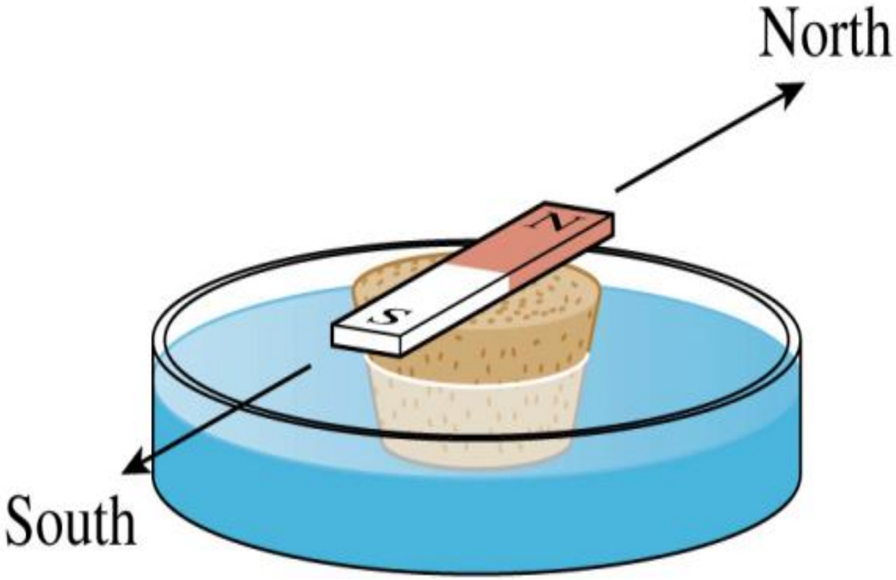
General Physics II

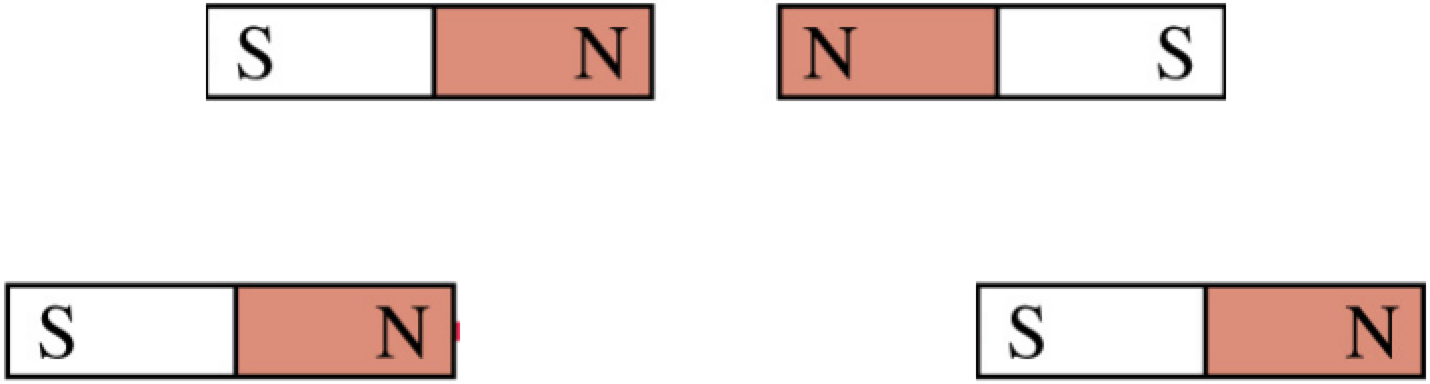
Lecture 10: Magnetic Fields and Forces

Experiments with Magnetism: Experiment 1

- Tape a bar magnet to a cork and allow it to float in a dish of water.
- The magnet turns and aligns itself with the north-south direction.
- The end of the magnet that points north is called the magnet's north-seeking pole, or simply its north pole. The other end is the south pole.



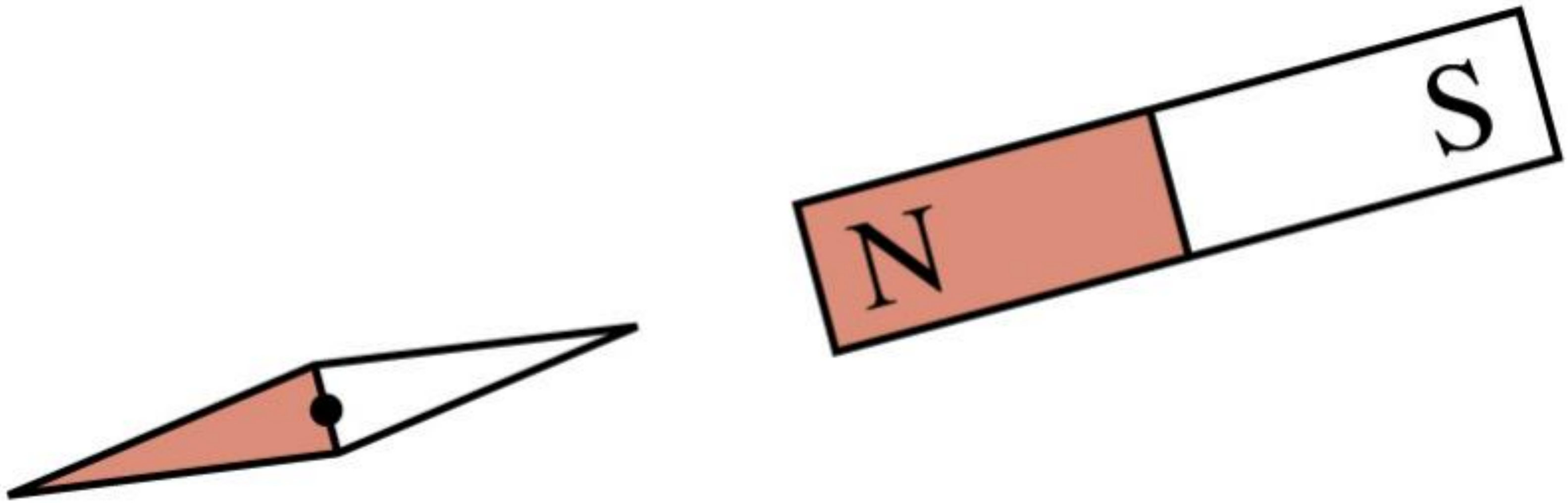
Experiments with Magnetism: Experiment 2



• Bring the north poles of two bar magnets near to each other. Then bring the north pole of one bar magnet near the south pole of another bar magnet.

• When the two north poles are brought near, a repulsive force between them is observed. When the a north and a south pole arebrought near, an attractive force between them is observed.

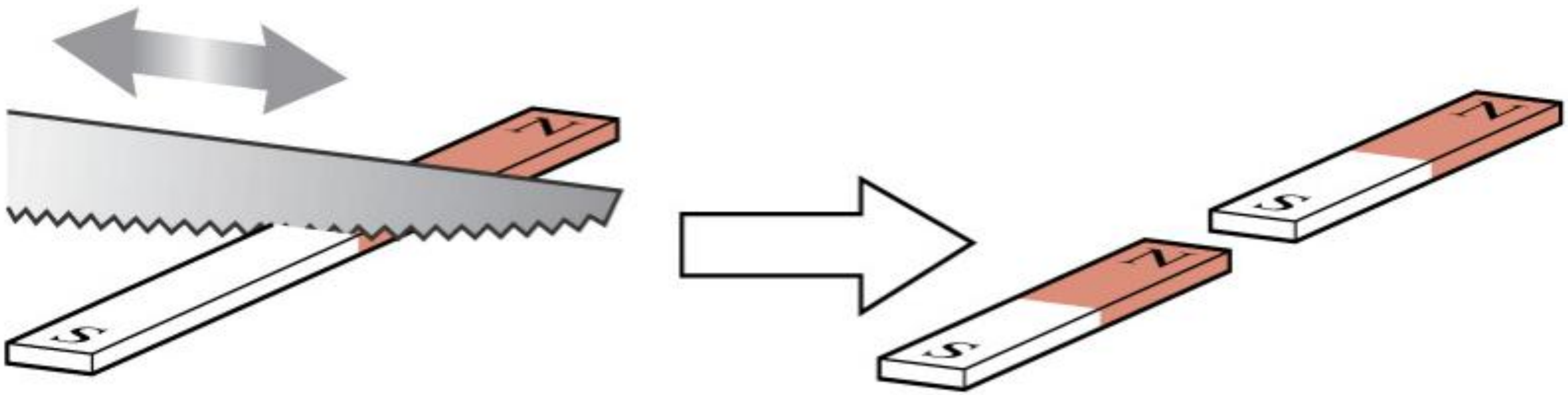
Experiments with Magnetism: Experiment 3



• Bring the north pole of a bar magnet near a compass needle.

• When the north pole is brought near, the north-seeking pole of the compass needle points away from the magnet's north pole. Apparently the compass needle is itself a little bar magnet.

Experiments with Magnetism: Experiment 1



• Use a hacksaw to cut a bar magnet in half. Can you isolate the north pole and the south pole on separate pieces?

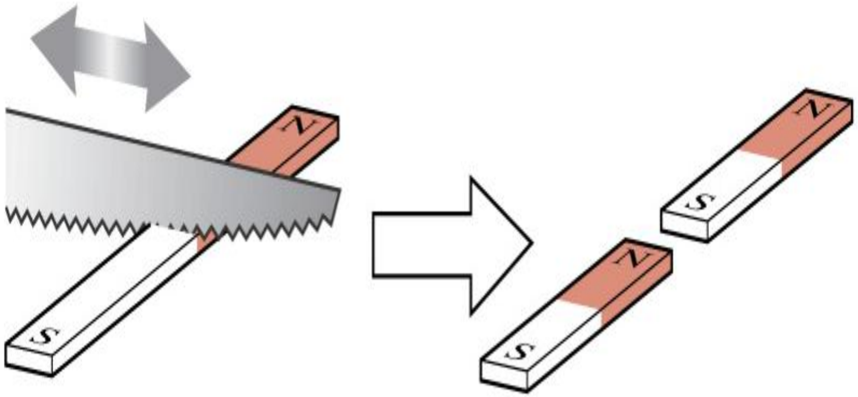
• No. When the bar is cut in half two new (but weaker) bar magnets are formed, each with a north pole and a south pole. The same result would be found, even if the magnet was sub-divided down to the microscopic level.

Monopoles and Dipoles

• Every magnet that has ever been observed is a magnetic dipole, containing separated north and south poles. Attempts to isolate one pole from the other fail.

• It is theoretically possible to have magnetic monopoles, i.e., isolated magnetic poles with a "north" or "south" magnetic charge. Search have been conducted, but no such object has ever been found in nature.

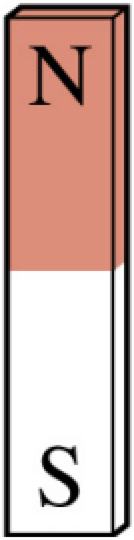
• For the purposes of this course, we will assume that isolated magnetic monopoles do not exist, but we will point out the places in the formalism where they would go if they did exist.



Experiments with Magnetism: Experiment 5

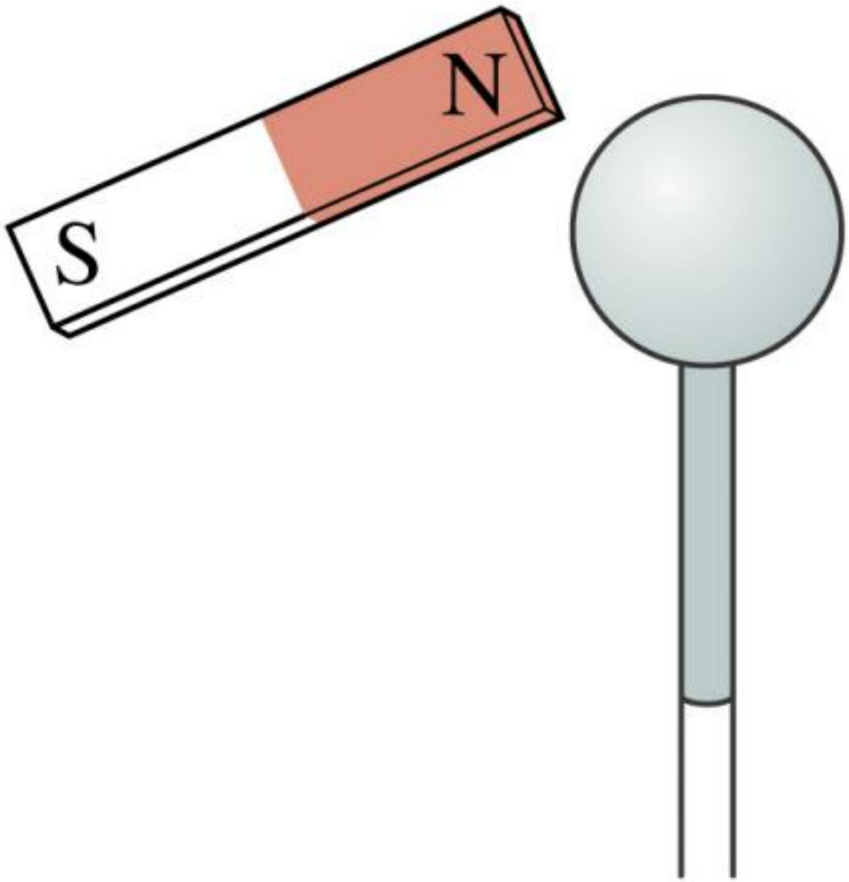
• Bring a bar magnet near an assortment of objects.

• Some of the objects, e.g. paper clips, will be attracted to the magnet. Other objects, e.g., glass beads, aluminum foil, copper tacks, will be unaffected. The objects that are attracted to the magnet are equally attracted by the north and south poles of the bar magnet



Experiments with Magnetism: Experiment 1

- Bring a magnet near the electrode of an electroscope.
- There is no observed effect, whether the electroscope is charged or discharged and whether the north or the south pole of the magnet is used.



Conclusions from Experiments

1. Magnetism is not the same as electricity. Magnetic poles are similar to charges but have important differences.

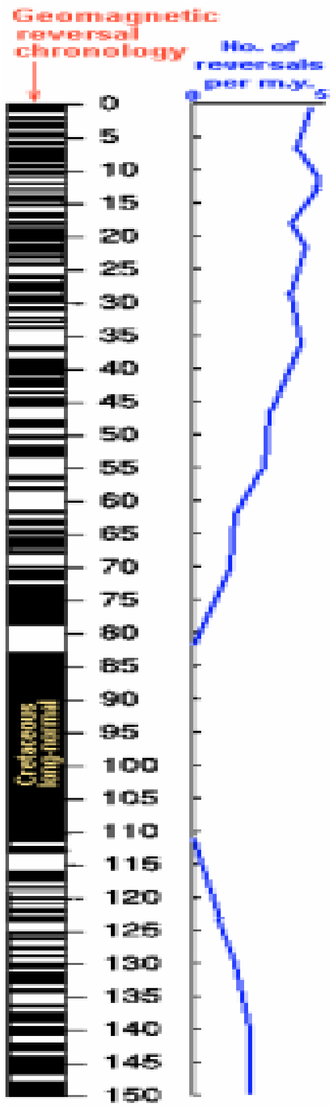
2. Magnetism is a long range force. The compass needle responds to the bar magnet from some distance away.

3. Magnets have two poles, north and south. Like poles repel and opposite poles attract.

4. Poles of a magnet can be identified with a compass. A north magnet pole attracts the south-seeking end of the compass needle (which is a south pole).

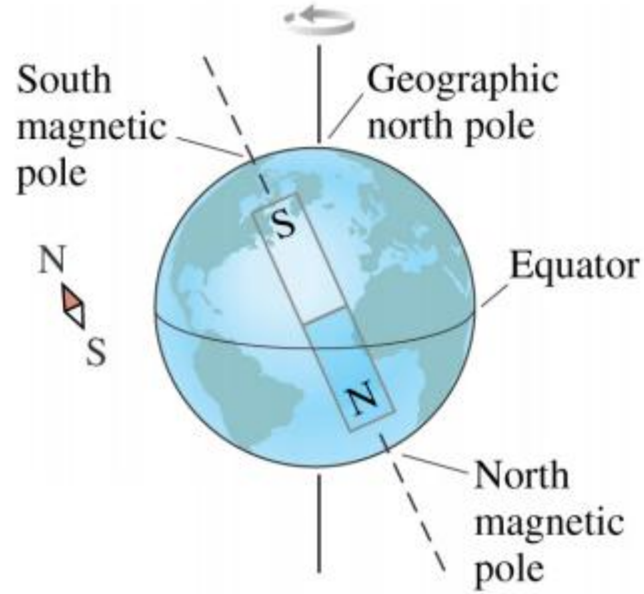
5. Some materials stick to magnets and others do not. The materials that are attracted are called magnetic materials. Magnetic materials are attracted by either pole of a magnet. This is similar in some ways to the attraction of neutral objects by an electrically charged rod.

Compasses and Geomagnetism



• The north pole of a compass needle is attracted to the geographical north pole of the Earth and repelled by its geographic south pole.

• Apparently, the Earth is a large magnet, and one with a magnetic south pole near the Earth's geographic north pole.



• The reasons for the Earth's magnetism are complex, involving standing currents in the Earth's molten interior. The Earth's magnetic poles are separated somewhat from the geographic poles, and move around some as a function of time.

• There is evidence in the geological record that the Earth's field has reversed directions at varying intervals spaced by millions of years. This is not well understood.

More About Magnetism

- An unmagnetized piece of iron can be magnetized by stroking it with a magnet
  - Somewhat like stroking an object to charge an object
- Magnetism can be induced
  - If a piece of iron, for example, is placed near a strong permanent magnet, it will become magnetized

Types of Magnetic Materials

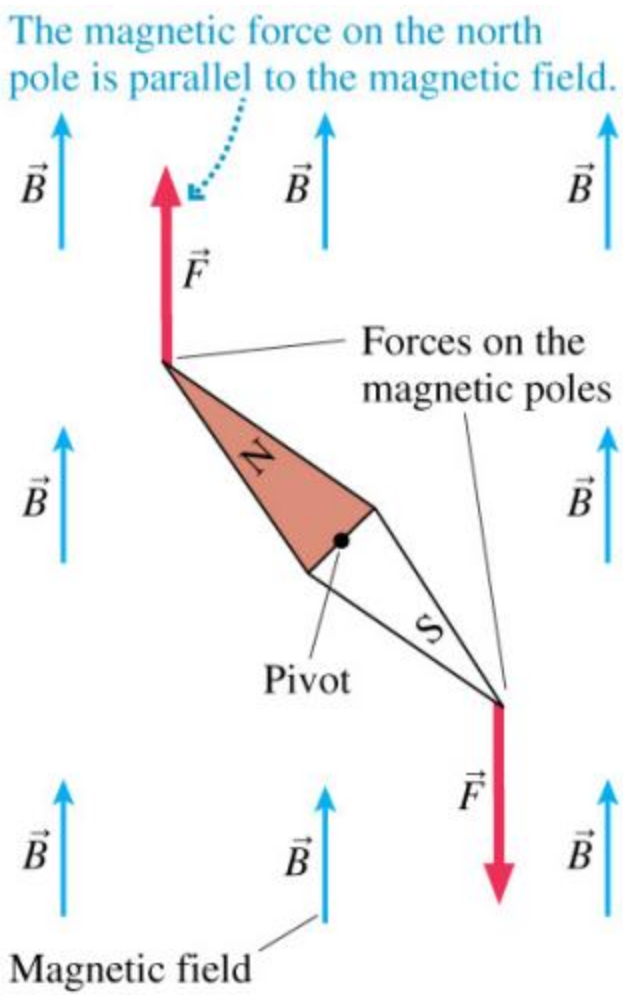
- Soft magnetic materials, such as iron, are easily magnetized
  - They also tend to lose their magnetism easily
- Hard magnetic materials, such as cobalt and nickel, are difficult to magnetize
  - They tend to retain their magnetism

Magnetic Fields

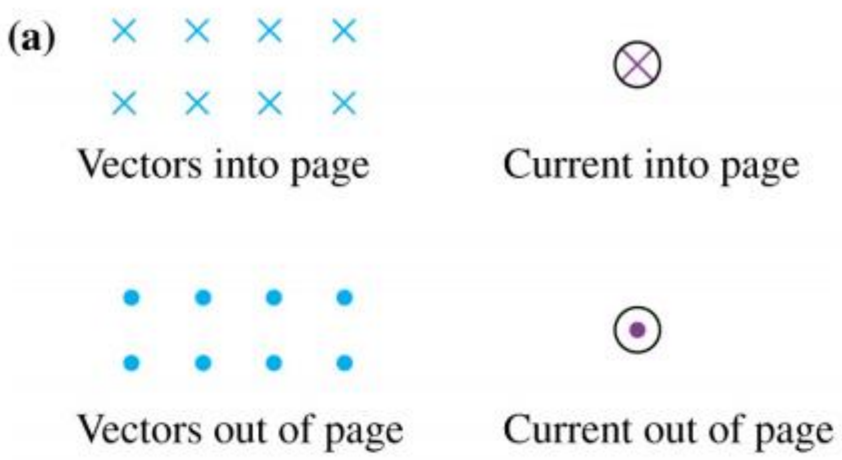
- A vector quantity
- Symbolized by B
- Direction is given by the direction a north pole of a compass needle points in that location
- Magnetic field lines can be used to show how the field lines, as traced out by a compass, would look

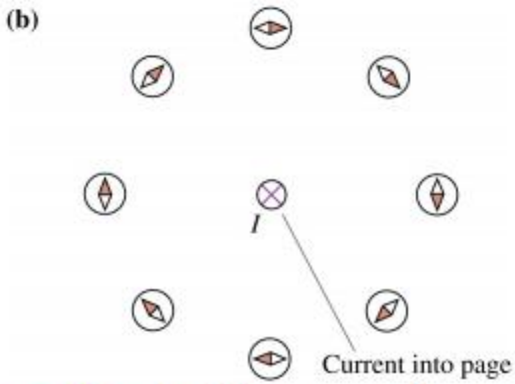
- Definition of the magnetic field:

1. The magnetic field at each point is a vector, with both a magnitude, which we call the magnetic field strength B, and a direction.
2. A magnetic field is created at all points in the space surrounding a current carrying wire.
3. The magnetic field exerts a force on magnetic poles. The force on a north pole is parallel to B, and the force on a south pole is antiparallel to B.



Vector Conventions





Example: field around a current.

For discussions of magnetism, we will need a three-dimensional perspective. , but we will use two-dimensional diagrams when we can. To get the 3rd dimension into a two-dimensional diagram, we will indicate vectors into and out of a diagram by using crosses and dots, respectively.

Rule:

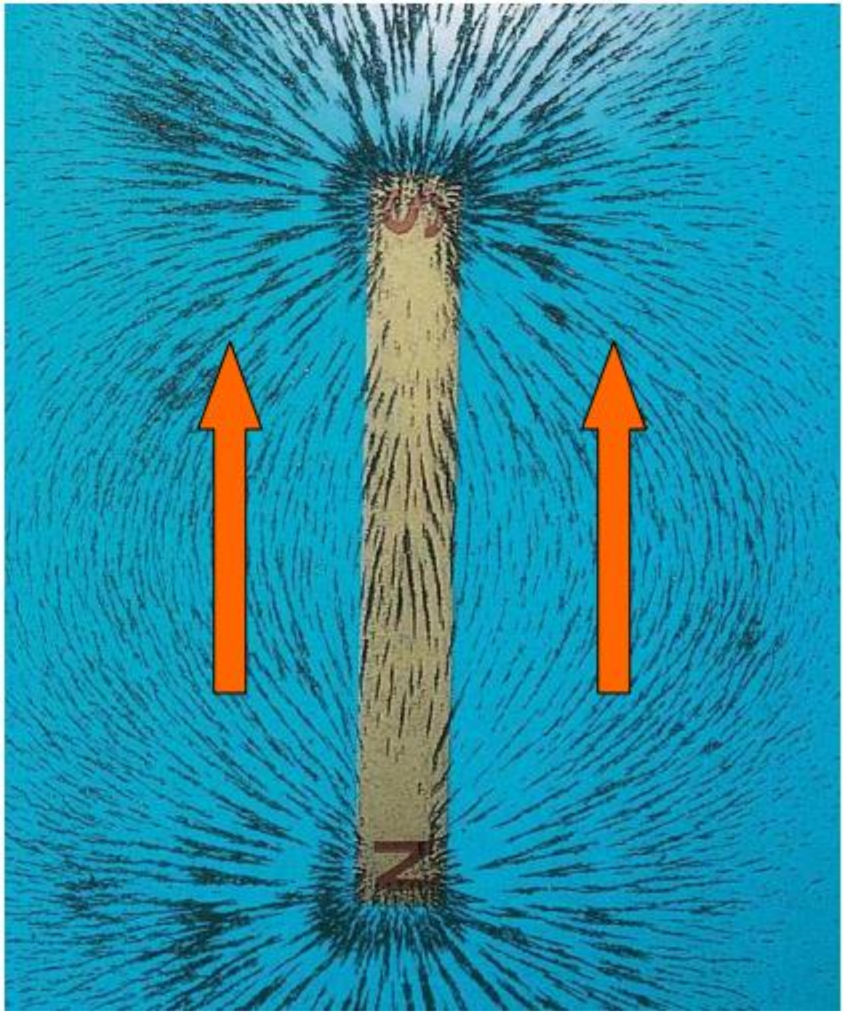
a dot (•) means you are looking at the point of an arrow coming toward you;

a cross (× ×× ×) means you are looking at the tail feathers of an arrow going away from you.

Magnetic Field Lines, Bar Magnet

• Iron filings are used to show the pattern of the electric field lines

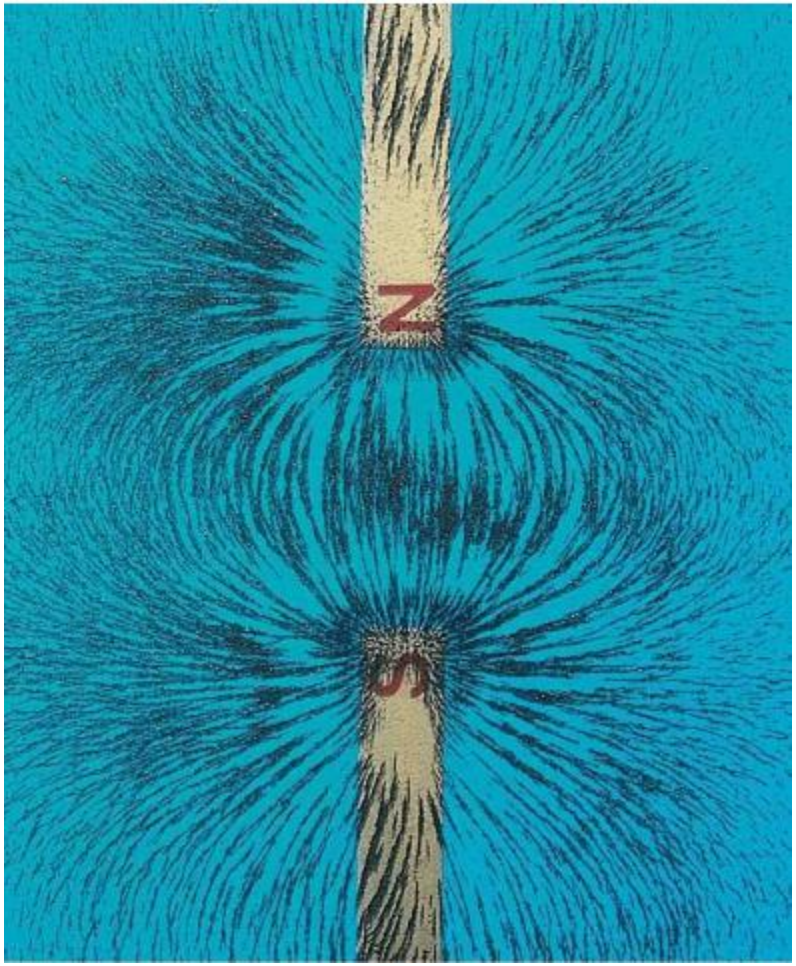
• The direction of the field is from the north to the south pole



Magnetic Field Lines, Unlike Poles

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

– Compare to the electric field produced by an electric dipole

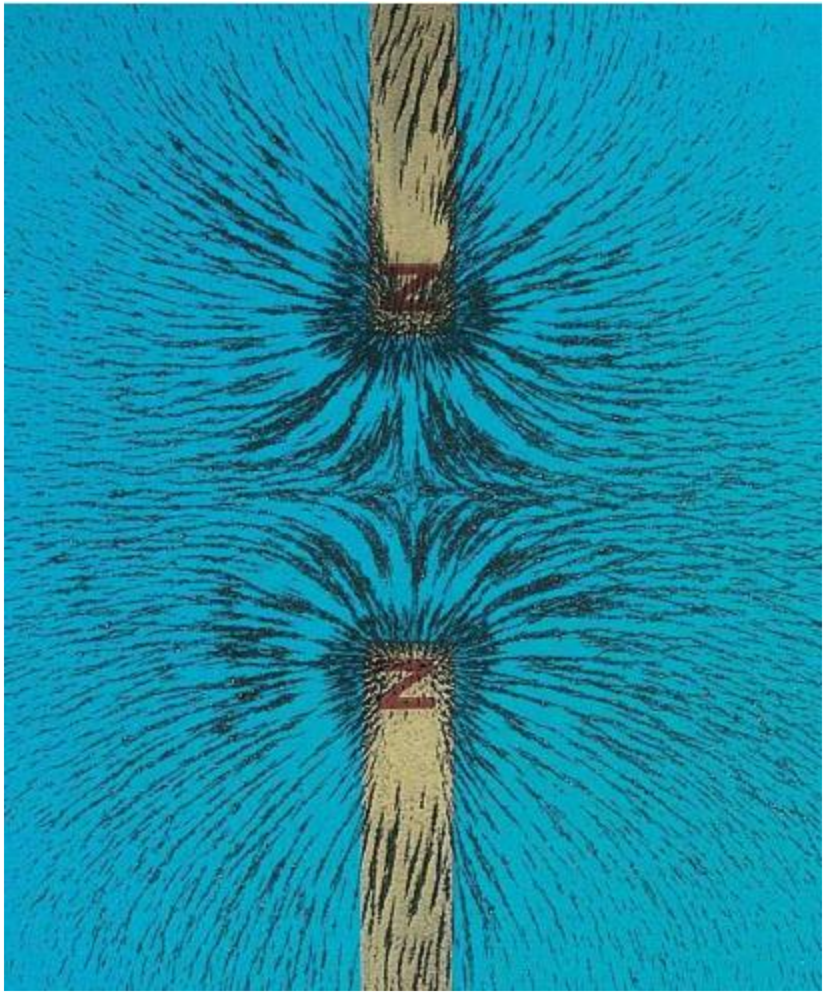


Magnetic Field Lines, Like Poles

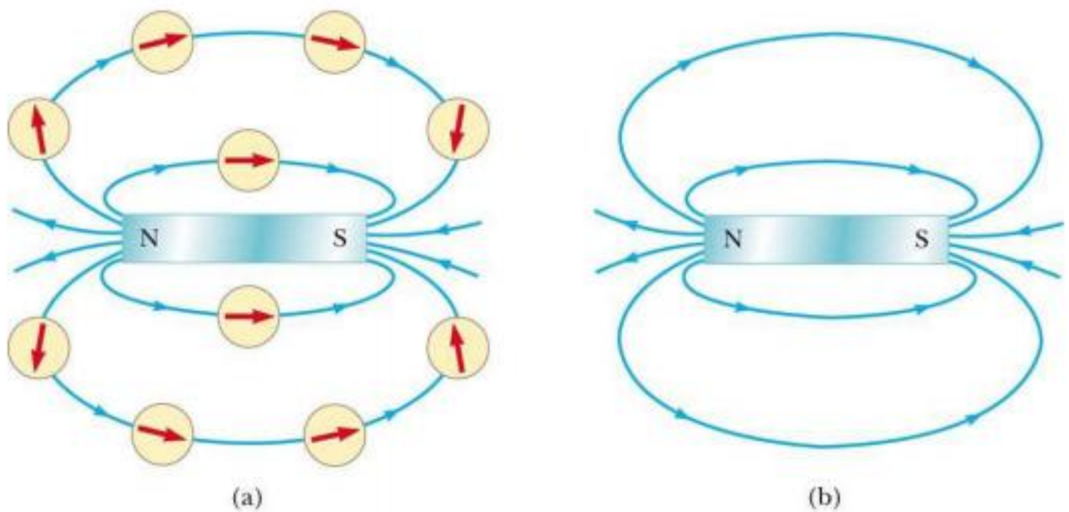
• Iron filings are used to show the pattern of the electric field lines

• The direction of the field is the direction a north pole would point

– Compare to the electric field produced by like charges



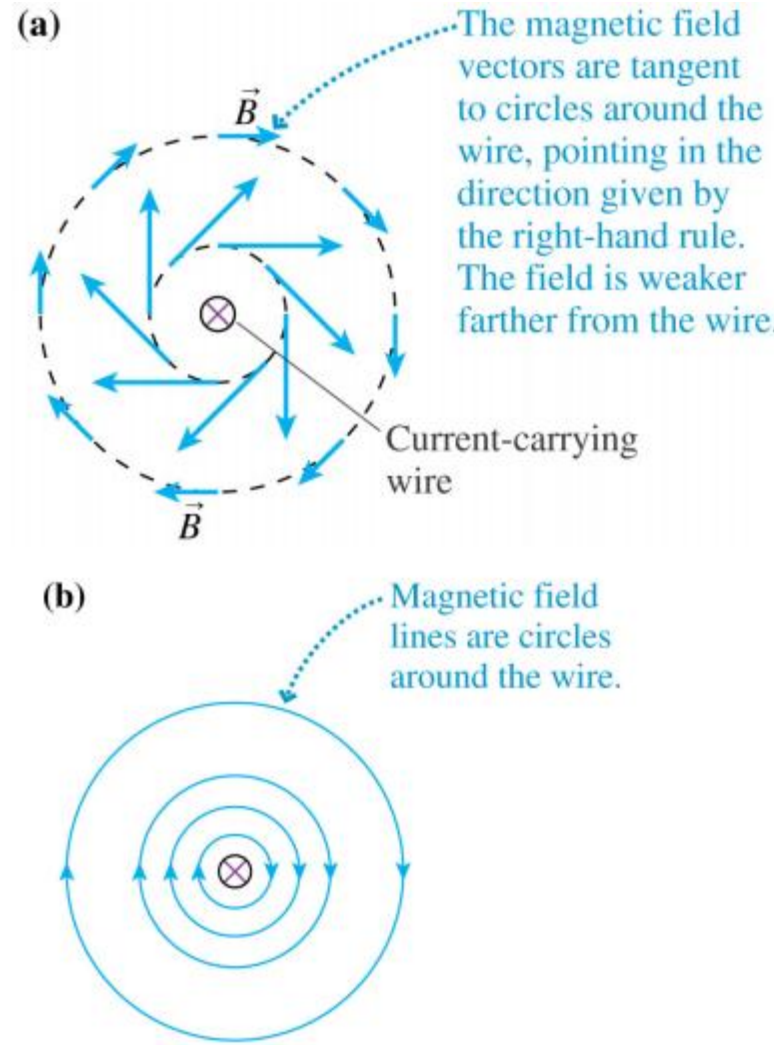
Magnetic Field Lines, sketch



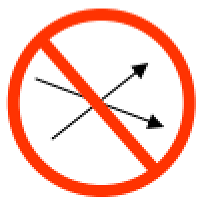
- A compass can be used to show the direction of the magnetic field lines (a)
- A sketch of the magnetic field lines (b)

Magnetic Field Lines

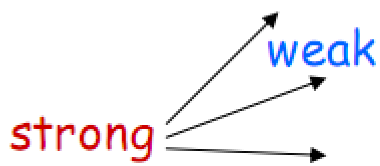
The magnetic field can be graphically represented as magnetic field lines, with the tangent to a given field line at any point indicating the local field direction and the spacing of field lines indicating the local field strength.



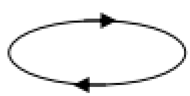
B-field lines never cross.



B-field line spacing indicates field strength



B-field lines form closed loops.

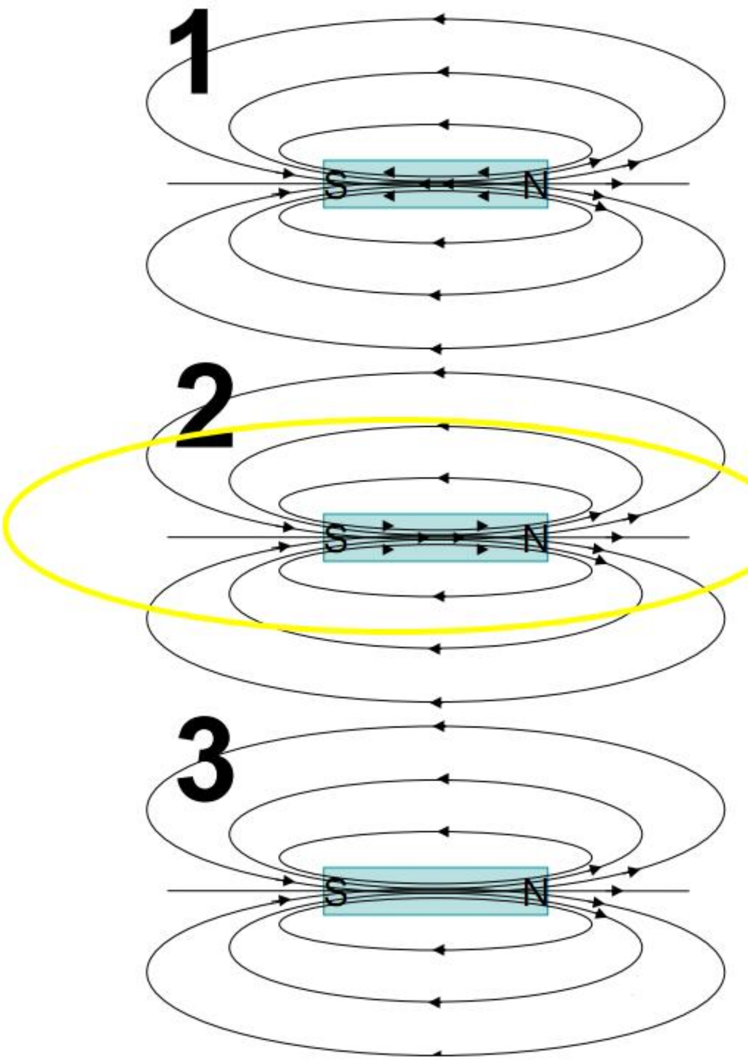


Magnetic Field Lines

Which drawing shows the correct field lines for a bar magnet?

• Magnetic field lines are continuous

• Arrows go from N to S outside the magnet (S to N inside).



Electric vs. Magnetic Field Lines

- **Similarities**

– Density gives strength
– Arrow gives direction

  ✓ Leave +, North
  ✓ Enter -, South

- **Differences**

– Start/Stop on electric charge
– No Magnetic Charge, lines are continuous

- **Notation**

– x x x x x x x INTO Page
– • • • • • • • • • OUT of Page

Magnetic and Electric Fields

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

Magnetic Fields

- When moving through a magnetic field, a charged particle experiences a magnetic force

– This force has a maximum value when the charge moves perpendicularly to the magnetic field lines

– This force is zero when the charge moves along the field lines

Definition of the Magnetic Field

Magnitude of the magnetic field

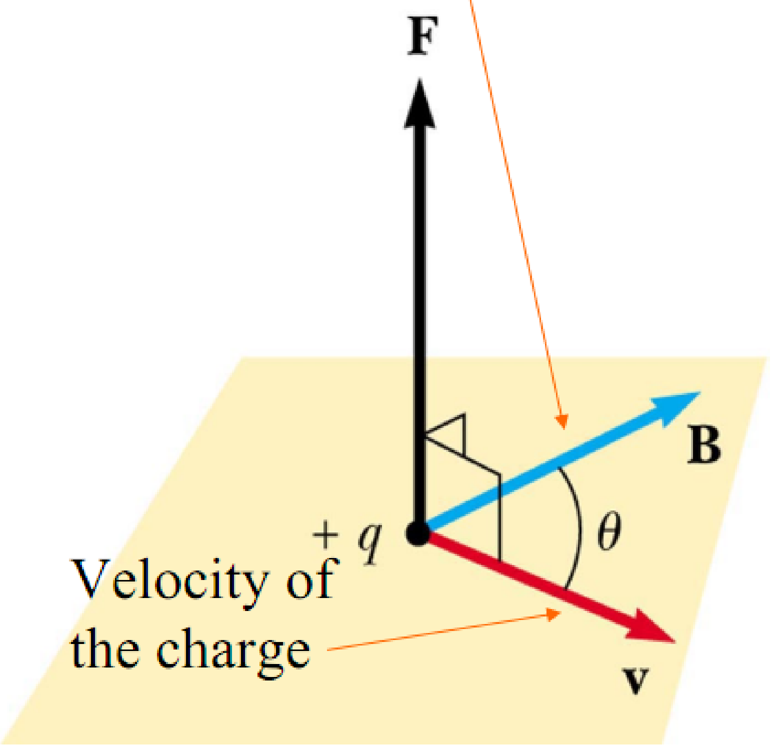
Magnitude of the magnetic force

$$B \equiv \underbrace{\frac{F}{qv\sin\theta}}$$

Test charge

This is the "difference" to the electric field

θ is the angle between the direction of $\boldsymbol{B}$ and $\boldsymbol{v}$



Velocity of the charge

Units of Magnetic Field

- The SI unit of magnetic field is the Tesla (T)
- Wb is a Weber
- The cgs unit is a Gauss (G)
- 1 T = 10^4 G

$$T = \frac{Wb}{m^2} = \frac{N}{C \cdot (m/s)} = \frac{N}{A \cdot m}$$

- Conventional laboratory magnets : – 25000 G or 2.5 T
- Superconducting magnets: 300000 G or 30 T
- Earth's magnetic field: 0.5 G or 5 x 10^{-5} T

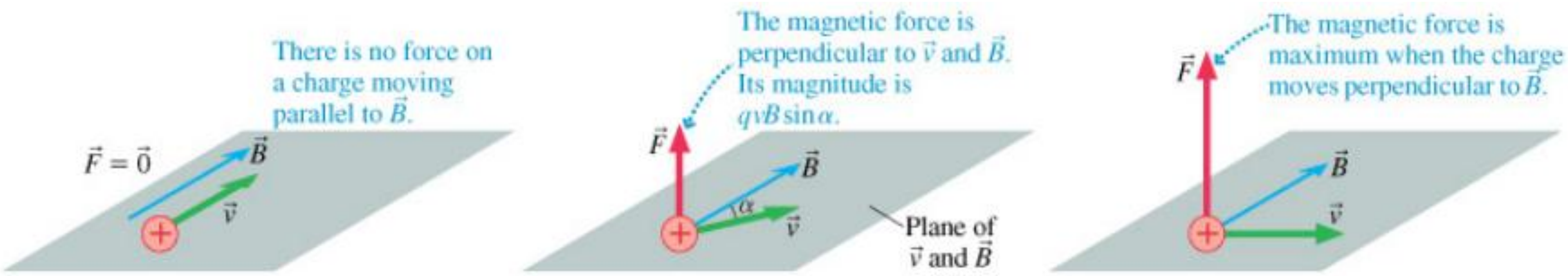
Magnetic Force

• A current consists of moving charges.

• Ampere's experiment implies that a magnetic field exerts a force on a moving charge. This is true, although the exact form of the force relation was not discovered until later in the 19th century.

• The force depends on the relative directions of the magnetic field and the velocity of the moving charge, and is perpendicular to both..

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



Magnetic Force on Moving Charges

Properties of the magnetic force:

1. Only moving charges experience the magnetic force. There is no magnetic force on a charge at rest (v = 0) in a magnetic field.

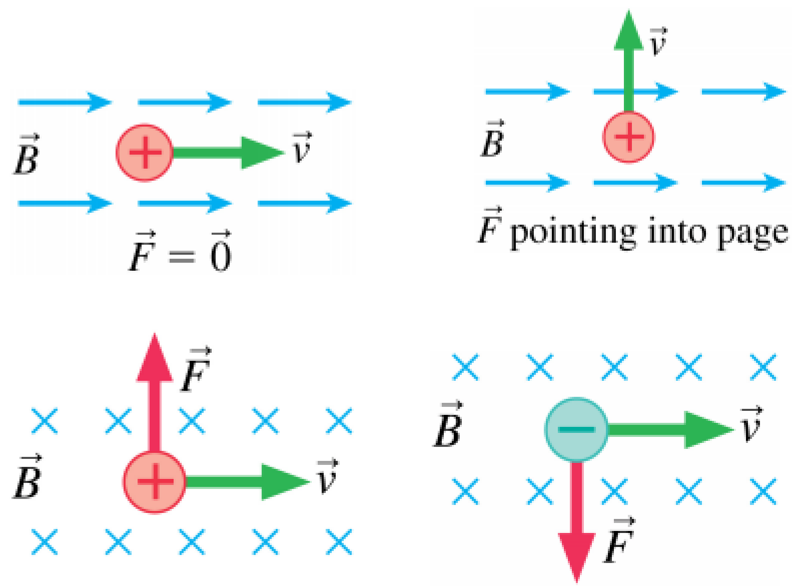
2. There is no magnetic force on a charge moving parallel ($\alpha = 0^0$) or anti-parallel ($\alpha = 180^0$) to a magnetic field.

3. When there is a magnetic force, it is perpendicular to both v and B.

4. The force on a negative charge is in the direction opposite to v x B.

5. For a charge moving perpendicular to B ($\alpha = 90^0$) , the magnitude of the force is $F=|q|vB$.

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



Magnetic and Electric Fields, Cont.

Charges at rest → electric field

$$\boxed{\vec{F} = q\,\vec{E}}$$

Moving charges → magnetic field

$$\boxed{\vec{F} = q\,\vec{\mathrm{v}} \times \vec{B}}$$

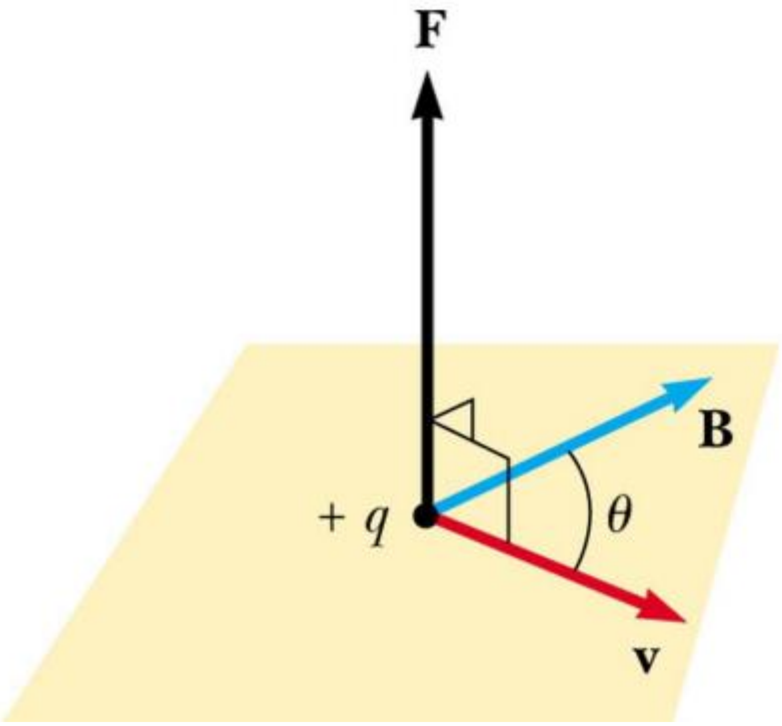
Finding the Direction of Magnetic Force

- Magnetic force on a charged particle:

$$F = qvB\sin\theta$$

- If v is perpendicular to B, θ = 90^o, F becomes maximum:

$$F = qvB$$



Direction of the Force

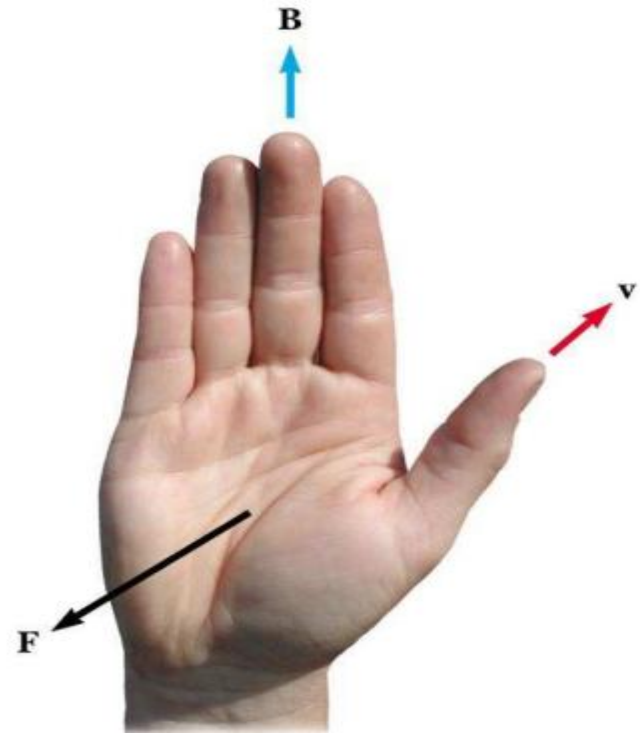
• Right-hand rule #1 for determining the direction of the magnetic force on a positive charge moving with a velocity v.

• A proton moves with $v = 5.0\times10^{6}$ m/s in a magnetic field of 0.40 T. The angle between v and B is 30°. Calculate the force on the proton.

• Solution

$F = (1.60\times10^{-19}\ C)(5.0\times10^{6}\ m/s)(0.40\ T)(\sin 30^{o})$

$F = 1.6\times10^{-13}$ N



Right Hand Rule

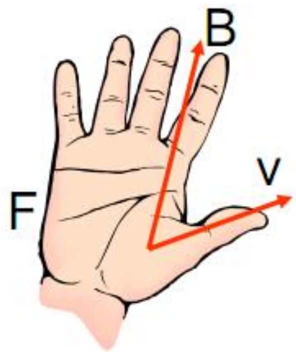
Thumb v, Fingers B, palm F

Direction of Magnetic Force on Moving Charges

Velocity	B	Force
out of page	right	
out of page	left	
out of page	up	
out of page	down	

Right Hand Rule

Thumb v, Fingers B, palm F

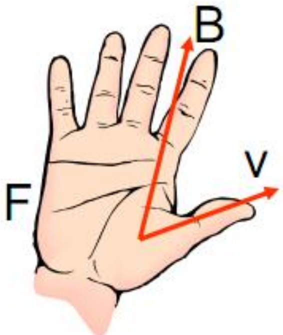


Direction of the Force

Velocity	B	Force
out of page	right	up
out of page	left	down
out of page	up	left
out of page	down	right

Right Hand Rule

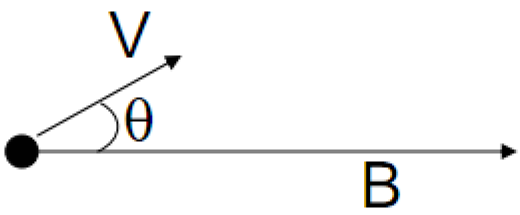
Thumb v, Fingers B, palm F



- Negative charge has opposite F

Magnitude of Magnetic Force on Moving Charges

• The magnetic force on a charge depends on the magnitude of the charge, its velocity, and the magnetic field.



$$\boxed{F = q\, v\, B \sin(\theta)}$$

• Note if v is parallel to B then F = 0

Moving Charges

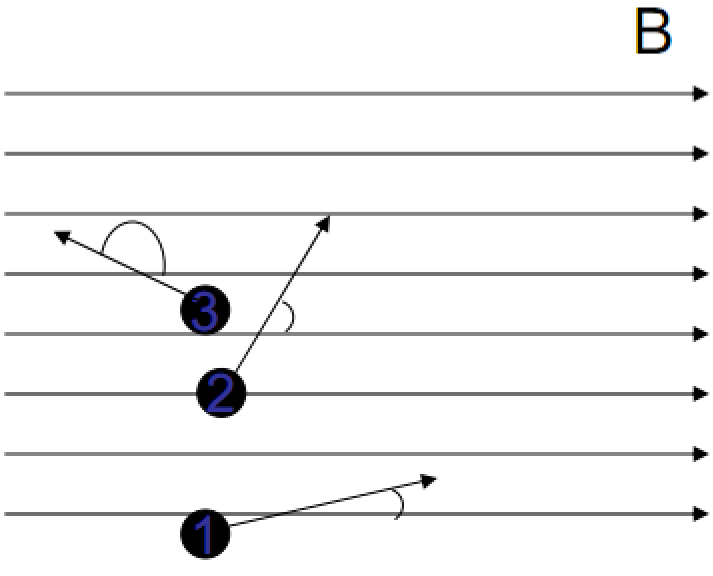
The three charges below have equal charge and speed, but are traveling in different directions in a uniform magnetic field.

1) Which particle experiences the greatest magnetic force?

1) 1 2) 2 3) 3 4) All Same

2) The force on particle 3 is in the same direction as the force on particle 1.

1) True 2) False



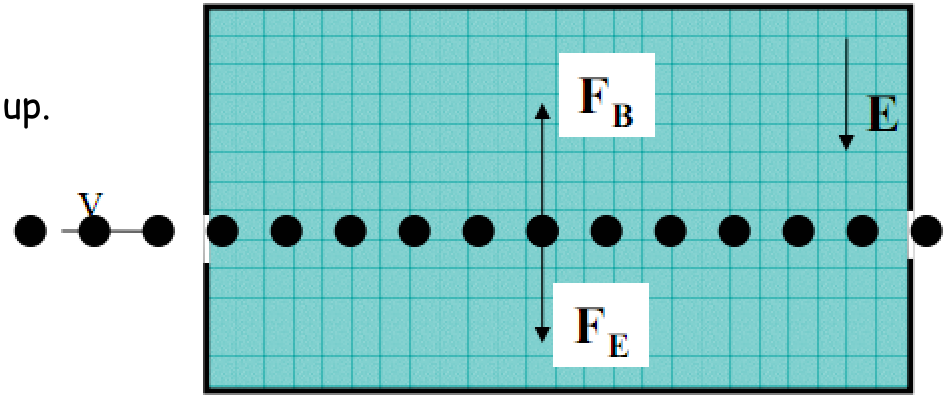
Thumb (v), fingers (B), palm (F) into page

Comparison: Electric vs. Magnetic

	Electric	Magnetic
Source:	Charges	Moving Charges
Act on:	Charges	Moving Charges
Magnitude:	$F = qE$	$F = q\ v\ B \sin(\theta)$
Direction:	Parallel to E	Perpendicular to v,B

Velocity Selector

Determine magnitude and direction of magnetic field such that a positively charged particle with initial velocity v travels straight through and exits the other side.



Electric force is down, so need magnetic force up.

By RHR, B must be into page

For straight line, need $|F_E| = |F_B|$

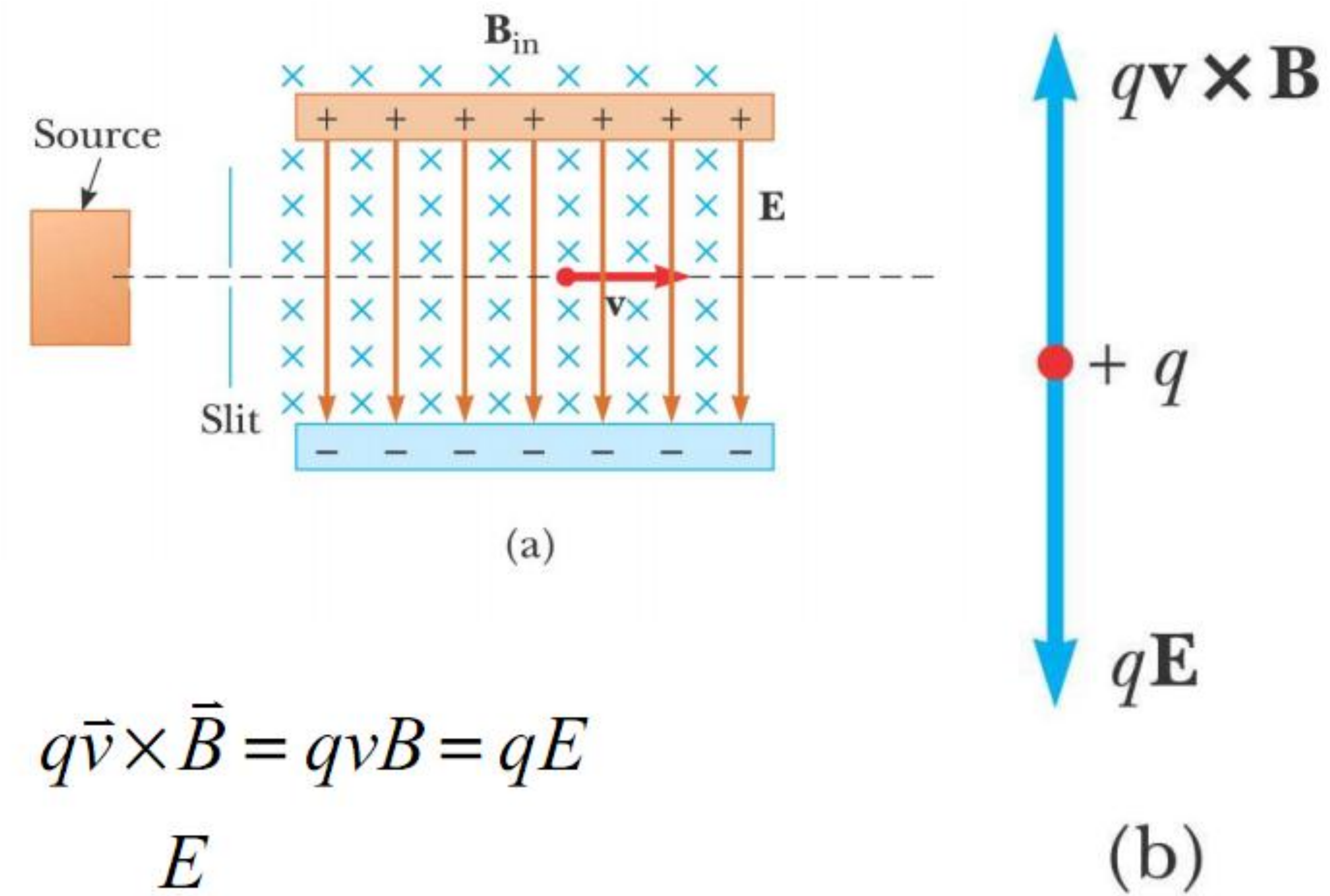
$qE = qvB\sin(90)$
$B = E/v$

What direction should B point if you want to select negative charges?

1) Into Page   2) Out of page   3) Left   4) Right

F_E would be up so FB must be down.

Velocity Selector

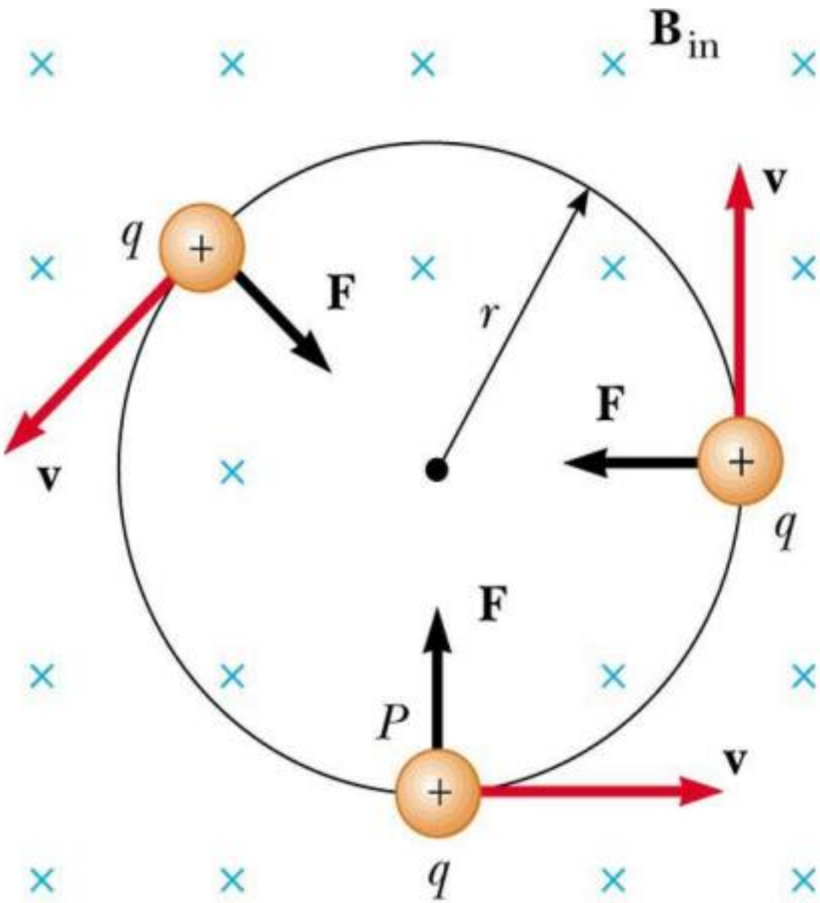


$$q\vec{v}\times\vec{B} = qvB = qE$$

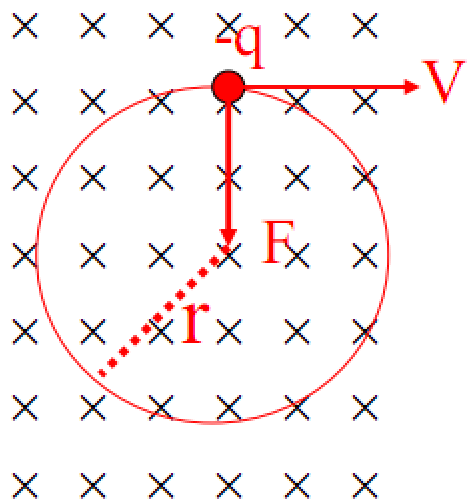
$$v = \frac{E}{B}$$

Force on a Charged Particle in a Magnetic Field

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



Circular Motion: General



$$\overrightarrow{F_B} = q\vec{V} \times \vec{B}$$

$$F_B = qVB\sin\theta$$

$$= qVB \qquad = m\frac{V^2}{r}$$

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

$$T = \frac{2\pi r}{V} = \frac{2\pi m}{qB} \qquad f = \frac{1}{T} = \frac{qB}{2\pi m}$$

Cyclotron Motion

Consider a positive charged particle with mass m and charge q moving at velocity v perpendicular to a uniform magnetic field B.

The particle will move in a circular path of radius r_{cyc} because of the force F (centripetal forces) on the particle, which is:

$$F = qvB = \frac{mv^2}{r_{\text{cyc}}} \qquad r_{\text{cyc}} = \frac{mv}{qB}$$

$$f_{\text{cyc}} = \frac{v}{2\pi r_{\text{cyc}}} = \frac{q}{m}\frac{B}{2\pi} \text{ (independent of } r_{\text{cyc}} \text{ and } v\text{)}$$