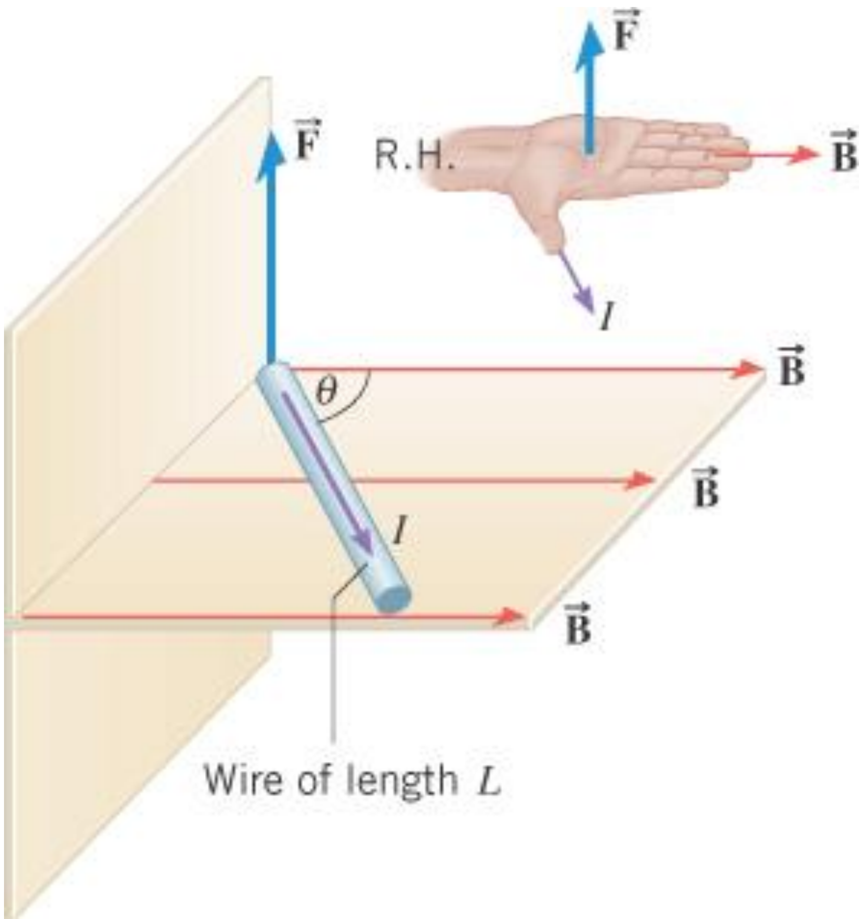
$$F = qvB\sin\theta$$

$$\Downarrow$$

$$F = \underbrace{\left(\frac{\Delta q}{\Delta t}\right)}_{I}\underbrace{(v\Delta t)}_{L}B\sin\theta$$

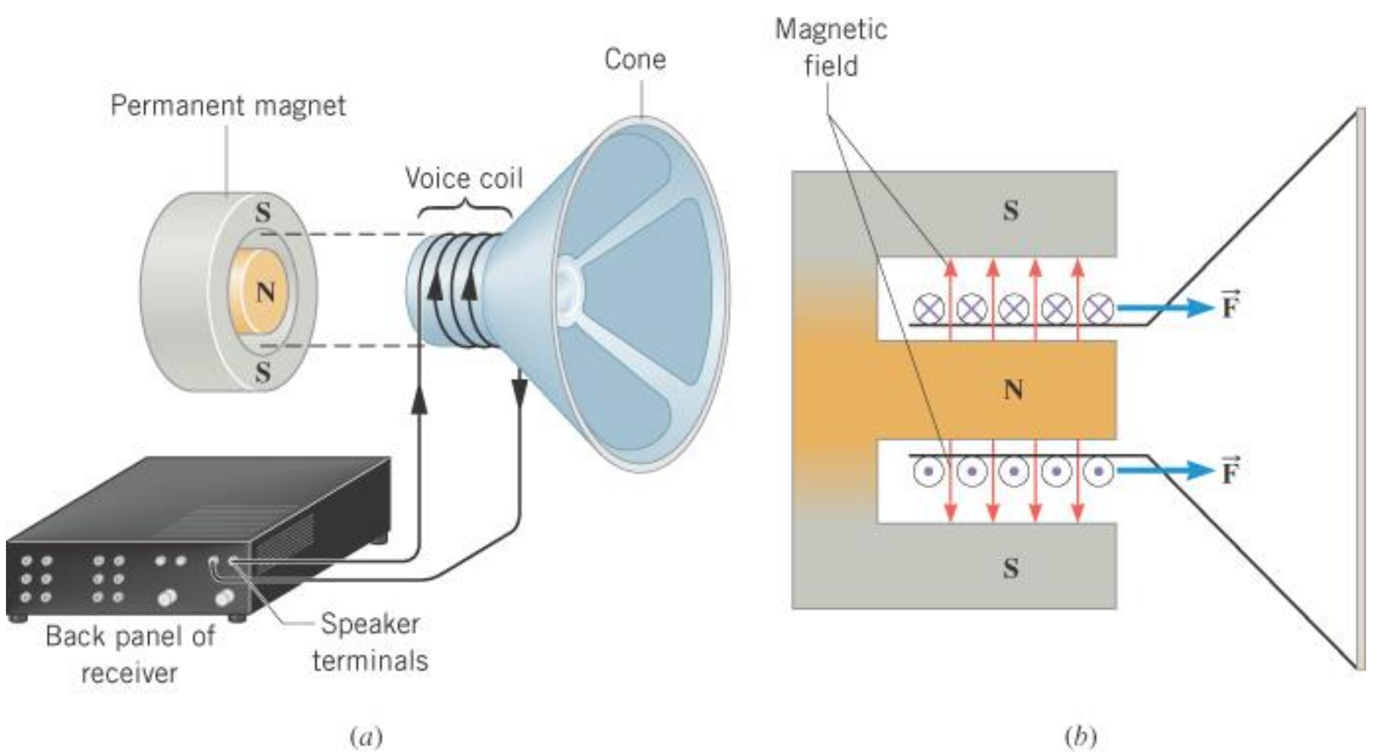
$$\Downarrow$$

$$F = ILB\sin\theta$$

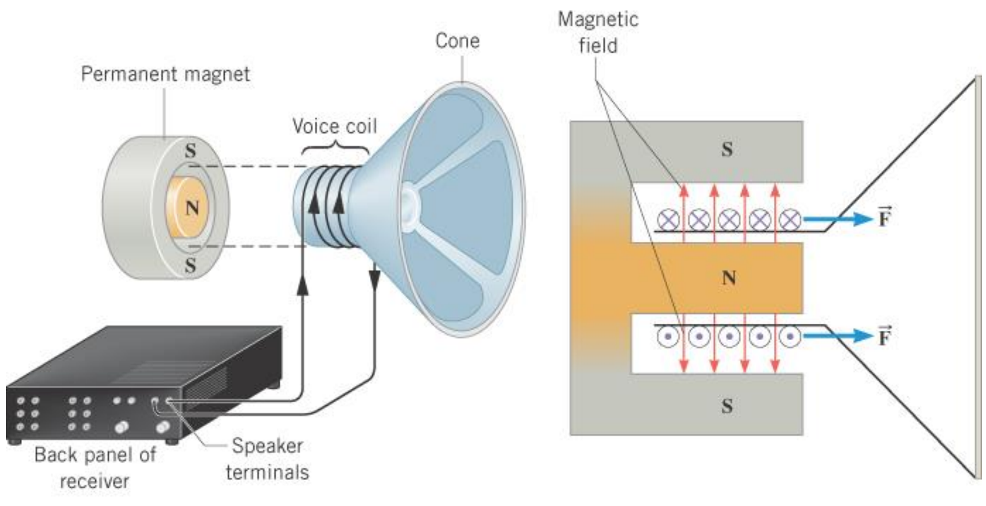


Example 5 The Force and Acceleration in a Loudspeaker

The voice coil of a speaker has a diameter of 0.0025 m, contains 55 turns of wire, and is placed in a 0.10-T magnetic field. The current in the voice coil is 2.0 A. (a) Determine the magnetic force that acts on the coil and the cone. (b) The voice coil and cone have a combined mass of 0.0200 kg. Find their acceleration.



21.5 The Force on a Current in a Magnetic Field



(a) (b)

(a)

$$F = ILB\sin\theta$$

$$= (2.0\ \text{A})\left[55\pi(0.0025\ \text{m})\right](0.10\ \text{T})\sin 90^\circ$$

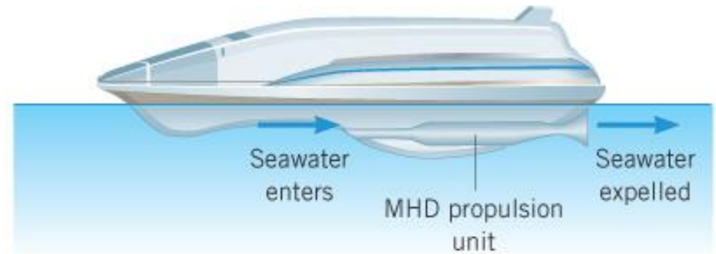
$$= 0.86\ \text{N}$$

(b)

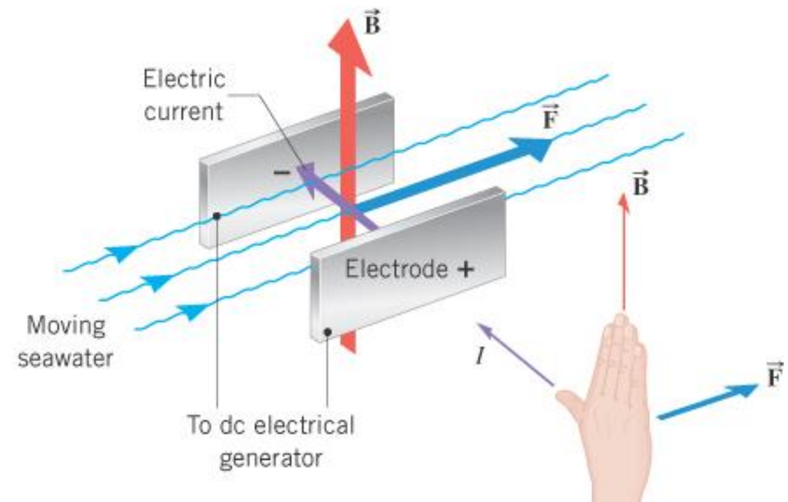
$$a = \frac{F}{m} = \frac{0.86\ \text{N}}{0.020\ \text{kg}} = 43\,\text{m/s}^2$$

21.5 The Force on a Current in a Magnetic Field

(a)

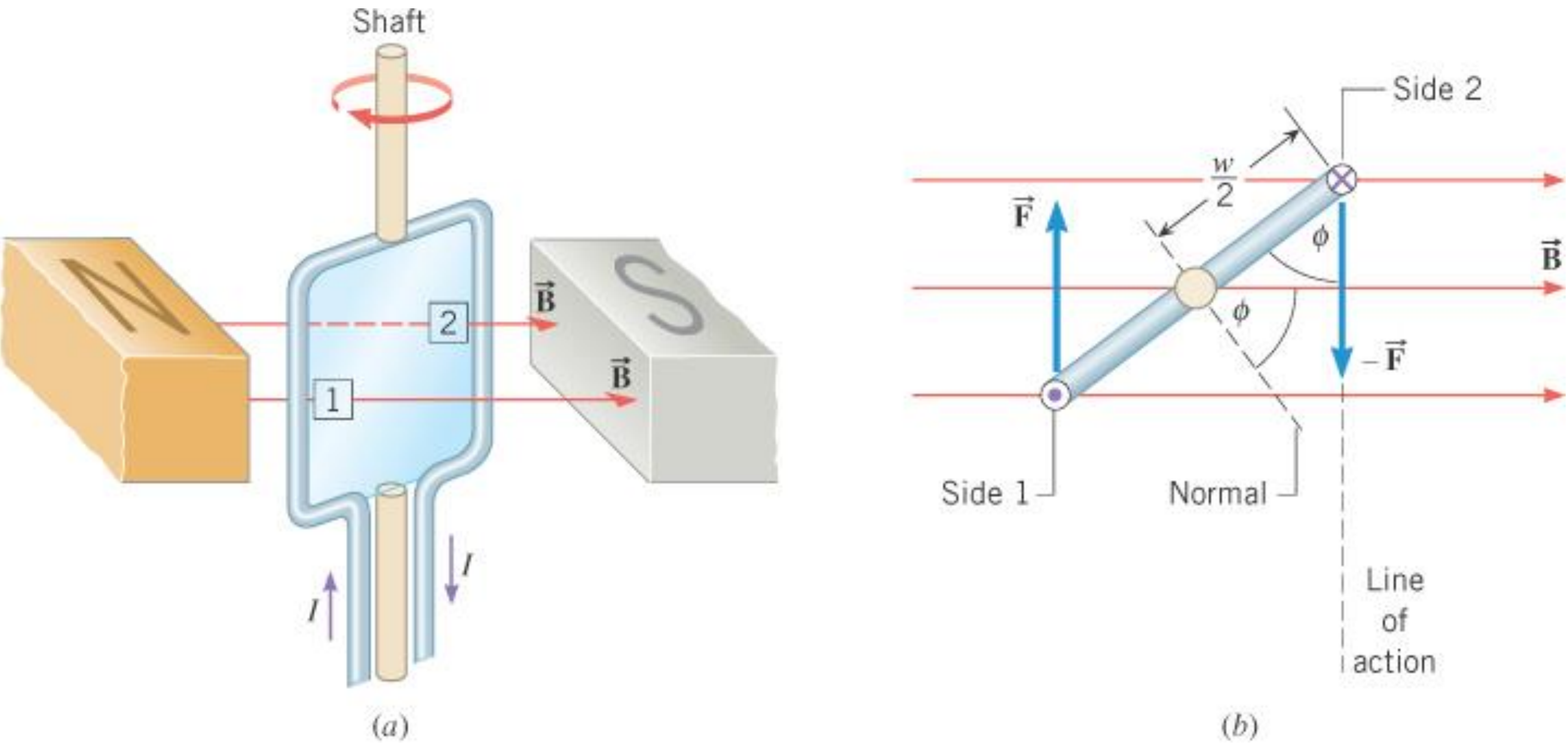


(b)



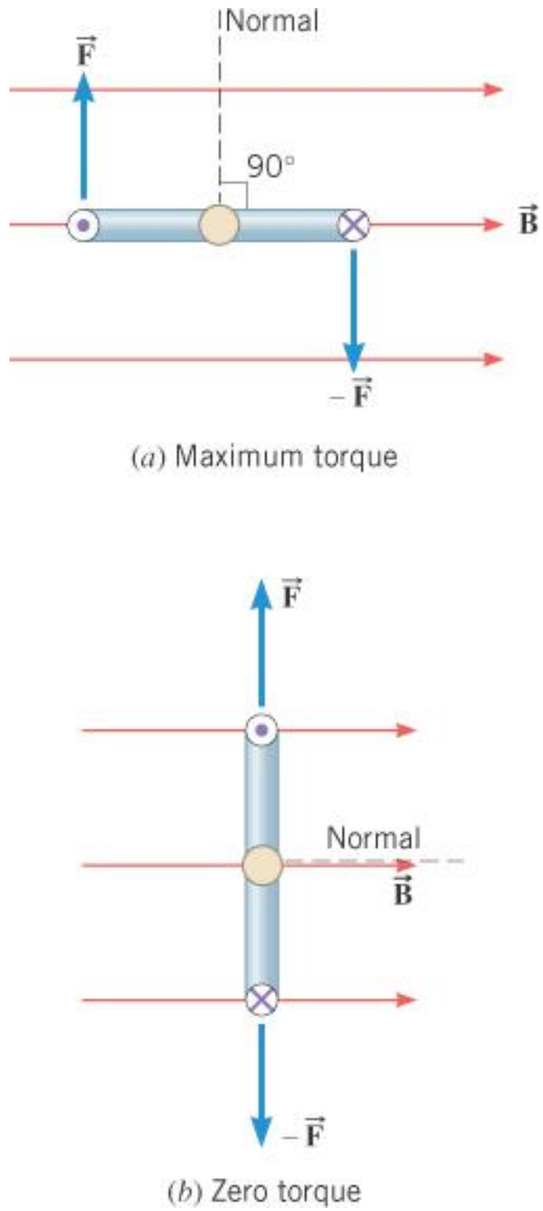
(c)

The two forces on the loop have equal magnitude but an application of RHR-1 shows that they are opposite in direction.

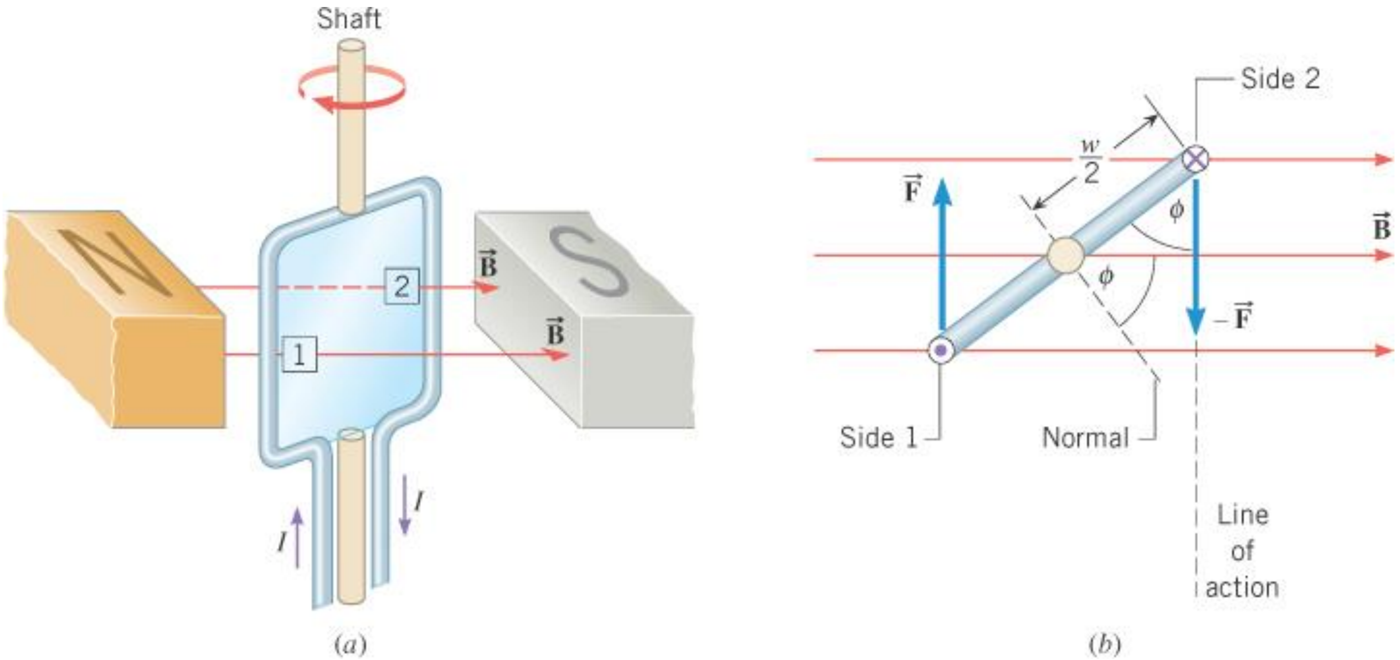


21.6 The Torque on a Current-Carrying Coil

The loop tends to rotate such that its normal becomes aligned with the magnetic field.



$$\text{Net torque} = \tau = ILB\left(\tfrac{1}{2}w\sin\phi\right) + ILB\left(\tfrac{1}{2}w\sin\phi\right) = IAB\sin\phi$$



$$\tau = \overbrace{NIA}^{\text{magnetic moment}}\,B\sin\phi$$

number of turns of wire

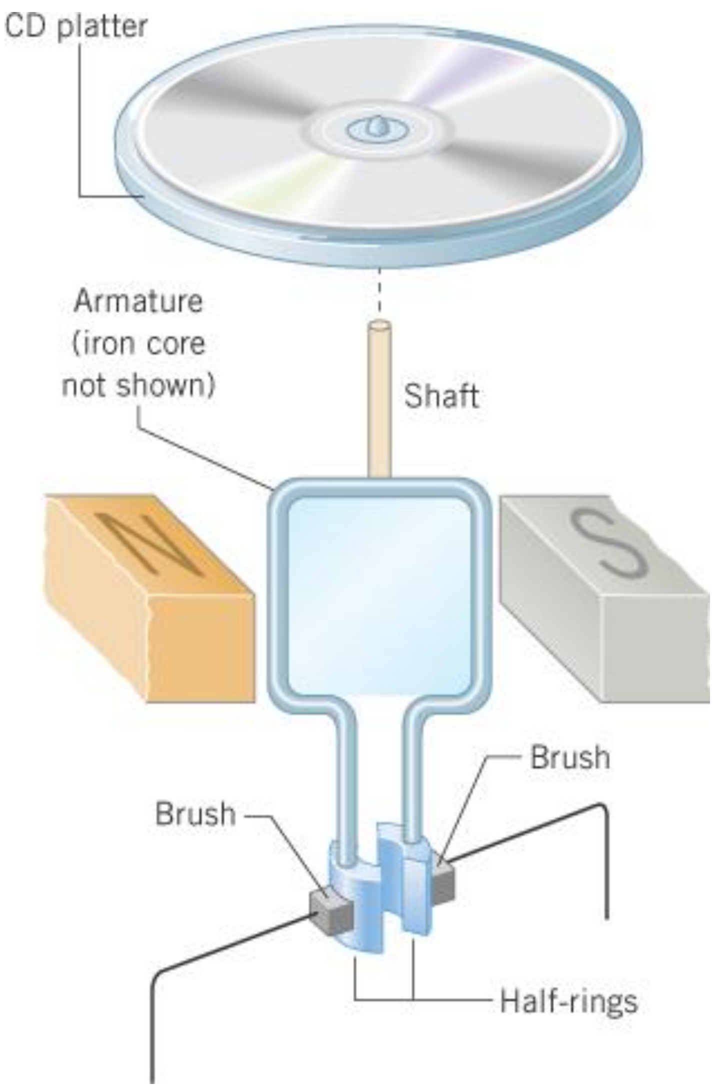
Example 6 The Torque Exerted on a Current-Carrying Coil

A coil of wire has an area of $2.0 \times 10^{-4} m^2$, consists of 100 loops or turns, and contains a current of 0.045 A. The coil is placed in a uniform magnetic field of magnitude 0.15 T. (a) Determine the magnetic moment of the coil. (b) Find the maximum torque that the magnetic field can exert on the coil.

(a) $$\overbrace{NIA}^{\substack{\text{magnetic}\\ \text{moment}}} = (100)(0.045\text{ A})\left(2.0\times10^{-4}\text{ m}^2\right) = 9.0\times10^{-4}\text{ A}\cdot\text{m}^2$$

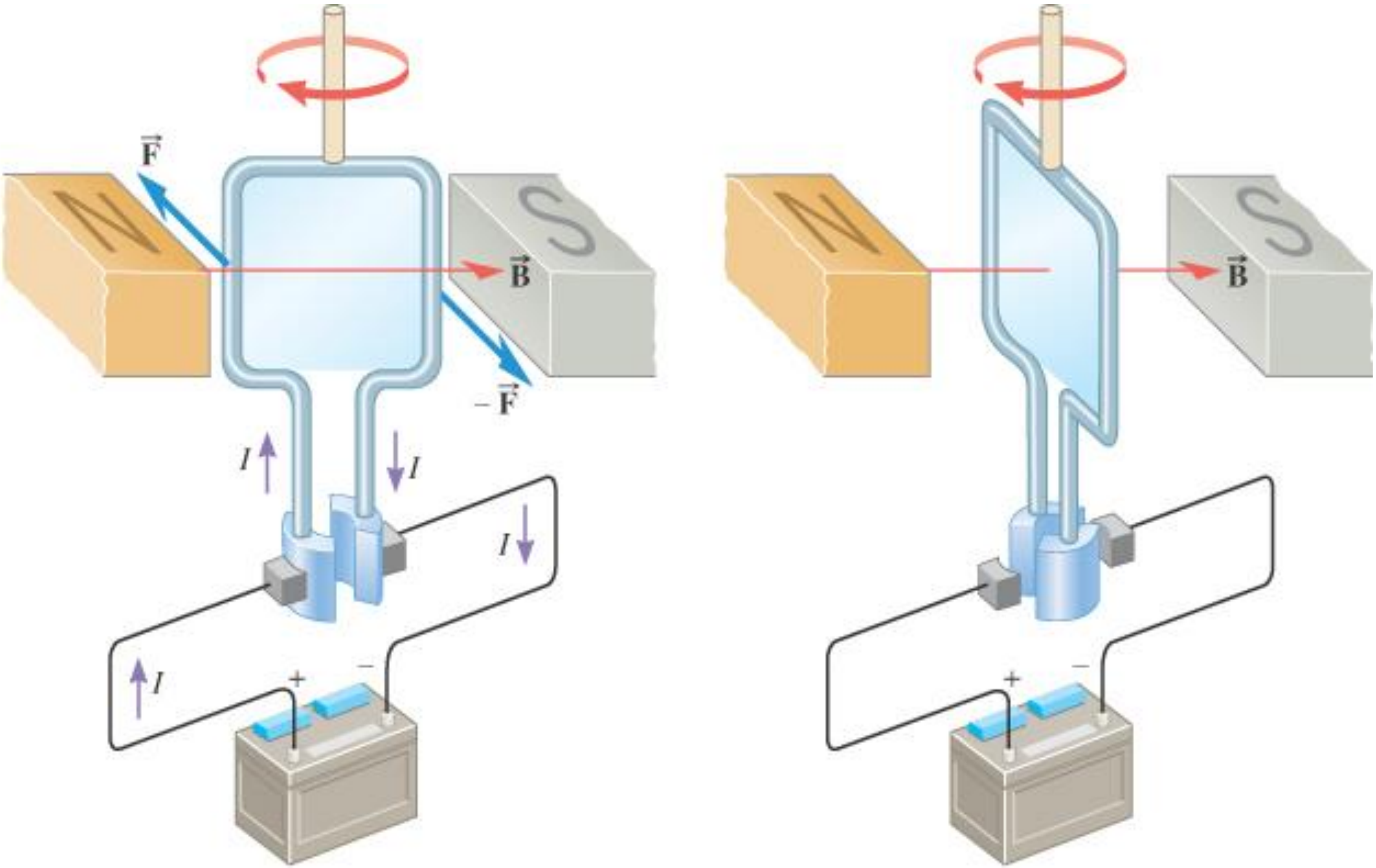
(b) $$\tau = \overbrace{NIA}^{\substack{\text{magnetic}\\ \text{moment}}} B\sin\phi = \left(9.0\times10^{-4}\text{ A}\cdot\text{m}^2\right)(0.15\text{ T})\sin 90^\circ = 1.4\times10^{-4}\text{ N}\cdot\text{m}$$

21.6 The Torque on a Current-Carrying Coil



The basic components of a dc motor.

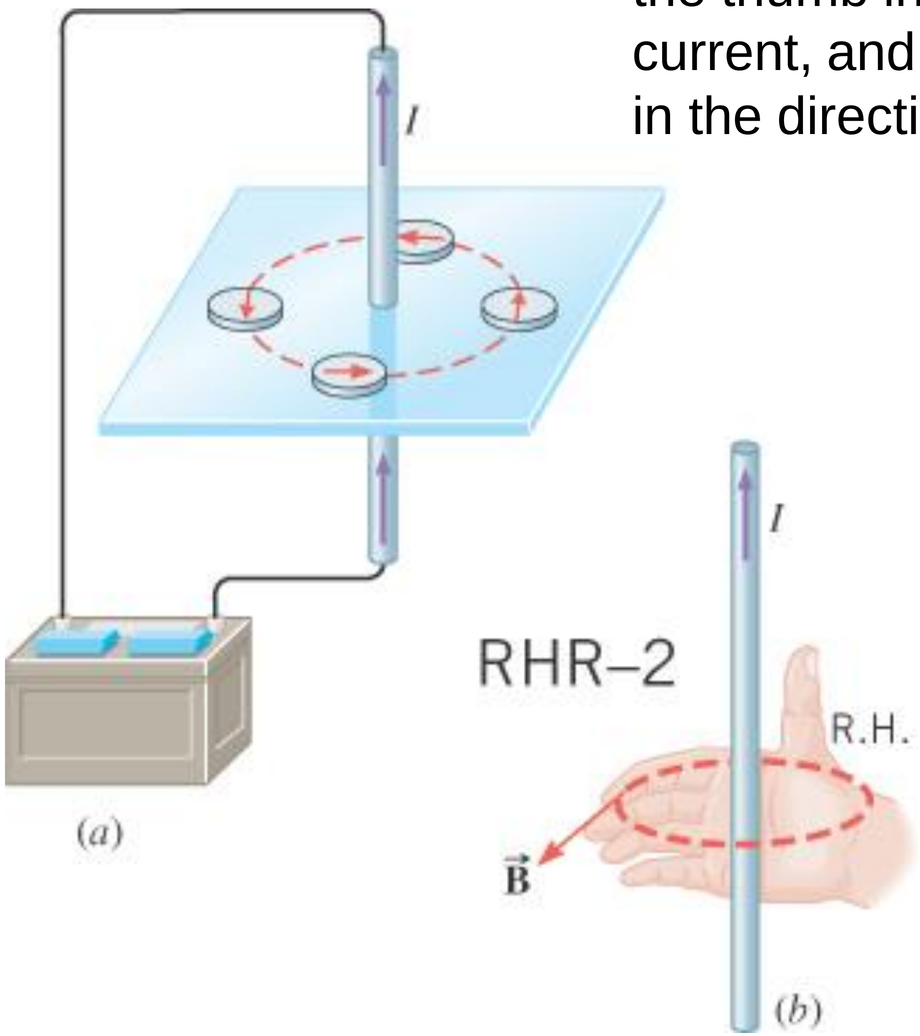
21.6 The Torque on a Current-Carrying Coil



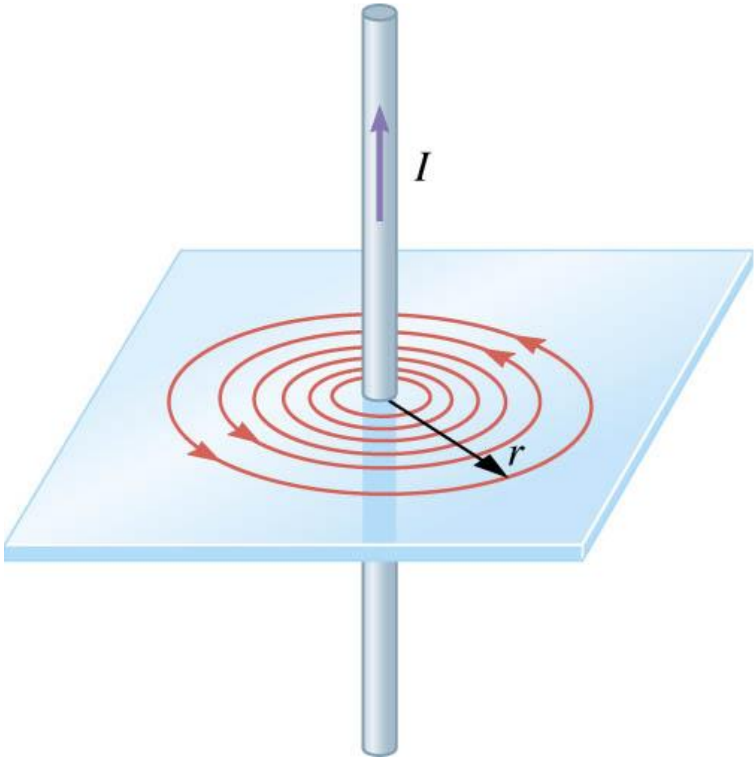
(a)

(b)

Right-Hand Rule No. 2. Curl the fingers of the right hand into the shape of a half-circle. Point the thumb in the direction of the conventional current, and the tips of the fingers will point in the direction of the magnetic field.



A LONG, STRAIGHT WIRE



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

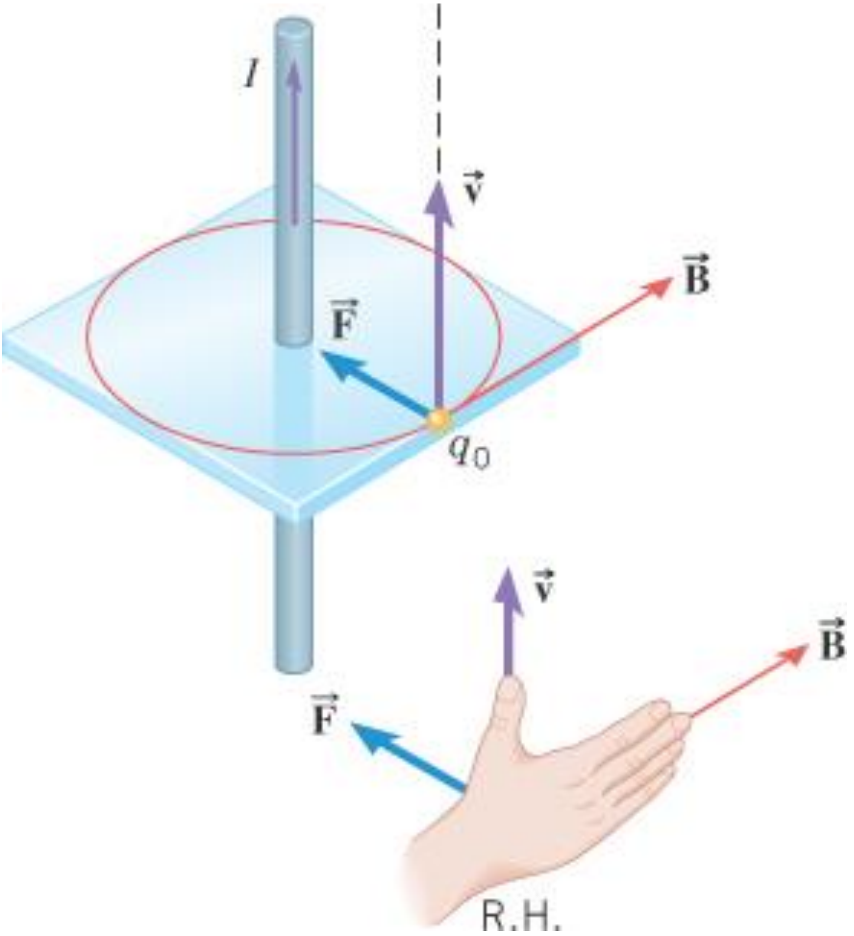
$$\mu_o = 4\pi \times 10^{-7}\ \mathrm{T \cdot m/A}$$

permeability of free space

Example 7 A Current Exerts a Magnetic Force on a Moving Charge

The long straight wire carries a current of 3.0 A. A particle has a charge of $+6.5\times10^{-6}$ C and is moving parallel to the wire at a distance of 0.050 m. The speed of the particle is 280 m/s.

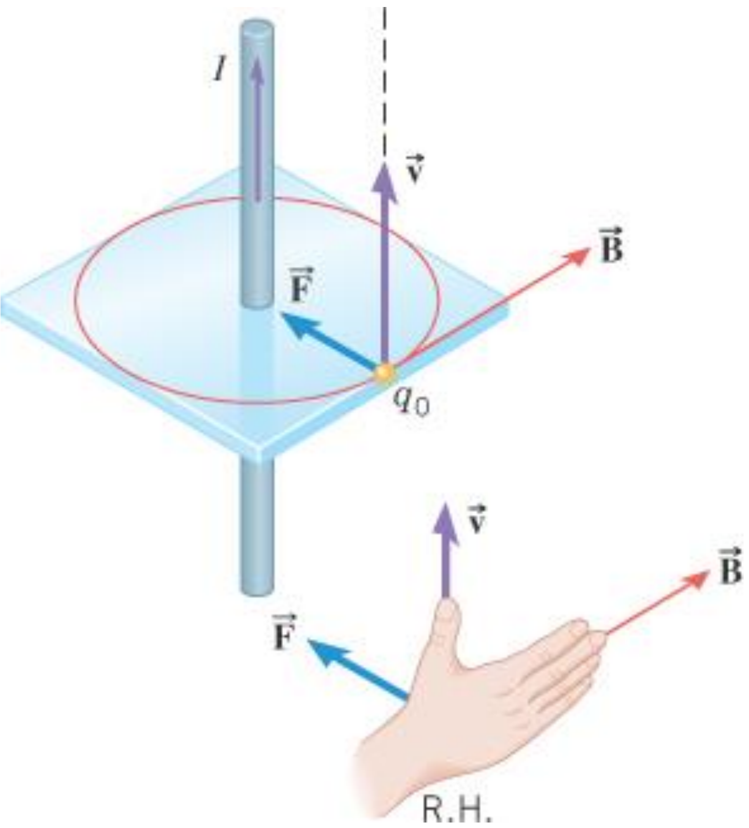
Determine the magnitude and direction of the magnetic force on the particle.



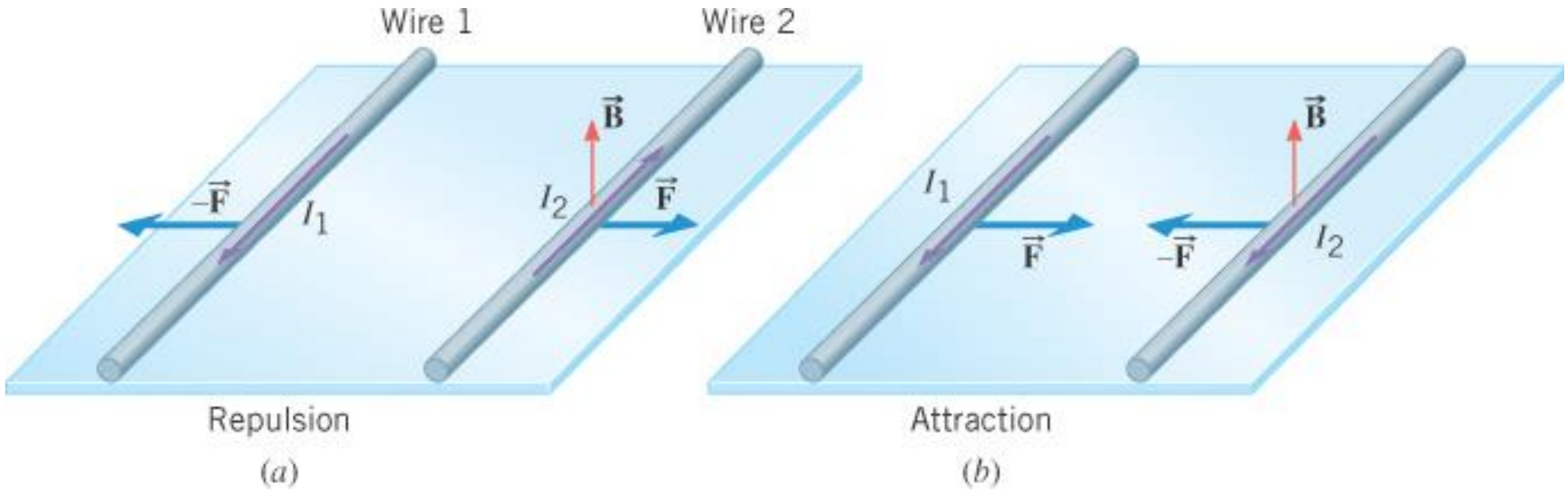
21.7 Magnetic Fields Produced by Currents

$$F = qvB\sin\theta = qv\left(\frac{\mu_o I}{2\pi r}\right)\sin\theta$$

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

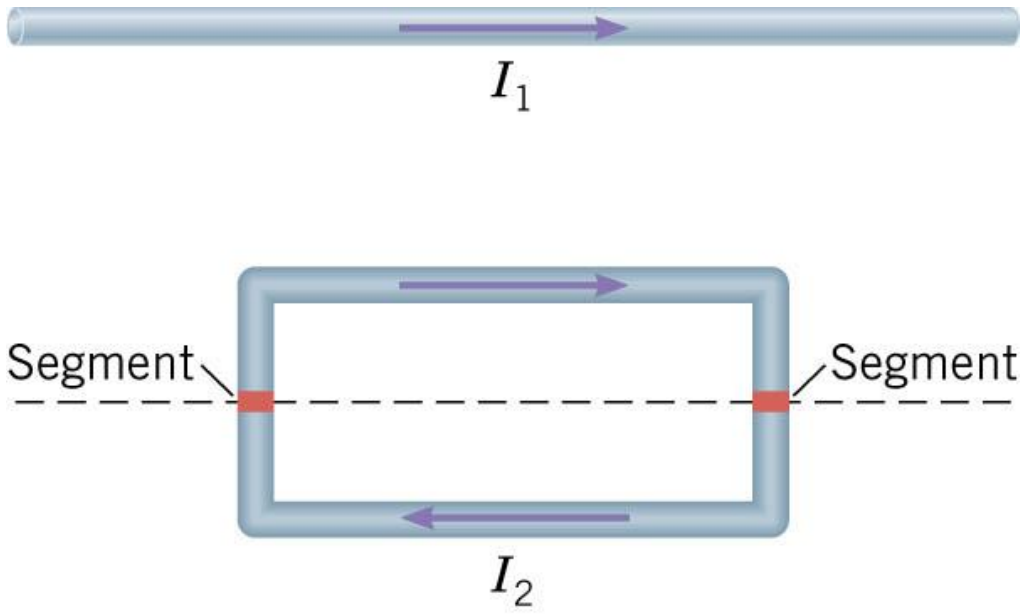


Current carrying wires can exert forces on each other.



Conceptual Example 9 The Net Force That a Current-Carrying Wire Exerts on a Current Carrying Coil

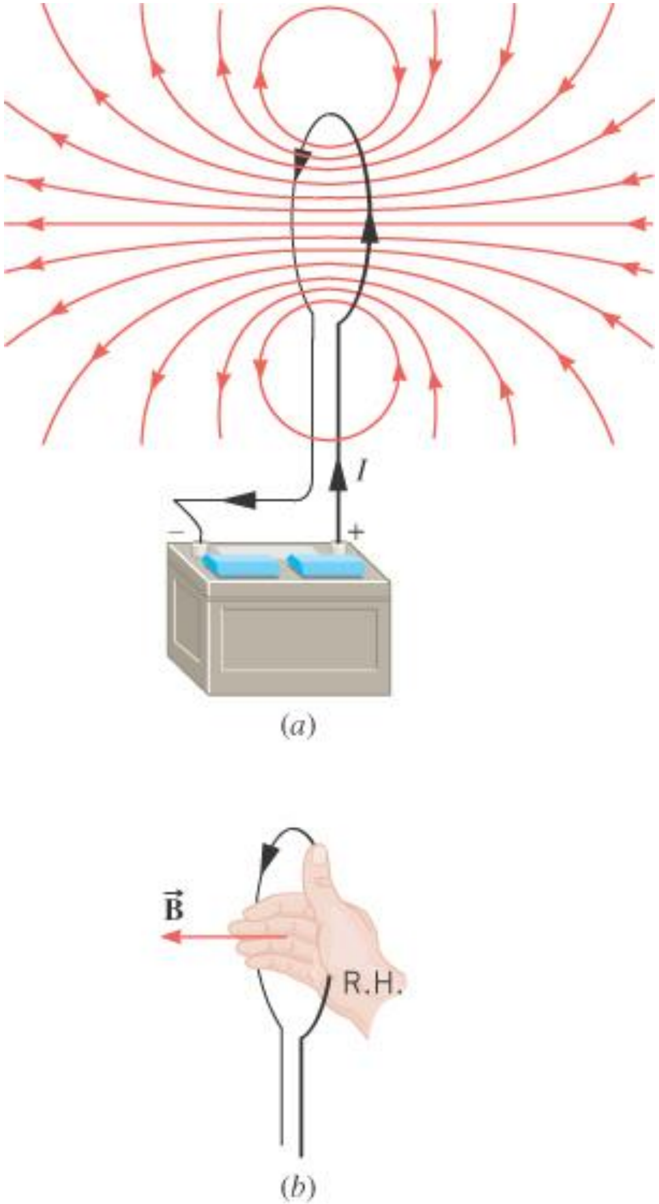
Is the coil attracted to, or repelled by the wire?



A LOOP OF WIRE

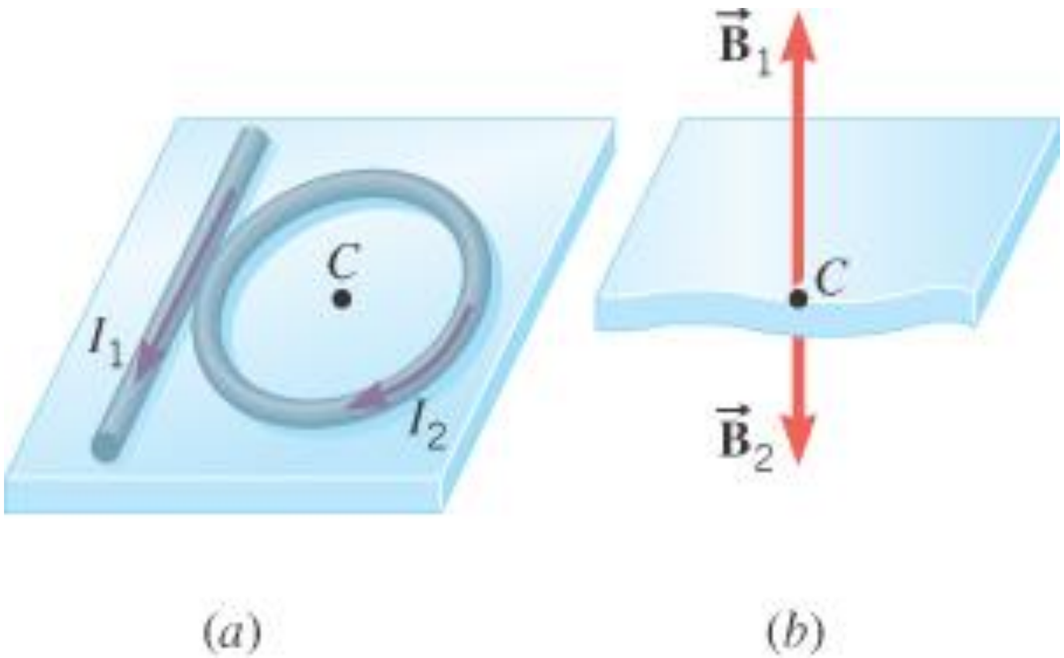
$$B = \frac{\mu_o I}{2R}$$

center of circular loop

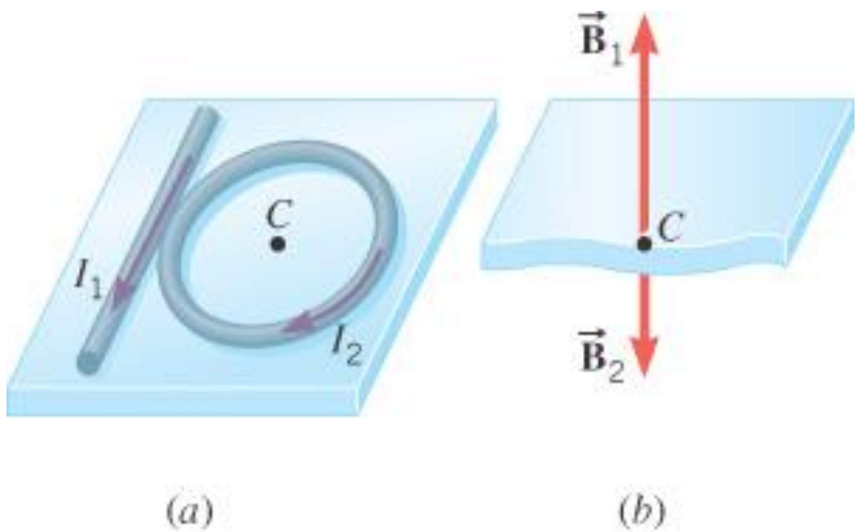


Example 10 Finding the Net Magnetic Field

A long straight wire carries a current of 8.0 A and a circular loop of wire carries a current of 2.0 A and has a radius of 0.030 m. Find the magnitude and direction of the magnetic field at the center of the loop.

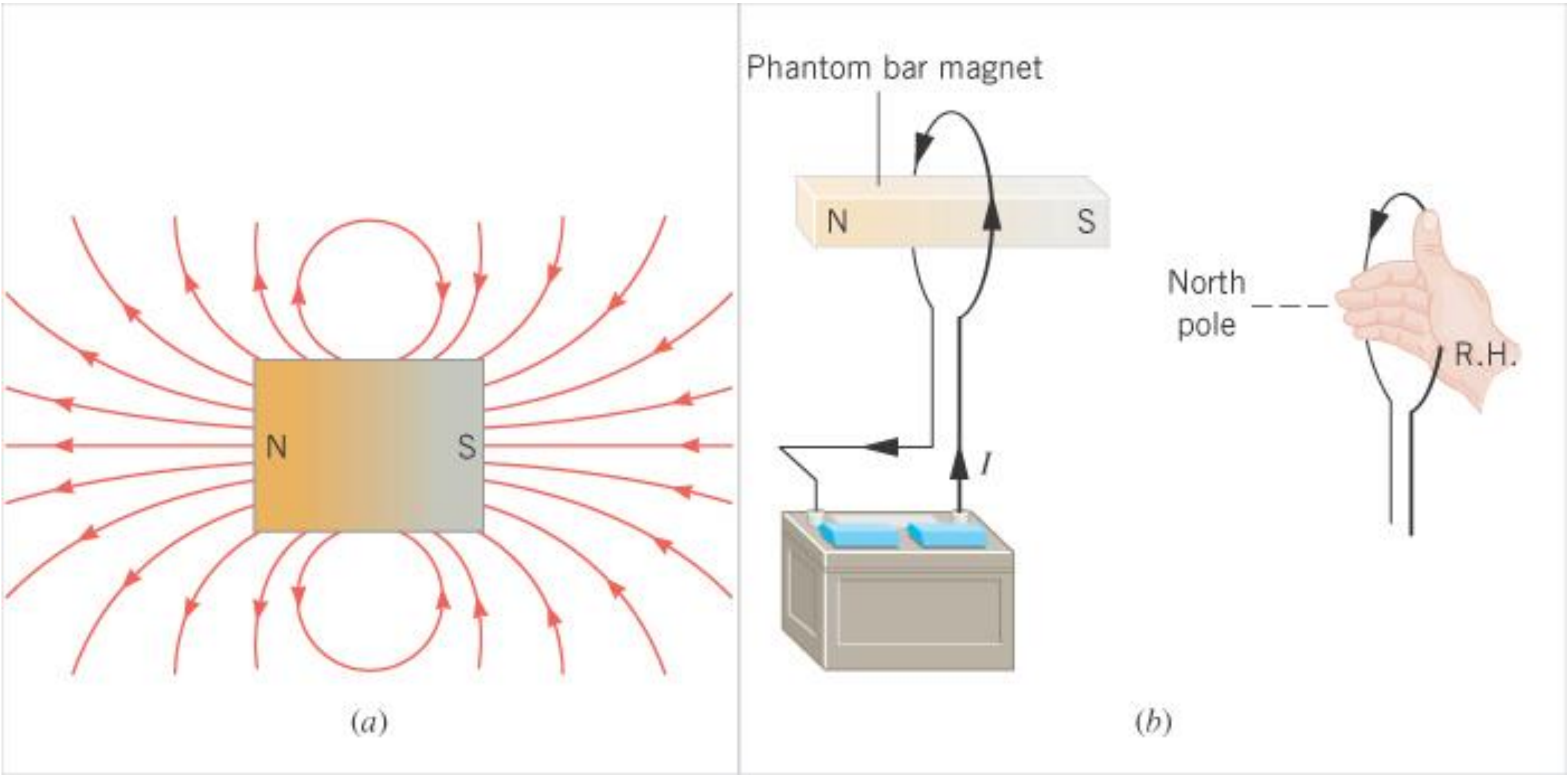


$$B = \frac{\mu_o I_1}{2\pi r} - \frac{\mu_o I_2}{2R} = \frac{\mu_o}{2}\left(\frac{I_1}{\pi r} - \frac{I_2}{R}\right)$$

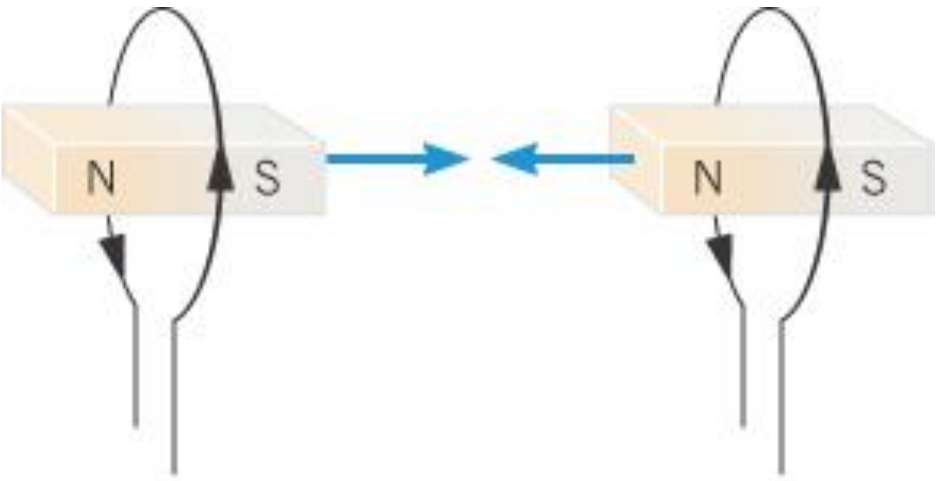


$$B = \frac{\left(4\pi \times 10^{-7}\ \mathrm{T\cdot m/A}\right)}{2}\left(\frac{8.0\ \mathrm{A}}{\pi\left(0.030\ \mathrm{m}\right)} - \frac{2.0\ \mathrm{A}}{0.030\ \mathrm{m}}\right) = 1.1\times 10^{-5}\ \mathrm{T}$$

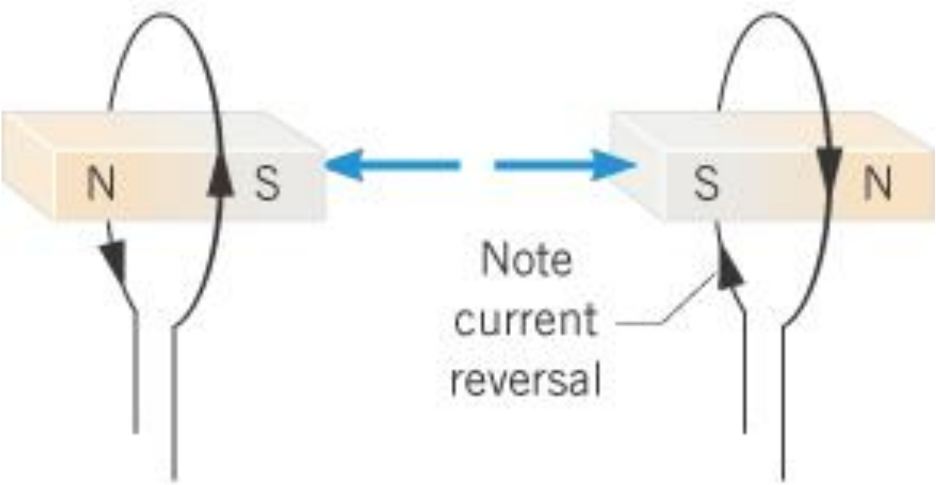
The field lines around the bar magnet resemble those around the loop.



21.7 Magnetic Fields Produced by Currents



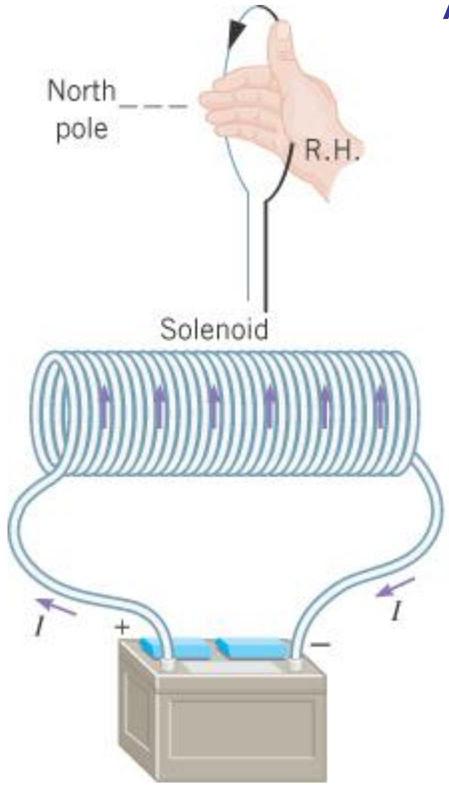
(a) Attraction

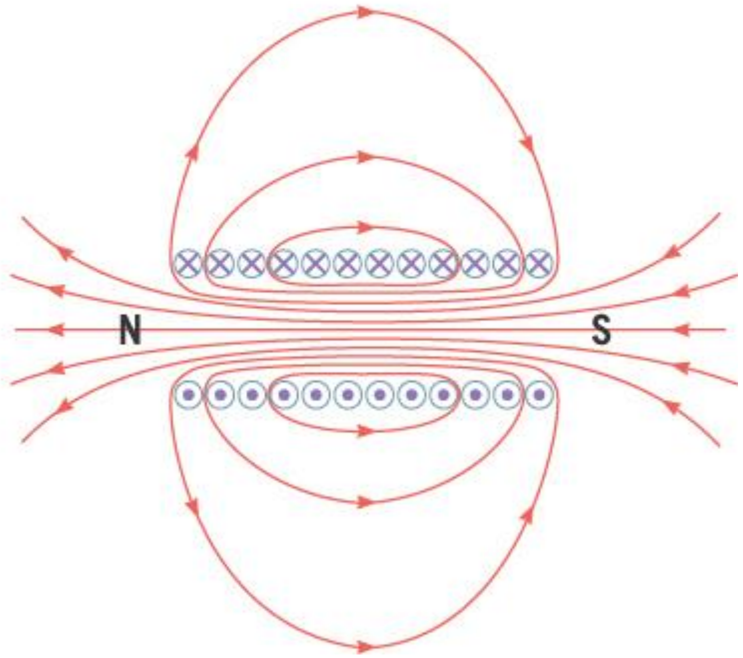


(b) Repulsion

21.7 Magnetic Fields Produced by Currents

A SOLENOID



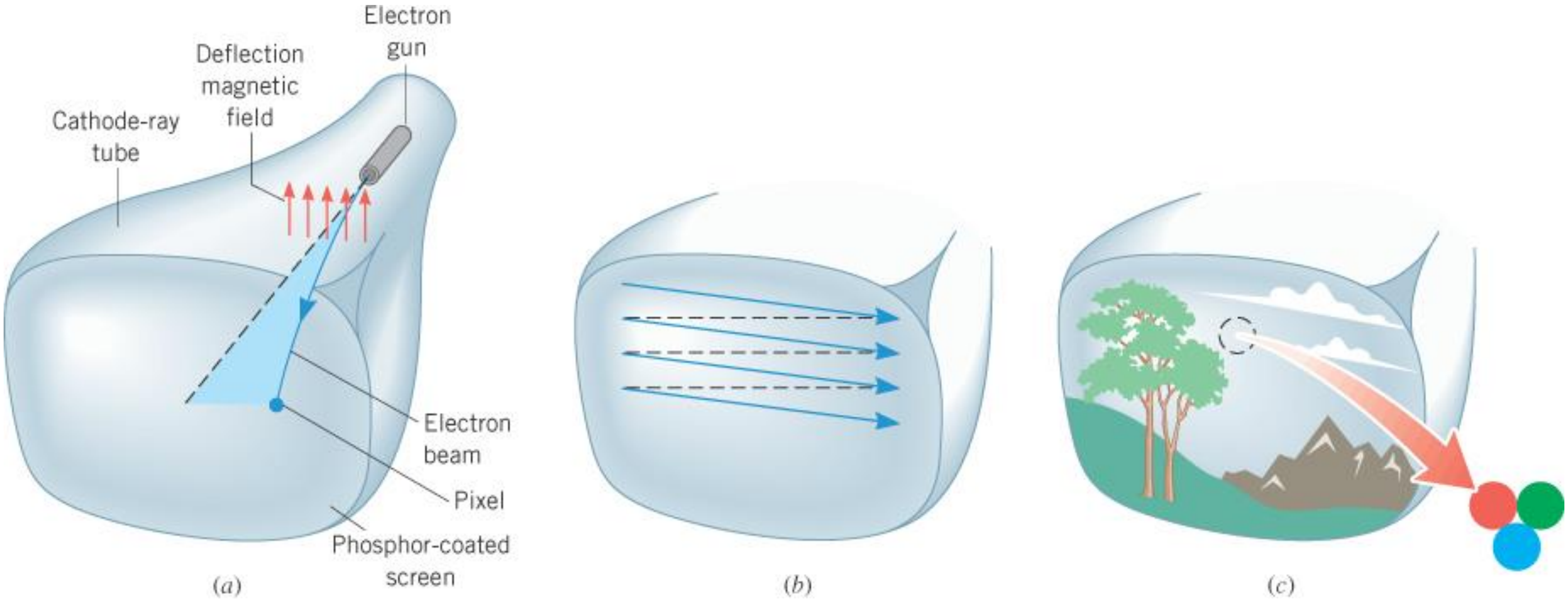


number of turns per unit length

Interior of a solenoid

$$B = \mu_o n I$$

A cathode ray tube.

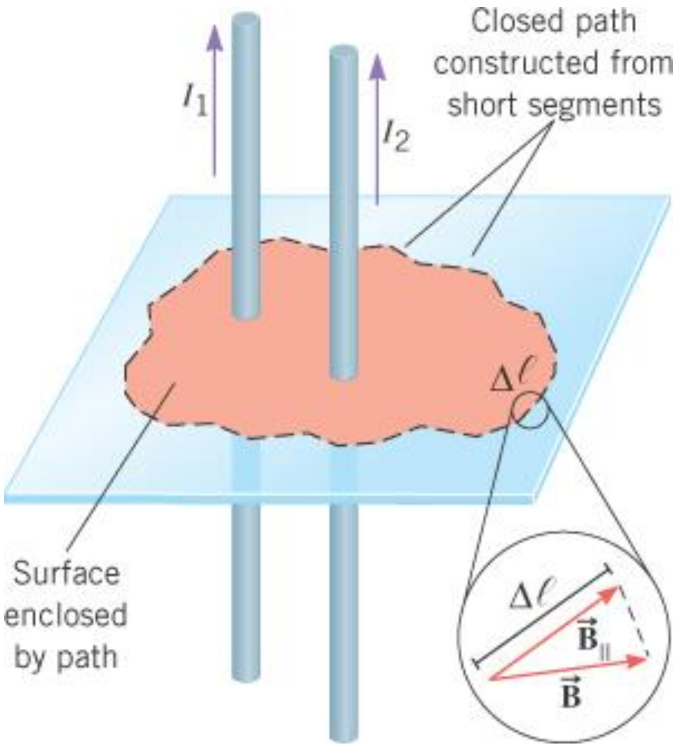


AMPERE'S LAW FOR STATIC MAGNETIC FIELDS

For any current geometry that produces a magnetic field that does not change in time,

$$\sum B_{\parallel} \Delta \ell = \mu_o I$$

net current passing through surface bounded by path



Example 11 An Infinitely Long, Straight, Current-Carrying Wire

Use Ampere's law to obtain the magnetic field.

$$\sum B_{\parallel}\Delta\ell = \mu_o I$$

$$\Downarrow$$

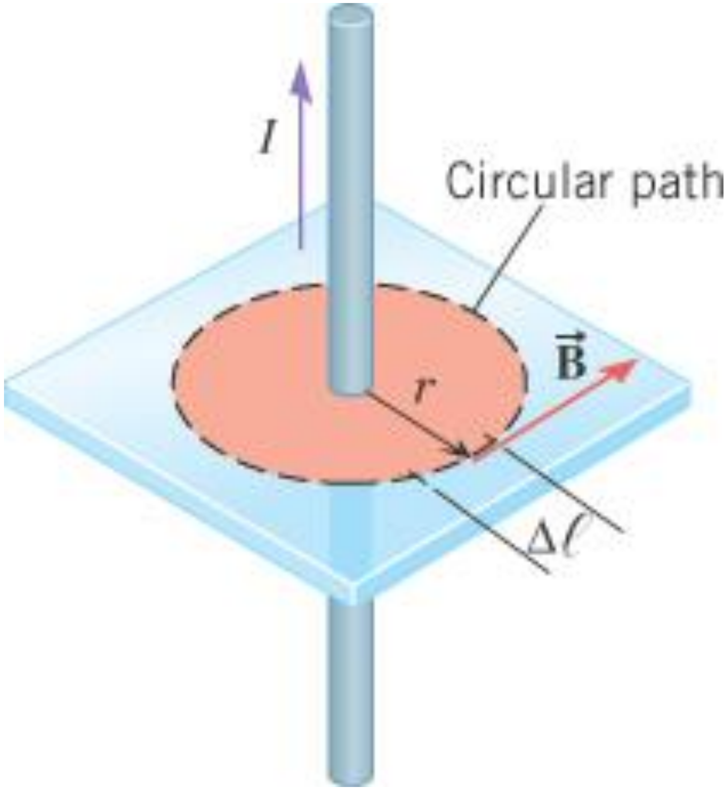
$$B\left(\sum \Delta\ell\right) = \mu_o I$$

$$\Downarrow$$

$$B 2\pi r = \mu_o I$$

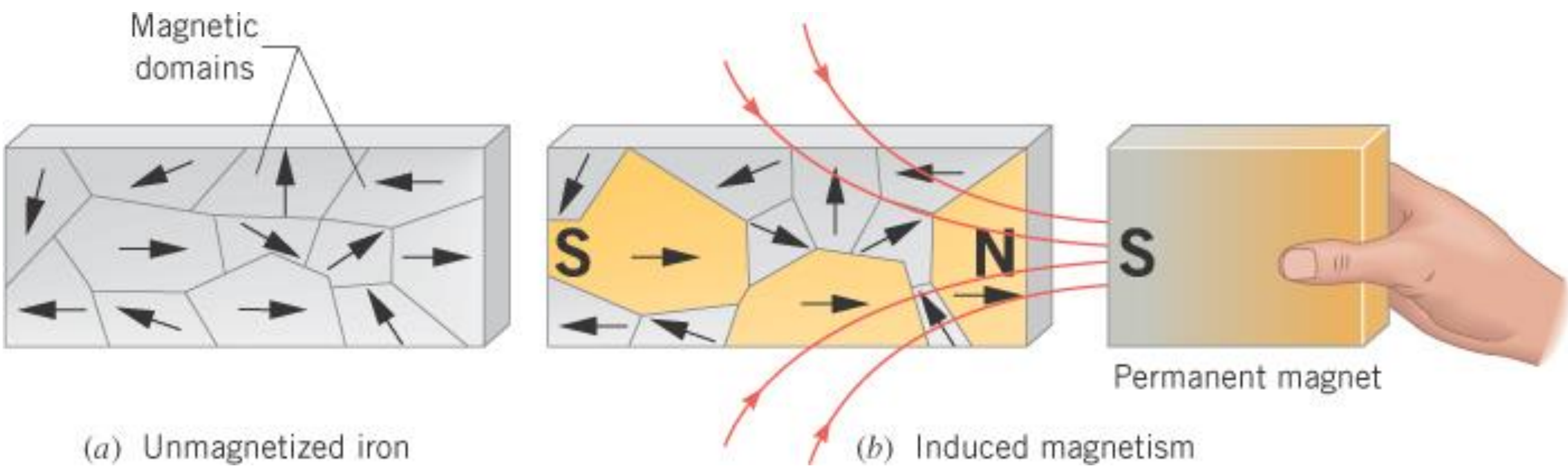
$$\Downarrow$$

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



The intrinsic "spin" and orbital motion of electrons gives rise to the magnetic properties of materials.

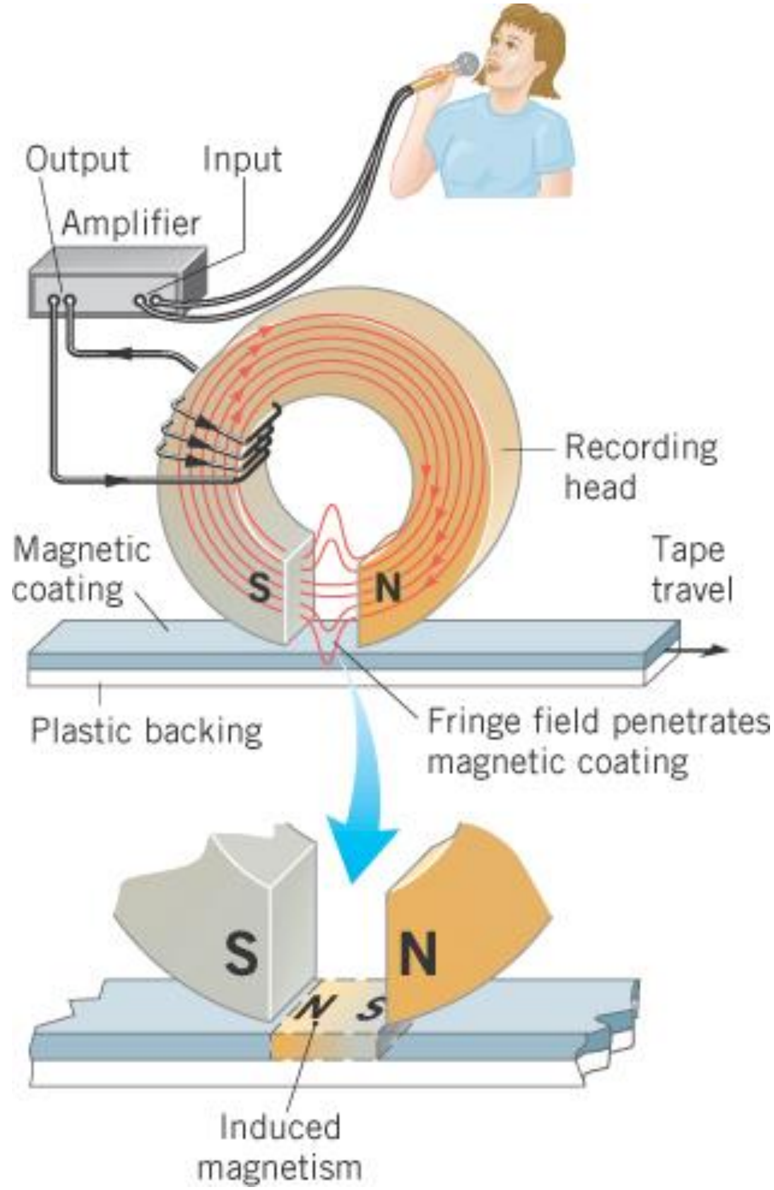
In ***ferromagnetic materials*** groups of neighboring atoms, forming ***magnetic domains,*** the spins of electrons are naturally aligned with each other.



(*a*) Unmagnetized iron

(*b*) Induced magnetism

21.9 Magnetic Materials



21.9 Magnetic Materials