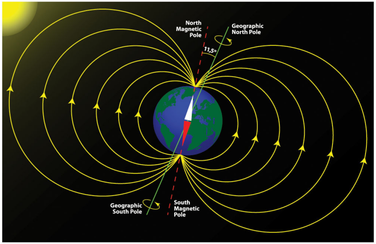
Magnetic Fields



"Magnetism, as you recall from physics class, is a powerful force that causes certain items to be attracted to refrigerators."

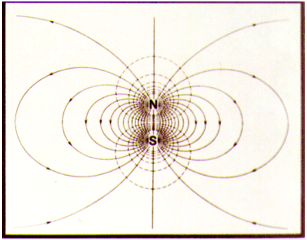
- *Dave Barry*

David J. Starling
Penn State Hazleton
PHYS 212

The Magnetic Field

The Magnetic Field is responsible for magnetic force

- Just like Electric field and Electric force
- We use the symbol $\vec{B}$
- Like $\vec{E}$, it has magnitude and direction
- For every point in space, we have a value of $\vec{B}$

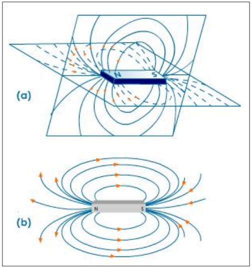


This is called a vector field.

The Magnetic Field

We draw the magnetic field lines just like electric field lines

- Lines come out of the north pole
- Lines go into the south pole
- The spacing signifies the strength of the field
- The field points tangent to the lines at each point



Field Lines

Magnetic Liquid

The Magnetic Field

A magnetic field can be created by

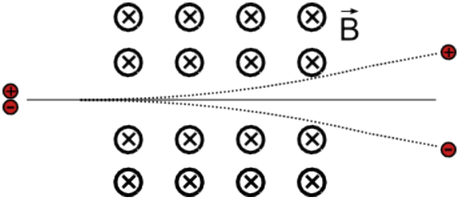
- Stationary charges
    - Intrinsic magnetic field (spin)
    - Permanent magnets
- *Moving* charges
    - Electric motors
    - Current in a wire

Let's focus on moving charges:

- Fire a charged particle q at a speed v through a magnetic field $\vec{B}$.
- What happens?

The Magnetic Field

The charge gets deflected:



- Is the path parabolic, like with an electric or gravitational field?
- No, it appears to be *circular*
- And it doesn't move *along* $\vec{B}$, but *perpendicular* to it

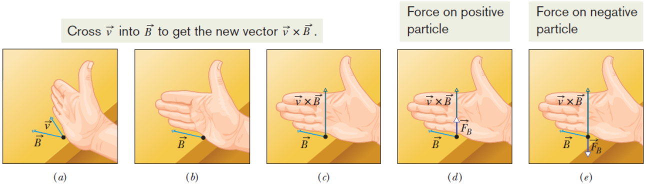
This behavior is like a cross product:

$$\vec{F} = q\,\vec{v} \times \vec{B} \tag{1}$$

The Magnetic Field

The force on a charge in a magnetic field is:

- $\vec{F} = q\,\vec{v} \times \vec{B}$
- $F = qvB\sin(\phi)$
- ϕ is the angle between $\vec{v}$ and $\vec{B}$
- Use right-hand rule to find direction of $\vec{F}$



The Magnetic Field

The magnetic field has S.I. units of tesla (T).

- 1 T = 1 N/A-m (from $F = qvB \rightarrow B = F/qv$)

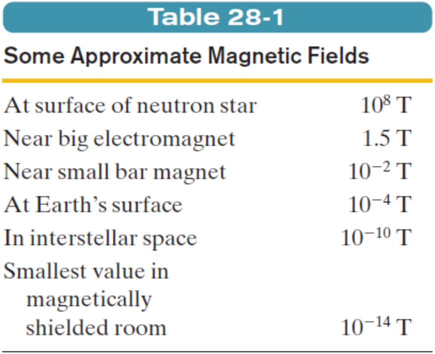


Table 28-1

Some Approximate Magnetic Fields

At surface of neutron star	10^{8} T
Near big electromagnet	1.5 T
Near small bar magnet	10^{-2} T
At Earth's surface	10^{-4} T
In interstellar space	10^{-10} T
Smallest value in magnetically shielded room	10^{-14} T

- $1\ \text{T} = 10^{4}$ gauss (more common unit)

The Magnetic Field

Lecture Question 11.1

For a charged particle in a magnetic field,

(a) the magnitude of the force is largest when the particle is not moving.

(b) the force is zero if the particle moves perpendicular to the field.

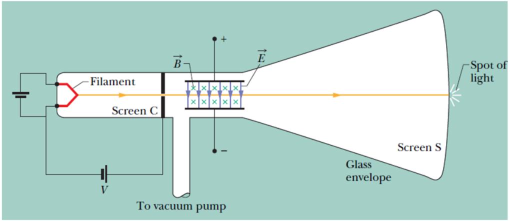
(c) the magnitude of the force is largest when the particle moves parallel to the direction of the magnetic field.

(d) the force depends on the component of the particle's velocity that is perpendicular to the field.

(e) the force acts in the direction of motion for a positively charged particle.

Crossed Fields ($\vec{E}$ and $\vec{B}$)

What if there is both an electric and magnetic field pushing on a charge?



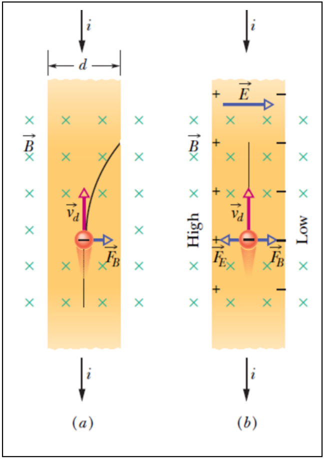
- Charges are accelerated through two fields
- The charges are pulled opposite directions
- From this experiment, for the electron:

$$\frac{m}{|q|} = \frac{B^2L^2}{2yE} \qquad (2)$$

Crossed Fields ($\vec{E}$ and $\vec{B}$)

The Hall Effect

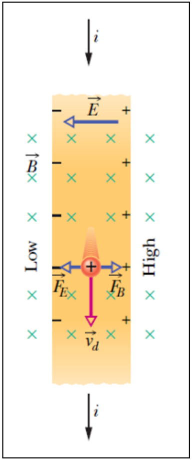
- If a wire is submerged in a magnetic field, the moving charges feel a force
- If electrons are moving:
- Electrons are pushed to the right
- The potential is lower on the right



Crossed Fields ($\vec{E}$ and $\vec{B}$)

The Hall Effect

- If positive charges are moving:



- Positive charges are pushed to the right
- The potential is lower on the left

Crossed Fields ($\vec{E}$ and $\vec{B}$)

The Hall Effect

- Once the charges are in equilibrium

$$F_q = F_B \rightarrow qE = qvB \rightarrow v = E/B = (V/d)/B$$

- From way back, we know that the speed of charges is given by

$$v = \frac{i}{nqA}$$

where n is the charges per unit volume m^{-3}

- This gives

$$n = \frac{Bi}{Vq}\frac{d}{A} \tag{3}$$

- Hall effect tells us the sign of the charge carrier but also the *density* of charge carriers.

Crossed Fields ($\vec{E}$ and $\vec{B}$)

Lecture Question 11.2

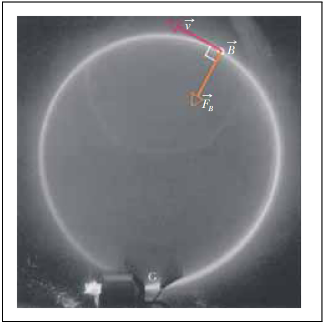
A negatively-charged particle travels parallel to magnetic field lines within a region of space.

- **(a)** The force is directed perpendicular to the magnetic field.
- **(b)** The force is perpendicular to the direction in which the particle is moving.
- **(c)** The force slows the particle.
- **(d)** The force accelerates the particle.
- **(e)** The force is zero.

Circulating Charges

Consider a charge q moving at a speed v perpendicular to a uniform magnetic field $\vec{B}$.

- The force $\vec{F}$ is always perpendicular to $\vec{v}$
- The magnitude of the force is constant ($\vec{B}$ and v are both constant!)
- This is *uniform circular motion*



Circulating Charges

For circular motion, we need to use

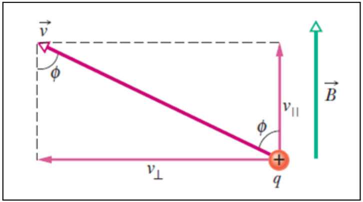
$$\vec{F}_{net} = m\vec{a} \to F_r = mv^2/r. \tag{4}$$

- The force: $F_r = qvB = mv^2/r$
- The velocity: $v = r|q|B/m$
- The radius: $r = mv/|q|B$
- The period $T = 2\pi r/v = 2\pi m/|q|B$
- The frequency $f = 1/T = |q|B/2\pi m$

Circulating Charges

Consider a charge q moving at a speed v in a uniform magnetic field $\vec{B}$.

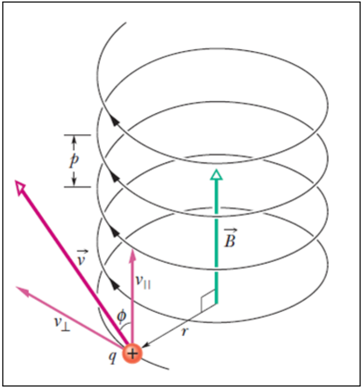
- Now, $\vec{v}$ and $\vec{B}$ are not perpendicular



- The parallel component $v_{\parallel}$ contributes no force.
- The perpendicular component $v_{\perp}$ keeps the charge in a circular motion

Circulating Charges

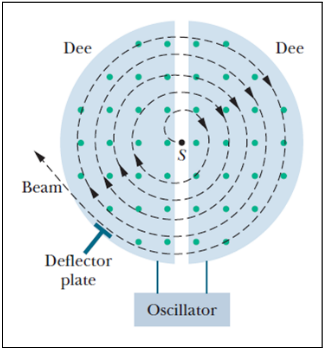
The result looks like a helix:



Circulating Charges

We often accelerate charges using large potentials.

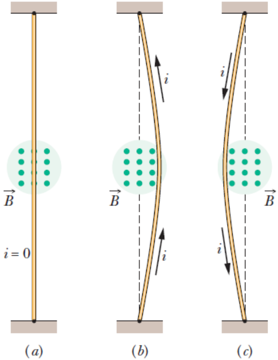
- But what happens if we run out of room?
- We can curve the path of our charges using a magnetic field:



- This is called a Cyclotron.

Force on a Current

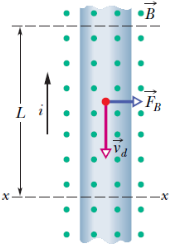
Moving charges feel a force in a magnetic field. What about a wire with current?



How can we calculate the force?

Force on a Current

Let's look at a wire of length L with current i in a uniform magnetic field $\vec{B}$:



- In a time t, we have $q = it = iL/v_d$
- The force is given by

$$\begin{aligned} F_B &= qv_dB \\ &= \frac{iL}{v_d} v_d B \\ &= iLB \end{aligned}$$

Force on a Current

What if the wire isn't perpendicular to $\vec{B}$?
Then we use the cross product:

$$\vec{F}_B = i\vec{L} \times \vec{B}$$

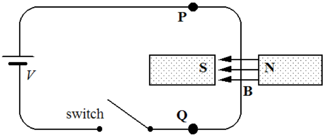
- $\vec{L}$ has direction along the conventional current
- $\vec{L}$ has magnitude equal to the length of the wire
- For non-uniform fields, or bending wires, we have:

$$d\vec{F}_B = id\vec{L} \times \vec{B}$$

and then integrate.

The Magnetic Field

Lecture Question 11.4



When the switch is thrown,

(a) the wire moves toward the north pole of the magnet.

(b) the wire moves toward the south pole of the magnet.

(c) the wire moves upward (toward us).

(d) the wire moves downward (away from us).

(e) the wire doesn’t move.