- Chinese as early as 121 AD knew that an iron rod which had been brought near one of these natural magnets would acquire and retain the magnetic property…and that such a rod when suspended from a string would align itself in a north-south direction.

- Use of magnets to aid in navigation can be traced back to at least the eleventh century.

Basically, we knew the phenomenon existed and we learned useful applications for it.
We just did not understand it

A Brief History of the World

- Not until 1819 was a connection between electrical and magnetic phenomena shown. Danish scientist Hans Christian Oersted observed that a compass needle in the vicinity of a wire carrying electrical current was deflected!

This link between electricity and magnetism was the first connection between the forces of the universe…

A Brief History of the World

- In 1831, Michael Faraday discovered that a momentary current existed in a circuit when the current in a nearby circuit was started or stopped
- Shortly thereafter, he discovered that motion of a magnet toward or away from a circuit could produce the same effect.
- *SUMMARY:* Oersted showed that magnetic effects could be produced by moving electrical charges; Faraday and Henry showed that electric currents could be produced by moving magnets

A Brief History of the World

Magnetic phenomena result from forces between electric charges in motion.

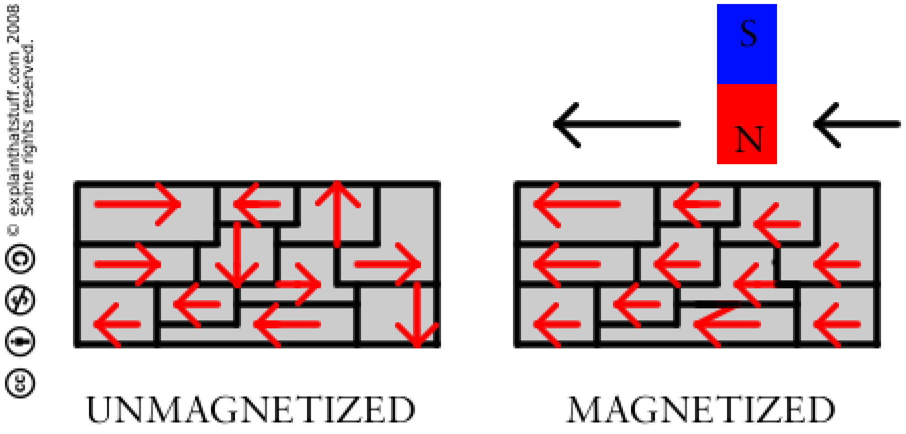
- Ampere first suggested in 1820 that magnetic properties of matter were due to tiny atomic currents (close but not quite)
- All atoms exhibit magnetic effects
- Look at the electron configuration of iron:

			3d					4s
Scandium,	Sc (Z=21)	$[Ar]3d^1 4s^2$	↑					↑↓
Titanium,	Ti (Z=22)	$[Ar]3d^2 4s^2$	↑	↑				↑↓
Vanadium,	V (Z=23)	$[Ar]3d^3 4s^2$	↑	↑	↑			↑↓
Chromium,	Cr (Z=24)	$[Ar]3d^5 4s^1$	↑	↑	↑	↑	↑	↑
Manganese,	Mn (Z=25)	$[Ar]3d^5 4s^2$	↑	↑	↑	↑	↑	↑↓
Iron,	Fe (Z=26)	$[Ar]3d^6 4s^2$	↑↓	↑	↑	↑	↑	↑↓
Cobalt,	Co (Z=27)	$[Ar]3d^7 4s^2$	↑↓	↑↓	↑	↑	↑	↑↓
Nickel,	Ni (Z=28)	$[Ar]3d^8 4s^2$	↑↓	↑↓	↑↓	↑	↑	↑↓
Copper,	Cu (Z=29)	$[Ar]3d^{10} 4s^1$	↑↓	↑↓	↑↓	↑↓	↑	↑
Zinc,	Zn (Z=30)	$[Ar]3d^{10} 4s^2$	↑↓	↑↓	↑↓	↑↓	↑↓	↑↓

The Cause of Magnetic Phenomena

This is the explanation I have…

- Any movement of an electron gives magnetism. However, most electrons are paired with another with opposite spin, cancelling out the magnetic properties.
- <u>Magnetic Domain</u> - occurs when the spins of electrons are aligned creating magnetic properties



Types of Magnetic Materials

- *Soft magnetic* materials, such as iron, are easily magnetized
  - They also tend to lose their magnetism easily
- *Hard magnetic* materials, such as cobalt and nickel, are difficult to magnetize
  - They tend to retain their magnetism
- There is a lot of interesting material science that goes into the details of this trend

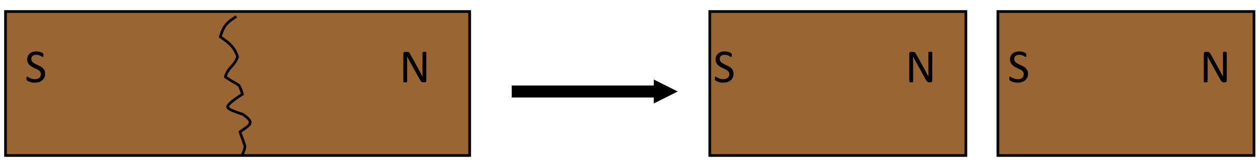
For Every North, There is a South

Like poles repel each other and unlike poles attract each other

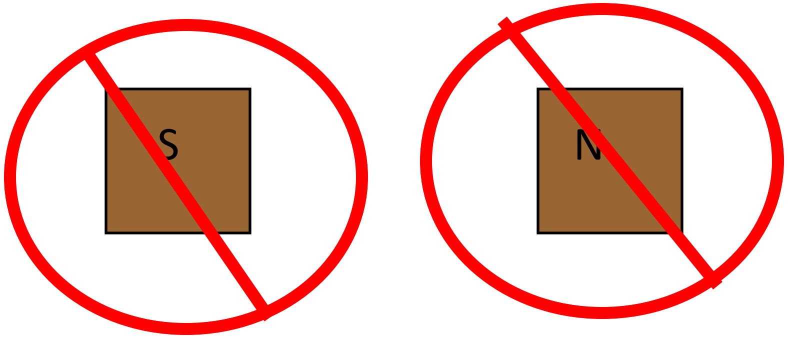
Similar to electric charges

Magnetic poles cannot be isolated

If a permanent magnetic is cut in half repeatedly, you will still have a north and a south pole



No Monopoles Allowed



An explanation from *howstuffworks.com*

Even though an atom's electrons don't move very far, their movement is enough to create a tiny magnetic field. Since paired electrons spin in opposite directions, their magnetic fields cancel one another out. Atoms of ferromagnetic elements, on the other hand, have several unpaired electrons that have the same spin. Iron, for example, has four unpaired electrons with the same spin. Because they have no opposing fields to cancel their effects, these electrons have an **orbital magnetic moment**. The magnetic moment is a **vector** -- it has a magnitude and a direction. It's related to both the magnetic field strength and the torque that the field exerts. A whole magnet's magnetic moments come from the moments of all of its atoms.

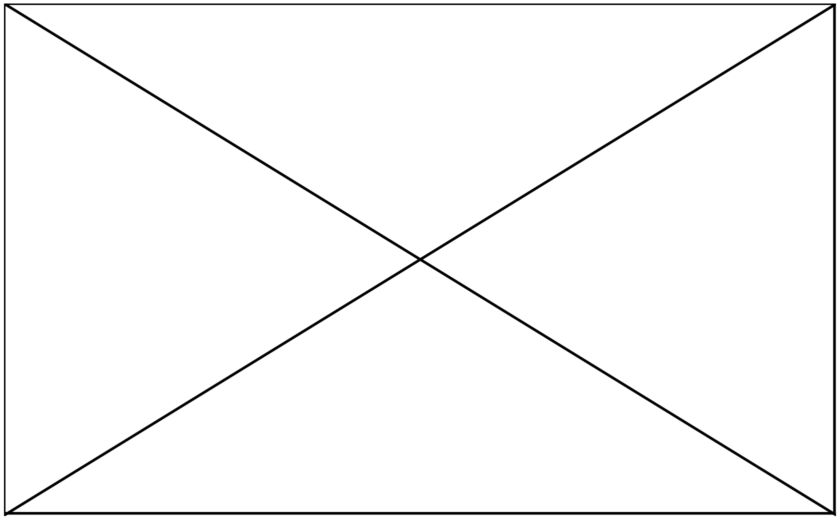
In metals like iron, the orbital magnetic moment encourages nearby atoms to align along the same north-south field lines. Iron and other ferromagnetic materials are crystalline. As they cool from a molten state, groups of atoms with parallel orbital spin line up within the crystal structure. This forms the magnetic domains discussed in the previous section.

You may have noticed that the materials that make good magnets are the same as the materials magnets attract. This is because magnets attract materials that have unpaired electrons that spin in the same direction. In other words, the quality that turns a metal into a magnet also attracts the metal to magnets. Many other elements are **diamagnetic** -- their unpaired atoms create a field that weakly repels a magnet. A few materials don't react with magnets at all.

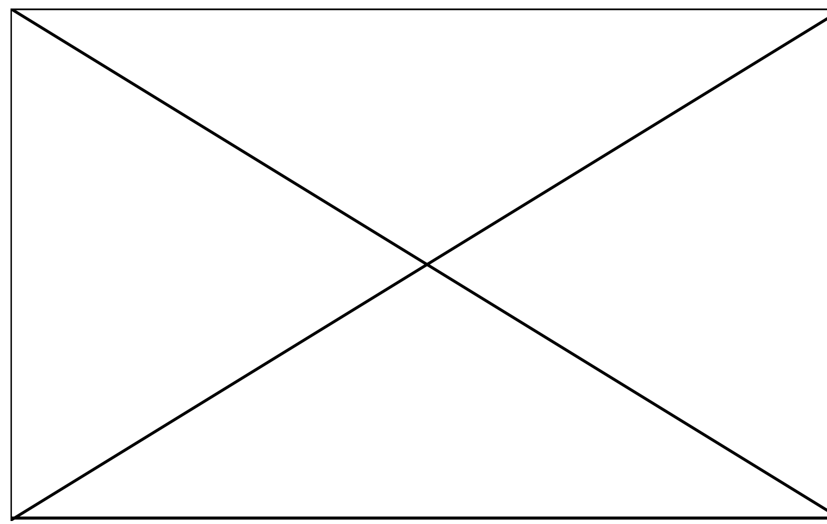
This explanation and its **underlying quantum physics** are fairly complicated, and without them the idea of magnetic attraction can be mystifying. So it's not surprising that people have viewed magnetic materials with suspicion for much of history. In the next section, we'll take a look at the powers ascribed to magnets, as well as what they can and can't do.

Taken March 13, 2012 from http://science.howstuffworks.com/magnet3.htm

Video Explanation of Magnetism



https://youtu.be/1TKSfAkWWN0
https://youtu.be/hFAOXdXZ5TM
Just in case the videos don't work…



Magnets Have Magnetic Fields

We will say that a moving charge sets up in the space around it a magnetic field,

and

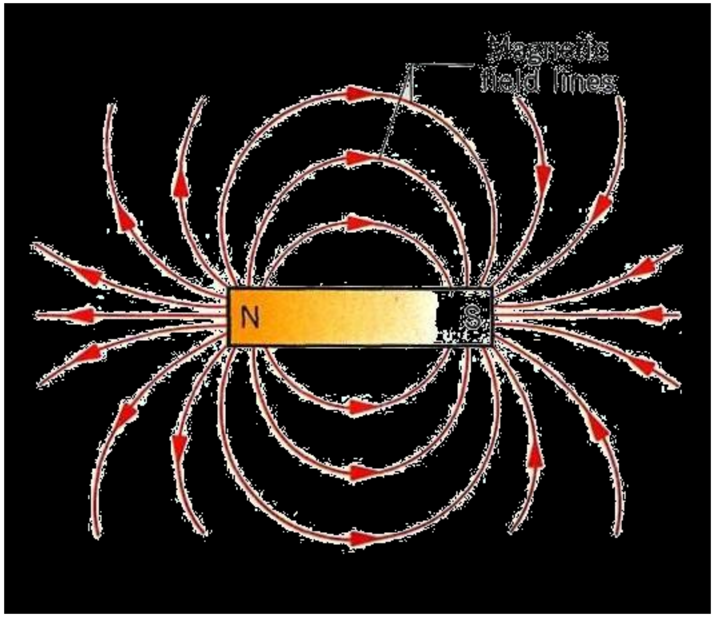
it is the magnetic field which exerts a force on any other charge moving through it.

Magnetic fields are vector quantities….that is, they have a magnitude and a direction!

The Concept of "Fields"

Michael Faraday realized that ...

A magnet has a
'magnetic field'
distributed throughout
the surrounding space



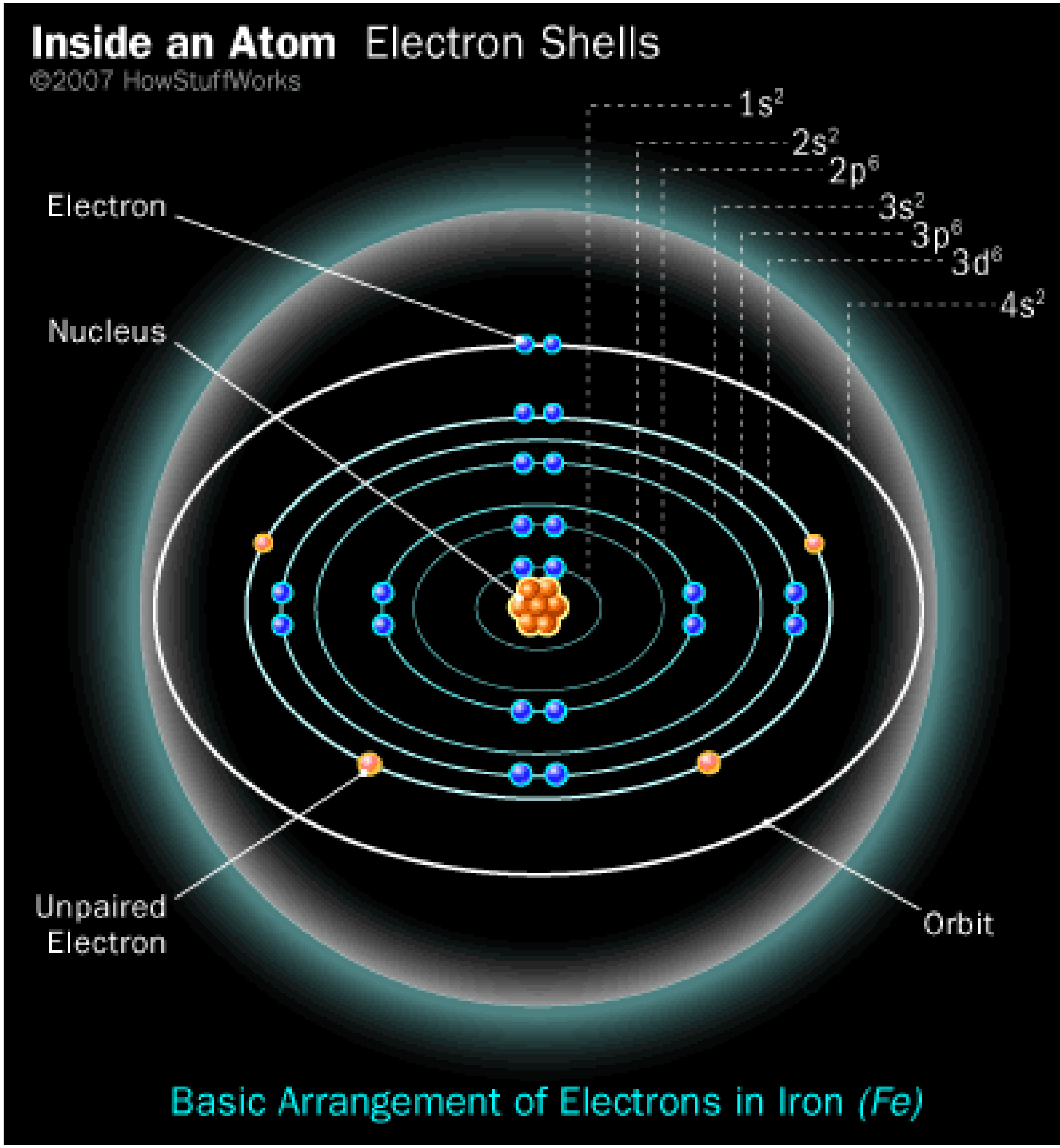
Magnetic Fields

- A vector quantity
- Symbolized by **B**
- Direction is given by the direction a *north pole* of a compass needle points in that location
- *Magnetic field lines* can be used to show how the field lines, as traced out by a compass, would look

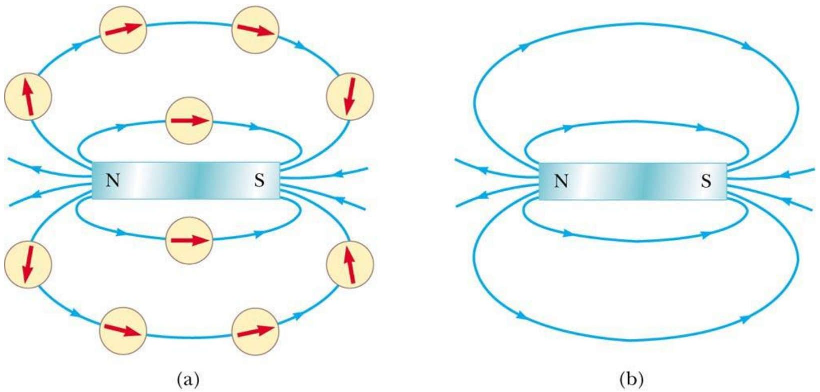
An explanation from *howstuffworks.com*

This explanation and its **underlying quantum physics** are fairly complicated, and without them the idea of magnetic attraction can be mystifying. So it's not surprising that people have viewed magnetic materials with suspicion for much of history. In the next section, we'll take a look at the powers ascribed to magnets, as well as what they can and can't do.

Taken March 13, 2012 from http://science.howstuffworks.com/magnet3.htm



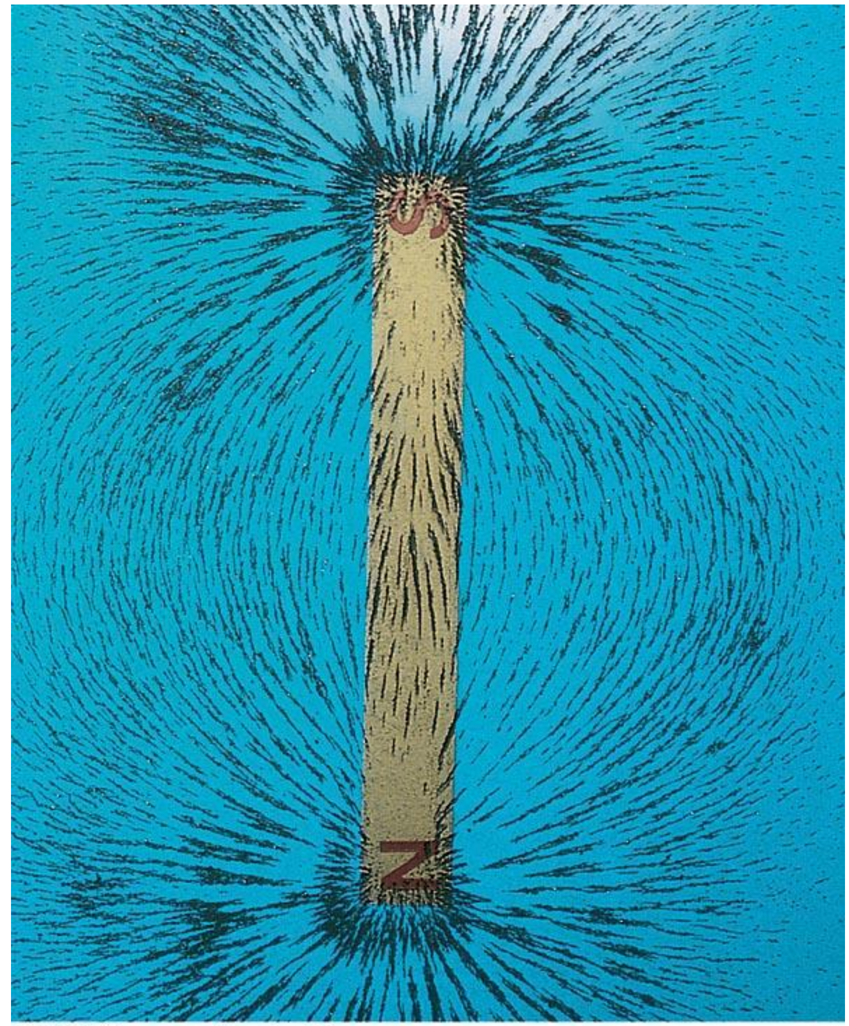
Magnetic Field Lines, sketch



- A compass can be used to show the direction of the magnetic field lines (a)
- A sketch of the magnetic field lines (b)

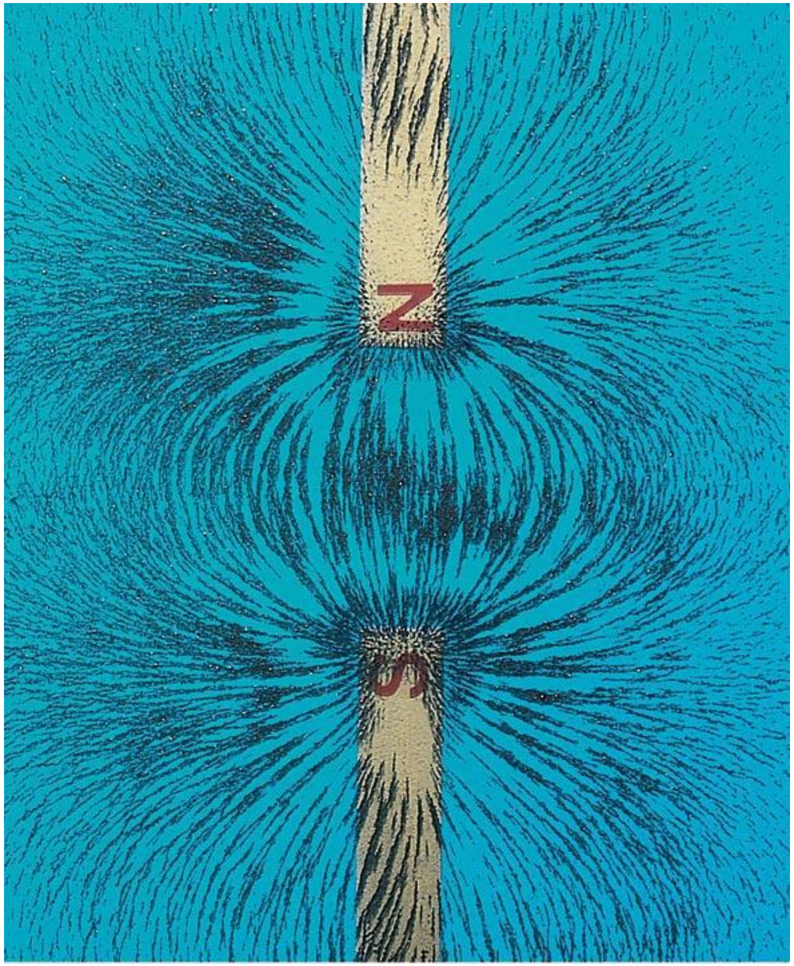
Magnetic Field Lines, Bar Magnet

- Iron filings are used to show the pattern of the electric field lines
- The direction of the field is the direction a north pole would point



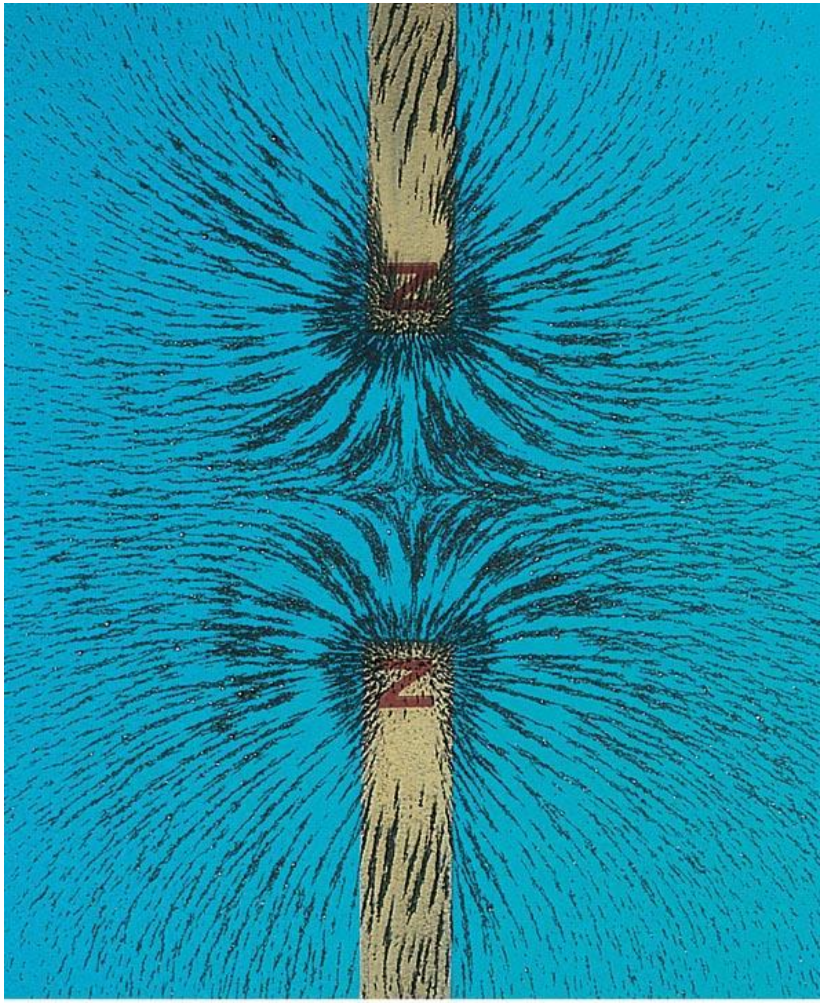
Magnetic Field Lines, Unlike Poles

- Iron filings are used to show the pattern of the electric field lines
- The direction of the field is the direction a north pole would point
  - Compare to the electric field produced by an electric dipole



Magnetic Field Lines, Like Poles

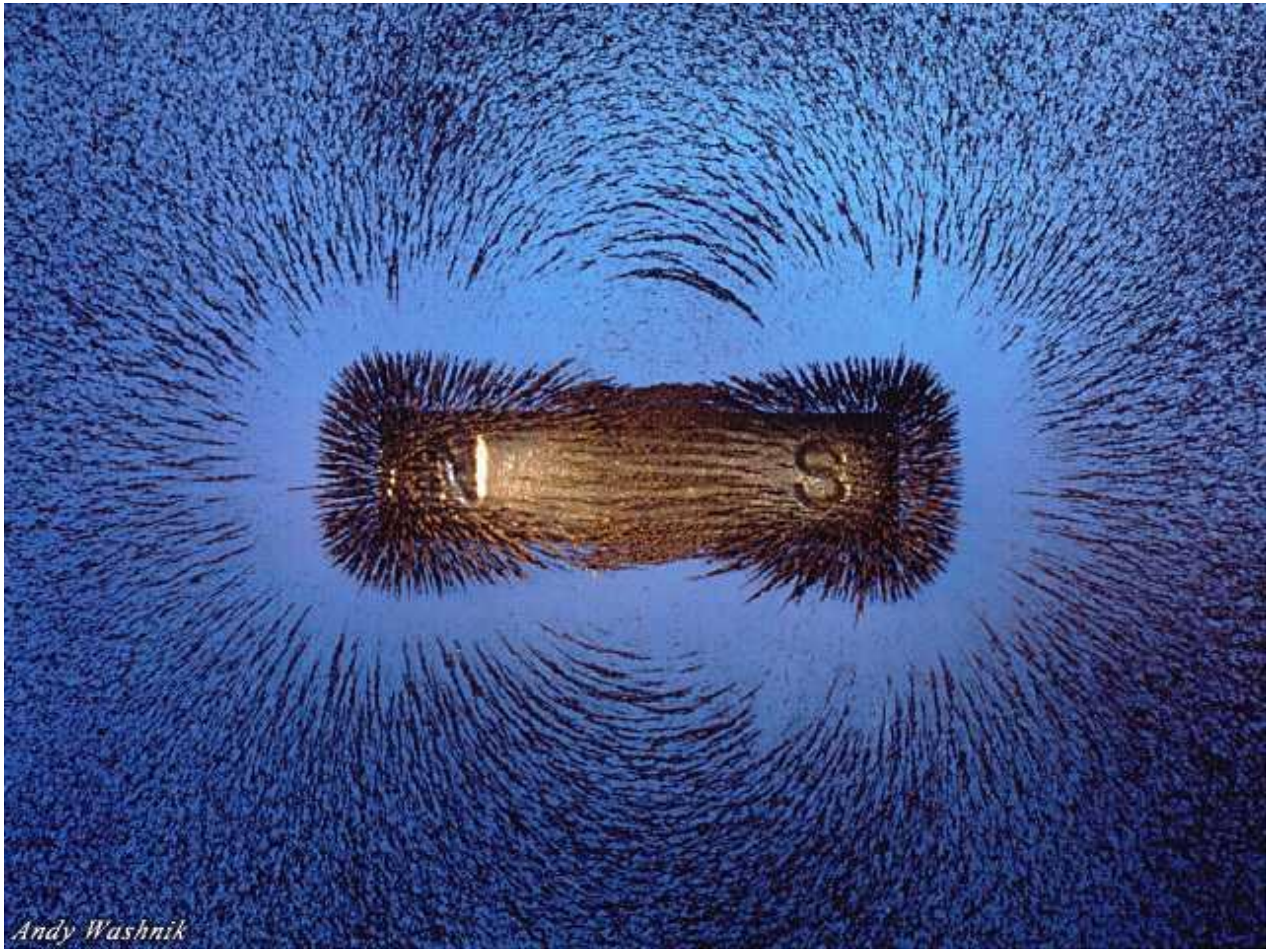
- Iron filings are used to show the pattern of the electric field lines
- The direction of the field is the direction a north pole would point
  - Compare to the electric field produced by like charges



Magnetic and Electric Fields

- An electric field surrounds any stationary electric charge
- A magnetic field surrounds any *moving* electric charge
- A magnetic field surrounds any magnetic material

Field Lines Around a Magnet

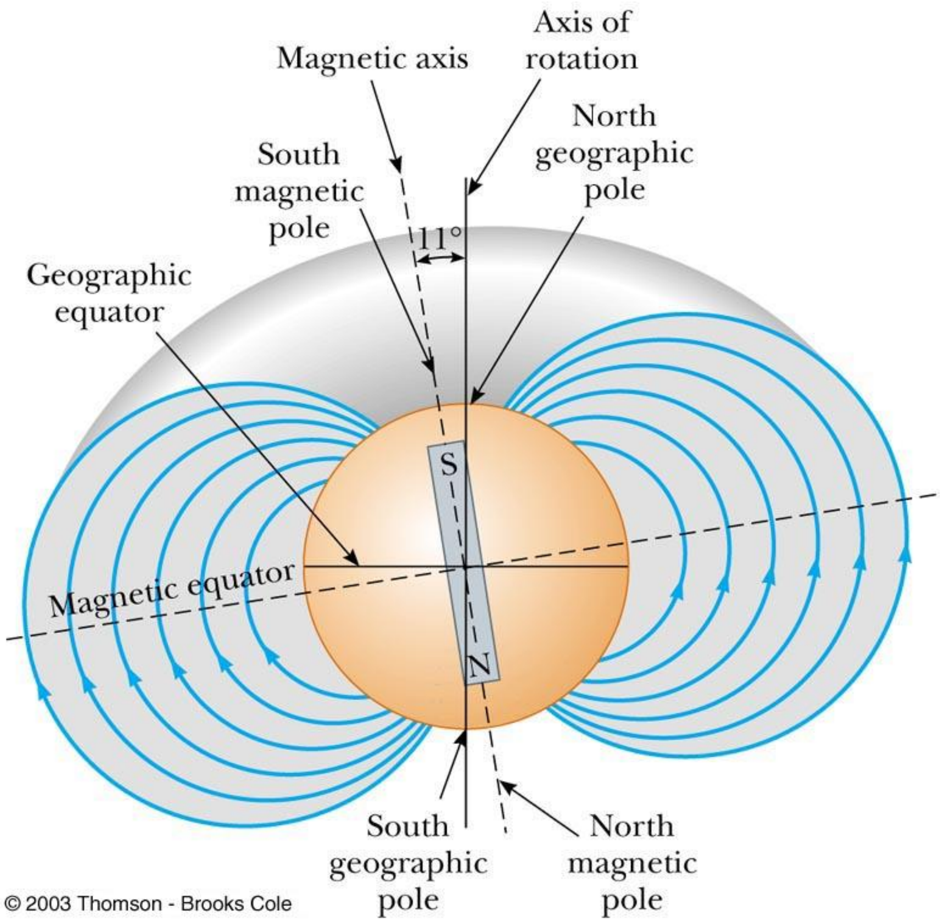


Earth’s Magnetic Field

- The Earth’s geographic north pole corresponds to a magnetic south pole
- The Earth’s geographic south pole corresponds to a magnetic north pole
  - Strictly speaking, a north pole should be a “north-seeking” pole and a south pole a “south-seeking” pole

Earth’s Magnetic Field

- The Earth’s magnetic field resembles that achieved by burying a huge bar magnet deep in the Earth’s interior



Right hand rule #1

FORCE ON CHARGES MOVING THROUGH A MAGNETIC FIELD

Magnetic Fields

- One can define a magnetic field in terms of the magnetic force exerted on a test charge
  - Similar to the way electric fields are defined
- When moving through a magnetic field, a charged particle experiences a magnetic force
  - This force has a maximum value when the charge moves perpendicularly to the magnetic field lines
  - This force is zero when the charge moves along the field lines
- The force is always perpendicular to both the field and motion

$$F_B = Bvq \cancel{\sin\theta}$$

B- magnetic field
v- velocity of charge
q- size of charge

We will not use the sinθ part because we will only look at cases where the *v* and *B* are perpendicular or parallel

Units of Magnetic Field

- The SI unit of magnetic field is the *Tesla* (T)

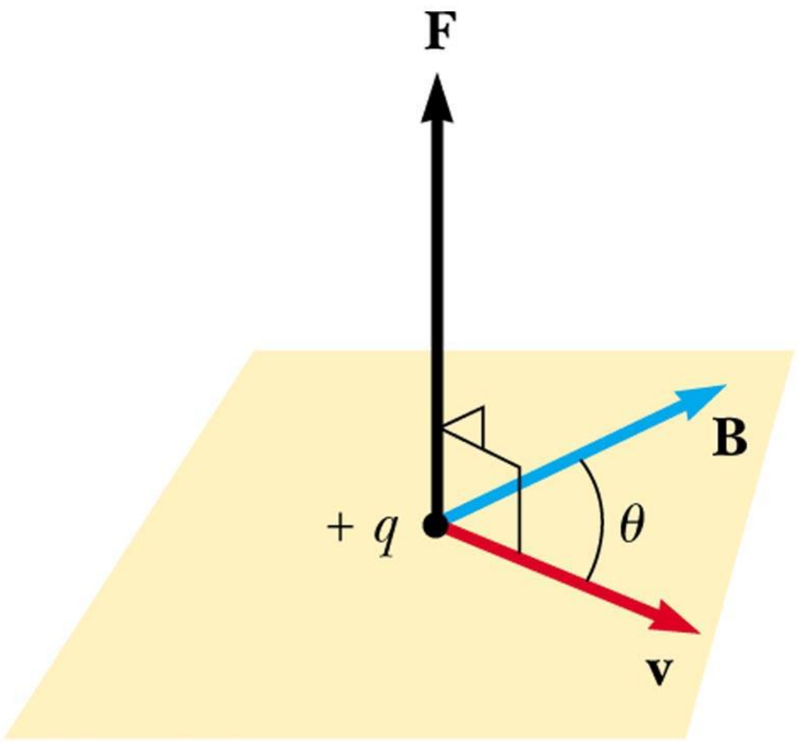
$$T = \frac{N}{C \cdot (m/s)} = \frac{N}{A \cdot m}$$

A Few Typical B Values

- Conventional laboratory magnets
  - 2.5 T
- Superconducting magnets
  - 30 T
- Earth's magnetic field
  - 5×10^{-5} T

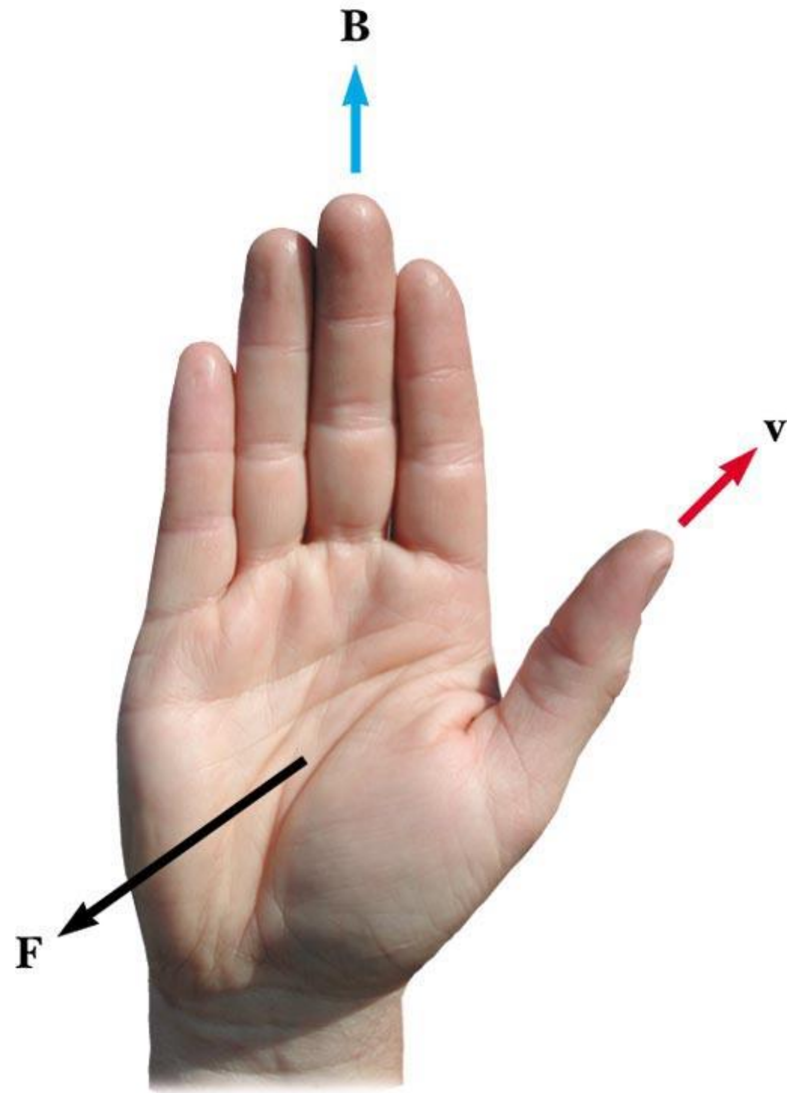
Finding the Direction of Magnetic Force

- Experiments show that the direction of the magnetic force is always perpendicular to both **v** and **B**
- F_{max} occurs when v is perpendicular to B
- F = 0 when v is parallel to B

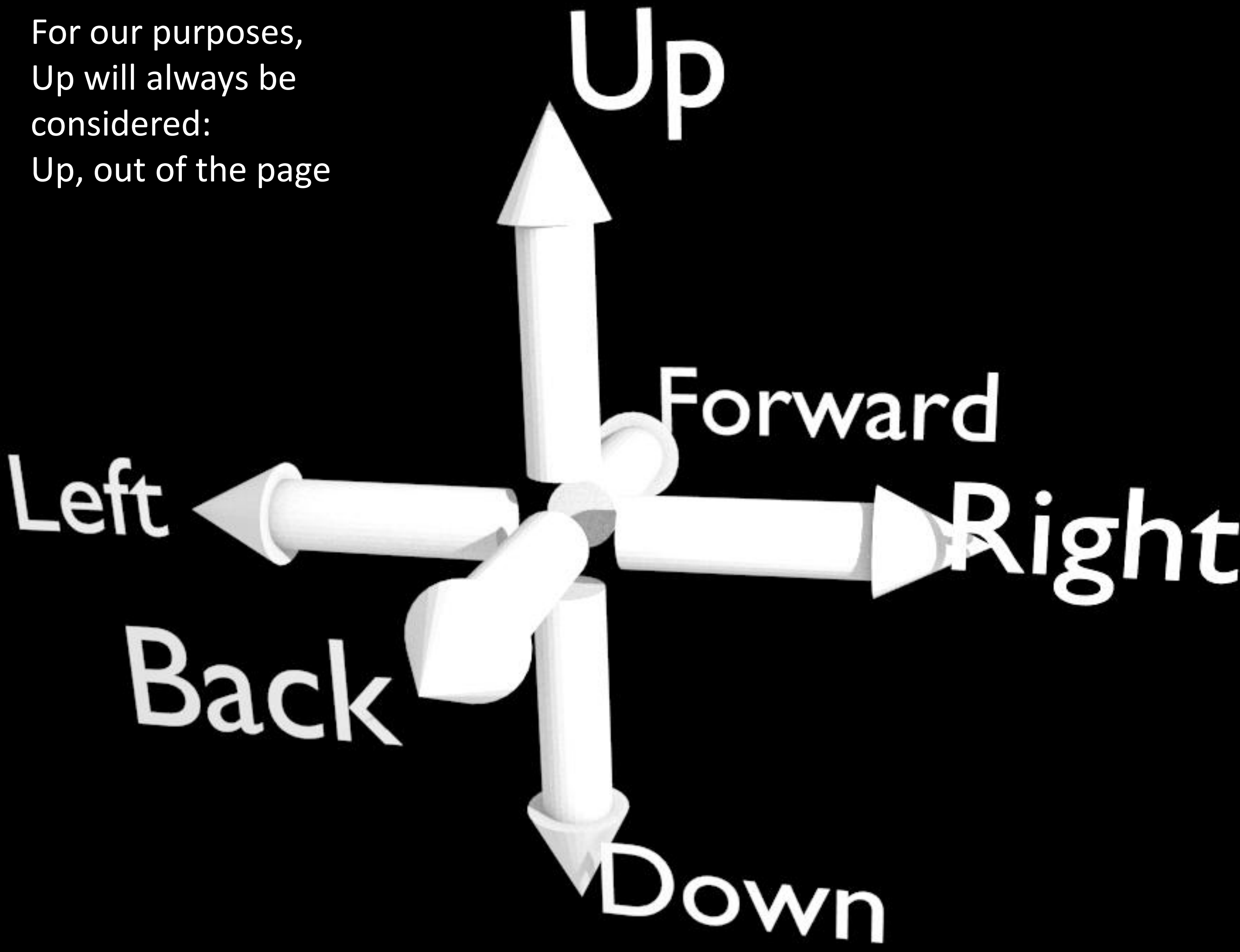


Right Hand Rule #1

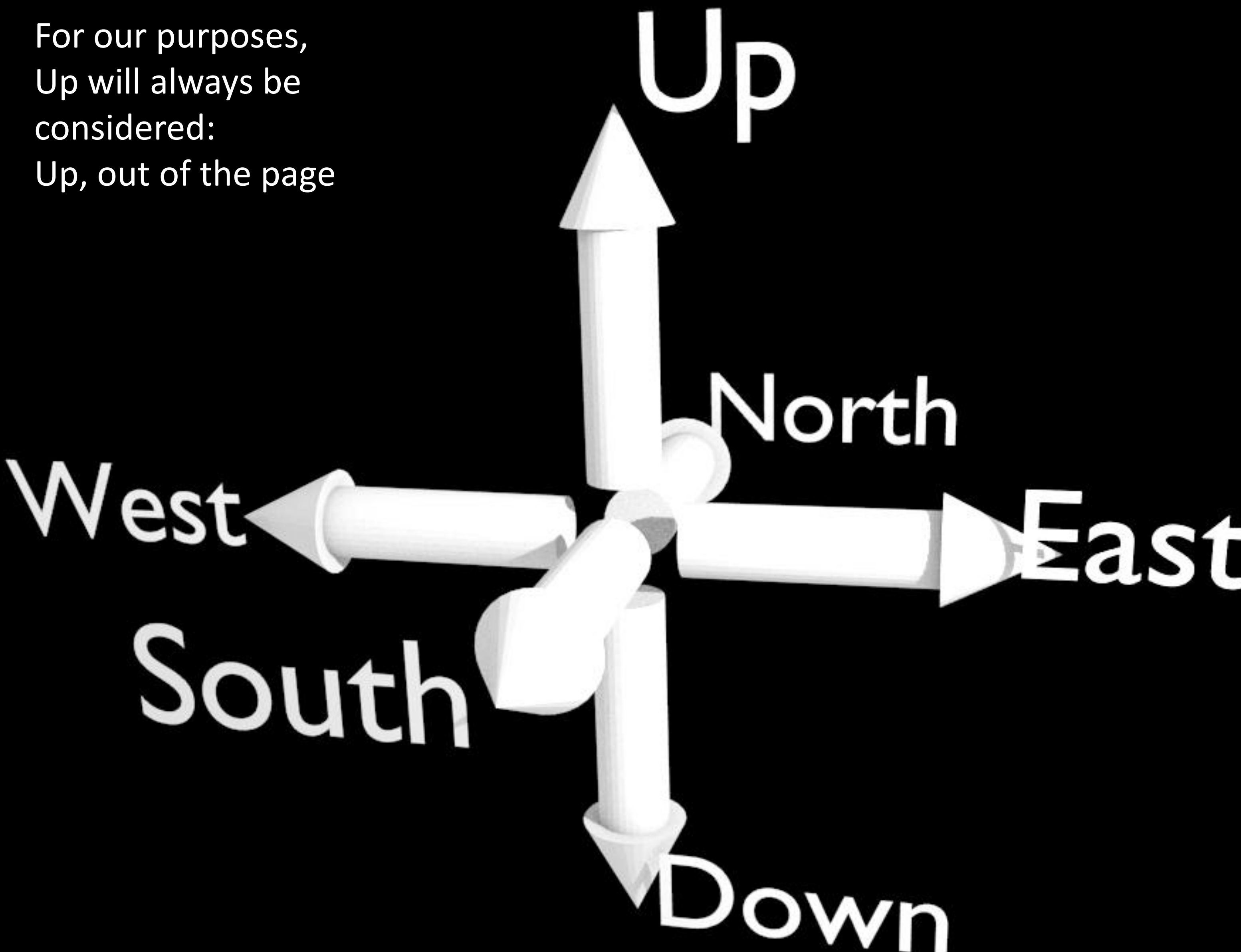
- Hold your right hand open
- Place your fingers in the direction of B
- Place your thumb in the direction of v
- The direction of the force on a positive charge is directed out of your palm
  – If the charge is negative, the force is opposite that determined by the right hand rule



For our purposes,
Up will always be
considered:
Up, out of the page



For our purposes,
Up will always be
considered:
Up, out of the page



A 3C charge is moving 4m/s to the east through a magnetic field. The field has a strength of 2T, and is directed downward. What is the magnitude and direction of the force enacted on the charge by the magnetic field?

24N to the North

First Practice

A 6C charge is moving downward through a magnetic field. The field has a strength of 5T, and is directed Westward. If the force felt by the charge is 75N, how fast is the charge moving?

2.5m/s

Second Practice

A 1.5C charge is moving 2m/s to the south through a magnetic field. The field has a strength of 1T, and is directed to the north. What is the force enacted on the charge?

0N – direction of motion is (anti)parallel to field

Third Practice

Right hand rule #1

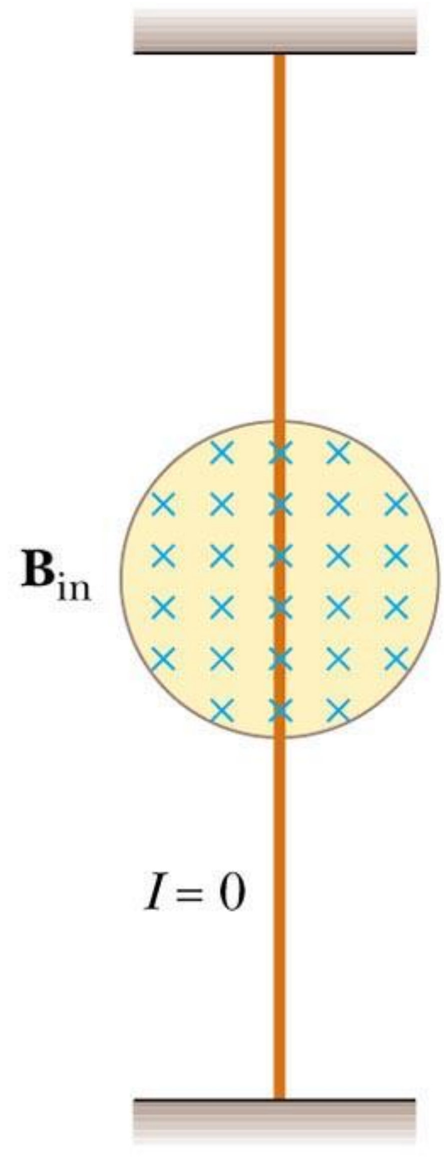
FORCE ON CURRENT-CARRYING WIRES IN A MAGNETIC FIELD

Magnetic Force on a Current Carrying Conductor

- A force is exerted on a current-carrying wire placed in a magnetic field
  - The current is a collection of many charged particles in motion
- The direction of the force is given by right hand rule #1
  - Replace the "v" on the thumb with an "I" that represents the direction of positive current

Force on a Wire

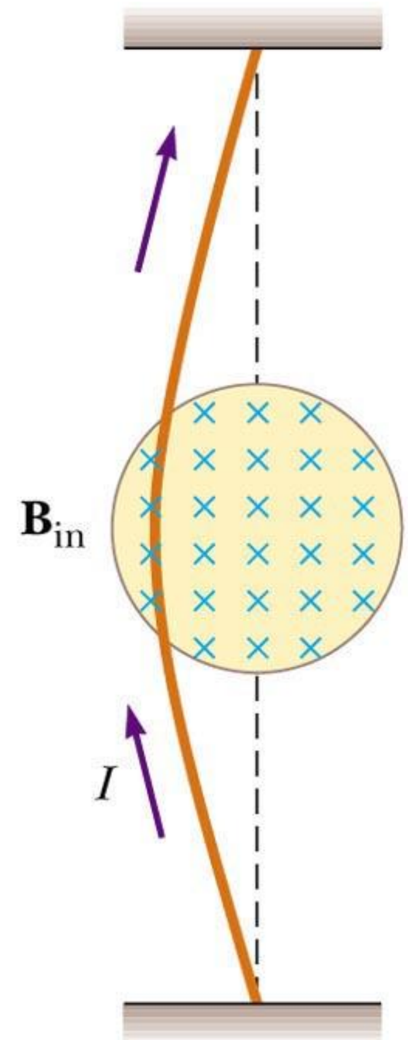
- The blue x's indicate the magnetic field is directed *into* the page
  - The x represents the tail of the arrow
- Blue dots would be used to represent the field directed *out of* the page
  - The • represents the head of the arrow
- In this case, there is no current, so there is no force



(a)

Force on a Wire, co

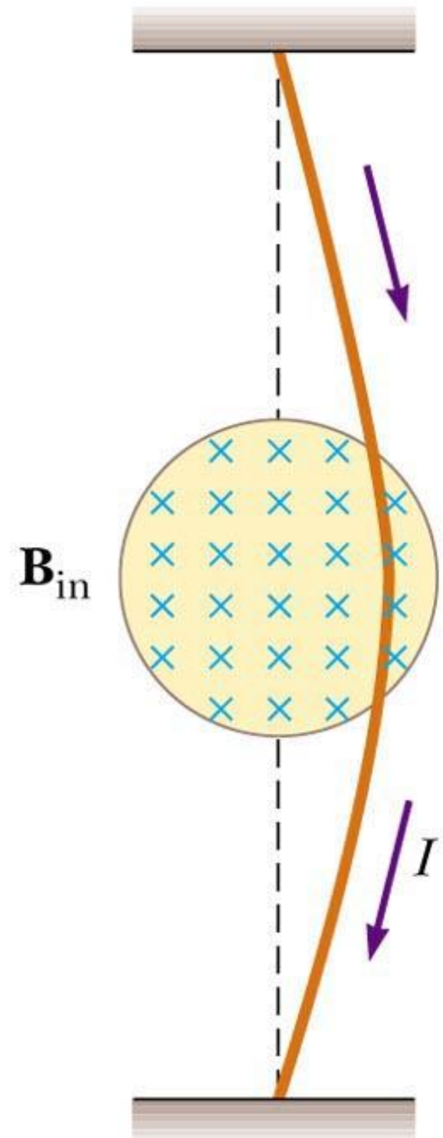
- B is into the page
  - Point your fingers into the page
- The current is up the page
  - Point your thumb up the page
- The force is to the left
  - Your palm should be pointing to the left



(b)

Force on a Wire, fin

- B is into the page
  - Point your fingers into the page
- The current is down the page
  - Point your thumb down the page
- The force is to the right
  - Your palm should be pointing to the right



(c)

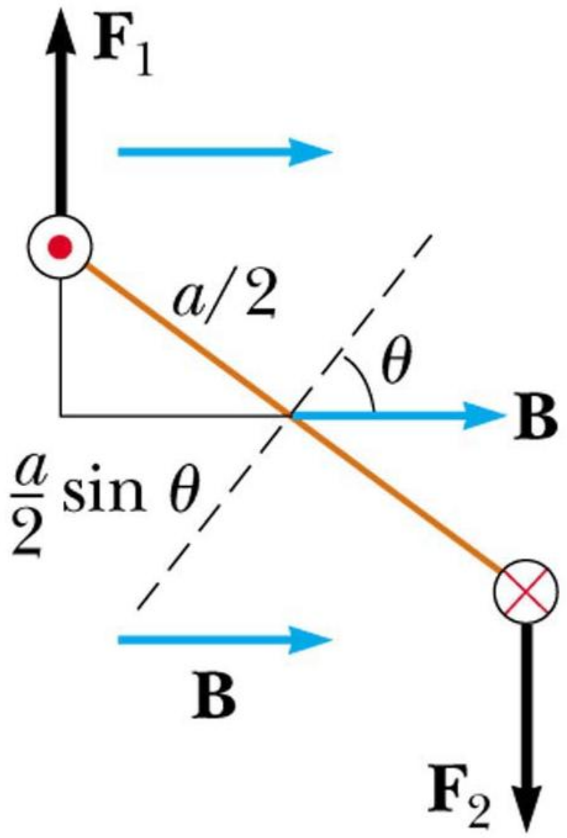
Force on a Wire, equation

- The magnetic force is exerted on each moving charge in the wire
- The total force is the sum of all the magnetic forces on all the individual charges producing the current
- $F = B I \ell \sin\theta$
  - θ is the angle between B and I
  - The direction is found by the right hand rule, pointing your thumb in the direction of I instead of v

Torque on a Current Loop

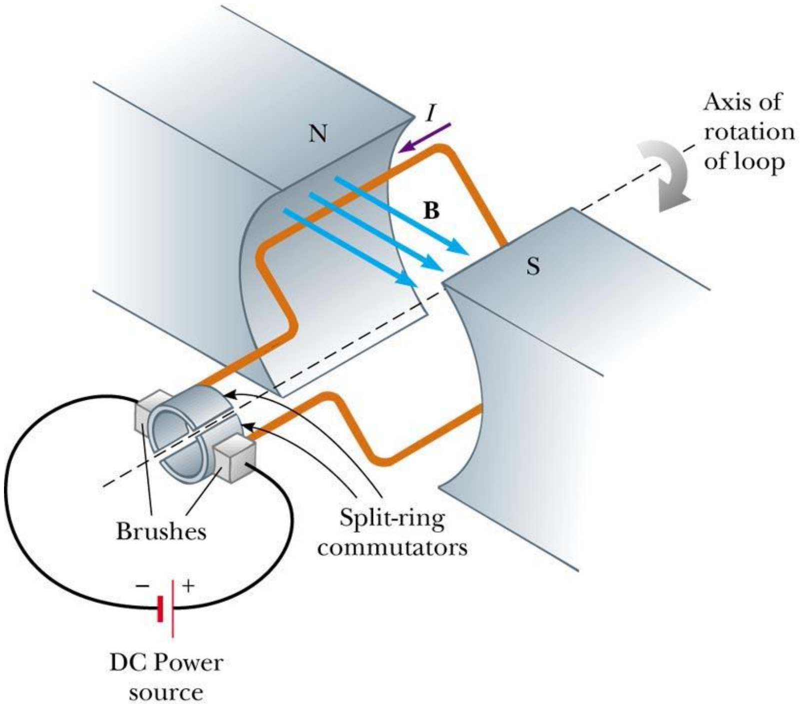
$$\tau = nBIA\sin\theta$$

– Applies to any shape loop
– N is the number of turns in the coil



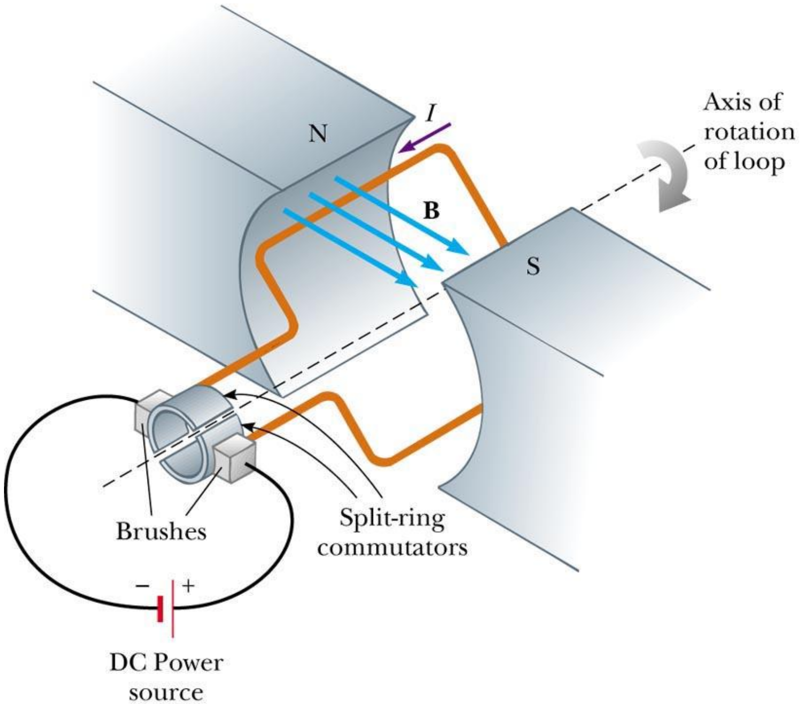
Electric Motor

- An electric motor converts electrical energy to mechanical energy
  - The mechanical energy is in the form of rotational kinetic energy
- An electric motor consists of a rigid current-carrying loop that rotates when placed in a magnetic field



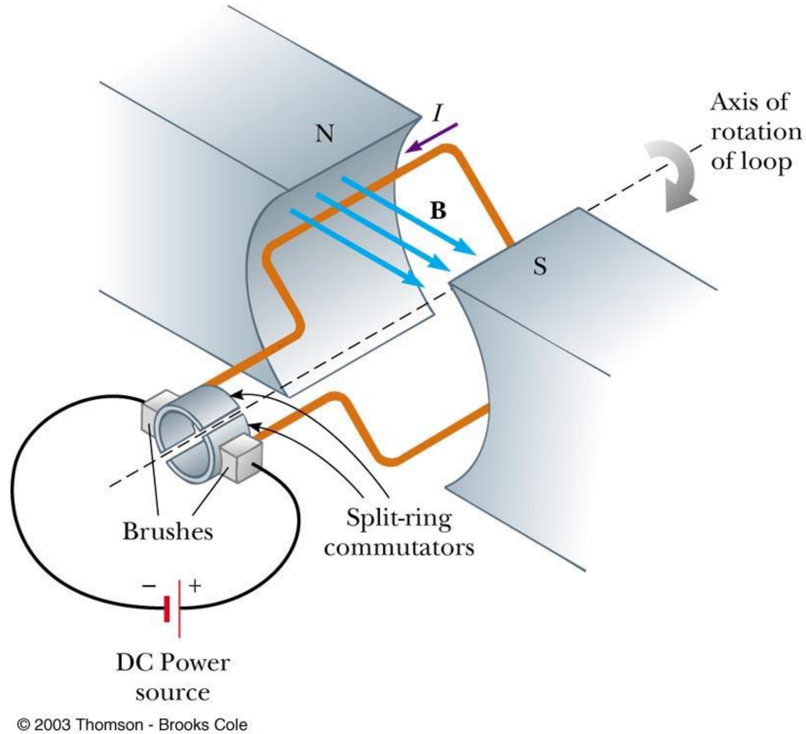
Electric Motor

- The torque acting on the loop will tend to rotate the loop to smaller values of θ until the torque becomes 0 at θ = 0°
- If the loop turns past this point and the current remains in the same direction, the torque reverses and turns the loop in the opposite direction



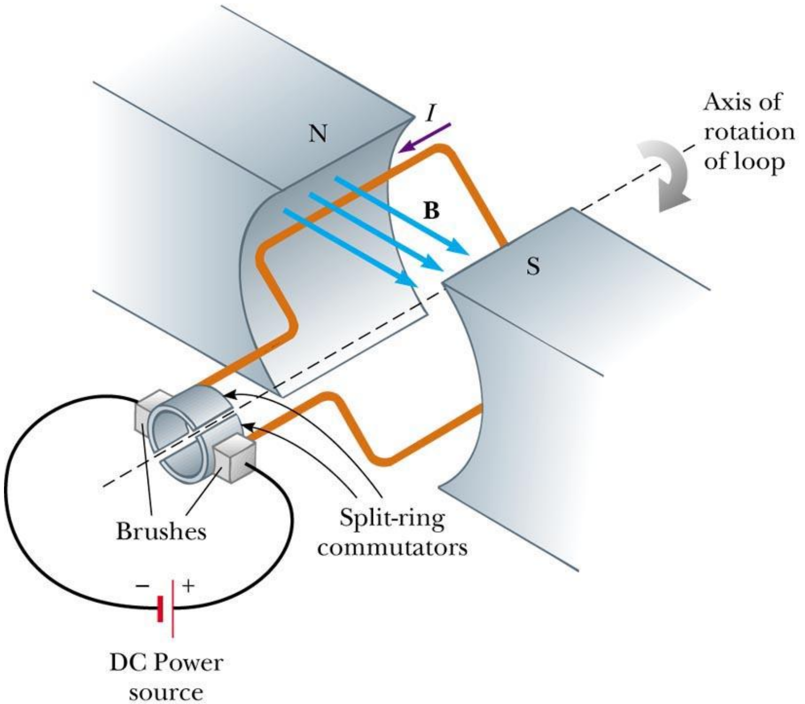
Electric Motor

- To provide continuous rotation in one direction, the current in the loop must periodically reverse
  - In ac motors, this reversal naturally occurs
  - In dc motors, a *split-ring commutator* and brushes are used
    - Actual motors would contain many current loops and commutators



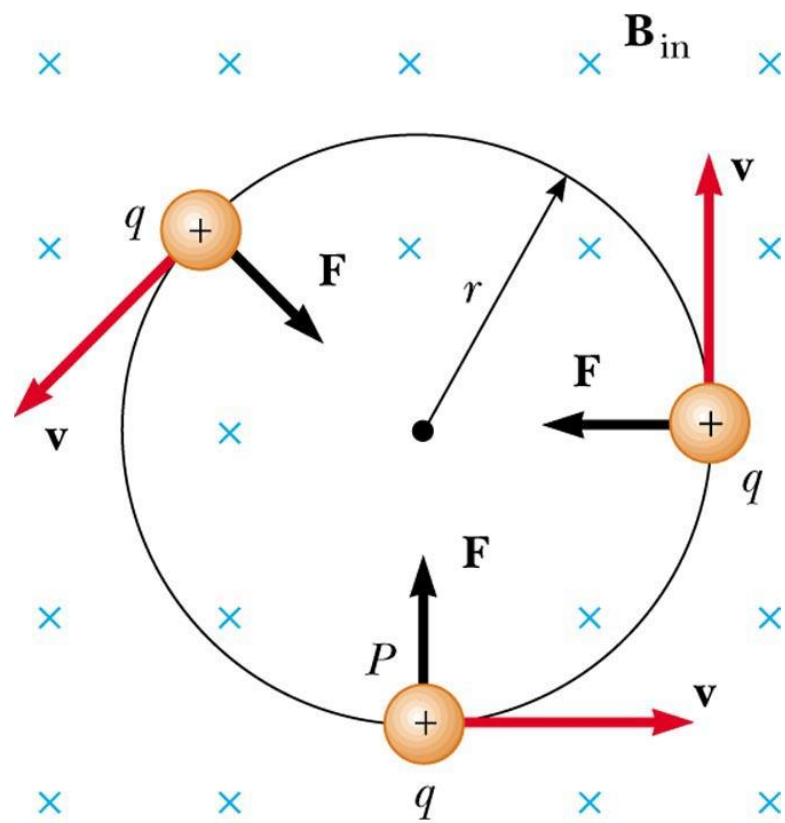
Electric Motor

- Just as the loop becomes perpendicular to the magnetic field and the torque becomes 0, inertia carries the loop forward and the brushes cross the gaps in the ring, causing the current loop to reverse its direction
  - This provides more torque to continue the rotation
  - The process repeats itself



Force on a Charged Particle in a Magnetic Field

- Consider a particle moving in an external magnetic field so that its velocity is perpendicular to the field
- The force is always directed toward the center of the circular path
- The magnetic force causes a centripetal acceleration, changing the direction of the velocity of the particle



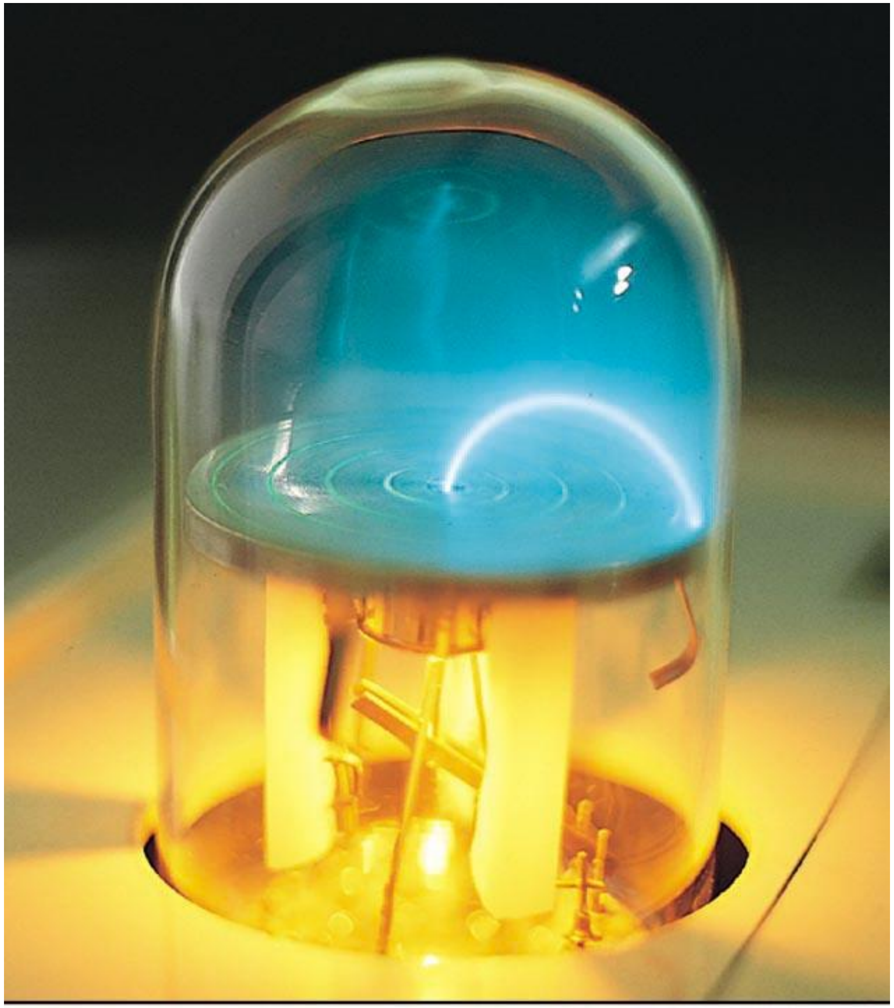
Force on a Charged Particle

- Equating the magnetic and centripetal forces:

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

- Solving for r: $$r = \frac{mv}{qB}$$
  - r is proportional to the momentum of the particle and inversely proportional to the magnetic field

Bending an Electron Beam in an External Magnetic Field



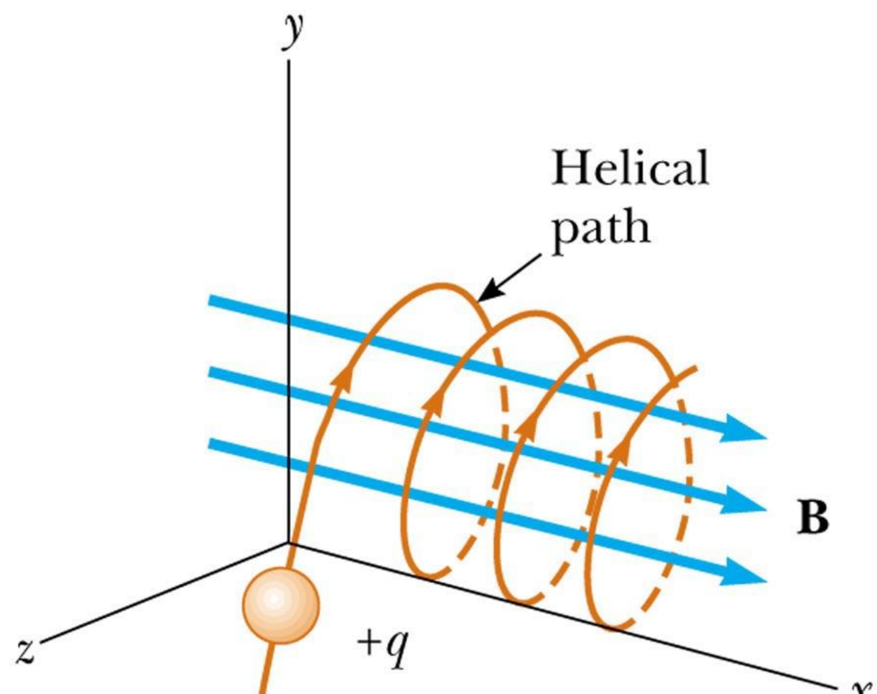
© 2003 Thomson - Brooks Cole

This is part of how J. J. Thompson determined the mass-to-charge ratio of the electron

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

Particle Moving in an External Magnetic Field, 2

- If the particle's velocity is *not* perpendicular to the field, the path followed by the particle is a spiral
  - The spiral path is called a *helix*



QUICK QUIZ 19.3

As a charged particle moves freely in a circular path in the presence of a constant magnetic field applied perpendicular to the particle's velocity, its kinetic energy (a) remains constant, (b) increases, or (c) decreases.

QUICK QUIZ 19.3 ANSWER

(a). The magnetic force acting on the particle is always perpendicular to the velocity of the particle, and hence to the displacement the particle is undergoing. Under these conditions, the force does no work on the particle and the particle's kinetic energy remains constant.

QUICK QUIZ 19.4

Two charged particles are projected into a region in which a magnetic field is perpendicular to their velocities. After they enter the magnetic field, you can conclude that (a) the charges are deflected in opposite directions, (b) the charges continue to move in a straight line, (c) the charges move in circular paths, or (d) the charges move in circular paths but in opposite directions.

QUICK QUIZ 19.4 ANSWER

(c). Anytime the velocity of a charged particle is perpendicular to the magnetic field, it will follow a circular path. The two particles will move in opposite directions around their circular paths if their charges have opposite signs, but their charges are unknown so (d) is not an acceptable answer.

Right hand Rule #2

MAGNETIC FIELD GENERATED BY A WIRE'S CURRENT

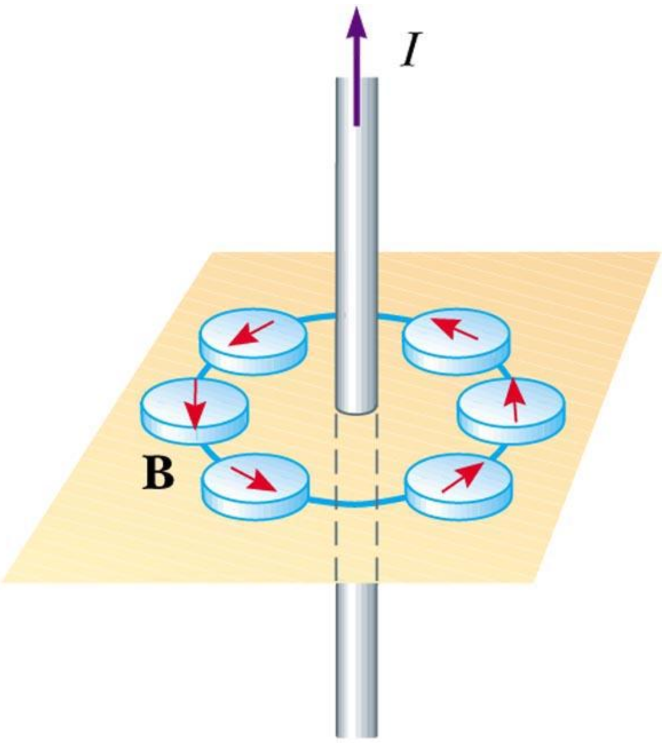
- Term comes from the ancient Greek city of Magnesia, at which many natural magnets were found. We now refer to these natural magnets as **lodestones** (also spelled loadstone; lode means to lead or to attract) which contain **magnetite**, a natural magnetic material Fe_3O_4.

- Pliny the Elder (23-79 AD Roman) wrote of a hill near the river Indus that was made entirely of a stone that attracted iron.

A Brief History of the World

Magnetic Fields – Long Straight Wire

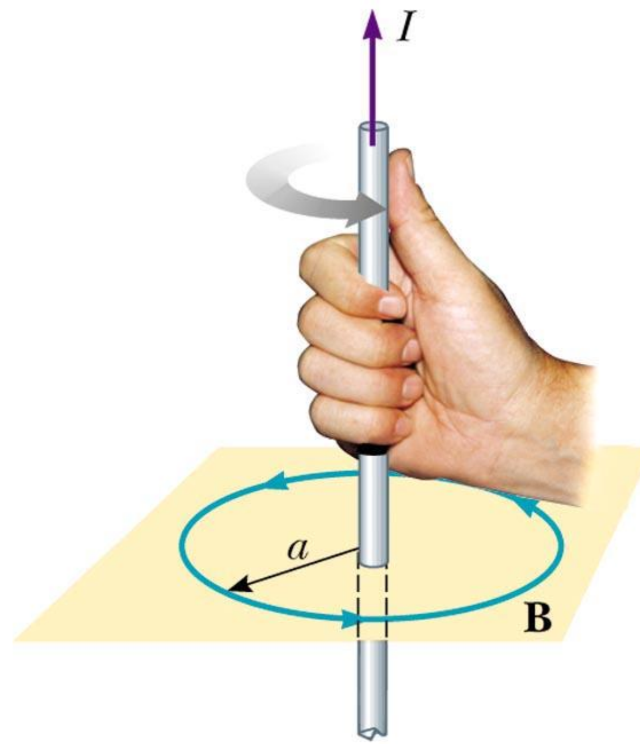
- A current-carrying wire produces a magnetic field
- The compass needle deflects in directions tangent to the circle
  – The compass needle points in the direction of the magnetic field produced by the current



(b)

Direction of the Field of a Long Straight Wire

- Right Hand Rule #2
  - Grasp the wire in your right hand
  - Point your thumb in the direction of the current
  - Your fingers will curl in the direction of the field



(a)

Magnitude of the Field of a Long Straight Wire

- The magnitude of the field at a distance r from a wire carrying a current of I is

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

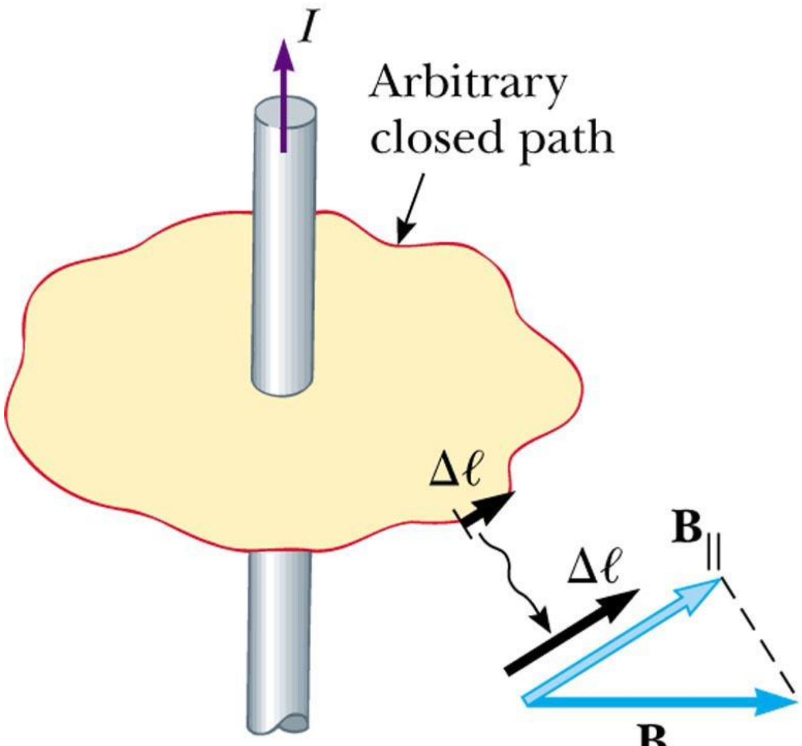
- $\mu_o = 4\,\pi \times 10^{-7}$ T m / A
  - μ_o is called the *permeability of free space*

Ampère's Law

- André-Marie Ampère found a procedure for deriving the relationship between the current in a arbitrarily shaped wire and the magnetic field produced by the wire
- Ampère's Circuital Law
  - $\Sigma B_{||} \Delta \ell = \mu_o I$
  - Sum over the closed path

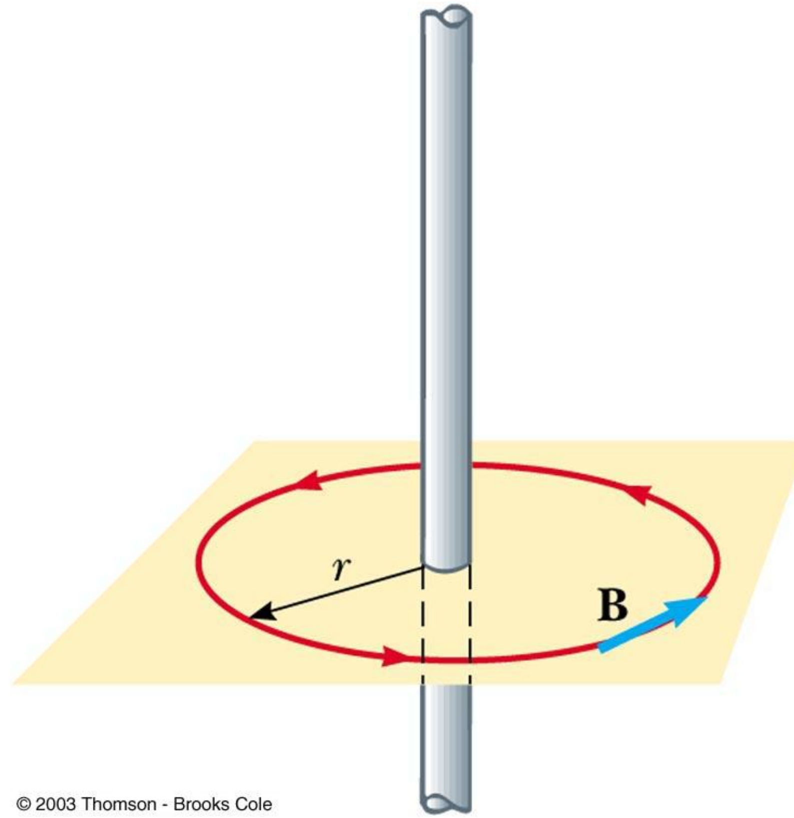
Ampère's Law, cont

- Choose an arbitrary closed path around the current
- Sum all the products of $B_{||}\,\Delta\ell$ around the closed path



Ampère's Law to Find B for a Long Straight Wire

- Use a closed circular path
- The circumference of the circle is $2\,\pi\,r$
- $$B = \frac{\mu_o I}{2\pi r}$$
  - This is identical to the result previously obtained

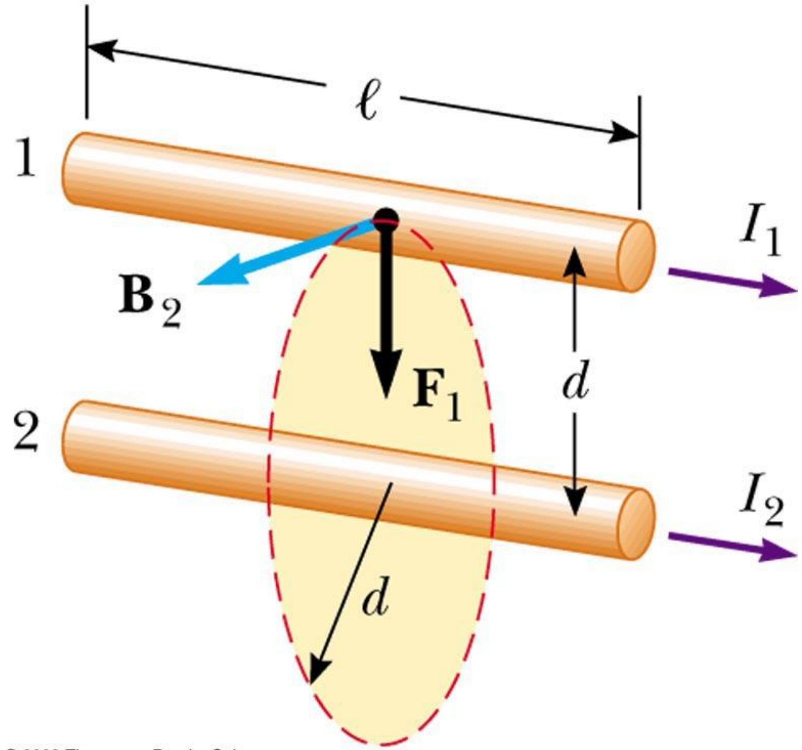


Magnetic Force Between Two Parallel Conductors

- The force on wire 1 is due to the current in wire 1 and the magnetic field produced by wire 2
- The force per unit length is:

$$\boxed{\frac{F}{\ell} = \frac{\mu_o I_1 I_2}{2 \pi d}}$$

Not a necessary equation



Force Between Two Conductors, cont

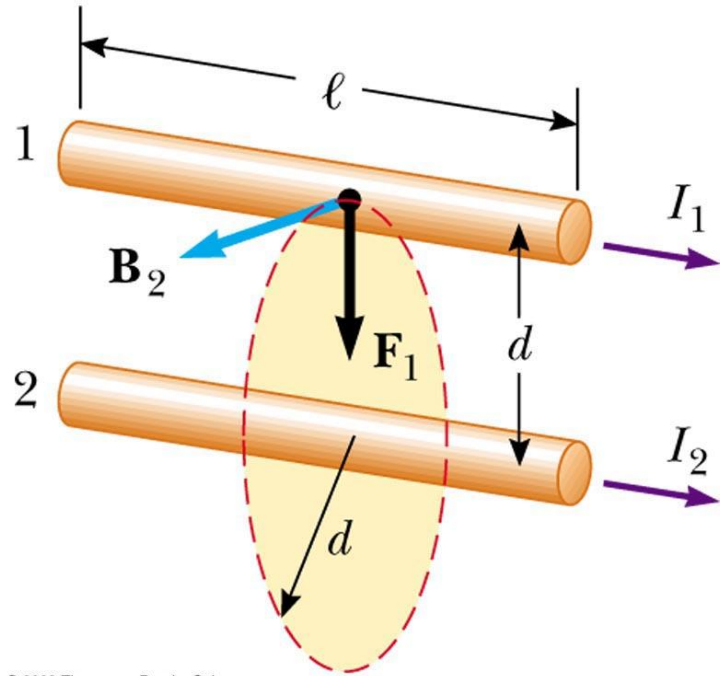
- Parallel conductors carrying currents in the same direction attract each other
- Parallel conductors carrying currents in the opposite directions repel each other

Defining Ampere and Coulomb

- The force between parallel conductors can be used to define the Ampere (A)
  - If two long, parallel wires 1 m apart carry the same current, and the magnitude of the magnetic force per unit length is 2×10^{-7} N/m, then the current is defined to be 1 A
- The SI unit of charge, the Coulomb (C), can be defined in terms of the Ampere
  - If a conductor carries a steady current of 1 A, then the quantity of charge that flows through any cross section in 1 second is 1 C

QUICK QUIZ 19.5

If $I_1 = 2$ A and $I_2 = 6$ A in the figure below, which of the following is true:
(a) $F_1 = 3F_2$, (b) $F_1 = F_2$, or (c) $F_1 = F_2/3$?

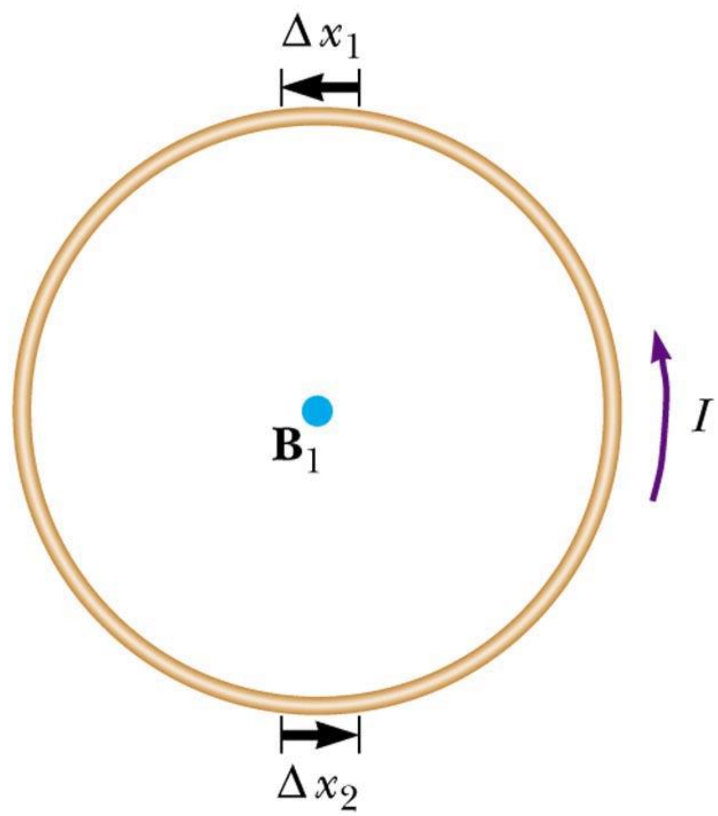


QUICK QUIZ 19.5 ANSWER

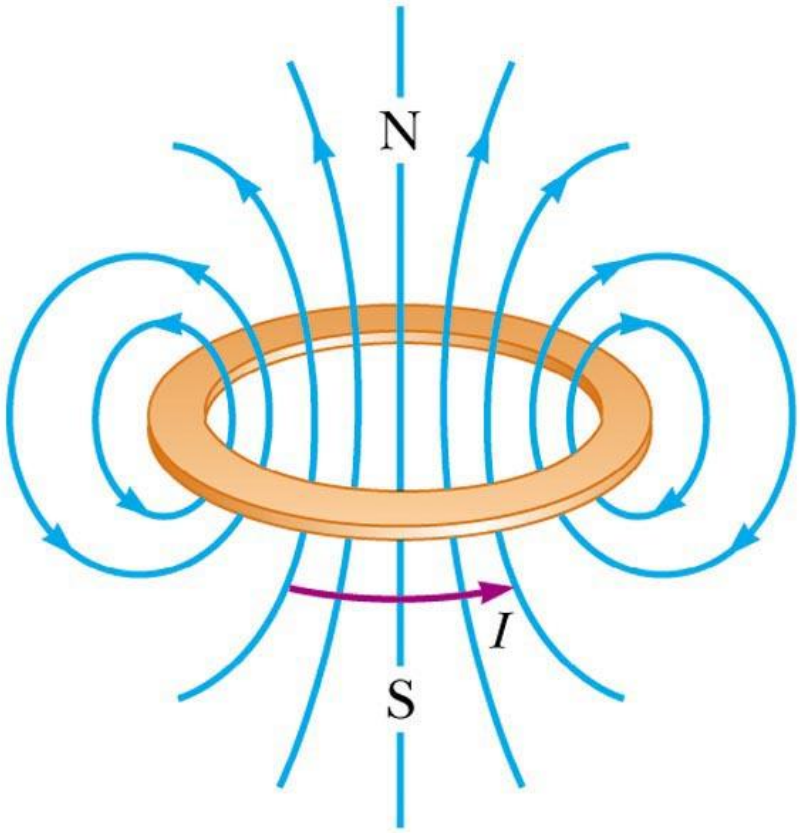
(b). The two forces are an action-reaction pair. They act on different wires, and have equal magnitudes but opposite directions.

Magnetic Field of a Current Loop

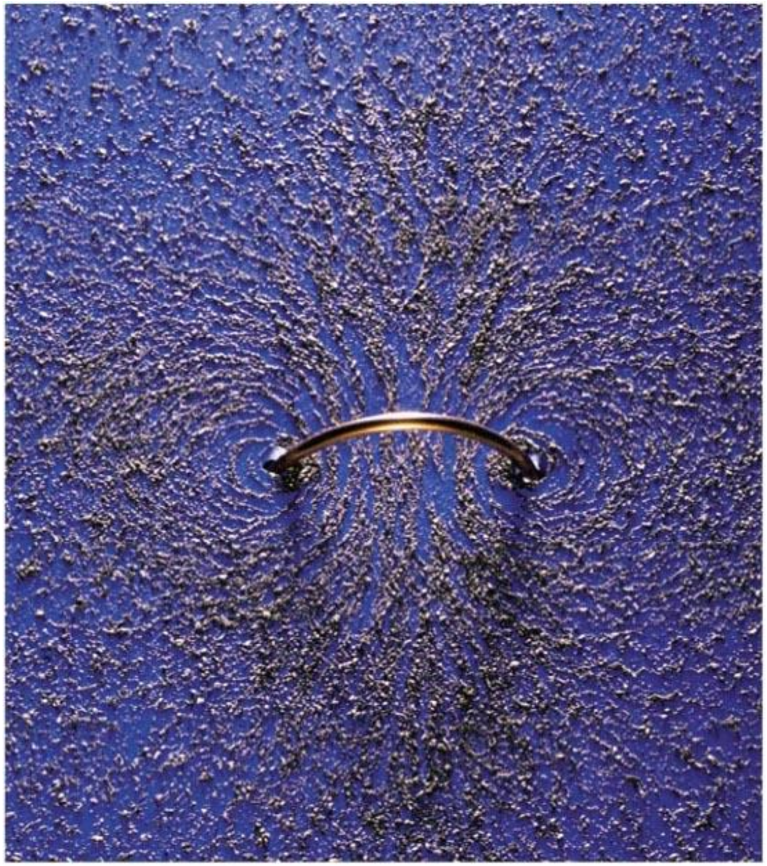
- The strength of a magnetic field produced by a wire can be enhanced by forming the wire into a loop
- All the segments, Δx, contribute to the field, increasing its strength



Magnetic Field of a Current Loop – Total Field



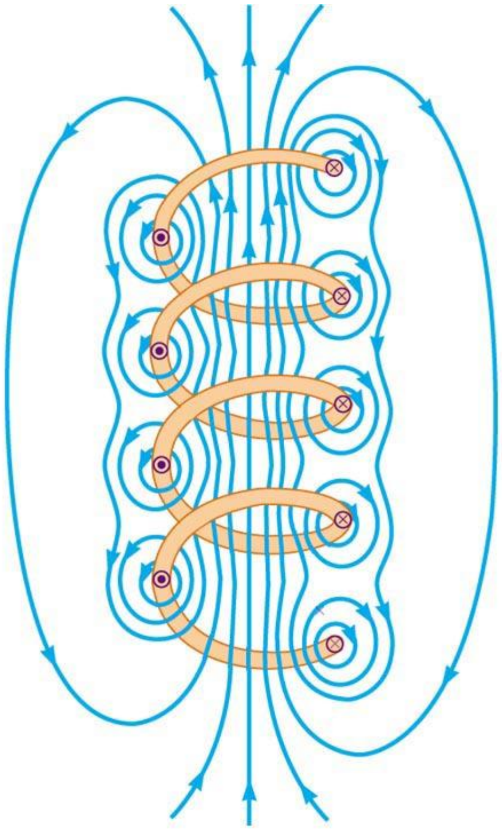
(a)



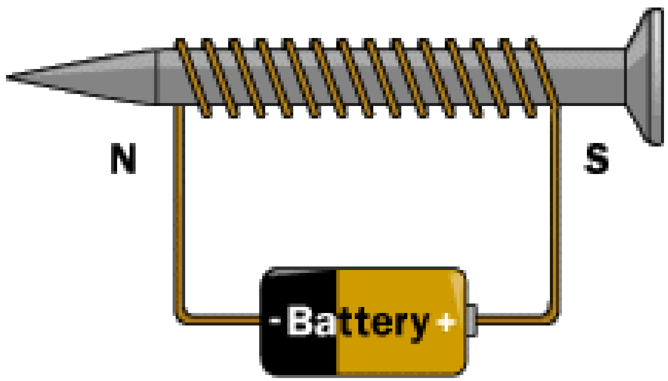
(b)

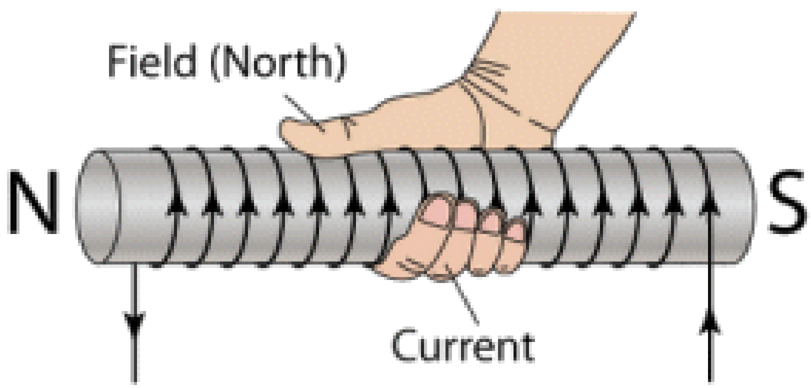
Magnetic Field of a Solenoid

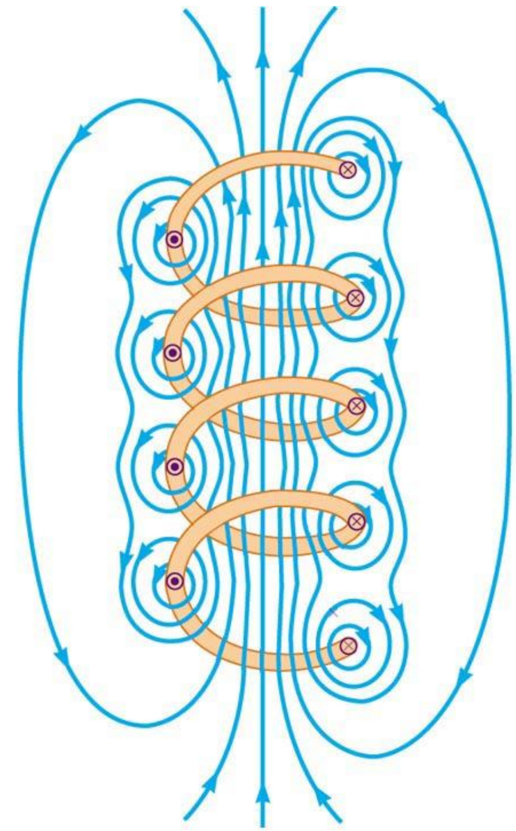
- If a long straight wire is bent into a coil of several closely spaced loops, the resulting device is called a solenoid
- It is also known as an electromagnet since it acts like a magnet only when it carries a current



Right Hand Rule #3





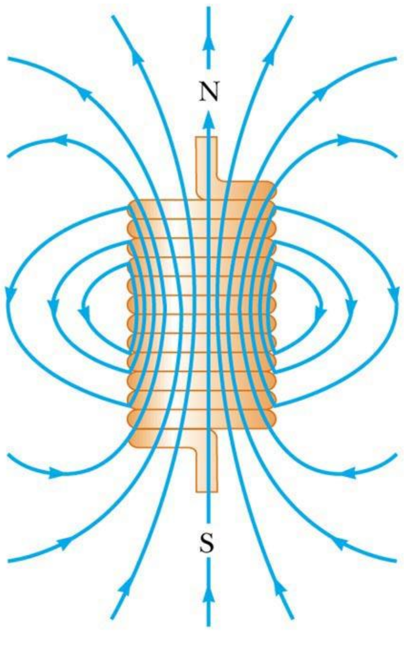


Magnetic Field of a Solenoid, 2

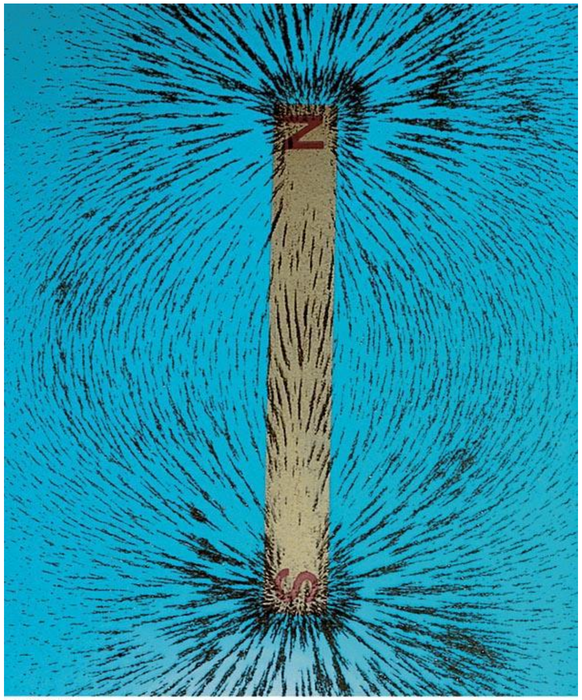
- The field lines inside the solenoid are nearly parallel, uniformly spaced, and close together
  - This indicates that the field inside the solenoid is nearly uniform and strong
- The exterior field is nonuniform, much weaker, and in the opposite direction to the field inside the solenoid

Magnetic Field in a Solenoid, 3

- The field lines of the solenoid resemble those of a bar magnet



(a)

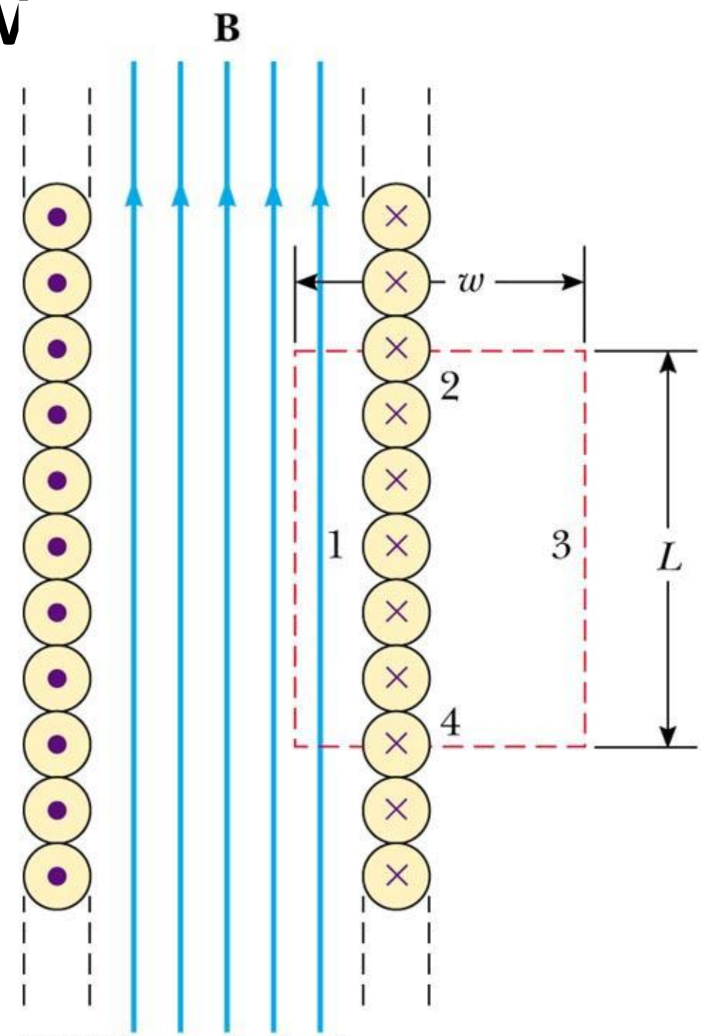


Magnetic Field in a Solenoid, Magnitude

- The magnitude of the field inside a solenoid is constant at all points far from its ends
- $B = \mu_o n I$
  - n is the number of turns per unit length
  - $n = N / \ell$
- The same result can be obtained by applying Ampère's Law to the solenoid

Magnetic Field in a Solenoid from Ampère's Law

- A cross-sectional view of a tightly wound solenoid
- If the solenoid is long compared to its radius, we assume the field inside is uniform and outside is zero
- Apply Ampère's Law to the red dashed rectangle

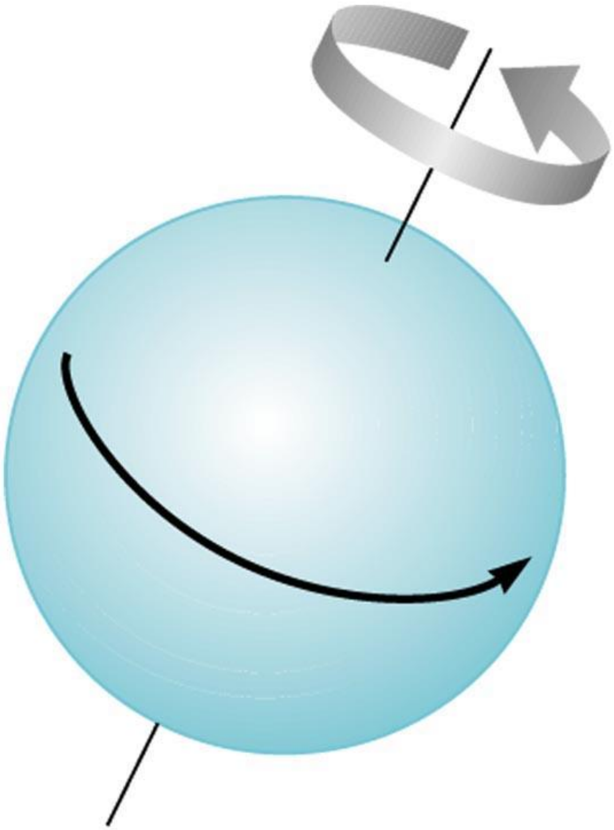


Revisited from much earlier in the presentation

THE CAUSE OF MAGNETIC PHENOMENA

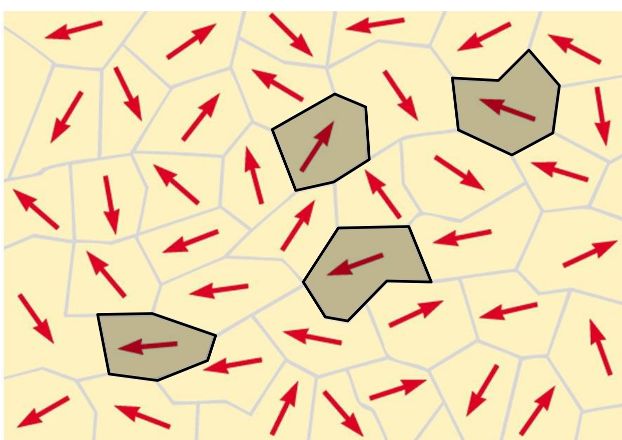
Magnetic Effects of Electrons -- Spins

- Electrons have spin
  - It is a property of the electron, and the fourth quantum number for atoms (s)
  - This spin in combination with the angular orbital momentum quantum number (l) make each electron, when in the correct orbital, the smallest source of magnetism. This was first proven by Niels Bohr's model of the atom and later reinforced by Paul Dirac.
  - More can be found at the following sites:
    - http://hyperphysics.phy-astr.gsu.edu/hbase/spin.html#c4
    - http://en.wikipedia.org/wiki/Spin_%28physics%29
    - http://en.wikipedia.org/wiki/Magnetic_dipole_moment
    - http://en.wikipedia.org/wiki/Spin_%28physics%29#Magnetic_moments
    - http://en.wikipedia.org/wiki/Angular_momentum_coupling
    - http://en.wikipedia.org/wiki/Bohr_magneton

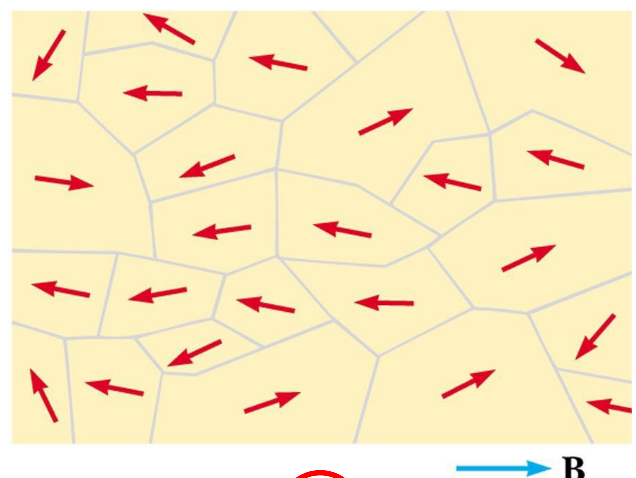


Magnetic Domains

- If each electron can be a magnet, atoms where electrons properly align (in things like iron atoms) can make magnetic atoms
  - These materials are called *ferromagnetic*
- Magnetic atoms will then line-up with neighboring atoms so that the small crystals (within the gray outlined sections below) are areas of aligned atoms called **magnetic domains**
- Usually those domains are randomly distributed (shown in *a*), but if the magnetic domains are aligned or partially aligned (shown in *b*) the sum of these domains can add up to an overall magnetic material (called a *magnetic dipolarization* of the material)



(a)



(b)

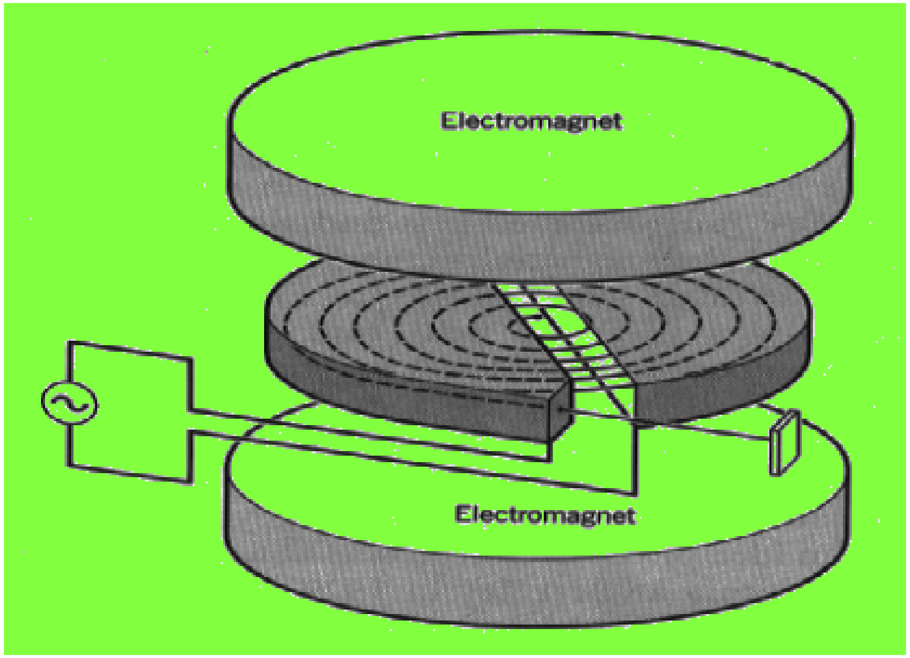
Cyclotron

→ Developed in 1931 by E. O. Lawrence and M. S. Livingston at UC Berkeley

→ Uses electric fields to accelerate and magnetic fields to guide particles at very high speeds

How a Cyclotron Works

→ Pair of metal chambers shaped like a pillbox cut along one of its diameters (cleverly referred to as “D”s) and slightly separated



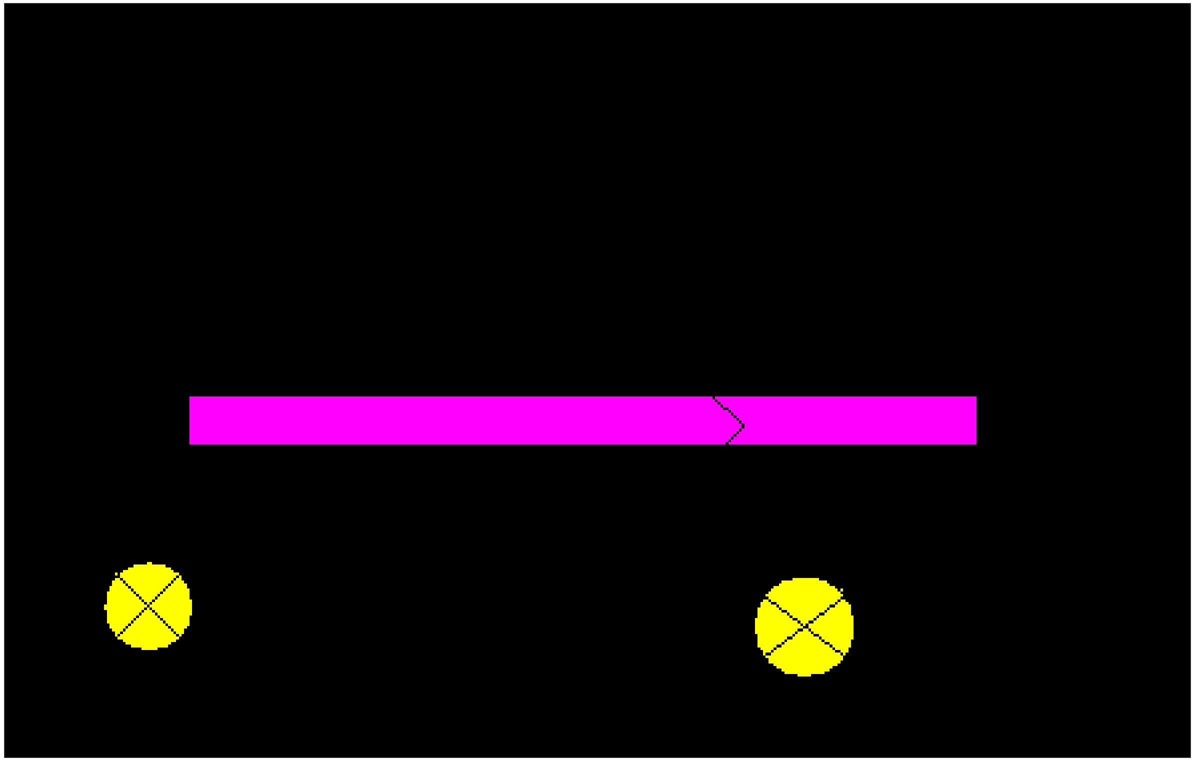
→ Ds connected to alternating current

→ Ions injected near gap

→ Ions are accelerated as long as they remain “in step” with alternating electric field

Magnetic Force on Current-Carrying Wire

Since moving charges experience a force in a magnetic field, a current-carrying wire will experience such a force, since a current consists of moving charges. This property is at the heart of a number of devices.



Electromagnet (Magnetism from Electricity)

An **electromagnet** is simply a coil of wires which, when a current is passed through, generate a magnetic field, as below.