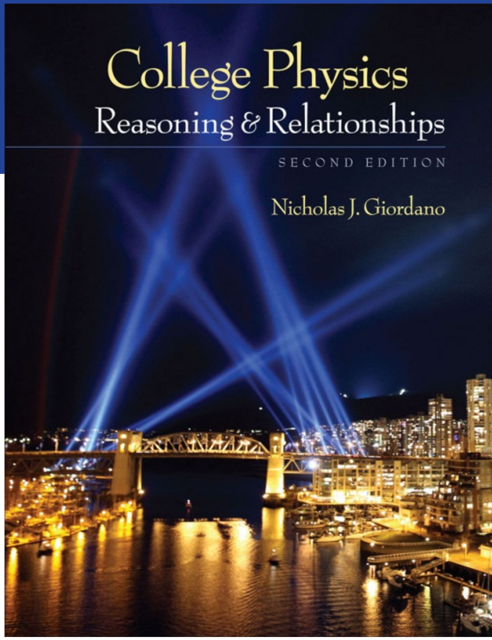

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Chapter 20

Magnetic Fields and Forces

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Magnetism

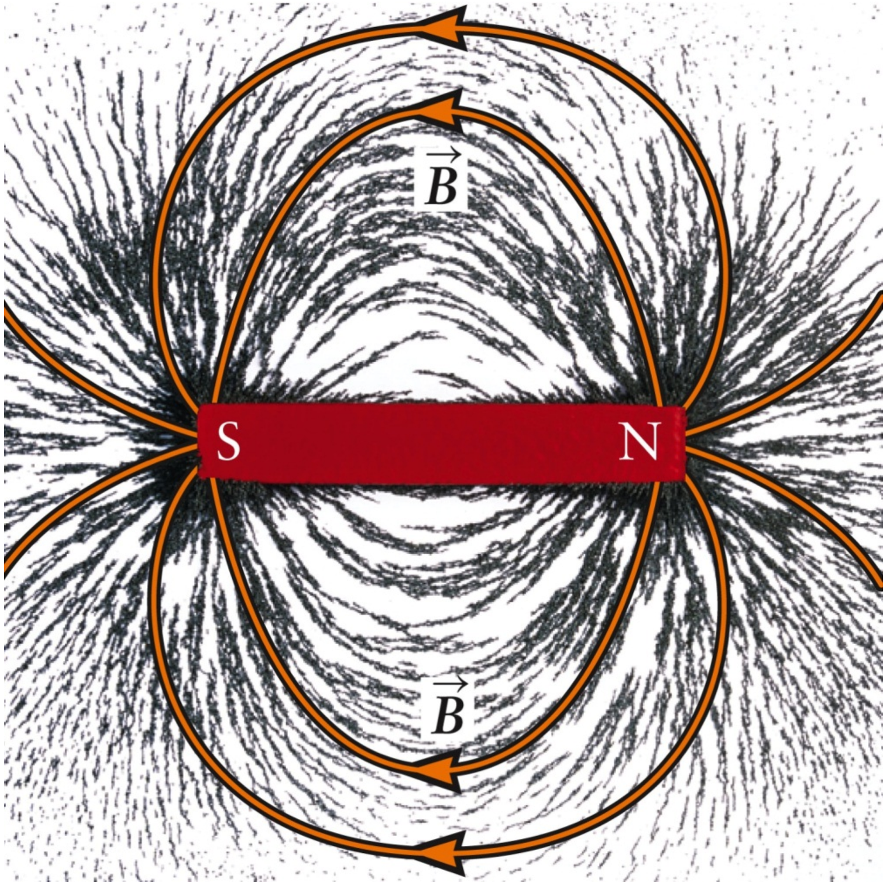
- Magnetic fields are produced by moving electric charges
- Magnetic fields exert forces on other moving charges
- Focus of this chapter
  - To understand the sources of magnetic fields and the fields they produce
  - To calculate the magnetic force on a charged particle
- Magnetism and electricity are connected
  - Connections will be studied in later chapters

Magnets

- The first observations of magnetic fields involved permanent magnets
  - Many ancient cultures discovered natural magnetic properties of materials
    - Magnetite
- Permanent magnetic applications include
  - Compass needles
  - Speakers
  - Computer hard disks

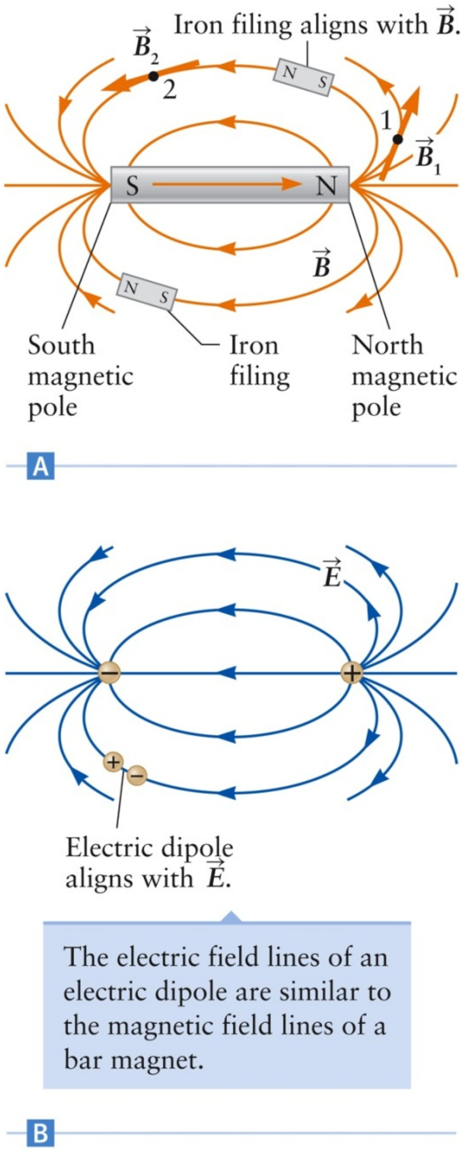
Bar Magnet

- A bar magnet is a permanent magnet in the shape of a bar
- The symbol for the magnetic field is $\vec{\mathbf{B}}$
- The magnetic field lines can be deduced from the pattern of the iron filings
  - The filings are small, needle-shaped, permanent magnets



Magnetic Field Lines

- The magnetic poles are indicated at the ends of the bar magnet
  - Called north and south
- The magnetic poles are analogous to positive and negative charges
- The north poles of the filings are attracted to the south pole of the bar magnet

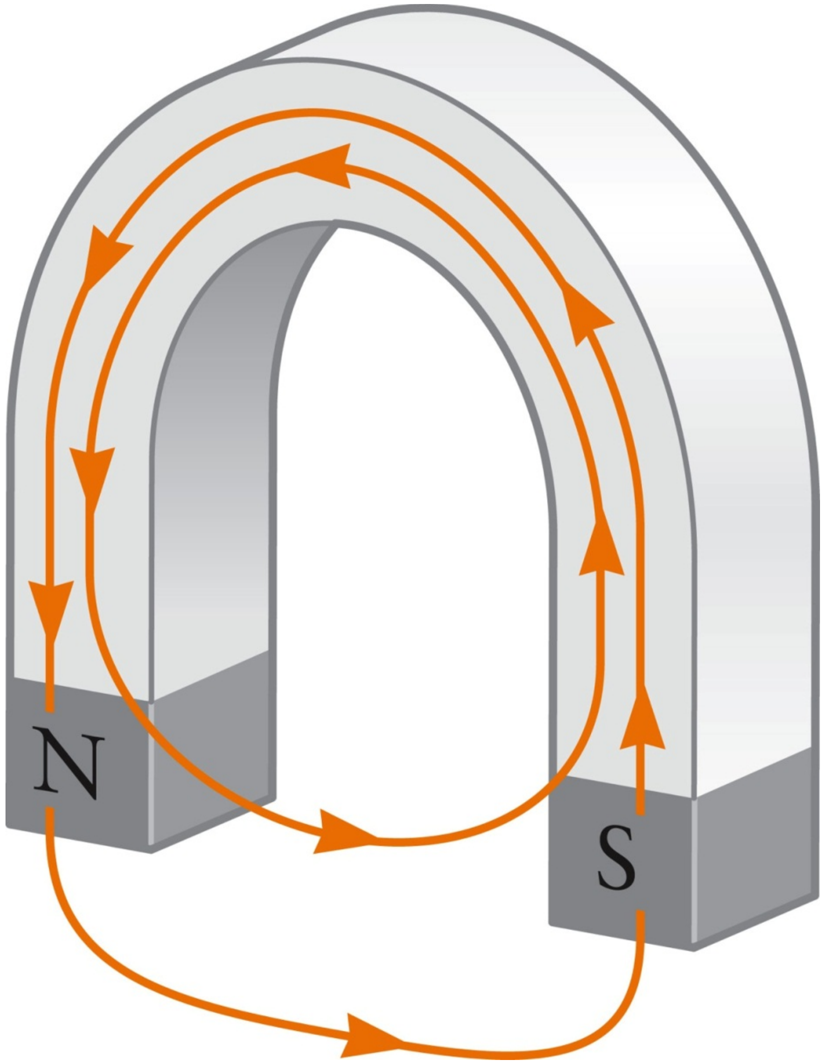


Magnetic Fields, cont.

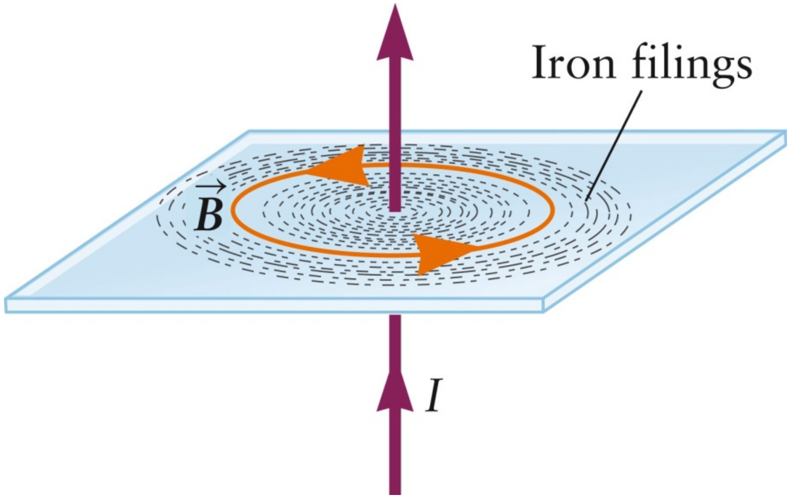
- The iron filings align parallel to the magnetic field lines
  - As shown in fig. 20.2 A
- The SI unit of the magnetic field is the tesla (T)
- The magnetic field lines go from the north pole toward the south pole
- The magnitude of the field decreases as you move farther from a pole
- The magnetic field lines form closed loops
  - A general property of magnetic fields, not just bar magnets

Horseshoe Magnet

- Can be made by bending a bar magnet
- There are poles at the ends of the horseshoe
- The field is largest in the horseshoe gap
- The field is directed across the gap



Magnetic Field from Current



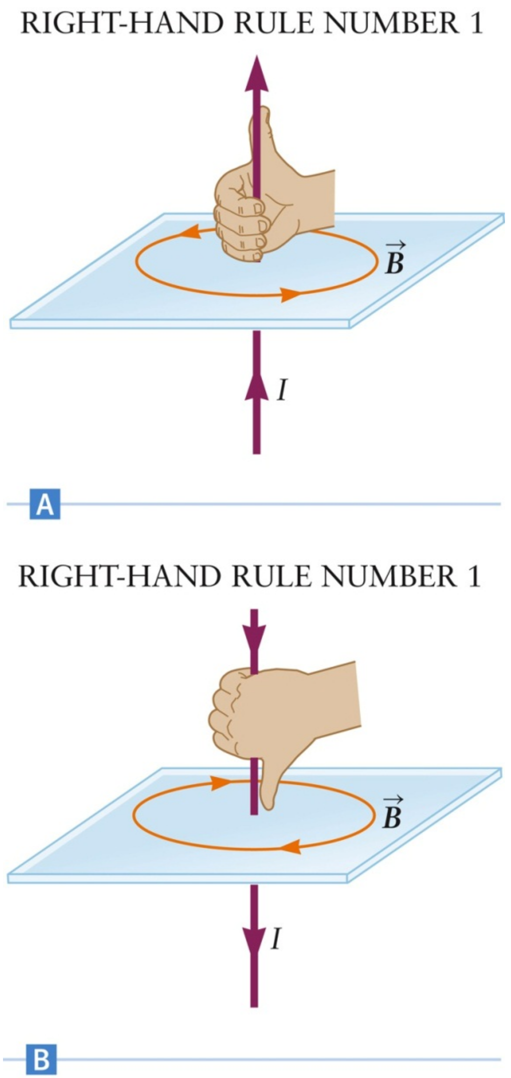
- Moving charges produce magnetic fields
  - An electric current consists of moving charges, so it will produce a magnetic field
- The iron filings show the magnetic field pattern due to the current

Magnetic Field from Current, cont.

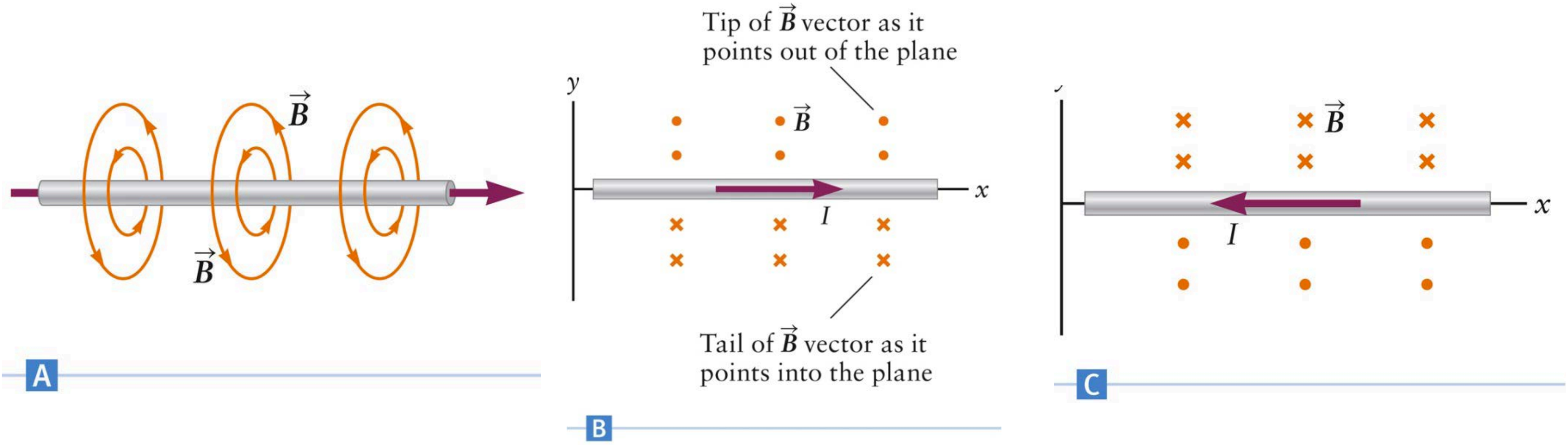
- For a straight wire, the magnetic field lines form circles
- The magnitude of the field decreases as the distance from the wire increases
- The direction of the field is always tangent to the circles
- The direction of the field is given by the **right-hand rule**

Right-Hand Rule Number 1

- Point the thumb of your right hand in the direction of the current
  - You thumb will be parallel to the wire
- Curling the fingers of your right hand around the wire gives the direction of the magnetic field
- If the direction of the current is reversed, the direction of the field is also reversed



Plotting Field Lines

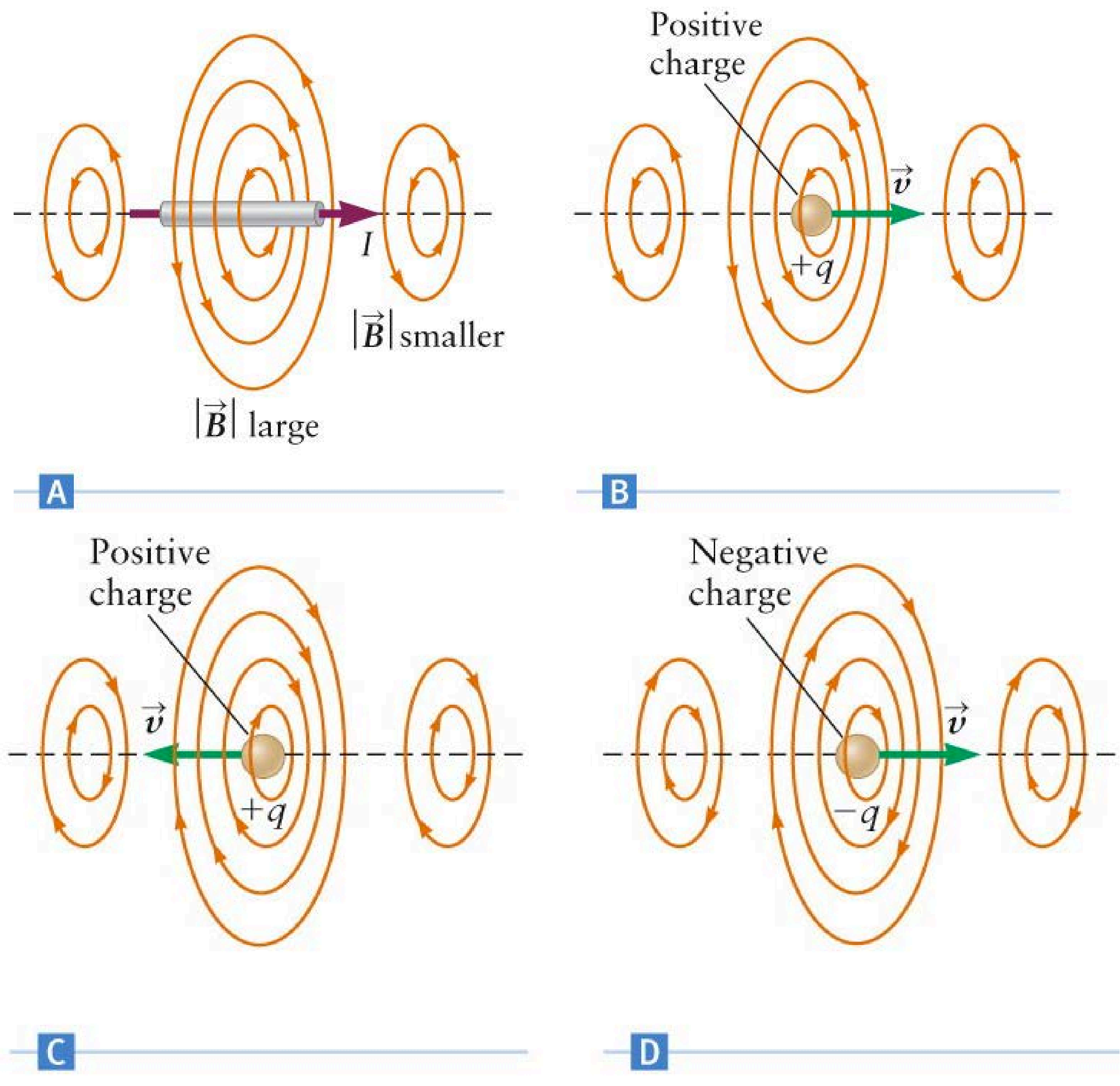


- Field lines are three-dimensional
- A large dot (•) indicates the tip of the vector when it points out of the plane
- A cross (×) denotes the tails of the vector when it points into the plane

Charges and Magnetic Fields

- The electric current can be modeled as a collection of positive electric charges
- The charges would be moving with a velocity parallel to the current direction
- The direction of the magnetic field is given by the right-hand rule
  - Your thumb will be in the direction of the velocity of the charges
- A positive charge moving to the left produces the same magnetic field as a negative charge moving to the right

Magnetic Fields of Moving Charges

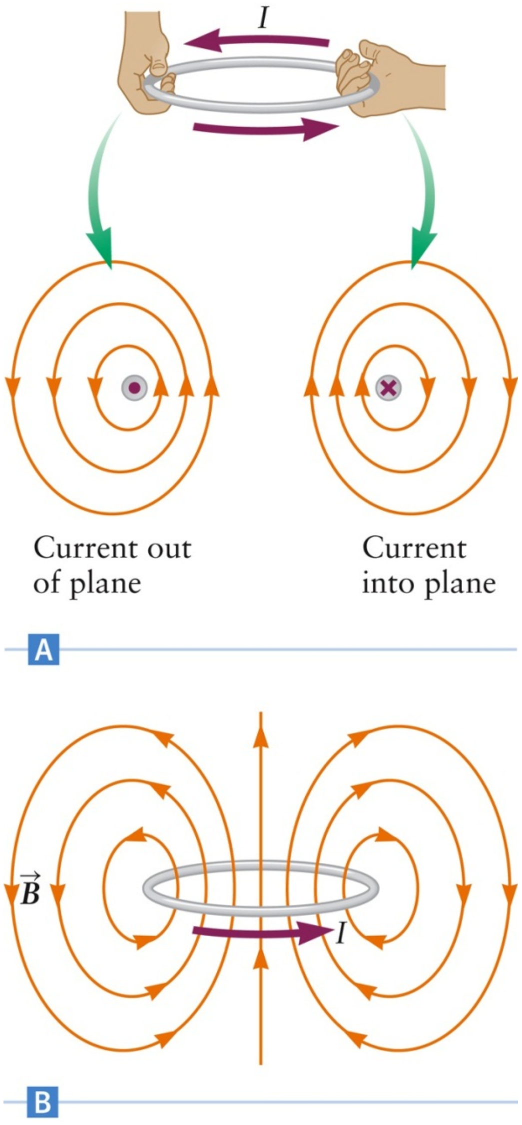


Superposition

- The ***Principle of Superposition*** states the total magnetic field produced by two or more different sources is equal to the sum of the fields produced by each source individually
  - The principle of superposition can be used to find the pattern of magnetic field lines in virtually all situations

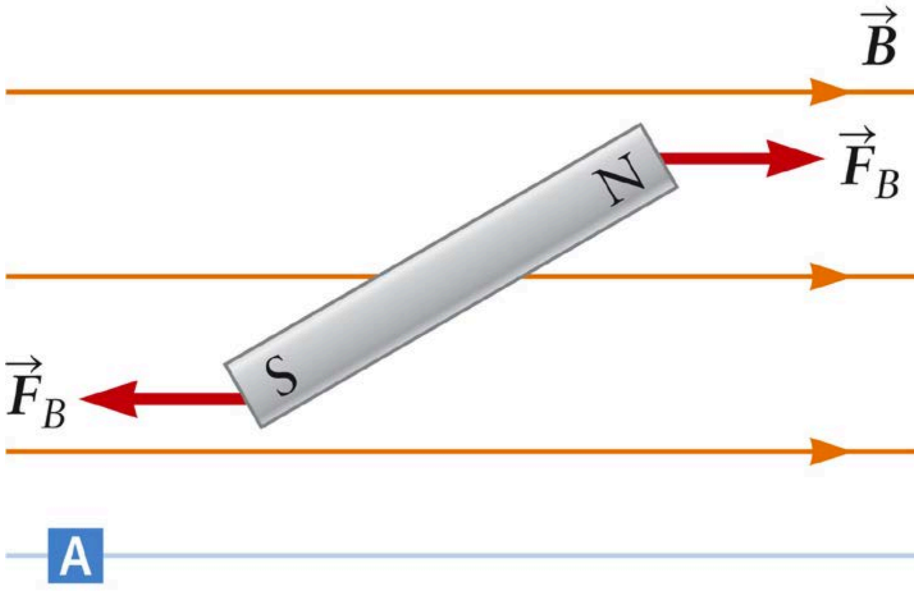
Magnetic Field and Current Loop

- Treat the loop as many small pieces of wire
- Apply the right-hand rule to find the field from each piece of wire
- Applying superposition gives the overall pattern shown in B



Magnetic Forces & Bar Magnets

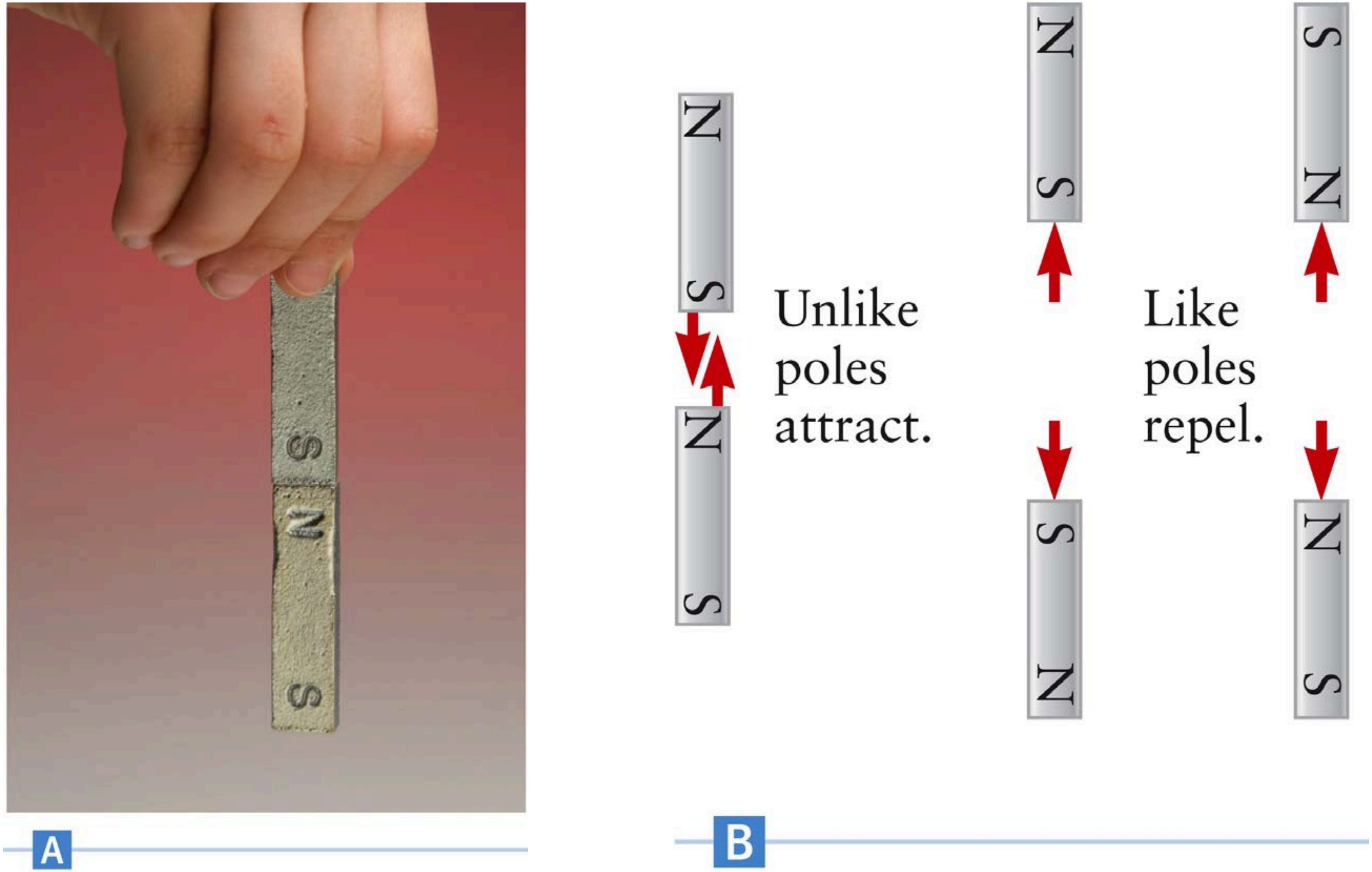
- To determine the total force on the bar magnet, you must look at the forces on each pole
- The total force is zero
- The total torque is non-zero
- The torque acts to align the bar magnet along the magnetic field



Magnetic Moment

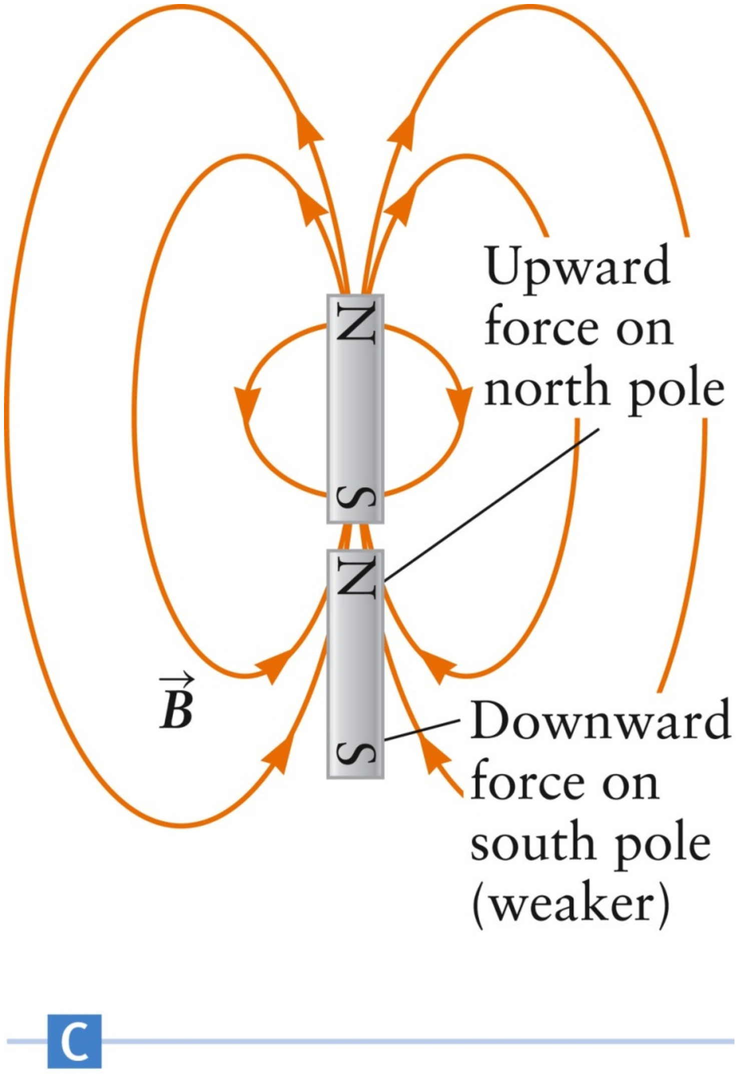
- The bar magnet possesses a ***magnetic moment***
  - The bar magnet is similar to an electric dipole
  - The poles of the magnet can be thought of as a sort of "magnetic charge"
- The north pole of one magnet will attract the south pole of another magnet
  - Unlike poles attract
- Like poles will repel
- Similar to electric charges

Like and Unlike Poles



Magnetic Force – Another View

- The axes of the magnets are aligned
- The upward force on the north pole of the lower magnet is stronger than the downward force on its south pole
  - Due to distances
- The total force on the lower magnet is upward
  - The magnets attract



Comparing Electric and Magnetic Fields and Forces

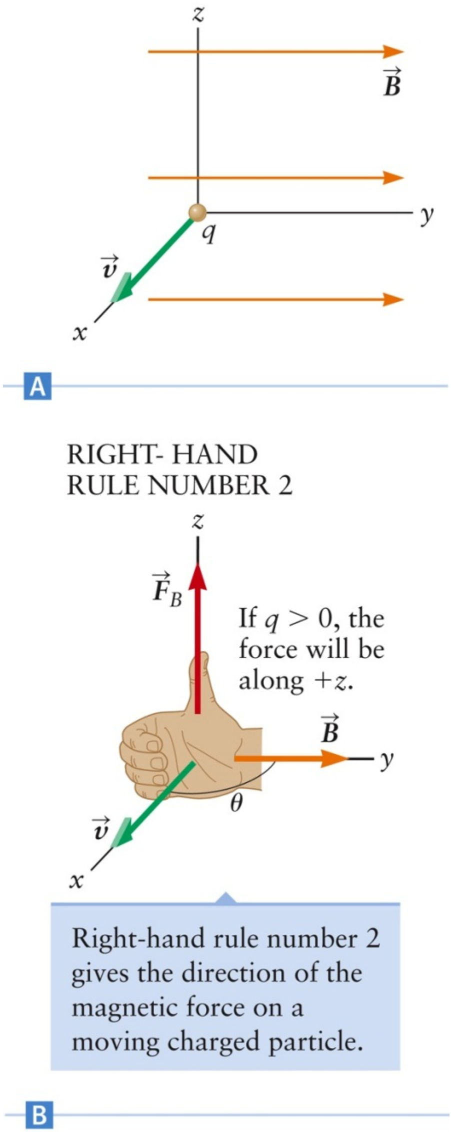
- There are many similarities in the behavior of electric charges and magnetic poles
  - Unlike charges and unlike poles attract
  - Like charges and like poles repel
- North and south magnetic poles always occur in pairs
  - It is not possible to obtain an isolated magnetic pole

Force on Moving Charge

- Magnetic force acts on individual charges
- The force depends on the velocity of the charge
  - If the charge is not moving, there is no magnetic force
- If a positive charge, q, is moving with a given velocity in an external magnetic field, then the magnitude of the force on the charge is
  - $F_B = q\ v\ B \sin\theta$
  - The angle θ is the angle between the velocity and the field

Right Hand Rule Number 2

- To determine the direction of the force, use right hand rule number 2
- Point the figures of your right hand in the direction of the velocity and wrap them in the direction of the field
- Your thumb points in the direction of the force



Right Hand Rule Number 2, cont.

- Take the smallest angle between the velocity and the field
- This process is for a positive charge
  - For a negative charge, reverse the direction of the force
- The magnetic force is always perpendicular to both the magnetic field and the particle's velocity

Comparison of Forces

- The magnetic force is dependent on velocity
  - Electric and gravitational fields are not
- The direction of the magnetic force is always perpendicular to both the magnetic field and the particle’s velocity
  - The field and the force are always parallel for electric and gravitational forces

Units: Details

- From the equation for the magnitude of the magnetic force,

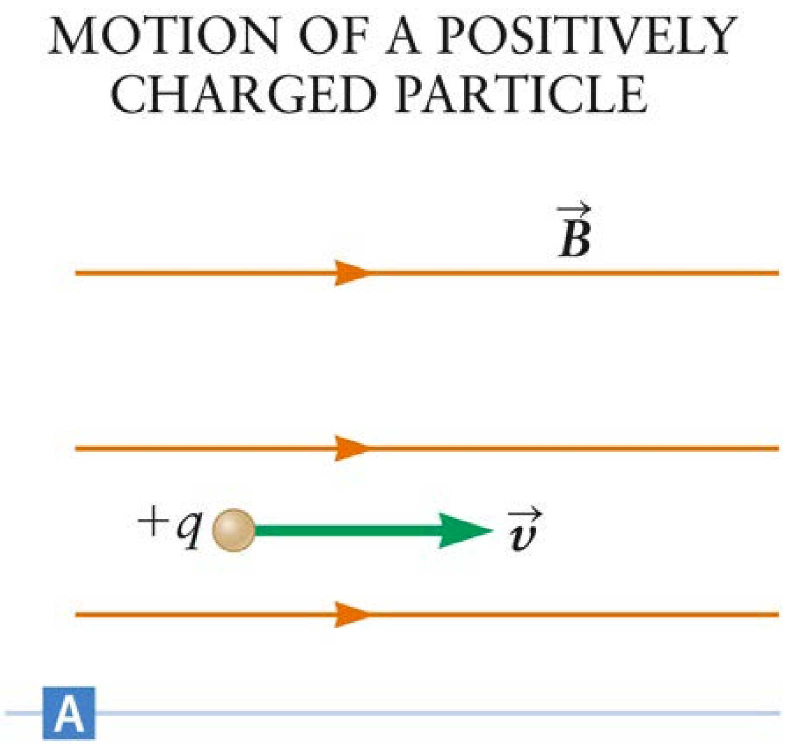
$$1N = 1\frac{C \cdot m \cdot T}{s}$$

- The Tesla (T) is then

$$1T = 1\frac{N \cdot s}{C \cdot m} = 1\frac{kg}{C \cdot s}$$

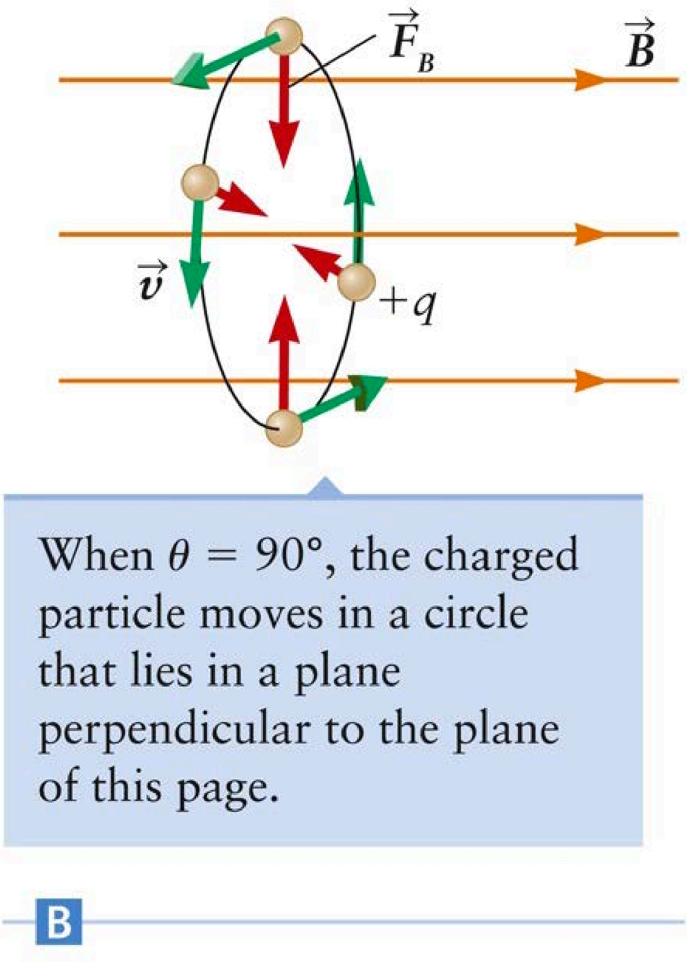
Motion of a Charged Particle

- Assume a charged particle moves parallel to the magnetic field
- The angle between the velocity and the field is zero
- Therefore, the force is also zero
  - Since $\sin \theta = 0$



Motion of a Charged Particle, 2

- Assume a charged particle moves perpendicular to the magnetic field
- The angle between the velocity and the field is 90°
- Therefore, the force is qvB
- The particle will move in a circle



When $\theta = 90°$, the charged particle moves in a circle that lies in a plane perpendicular to the plane of this page.

Motion, 2, cont.

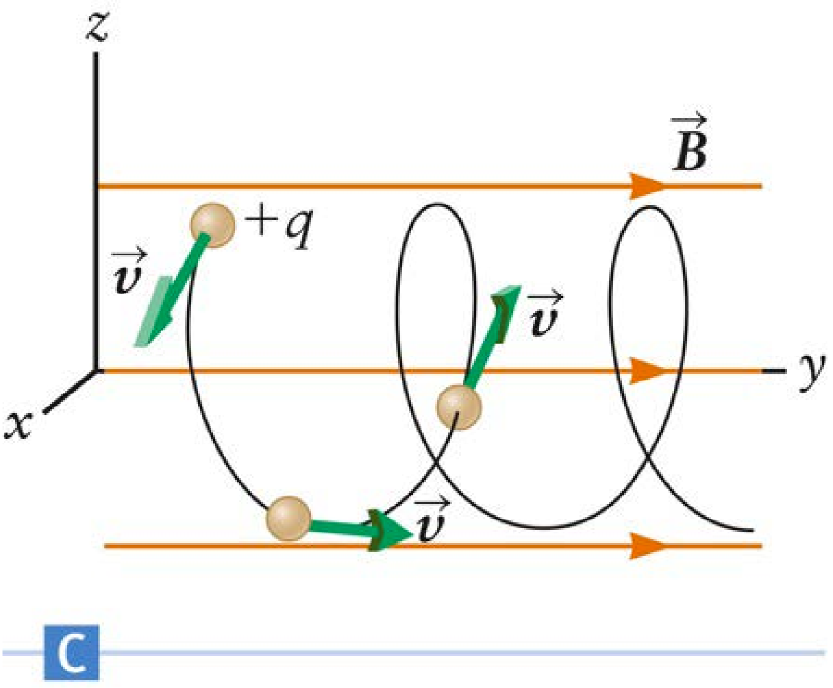
- The circle lies in the plane perpendicular to the magnetic field lines
- The radius of the circle can be calculated from noting there must be a centripetal force acting on the particle

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

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

Motion of a Charged Particle, 3

- Assume a charged particle moves neither parallel nor perpendicular to the magnetic field
- The angle between the velocity and the field varies
- The path of the particle is helical
  - The charged particle will spiral around the magnetic field lines



Motion of a Charged Particle, Summary

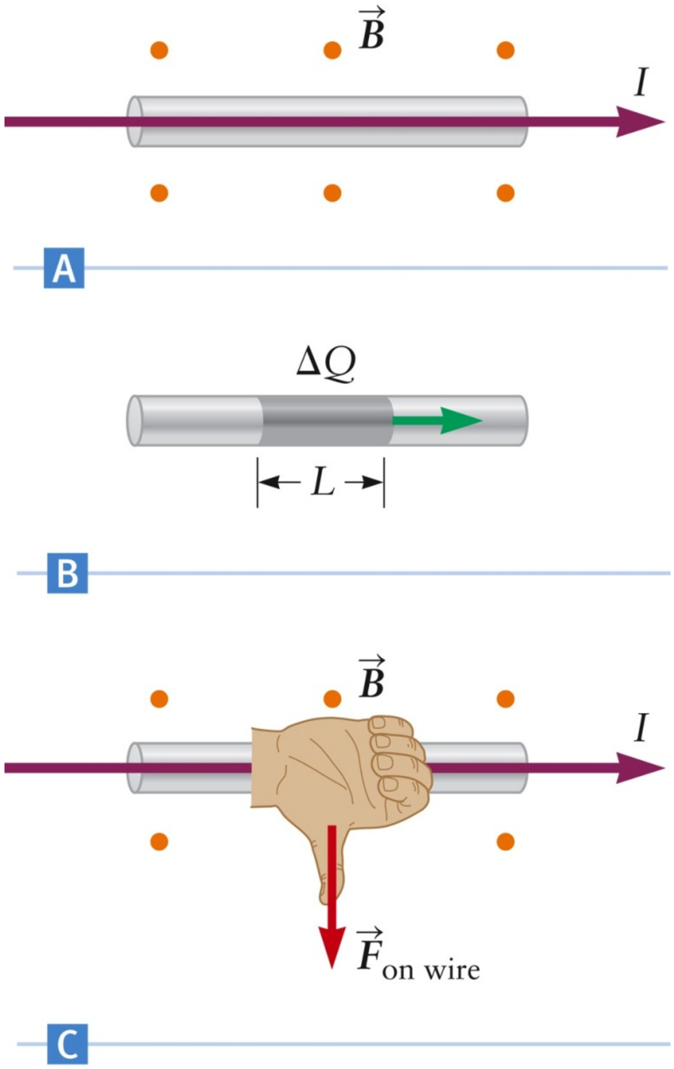
- If a charged particle has a velocity parallel to the magnetic field, the magnetic force on the particle is zero
- If a charged particle is moving perpendicular to a constant magnetic field, the particle will move in a circle
- If a charged particle is moving with a velocity at some angle between 0° and 90°, it will spiral around the magnetic field lines

Right Hand Rules, Summary

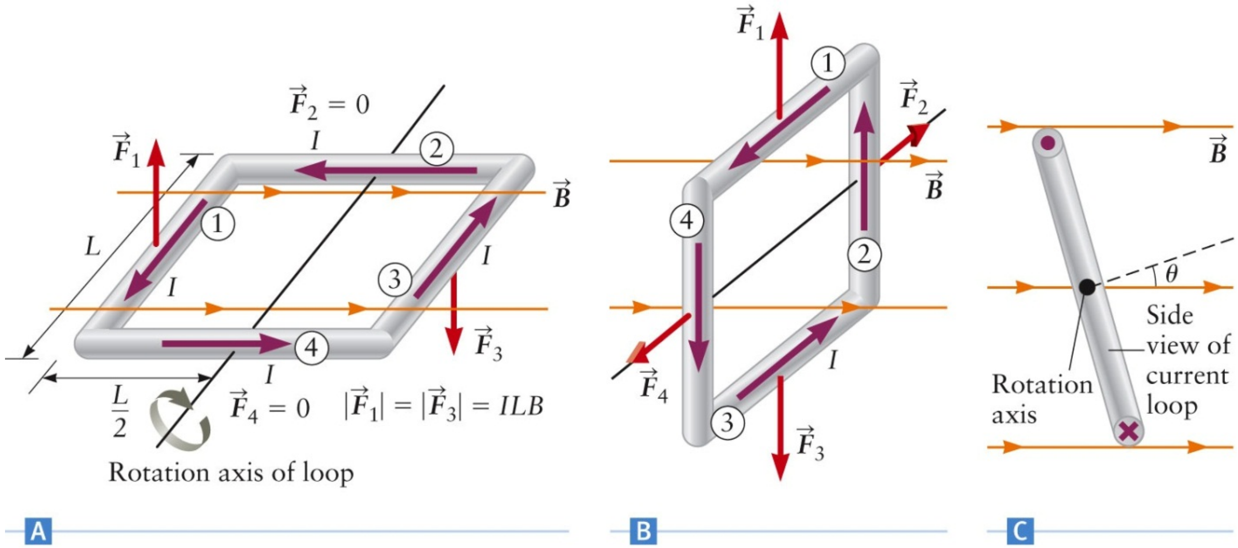
- ***Right-hand rule number 1***: Finding the direction of the magnetic field from an electric current
  - Place the thumb of your right hand along the direction of the current
  - Curl your fingers; they will then give the direction of the magnetic field as the field lines encircle the current
- ***Right-hand rule number 2***: Finding the direction of the magnetic force on a moving charge, q
  - Point the fingers of your right hand along the direction of the velocity
  - Curl your fingers in the direction of the field
    - Curl your fingers through the smallest angle that connects the velocity and the field
  - If q is positive, the magnetic force is parallel to your thumb. If q is negative, the magnetic force is in the opposite direction

Magnetic Force on a Current

- An electric current is a collection of moving charges, a force acts on a current
- From the equation of the force on a moving charge, the force on a current-carrying wire is $F_{\text{on wire}} = I L B \sin\theta$
- The direction of the force is given by the right-hand rule number 2



Torque on a Current Loop



- A magnetic field can produce a torque on a current loop
- Assume a square loop with sides of length *L* carrying a current *I* in a constant magnetic field
- The directions of the forces can be found from right-hand rule 2

Torque, cont.

- On two sides, the current is parallel or antiparallel to the field, so the force is zero on those sides
- The forces on sides with the current perpendicular to the field are in opposite directions and produce a torque on the loop
  - Denoted sides 1 and 3 in fig. 20.24
- When the angle between the loop and the field is θ, the torque is

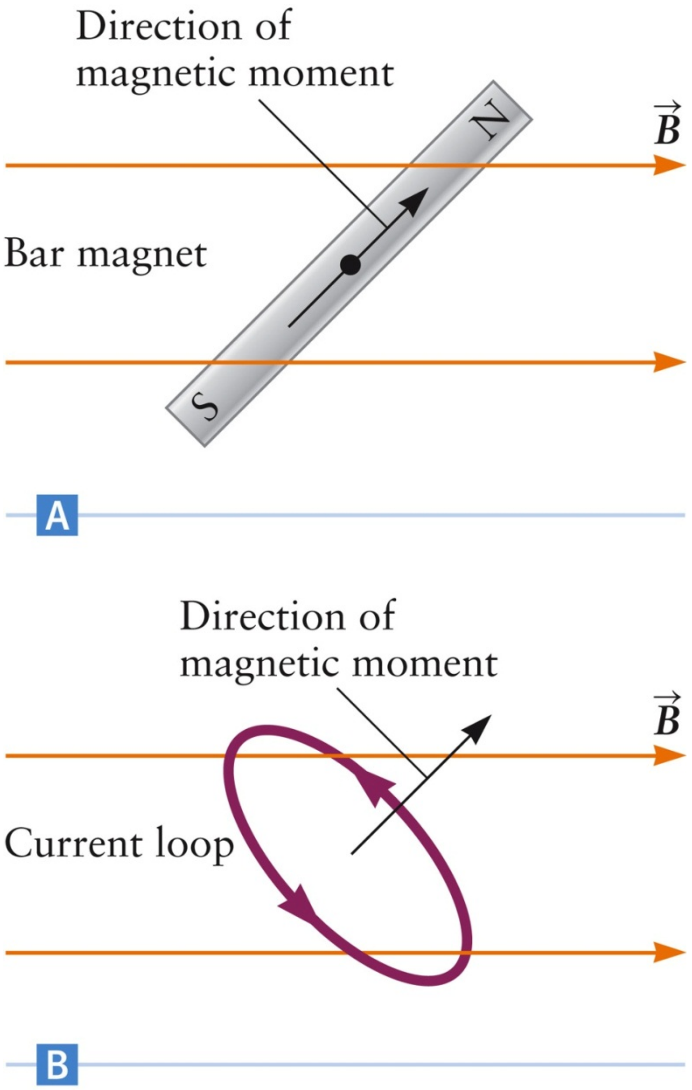
$$\tau = I\,L^2\,B \sin\theta$$

- For different shapes, this becomes

$$\tau = I\,A\,B \sin\theta$$

Magnetic Moment

- For a current loop, the magnetic moment is I A
- The direction of the magnetic moment is either along the axis of the bar magnet or perpendicular to the current loop
- The strength of the torque depends on the magnitude of the magnetic moment

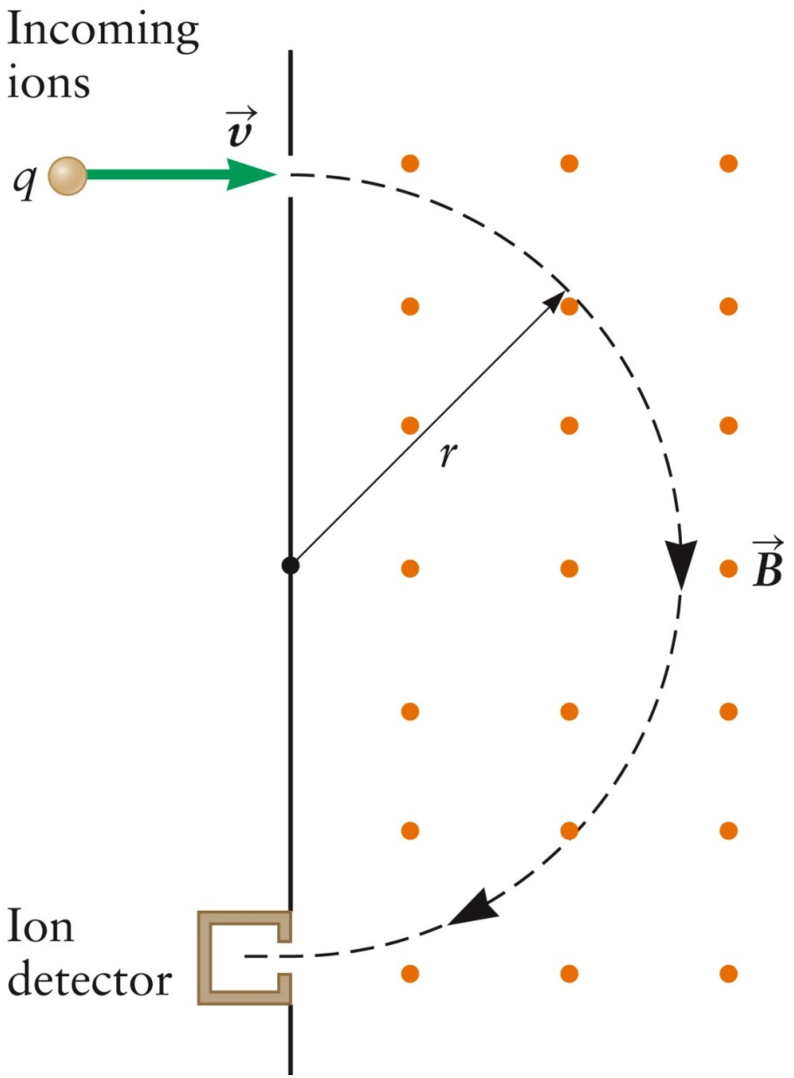


Motion in Two Fields

- The motion of an electric charge in the presence of both an electric field and a magnetic field is of interest
- Two applications include
  - Mass spectrometer
  - Hall Effect

Mass Spectrometer

- Allows for the separation of ions according to their mass or charge
- The ions enter with some speed v
- They pass into a region where the magnetic field is perpendicular to the velocity



Mass Spectrometer, cont.

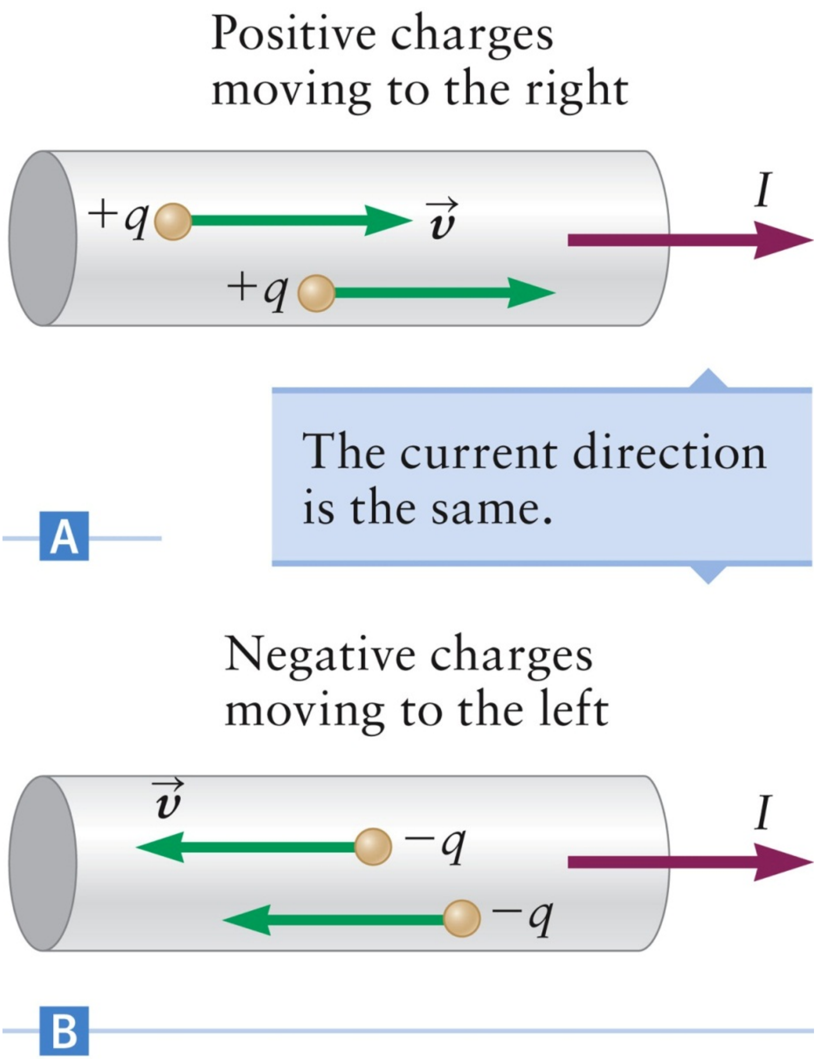
- The ions travel in a circle in the mass spectrometer
- The radius of the circle is *mv/qB*
  - Ions with different masses will travel in arcs with different radii
- Mass spectrometer can also be used to find the composition of a material
  - Measure the values of *v*, *B* and *r*
  - Calculate *q/m*
    - Charge to mass ratio

Mass Spectrometer Uses

- Mass spectrometers are now being used in work on genomics and proteomics
  - A protein is “cut” into fragments
    - Peptides
  - The fragments are analyzed in a mass spectrometer
  - The ratios of q / m are found
  - The pattern of mass spectrometer intensities is also found
  - The information is compared to the mass spectrometer data on known peptides
  - Based on the comparison, the sequence of the original protein can be determined

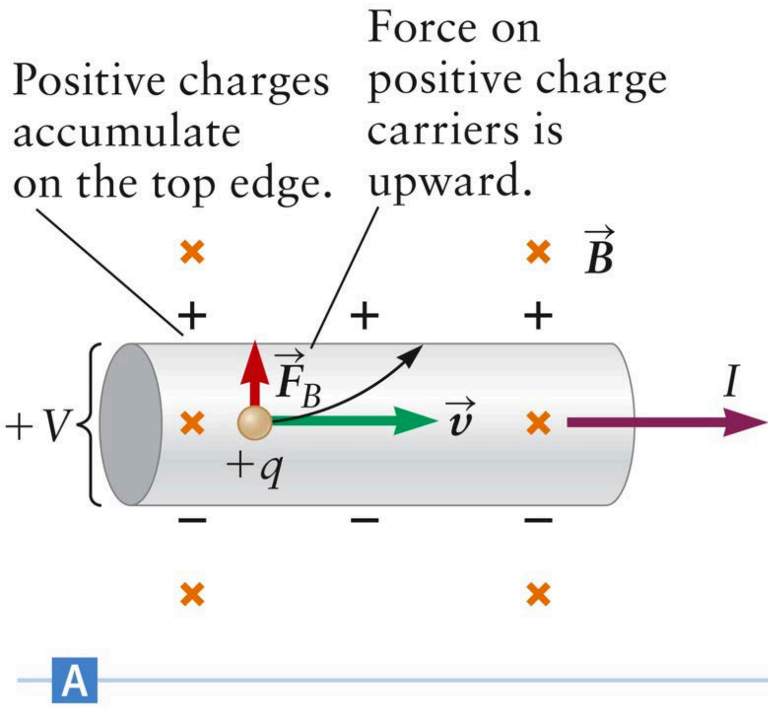
Hall Effect

- An electric current is produced by moving electric charges
- A particular value of current can be produced by positive charges moving to the right or negative charges to the left
- The Hall Effect can distinguish between the two options



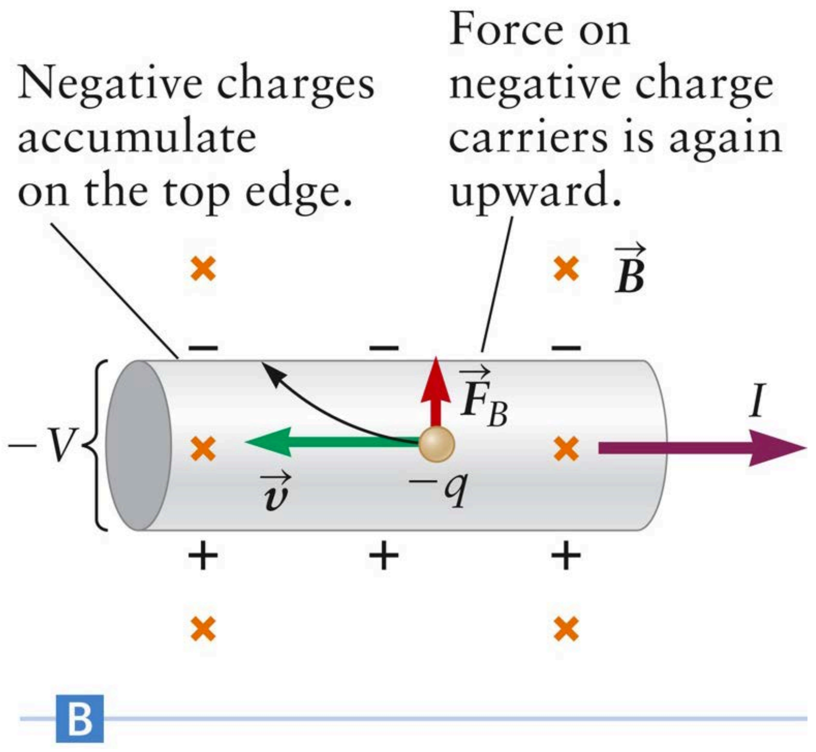
Hall Effect, cont.

- Place a current-carrying wire in a magnetic field directed perpendicular to the current
- With positive charge carriers, an excess positive charge accumulates on the top edge



Hall Effect, final

- With negative charge carriers, an excess negative charge accumulates on the top edge
- Measuring the potential difference distinguishes between positive or negative charge carriers producing the current



Ampère's Law

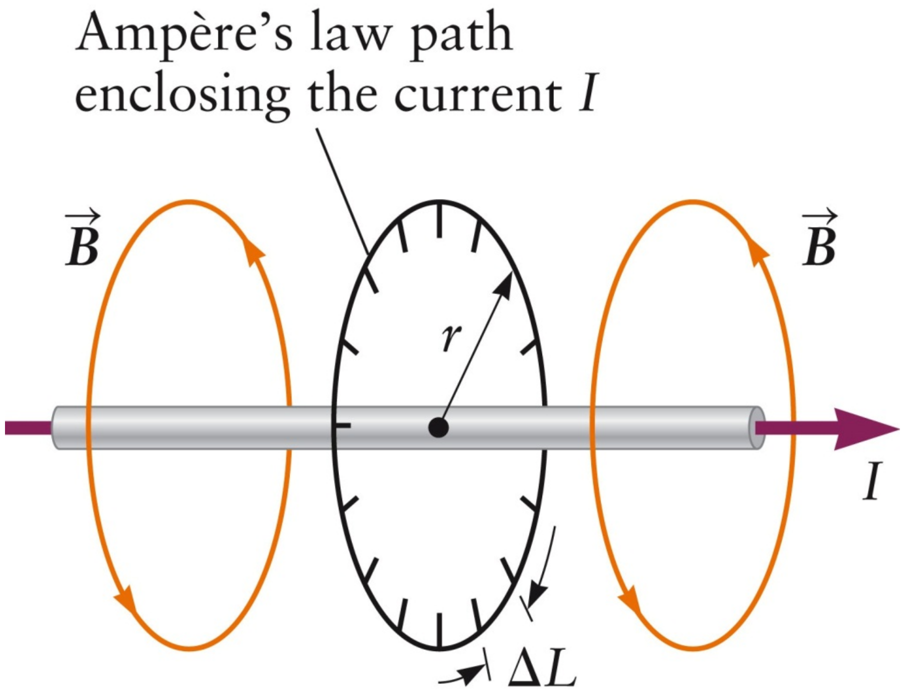
- There are two ways to calculate the magnetic field produced by a current
  - One way treats each small piece of wire as a separate source
    - Similar to using Coulomb's Law for an electric field
    - Mathematically complicated
  - Second way is to use Ampère's Law
    - Most useful when the field lines have high symmetry
    - Similar to using Gauss's Law for an electric field

Ampère's Law, cont.

- Relates the magnetic field along a path to the electric current enclosed by the path
- For the path shown, Ampère's Law states that

$$\sum_{\substack{closed\\ path}} B_{\parallel}\,\Delta L = \mu_o\, I_{enclosed}$$

  - μ_o is the ***permeability of free space***
  - $\mu_o = 4\pi \times 10^{-7}\ T \cdot m / A$



Magnetic Field of a Long Straight Wire

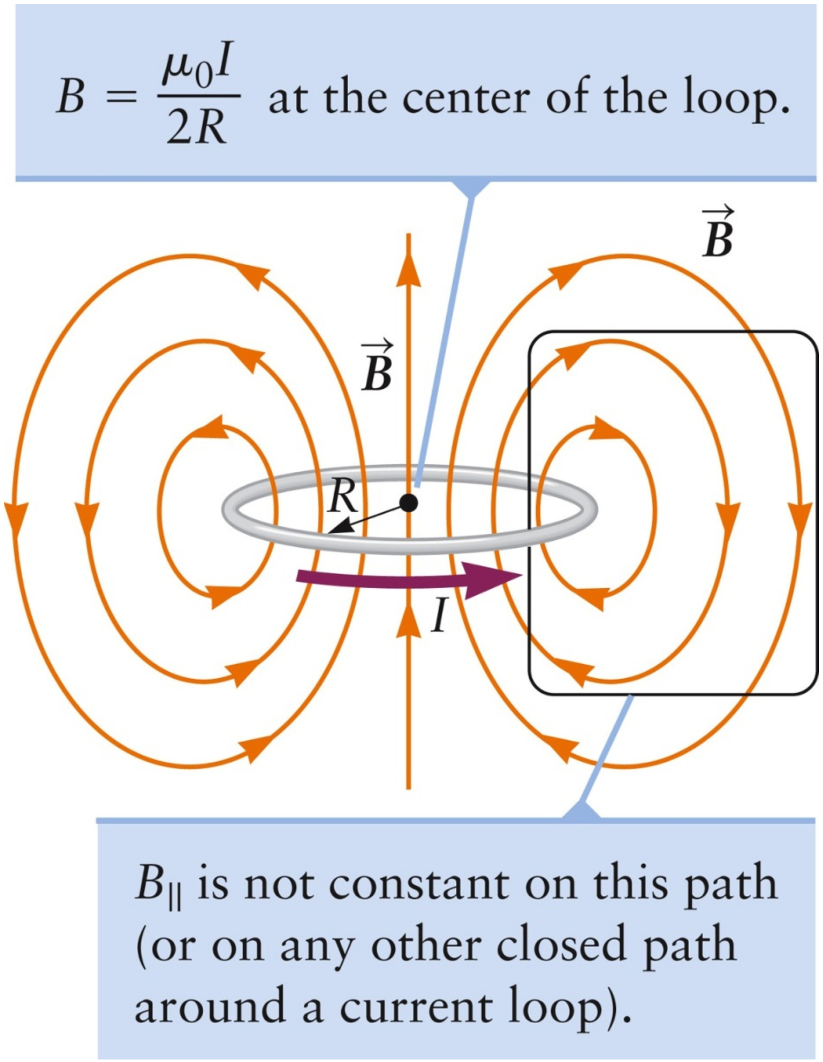
- If B varies along the path, Ampère's Law can be impossible to apply in practice
- Ampère's Law can be used to find the magnetic field near a long, straight wire
- $B_{||}$ is the same all along the path
- If the circular path has a radius *r,* then the total path length is 2 π r
- Applying Ampère's Law gives

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

Field from a Current Loop

- It is not possible to find a path along which the magnetic field is constant
  - So Ampère' s Law cannot be easily applied
- From other techniques, the field at the center of the loop is

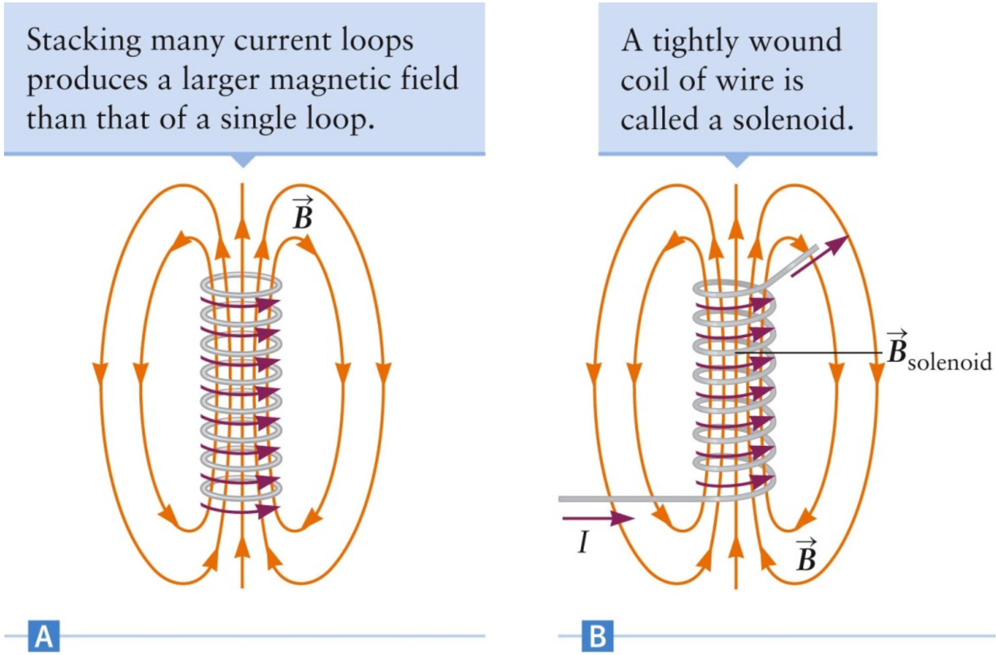
$$B = \frac{\mu_o I}{2R}$$



Notes About Ampère's Law

- In some cases, there is no path around a current for which the magnetic field is constant along the entire path
- Ampère's Law may not lead to a simple way of finding the magnetic field in such cases
- Ampère's Law is still true in cases where the magnetic field varies

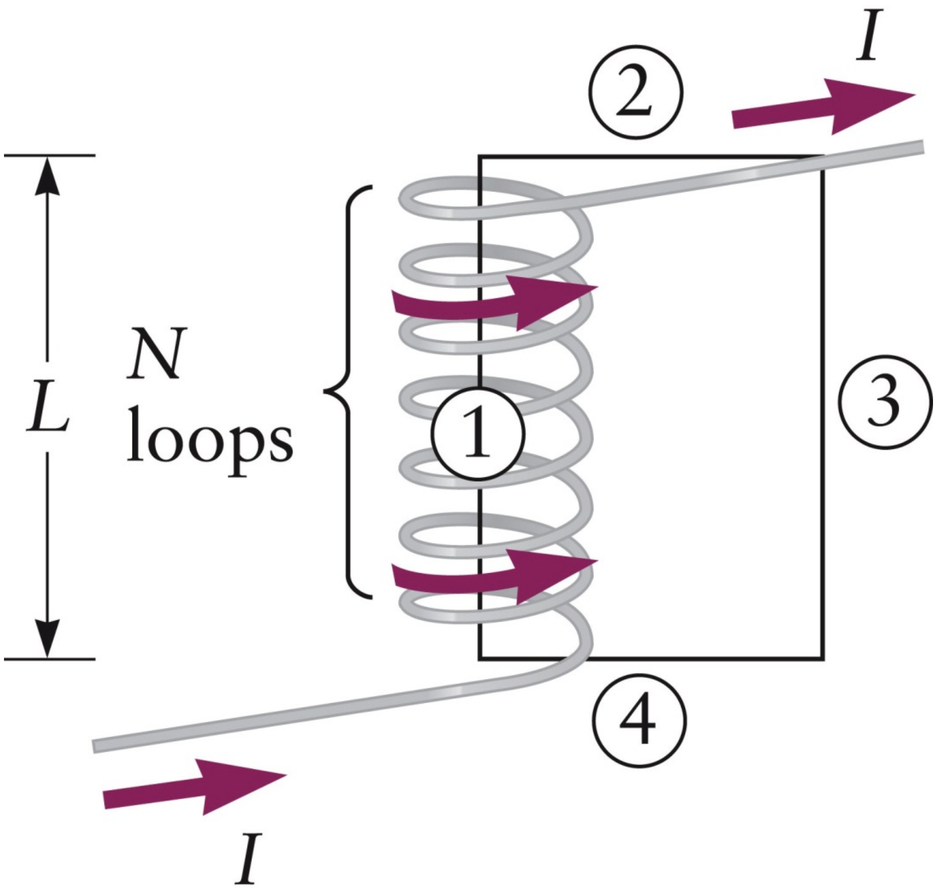
Field Inside a Solenoid



- By stacking many loops close together, the field along the axis is much larger than for a single loop
- A helical winding of wire is called a ***solenoid***
  - More practical than stacking single loops

Solenoid, cont.

- For a very long solenoid, it is a good approximation to assume the field is constant inside the solenoid and zero outside
- Use the path shown in the figure
- Only side 1 contributes to the magnetic field



Solenoid, final

- The magnetic field inside the solenoid is given by

$$B_{solenoid} = \frac{\mu_o N I}{L}$$

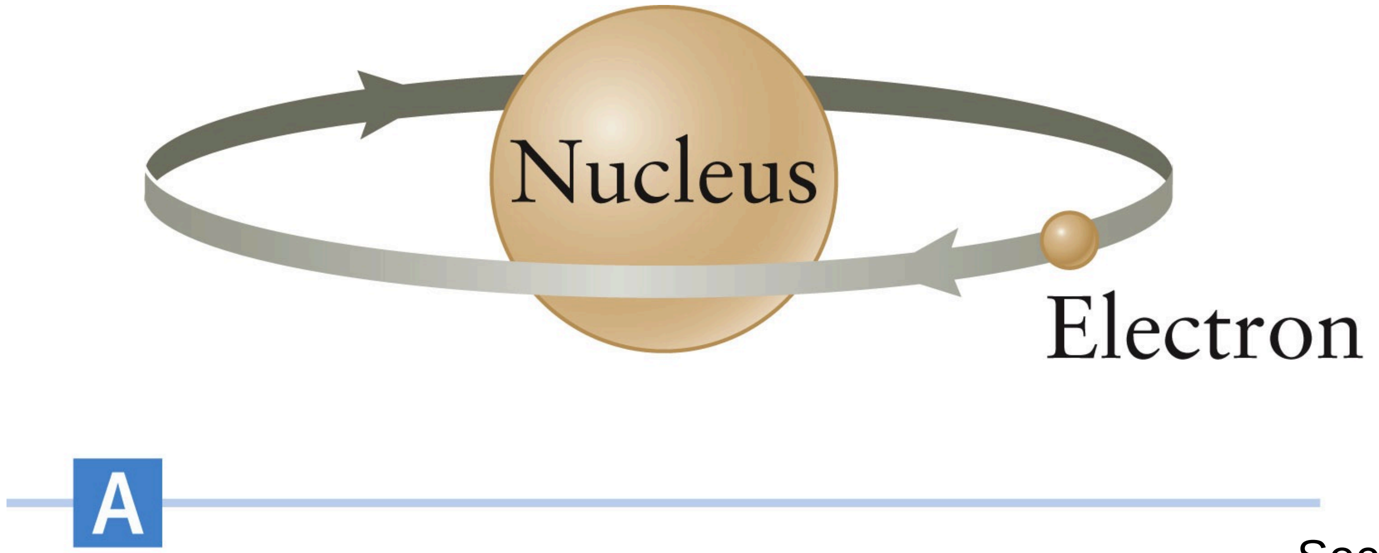
  - For a solenoid with a length much greater than the diameter

Magnetic Materials

- Magnetic poles always come in pairs
- To understand why, the atomic origin of permanent magnetism must be considered

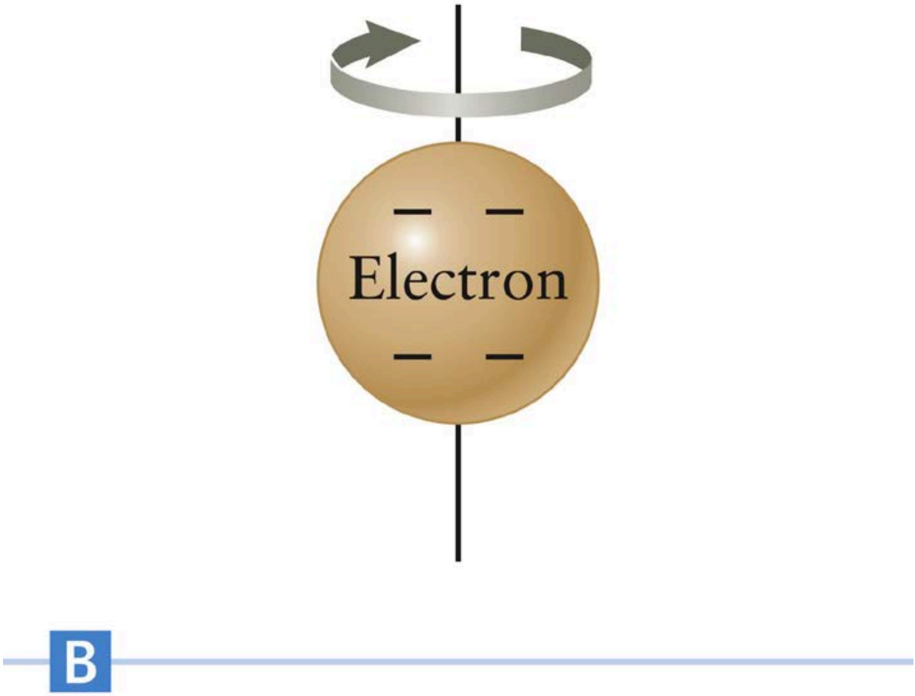
Motion of Electrons

- The motion of an electron around a nucleus can be pictured as a tiny current loop
  - The radius is approximately the radius of the atom
  - The direction of the resulting magnetic field is determined by the orientation of the current loop
    - Using right-hand rule 1



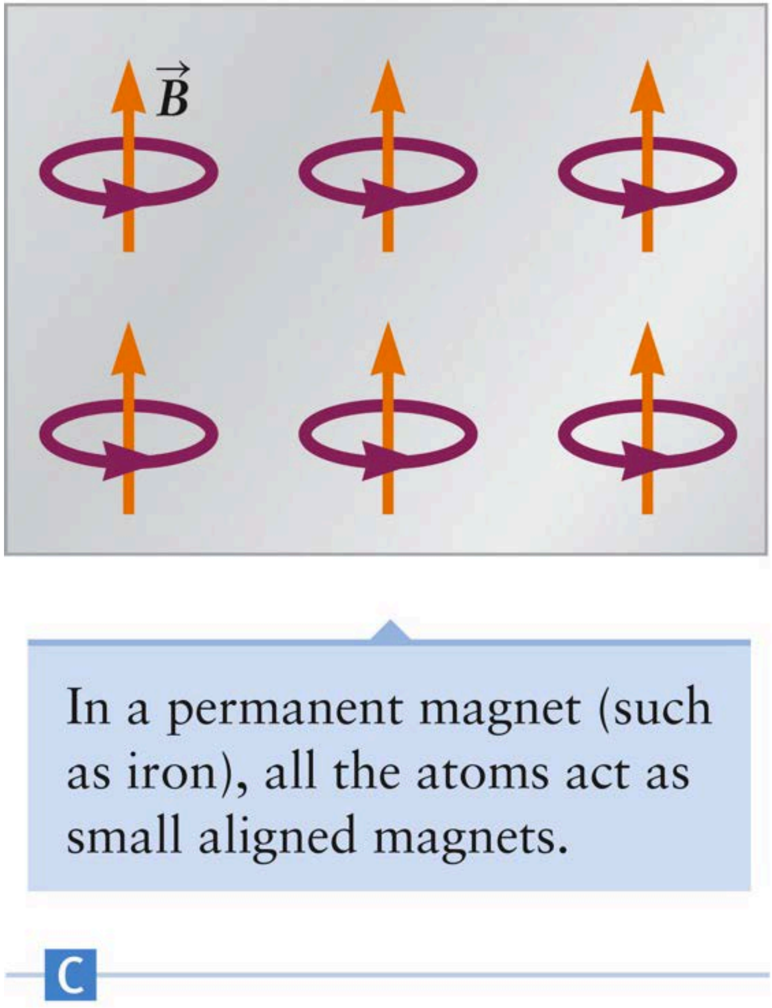
Electron Spin

- The electron also produces a magnetic field due to an effect called ***electron spin***
- The spinning charge acts as a circulating electric current
- The electron has a ***spin magnetic moment***



Electron Spin, cont.

- When an electron is placed in a magnetic field, it will tend to align its spin magnetic moment with the magnetic field

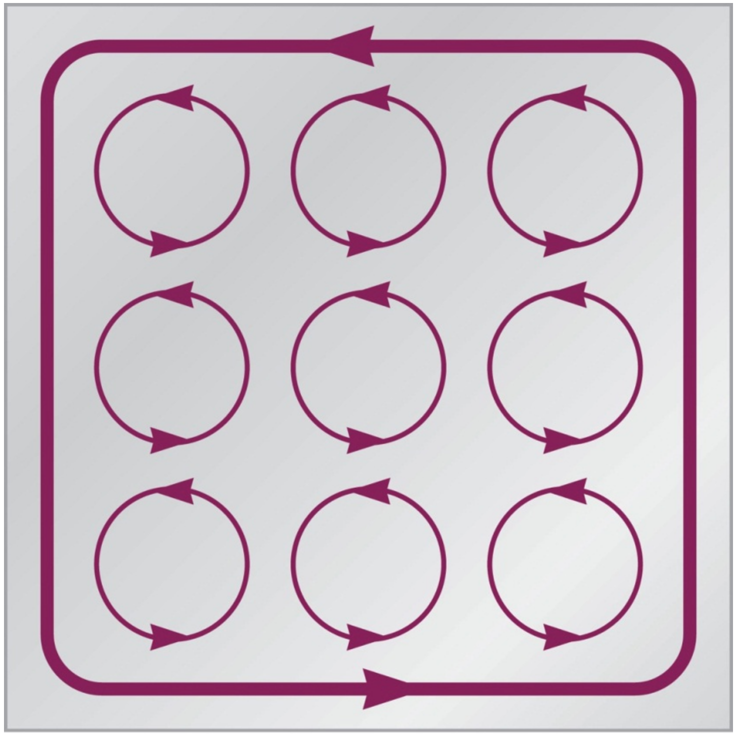


Magnetic Field in an Atom

- The correct explanation of electron spin requires quantum mechanics
- Confirms an atom can produce a magnetic field in two ways
  - Through the electron's orbital current loop
  - Through the electron's spin
- The total magnetic field produced by a single atom is the sum of these two fields

Magnetic Field from Atoms, cont.

- Each atom produces a current loop
- The collection of small current loops acts as one large loop
- This produces the magnetic field in the magnetic material
- The current in each atomic loop is very small, but the large number of atoms results in a large effective current



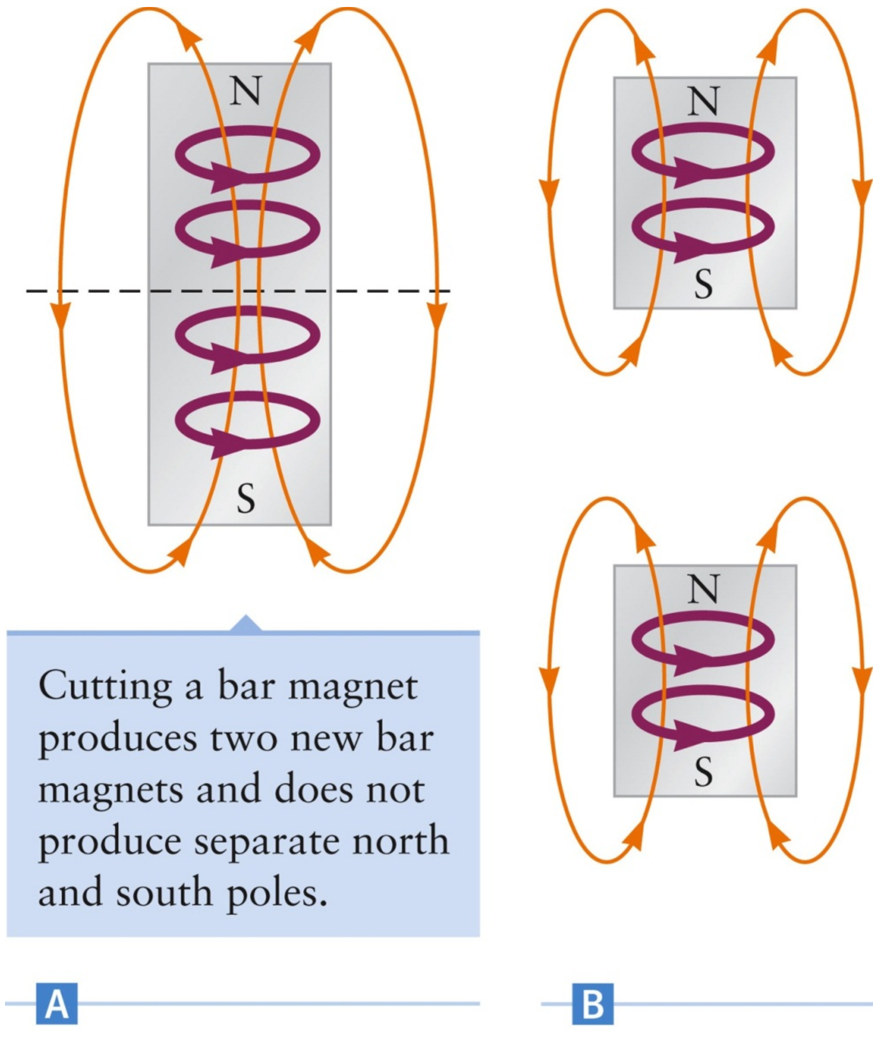
The net effect is the same as that of one large current loop around the perimeter.

Atomic Magnets to Permanent Magnets

- Not all atoms will actually be magnetic since the current loops of different electrons can point in different directions
  - Their magnetic fields could cancel
- The total magnetic field will depend on how the atomic magnetic fields are aligned
- A permanent magnet has the atomic fields aligned

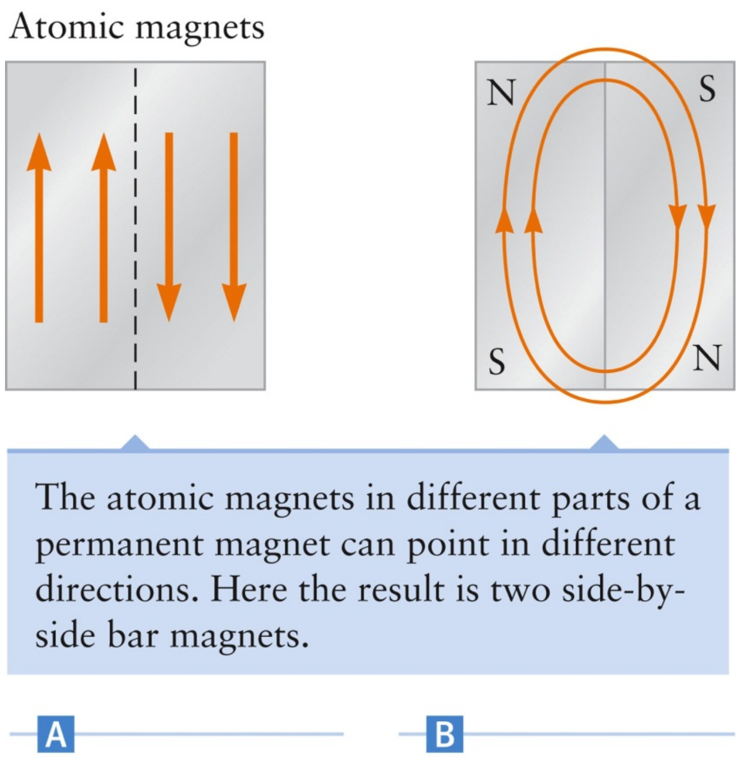
Isolated Magnetic Poles

- A bar magnet is produced by a collection of aligned atomic-scale current loops
- Cutting the magnet in half produces two new complete bar magnets
- Each resulting piece still produces the magnetic field of a complete bar magnet with a north and south pole



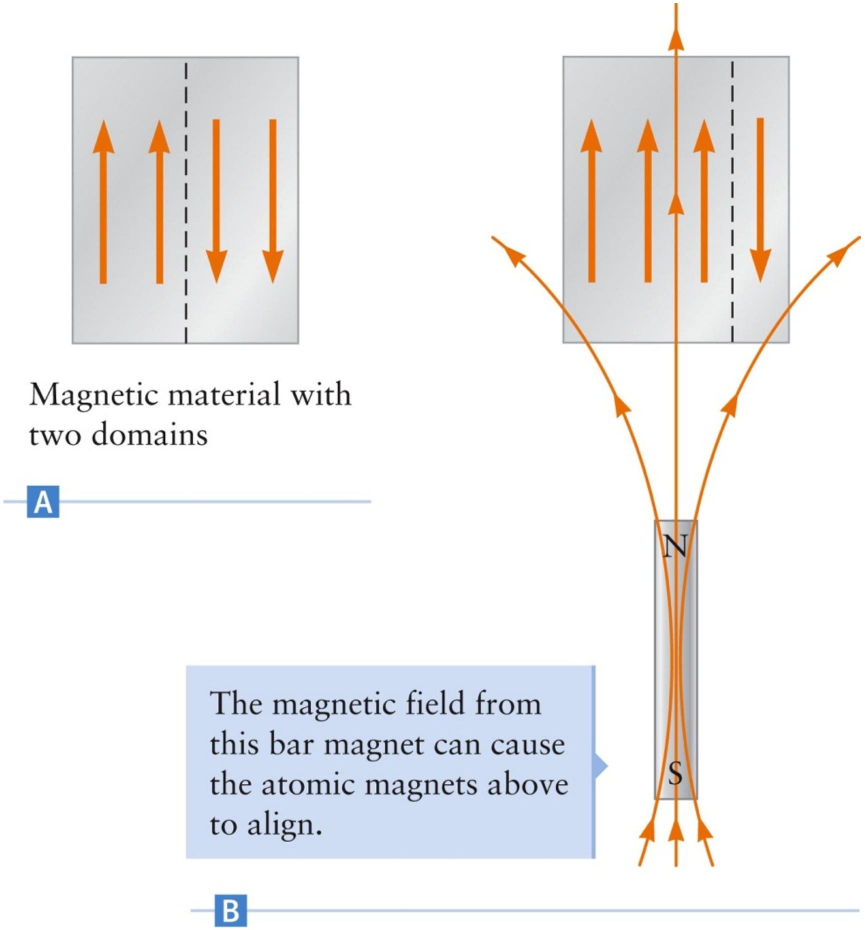
Magnetic Domains

- It is possible for the atomic magnets in different regions within a magnetic material to point in different directions
  - Called magnetic domains
- The arrangement shown is equivalent to two bar magnets
- Because the atomic magnets are aligned in opposite directions, this would appear to be nonmagnetic

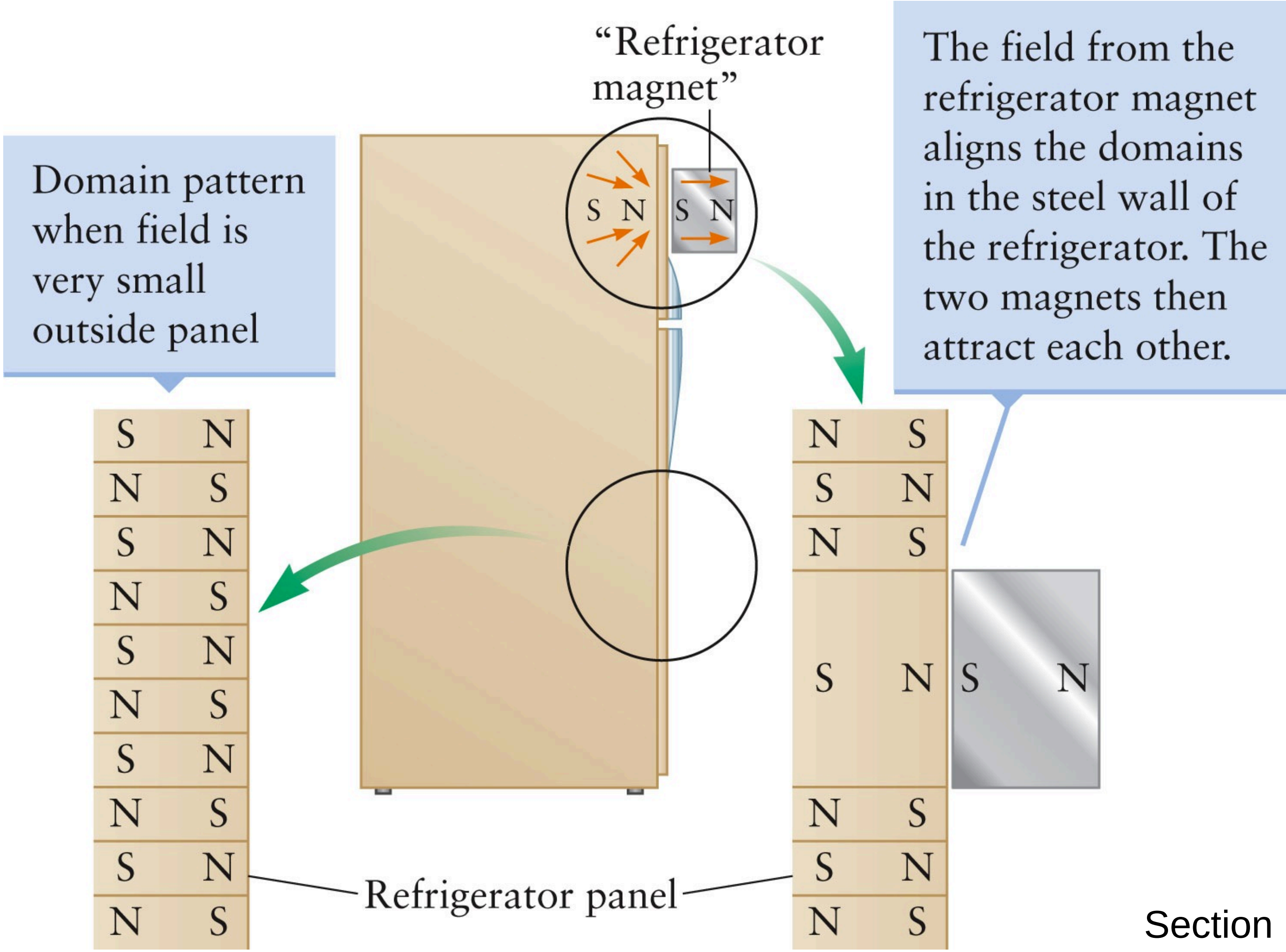


Properties of Magnetic Domains

- A material has two domains of approximately the same size
- Apply a magnetic field from a bar magnet
- The domain aligned with the magnetic field grows at the expense of the other domain
- The material now acts like a bar magnet

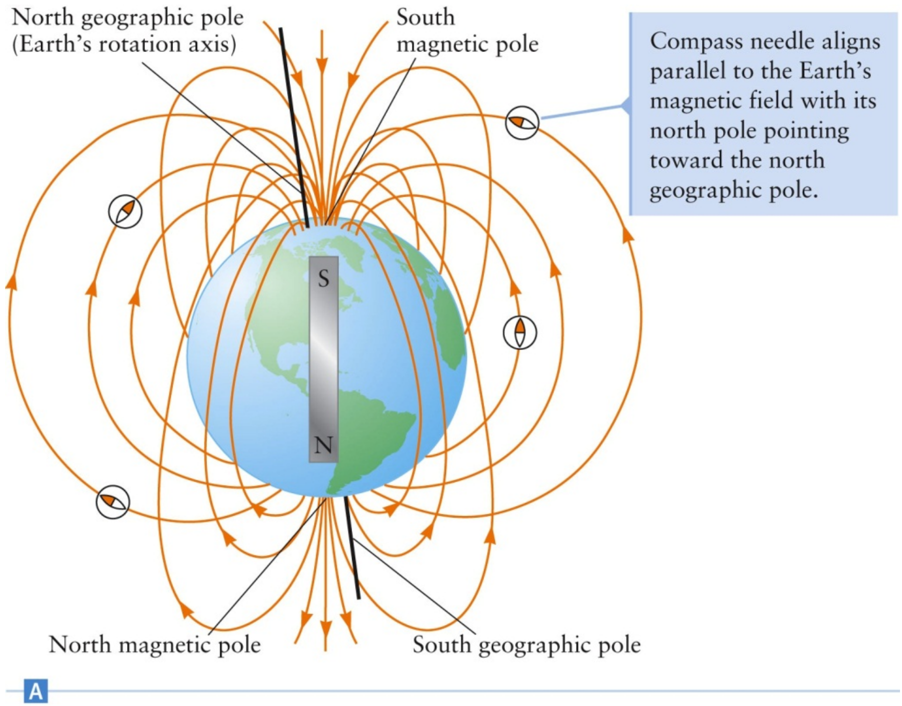


Refrigerator Magnet



Earth’s Magnetic Field

- The Earth acts like a very large magnet
- A compass needle aligns with its north magnetic pole pointing approximately toward the Earth’s geographic north pole
  - So the Earth’s geographic north pole is actually a south magnetic pole

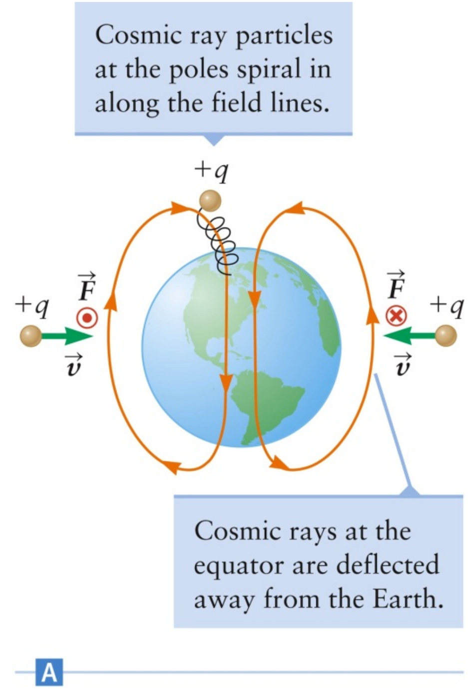


Earth’s Magnetic Field, cont.

- The location of the Earth’s south magnetic pole does not correspond exactly with the geographic north pole
- The Earth’s south magnetic pole moves slowly
  - Currently at about 40 km/year
- The Earth’s magnetic field has completely reversed direction
- The field is probably produced by electric currents in the core

Cosmic Rays

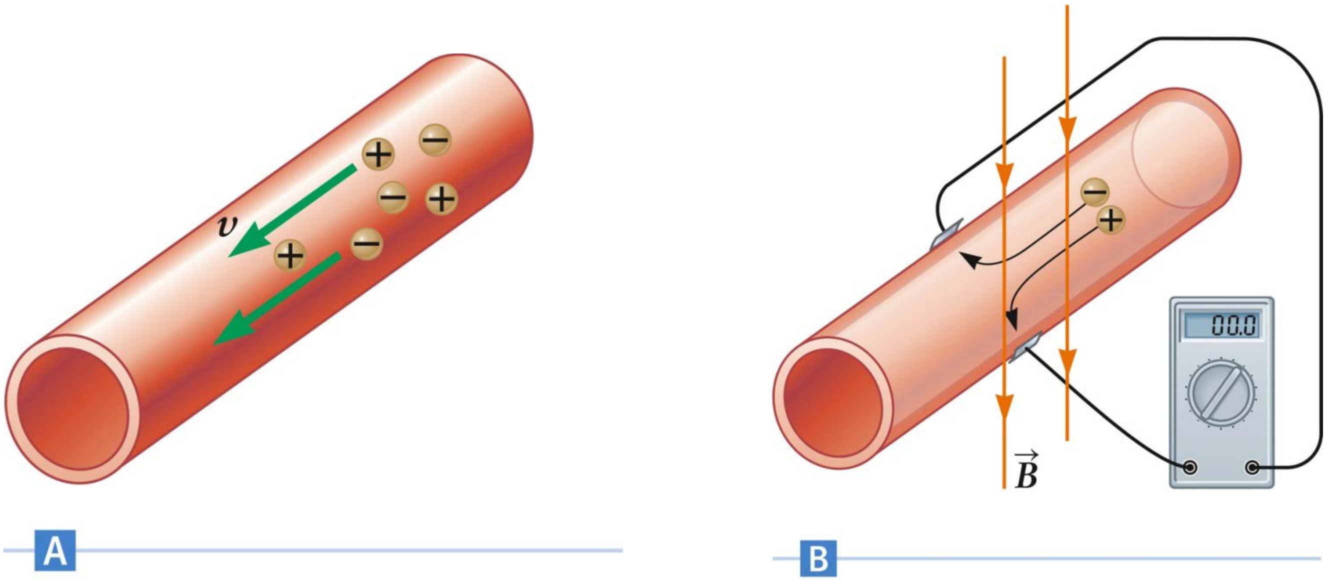
- Charged particles from space are called ***cosmic rays***
- Their motion is affected by the Earth’s magnetic field
- At the equator, the particles are deflected away from the Earth’s surface
- At the poles, the particles follow a helical path and spiral into the poles
- They interact with the Earth’s atmosphere and produce aurora



Applications of Magnetism

- Magnetism is used by doctors, engineers, archeologists, and others
- Applications include
  - Blood-flow meters
  - Relays
  - Electric motors
  - Bacteria
  - Magnetic dating

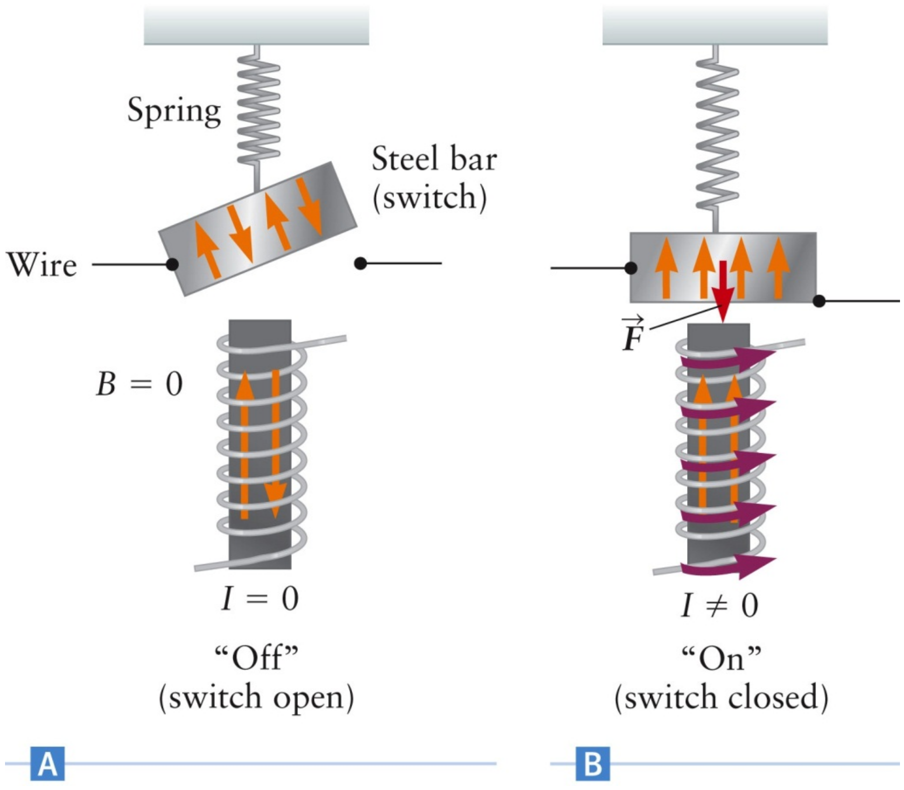
Blood-Flow Meter



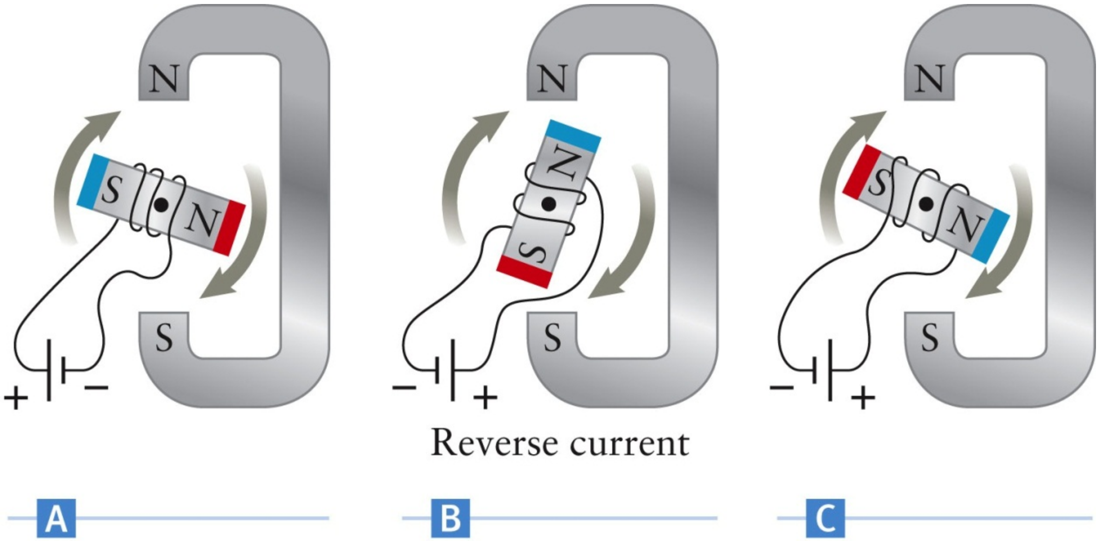
- Measures the blood velocity in arteries
- Blood contains ions
- A magnetic field is applied to the artery
- The resulting potential difference across the artery can be measured
- Blood velocity can be measured

Relays

- The field produced by a solenoid can be made larger by filling it with a magnetic material
- A magnetic force is exerted on the moveable part of the switch
- A small current through the solenoid can control a much larger current through the switch



Electric Motor



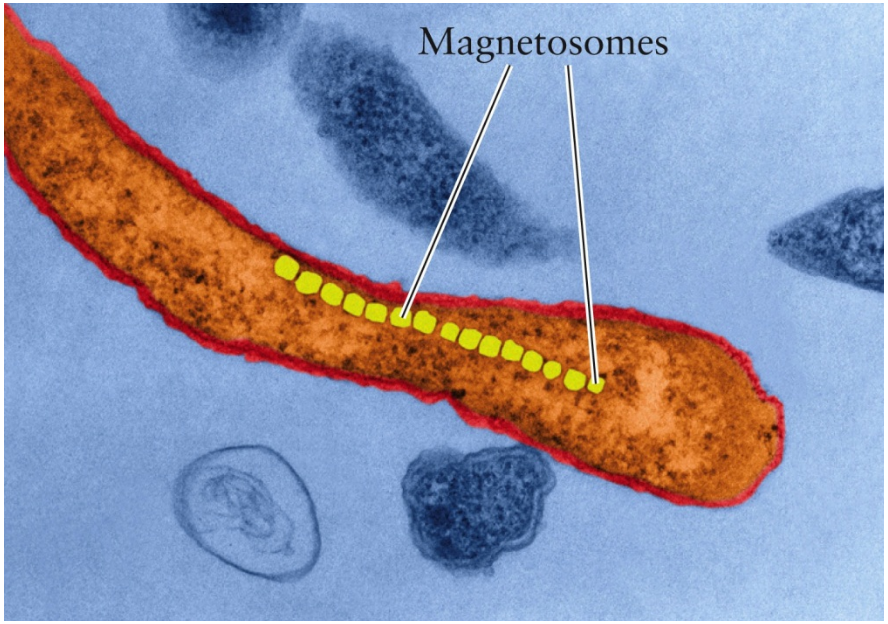
- A magnetic field can produce a torque on a current loop
- If the loop is attached to a rotating shaft, an electric motor is formed
- In a practical motor, a solenoid is used instead of a single loop
- Reversal of the current is needed to keep the shaft rotating

Electric Generator

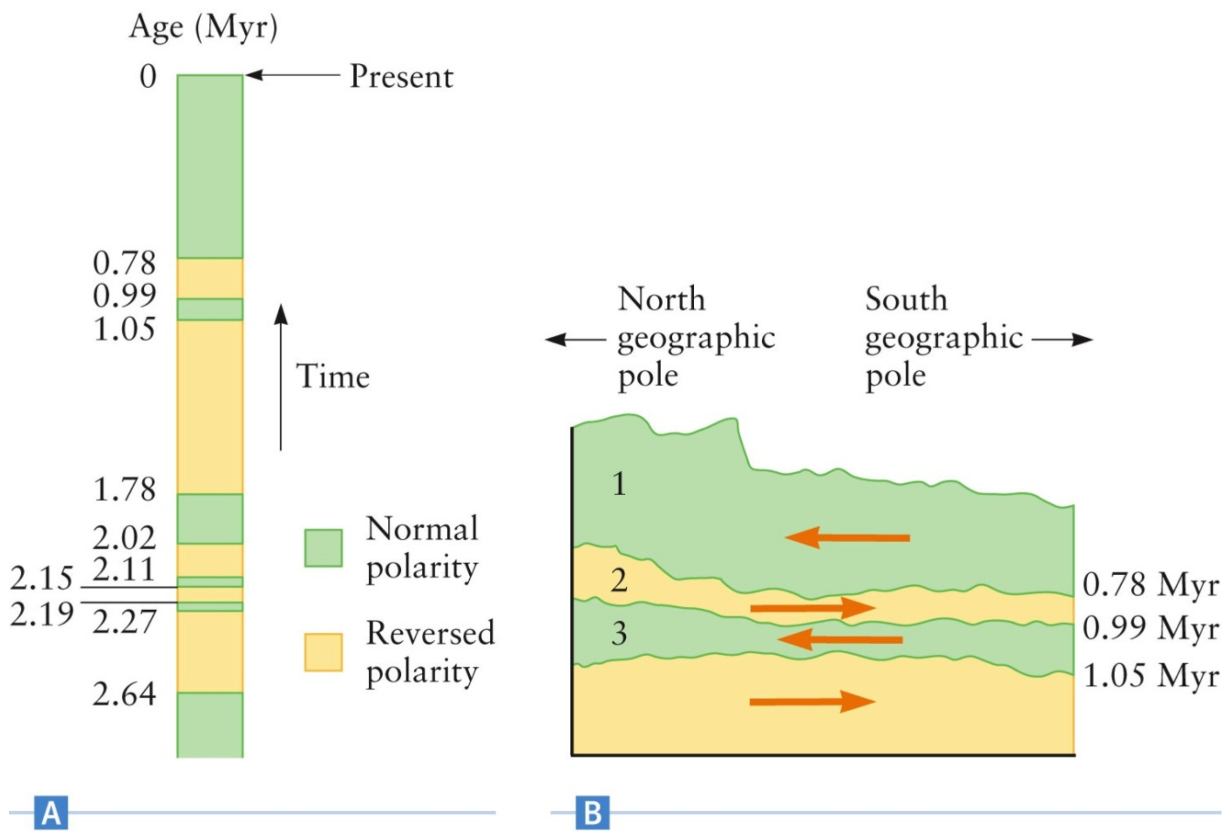
- Electric generators are closely related to motors
- A generator produces an electric current by rotating a coil between the poles of the magnet
  - A motor in reverse

Magnetic Bacteria

- Magnetotactic bacteria possess small grains of iron called magnetosomes
- Each grain acts as a bar magnet
- Bacteria use the magnetosomes to orient themselves with the Earth's magnetic field
  - Allows them to determine up and down



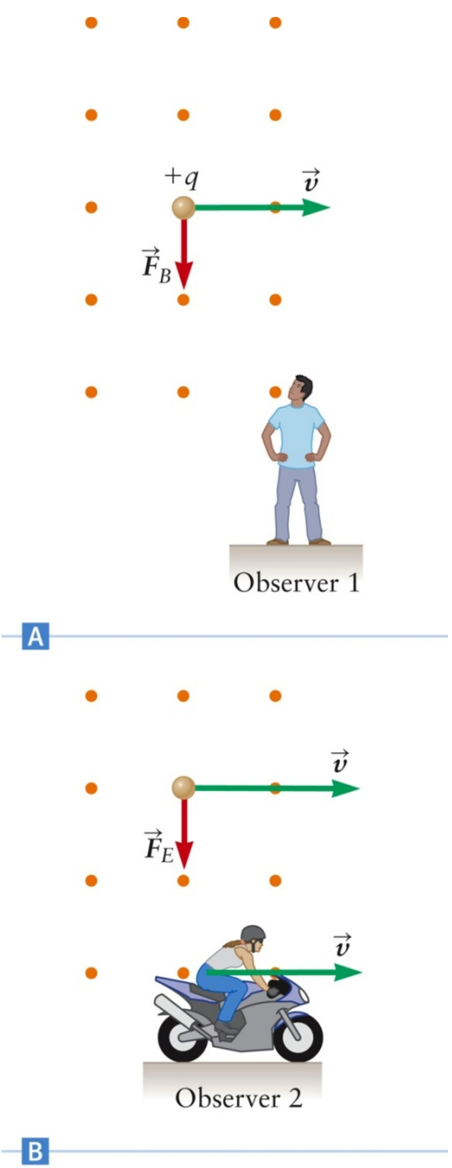
Magnetic Dating



- Reversals in the Earth's magnetic field can be used to date past events
- Dates of more than 25 reversals are known

Velocity-Dependent Force

- The magnetic force exerted on a moving charged particle is dependent on its velocity
  - Differs from gravitational and electrical forces
- The two observers shown both agree the particle is accelerated, but only observer 1 says there is a magnetic force acting on the particle



Velocity-Dependent Force, cont.

- Special relativity solves the dilemma
- Observer 2 will actually say the particle experiences an electric force
- This shows a deep connection between electric and magnetic forces
- The connection is a critical part of the theory of electromagnetism