

Chapter 19

Magnetism

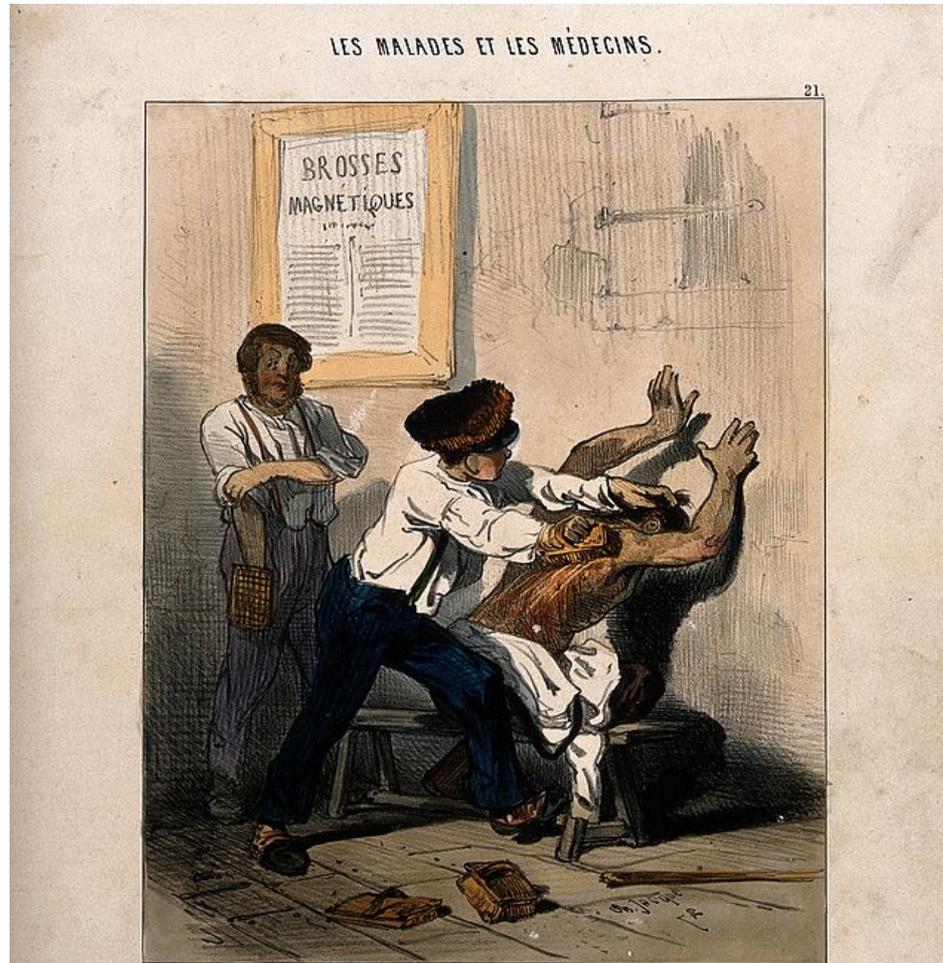
Magnetic Fields and Forces

Fundamentally they do not exist

If we had special relativity we would find there is no such thing as a magnetic field. It is only a relativistic transformation of an electric field

Magnetism and Medical School

Attractive



Cher Fosseur, Editeur R. de Croissant 16.

Cher Albert, Pl. de la Bourse.

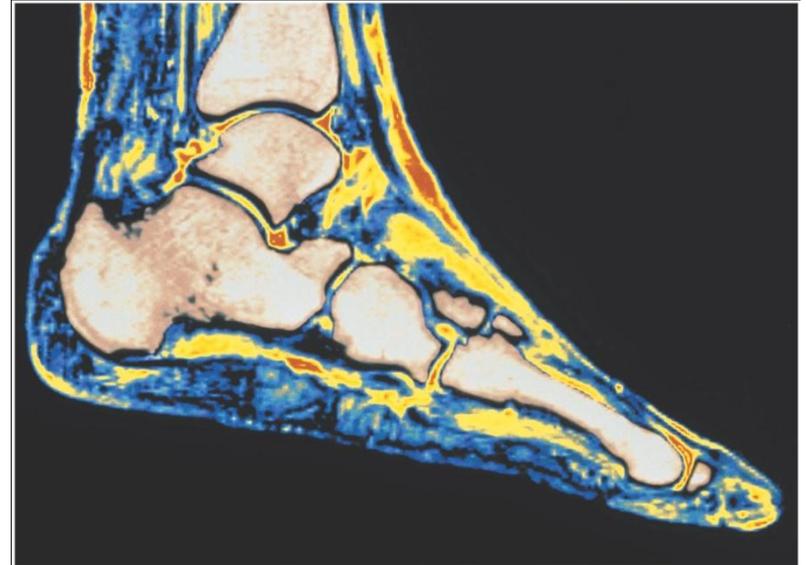
Imp. J. Aubert & Co.

LE SYSTÈME DES BROSSES MAGNETIQUES.

— Oh! là là... oh là là!... mais vous m'écorchez tout vif... — Parbleu c'est tout simple... puisqu'on m'a bien recommandé de vous faire circuler le sang... j'm'en vas vous le faire circuler dans tout l'appartement!...

Introduction

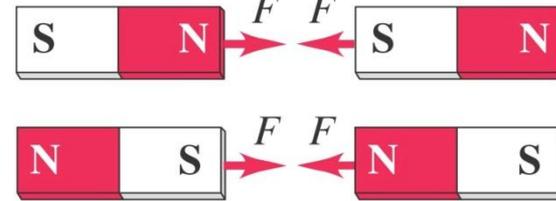
- Magnets exert forces on each other just like charges. You can draw magnetic field lines just like you drew electric field lines.
- Electrostatics, electrodynamics, and magnetism are deeply interwoven.
- MRI scan of a human foot. The magnetic field interacts with molecules in the body to orient spin before radiofrequencies are used to make the spectroscopic map. The different shades are a result of the range of responses from different types of tissue in the body.



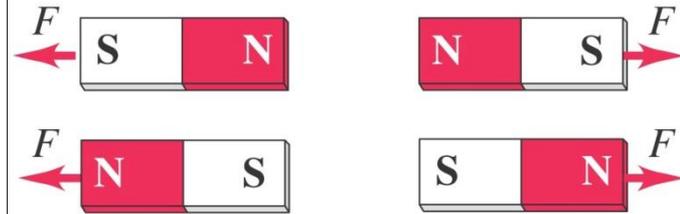
Magnetism

- Magnetic north and south poles' behavior is not unlike electric charges. For magnets, like poles repel and opposite poles attract. BUT the poles of a magnet are NOT literally magnetic monopoles. In an electrostatic dipole the “pole ends” are in fact monopoles.
- **We have never found a magnetic monopole.**

(a) Opposite poles attract.

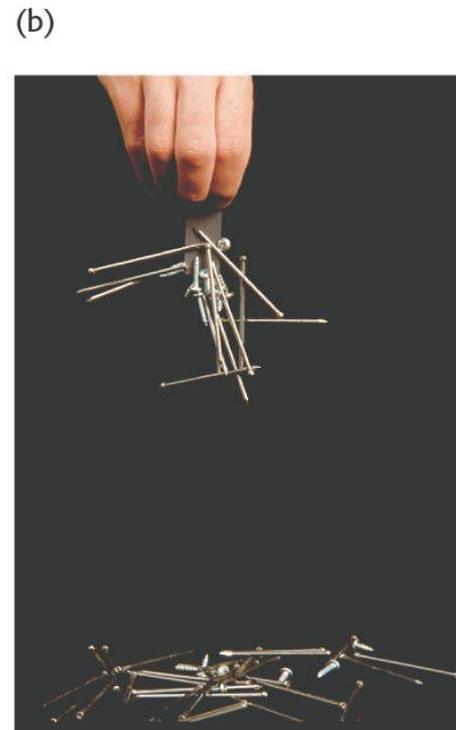
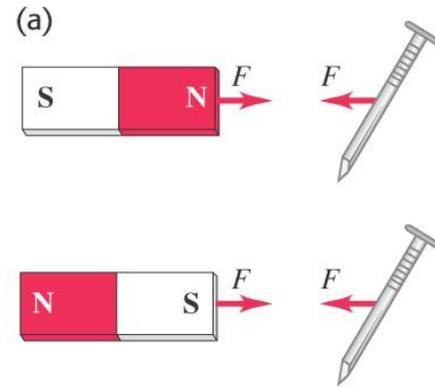


(b) Like poles repel.



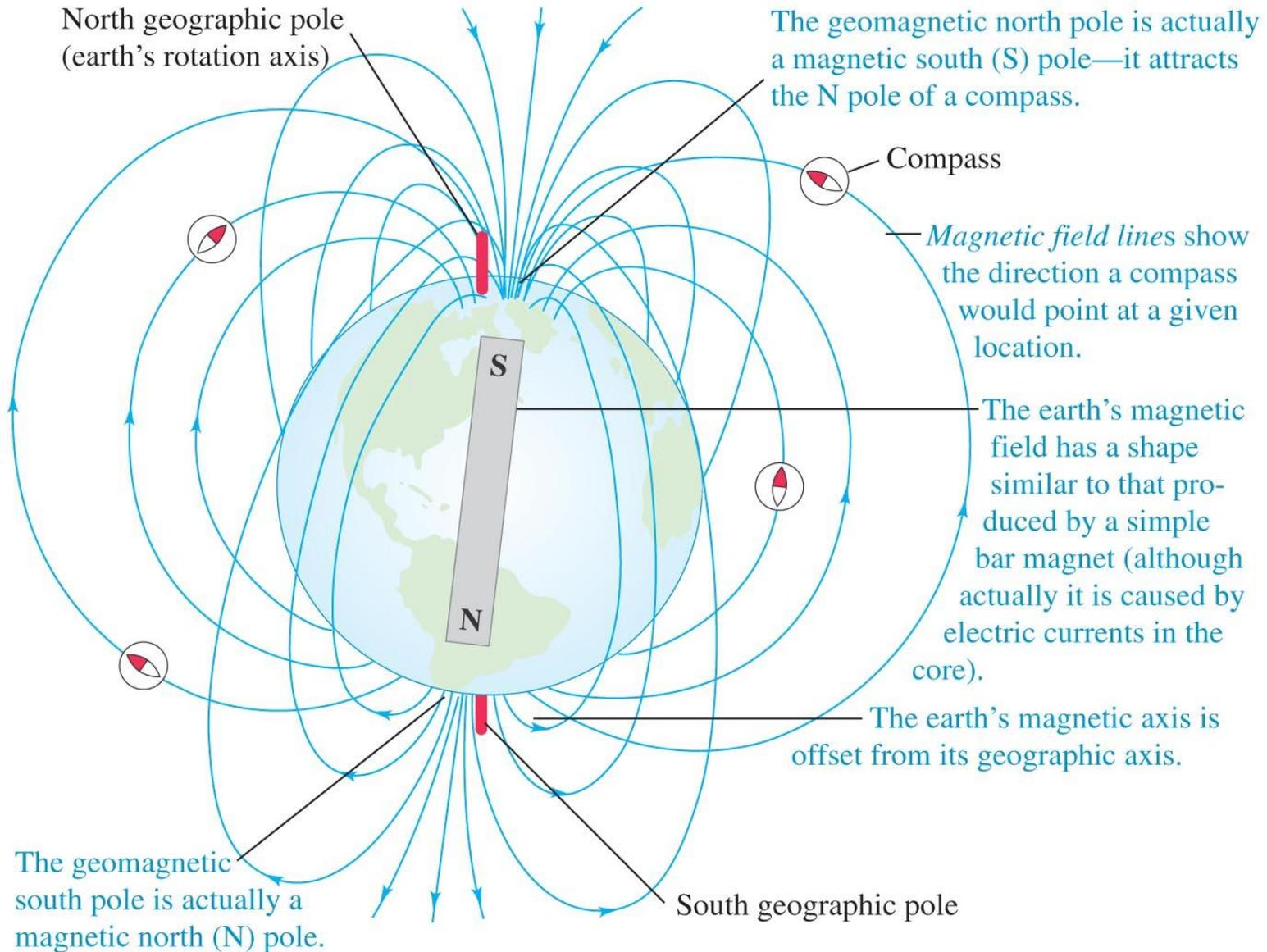
Magnetism and certain metals

- A permanent magnet will attract a metal like iron with either the north or south pole.
- Remember the electrostatic case of “static cling” from induced electric dipoles. Here all magnets are dipoles no monopoles known.



The magnetic poles about our planet

North is South

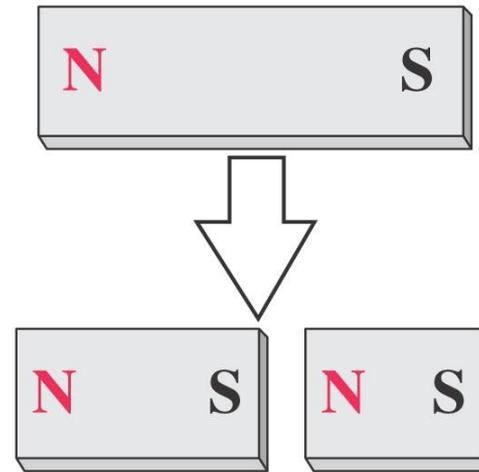


Magnetic pole(s)?

- We observed monopoles in electricity. A (+) or (-) alone was stable and field lines could be drawn around it.
- Magnets cannot exist as monopoles. If you break a bar magnet between N and S poles, you get two smaller magnets, each with its own N and S pole.

In contrast to electric charges, magnetic poles always come in pairs and can't be isolated.

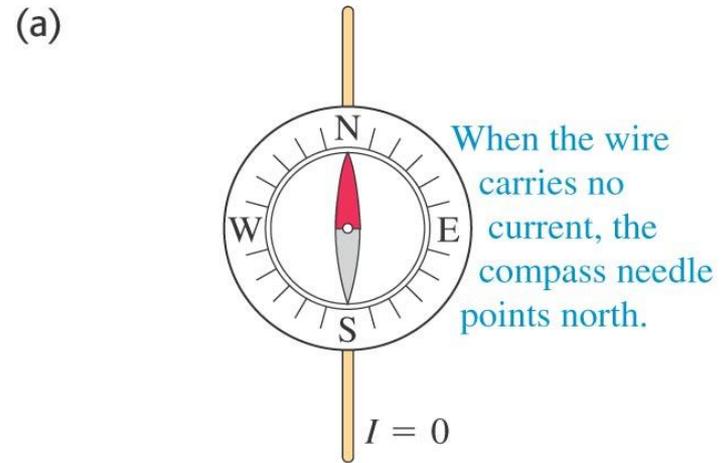
Breaking a magnet in two ...



... yields two magnets,
not two isolated poles.

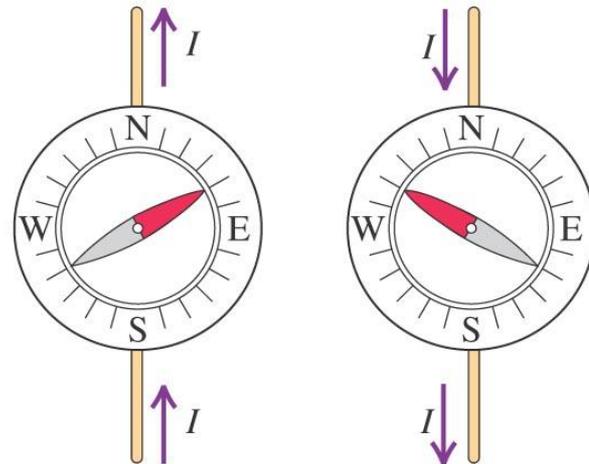
Electric current and magnets

- In 1820, Hans Oersted ran a series of experiments with conducting wires run near a sensitive compass. The result was dramatic. The orientation of the wire and the direction of the flow both moved the compass needle.
- There had to be something magnetic about current flow.



(b)

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

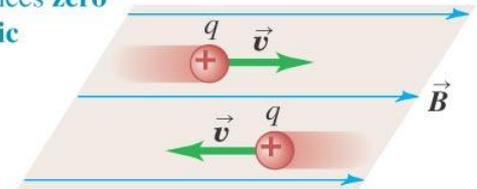


The interaction of magnetic force and charge

- The moving charge interacts with the fixed magnet. The force between them is at a maximum when the velocity of the charge is perpendicular to the magnetic field.

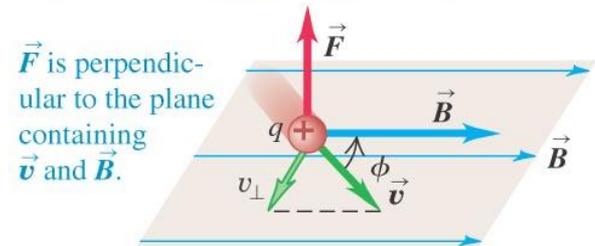
(a)

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



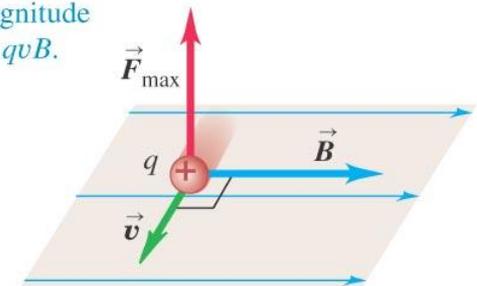
(b)

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



(c)

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



The “right-hand rule” I

- This is for a positive charge moving in a magnetic field.
- Place your hand out as if you were getting ready for a handshake. Your fingers represent the velocity vector of a moving charge.
- Move the fingers of your hand toward the magnetic field vector.
- Your thumb points in the direction of the force between the two vectors.

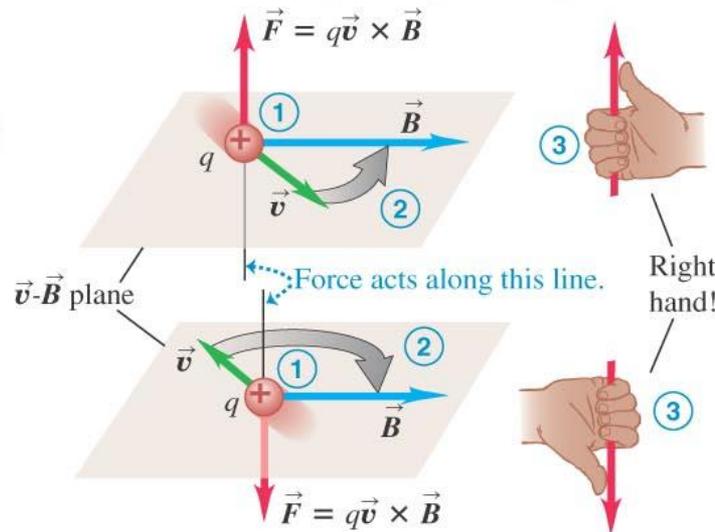
(a)

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.

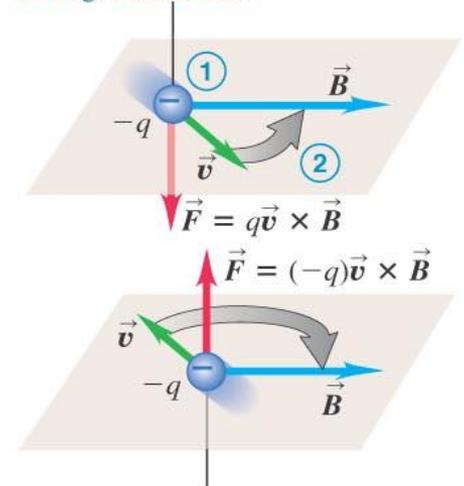
② Imagine turning \vec{v} toward \vec{B} in the \vec{v} - \vec{B} plane (through the smaller angle).

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.



(b)

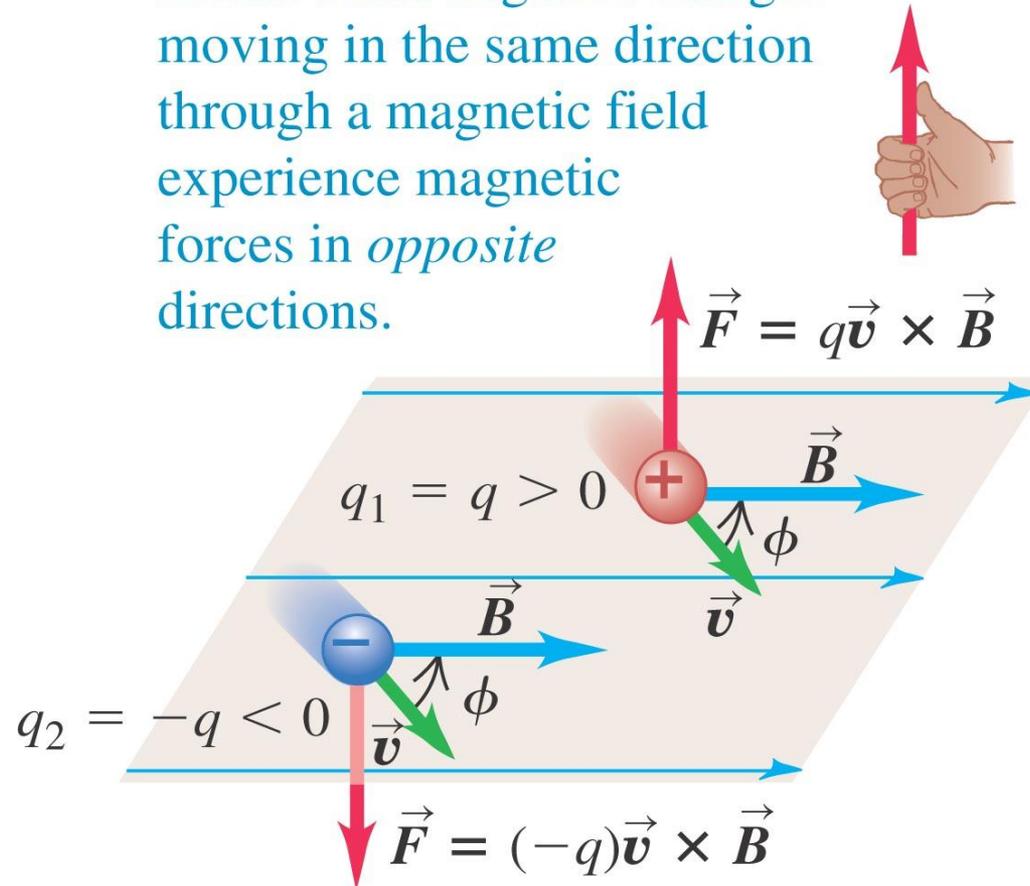
If the charge is negative, the direction of the force is *opposite* to that given by the right-hand rule.



Right-hand rule II

- Two charges of equal magnitude but opposite signs moving in the same direction in the same field will experience force in opposing directions.

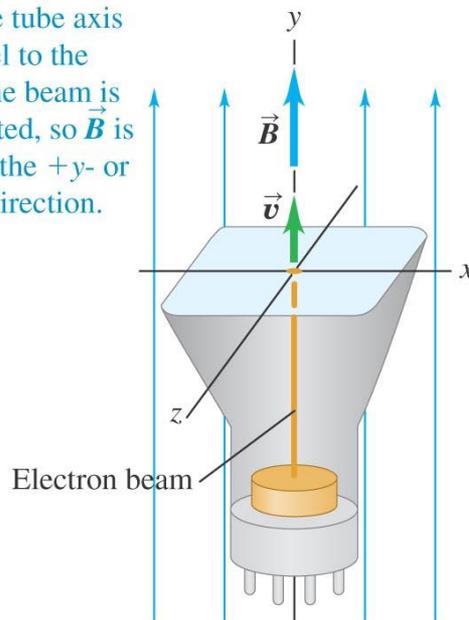
Positive and negative charges moving in the same direction through a magnetic field experience magnetic forces in *opposite* directions.



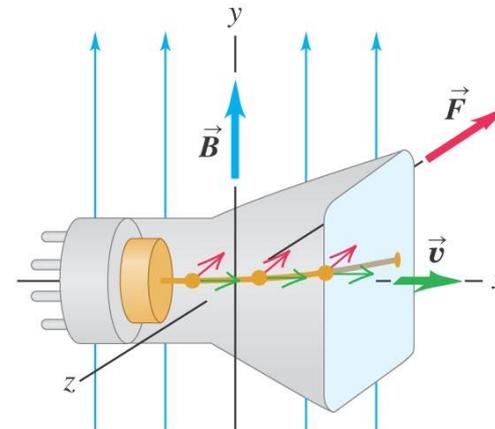
Direction of a magnetic field with your CRT

- A TV or a computer screen is a cathode ray tube, an electron gun with computer aiming control. Place it in a magnetic field going “up and down.”
- You point the screen toward the ceiling and nothing happens to the picture. The magnetic field is parallel to the electron beam.
- You set the screen in a normal viewing position and the image distorts. The magnetic force is opposite to the thumb in the RHR.

(a) If the tube axis is parallel to the y -axis, the beam is undeflected, so \vec{B} is in either the $+y$ - or the $-y$ -direction.

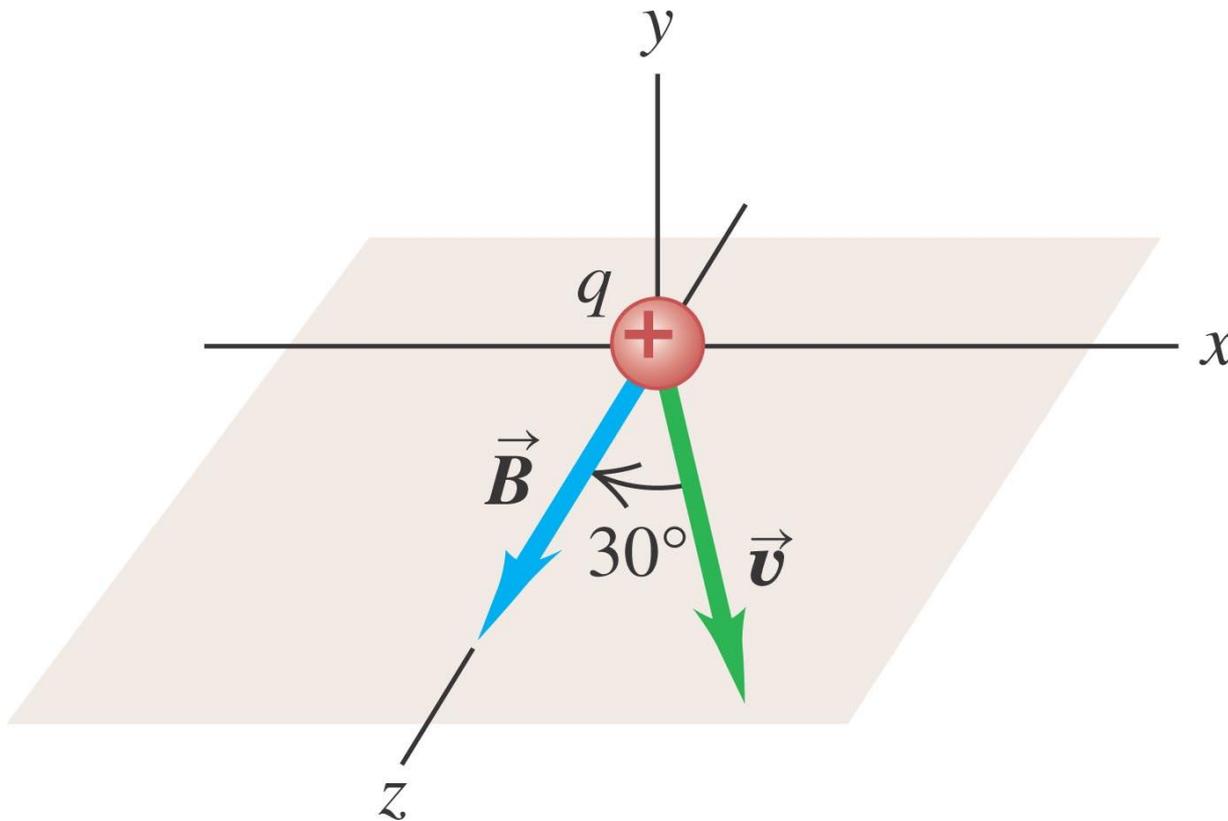


(b) If the tube axis is parallel to the x -axis, the beam is deflected in the $-z$ -direction, so \vec{B} is in the $+y$ -direction.



Magnetic forces

- $\mathbf{F} = q (\mathbf{v} \times \mathbf{B})$

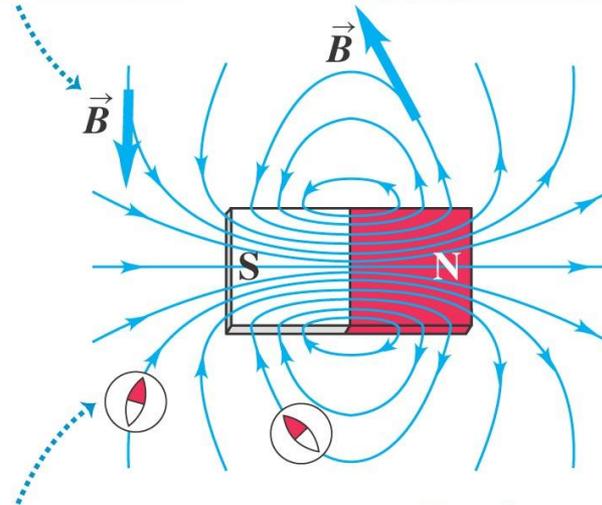


Magnetic field lines may be traced

- Magnetic field lines may be traced from N toward S in analogous fashion to the electric field lines.
- Refer to Figure 27.11.

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.

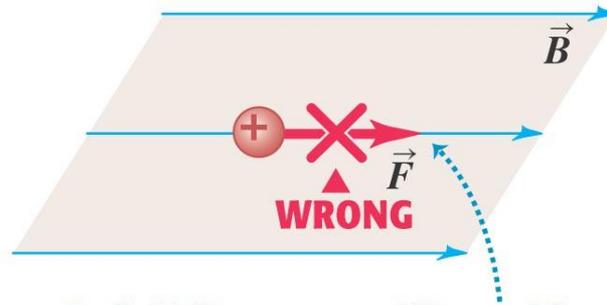


At each point, the field lines point in the same direction a compass would . . .

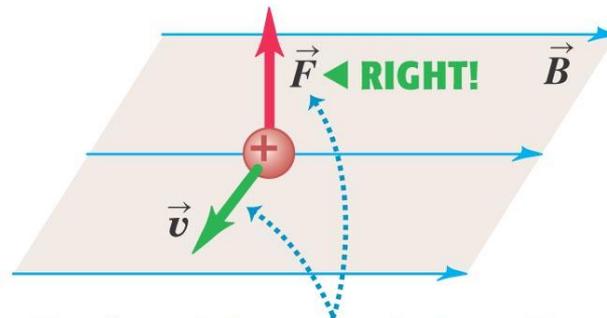
. . . therefore, magnetic field lines point *away from N poles and toward S poles.*

Field lines are not lines of force

- The lines tracing the magnetic field crossed through the velocity vector of a moving charge will give the direction of force by the RHR.



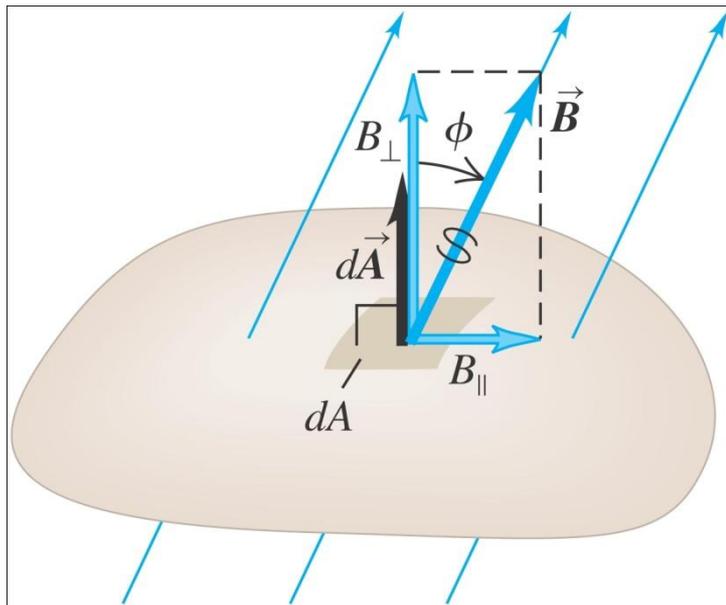
Magnetic field lines are *not* “lines of force.” The force on a charged particle is not along the direction of a field line.



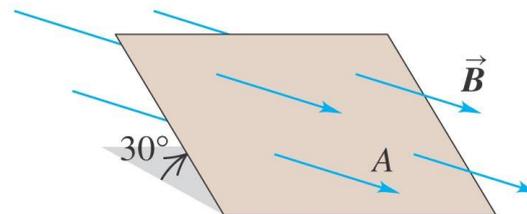
The direction of the magnetic force depends on the velocity \vec{v} , as expressed by the magnetic force law $\vec{F} = q\vec{v} \times \vec{B}$.

Magnetic flux through an area

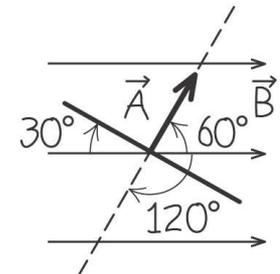
- We define the magnetic flux through a surface just as we defined electric flux.



(a) Perspective view



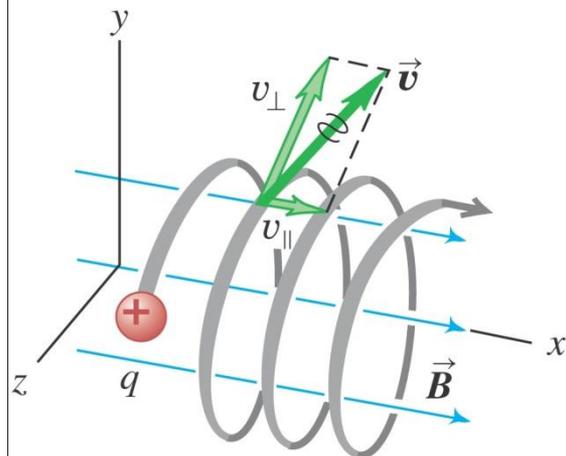
(b) Our sketch of the problem (edge-on view)



Motion of charged particles in a magnetic field

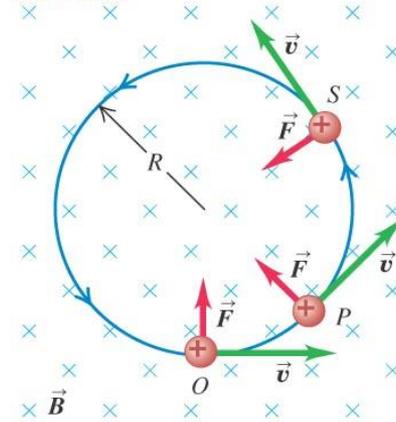
- A charged particle will move in a plane perpendicular to the magnetic field.
- Figure at right illustrates the forces and shows an experimental example.
- Figure below shows the constant kinetic energy and helical path.

This particle's motion has components both parallel (v_{\parallel}) and perpendicular (v_{\perp}) to the magnetic field, so it moves in a helical path.

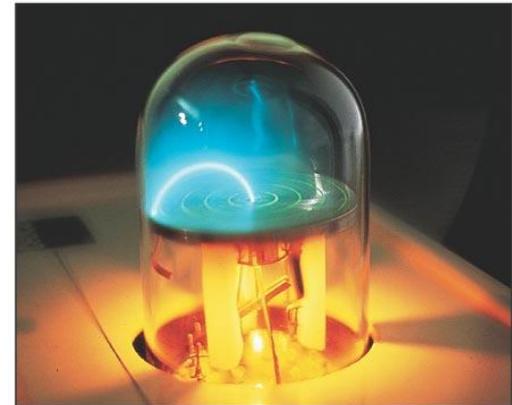


(a) The orbit of a charged particle in a uniform magnetic field

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.

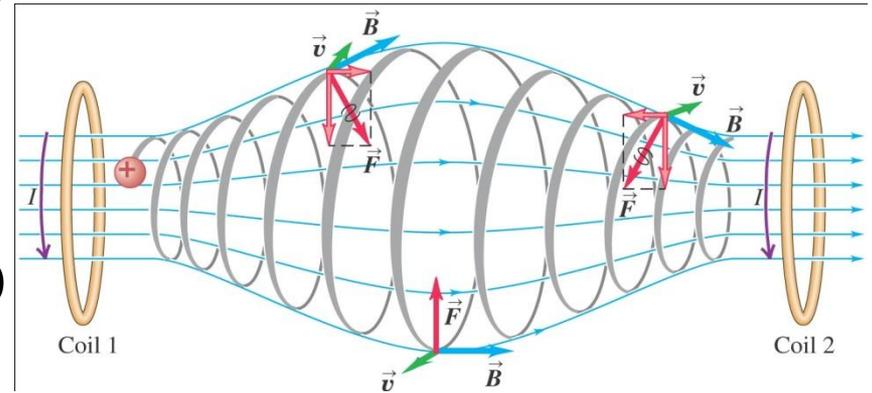


(b) An electron beam (seen as a blue arc) curving in a magnetic field

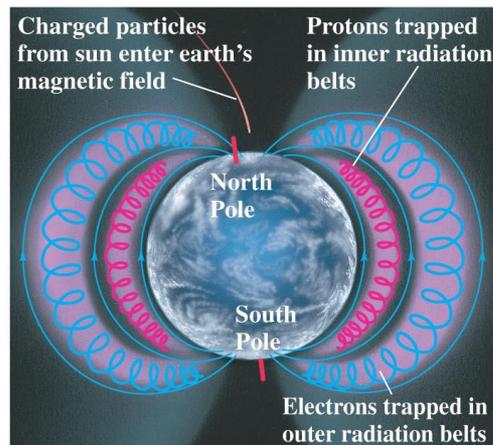


A magnetic bottle

- If we ever get seriously close to small-lab nuclear fusion, the magnetic bottle will likely be the only way to contain the unimaginable temperatures \sim a million K.
- Figure 27.19 diagrams the magnetic bottle and Figure 27.20 shows the real-world examples ... northern lights and southern lights.



(a)

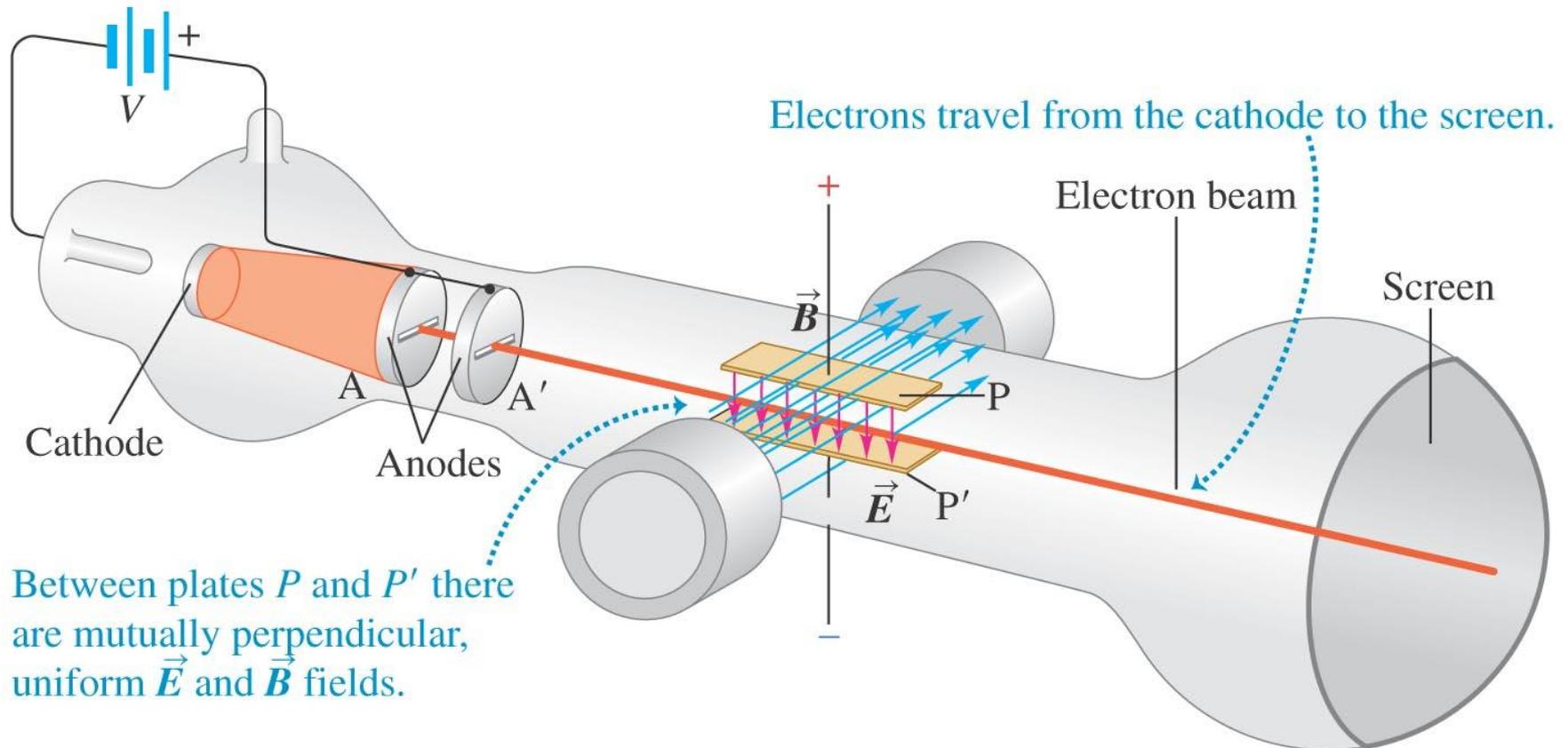


(b)



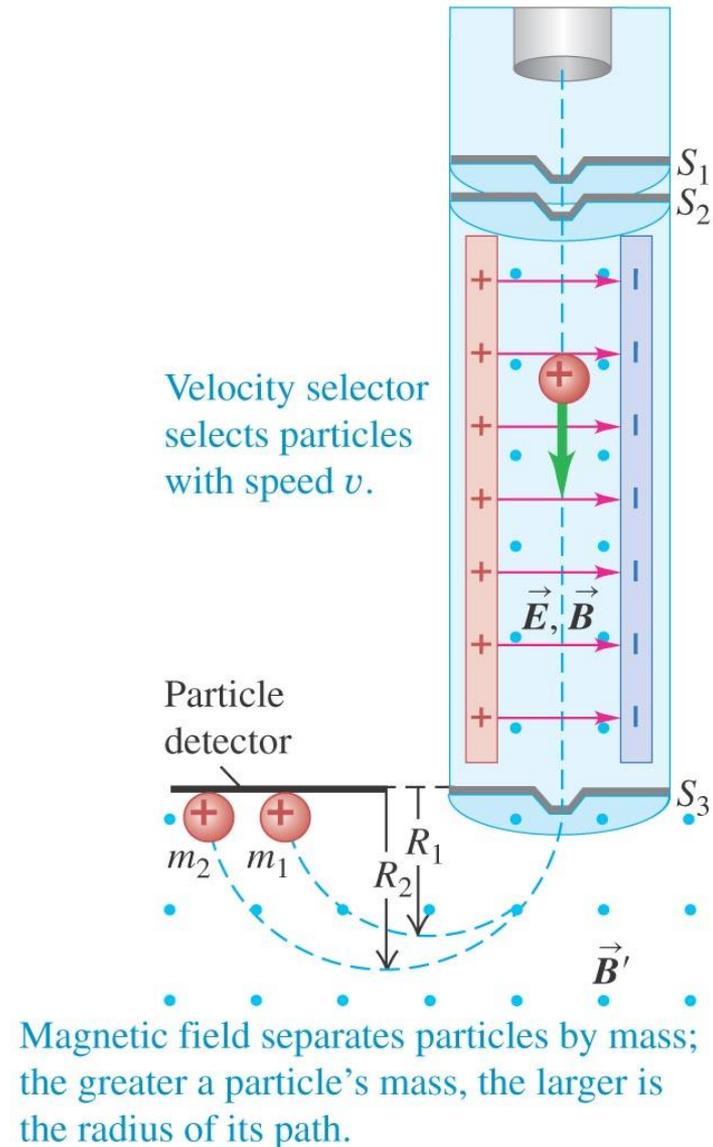
J.J. Thompson was able to characterize the electron

- Thompson's experiment used a combination of electron linear acceleration and magnetic "steering."



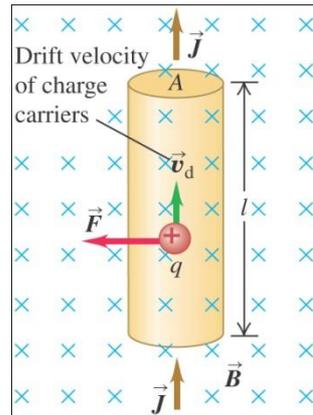
Bainbridge's mass spectrometer

- Using the same concept as Thompson, Bainbridge was able to construct a device that would only allow one mass in flight to reach the detector. The fields could be “ramped” through an experiment containing standards



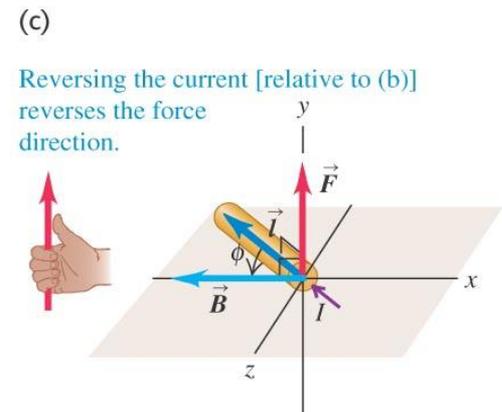
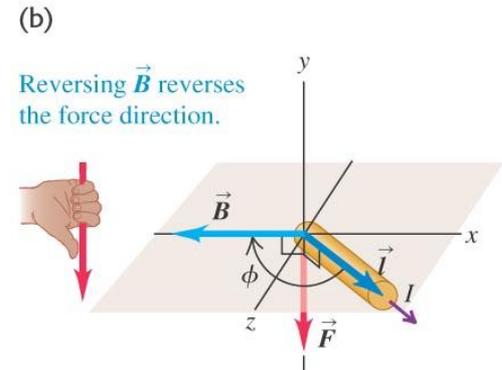
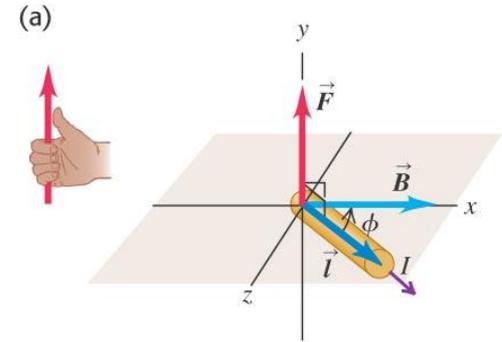
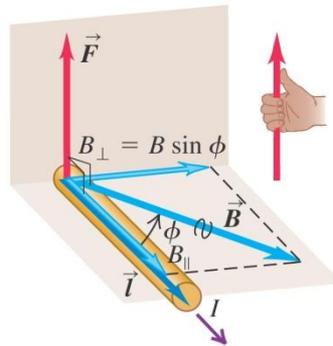
The magnetic force on a current-carrying conductor

- The force is always perpendicular to the conductor and the field.



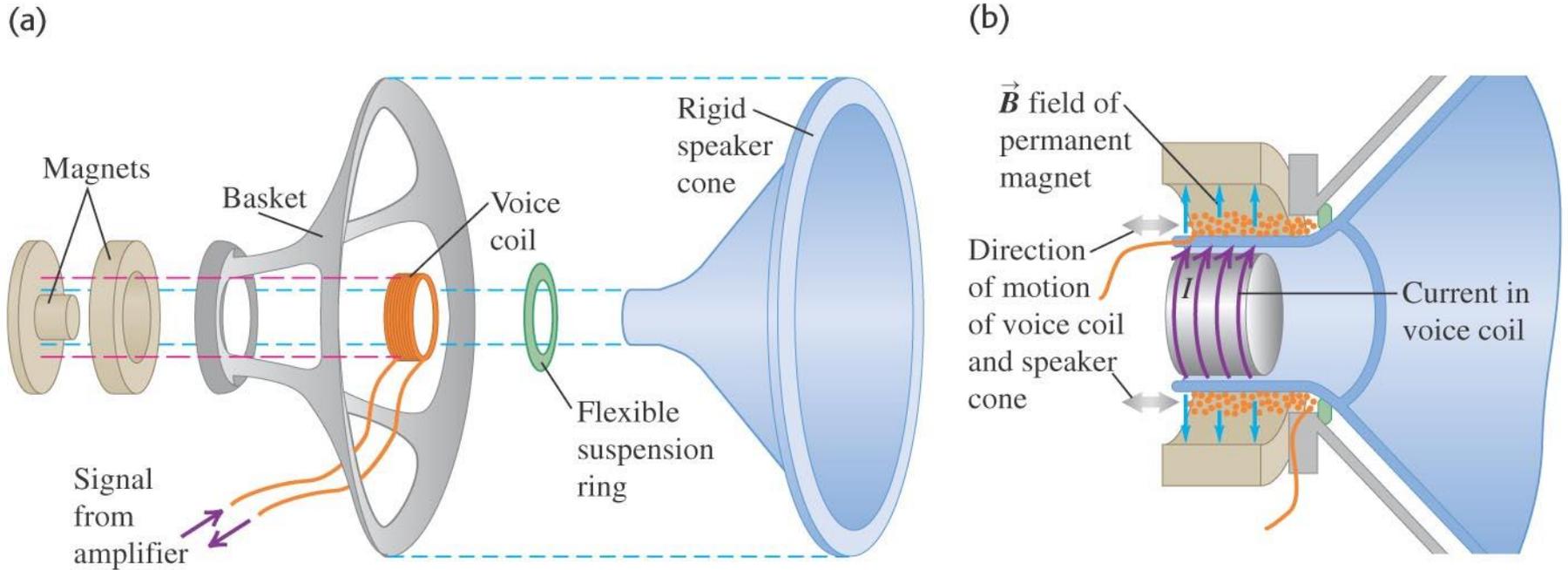
Force \vec{F} on a straight wire carrying a positive current and oriented at an angle ϕ to a magnetic field \vec{B} :

- Magnitude is $F = IlB_{\perp} = IlB \sin \phi$.
- Direction of \vec{F} is given by the right-hand rule.



Loudspeakers – Similar to ear buds

- To create music, we need longitudinal pulses in the air. The speaker cone is a combination of induced and permanent magnetism arranged to move the cone to create compressions in the air



Force and torque on a current loop

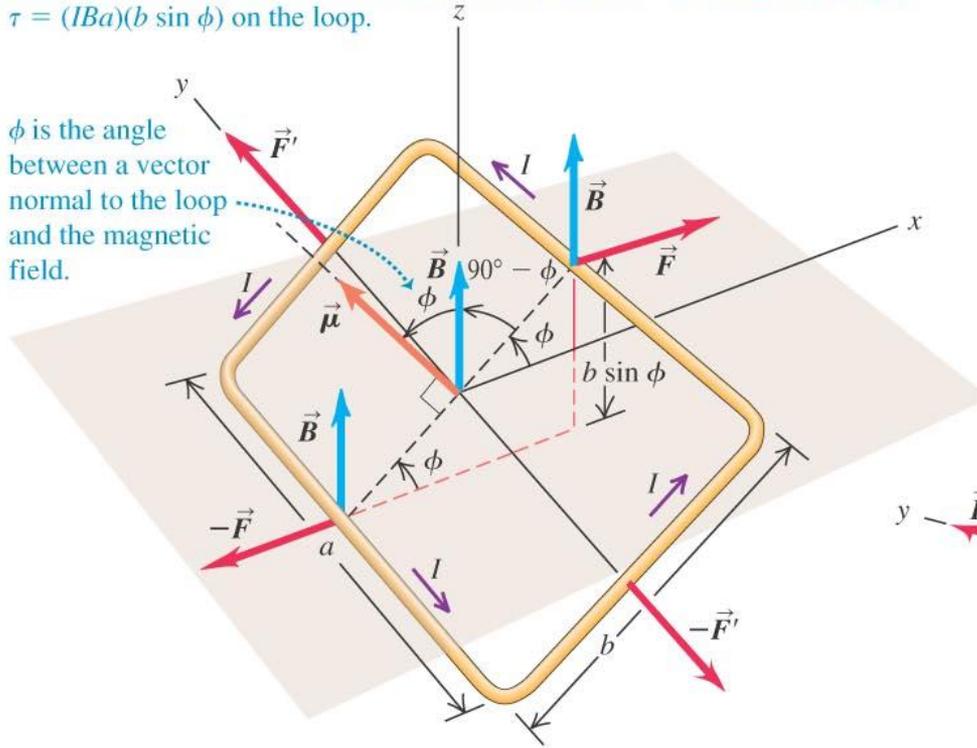
- This is the basis of electric motors.

(a)

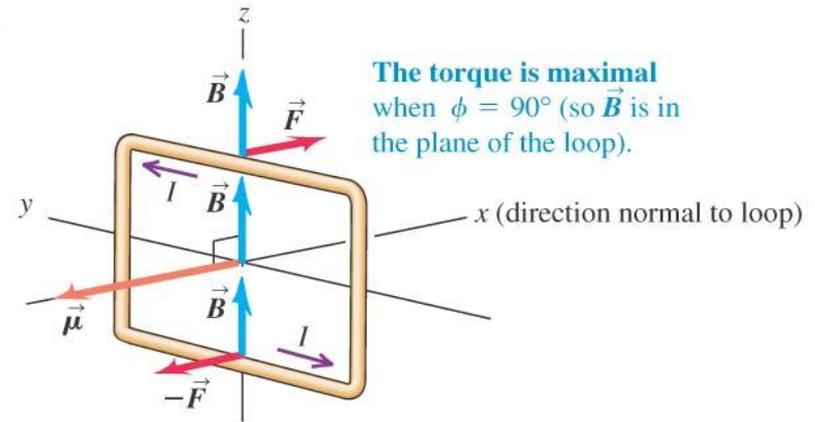
The two pairs of forces acting on the loop cancel, so no net force acts on the loop.

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

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

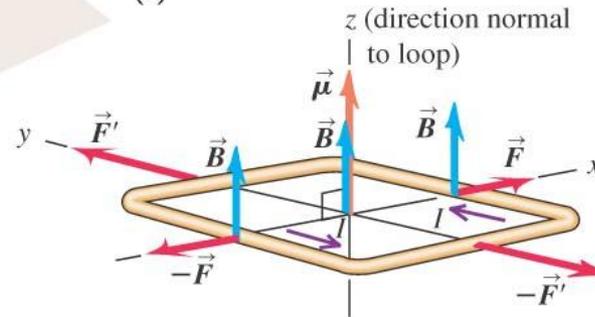


(b)



The torque is maximal when $\phi = 90^\circ$ (so \vec{B} is in the plane of the loop).

(c)



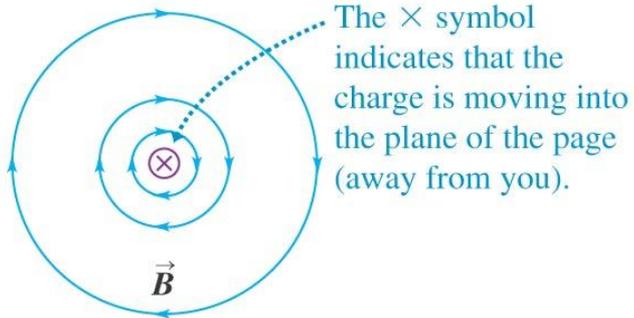
The torque is zero when $\phi = 0^\circ$ (as shown here) or $\phi = 180^\circ$. In both cases, \vec{B} is perpendicular to the plane of the loop.

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

The magnetic field of a moving charge – all B fields due to relativistic transformation of moving E fields

- A moving charge will generate a magnetic field relative to the velocity of the charge. Special Relativity.

View from behind the charge

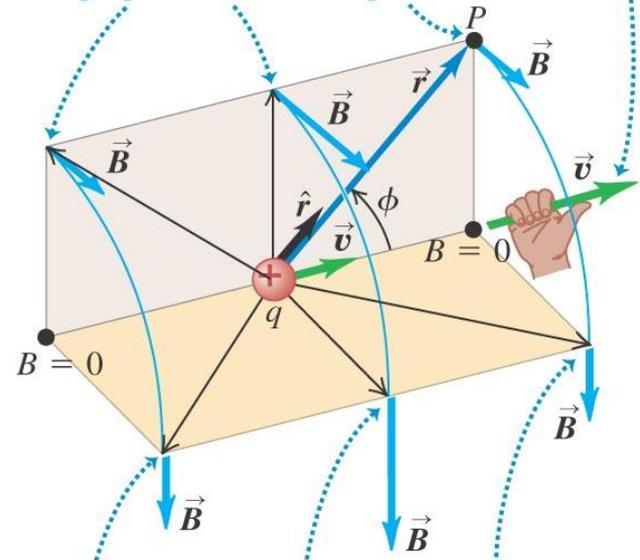


The \times symbol indicates that the charge is moving into the plane of the page (away from you).

Perspective view

Right-hand rule for the magnetic field due to a positive charge moving at constant velocity: Point the thumb of your right hand in the direction of the velocity. Your fingers now curl around the charge in the direction of the magnetic field lines. (If the charge is negative, the field lines are in the opposite direction.)

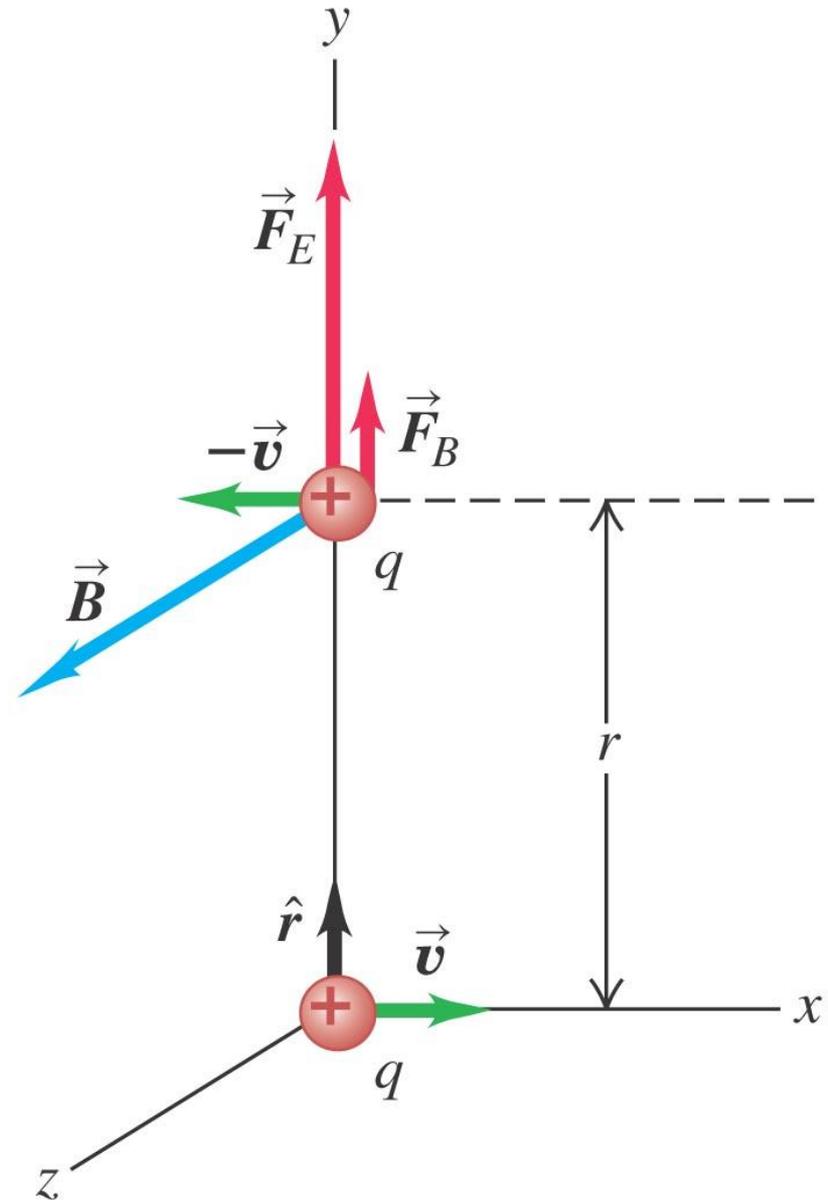
For these field points, \vec{r} and \vec{v} both lie in the beige plane, and \vec{B} is perpendicular to this plane.



For these field points, \vec{r} and \vec{v} both lie in the gold plane, and \vec{B} is perpendicular to this plane.

Moving charges—field lines

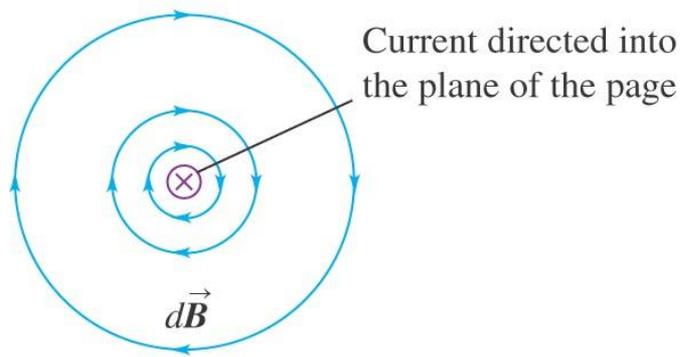
- The moving charge will generate field lines in circles around the charge in planes perpendicular to the line of motion.
- $\mathbf{B} = \mu_0 (q \mathbf{v} \times \mathbf{r}) / 4\pi r^2$



Magnetic field of a current element

- The magnetic field of several moving charges will be the vector sum of each field.
- $d\mathbf{B} = \mu_0 (I d\mathbf{l} \times \mathbf{r})/4\pi r^2$

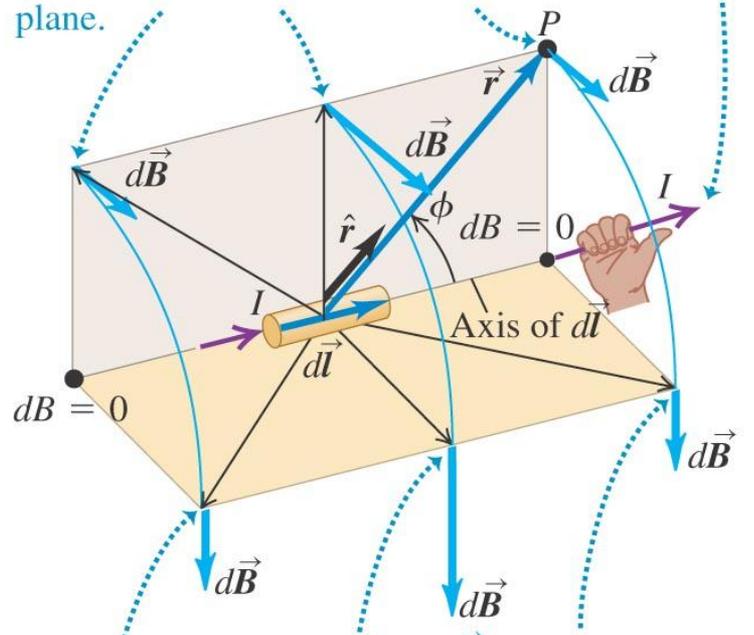
View along the axis of the current element



Perspective view

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

For these field points, \mathbf{r} and $d\mathbf{l}$ both lie in the beige plane, and $d\mathbf{B}$ is perpendicular to this plane.

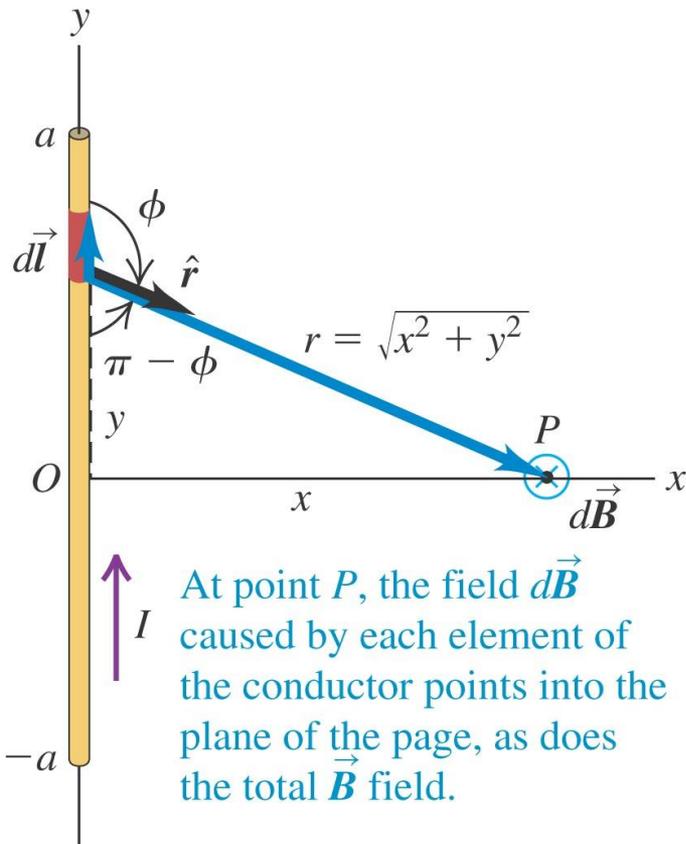


For these field points, \mathbf{r} and $d\mathbf{l}$ both lie in the gold plane, and $d\mathbf{B}$ is perpendicular to this plane.

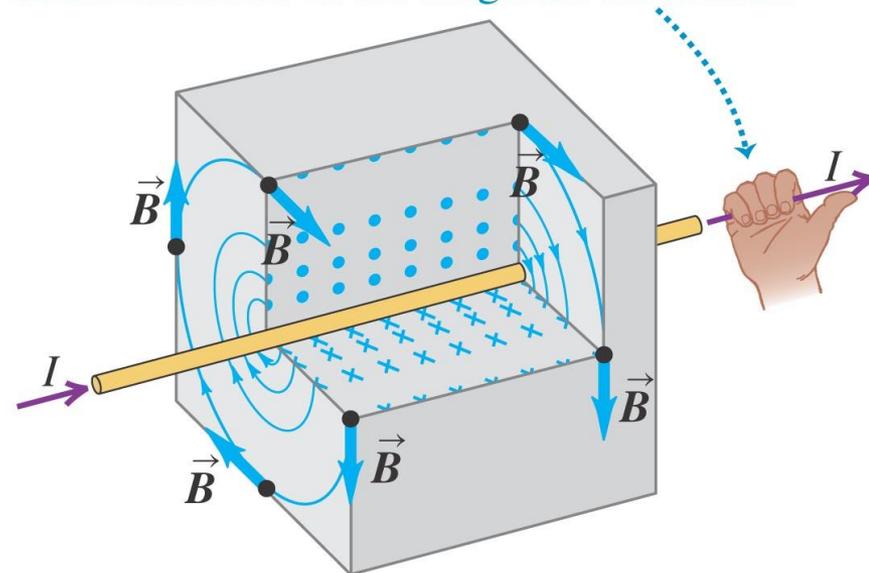
Magnetic field of a straight current-carrying conductor

- Biot and Savart “Law” - finding the magnetic field produced by a single current-carrying conductor. Integrate over the wire

- $\mathbf{B} = \mu_0 \int (I \, d\mathbf{l} \times \mathbf{r}) / 4\pi r^2$

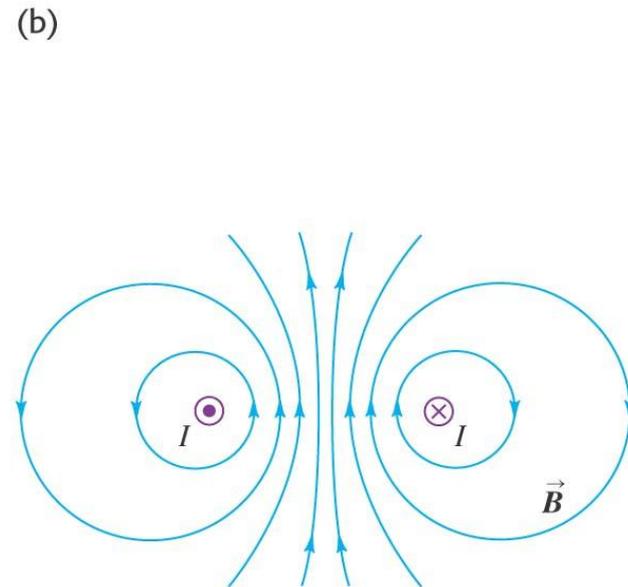
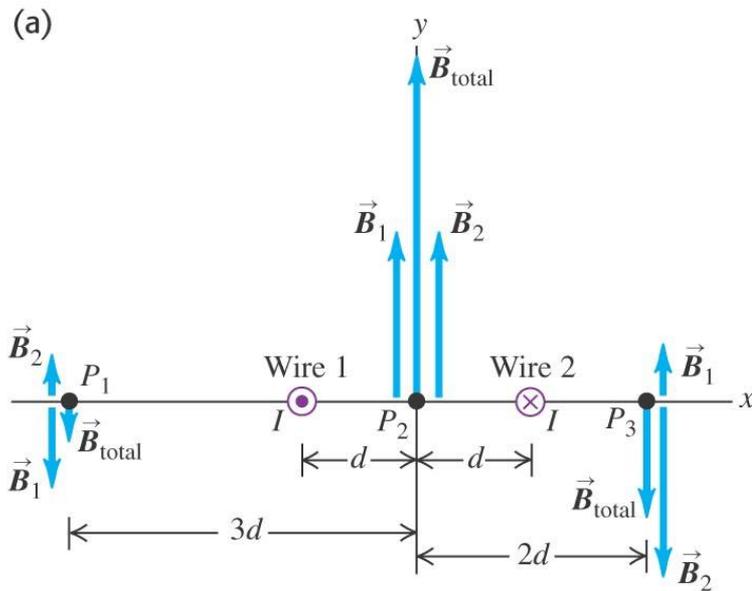


Right-hand rule for the magnetic field around a current-carrying wire: Point the thumb of your right hand in the direction of the current. Your fingers now curl around the wire in the direction of the magnetic field lines.



Fields around single wires

- Current carrying wires are common in your life.
- They are in the wires in the wall carry power
- They are in your computer
- In your “ear bud”

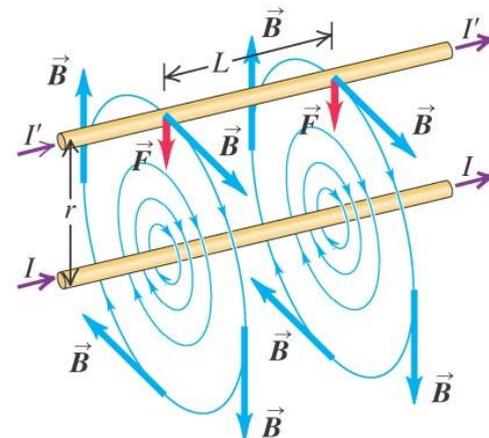
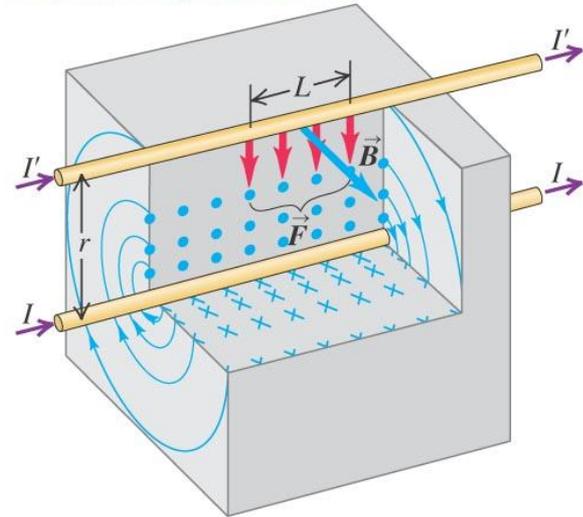


Forces and parallel conductors

The magnetic field of the lower wire exerts an attractive force on the upper wire. By the same token, the upper wire attracts the lower one.

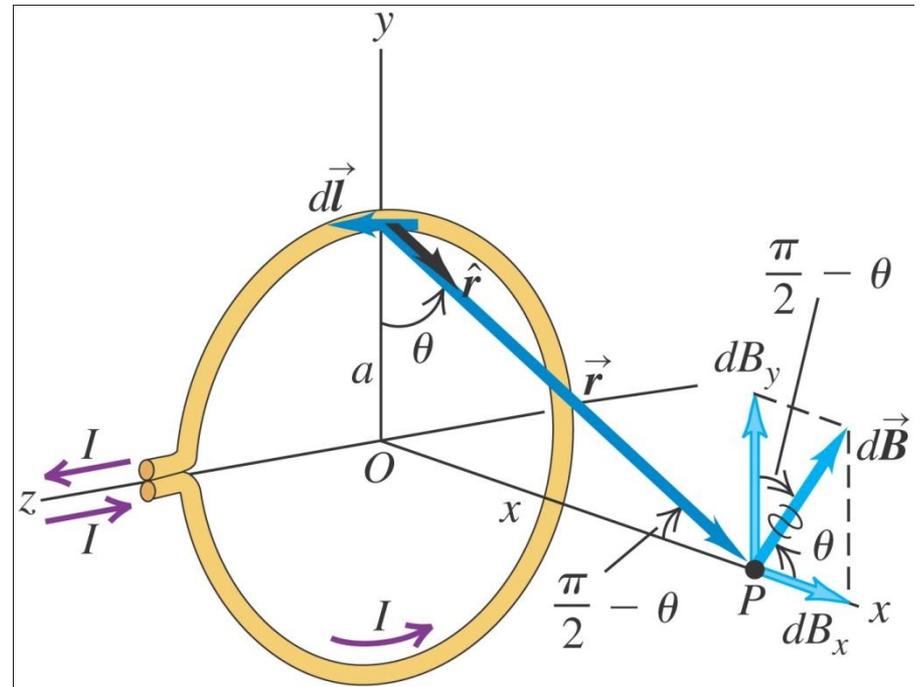
If the wires had currents in *opposite* directions, they would *repel* each other.

- When you run the current one way through one rod and the other way through the second, they will repel each other. If you reverse the connections on one rod so that **both currents run the same way**, the rods will be **attracted to each other**. See **diagram**.



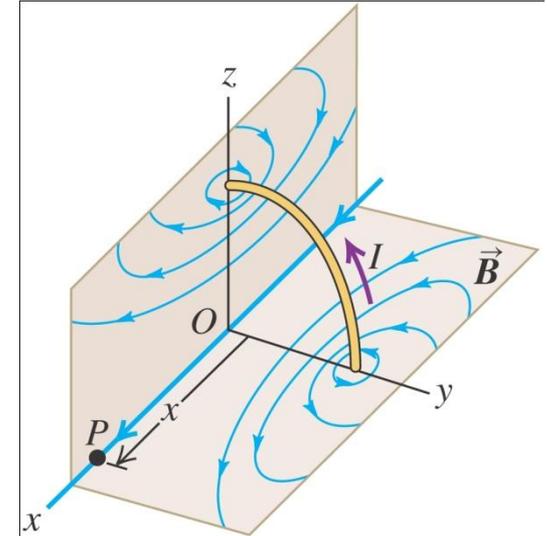
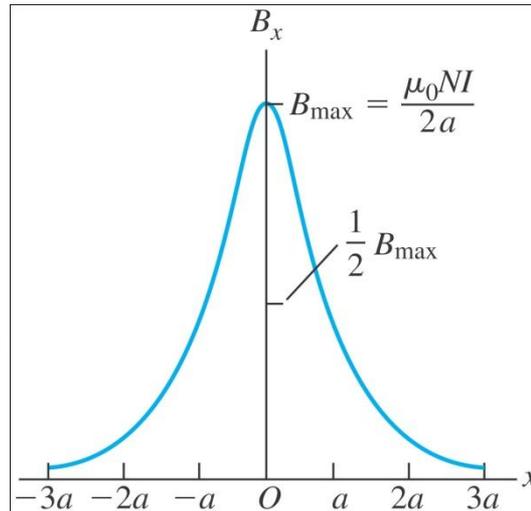
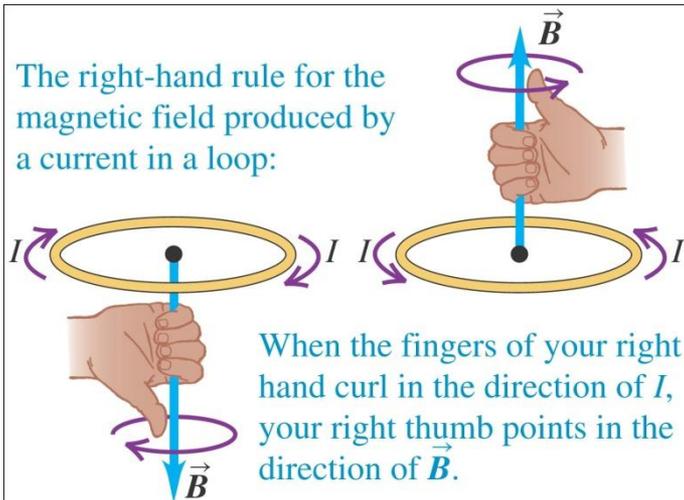
Magnetic field of a circular current loop

- A loop in the x,y plane will experience magnetic attraction or repulsion above and below the loop.



Magnetic fields in coils

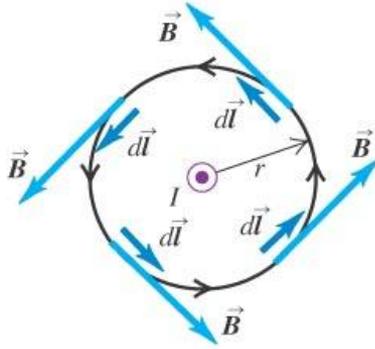
- Use the right hand rule to determine \vec{B} field direction
- Here N is the number of turns in the coil. Below $N=1$



Ampere's Law I—specific then general

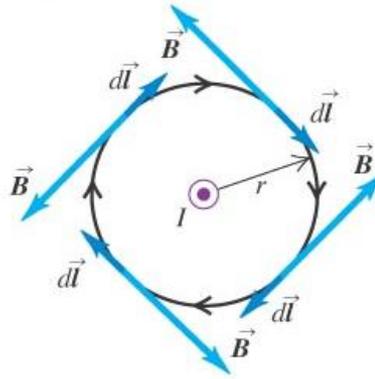
(a) Integration path is a circle centered on the conductor; integration goes around the circle counterclockwise.

Result: $\oint \vec{B} \cdot d\vec{l} = \mu_0 I$



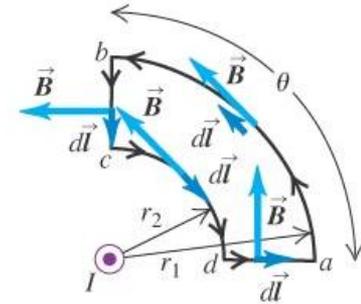
(b) Same integration path as in (a), but integration goes around the circle clockwise.

Result: $\oint \vec{B} \cdot d\vec{l} = -\mu_0 I$

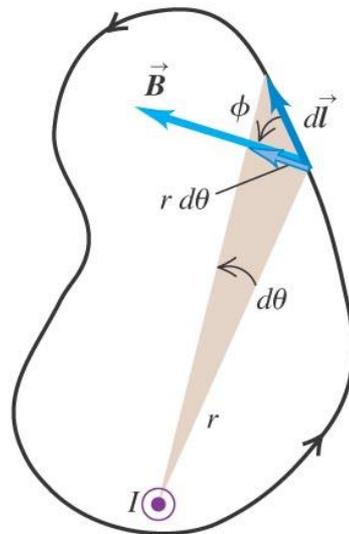


(c) An integration path that does not enclose the conductor.

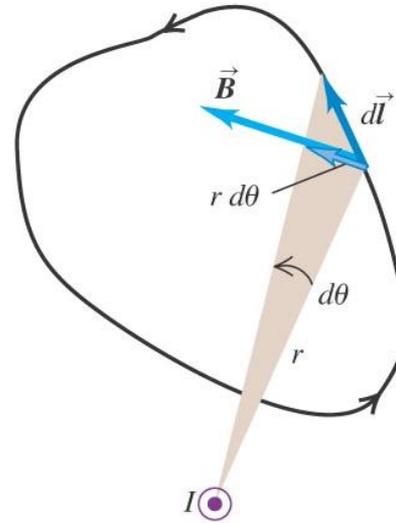
Result: $\oint \vec{B} \cdot d\vec{l} = 0$



(a)

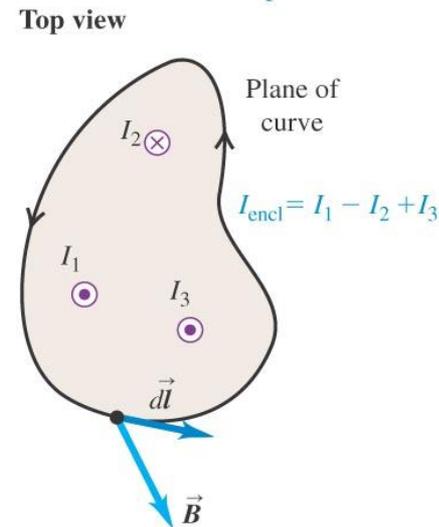
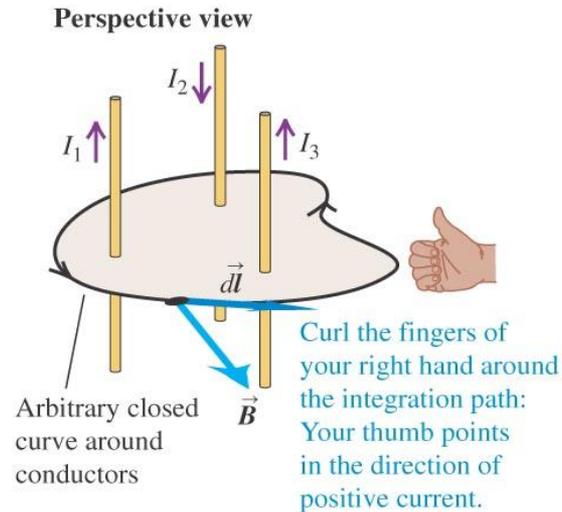


(b)



Ampere's Law II

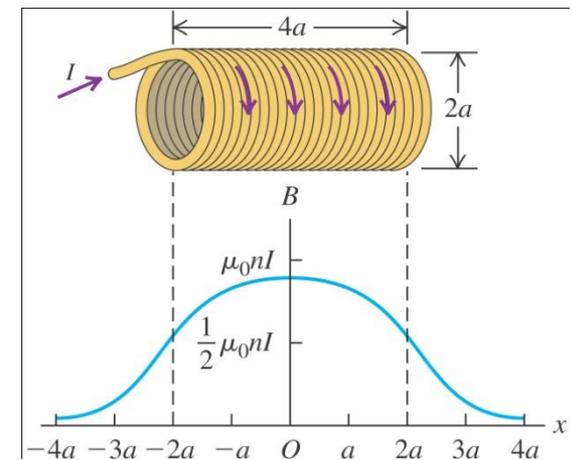
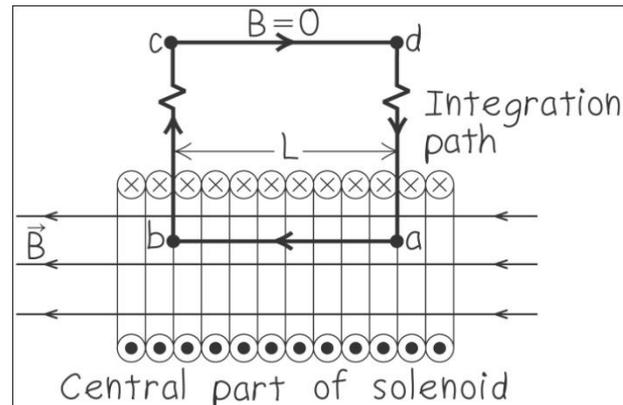
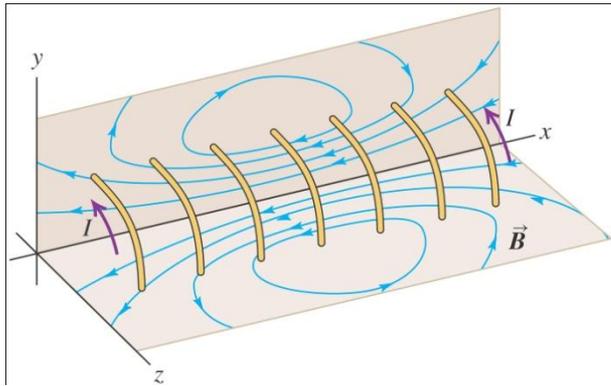
- Line integral of \mathbf{B} over closed loop $= \mu_0 \mathbf{I}$
- $\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 \mathbf{I}$ where \mathbf{I} is the sum of ALL currents inside the loop
- This is part of one of Maxwells Equations
- For a long wire $\oint \mathbf{B} \cdot d\mathbf{l} = 2\pi r B$
- Where r is the radius from the center of the wire to the desired distance r
- Thus long wire $\mathbf{B} = \mu_0 \mathbf{I} / 2\pi r$



Ampere's law: If we calculate the line integral of the magnetic field around a closed curve, the result equals μ_0 times the total enclosed current:
 $\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_{\text{encl}}$

Field of a solenoid

- A helical winding of wire on a cylinder.
- Your car starter has a solenoid to engage the starter motor.
- Every time you start your car you are using a solenoid
- Here $n = \#$ wire turns (loops) per meter along solenoid
- In an infinite length solenoid the field inside is uniform – outside $B=0$
- Apply Ampere's Law $\int \mathbf{B} \cdot d\mathbf{l} = \mu_0 I$ but note there are n turns per meter hence $I \rightarrow nLI$
- $\int \mathbf{B} \cdot d\mathbf{l} = BL = \mu_0 nLI$
- $\rightarrow \mathbf{B} = \mu_0 n\mathbf{I}$



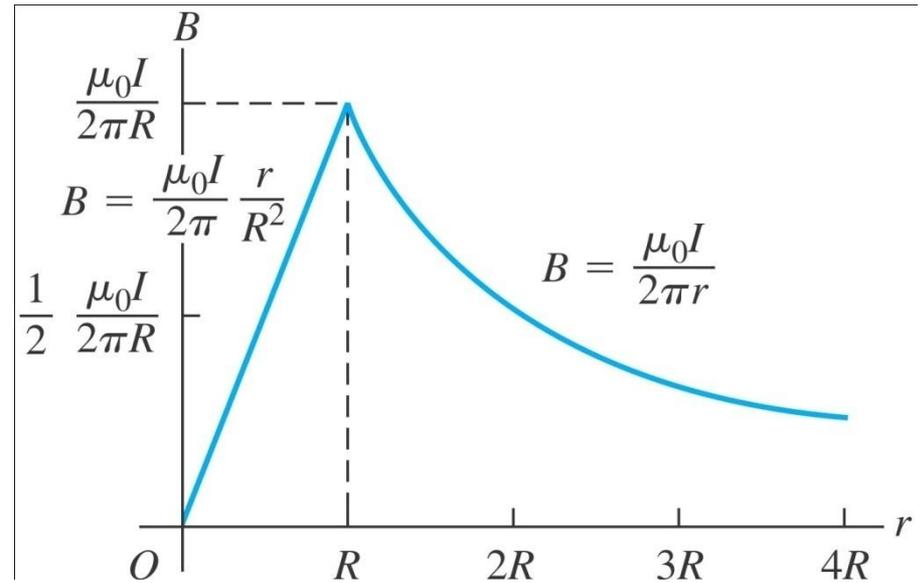
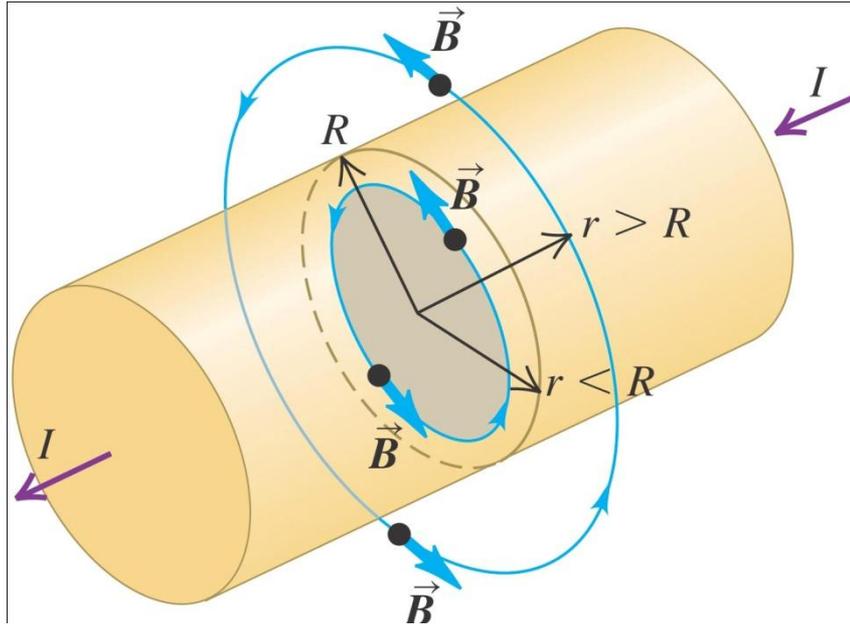
MRI – Magnetic Resonance Imaging

You are inside a large superconducting magnetic solenoid



Field inside a long cylindrical conductor

- A cylinder of radius R carrying a current I – uniform current density.
- This is similar to our use of Gauss' Law for electrostatics
- This is sometimes called (badly) magnetostatics



Coaxial cable – cable for internet “Cox cable”, TV etc

