Magnetic Fields-I

Phy 108 course
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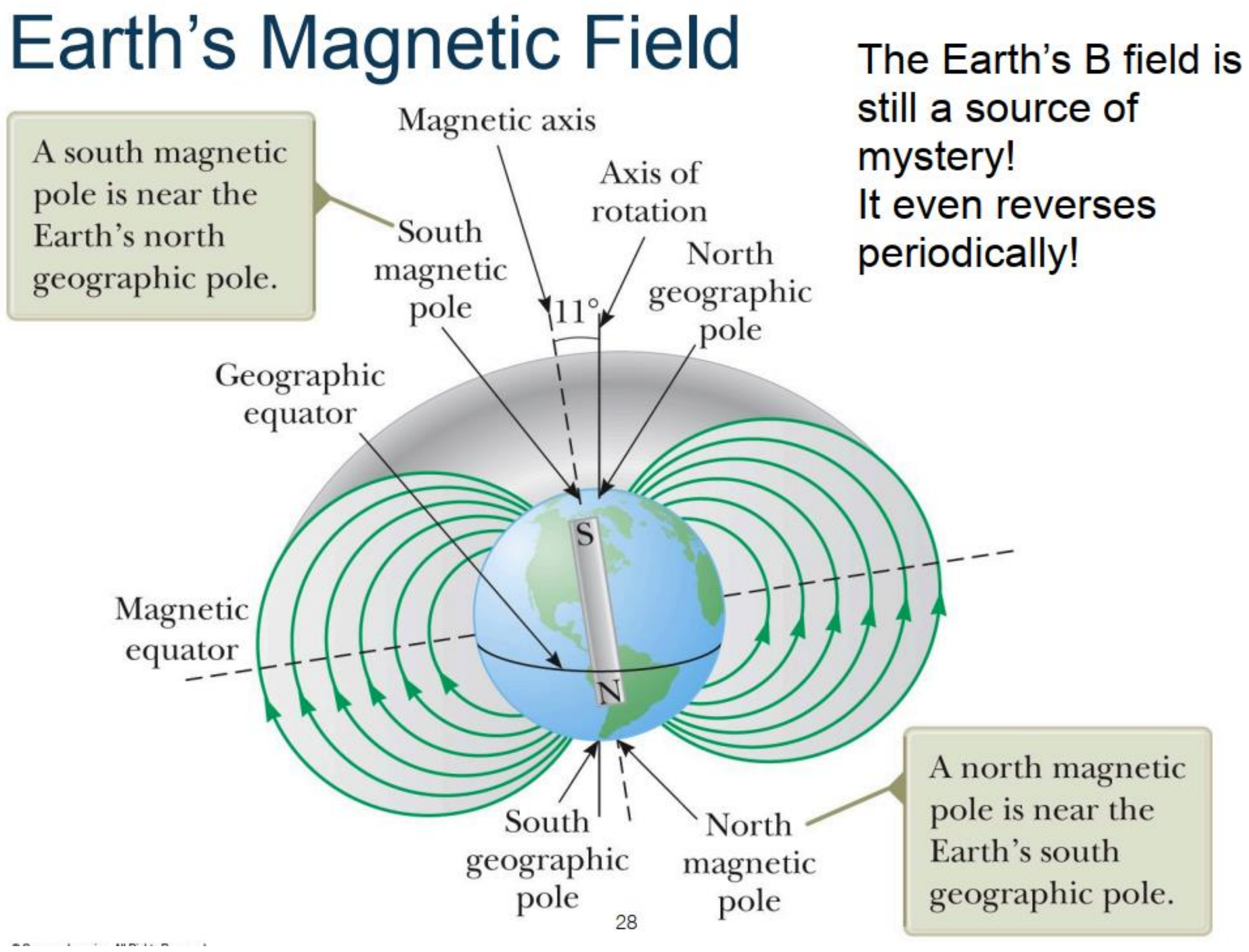
Magnetic field surrounding us!

This beautiful display of light in the sky is known as the northern lights (aurora borealis). It occurs when electrons, streaming from the sun, become trapped by the earth's magnetic field. The electrons collide with molecules in the upper atmosphere, and the result is the production of light. Magnetic forces and magnetic fields are the subjects of this chapter. (United States Air Force photo by Senior Airman Joshua Strang)

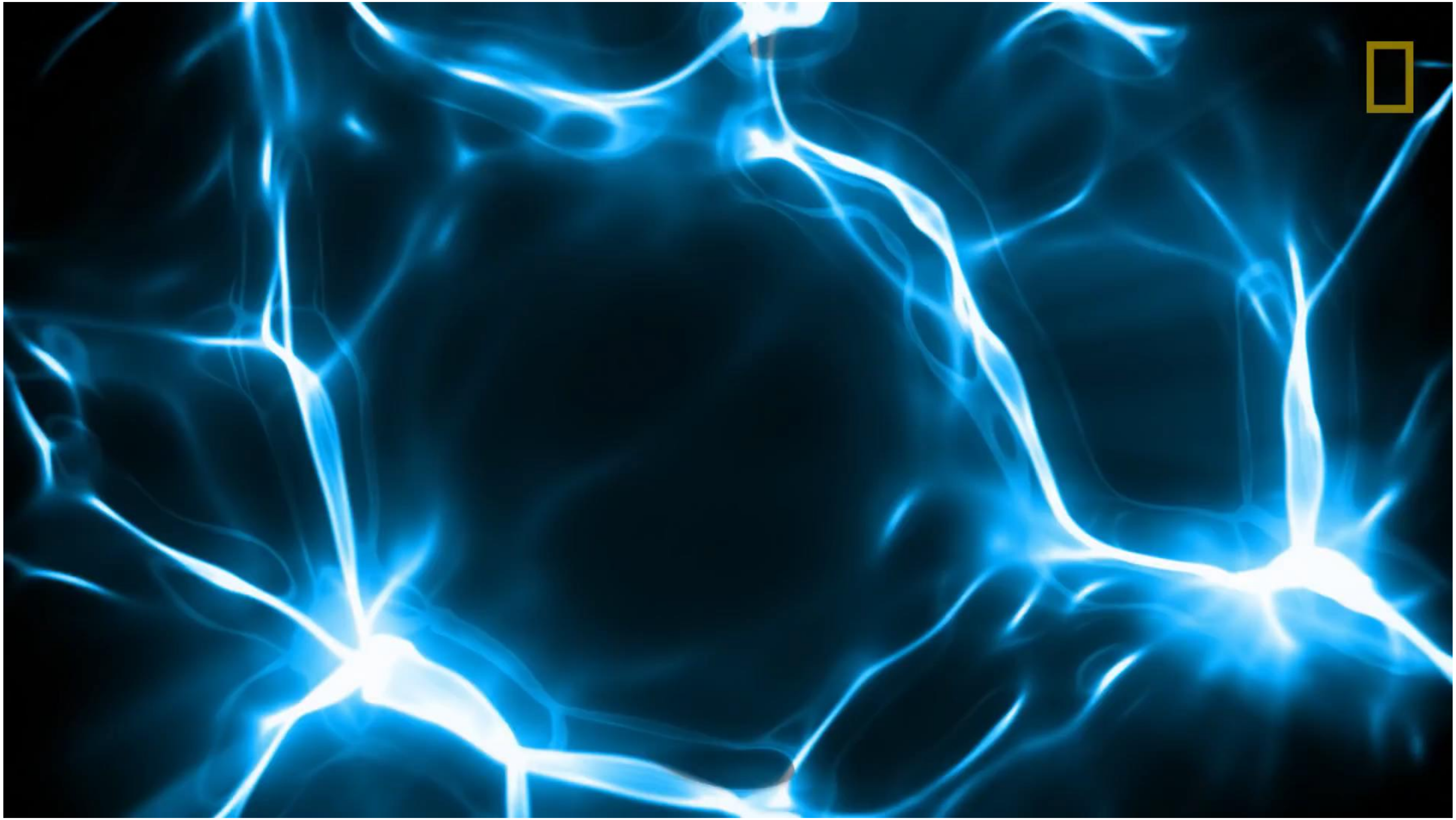
Magnetic field surrounding us!



Earth has a magnetic field that is produced in its core by still unknown mechanisms.

On Earth's surface, we can detect this magnetic field with a compass, which is essentially a slender bar magnet on a low-friction pivot.

This bar magnet, or this needle, turns because its north-pole end is attracted toward the Arctic region of Earth. Thus, the *south* pole of Earth's magnetic field must be located toward the Arctic. Logically, we then should call the pole there a south pole. However, because we call that direction north, we are trapped into the statement that Earth has a *geomagnetic north pole* in that direction.



https://www.youtube.com/watch?v=EIv3WpL32UE

Magnetic field surrounding us!

Figure 21.6 Spiny lobsters use the earth's magnetic field to navigate and determine their geographic position. (Courtesy Kenneth Lohmann, University of North Carolina at Chapel Hill)

Application Magnetic Fields of the Body

All living cells are electrically active, and the feeble electric currents within the body produce weak but measurable magnetic fields. The fields produced by skeletal muscles have magnitudes less than 10^{-10} T, about one-millionth as strong as the earth's magnetic field. The brain produces magnetic fields that are far weaker, only about 10^{-12} T.

Magnetic field surrounding us!

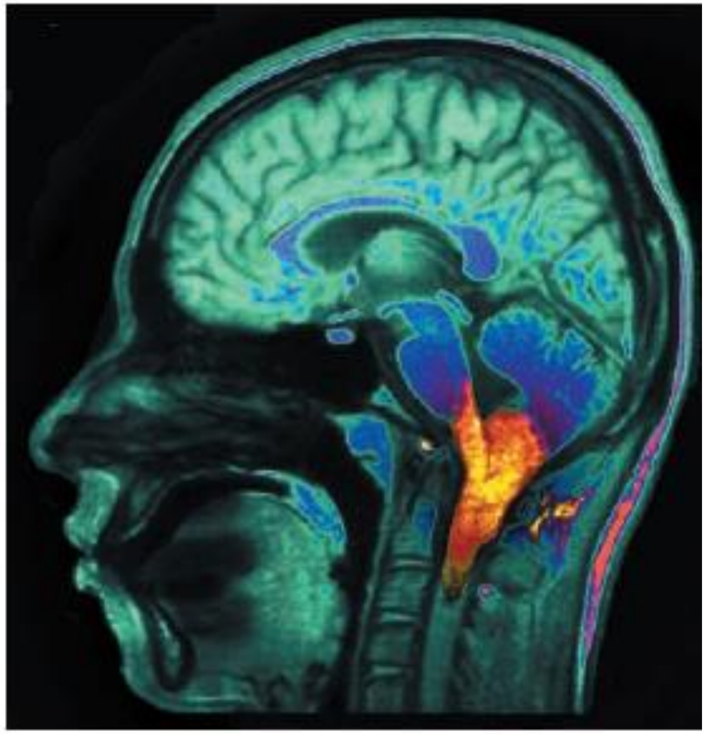
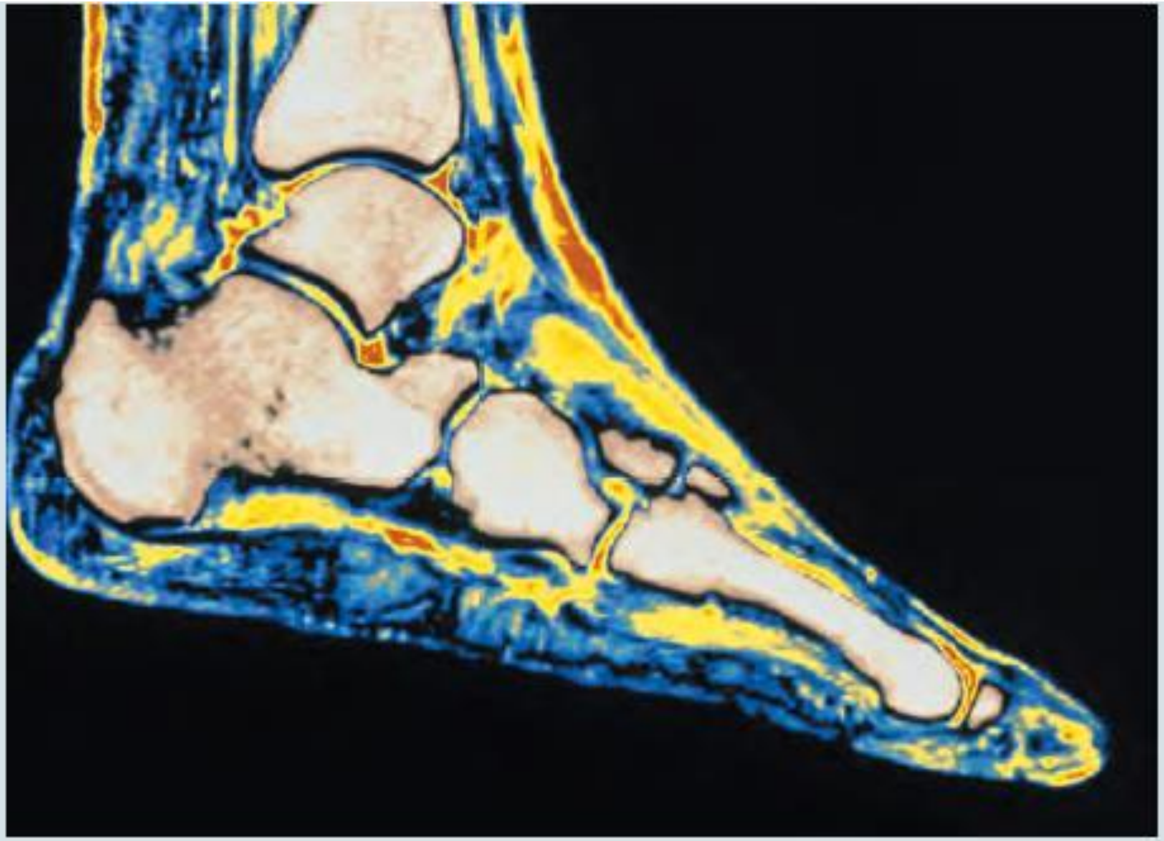


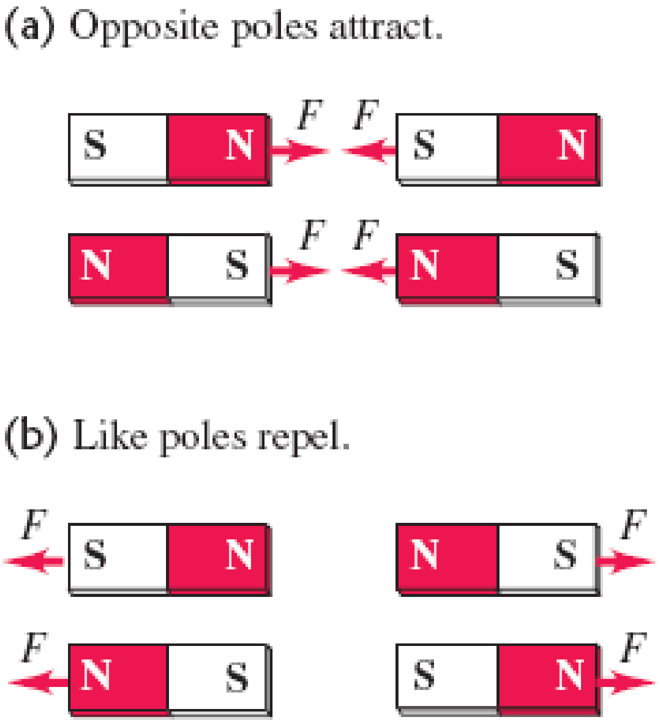
Figure 21.34 Magnetic resonance imaging provides one way to diagnose brain disorders. This image shows the brain of a patient with an Arnold-Chiari deformity. In this congenital anomaly, an abnormally elongated cerebellum and medulla oblongata (the red-orange-yellow region just to the right of the top of the spine) protrude down into the spinal canal. (© ISM/Phototake)

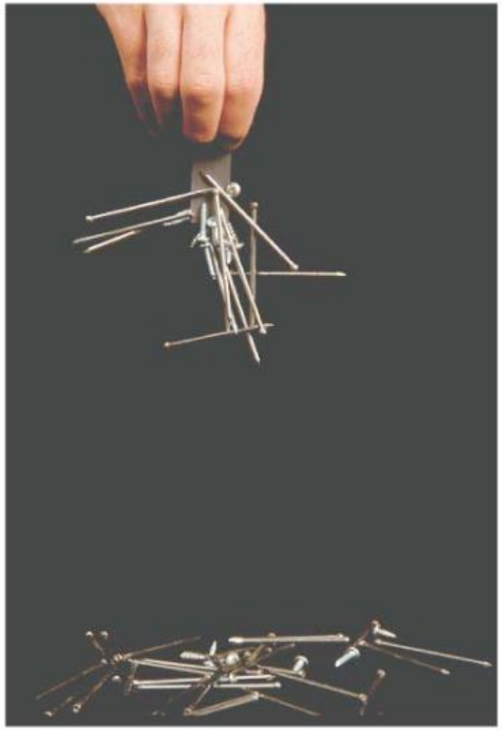


? Magnetic resonance imaging (MRI) makes it possible to see details of soft tissue (such as in the foot shown here) that aren't visible in x-ray images. Yet soft tissue isn't a magnetic material (it's not attracted to a magnet). How does MRI work?

Magnet: Basics

(a) Two bar magnets attract when opposite poles (N and S, or S and N) are next to each other. (b) The bar magnets repel when like poles (N and N, or S and S) are next to each other.





Magnetic Field

A permanent magnet will attract a metal like iron with either the north or south pole by inducing magnetic dipole in the iron

Electric Field

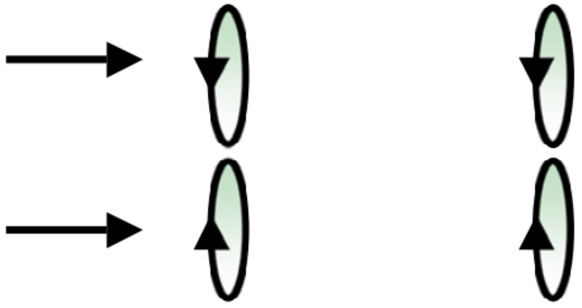
A positive charge or negative charge attract a neutral object by inducing a electric dipole in the neutral object

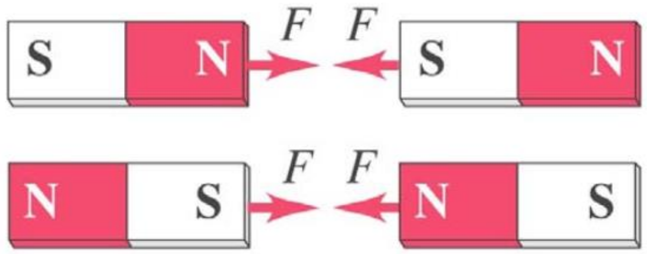
Our present understanding is that inside a magnet are small current loops (motions of electrons inside the atom)

– current loops moving in the same direction attract

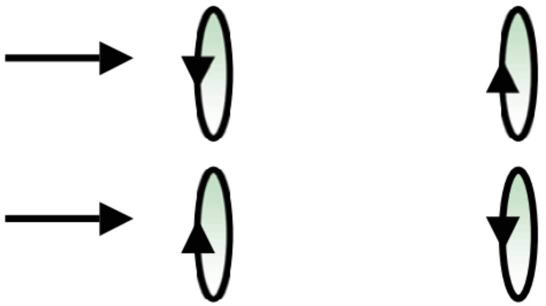
– current loops moving in opposite direction repel

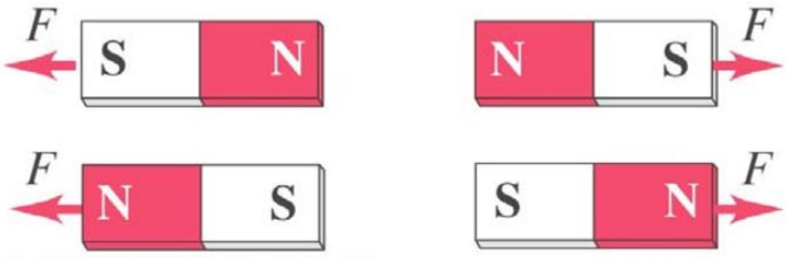
same direction current loops attract





opposite direction current loops repel



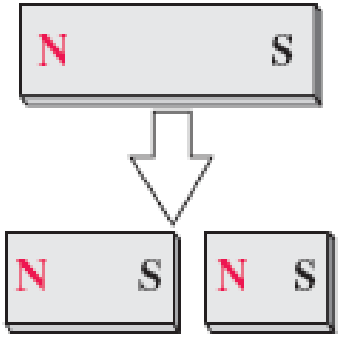


Magnets cannot exist as monopoles. If you break a bar magnet between N and S poles, you get two smaller magnets, each with its own N and S pole

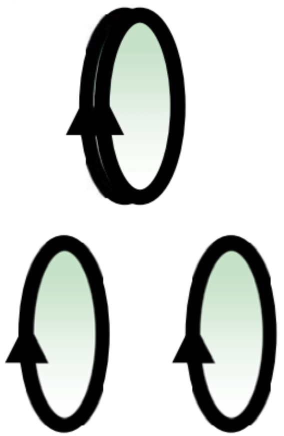
27.4 Breaking a bar magnet. Each piece has a north and south pole, even if the pieces are different sizes. (The smaller the piece, the weaker its magnetism.)

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

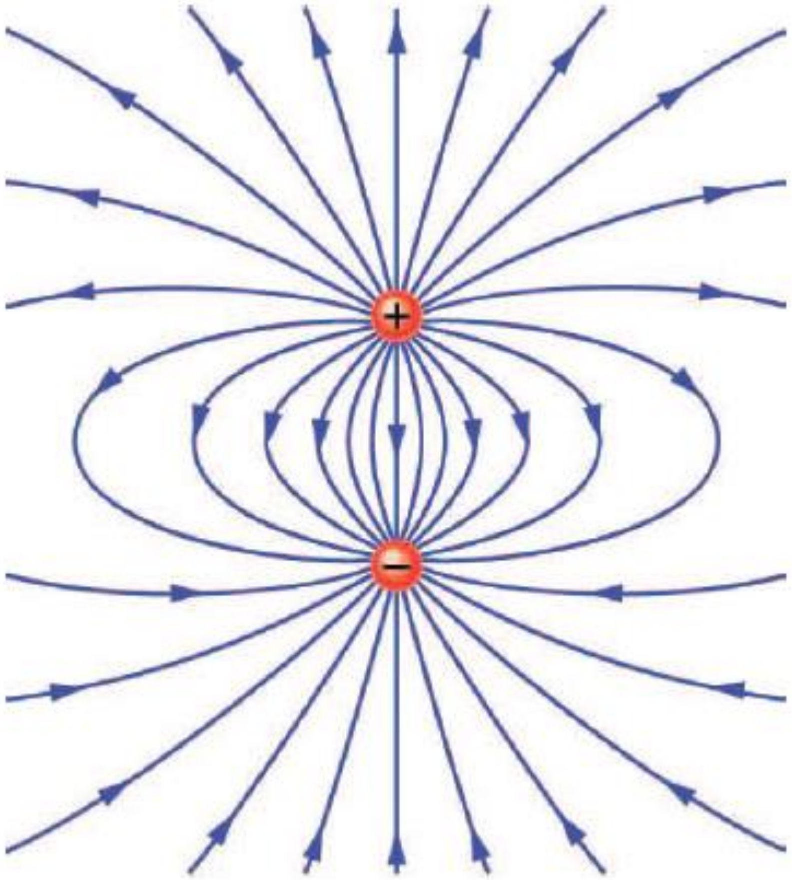
Breaking a magnet in two ...

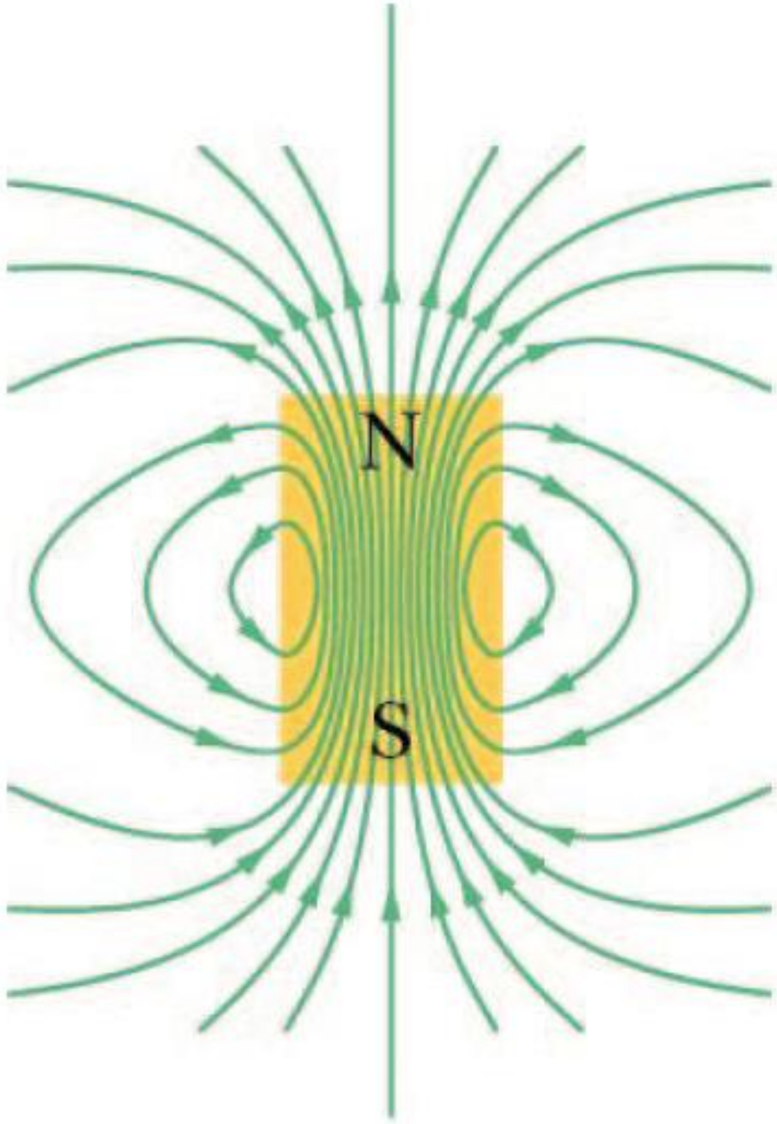


... yields two magnets, not two isolated poles.



Sliding a thick current loop into half gives two thinner current loops





Note: Isolated magnetic monopoles do not exist.

Magnet: Basics

One way is to use moving electrically charged particles, such as a current in a wire, to make an electromagnet.

The other way to produce a magnetic field is by means of elementary particles such as electrons because these particles have an *intrinsic* magnetic field around them. That is, the magnetic field is a basic characteristic of each particle just as mass and electric charge (or lack of charge) are basic characteristics.

The magnetic fields of the electrons in certain materials add together to give a net magnetic field around the material. Such addition is the reason why a permanent magnet, the type used to hang refrigerator notes, has a permanent magnetic field.

In other materials, the magnetic fields of the electrons cancel out, giving no net magnetic field surrounding the material. Such cancellation is the reason you do not have a permanent field around your body

The Definition of magnetic field $\vec{B}$

The magnetic field for a charge q moving with velocity $\vec{v}$ defined as,

$$q\vec{v} \times \vec{B} = \vec{F}_B$$

Magnitude of magnetic filed

$$|\vec{B}| = \frac{|\vec{F}_B|}{|q\vec{v}|}$$

Magnitude of the force

$$F_B = qvB\, sin\varphi$$

Where φ is the angle between velocity and magnetic field

The force $\vec{F}_B$ acting on a charged particle moving with velocity $\vec{v}$ through a magnetic field $\vec{B}$ is *always* perpendicular to $\vec{v}$ and $\vec{B}$.

The Definition of magnetic field $\vec{\boldsymbol{B}}$

The electric field for a charge q defined as, $\vec{E} = \frac{\vec{F}_E}{q}$

If a magnetic monopole were available, we could define magnetic field $\vec{\boldsymbol{B}}$ in a similar way. Because such particles have not been found, we must define the magnetic field $\vec{\boldsymbol{B}}$ in another way! In terms of magnetic force exerted on a moving charged particle.

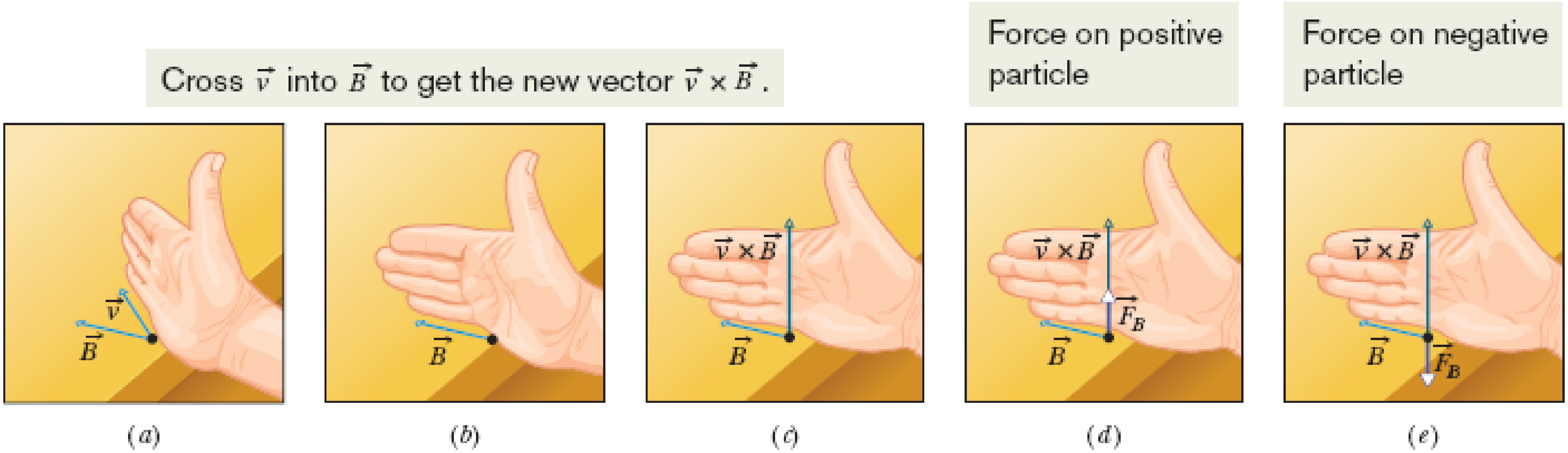
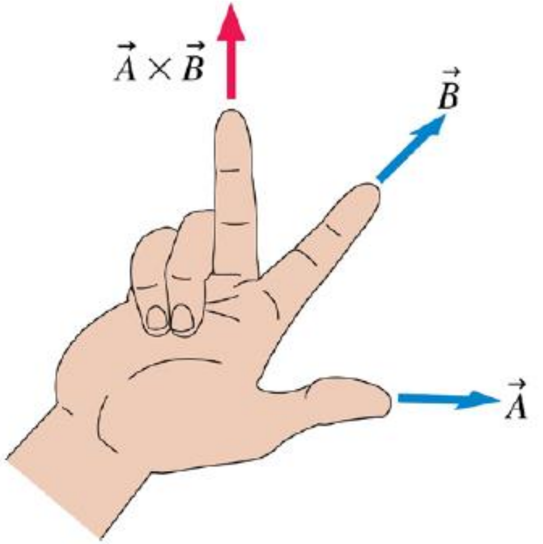
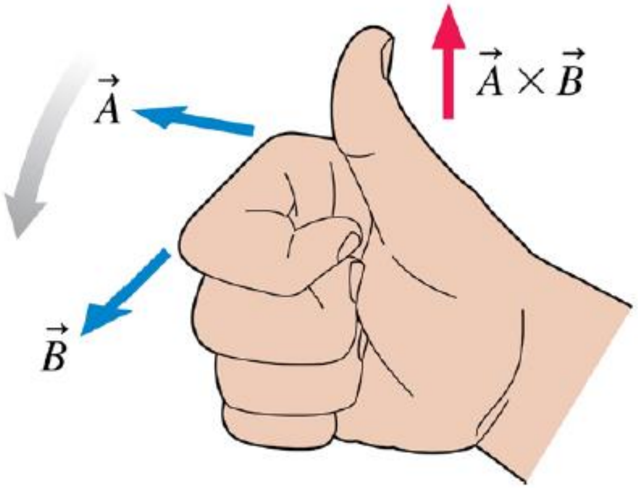
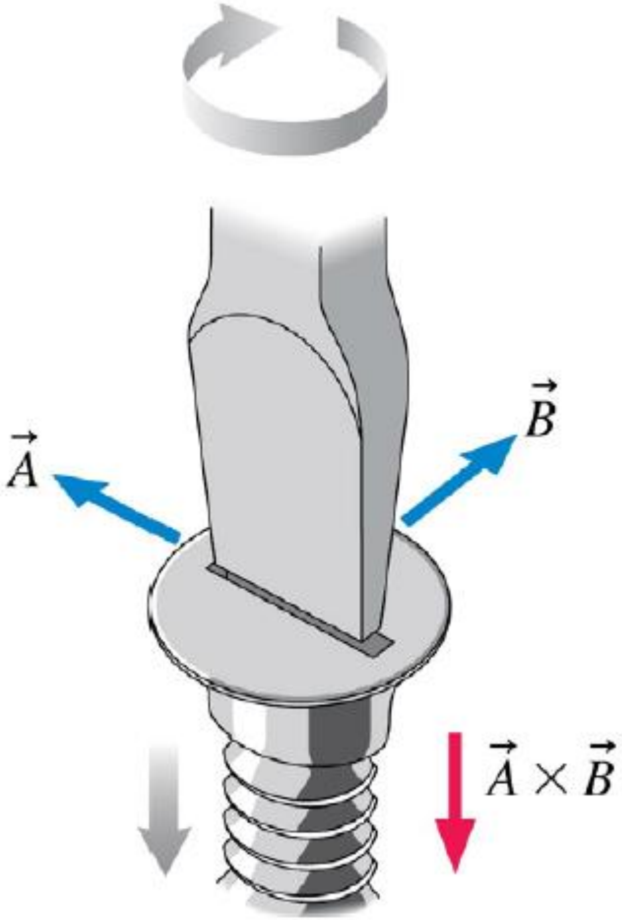


Figure 28-2 (*a*)–(*c*) The right-hand rule (in which $\vec{v}$ is swept into $\vec{B}$ through the smaller angle ϕ between them) gives the direction of $\vec{v} \times \vec{B}$ as the direction of the thumb. (*d*) If q is positive, then the direction of $\vec{F}_B = q\vec{v} \times \vec{B}$ is in the direction of $\vec{v} \times \vec{B}$. (*e*) If q is negative, then the direction of $\vec{F}_B$ is opposite that of $\vec{v} \times \vec{B}$.


$\vec{A} \times \vec{B}$
$\vec{B}$
$\vec{A}$


$\vec{A}$
$\vec{A} \times \vec{B}$
$\vec{B}$


$\vec{A}$
$\vec{B}$
$\vec{A} \times \vec{B}$

The magnetic force $\vec{F}$ acting on a positive charge q moving with velocity $\vec{v}$ is perpendicular to both $\vec{v}$ and the magnetic field $\vec{B}$. For given values of the spee v and magnetic field strength B, the force is greatest when $\vec{v}$ and $\vec{B}$ are perpendicula

(a)

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

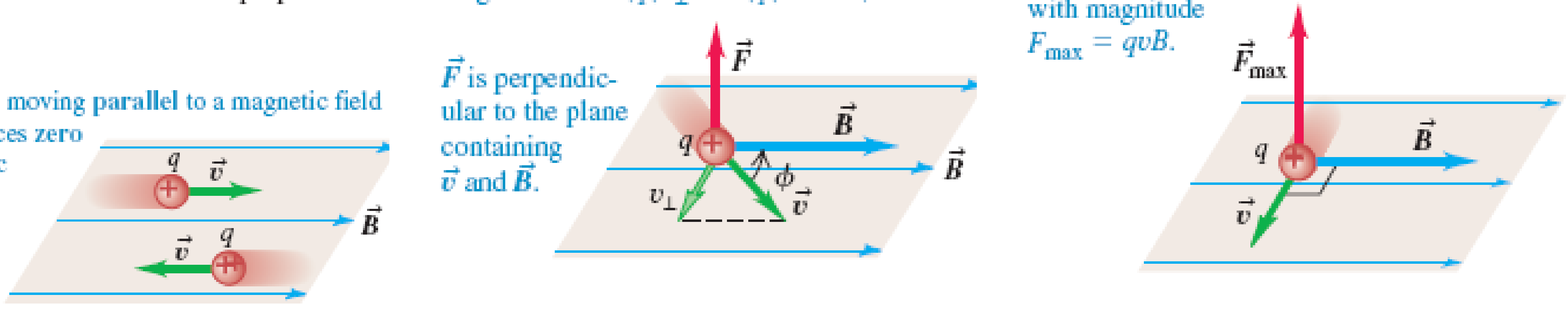
(b)

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

$\vec{F}$ is perpendicular to the plane containing $\vec{v}$ and $\vec{B}$.

(c)

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

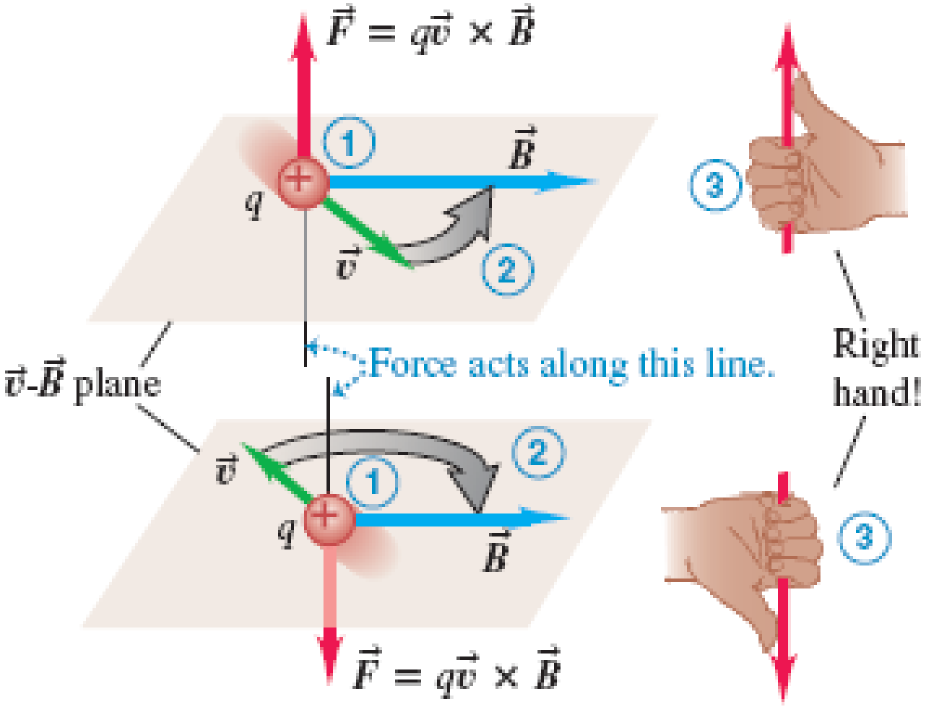


Finding the direction of the magnetic force on a moving charged particle.

(a)

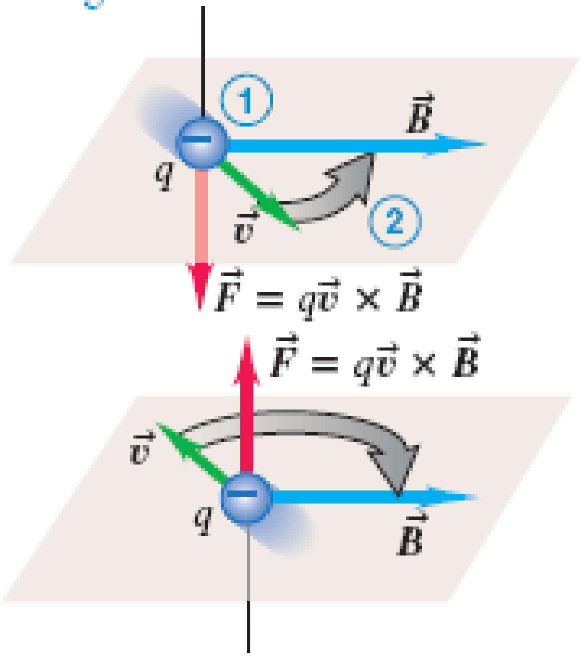
Right-hand rule for the direction of magnetic force on a **positive** charge moving in a magnetic field:

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.



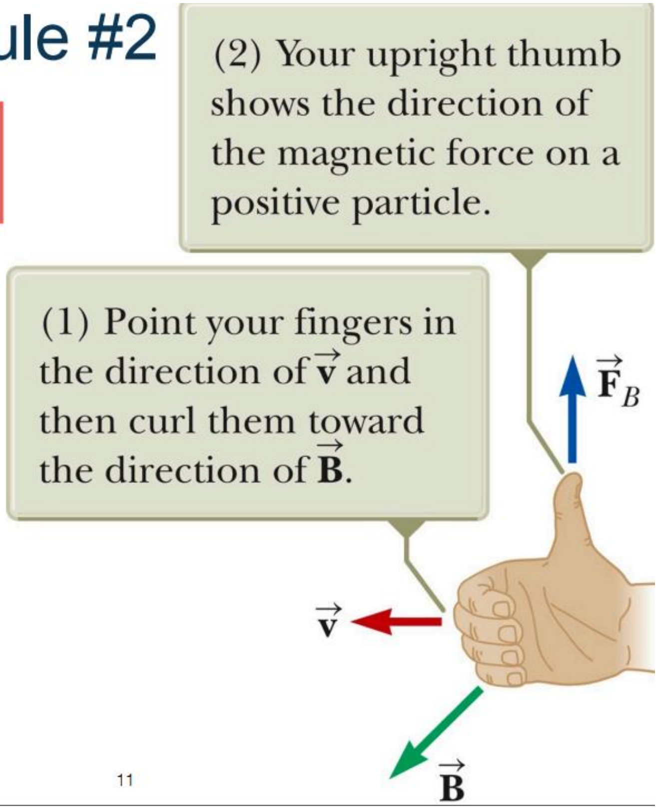
(b)

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

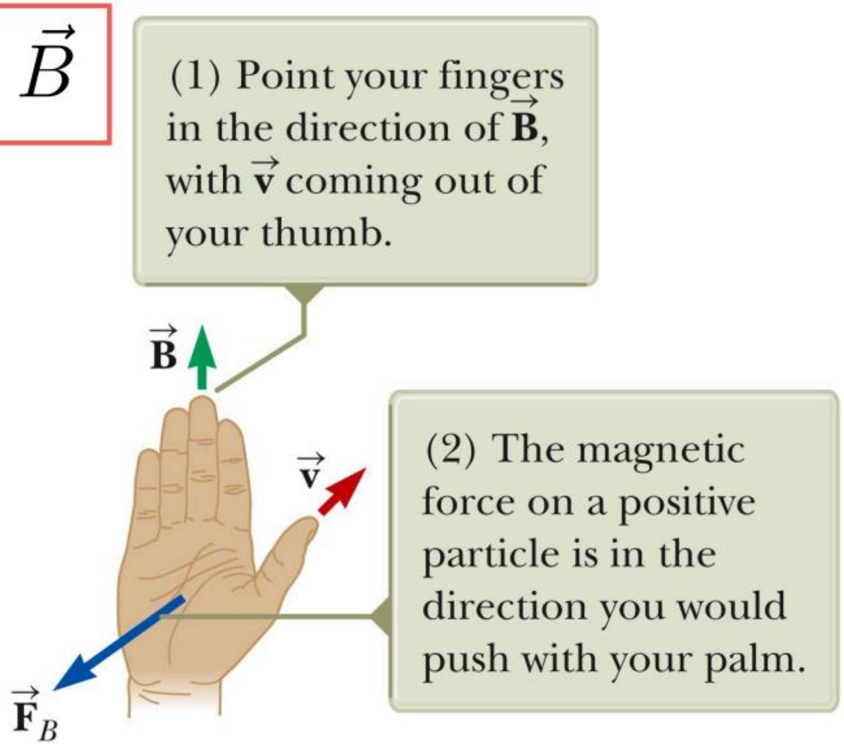


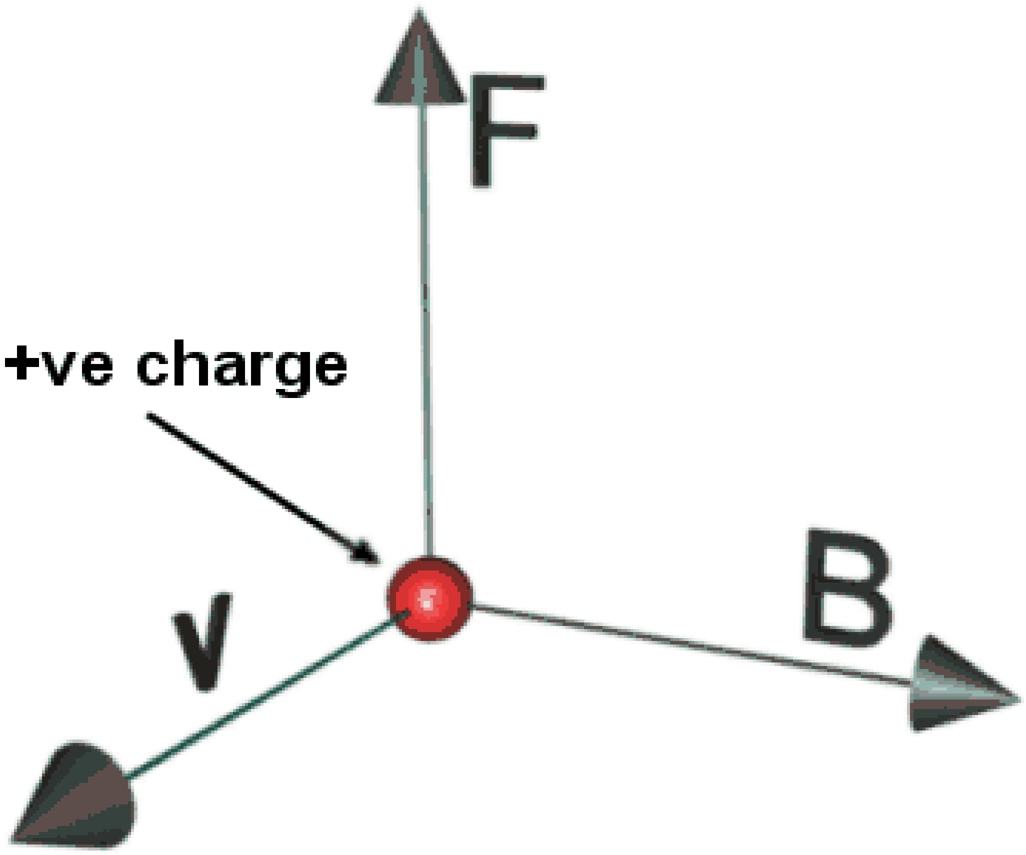
Right Hand Rule #2

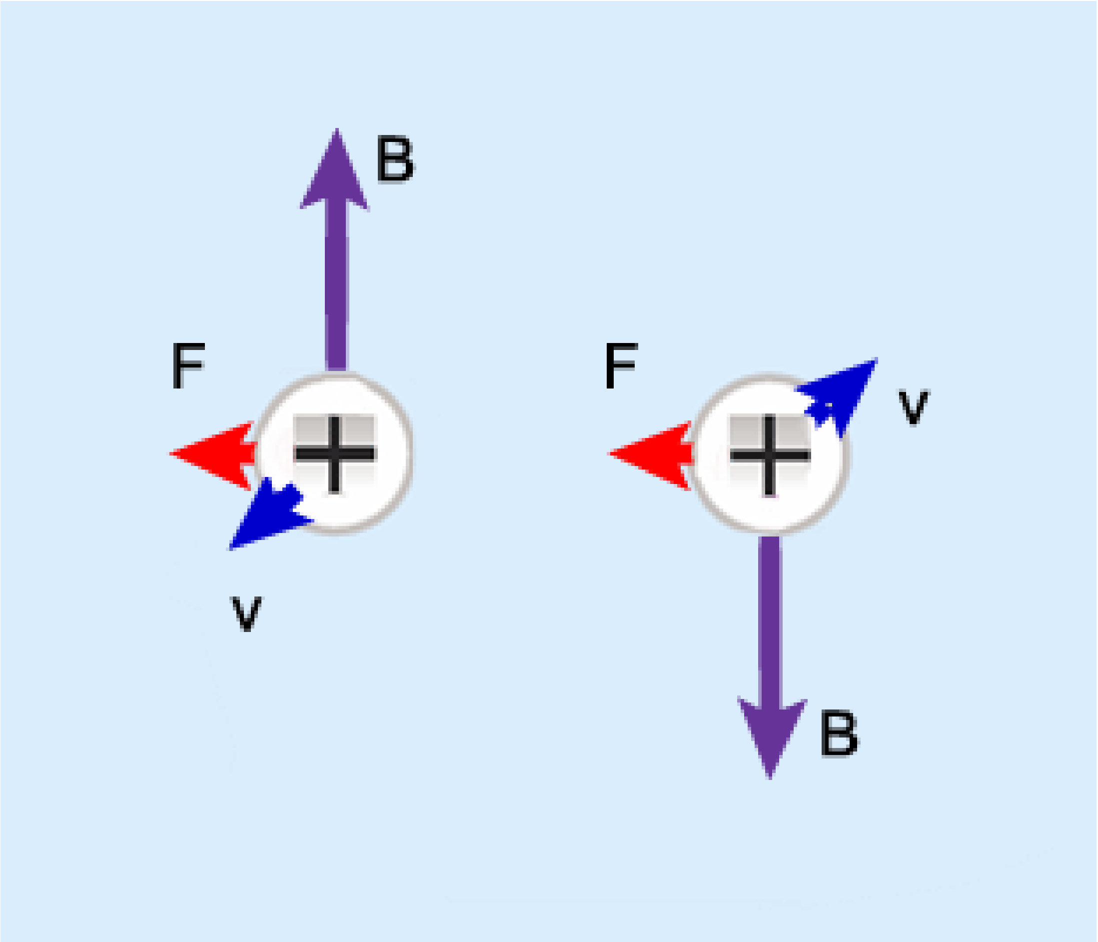
$$\vec{F} = q\vec{v} \times \vec{B}$$



$$\vec{F} = q\vec{v} \times \vec{B}$$

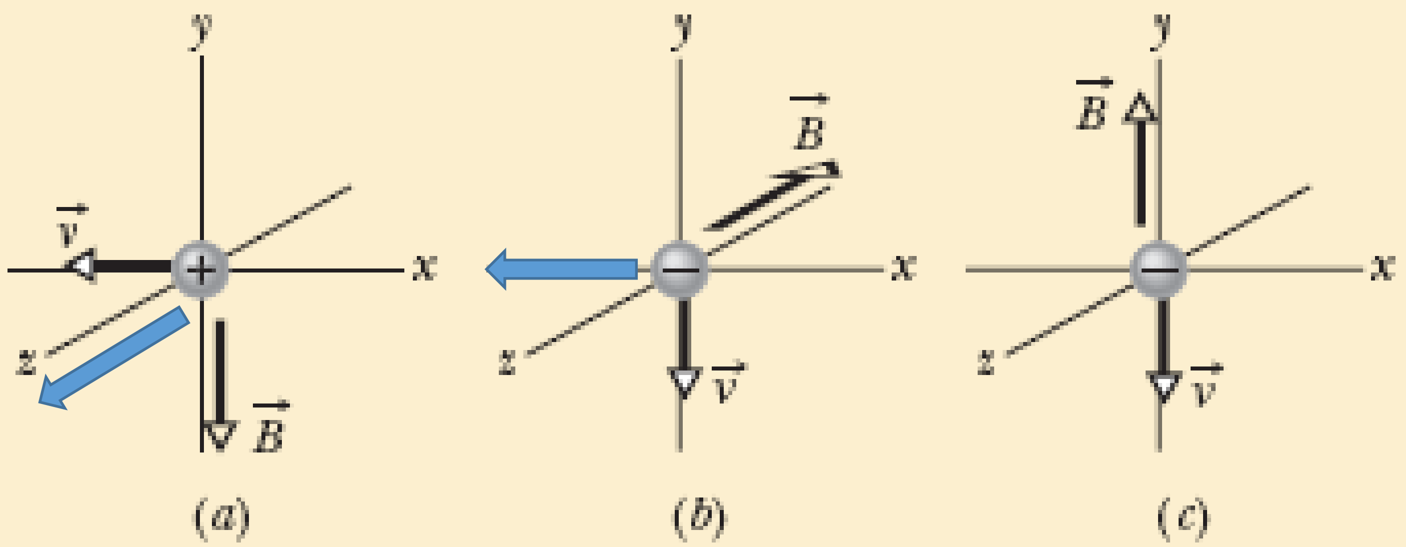



F
+ve charge
v
B


B
F
v
F
v
B

Checkpoint 1

The figure shows three situations in which a charged particle with velocity $\vec{v}$ travels through a uniform magnetic field $\vec{B}$. In each situation, what is the direction of the magnetic force $\vec{F}_B$ on the particle?



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

Magnetic filed measuring unit:

SI unit is called Tesla,

1 Tesla = 1 T = 1 Newton/ (Coulomb)(meter/second)

Coulomb/second is the current Ampere,

$$1\,T = N/A.m$$

Earlier unit is Gauss, 10^4 Gauss = 1 T

A charged particle, **Q = 0.5 C**, enters a region with a uniform magnetic field $\vec{B} = 2\hat{x} + 3\hat{y} + 4\hat{z}$ (**in Tesla**). If its velocity is given by $\vec{v} = 2\hat{x} + 3\hat{y} + 2\hat{z}$ (**in m/s**), what is the magnitude of the magnetic force on the particle (**in N**)?

Solution: We know that the magnetic force on a particle is

$$\vec{F} = Q\vec{v} \times \vec{B} = Q\begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ 2 & 3 & 2 \\ 2 & 3 & 4 \end{vmatrix} = Q(6\hat{x} - 4\hat{y}).$$

The **magnitude of the force** is

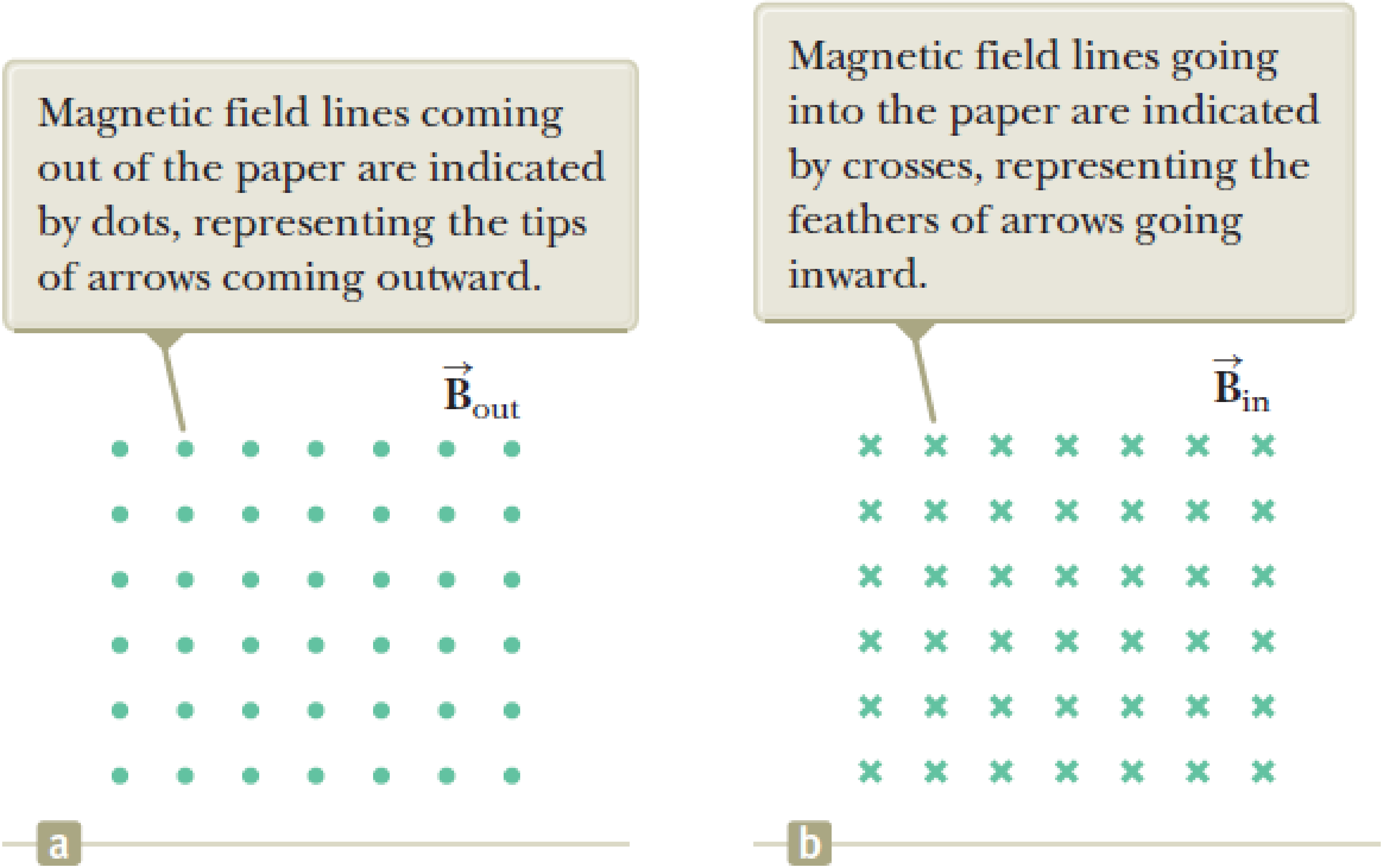
$$F = Q\sqrt{36+16} = (0.5)\sqrt{52}\,N = 3.6\,N.$$

A charged particle, **Q=0.5 C**, and mass **M = 200 grams** enters a region with a uniform magnetic field $\vec{B} = 2\hat{x} - 1\hat{y}$ (**in Tesla**). What is the magnitude of the magnetic force on the particle (**in N**), if its velocity is $\vec{v} = 4\hat{x} - 2\hat{y}$ (**in m/s**)?

Solution: We know that the magnetic force on a particle is

$$\vec{F} = Q\vec{v} \times \vec{B} = Q\begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ 4 & -2 & 0 \\ 2 & -1 & 0 \end{vmatrix} = 0.$$

Note that **v** is in the same direction as **B** and hence the magnetic force is zero.

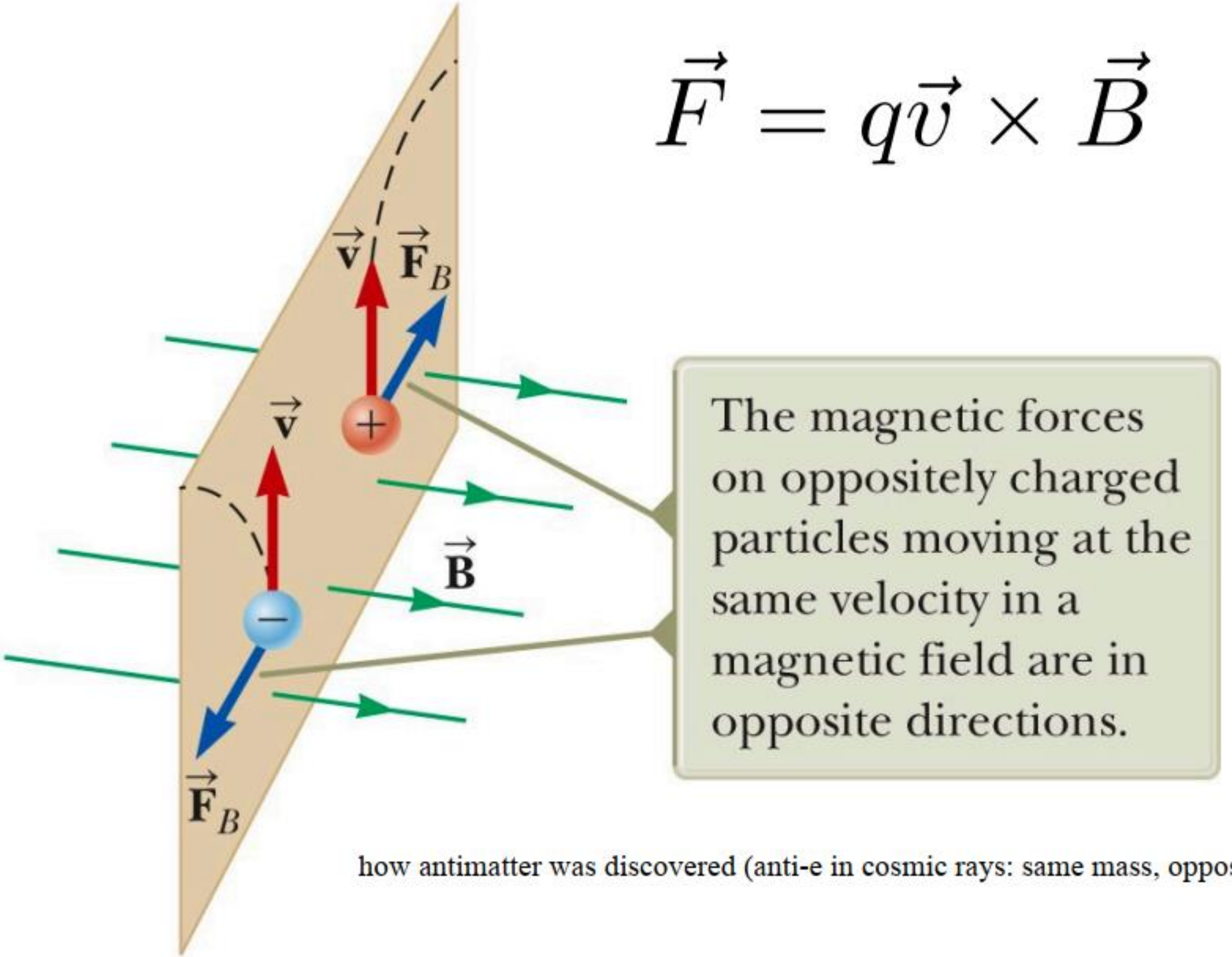


http://physics.bu.edu/~duffy/HTML5/charge_in_field.html

http://physics.bu.edu/~duffy/HTML5/threeD_magnetism.html

Magnetic Force due to opposite charges

$$\vec{F} = q\vec{v} \times \vec{B}$$



how antimatter was discovered (anti-e in cosmic rays: same mass, opposite charge)

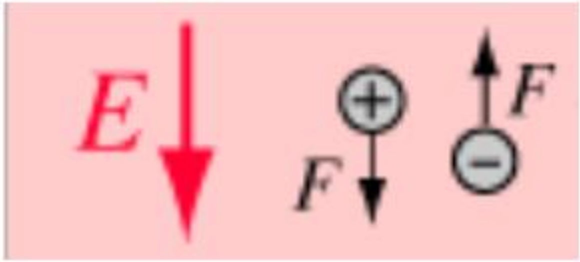
Electric and Magnetic Fields: Differences

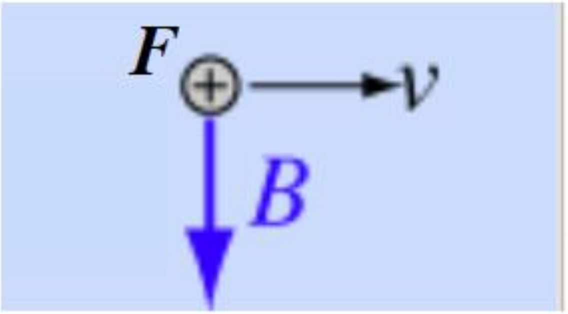
Motion

- The electric force acts on a charged particle regardless of whether the particle is moving.
- **The magnetic force acts on a charged particle only when the particle is in motion.**

Direction of force

- The electric force acts along the direction of the electric field.
- The **magnetic force acts perpendicular to the magnetic field.**





Electric and Magnetic Fields: Differences

Work

- The electric force does work in displacing a charged particle.
- The **magnetic force associated with a steady magnetic field does no work when a particle is displaced.**
  - This is because the force is perpendicular to the displacement of its point of application.

Kinetic Energy

- The electric field alone can alter the kinetic energy of a charged particle.
- The magnetic field **cannot alter the kinetic energy** of a charged particle.

Magnetic Field Lines

Just like you can picture an electric field in a space through electric field lines, so it is with magnetic fields.

Just like electric field lines, magnetic fields lines:

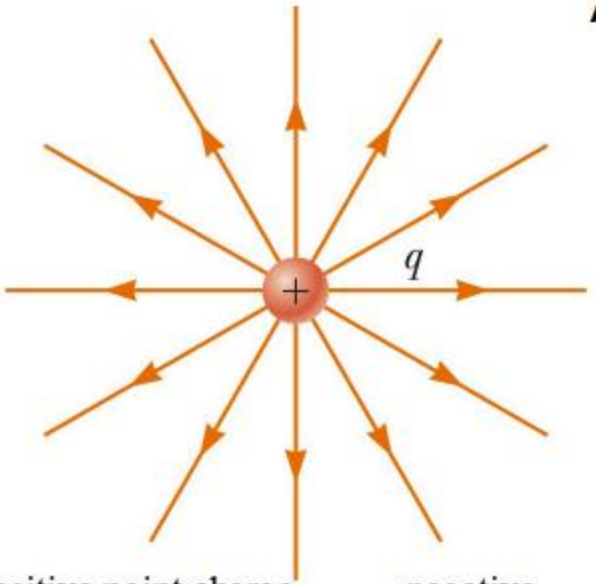
- can never cross
- the net magnetic field at any point is the vector sum of all magnetic fields present at that point
- are a pictorial representation of the field
- are present everywhere in space
- the higher the lines' density, the higher the strength of the field

Unlike electric fields lines, magnetic field lines:

visualizable using iron filings (for instance)

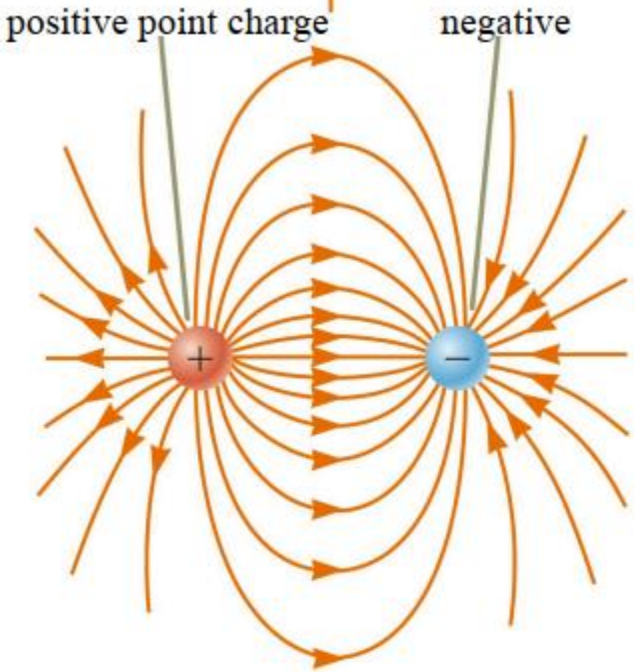
- can never be infinite, but **always form closed loops.**
- **do not represent the path of the charged particle**
- do not originate on charges, but **originate on poles**

Poles



A pole is the point where your field lines converge.

Example: **monopole** = 1 pole
A single, static + charge creates an electric field.
The + charge is the only pole.



Example: **dipole** = 2 poles
This is an electric dipole. Both charges are static (they don't move), they both produce electric field lines.
Each charge is a pole.

Magnetic Poles

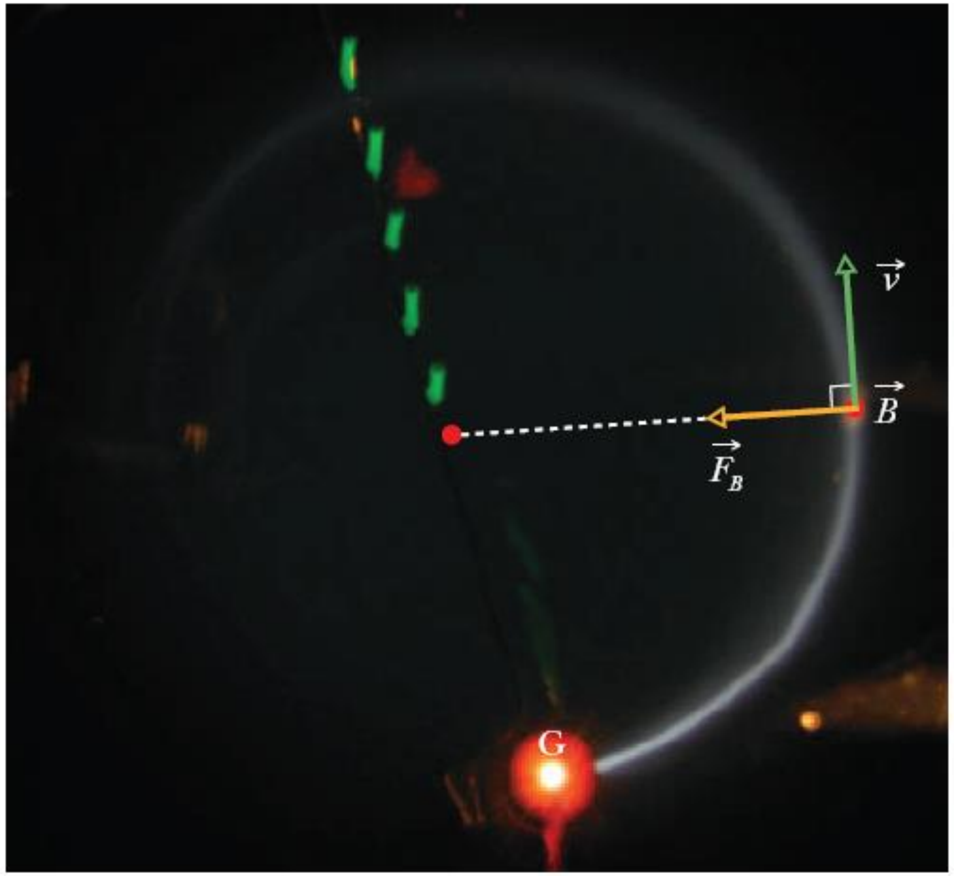
While electric monopoles exist, **THERE IS NO SUCH THING AS A MAGNETIC MONOPOLE ***

- magnetic poles always **come in pairs**.
- the simplest case is a magnetic **dipole**, which has 2 poles.
- these poles are named **North (N) and South (S)**
- these poles exert forces on each other
  - **Like poles repel** each other: N-N or S-S
  - **Unlike poles attract** each other : N-S

→ magnetic field lines originate and end on poles
→ magnetic fields are created by moving charges
→ moving charges create a dipole

A CIRCULATING CHARGED PARTICLE

For a charged particle moving through a uniform magnetic field, identify under what conditions it will travel in a straight line, in a circular path, and in a helical path.



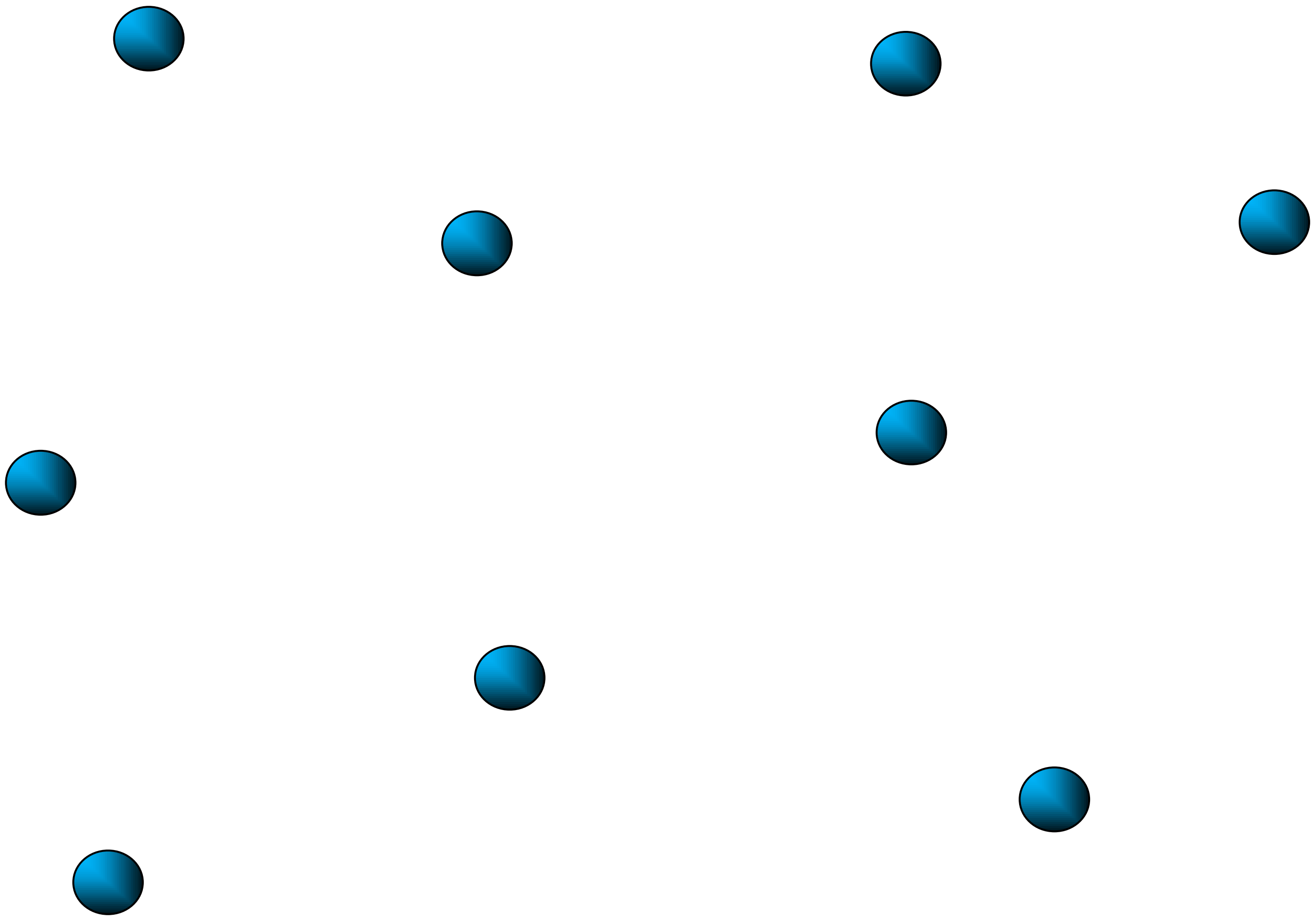
Courtesy Jearl Walker

Figure 28-10 Electrons circulating in a chamber containing gas at low pressure (their path is the glowing circle). A uniform magnetic field $\vec{B}$, pointing directly out of the plane of the page, fills the chamber. Note the radially directed magnetic force $\vec{F}_B$; for circular motion to occur, $\vec{F}_B$ *must* point toward the center of the circle. Use the right-hand rule for cross products to confirm that $\vec{F}_B = q\vec{v} \times \vec{B}$ gives $\vec{F}_B$ the proper direction. (Don't forget the sign of q.)

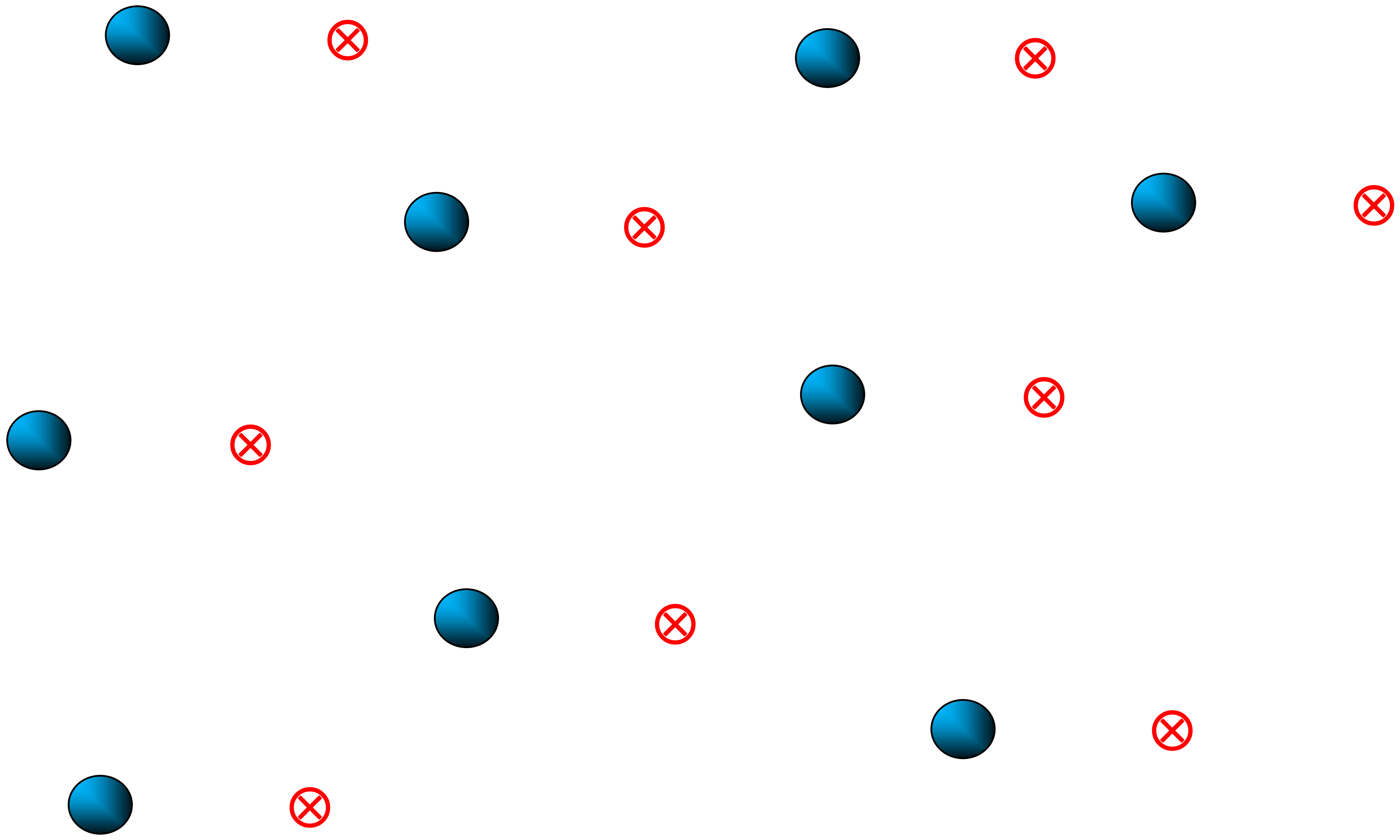
http://physics.bu.edu/~duffy/HTML5/charge_in_field_sim.html

Electrons confined to move in a plane

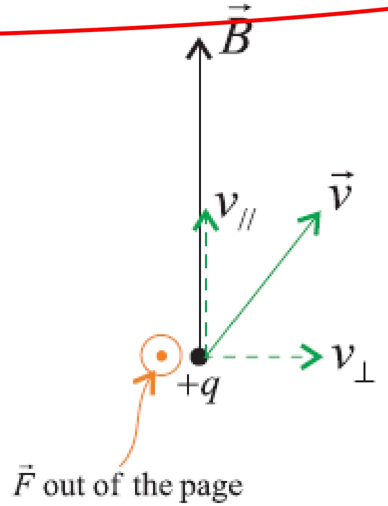
Apply B-field perpendicular to plane



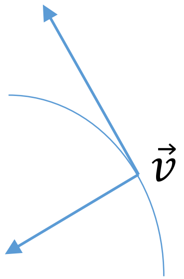
Apply B-field perpendicular to plane



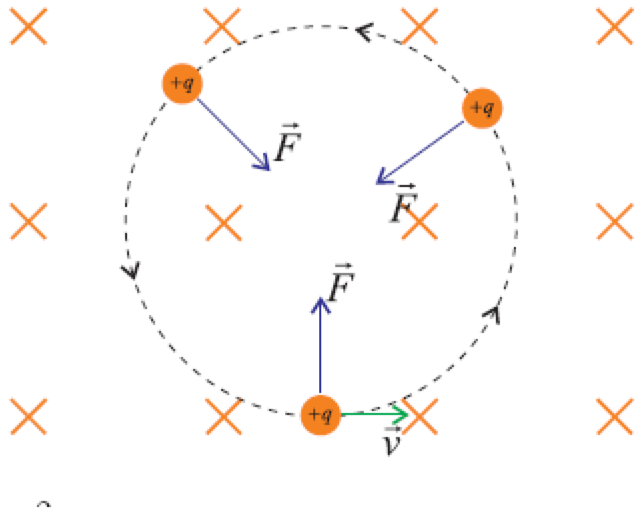
Since $\vec{F}_B \perp \vec{v}$, therefore B-field only changes the *direction* of the velocity but not its *magnitude*.

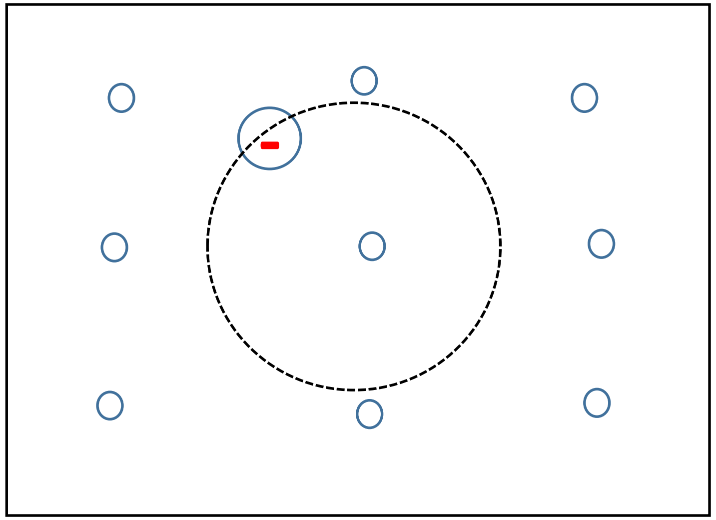


Generally, $\vec{F}_B = q\vec{v} \times \vec{B} = q\, v_{\perp} B$,
$\therefore$ We only need to consider the motion component $\perp$ to B-field.

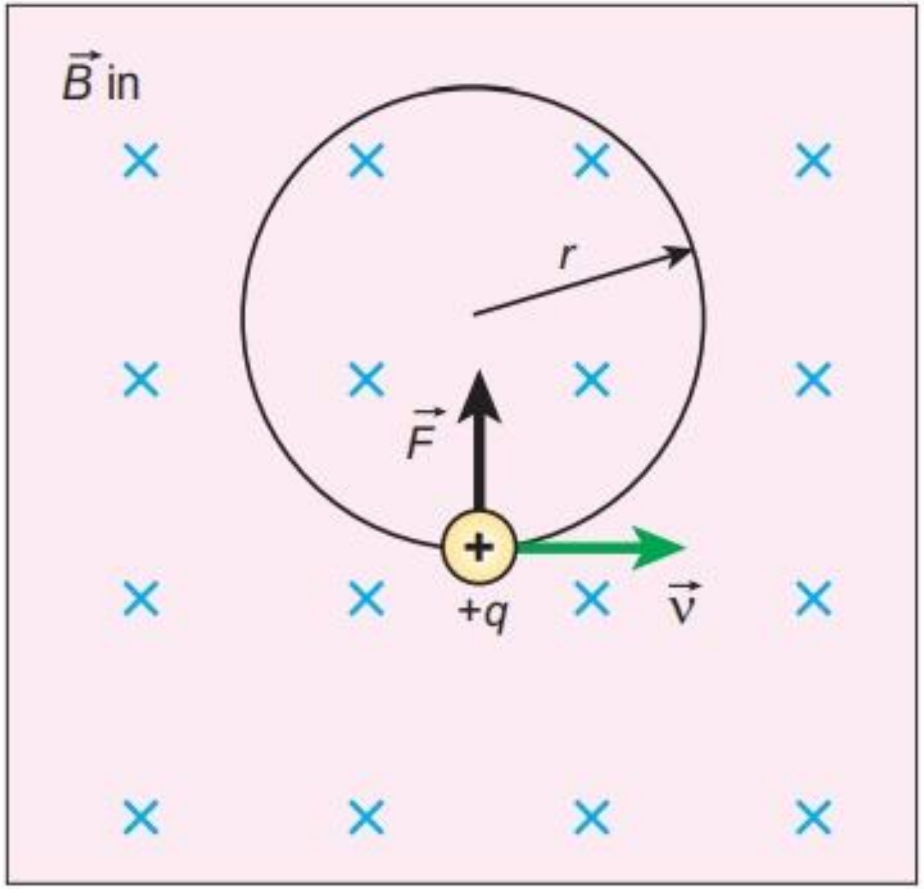


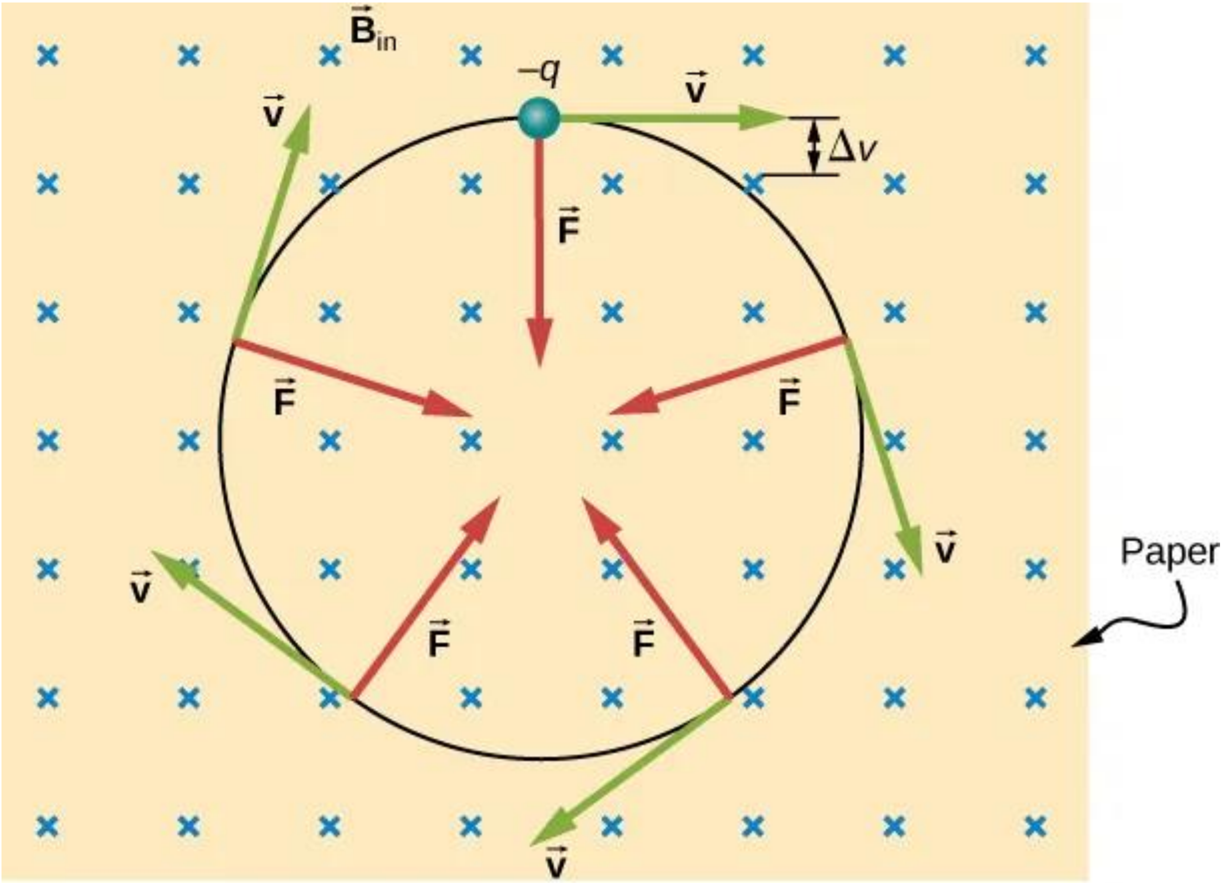
We have *circular motion*. Magnetic force provides the *centripetal force* on the moving charge particles.





+ particle counter-clockwise rotation.
- particle clockwise rotation.

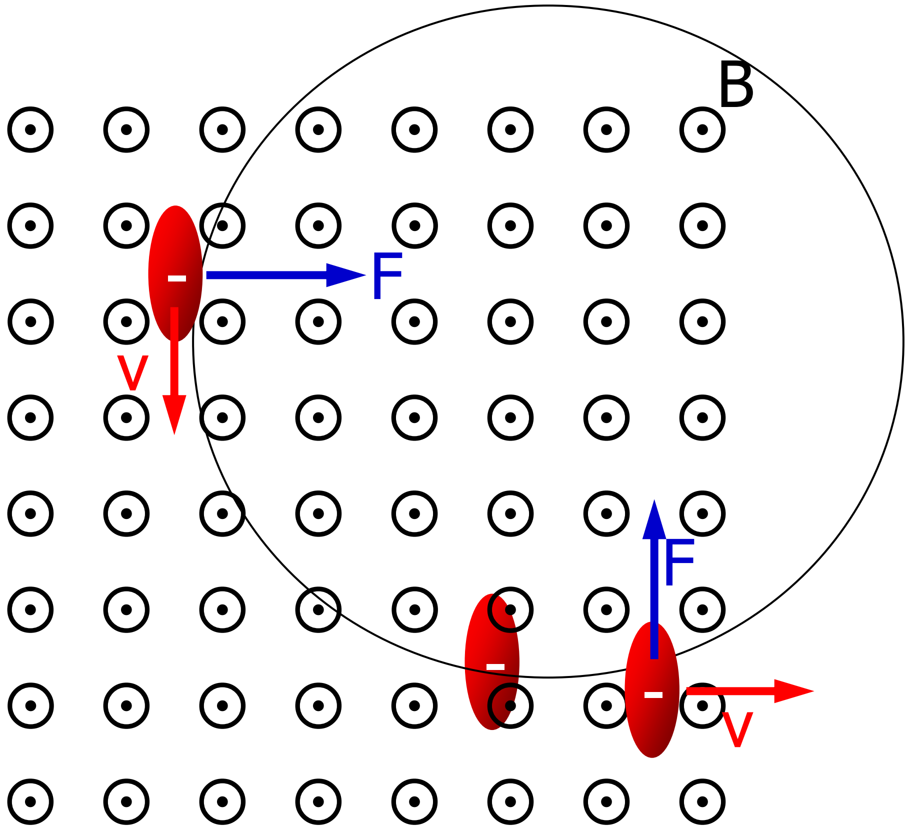




For negative charge and opposite direction of the magnetic field. What would you expect about the direction of circular path??

Example: an electron travels at $2x10^7$ m/s in a plane perpendicular to a 0.01 T magnetic field. Describe its path.

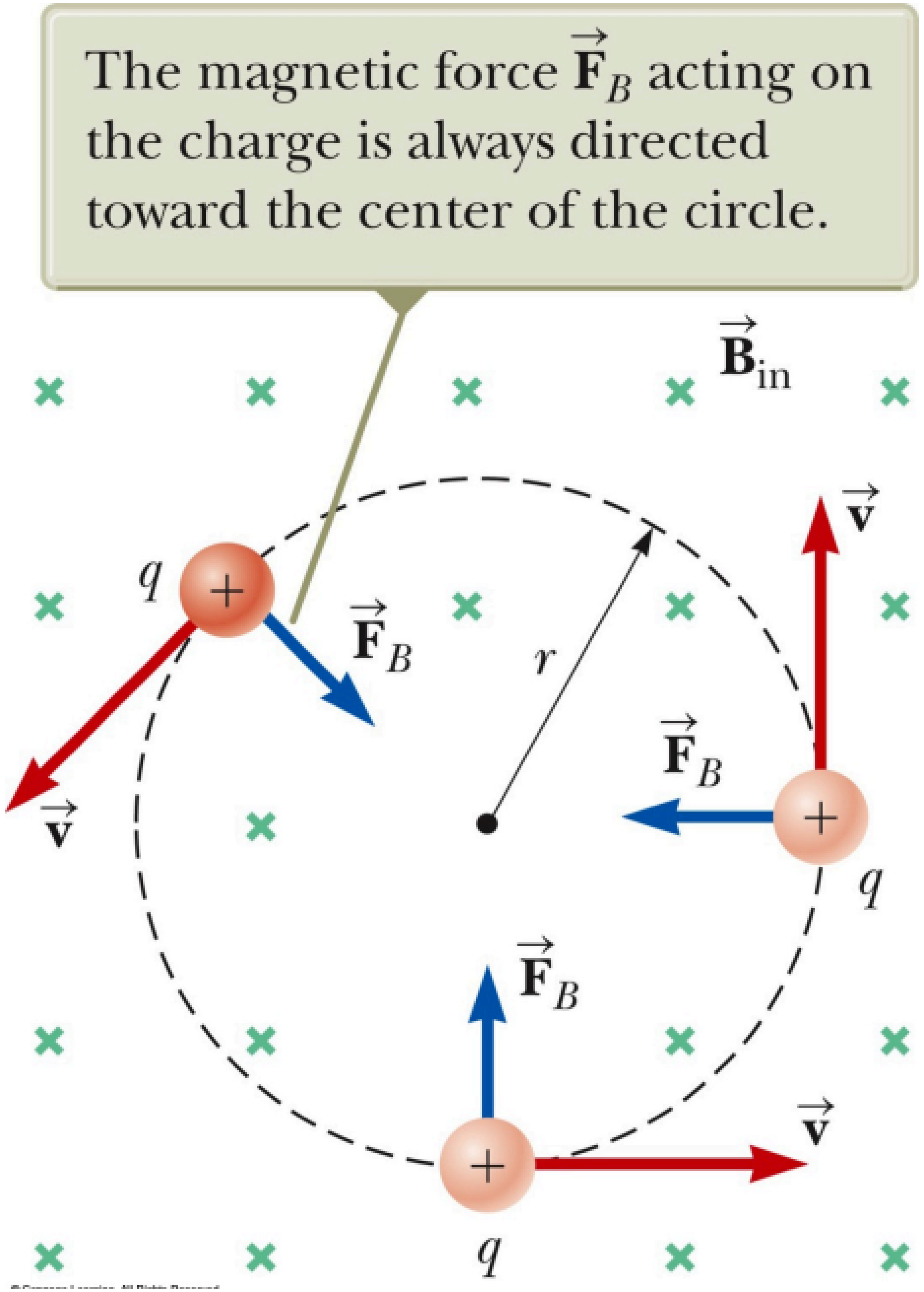
The force on the electron (remember, its charge is -) is always perpendicular to the velocity. If $\vec{v}$ and $\vec{B}$ are constant, then $\vec{F}$ remains constant (in magnitude).



The electron will move in a circular path with a constant speed and acceleration = v^2/r, where r is the radius of the circle.

http://labman.phys.utk.edu/3D%20Physics/spiral/spiral.html

Charged Particle in a uniform Magnetic Field



- Take a particle moving in a B field with a velocity v perpendicular to the field
- The magnetic force causes a **centripetal acceleration**, changing the direction of the velocity of the particle.

F = ma   gives :

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

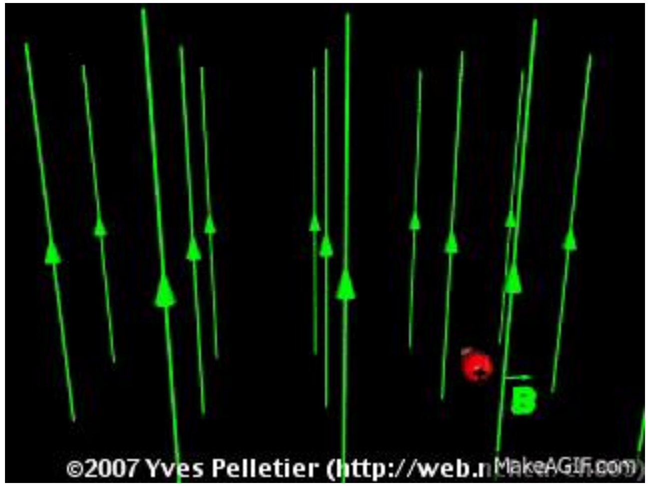
$$\boxed{r = \frac{mv}{qB} \qquad \omega = \frac{v}{r} = \frac{qB}{m} \qquad T = \frac{2\pi r}{v} = \frac{2\pi}{\omega} = \frac{2\pi m}{qB}}$$

ω = angular speed T = period.

$$\begin{aligned} \therefore \quad F_B &= m\frac{v^2}{r} \\ |q|\,vB &= m\frac{v^2}{r} \\ \therefore \quad r &= \frac{mv}{|q|B} \end{aligned}$$

centripetal force

where r is radius of circular motion.



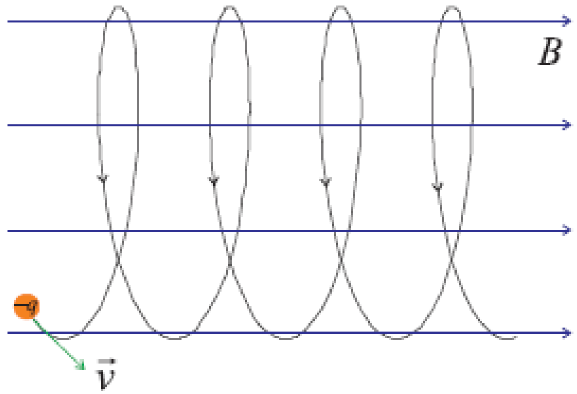
Time for moving around one orbit:

$$\boxed{T = \frac{2\pi r}{v} = \frac{2\pi m}{qB}}$$

Cyclotron Period

(1) Independent of v (non-relativistic)

(2) Use it to measure m/q



Generally, charged particles with constant velocity moves in **helix** in the presence of constant B-field.

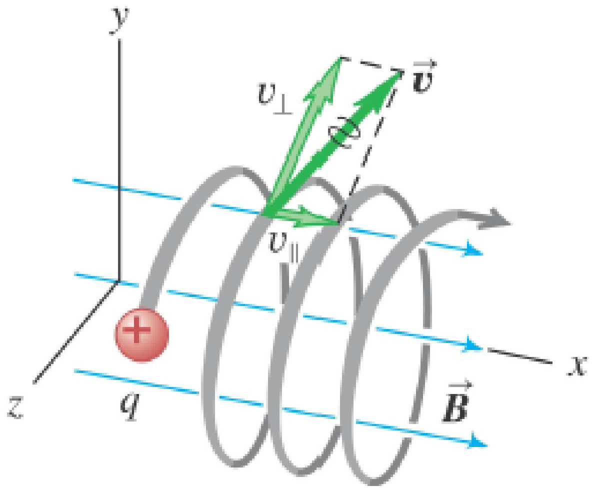
Cyclotron frequency

Angular speed: $\omega = v/R$ → $\boxed{\omega = v\frac{|q|B}{mv} = \frac{|q|B}{m}}$

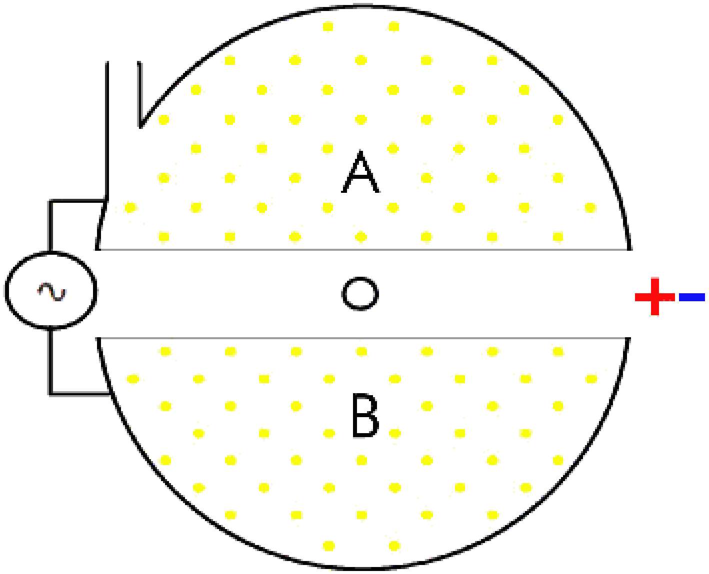
Cyclotron frequency: $f = \omega/2\pi$

- If v is not perpendicular to B → $v_{//}$ (parallel to B) constant because $F_{//} = 0$ → particle moves in a helix. (R same as before, with $v = v_\perp$).

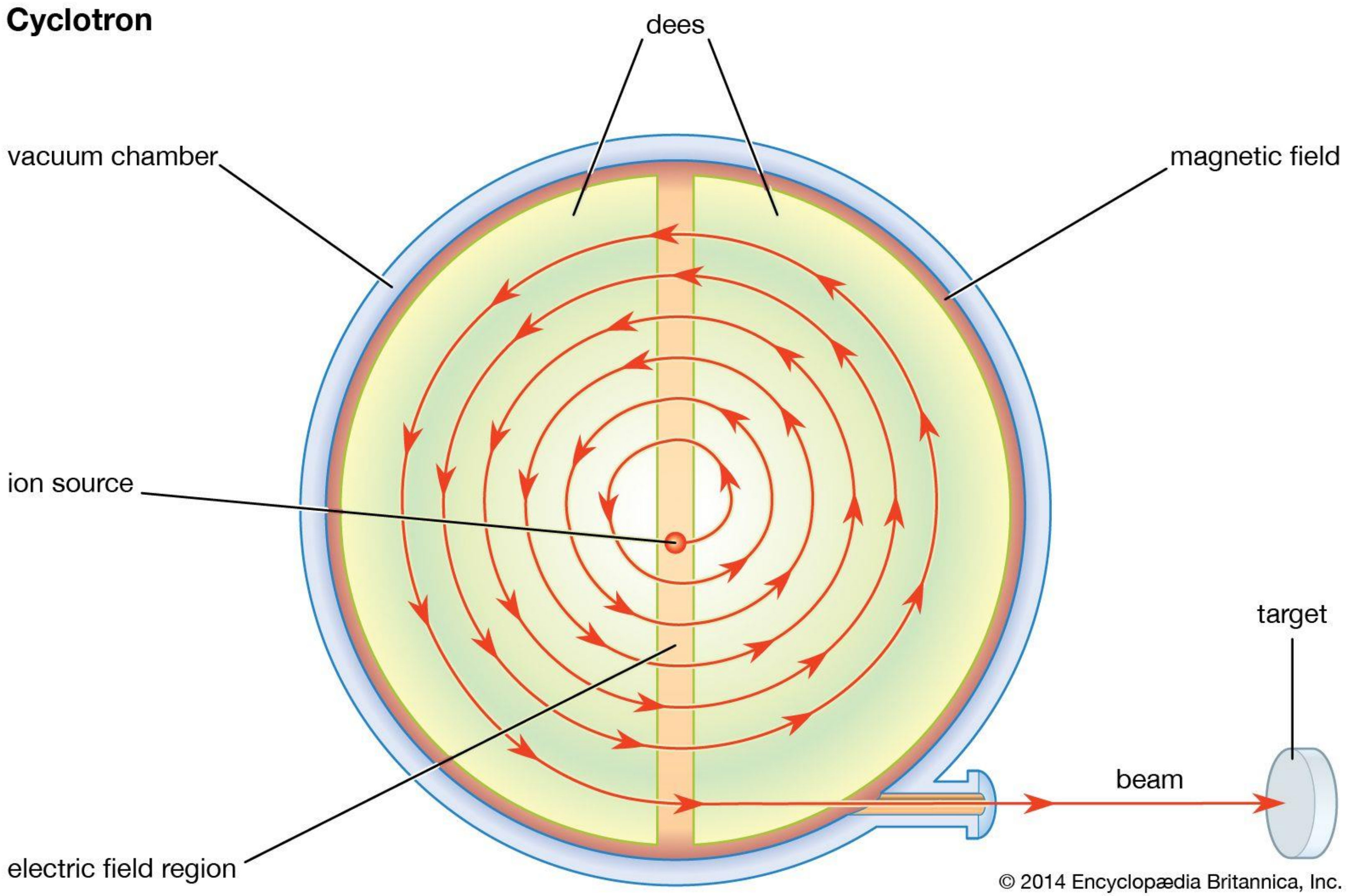
This particle's motion has components both parallel ($v_\parallel$) and perpendicular ($v_\perp$) to the magnetic field, so it moves in a helical path.



A charged particle will move in a plane perpendicular to the magnetic field.



http://physics.bu.edu/~duffy/HTML5/cyclotron.html



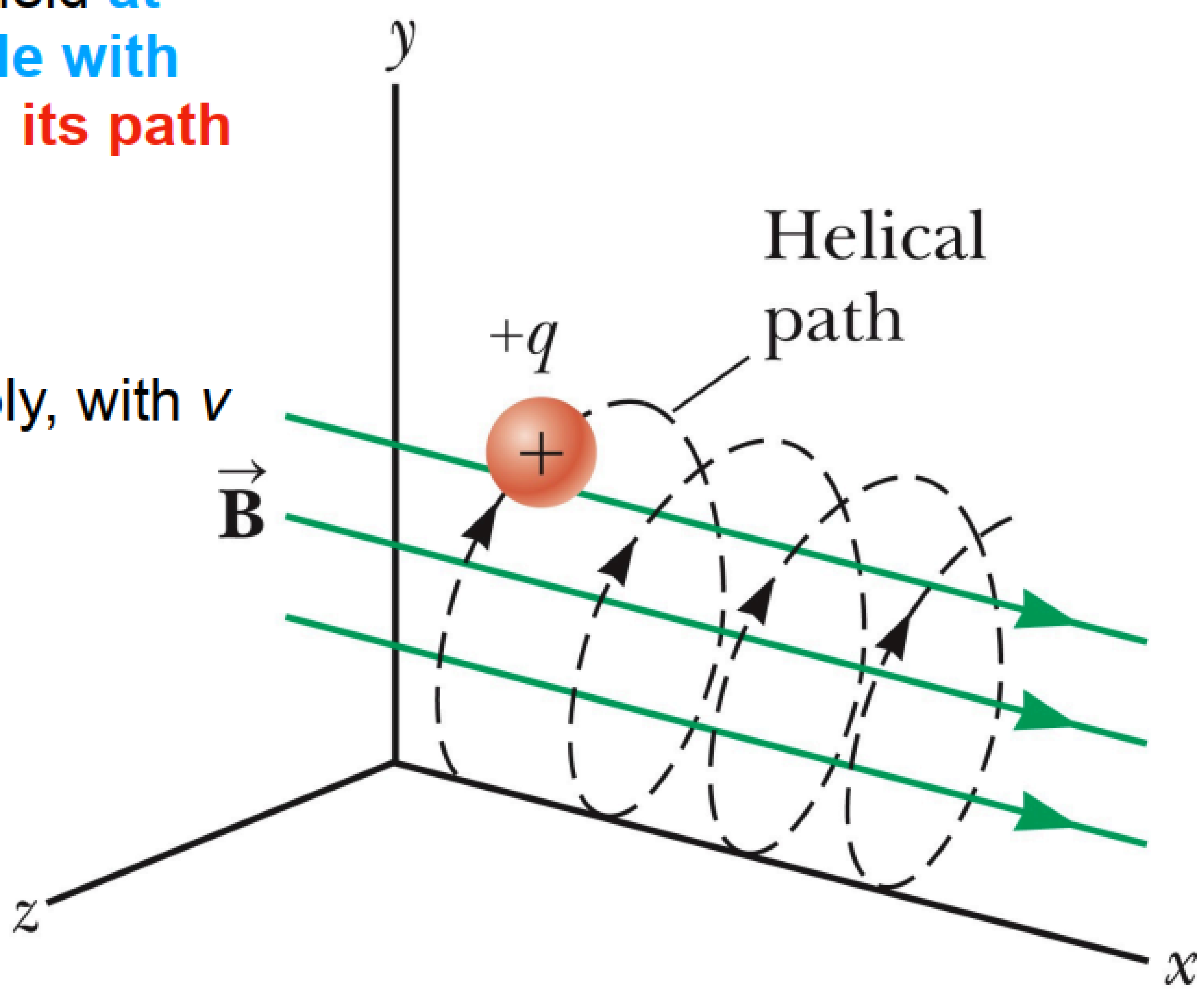
Cyclotrons are widely used to **accelerate charged particles in nuclear physics experiments and use them to bombard atomic nuclei**. For radiation therapy in the treatment of cancer, different cyclotrons are used. Cyclotrons can be used for nuclear transmutation (change of the nuclear structure).

Motion of a Particle, General

If a charged particle moves in a uniform magnetic field **at some arbitrary angle with respect to the field**, **its path is a helix.**

Same equations apply, with *v* replaced by

$$v_\perp = \sqrt{v_y^2 + v_z^2}$$

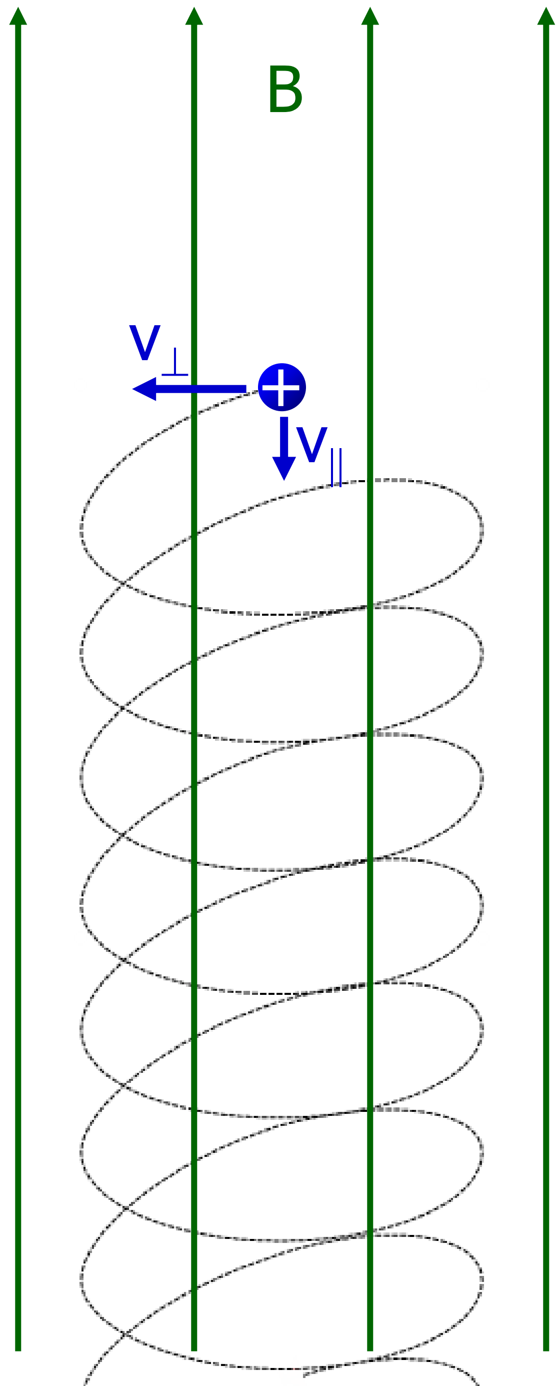


Helical motion in a uniform magnetic field

If $\vec{v}$ and $\vec{B}$ are perpendicular, a charged particle travels in a circular path. v remains constant but the direction of $\vec{v}$ constantly changes.

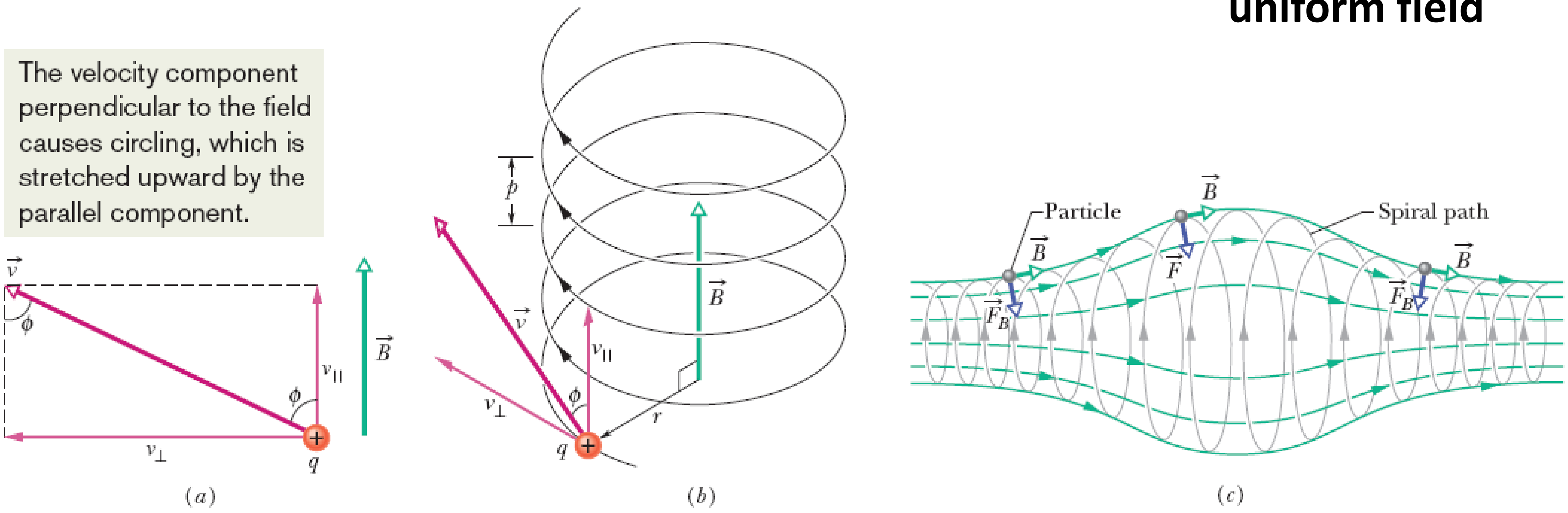
If $\vec{v}$ has a component parallel to $\vec{B}$, then $v_{\|}$ remains constant, and the charged particle moves in a helical path.

*or antiparallel



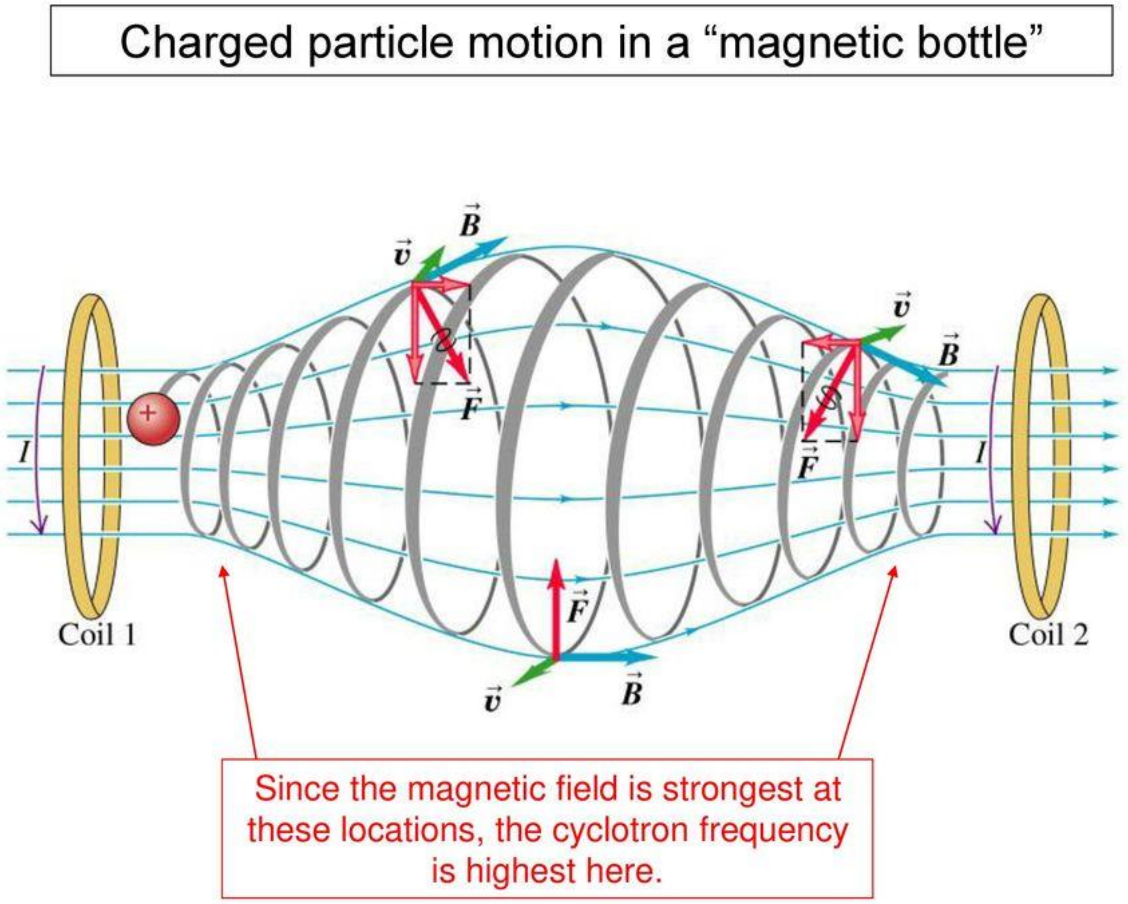
Helical path

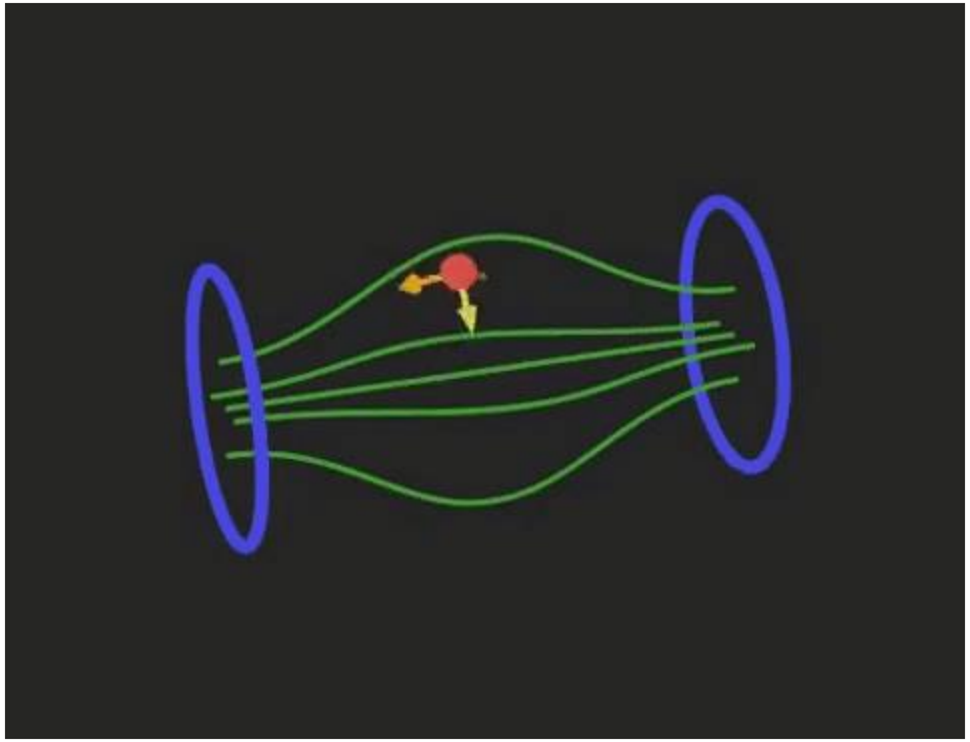
Spiraling path: Non uniform field



https://ophysics.com/em7.html

https://ophysics.com/em8.html





The motion is complex. For example, the particles can oscillate back and forth between two positions. This configuration is known as a ***magnetic bottle.***

https://www.youtube.com/watch?v=HGXk99frvYM

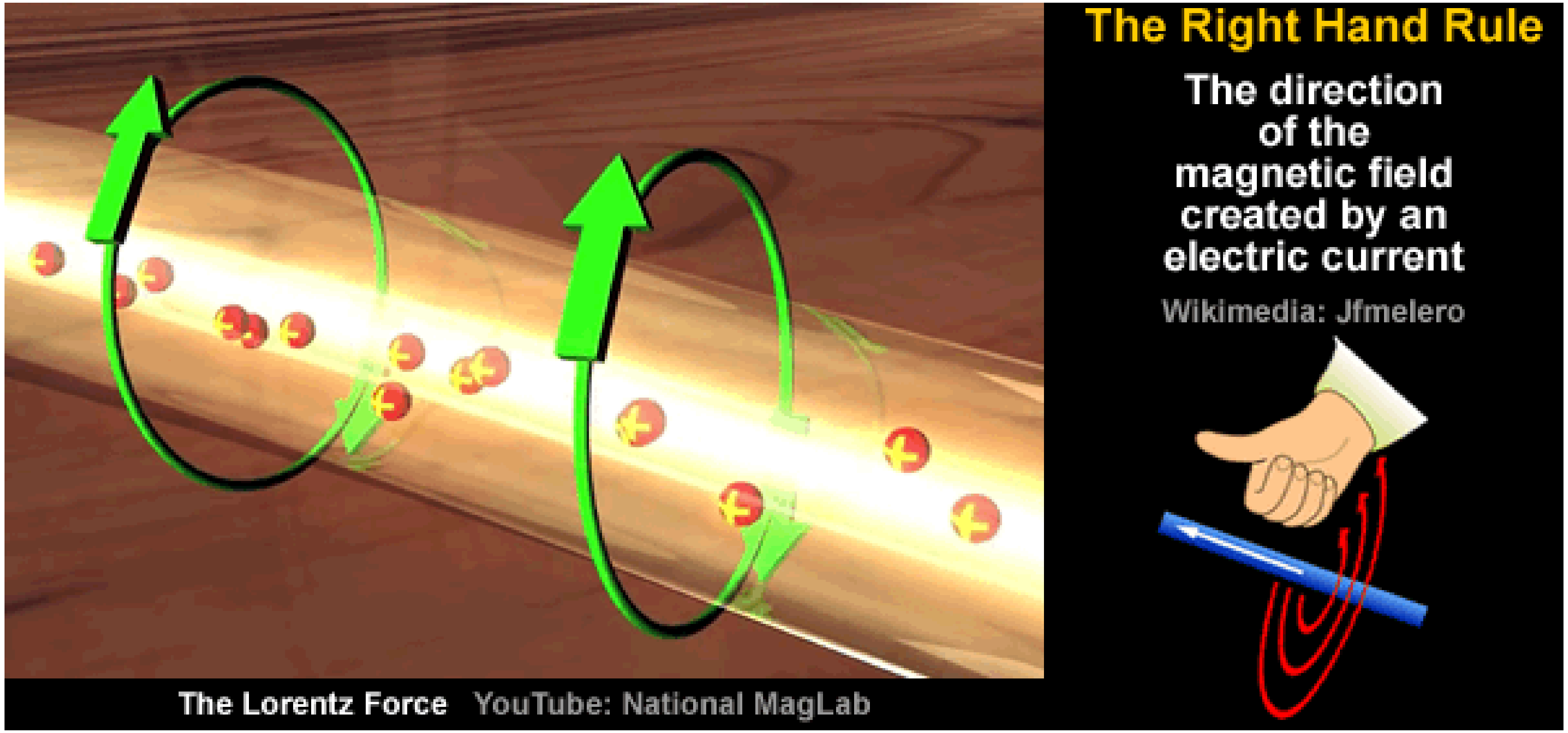
In a cyclotron, the potential difference between the plates oscillates with a period given by $T = \frac{2\pi m}{qB}$. Show that the expression to the right of the equal sign has units of seconds if *q*, *B* and *m* have units of coulombs, teslas and kilograms, respectively.

A ^{7}Li nucleus has a charge equal to +3*e* and a mass that is equal to the mass of seven protons. A ^{7}Li nucleus and a proton are both moving perpendicular to a uniform magnetic field. The magnitude of the momentum of the proton is equal to the magnitude of the momentum of the nucleus.
Find the ratios of the path of radius of curvature R^{p} and R^{Li}.

Crossed Fields: Discovery of the Electron

We can combine what we learned about the electric force to that we just learned about the magnetic force into one equation, the **Lorentz force equation**:

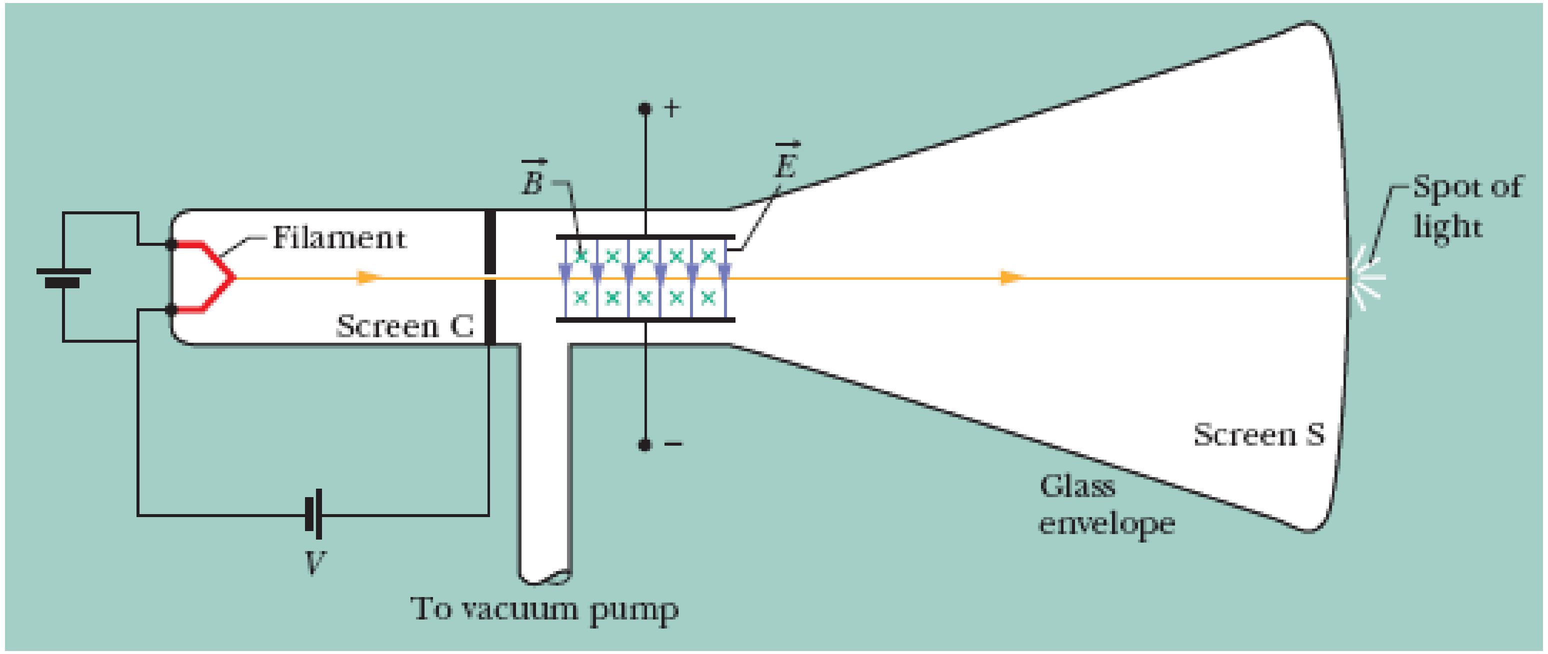
$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} = q(\vec{E} + \vec{v} \times \vec{B})$$



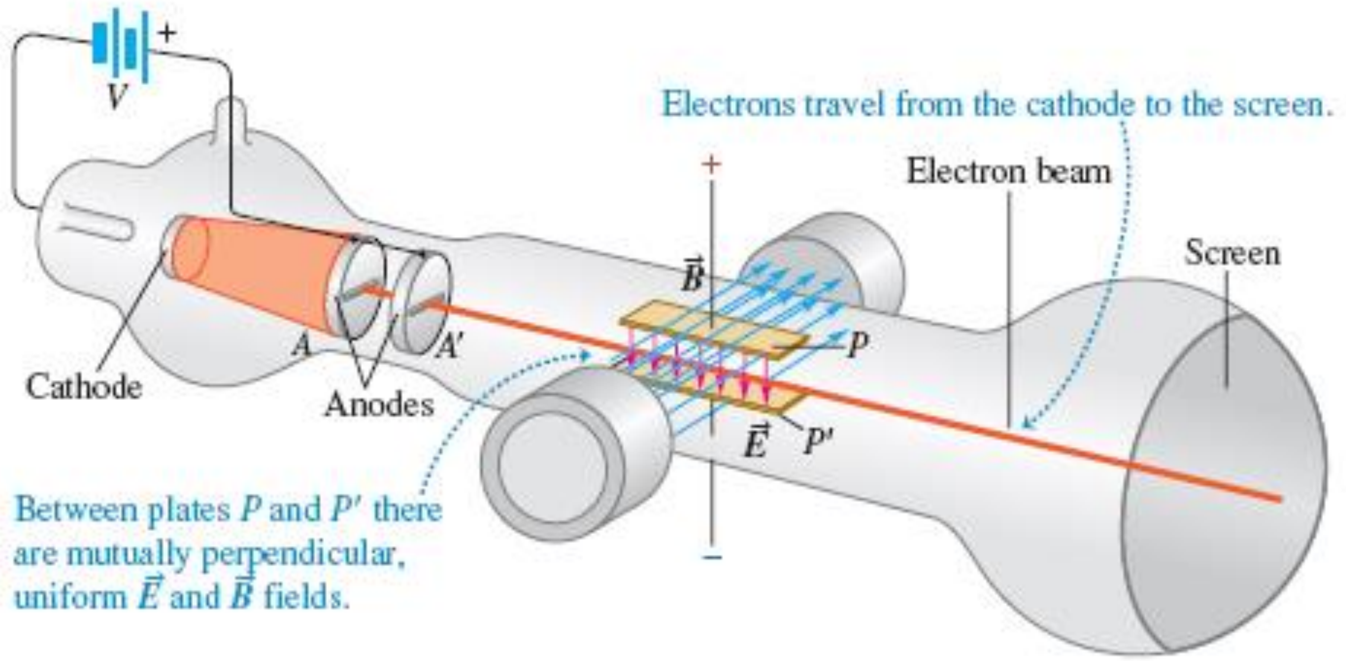
Crossed Fields: Discovery of the Electron

We can apply this to some historical work done by J.J. Thompson, who determined that the carrier of electricity was an electrically charged particle dubbed the "electron."

Figure 28-7 A modern version of J. J. Thomson's apparatus for measuring the ratio of mass to charge for the electron. An electric field $\vec{E}$ is established by connecting a battery across the deflecting-plate terminals. The magnetic field $\vec{B}$ is set up by means of a current in a system of coils (not shown). The magnetic field shown is into the plane of the figure, as represented by the array of Xs (which resemble the feathered ends of arrows).



Crossed Fields: Discovery of the Electron



The most significant aspect of Thomson’s measurements was that he found a *single value e/m* for this quantity. It did not depend on the cathode material, the residual gas in the tube, or anything else about the experiment.

This independence showed that the particles in the beam, which we now call electrons, are a common constituent of all matter. Thus Thomson is credited with the first discovery of a subatomic particle, the electron.

https://javalab.org/en/crt_en/

Thomson's *e/m* Experiment

$\Delta E = \Delta K + \Delta U = 0 \rightarrow 0.5\ m\ v^2 = U = e\ V$

$$v = \frac{E}{B} = \sqrt{\frac{2eV}{m}}$$

$$\boxed{\frac{e}{m} = \frac{E^2}{2VB^2}}$$

e/m does not depend on the cathode material or residual gas on tube → particles in the beam (electrons) are a common constituent of all matter.

Velocity selector

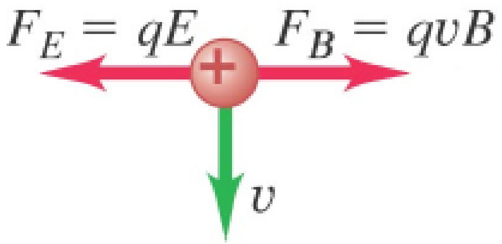
- Particles of a specific speed can be selected from the beam using an arrangement of E and B fields.

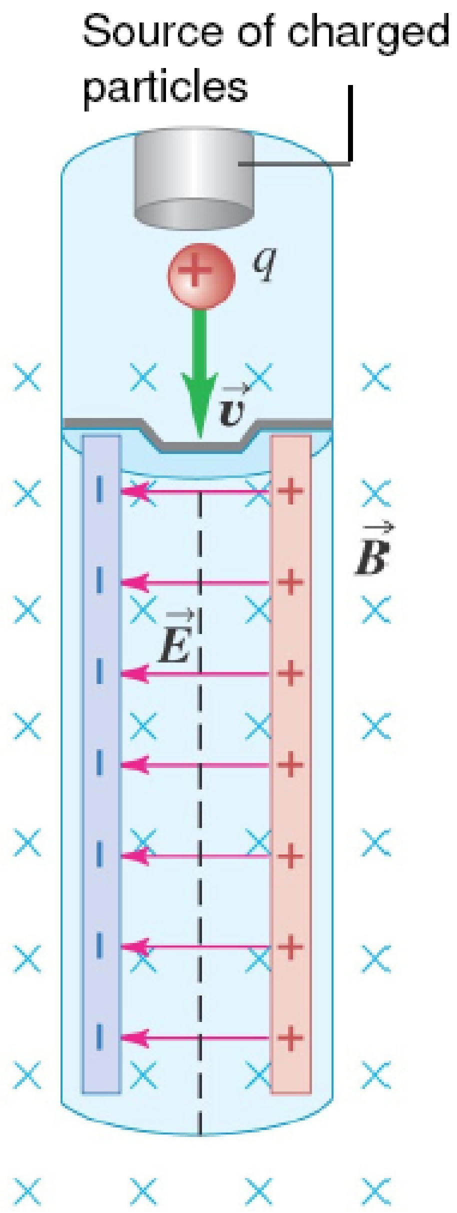
- F_m (magnetic) for + charge towards right (q v B).

- F_E (electric) for + charge to left (q E).

- $F_{net} = 0$ if $F_m = F_E \rightarrow -qE + q\,v\,B = 0 \rightarrow \boxed{v = E/B}$

- Only particles with speed E/B can pass through without being deflected by the fields.



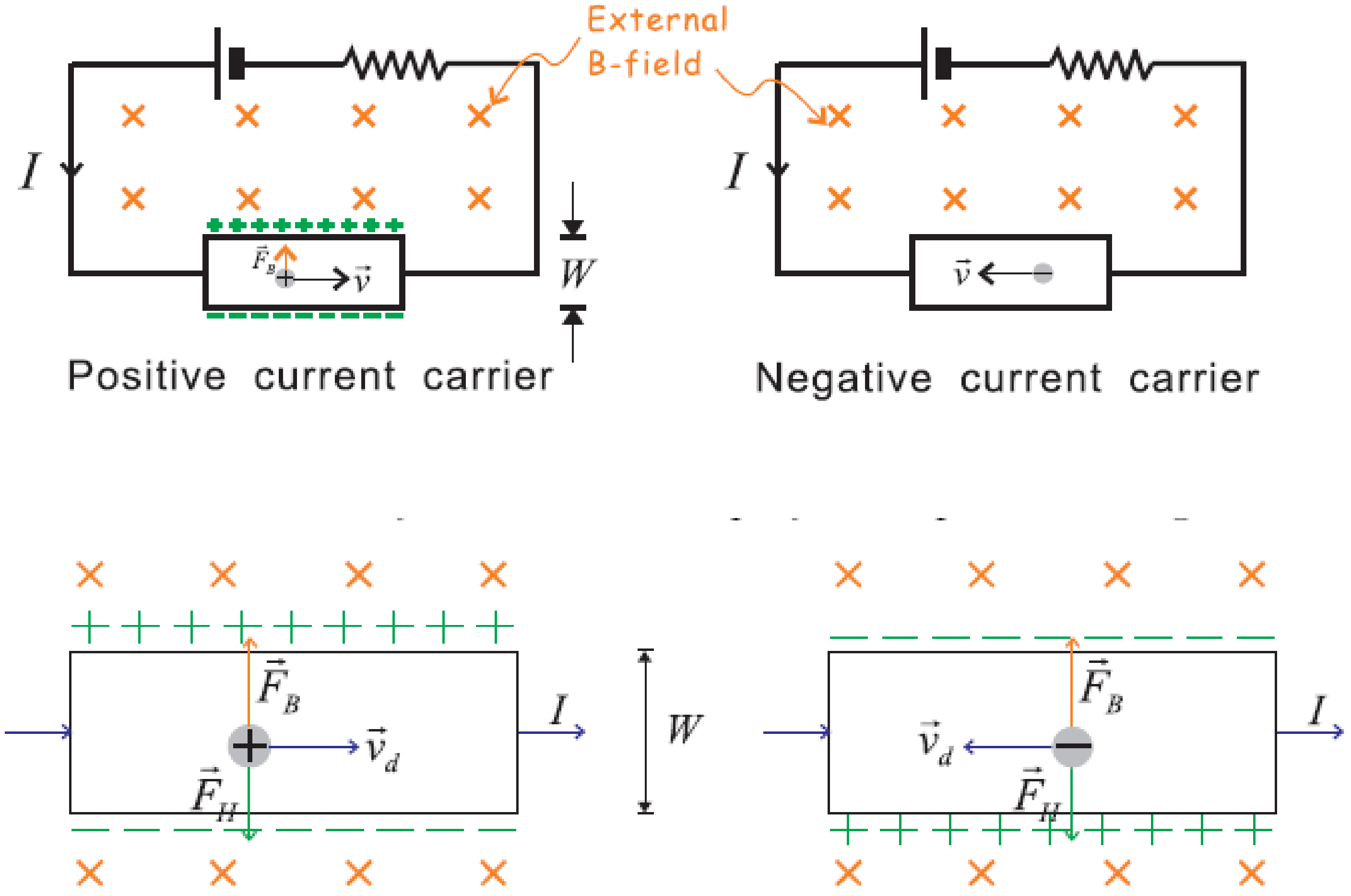


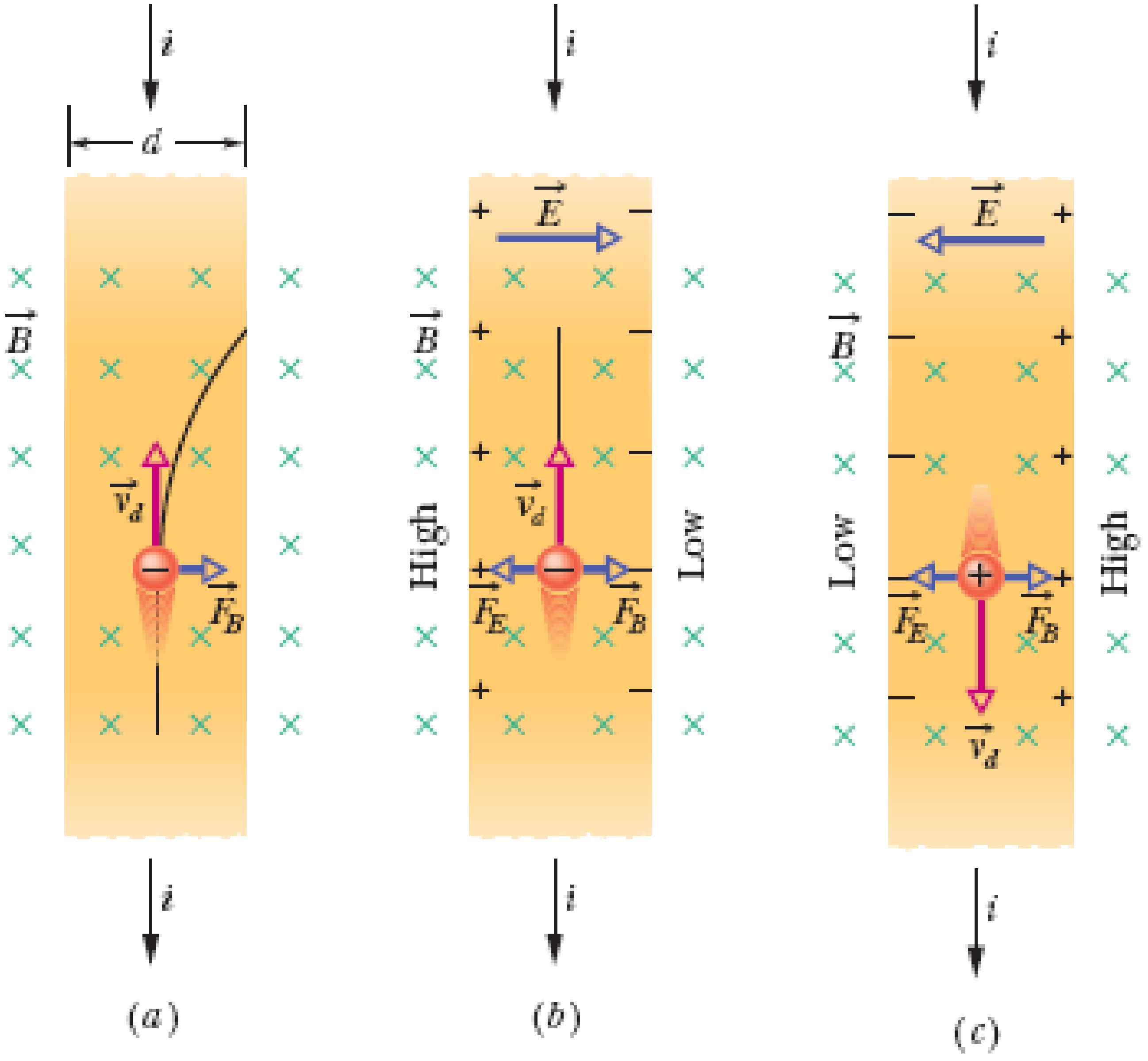
http://physics.bu.edu/~duffy/HTML5/mass_spectrometer.html

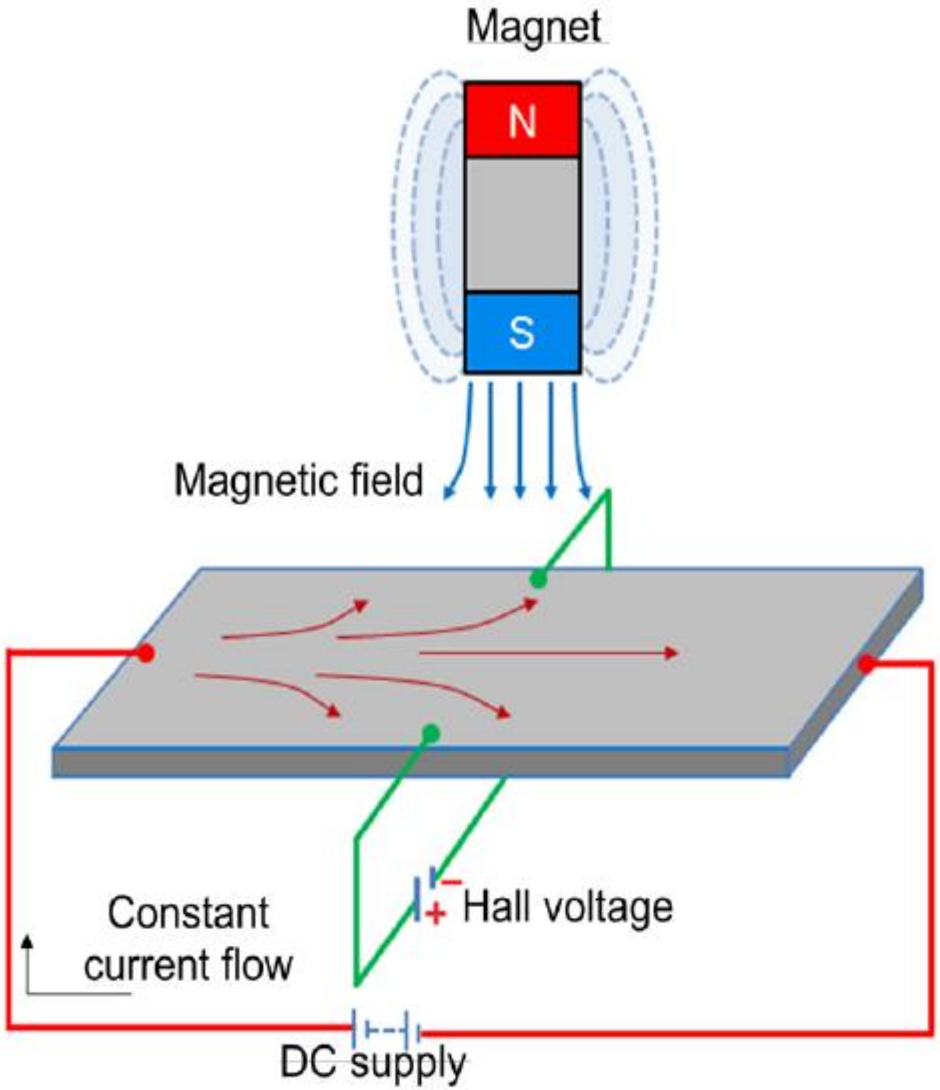
In a velocity selector, the speed of the undeflected charged particle is given by the ratio of the magnitude of the electric field to the magnitude of the magnetic field. Show that E/B in fact does have the units of m/s if E and B are in units of volts per meter and teslas, respectively.

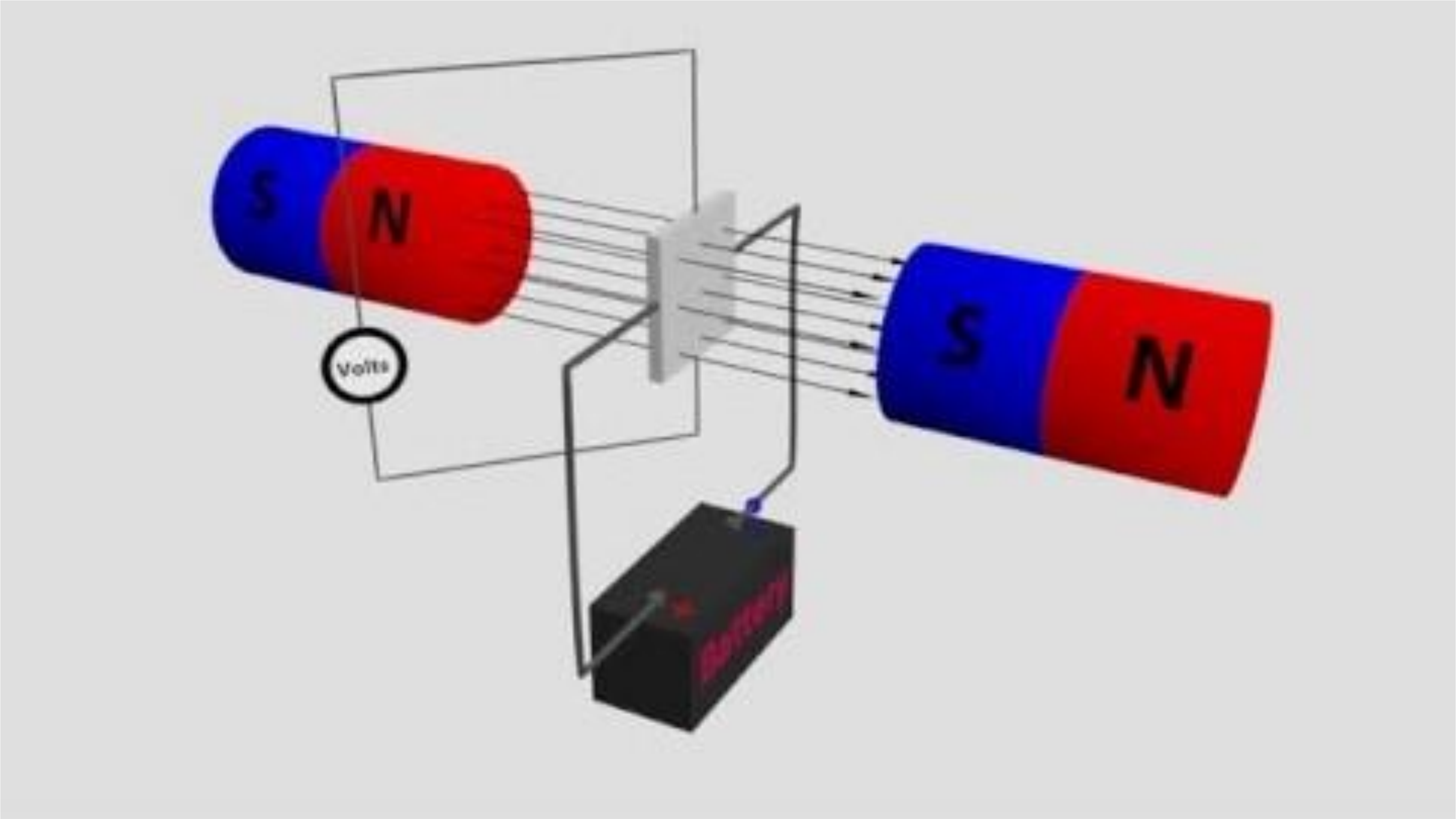
Crossed Fields: The Hall Effect

Charges travelling in a conducting wire will be *pushed to one side of the wire by the external magnetic field*. This separation of charge in the wire is called the Hall Effect.




i
d
B
v_d
F_B
E
F_E
High
Low
(a)
(b)
(c)


Magnet
N
S
Magnetic field
Constant
current flow
Hall voltage
DC supply



https://www.youtube.com/watch?v=Scpi91e1JKc

A *Hall potential difference V* is associated with the electric field across strip width *d*.
From electric potential definition, the magnitude of that potential difference is

$V = Ed$,where *d* is the width of the conducting strip

In equilibrium net force is zero, $\boldsymbol{q\vec{E} + q\vec{v}_d \times \vec{B} = 0}$

Considering the magnitudes, $\boldsymbol{\frac{V}{d} = v_d B}$

From definition of current, with density of charge carrier ***n***

$\boldsymbol{i = nqAv_d}$ **or** $\boldsymbol{v_d = \frac{\mathrm{i}}{\mathrm{nqA}} = \frac{\mathrm{i}}{\mathrm{nqtd}}}$ where t is the thickness

Then we can write, $\boldsymbol{\frac{V}{d} = \frac{i}{nqtd} B}$ **or** $\boldsymbol{V = \frac{i}{nqt} B}$

Charge density, $\boldsymbol{n = \frac{\mathrm{i}}{\mathrm{qt}V} B}$

Magnetic field, $\boldsymbol{B = \frac{nqt}{i} V}$

Applications of Hall Effect

- Calculation of carrier concentration
- Determination of semiconductor type
- Smart phones are equipped with magnetic compass