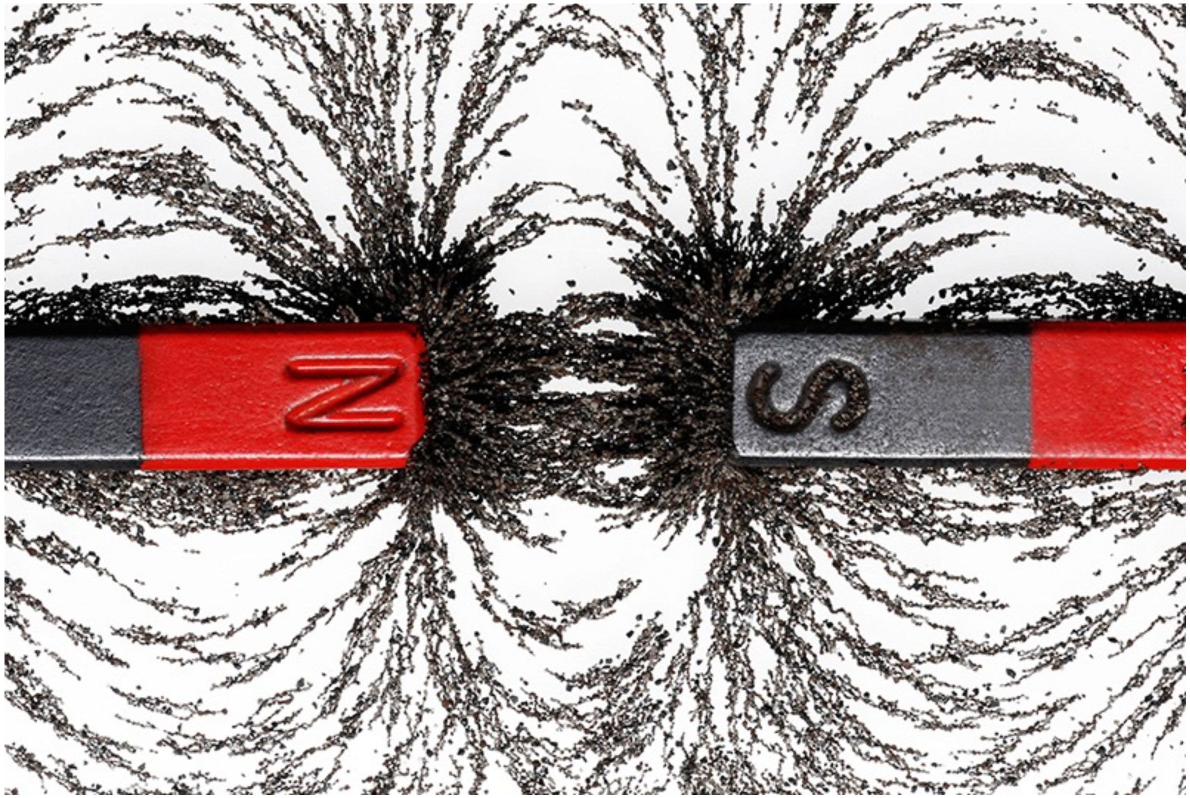
Studio Week 8
Magnetic Forces



Picture credit: accessscience.com.

Principles for Success

- **Treat everyone with respect.**
- **Learn by doing and questioning.**
- **Everything should make sense.**

Activity 8-1 – The Bar Magnet

- At your table is a large bar magnet and some compasses.
  1. Use the compass to explore the region near the bar magnet. Use your observations to develop a rule about which direction the compass points.
  2. On your large whiteboard, sketch vectors at several different points (at least 10) to represent the magnetic field near the bar magnet. You should be able to explain how you used the compass to construct your sketches.
  3. Open the simulation and play with it for a few minutes: https://phet.colorado.edu/en/simulation/magnets-and-electromagnets
     - A. Does the compass always point directly at one of a magnet's poles?
     - B. How does the magnetic field of the current loop compare to the magnetic field of the bar magnet?

8-1 The Bar Magnet

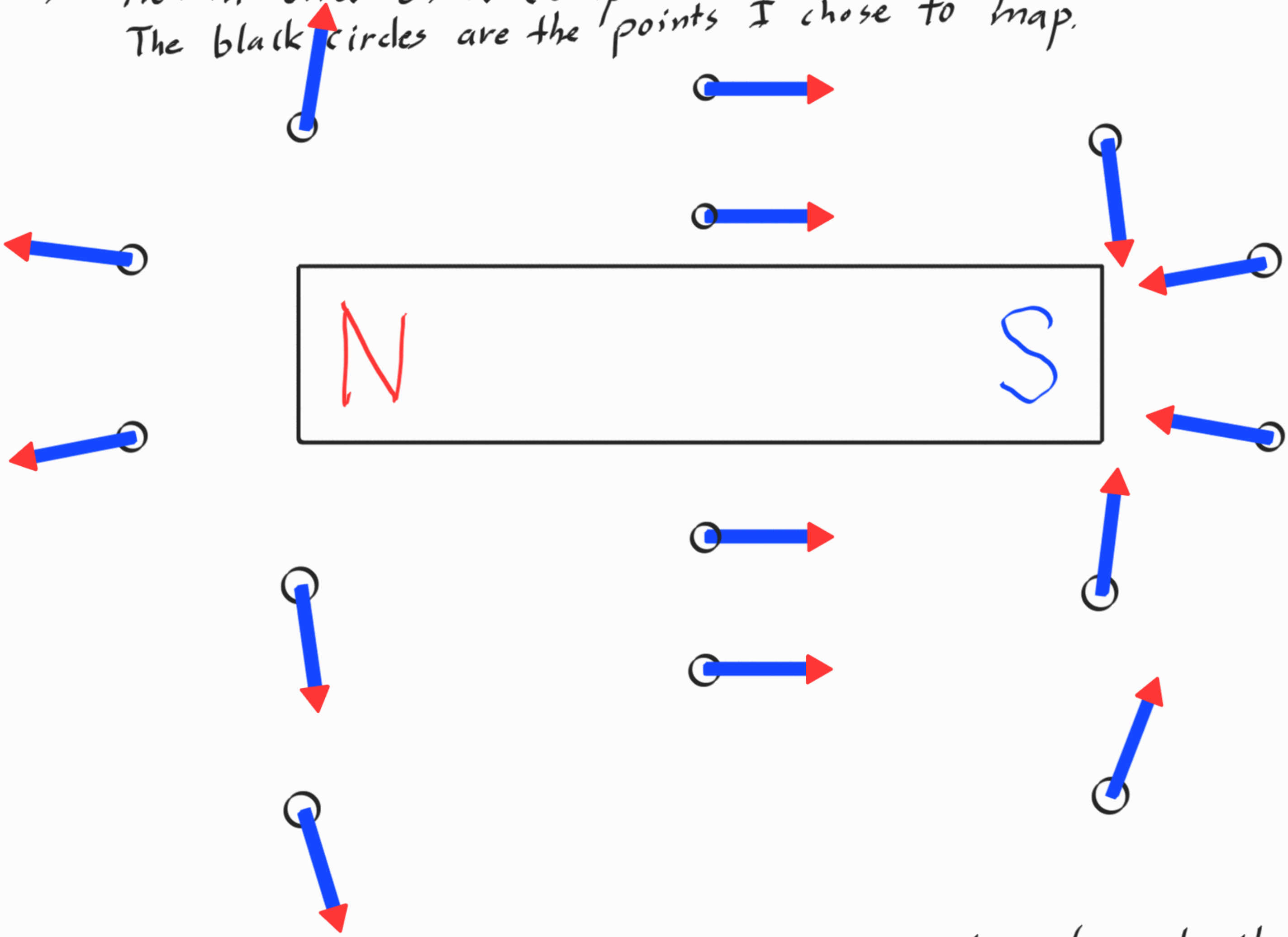
1) Near the poles of a magnet, the compass needle points its north end generally toward the south pole of the magnet, and vice versa (not necessarily directly at it, but it does prefer to have opposite polarities closer).

Near the middle of the magnet, the compass aligns its needle nearly parallel to the magnet, with its poles in the opposite direction.

You may have said that the north pole of the needle "points at" the south pole of the magnet. This isn't exactly accurate, but it is close. It is hard to write a general, exact rule in sentence format for this behavior.

Note: The compass needle's north pole points toward the Earth's geographic north (when not near a stronger magnetic field), so the geographic north pole is actually near the Earth's magnetic south pole!

2) The magnetic field vectors below point in the direction the north end of a compass needle would point.
The black circles are the points I chose to map.



3A) No. The compass needle wants its poles close to their opposites on the magnet, but that does not always lead to pointing straight at one of the magnet's poles. In the above drawing, we have examples of it pointing just past one of the poles, or being entirely parallel to the magnet with its poles in the opposite direction.

3B) Qualitatively, the magnetic field of the current loop is no different in its general shape than the magnetic field of the bar magnet.

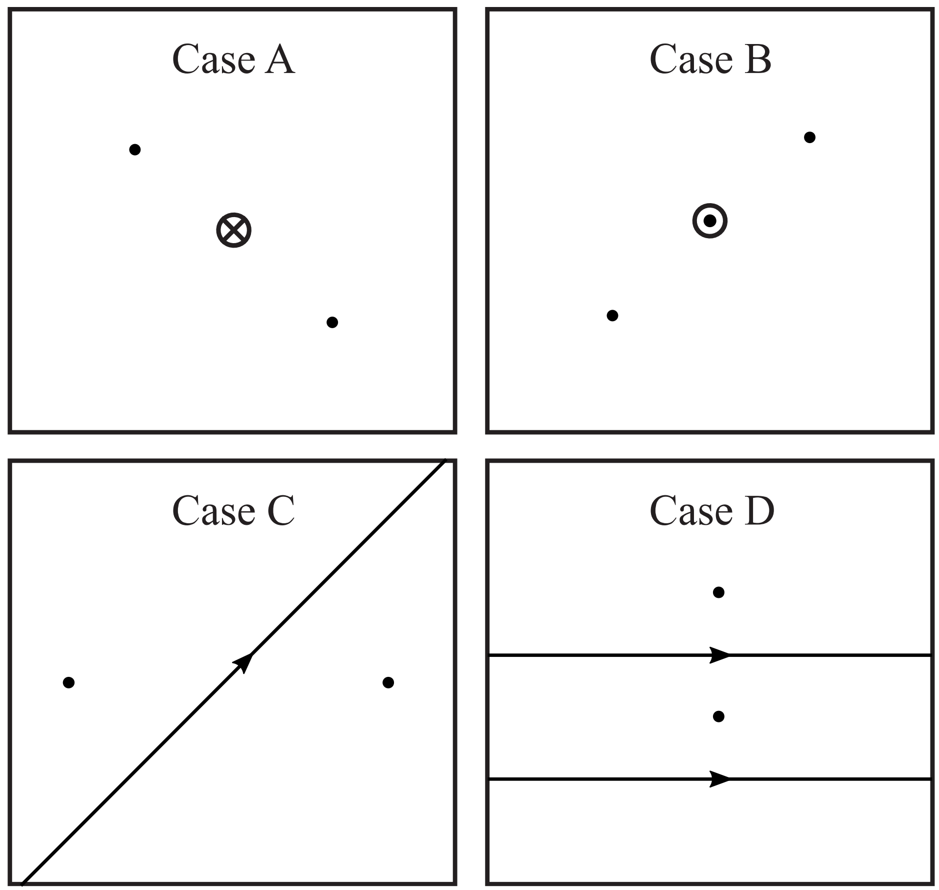
Magnetic Fields

- Magnetic field for a current-carrying wire

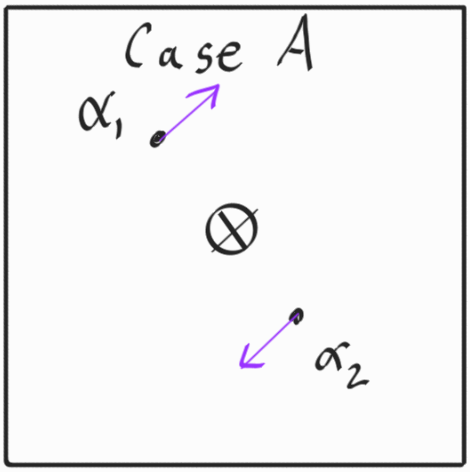
$$\vec{B}_{\text{wire}} = \frac{\mu_0}{2\pi} \frac{\vec{I} \times \hat{s}}{s}$$

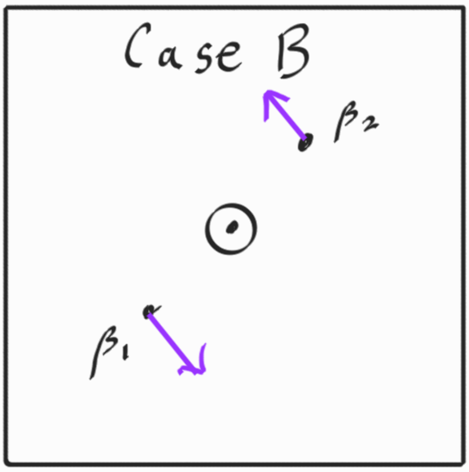
Activity 8-2 – Wires

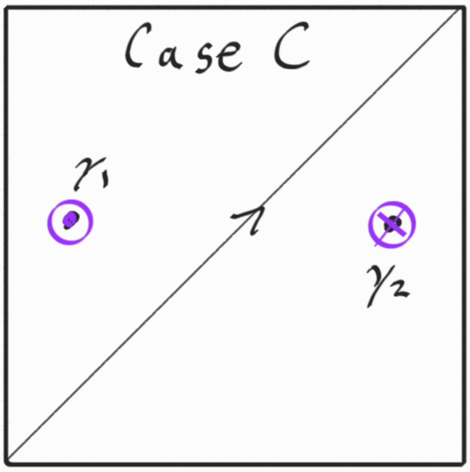
- For each of the cases below, draw a compass needle in its equilibrium position at each dot (label the poles of the compass needle). Explain how you determined your answers. (*Note:* each vector represents a current of 0.2 A flowing in that direction.)

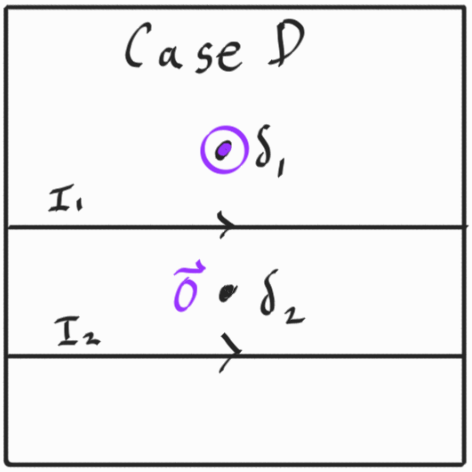


8-2 Wires









Since $\vec{B}_{wire} = \frac{\mu_0}{2\pi}\frac{\vec{I}\times\hat{s}}{s}$, I know that finding the direction of $\vec{I}\times\hat{s}$ by the right hand rule will give me the direction of $\vec{B}$, which is the direction the north end of a compass needle points.

Case A $\vec{I}$: ⊗

$\hat{s}$ of α_1: ↖ $\qquad$ $\hat{s}$ of α_2: ↘

$\vec{B}_{\alpha_1} \propto \vec{I}\times\hat{s}_{\alpha_1}$: ↗ $\qquad$ $\vec{B}_{\alpha_1} \propto \vec{I}\times\hat{s}_{\alpha_2}$: ↙

Case B $\vec{I}$: ⊙

$\hat{s}$ of β_1: ↙ $\qquad$ $\hat{s}$ of β_2: ↗

$\vec{B}_{\alpha_1} \propto \vec{I}\times\hat{s}_{\beta_1}$: ↘ $\qquad$ $\vec{B}_{\alpha_1} \propto \vec{I}\times\hat{s}_{\beta_2}$: ↖

Remember to judge $\vec{s}$ based on the radial distance from the wire to the field point.

Case C $\vec{I}$: ↗

$\hat{s}$ of γ_1: ↖ $\qquad$ $\hat{s}$ of γ_2: ↘

$\vec{B}_{\alpha_1} \propto \vec{I}\times\hat{s}_{\gamma_1}$: ⊙ $\qquad$ $\vec{B}_{\alpha_1} \propto \vec{I}\times\hat{s}_{\gamma_2}$: ⊗

Case D For D, we need to use superposition.

$\vec{I}_1$: →

$\hat{s}$ of δ_1 from I_1: ↑ $\qquad$ $\hat{s}$ of δ_2 from I_1: ↓

$\vec{B}_{1\delta_1} \propto \vec{I}_1\times\hat{s}_{\delta_1}$: ⊙ $\qquad$ $\vec{B}_{1\delta_2} \propto \vec{I}_1\times\hat{s}_{\delta_2}$: ⊗

Equal distance, equal magnitude.

This one is weaker because it is farther away.

$\vec{I}_2$: →

$\hat{s}$ of δ_1 from I_2: ↑ $\qquad$ $\hat{s}$ of δ_2 from I_2: ↑

$\vec{B}_{2\delta_1} \propto \vec{I}_2\times\hat{s}_{\delta_1}$: ⊙ $\qquad$ $\vec{B}_{2\delta_2} \propto \vec{I}_2\times\hat{s}_{\delta_2}$: ⊙

Net: $\vec{B}_{\delta_1} = \vec{B}_{1\delta_1}+\vec{B}_{2\delta_1}$: ⊙ $\qquad$ Net: $\vec{B}_{\delta_2} = \vec{B}_{1\delta_2}+\vec{B}_{2\delta_2} = \vec{0}$ Cancels (equal & opposite).

Activity 8-3 – Magnetic Force

- Complete section 11.5 (Magnetic Force) in the book:
- Use this simulation as you work on the following activities:

1. To begin, describe the direction of the magnetic field shown in the simulation.
2. Without changing any of the initial settings, press "start" and observe the path of the charged particle. Use your observation to describe the direction of the acceleration that the charged particle experiences while in the region of the magnetic field.
3. How is the direction of the force that the magnetic field acts on the charged particle related to the direction of the acceleration? Explain how you know.
4. Use your knowledge about circular motion to write a symbolic expression for the magnetic force, then solve this expression for the radius of the charged particle's path.
5. Adjust the settings of the simulation to investigate how the radius depends on each of the four changeable properties. Record your answers in a table.
6. Use your answers to the previous question to investigate how the magnetic force on the charged particle depends on each of the four changeable properties.
7. For each dependence that you identified above, do you think the magnetic force depends on that quantity in a linear or a non-linear way? Explain how you can tell.

8-3 Magnetic Force

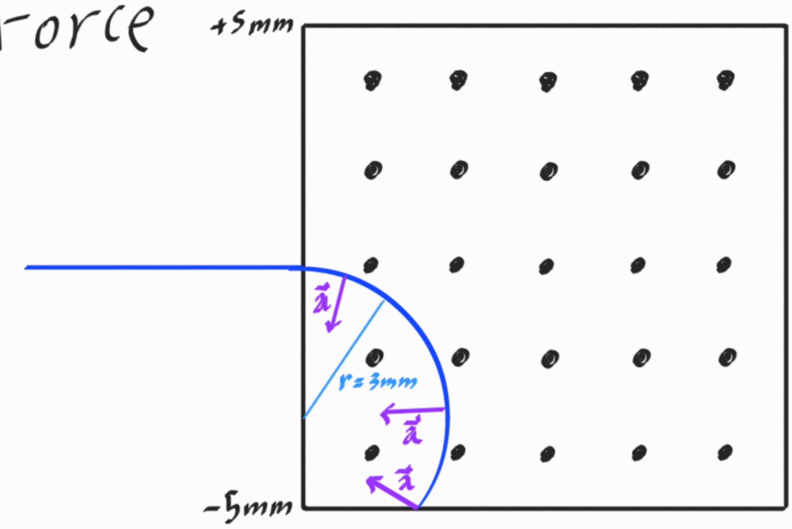
Initial Settings

$m = \boxed{6} \times 10^{-25}$ kg

$v = \boxed{7.5} \times 10^{6}$ m/s

$q = \boxed{5} \times 10^{-16}$ C

$B = \boxed{3}$ T



A) The magnetic field points out of the screen.

B) The acceleration is always perpendicular to the charge's velocity while in the field. This gives us the observed uniform circular motion.

C) Net force is always in the same direction as acceleration, so the magnetic force (which is the only force here) is also perpendicular to the velocity.

D) $F^B = ma,\ a_c = \frac{v^2}{r}$

$\Rightarrow F^B = m\frac{v^2}{r}$

$\Rightarrow r = m\frac{v^2}{F^B}$

E) Mass Dependence

$v = 7.5 \times 10^6$ m/s

$q = 5 \times 10^{-16}$ C $B = 3$ T

m (10^{-25} kg)	r (mm)
6	3
6.2	3.1
6.4	3.2
6.6	3.3
6.8	3.4
7	3.5
8	4
9	4.5
10	5

Speed Dependence

$m = 6 \times 10^{-25}$ kg

$q = 5 \times 10^{-16}$ C $B = 3$ T

v (10^6 m/s)	r (mm)
7.5	3
7.6	3.04
7.7	3.08
7.8	3.12
7.9	3.16
8	3.2
9	3.6
10	4

Charge Dependence

$m = 6\times10^{-25}$ kg $V = 7.5\times10^{6}$ m/s
$B = 3$ T

q^{-1} (10^{16} C^{-1})	q (10^{-16} C)	r (mm)
2/10	5	$3 = r_0$
	5.2	2.88
	5.4	2.78
	5.6	2.68
1/10	10	$1.5 = \frac{1}{2}r_0$
4/10	2.5	$6 = 2r_0$
8/10	1.25	$12 = 4r_0$
-8/10	-1.25	12*
-4/10	-2.5	6*

Dependence

$m = 6\times10^{-25}$ kg $V = 7.5\times10^{6}$ m/s
$q = 5\times10^{-16}$ C

B^{-1} (T^{-1})	B (T)	r (mm)
1/3	3	$3 = r_0$
	3.2	2.81
	3.4	2.65
	3.6	2.5
1/6	6	$1.5 = \frac{1}{2}r_0$
1/9	9	$1 = \frac{1}{3}r_0$
2/3	1.5	$6 = 2r_0$
4/3	0.75	$12 = 4r_0$
	-3	3*

* These charges were deflected up instead of down.

When I changed mass and speed by consistent increments, I observed changes of a constant size in radius, which suggests a linear dependence of r on m and V. Similar changes in charge and magnetic field did not result in constant-sized changes in radius. However, when I doubled, tripled, or halved charge or magnetic field strength, I observed the radius being halved, reduced to a third, or doubled, respectively. This suggests an inverse dependence of r on m and V. In summary: $r \propto \frac{mV}{qB}$.

proportional up to some dimensionless constant

F) Comparing $r = m\frac{v^2}{F^B}$ and $r \propto \frac{mv}{qB}$, we can see that both equations depend linearly on m, so F^B cannot depend on m without messing this up.

The first equation has no dependence on q or B, and a quadratic dependence on v not seen in the second equation. F^B must depend on q, B, and v to correct these dependencies for the first r equation. Specifically, the magnitude of F^B must increase when any one of these three quantities increases in magnitude.

G) Since $r = m\frac{v^2}{F^B}$ and $r \propto \frac{mv}{qB}$, then

$$\cancel{m}\frac{v^{\cancel{2}}}{F^B} \propto \frac{\cancel{m}\cancel{v}}{qB}$$

$$\Rightarrow \frac{v}{F^B} \propto \frac{1}{qB}$$

$$\Rightarrow F^B \propto qvB$$

The magnetic force will be linearly dependent on charge, speed, and magnetic field. Mass does not affect this force.

This analysis mainly accounts for the size of the force. Its direction reverses for negative charge and reversed magnetic field, but that does not affect its strength.

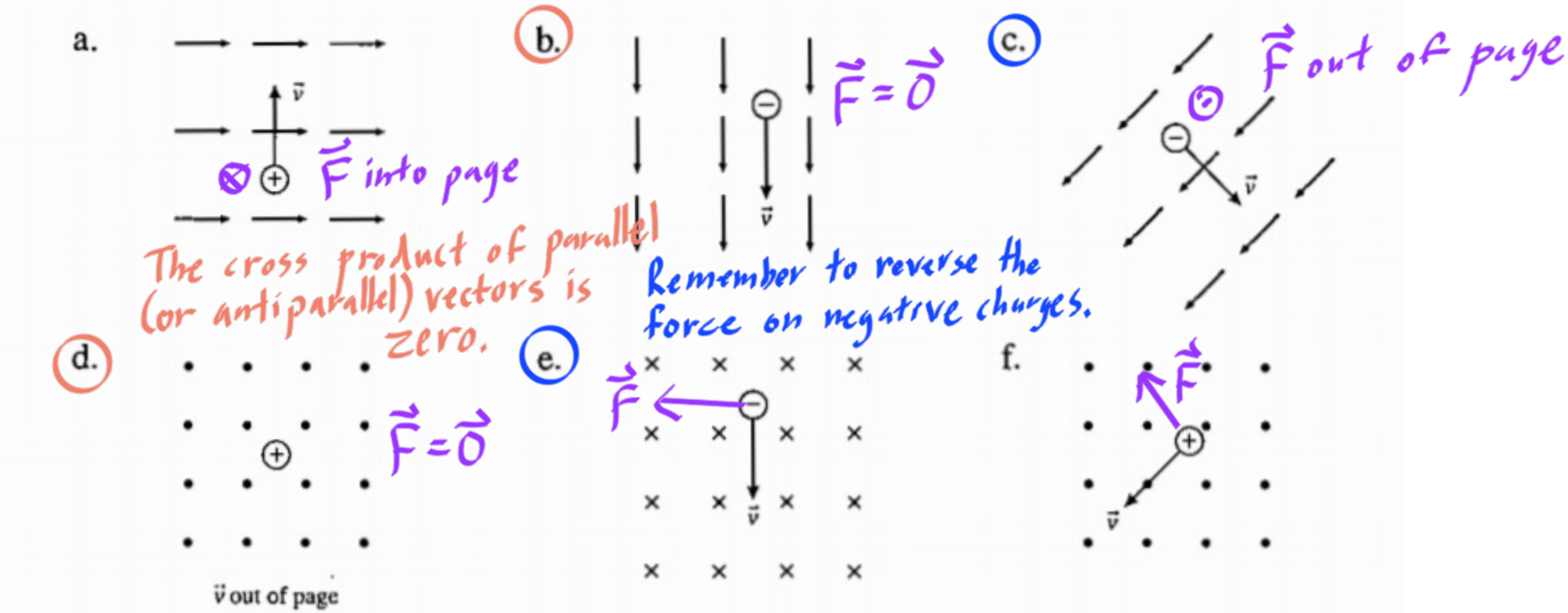
Magnetic Forces

- The Lorentz Force Law

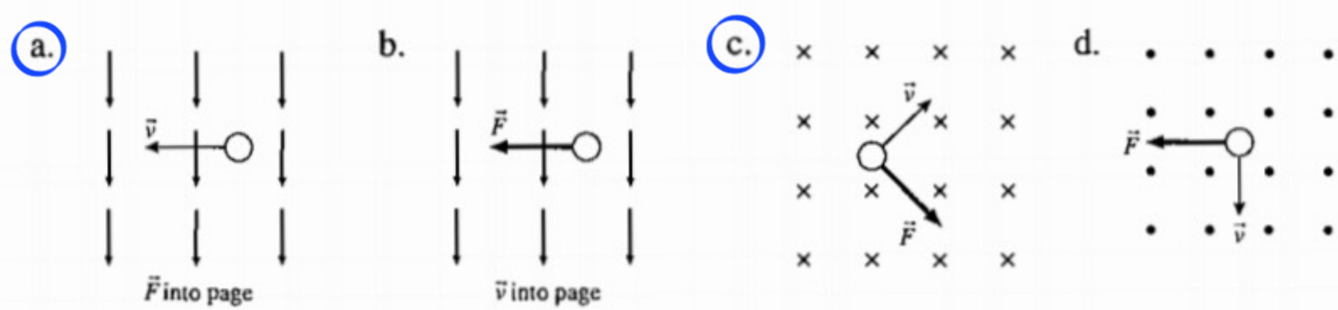
$$\vec{F}_{\text{magnetic}} = q\vec{v} \times \vec{B}$$

Activity 8-4 – Magnetic Force Practice

1. For each of the following, draw the magnetic force vector on the charge or, if appropriate, write "$\vec{F}$ into page," "$\vec{F}$ out of page," or "$\vec{F} = \vec{0}$."



2. For each of the following, determine the sign of the charge (+ or −).

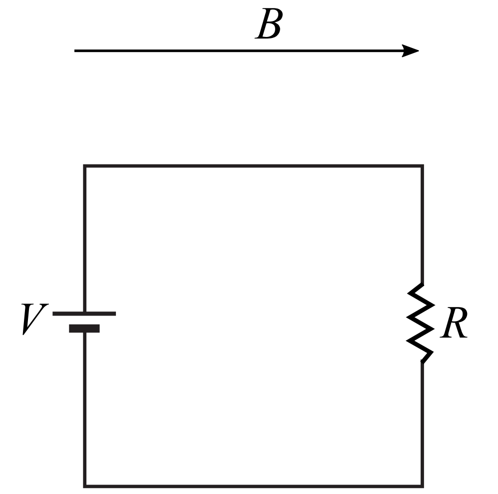


a. $q =$ − b. $q =$ + c. $q =$ − d. $q =$ +

$\vec{F}$ would be opposite what is indicated for a positive charge in (a) or (c).

Activity 8-5 – Force on a Circuit

- The square circuit at right is in a region with a uniform magnetic field.
  - A. Determine the current through each side of the square circuit.
  - B. Determine the direction of the magnetic force on each side of the square circuit.
  - C. Does the magnetic field exert a net nonzero magnetic force on the loop? If so, what direction is the net force?
  - D. Does the magnetic field exert a net nonzero magnetic torque on the loop? If so, what direction would you expect the loop to rotate (starting from rest)?

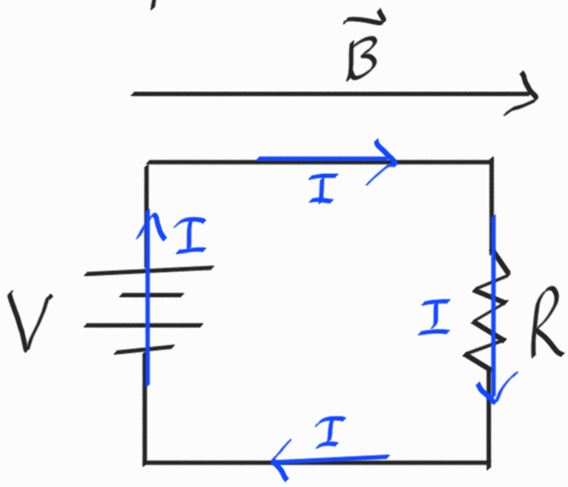


8-5 Force on a Circuit

A) Current

Magnitude: $I = \frac{V}{R}$

Direction: clockwise



B) Magnetic Force

$\vec{I}$ is positive charge traveling in the $\hat{I}$ direction (or physically, negative charge traveling in the $-\hat{I}$ direction), so $q\vec{v}\times\vec{B}$ has the same direction as $\vec{I}\times\vec{B}$.

Top

$\vec{I}\times\vec{B} = \rightarrow \times \rightarrow = \vec{0}$

Left Side

$\vec{I}\times\vec{B} = \uparrow \times \rightarrow = \otimes$

Right Side

$\vec{I}\times\vec{B} = \downarrow \times \rightarrow = \odot$

Bottom

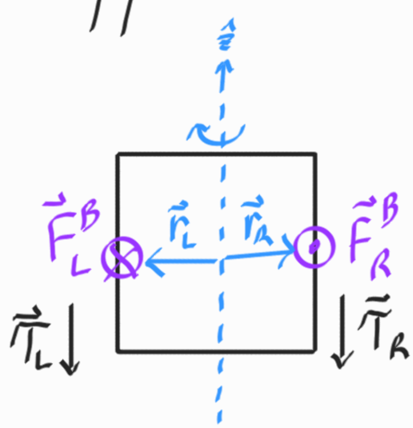
$\vec{I}\times\vec{B} = \leftarrow \times \rightarrow = \vec{0}$

C) The net force on the loop is zero.

Since each side has the same magnitude of current and magnitude of magnetic field, the left and right side forces have the same magnitude. Since they are in opposite directions, the net force is zero.

D) Both forces exert the same torque, so there is a nonzero net torque.

The loop should begin to rotate such that the left side moves into the page and the right side moves out (clockwise about $\hat{z}$).



Magnetic Forces

- The Lorentz Force Law

$$\vec{F}_{\text{magnetic}} = q\vec{v} \times \vec{B}$$

- Force on a current-carrying wire

$$\vec{F} = l\vec{I} \times \vec{B}$$