

Chapter 27 – Magnetic Fields and Forces

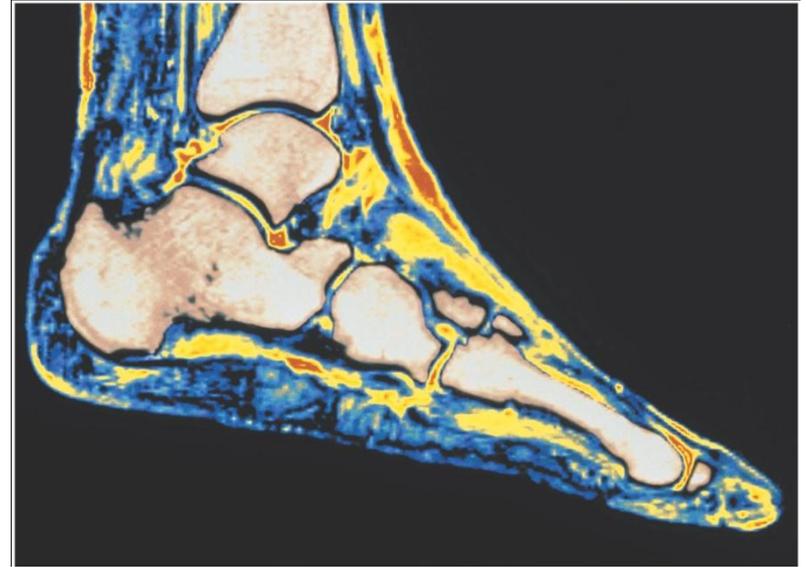
If we had special relativity we would find there is no such thing as a magnetic field. It is only a relativistic transformation of an electric field

Goals for Chapter 27

- To study magnetic forces
- To consider magnetic field and flux
- To explore motion in a magnetic field
- To calculate the magnetic force on a semiconductor
- To consider magnetic torque
- To apply magnetic principles and study the electric motor
- To study the Hall effect

Introduction

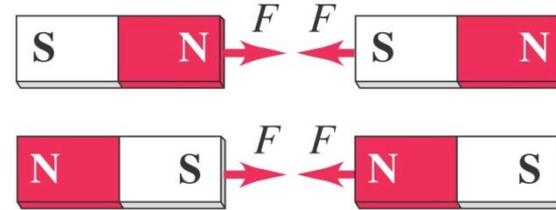
- Magnets exert forces on each other just like charges. You can draw magnetic field lines just like you drew electric field lines.
- Electrostatics, electrodynamics, and magnetism are deeply interwoven.
- MRI scan of a human foot. The magnetic field interacts with molecules in the body to orient spin 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.



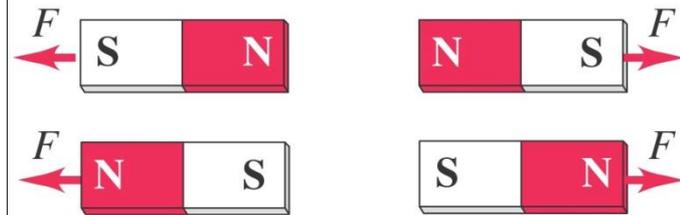
Magnetism

- 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.

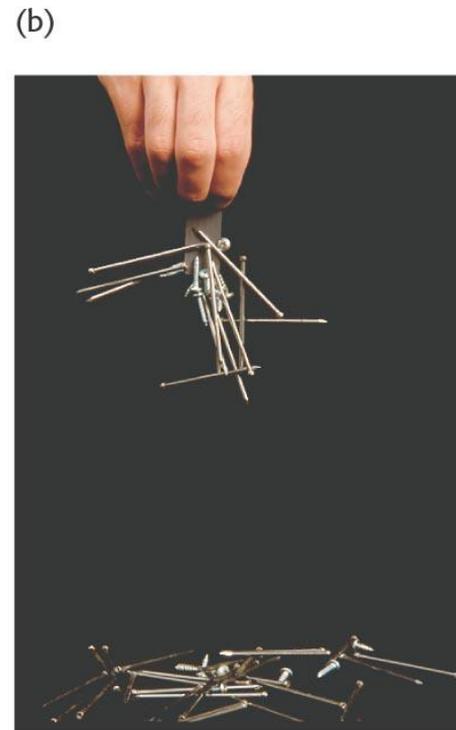
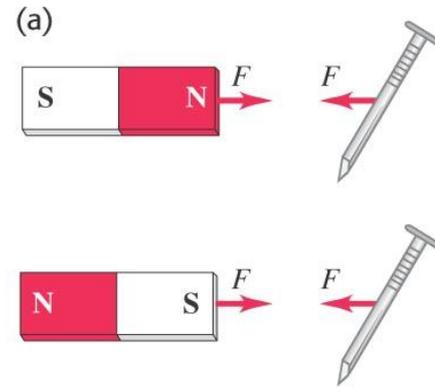


(b) Like poles repel.



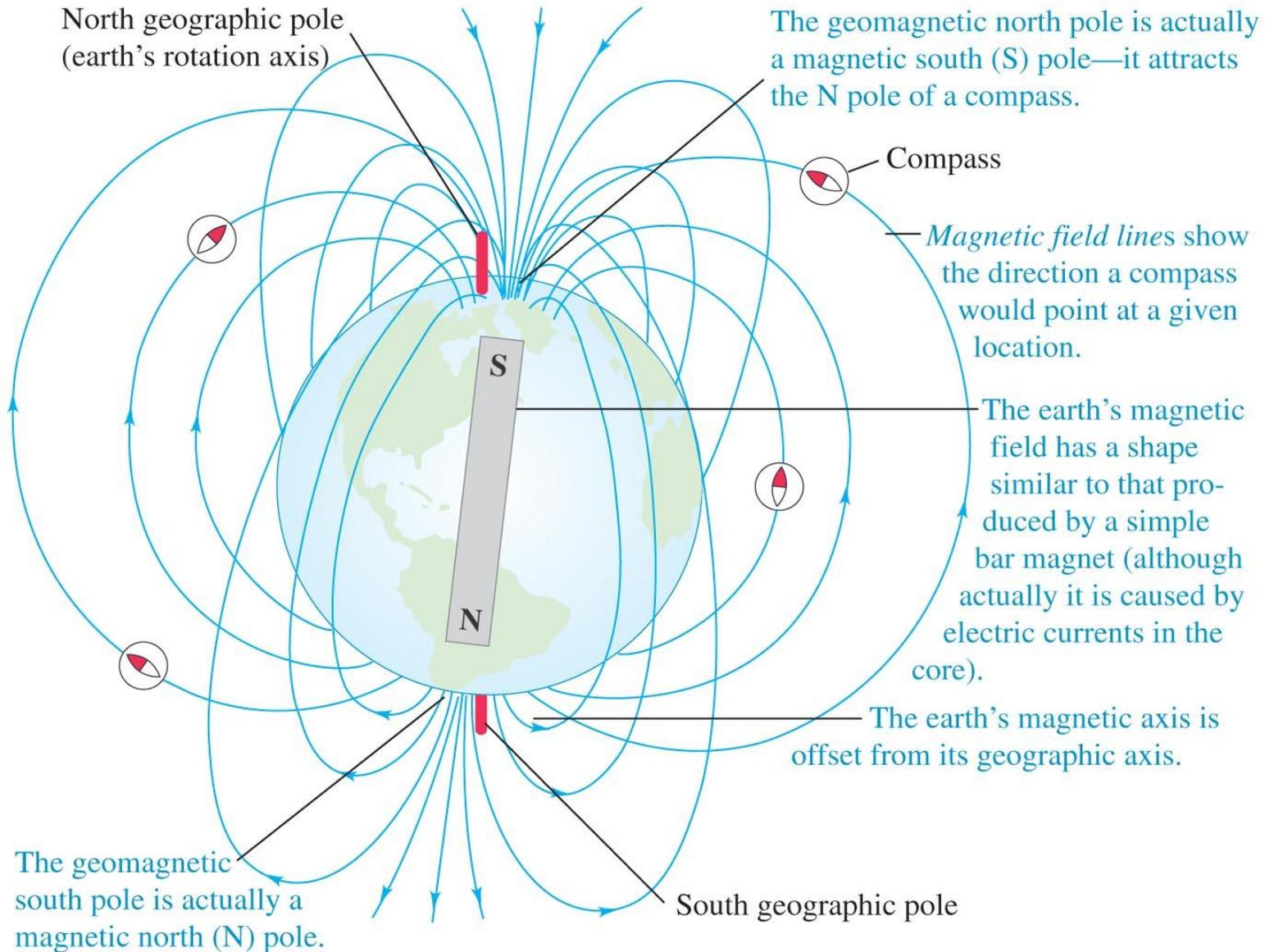
Magnetism and certain metals

- 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

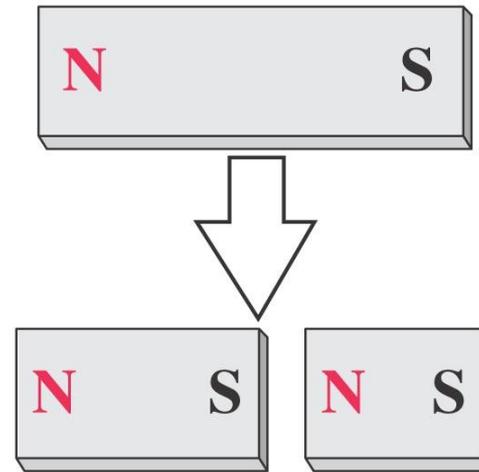


Magnetic pole(s)?

- 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.

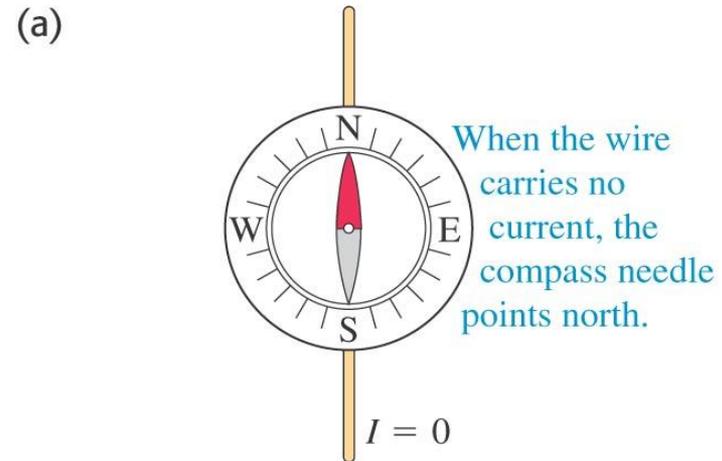
Breaking a magnet in two ...



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

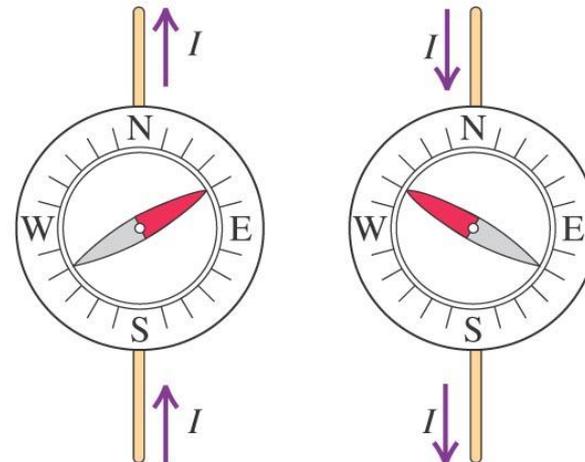
Electric current and magnets

- 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.

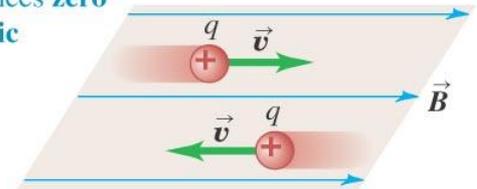


The interaction of magnetic force and charge

- 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.

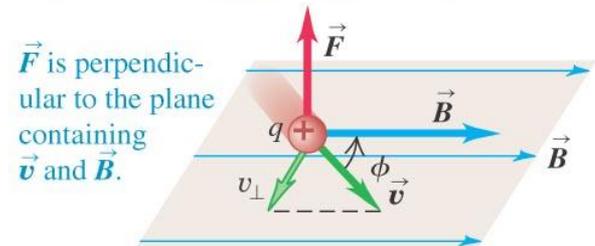
(a)

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



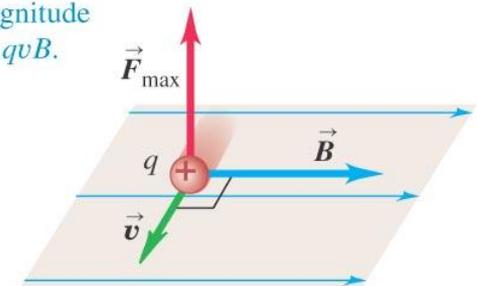
(b)

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.

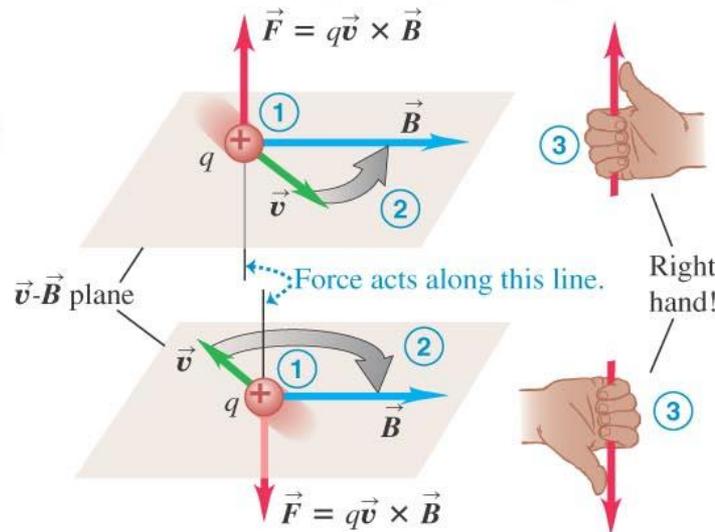
(a)

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.

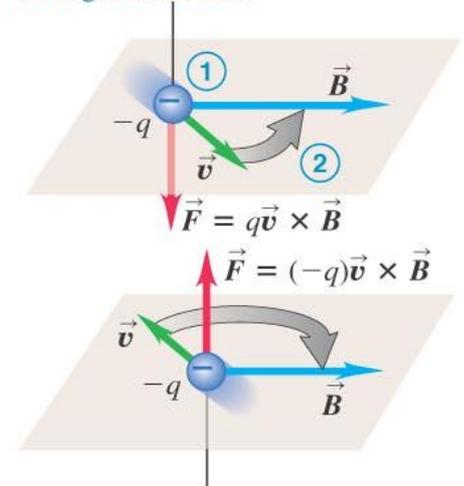
② Imagine turning \vec{v} toward \vec{B} in the \vec{v} - \vec{B} plane (through the smaller angle).

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)

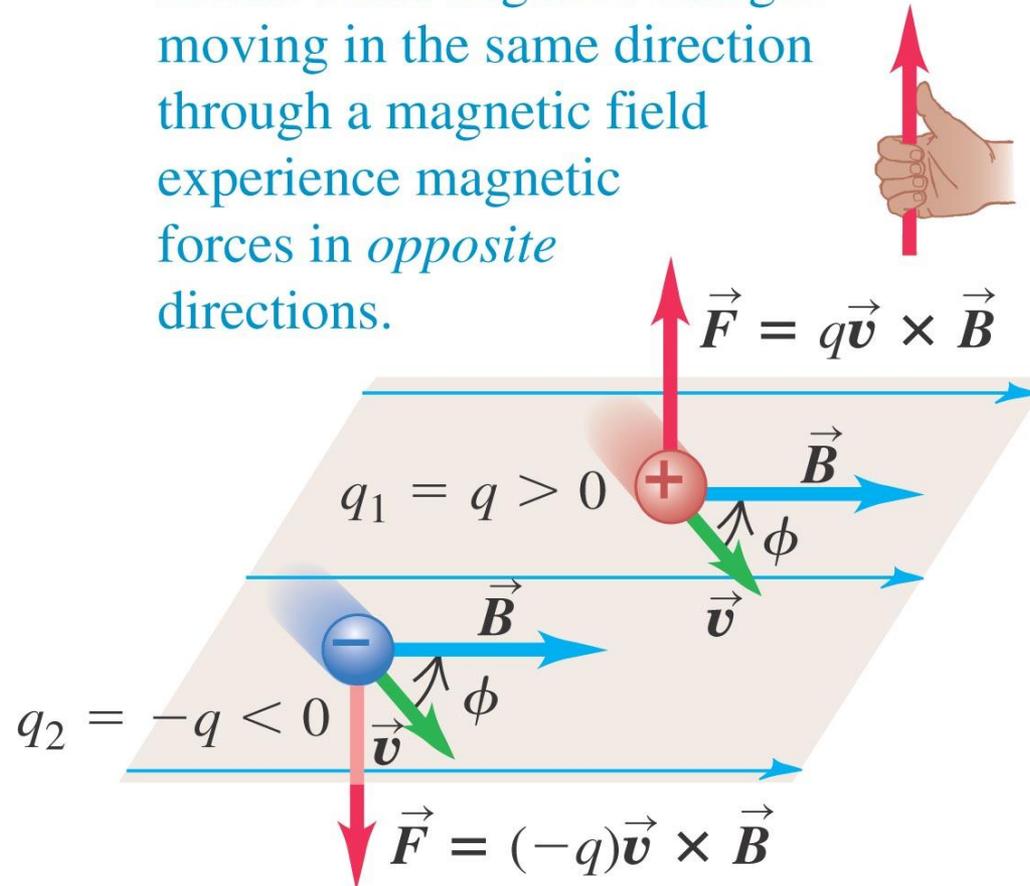
If the charge is negative, the direction of the force is *opposite* to that given by the right-hand rule.



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.

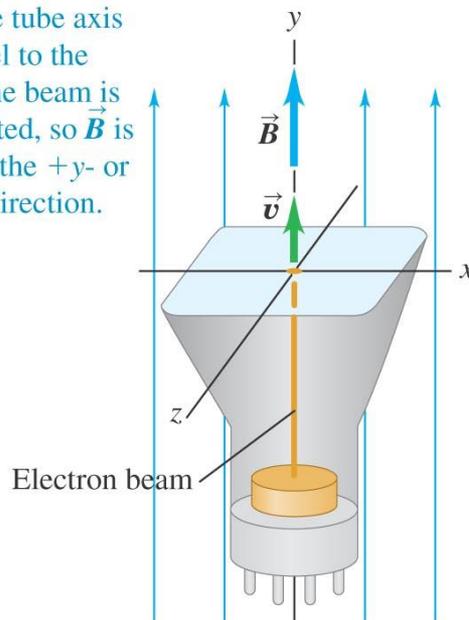
Positive and negative charges moving in the same direction through a magnetic field experience magnetic forces in *opposite* directions.



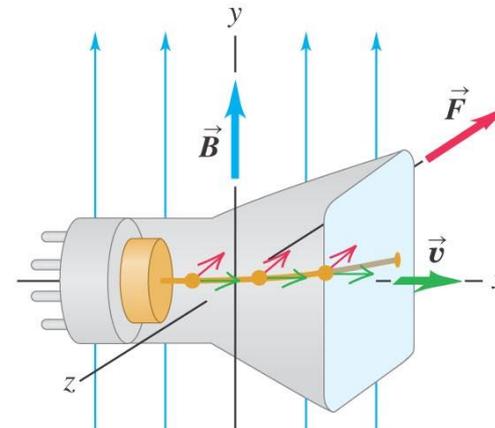
Direction of a magnetic field with your CRT

- 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.

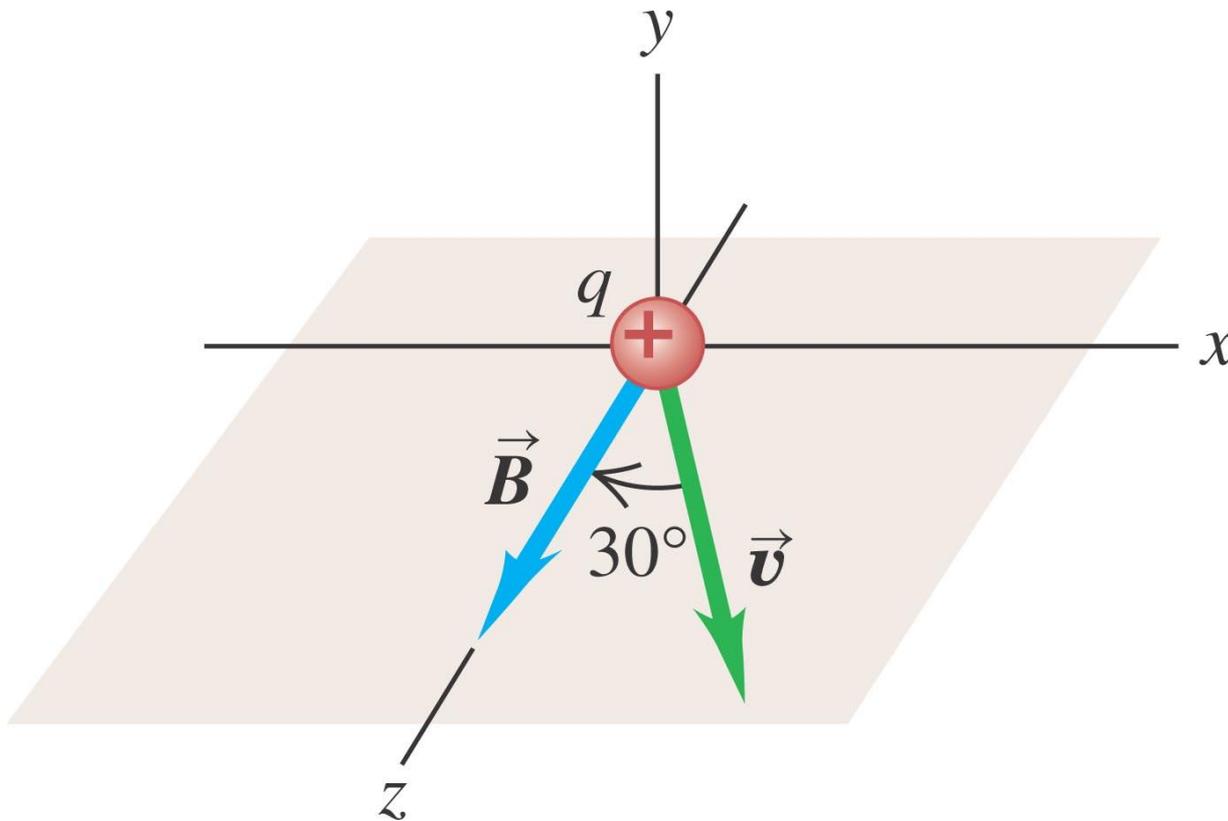


(b) If the tube axis is parallel to the x -axis, the beam is deflected in the $-z$ -direction, so \vec{B} is in the $+y$ -direction.



Magnetic forces

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

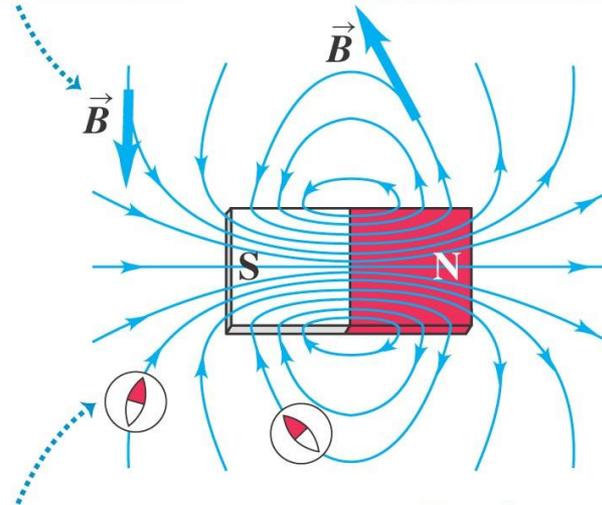


Magnetic field lines may be traced

- 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.

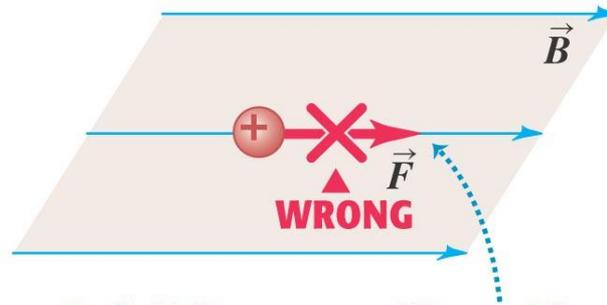


At each point, the field lines point in the same direction a compass would . . .

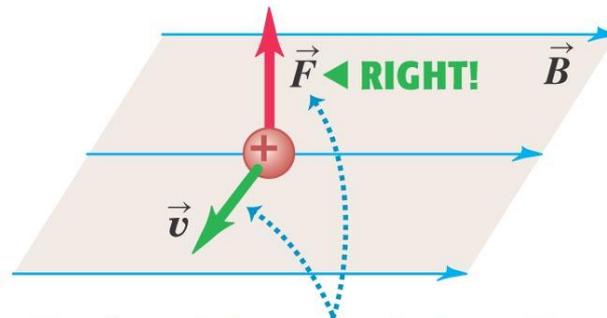
. . . therefore, magnetic field lines point *away from N poles and toward S poles.*

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.



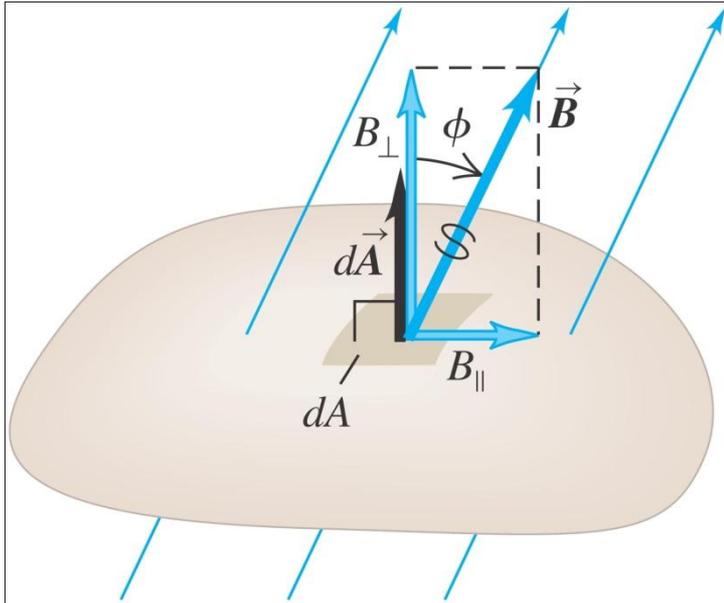
Magnetic field lines are *not* “lines of force.” The force on a charged particle is not along the direction of a field line.



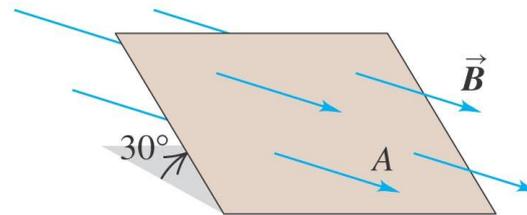
The direction of the magnetic force depends on the velocity \vec{v} , as expressed by the magnetic force law $\vec{F} = q\vec{v} \times \vec{B}$.

Magnetic flux through an area

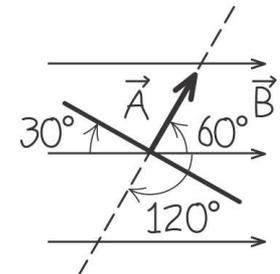
- We define the magnetic flux through a surface just as we defined electric flux.



(a) Perspective view



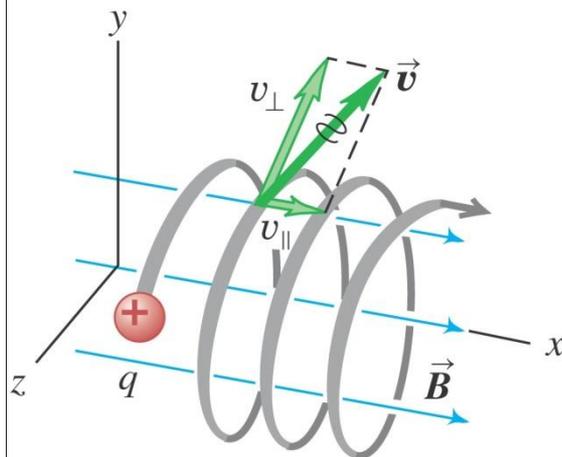
(b) Our sketch of the problem (edge-on view)



Motion of charged particles in a magnetic field

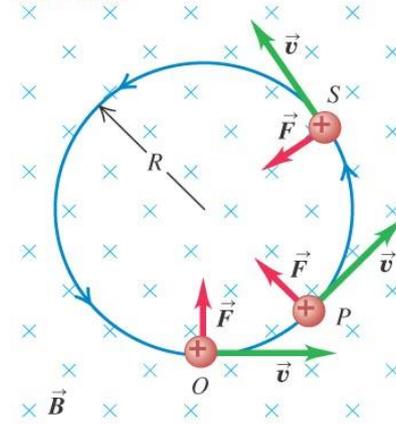
- A charged particle will move in a plane perpendicular to the magnetic field.
- Figure 27.17 at right illustrates the forces and shows an experimental example.
- Figure 27.18 below shows the constant kinetic energy and helical path.

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.

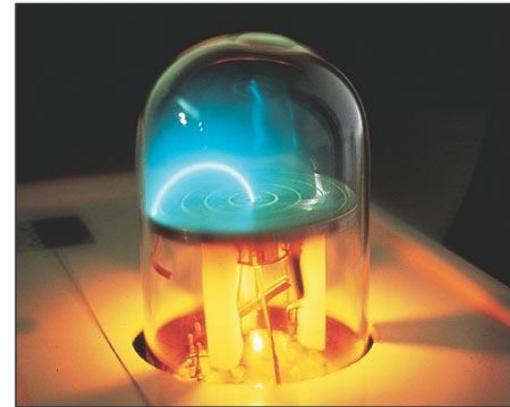


(a) The orbit of a charged particle in a uniform magnetic field

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.

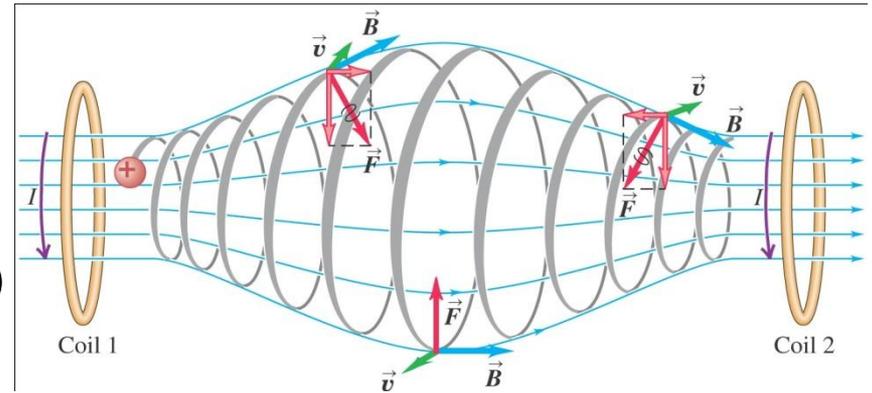


(b) An electron beam (seen as a blue arc) curving in a magnetic field

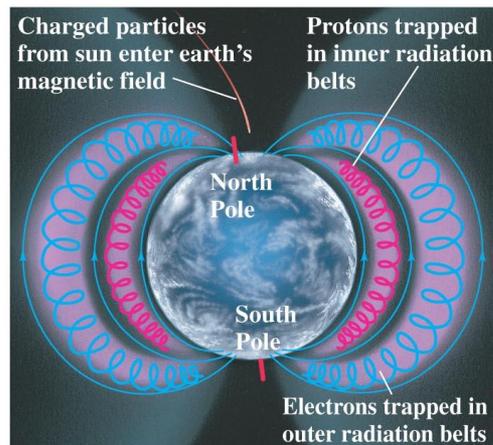


A magnetic bottle

- 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)

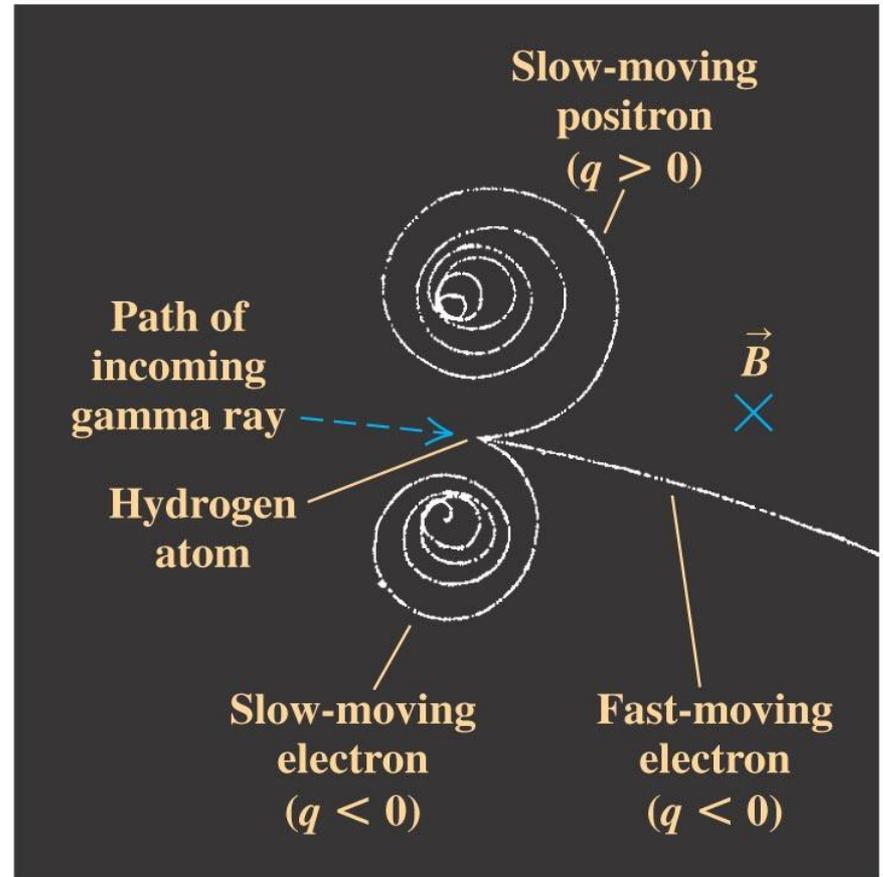


(b)



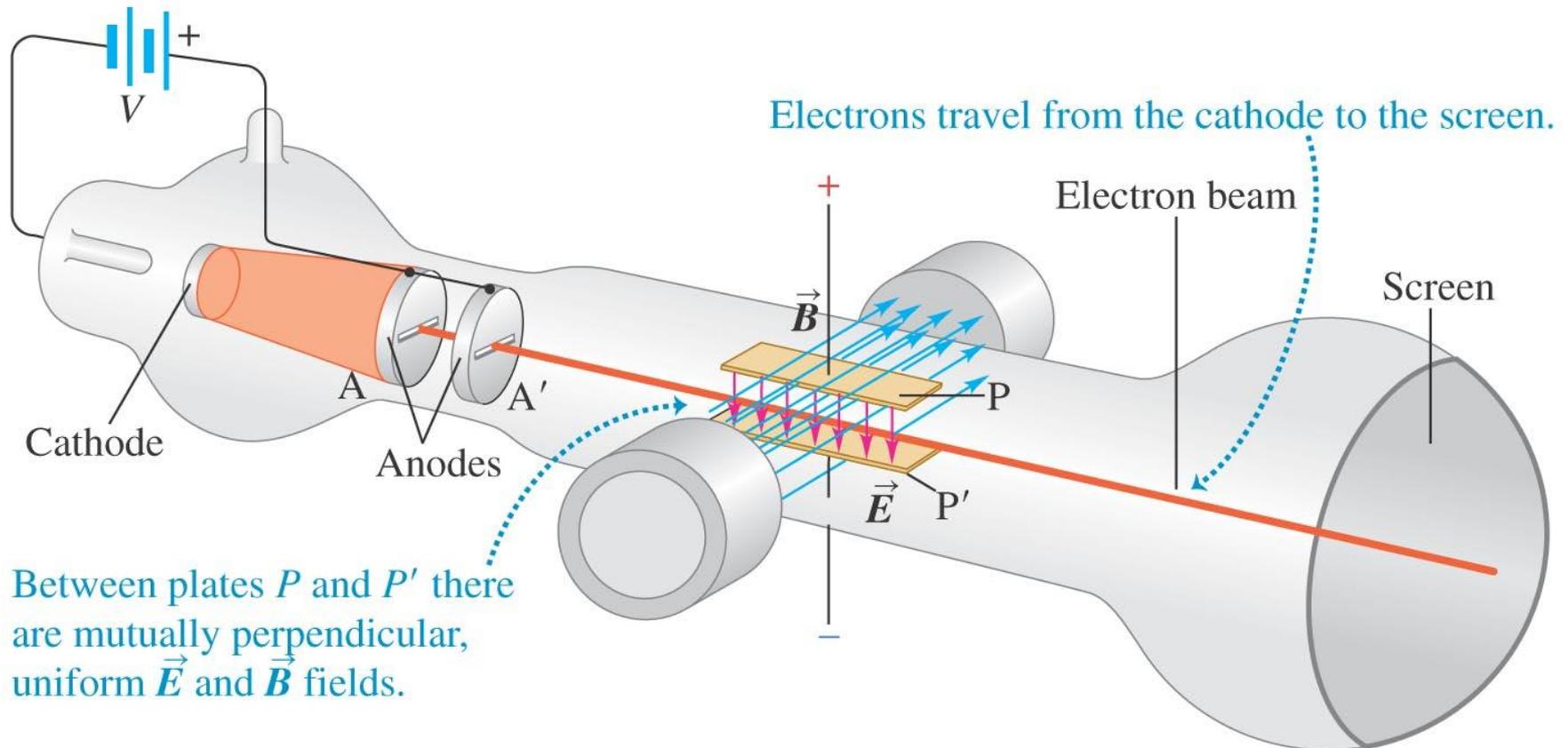
Motion in magnetic fields

- Bubble chambers were used extensively in the 1950 and 60's to image high energy particle tracks in accelerator collisions.



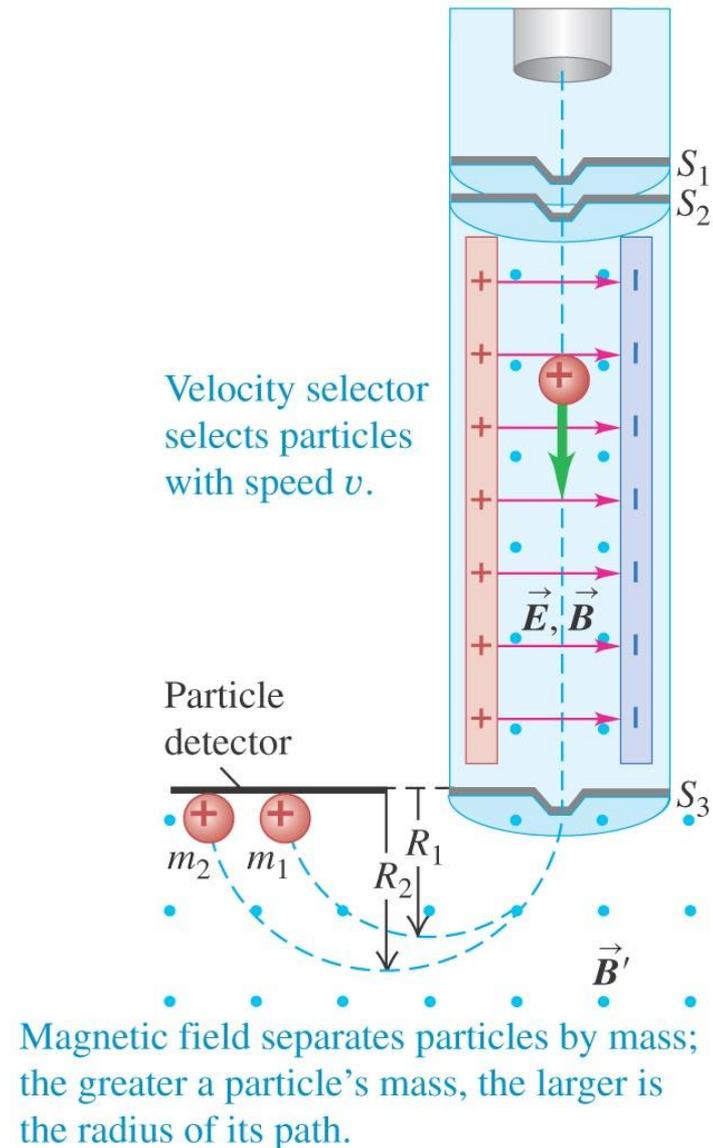
J.J. Thompson was able to characterize the electron

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



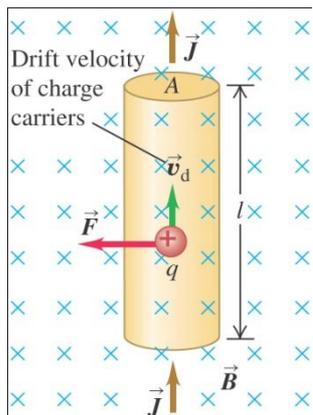
Bainbridge's mass spectrometer

- 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



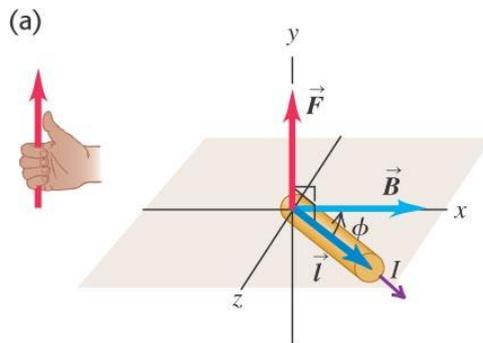
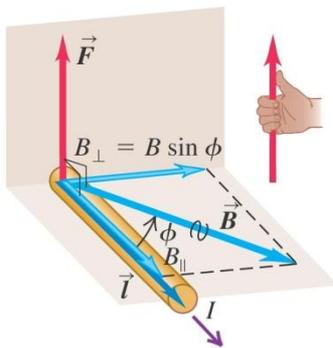
The magnetic force on a current-carrying conductor

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



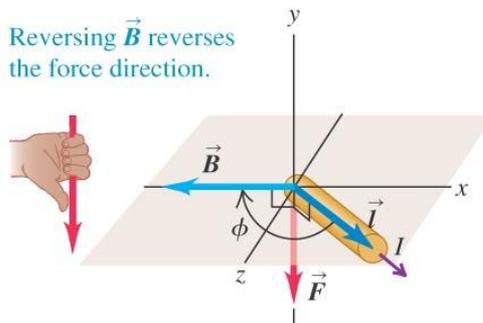
Force \vec{F} on a straight wire carrying a positive current and oriented at an angle ϕ to a magnetic field \vec{B} :

- Magnitude is $F = I l B_{\perp} = I l B \sin \phi$.
- Direction of \vec{F} is given by the right-hand rule.



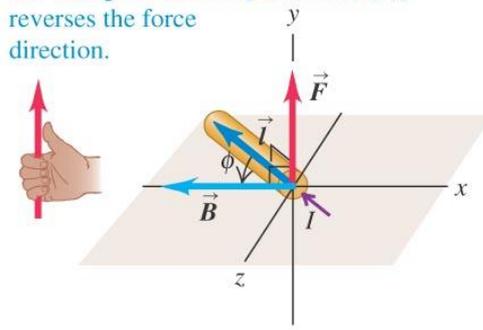
(b)

Reversing \vec{B} reverses the force direction.



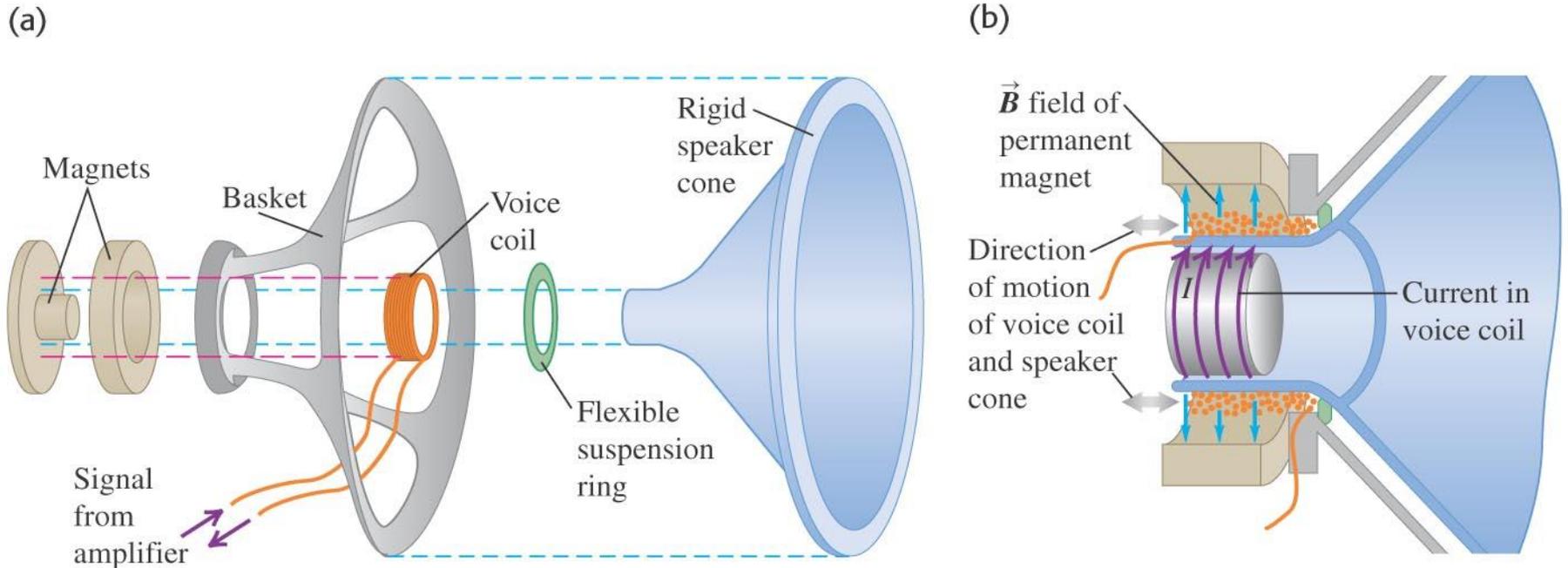
(c)

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

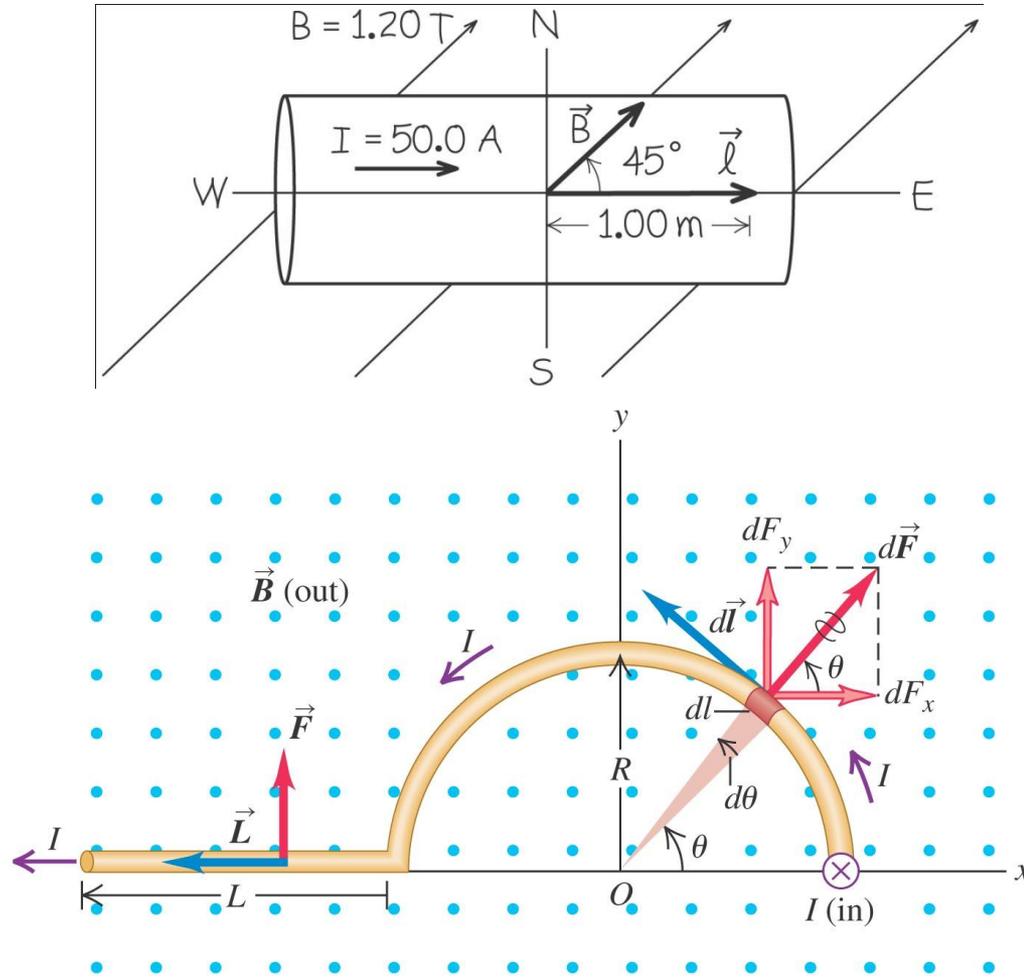


Loudspeakers – Similar to ear buds

- 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



Magnetic force on a straight then curved conductor



Force and torque on a current loop

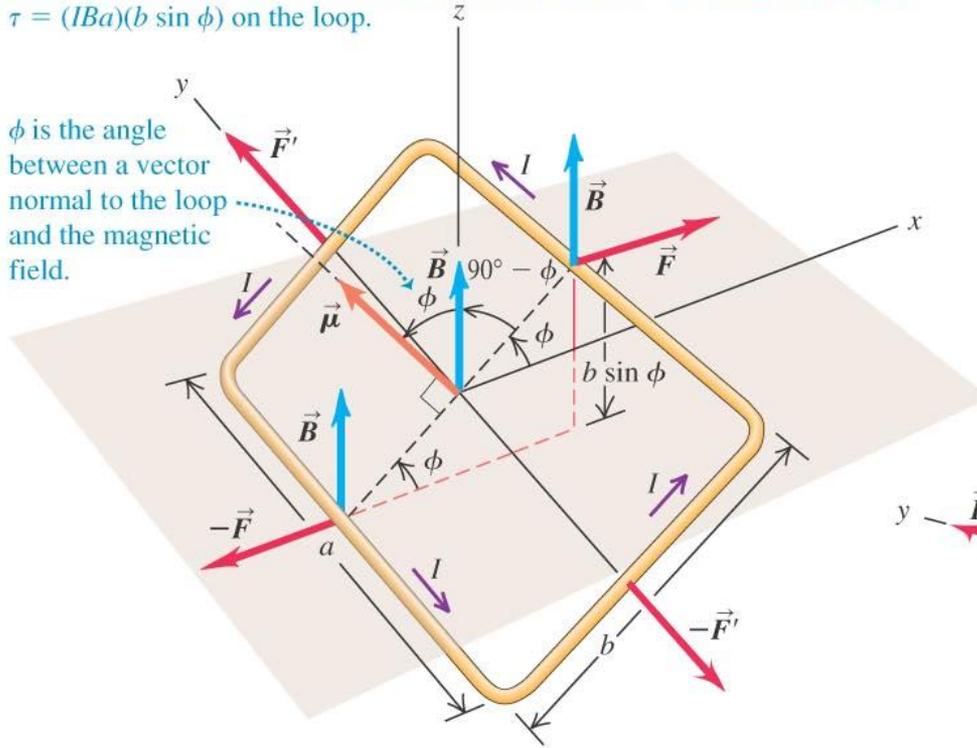
- This is the basis of electric motors.

(a)

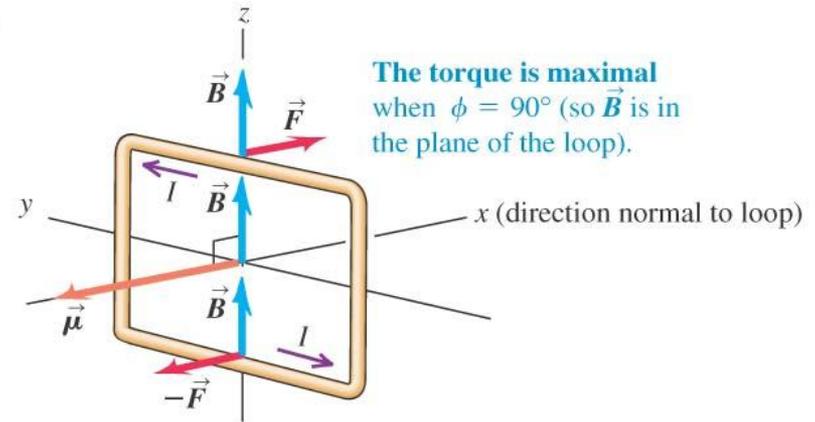
The two pairs of forces acting on the loop cancel, so no net force acts on the loop.

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.

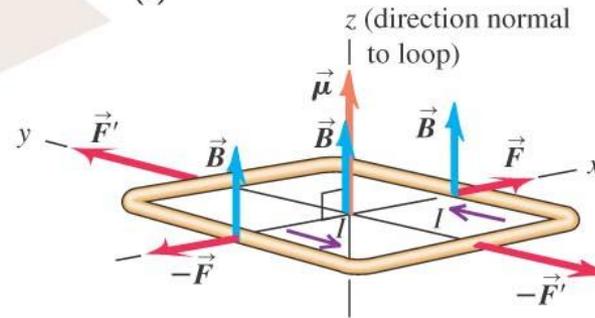


(b)



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.

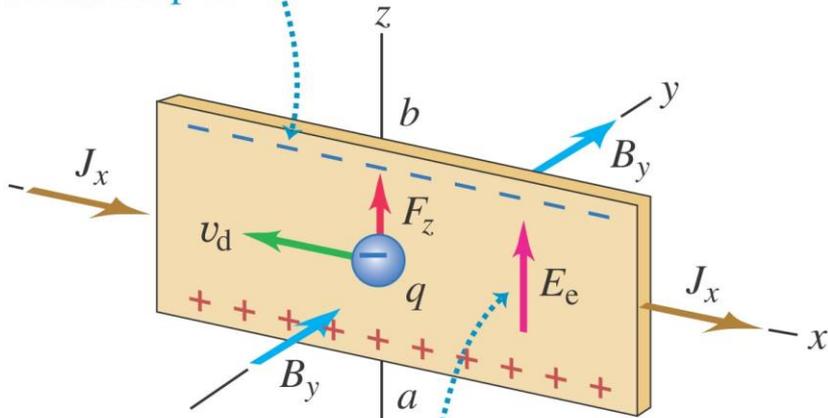
The loop is in stable equilibrium when $\phi = 0$; it is in unstable equilibrium when $\phi = 180^\circ$.

The Hall Effect

- Consider the forces on charge carriers as they move through a conductor in a magnetic field. You get charge separation and hence you can measure the voltage. This is called the Hall effect.

(a) Negative charge carriers (electrons)

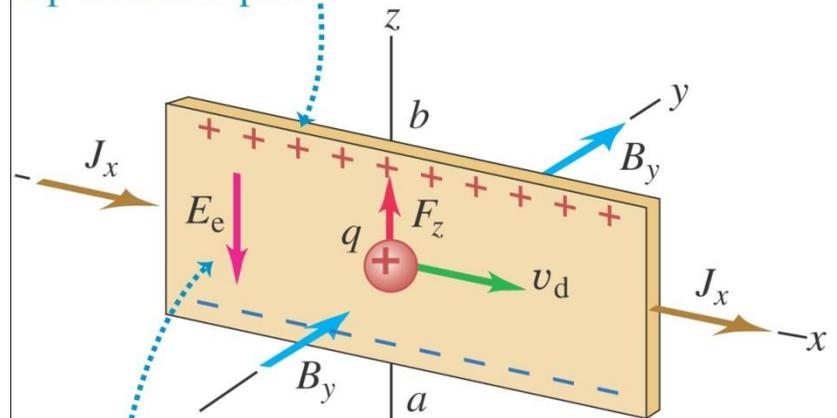
The charge carriers are pushed toward the top of the strip ...



... so point *a* is at a higher potential than point *b*.

(b) Positive charge carriers

The charge carriers are again pushed toward the top of the strip ...



... so the polarity of the potential difference is opposite to that for negative charge carriers.