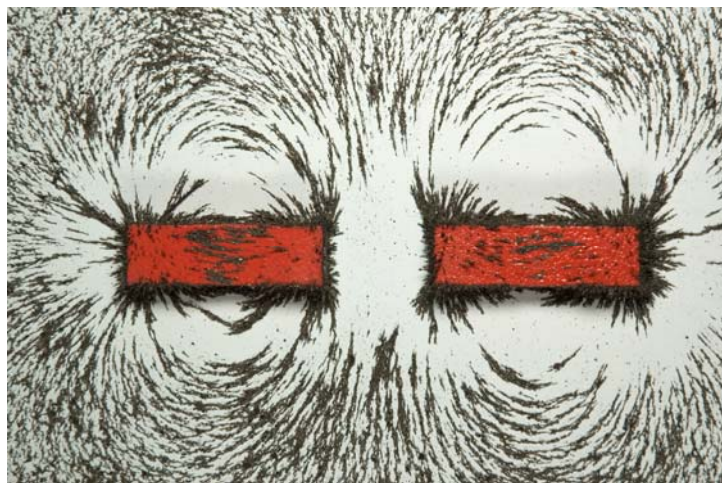


Chapter 19 – Magnetism

In this chapter, we will explore magnetism. We will discuss how magnetic fields influence charged particles and currents, and we will also discuss where magnetic fields come from.

One way to visualize a magnetic field is to use iron filings. Each iron filing aligns with the field. In the photo at right, the iron filings indicate that the magnets repel one another. Also, the field is strongest at the ends (poles) of the magnets, where the density of filings is largest. Photo credit: Thomas Mounsey / iStockphoto.



19-1 The Magnetic Field

Magnetic fields are very useful things. Among other uses, the magnetic field from a magnet can interact with the steel door of a refrigerator to hold a child's artwork to the fridge; a hiker can use a compass, which has a magnetic needle that interacts with the Earth's magnetic field, to determine which way to walk to get out of the woods; and the magnetic field generated by a magnetic resonance imaging (MRI) machine in a hospital can interact with molecules in your body to investigate what is causing a particular pain in your knee.

Challenge yourself. Write down any similarities you see between magnetic fields and electric fields, as well as any differences you see. Then check your list against the list below. As we will learn later, there are two ways to generate a magnetic field. One way is to use a current, and the similarities and differences below apply to magnetic fields generated by currents. The second way to produce a magnetic field is by changing an electric field, which we will investigate later in the book.

Some Similarities between Electric Fields and Magnetic Fields

- Electric fields are produced by two kinds of charges, positive and negative. Magnetic fields are associated with two magnetic poles, north and south. As we will learn in this chapter, magnetic fields are also produced by charges (but moving charges).
- Like electric charges repel, while unlike charges attract. Like magnetic poles repel, while unlike poles attract.
- The electric field points in the direction of the force experienced by a positive charge. The magnetic field points in the direction of the force experienced by a north pole.

Some Differences between Electric Fields and Magnetic Fields

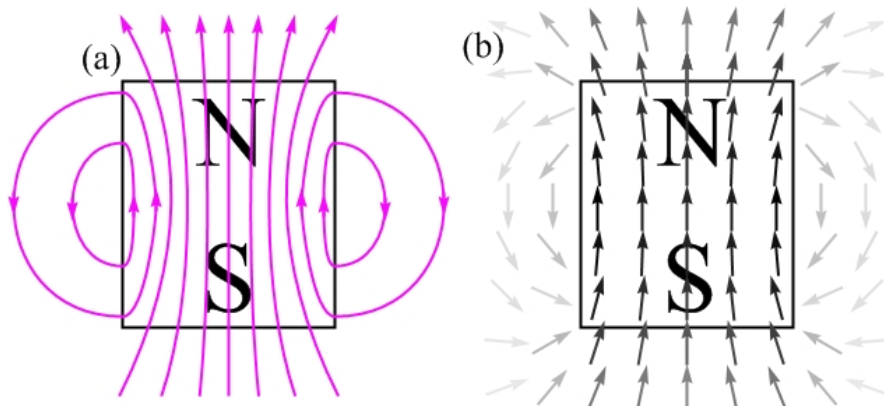
- Positive and negative charges can exist separately. North and south poles always come together. Single magnetic poles, known as magnetic monopoles, have been proposed theoretically, but a magnetic monopole has never been observed.
- Electric field lines have definite starting and ending points. Magnetic field lines are continuous loops. Outside a magnet, the magnetic field is directed from the north pole to the south pole. Inside a magnet, the magnetic field runs from south to north.

The magnetic fields we will deal with in this chapter are associated with currents (this includes fields from a refrigerator magnet, the Earth, and an MRI machine). The symbol we use for magnetic field is B . The SI unit of magnetic field is the tesla (T).

Visualizing Magnetic Fields

As with electric fields, we use field lines and field vectors to visualize magnetic fields. Figure 19.1(a) shows magnetic field lines near a bar magnet, where we can see that the field lines are continuous. Recall that the field is strongest where the field lines are densest, which is inside the magnet itself. The field-vector view, in Figure 19.1(b), emphasizes that the magnetic field exists at all points in space. The field vectors are darkest where the field is strongest.

Figure 19.1: Two views of the magnetic field near a bar magnet. Figure (a) shows the magnetic field lines, while figure (b) shows the field vectors. Each of the field vectors can be thought of as compass needles.



The Magnetic Field of the Earth

The Earth's magnetic field is weak compared to a magnet on your refrigerator, but the Earth's field is strong enough to be used by humans, birds, and bacteria for navigation, and to act as a protective shield for the Earth. The Earth's field has a strength of about 5×10^{-5} T at the surface of the Earth, depending on the location. For comparison, a typical refrigerator magnet has a magnetic field in the millitesla range, while a strong magnet in a research lab has a field of about 10 T. At the surface of the Earth, the magnetic field is stronger near the poles, where the field lines are vertical, and weaker near the equator, where the field lines are horizontal. The Earth's field is similar in form to that from a bar magnet, and thus resembles the field in Figure 19.1. Presently, the Earth's field is gradually decreasing in strength.

What produces the Earth's magnetic field? This question is one that scientists are working to answer completely, but the basic mechanism is that is associated with electric charge carried by swirling flows of molten iron deep within the Earth's core.

The location of the Earth's magnetic poles changes over time, as the currents within the Earth change. Mostly, the magnetic poles wander around gradually, but roughly every 250 000 years or so, on average, the Earth's magnetic field flips direction (taking a couple of thousand years to flip). The last flip was about 780 000 years ago, so we are overdue for a change. A reversal of the Earth's field direction requires a major change in the flow patterns of the molten iron within the Earth. Understanding such major changes is an area of cutting-edge research.

Related End-of-Chapter Exercises: 31, 34, 36.

Essential Question 19.1: If the north pole of a compass needle points toward the south pole of a magnet, why does the north pole of a compass point north on the Earth?

Answer to Essential Question 19.1: The magnetic south pole of the Earth is actually near the geographic north pole of the Earth (the geographic poles correspond to the Earth's axis of rotation), and the Earth's magnetic north pole is near the geographic south pole.

19-2 The Magnetic Force on a Charged Object

In chapter 16, we investigated the force experienced by a charged object in an electric field. This force is given by equation 16.3, $\vec{F}_E = q\vec{E}$. The relationship between the magnetic force exerted on a charged particle and the magnetic field is a little more complicated than that between the electric force and the electric field. Let's try to understand the relationship, in the magnetic situation, by making some observations (see Table 19.1) involving various charged particles in a uniform magnetic field (a magnetic field with constant magnitude and direction).

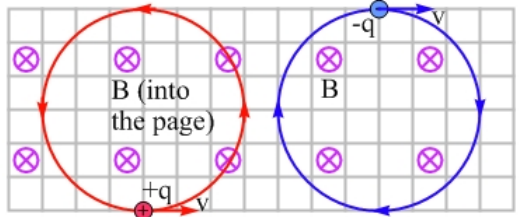
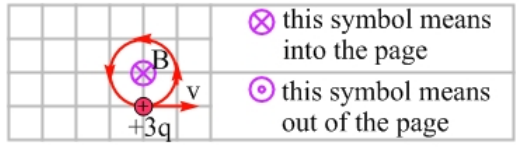
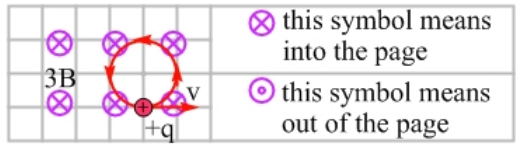
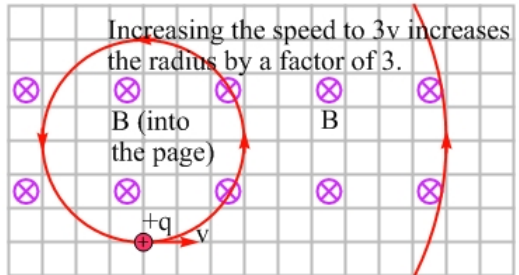
Experiment	Result	Comment or pictorial representation
1. The charged particle is released from rest in the magnetic field.	The particle remains at rest.	The particle experiences no force. (Note: if the particle was in an electric field instead, it would have a constant acceleration.)
2. The particle has an initial velocity parallel to the magnetic field.	The particle moves at constant velocity.	The particle experiences no force! The magnetic field has no influence on a charged particle moving parallel to the field.
3. The particle is given an initial velocity in a direction perpendicular to the magnetic field. The field is directed into the page.	Figure 19.2: The particle moves in a circular path at constant speed in a plane perpendicular to the magnetic field. Particles with charges of opposite sign orbit in opposite senses.	
4. The charge of the positively charged particle in experiment 3 is tripled to $+3q$.	Figure 19.3: The radius of the circular path is reduced by a factor of 3, indicating that the force on the particle has tripled.	
5. The strength of the magnetic field for the particle in situation 3 is tripled.	Figure 19.4: The radius of the circular path is reduced by a factor of 3, indicating that the force on the particle has tripled.	
6. The magnitude of the initial velocity for the particle in situation 3 is tripled.	Figure 19.5: The radius of the circular path is increased by a factor of 3, indicating that the force on the particle has tripled. Also, the period of the circular orbit is observed to be independent of the speed of the particle.	

Table 19.1: The behavior of various charged particles in a uniform magnetic field. All other influences (such as gravity) are neglected.

Related End-of-Chapter Exercises: 6 and 38.

For experiments 3 – 6 in Table 19.1, the particles experience uniform circular motion, so we can apply the analysis methods we used in chapter 5. The net force on the particle, which is directed toward the center of the circle, comes from the magnetic field. Thus, the magnitude of the magnetic force on a particle of mass m and speed v is: $F_M = mv^2 / r$. Solving for the radius, r :

$$r = \frac{mv^2}{F_M}. \quad (\text{Equation 19.1})$$

In experiments 4 and 5, the mass and speed of the particle are constant. Thus, any change in radius comes from a change in the force. In Experiment 4, tripling the charge decreases the radius by a factor of 3, so the magnetic force must increase by a factor of 3. Thus, we conclude that the magnetic force is proportional to the charge. Analyzing experiment 5 in the same way, we conclude that the magnetic force is proportional to the magnitude of the magnetic field.

The results of experiment 6 are interesting. Based on Equation 19.1, we might expect that tripling the speed would lead to an increase in radius by a factor of 9. Because we observe that the radius increases by a factor of 3, we conclude that there must be a factor of v hidden in F_M . In other words, the magnetic force on a charged particle is proportional to the speed of the particle. Let's write a compact equation for the force exerted by a magnetic field on a charged particle.

$$F_M = qvB \sin \theta, \quad (\text{Eq. 19.2: The magnitude of the magnetic force on a charge } q)$$

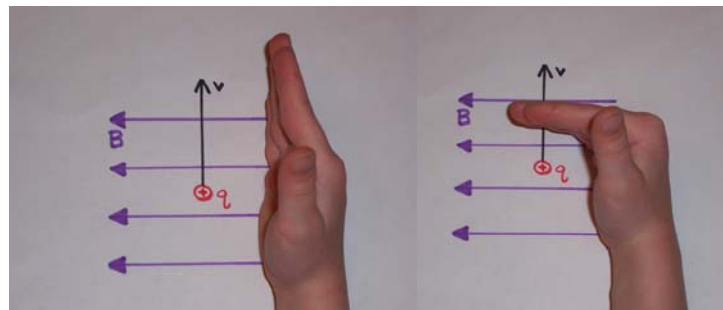
where θ is the angle between the velocity, $\vec{v}$, and the magnetic field, $\vec{B}$. The direction of the force is perpendicular to the plane defined by $\vec{v}$ and $\vec{B}$, and given by the right-hand rule.

The right-hand rule for determining the direction of the magnetic force on a moving charge

First, make sure you use your right hand!

- Point the fingers on your right hand in the direction of the charge's velocity.
- While keeping your fingers aligned with the velocity, rotate your hand so that, when you curl your fingers, you can curl them into the direction of the magnetic field.
- Hold out your thumb so it is perpendicular to your fingers. Your thumb points in the direction of the force experienced by a positively charged particle.
- If the particle has a negative charge, your right hand lies to you. Just reverse the direction of the force. The magnetic force on a negatively charged particle is opposite in direction to that of a positively charged particle if the particles are traveling in the same direction.

Figure 19.6: To find the magnetic force on a charged particle moving in a magnetic field, point the fingers on your right hand in the direction of the velocity, as in the photo on the left. Orient your hand so you can curl your fingers into the magnetic field, as in the photo on the right. Keep your thumb perpendicular to your fingers, and your thumb points in the direction of the force experienced by a positive charge (out of the page, in this case). A negative charge experiences a force in the opposite direction. Photo courtesy of A. Duffy.



Essential Question 19.2: A charge with an initial velocity directed parallel to a magnetic field experiences no magnetic force, and travels in a straight line. If the initial velocity is perpendicular to the field, the particle travels in a circle. Predict the shape of the path followed by a charge with a velocity component parallel to the field, and a velocity component perpendicular to the field.

Answer to Essential Question 19.2: Try this – walk in a straight line while whirling your hand in a circle around an axis parallel to your velocity. Your hand traces out a spiral, the shape of the path followed by the particle. For the particle, the spiral’s axis is parallel to the magnetic field.

19-3 Using the Right-hand Rule

Let’s practice using the right-hand rule (described at the end of section 19-2).

EXAMPLE 19.3 – Applying the right-hand rule

Draw a picture of each situation below, and use the picture to help answer the question.

(a) In what direction is the magnetic force on a particle that has a positive charge, and which has a velocity directed to the right in a uniform magnetic field directed up the page?

(b) In what direction is the magnetic force on a negatively charged particle, and which has a velocity directed down the page in a uniform magnetic field that has one component directed out of the page, and the other component directed down the page?

(c) In what direction is the velocity of a particle that has a positive charge, and which experiences a magnetic force directed into the page in a uniform magnetic field directed right?

SOLUTION

(a) Consider Figure 19.7. The magnetic force is perpendicular to the plane defined by the velocity and the magnetic field, which is the plane of the page. Thus, the force is either directed into or out of the page. Our right hands can distinguish between these directions. Place your right hand on the page, with the fingers pointing right. If the plane of the hand is perpendicular to the page, with the thumb sticking up out of the page, we can curl the fingers into the direction of the field. Thus, the force on the positive charge is out of the page.

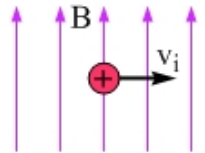


Figure 19.7: A positively charged particle is directed right, in a field directed up.

(b) A magnetic field that is parallel to the particle’s velocity exerts no force. Thus, we can focus on the perpendicular component of the field. Place your right hand flat on the page with the palm up and the fingers directed to the bottom of the page, so you can curl the fingers up, out of the page. The thumb points to the left, in the direction of the force on a positive charge. Our charge is negative, so the right hand lies to us and the force is directed to the right.

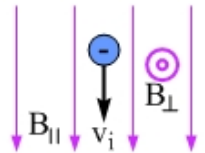


Figure 19.8: A negatively charged particle is moving down, in a field directed both down the page, parallel to the velocity, ($B_{\parallel}$) and out of the page ($B_{\perp}$), perpendicular to the velocity.

(c) First, remember that the velocity is perpendicular to the force, so if the force is perpendicular to the page the velocity must be in the plane of the page. Let’s apply the right-hand rule in reverse order. Curl the fingers of your right hand, and hold your hand with the thumb pointing down, into the page, and with your curled fingers directed right. When you un-curl your fingers 90° , they point up the page in the direction of the velocity component that is perpendicular to the magnetic field. However, there may or may not be a velocity component directed left or right, parallel to the magnetic field lines. This case is ambiguous – we can’t say for certain which direction the velocity is in because the angle between $\vec{v}$ and $\vec{B}$ does not have to be 90° .

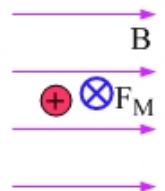


Figure 19.9: A moving positively charged particle experiences a force directed into the page, in a field directed right.

Related End-of-Chapter Exercises: 7 – 10.

A special case: a charged particle with a velocity perpendicular to the magnetic field

When the velocity of a charged particle is perpendicular to the field, the particle follows a circular path. Applying the form of Newton's Second Law for circular motion, $\Sigma F = mv^2 / r$:

$$qvB \sin \theta = \frac{mv^2}{r}.$$

The velocity and magnetic field are perpendicular, so we have $\sin(90^\circ) = 1$. Solving for r :

$$r = \frac{mv}{qB}. \quad (\text{Equation 19.3: Radius of the path, when } \vec{v} \text{ and } \vec{B} \text{ are perpendicular})$$

We can find the time it takes the particle to go around the circle once, which we call the period of the orbit, by dividing the circumference of the orbit by the particle's speed:

$$T = \frac{2\pi r}{v} = \frac{2\pi mv}{vqB} = \frac{2\pi m}{qB}. \quad (\text{Equation 19.4: The period of the circular orbit})$$

the circular orbit)

Note that **the period is independent of the speed** of the particle.

EXPLORATION 19.3 – Identifying the particles

As shown in Figure 19.10, four particles pass through a square region of uniform magnetic field directed perpendicular to the page.

Particle	Charge	Mass	Speed	Path taken
1	0	$2m$	$6v$	
2	$+q$	m	$4v$	
3	$+2q$	$4m$	v	
4	$-q$		$2v$	

Table 19.2: The charge, mass, and speed for four particles passing through a magnetic field.

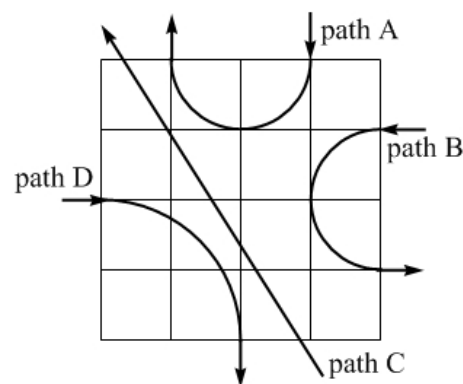


Figure 19.10: The paths followed by the particles.

Step 1 – Identify the path taken by particle 1. Because particle 1 has no charge, the field exerts no force on it. Particle 1 travels through the field in a straight line – so, it follows path C.

Step 2 – Are the paths clockwise or counterclockwise? Use your answer to determine the direction of the magnetic field. Positive charges travel in one sense, while negative charges travel in the opposite sense. Paths A and D both show clockwise motion, so these are the paths taken by the two positive charges. Path B shows a counterclockwise motion, so path B is taken by particle 4, the only particle with a negative charge. Applying the right-hand rule the positive particle traveling along path D, we find that the magnetic field is directed out of the page.

Step 3 – Apply Equation 19.3 to see which particle follows path A and which follows path D.

Equation 19.3 tells us that the radius of the path is proportional to the mass multiplied by speed divided by the charge (we neglect the factor of the magnetic field, which is the same for all the charges). This combination is $4mv/q$ for particle 2, and $2mv/q$ for particle 3. Thus, the path followed by particle 2 has twice the radius (path D) as that followed by particle 3 (path A).

Key idea: The radius of curvature, and the direction of curvature, provides information about the speed, charge, and/or the mass of a particle. **Related End-of-Chapter Exercises: 11 – 14.**

Essential Question 19.3: Rank the four particles in Exploration 19.3 in terms of the magnitude of the force applied to them by the magnetic field, from largest to smallest.