Magnetism

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CHAPTER 1 Magnetism

CHAPTER OUTLINE

We are familiar with magnets mostly as devices to stick to a refrigerator, or perhaps as the inner working of a compass. Magnetic fields really are related to electricity. A permanent magnet like a refrigerator magnet or a compass needle creates a magnetic field from the inner motion of its electrons. However, any *moving* charge can create a magnetic field, however, small.

1.1 Magnetic Fields

Objectives

The student will:

- Know how to determine the direction of a permanent magnetic field.
- Know that a current-carrying wire creates a magnetic field.
- Know how to determine the direction of the magnetic field produced by a current-carrying wire.

Vocabulary

- **magnetic domains:** Certain regions of a material that align with the Earth's external magnetic field. These regions are responsible for the magnetic properties of the material.

- **magnetic poles:** The two end of a magnet, known as the north pole and the south pole. Like poles repel each other, and opposite poles attract each other. Magnetic poles always come in pairs.

- **magnetism:** Certain materials, because of their atomic structure, will have their atoms align parallel to an external magnetic field.

- **right-hand rule:** Used to determine the directio of the magnetic field around a wire. Point the thumb of the right hand in the direction of the (conventional) current and then curl the fingers into a fist. The fingers curl in the direction of the magnetic field around the wire.

Introduction

Magnets are common items in our daily lives. Playing around with some magnets, we can see some basic features:

- Magnets exert force on each other, as well as on certain metals.
- This force is strongest when they are touching, but also acts at a distance.
- Magnets can either attract or repel each other, depending on how they are held.

A bit of playing around with real magnets will show that there are two faces to the magnet. Held one way, two magnets attract each other, but if you flip one of them around, the magnets then repel each other. We call the two ends of the magnet the **magnetic poles**. Each magnet has a north pole and a south pole. Similar to electric charges, like poles repel and opposite poles attract.

Unlike electric charges, though, magnetic poles always come in pairs. Every magnet has one north pole and one south pole. If you break a magnet in half, each half will have its own pair of two poles.

Magnetic Compasses

The basic properties of magnets have been known since ancient times, based on observations of natural lodestones. The first person to describe a magnetic needle compass was the Chinese scientist Shen Kuo (1031–1095), who described that when a magnetic material is freely suspended, it tends to align itself in a north-south direction. Since magnets line up with each other, this fact led to the reasonable conclusion that the Earth itself behaves as a magnet. By convention, we define the north magnetic pole of a compass needle as the pole that points northward, and the south magnetic pole of a compass needle as the pole that points southwards.

In 1269, the Frenchman Pierre de Maricourt used a magnetic needle and a spherical magnet, inspired by the shape of the Earth, to map out the shape of what we know today as the magnetic field lines of the Earth.

It is important to know that the north geographic pole and the south magnetic pole are not located at exactly the same spot (same goes for the south geographic pole and the north magnetic pole). The magnetic poles of the Earth are not fixed, but migrate all over the globe. We know today that **magnetism** is the result of the atomic alignment of large numbers of "atomic magnets." By this we mean (roughly) that certain materials, because of their atomic structure, will have their atoms align parallel to an external magnetic field. This process is very similar to an array of compass needles aligning in the same direction, in parallel, with in the Earth's magnetic field. The entire material does not have its atoms align. Only certain regions of the material called **magnetic domains** align with the external field. These regions then are responsible for the magnetic properties of the material. During volcanic eruptions, molten rock containing magnetic materials is very susceptible to having magnetic domains form. The alignment of the atoms within the magnetic domains indicates the direction of the Earth's magnetic field at the time the rock solidified. Thus, they offer a record over many thousands and millions of years of the orientation of the Earth's magnetic field at different moments in time. Such rocks indicate that the magnetic field of the Earth is very dynamic and does not stay in one place. In fact, we know that within a few decades, the magnetic field of the Earth will be a good deal off from its present location.

It wasn't until 1750 that a mathematical relationship was determined, much like Newton's universal law of gravity and Coulomb's law for electrostatic charges, for the forces that one magnetic pole exerted upon the other. It was Coulomb who determined it. One of the major difficulties with a mathematical description of the magnetic force is in the determination of exactly where the pole of a magnet resides. As tempting as it is to think of magnetism in the same terms as we think of electrostatics, it would be incorrect. Isolated electric charges do exist in nature. As far as we know, there is no such thing as an isolated magnetic pole. One or more north magnetic poles cannot be separated from one or more south magnetic poles. Magnetic poles always remain in pairs. Break a bar magnet in half and you'll have two smaller bar magnets with two poles each.

A Magnetic Field

Michael Faraday's description of the lines of force surrounding an electric charge is also useful when we discuss magnetic phenomena. Just as we imagine an electric field E surrounding electrical charges, we also imagine a magnetic field B surrounding a magnet. The field lines of the magnetic field, however, do not begin on the north pole of the magnet and end on the south pole of the magnet. Because magnetic poles come only in pairs, the magnetic field lines between the poles of a magnet form closed loops. However, the magnetic field, like the electric field, has a magnitude and a direction at every point in space, and thus is a vector quantity.

The Earth's Magnetic Field

The magnetic field surrounding the Earth is similar to the field produced by a permanent bar magnet, **Figure** 1.2. (The magnetic field of the Earth is more complicated, but the model is a useful starting point.) A compass needle that is moved from the north-pole to south-pole of a bar magnet shows the same alignment as a compass needle that is moved near the surface of the Earth (illustrated in the top half of the figure). Your teacher may show you a demonstration using iron filings which dramatically outline the field lines of a bar magnet (illustrated in the lower half of the figure).

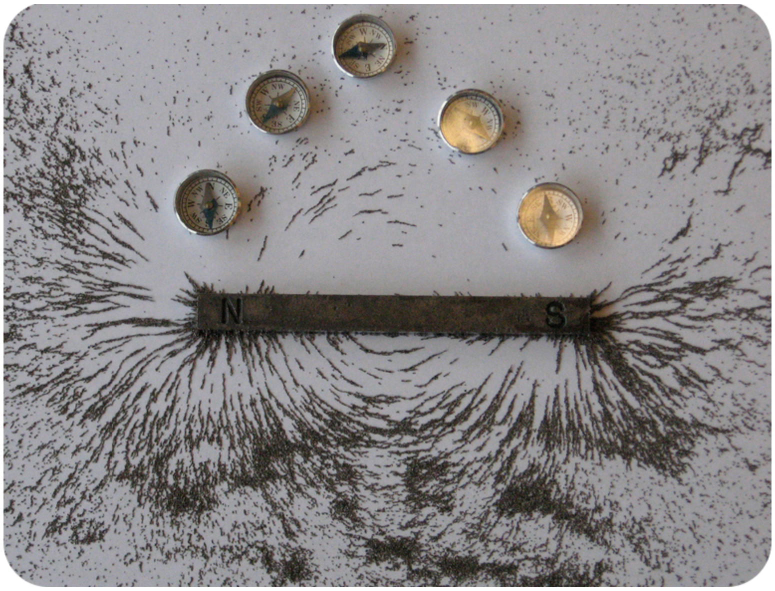

FIGURE 1.1

http://demonstrations.wolfram.com/ObservingMagneticFieldsWithIronFilings/

Magnetism from an Electric Current

During the early 18th century, physicists were looking for possible connections between electrical and magnetic phenomena. In 1820, Hans Christian Oersted (1777-1851), made the discovery that a current-carrying wire created a magnetic field.

Oersted arranged a long straight conducting wire and a compass as shown in **Figure** 1.2 to show the magnetic field around the wire. **Figure** 1.3 shows iron filings aligned with the magnetic field around the wire.

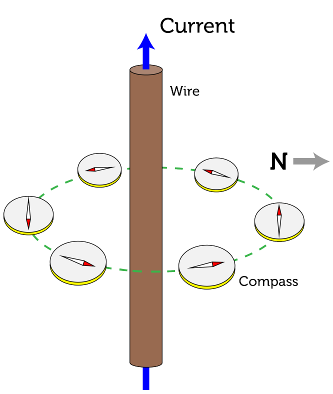

FIGURE 1.2

As soon as a current was initiated in the wire, the compass needle deflected. A magnetic force must be present, produced by an electric current! The compass needle aligned itself perpendicular to the direction of the current. Moving the compass in a plane perpendicular to the wire showed that a magnetic field circled around the wire as in **Figure** 1.2 and **Figure** 1.3.

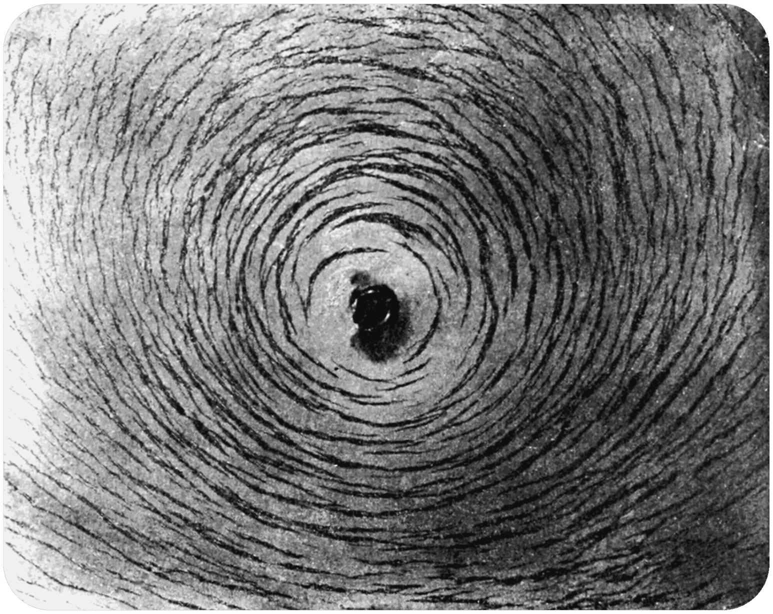

FIGURE 1.3

The Direction of the Magnetic Field for a Current-Carrying Wire

The direction of the magnetic field around a wire can be found using the **right-hand rule**. Point the thumb of the right hand in the direction of the (conventional) current and then curl the fingers into a fist. The fingers curl in the direction of the magnetic field around the wire. **Figure** 1.4 shows the magnetic field represented as a series of circles around the wire. If the current were in the opposite direction, the field would circle around the wire in the opposite direction.

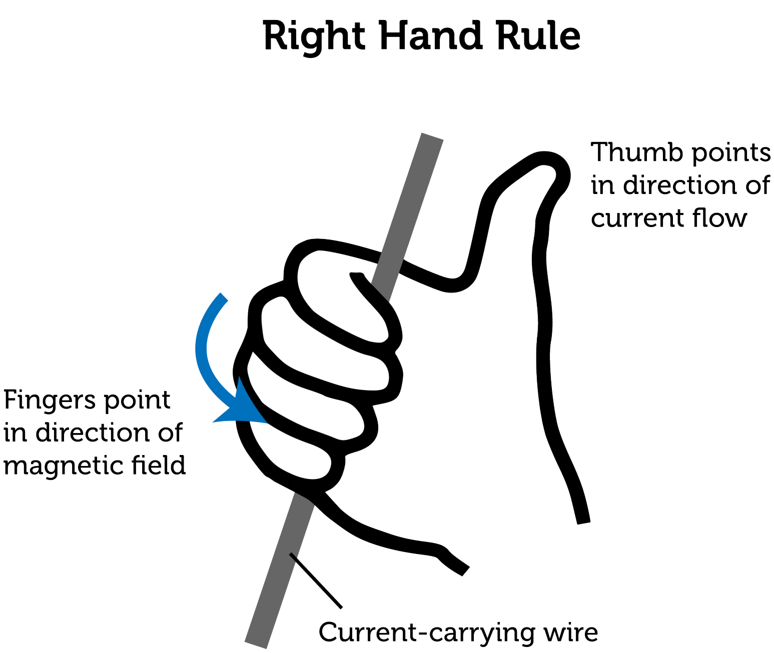

FIGURE 1.4
The direction of the magnetic field around a wire.

http://demonstrations.wolfram.com/CreationOfAMagneticFieldByAnElectricCurrent/

Magnetic Field of a Current-Carrying Loop/Coil of Wire

Imagine forming a loop from a long, straight wire. What would the magnetic field of the loop of wire look like? Using the right-hand rule, point your thumb in the direction of the current and imagine your hand moving around the wire. Your fingers would curl, showing the magnetic field as circles through and around the wire as shown in **Figure** 1.5. Of course, a compass would work just as well for a loop of wire as *s* straight wire in showing the field.

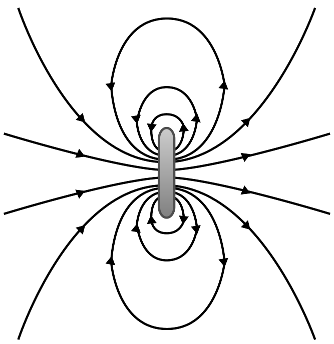

FIGURE 1.5

Now, imagine multiple turns of wire, as shown in **Figure** 1.6. The magnetic field through the loops would be greatly increased. The coil shown in **Figure** 1.6 is often called a solenoid. Another name for a solenoid is an electromagnet.

If the north pole of a bar magnet (or a thin iron rod) is brought close to bottom of the solenoid, it will be attracted (pulled) into the solenoid. If the solenoid is disconnected from the battery (say, by a switch) the magnet will no longer be attracted to the solenoid.

Solenoids have many practical applications. The first telegraph system operated by turning an electromagnet on and off which, in turn, attracted a magnetic object (the telegraph key). The key produced a series of clicks as it struck the electromagnet. Nowadays, solenoids are used, for instance, as electromagnetic switches in the ignition system of automobiles.

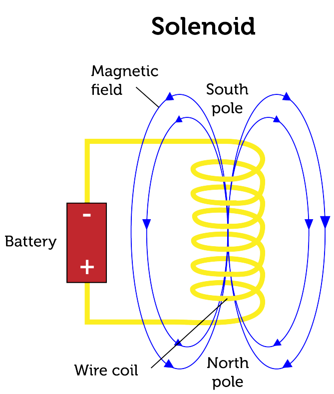

FIGURE 1.6
A solenoid.

http://demonstrations.wolfram.com/TheSolenoid/

1.2 The Magnetic Force acting on a Current-Carrying Wire

Objectives

The student will:

- Know under which conditions a current-carrying wire experiences a force when placed in a magnetic field.
- Use the right-hand rule to determine the force on a current-carrying wire in a magnetic field.
- Solve problems involving the force on a current-carrying wire in a magnetic field.

Introduction

If a current-carrying wire is able to exert a force upon a magnet, is it possible for a magnet to exert an equal and opposite force on a current-carrying wire? Newton's Third Law suggests this should be so.

Current-Carrying Wires in Magnetic Fields

In **Figure** 1.7, a current-carrying wire with current I is placed between the south and north magnetic poles of a magnet.

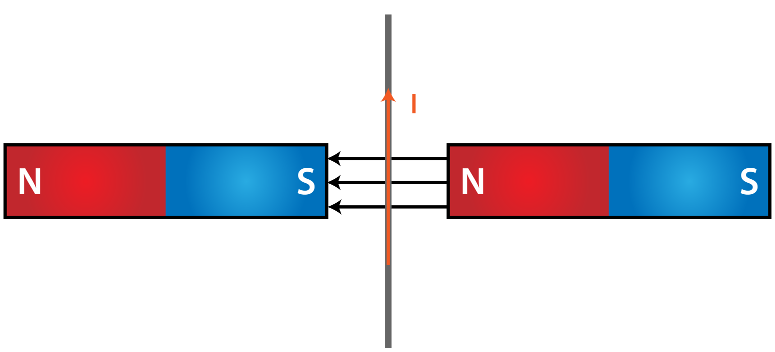

FIGURE 1.7

The magnetic field lines are perpendicular to the direction of the current in the wire. Under these circumstances, the wire is observed to be pushed toward the reader ("out of the page"). If the current in the wire is reversed, the wire is observed to be pushed away from the reader ("into the page."). We use a slightly different version of the right-hand rule to determine the direction of the force on a current-carrying wire in a magnetic field.

Aim your fingers in the direction of the current I and curl your hand toward the direction of the magnetic field B as shown in **Figure** 1.8 and **Figure** 1.9. The direction your thumb points is the direction of the force F on the current-carrying wire. The symbol with the circle and the dot below represents a vector with the force directed *out of the page*. The symbol with the circle and the cross below represents a vector with the force directed into the page.

Notice that the force F is perpendicular to the plane formed by the current-carrying wire and the magnetic field. The result is a rather unintuitive one. The force is not in the direction of the magnetic field. It is perpendicular to it!

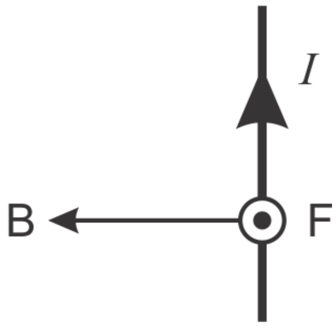

FIGURE 1.8

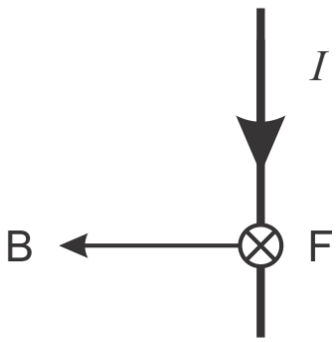

FIGURE 1.9

http://www.youtube.com/watch?v=EpuLrNTlxwA&feature=related

The magnitude of the force is found experimentally to equal the product of the current, I the length of wire L, the magnetic field B, and the sine of the angle between the vector L (in the direction of the current) and the direction of the magnetic field. When the current is parallel to the magnetic field lines, the force is zero, and when the current is perpendicular to the magnetic field lines, the force is at a maximum.

The magnitude of the force on a straight current-carrying wire within a magnetic field is given by

$F = ILB \sin \theta$.

The magnetic field B can then be expressed as $B = \frac{F}{IL \sin \theta}$. The units of B are, therefore, $\frac{N}{A*m}$. We define the derived unit $\frac{N}{A*m}$ as a tesla (T) in honor of the physicist and inventor Nikola Tesla (1856-1943), **Figure** 1.10.

For more information on the magnetic forces between current-carrying wires, see the link below.

http://demonstrations.wolfram.com/AmperesForceLawForceBetweenParallelCurrents/

Check Your Understanding

A wire of length 0.600 m carrying a current of 2.50 A, placed perpendicular to a uniform magnetic field, experiences a force of 2.75 N. What is the magnitude of the magnetic field where the wire is located?

Answer:

$F = ILB \sin \theta \rightarrow B = \frac{F}{IL \sin \theta} = \frac{2.75\ N}{(2.50\ A)(0.600\ m) \sin 90^\circ} = 1.833 \rightarrow 1.83\ T$

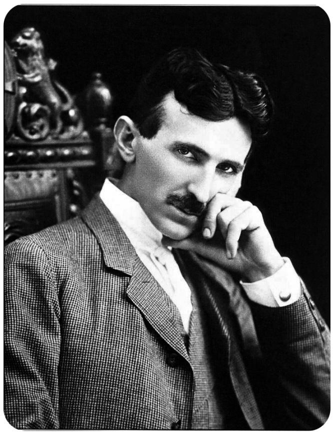

FIGURE 1.10
Nikola Tesla

Illustrative Example 19.2.1

A rectangular current-carrying loop of wire with constant current I is placed in a uniform magnetic field B such that the plane of the loop is perpendicular to the magnetic field, **Figure** 1.11. What is the net force acting on the loop?

Answer:

Using the right-hand rule, we find that the force F_{CD} on segment CD is directed away from the reader. The current direction in segment AB is opposite the direction of the current in segment CD, so the right-hand rule shows that the force F_{AB} on segment AB is directed toward the reader. The magnitudes of F_{CD} and F_{AB} are the same, since the lengths of both segments of wire are equal.

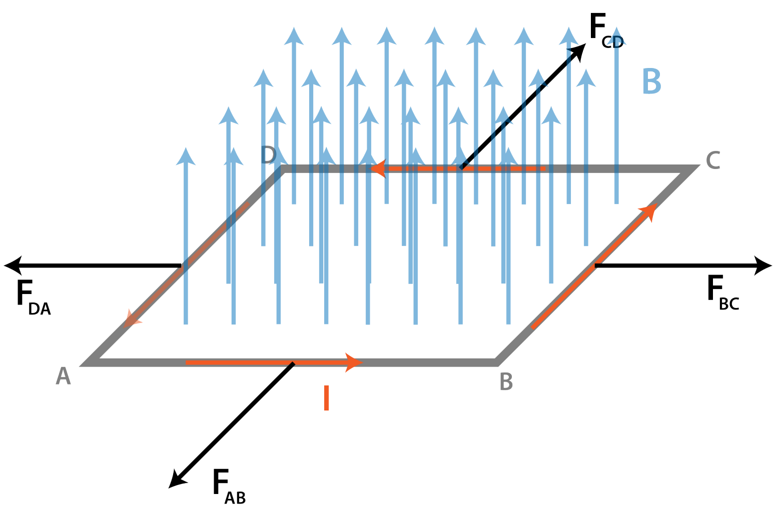

FIGURE 1.11

Applying the right-hand rule to segment BC of the loop, we find that a force F_{BC} on the wire is directed to the right. The direction of the current in segment DA of the loop is opposite to that in segment BC of the loop. The right-hand rule shows that the force F_{DA} is directed to the left. The magnitudes of F_{BC} and F_{DA} are the same, since the lengths of both segments of the loop are equal.

The net force on the loop of wire is, therefore, zero. The above argument can extend to non-rectangular loops, as well.

1.3 Magnetic Force on Moving Electric Charges

Objectives

The student will:

- Know under which conditions a moving electric charge experiences a force when placed in a magnetic field.
- Use the right-hand rule in order to determine the force on a moving electric charge in a magnetic field.
- Solve problems involving the force acting on a moving electric charge in a magnetic field.

Introduction

Electrically charged particles are everywhere. The sun sends forth an array of ionized particles into our solar system and into deep space, **Figure** 1.12. Some of the particles are trapped by the Earth's magnetic field and are responsible for interfering with electronic communication. Others initiate a chain of events culminating in the eerie and beautiful Aurora Borealis (the northern lights seen in high northern latitudes), **Figure** 1.13, and Aurora Australis (the southern lights seen in high southern latitudes).

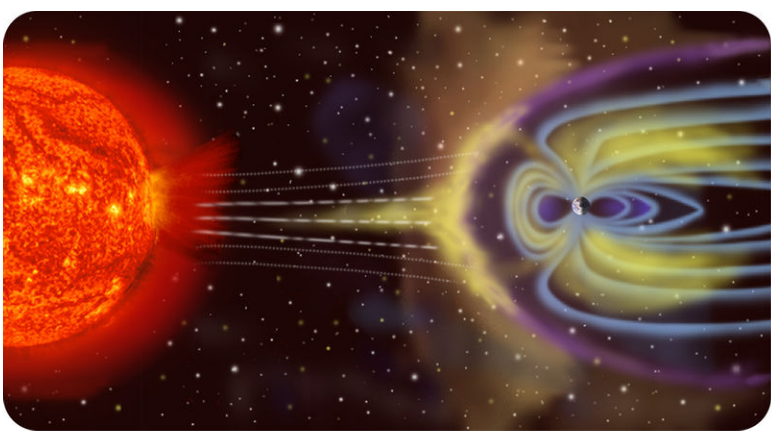

FIGURE 1.12

In the next section, we will investigate the effect that magnetic fields have on moving charges.

The Force on a Moving Electric Charge in a Magnetic Field

The force on a single charge moving through a magnetic field can be found by considering the force on a current-carrying wire.

A current is just the movement of many charged particles within a conductor. Using the definition of current, we have $I = \frac{\Delta Q}{\Delta t} = \frac{Nq}{\Delta t}$, where N is the total number of charges within the conductor, and q is the electric charge.

FIGURE 1.13
Aurora Borealis.

Substituting $I = \frac{Nq}{\Delta t}$ into $F = ILB\sin\theta$ gives:

$F = \frac{Nq}{\Delta t}LB\sin\theta$ (Equation A).

The displacement of a charge can be considered the length of the wire L, and therefore $L = v\Delta t$, where v is the velocity of the charge.

Substituting $v\Delta t$ into Equation A gives

$F = \frac{Nq}{\Delta t}v\Delta tB\sin\theta = NqvB\sin\theta$.

The force per charge is, therefore,

$\frac{F}{N} = qvB\sin\theta \rightarrow F_{on\ one\ charge} = qvB\sin\theta$.

The subscript above is dropped and it is understood that the force experienced by a charged particle moving through a magnetic field is

$F = qvB\sin\theta$.

The angle θ is the angle between the vectors representing velocity and the magnetic field.

Determining the Direction of the Force on a Charged Particle

The right-hand rule can be used in order to determine the direction of the force acting on a charged particle as it moves through a magnetic field.

As with a current-carrying wire, we point our fingers in the direction of motion of the charged particle (the direction of its velocity), and curl our fingers into the direction of the magnetic field. The outstretched thumb gives the direction of the force acting on the particle. The particle is assumed to have positive charge. If the particle is negatively charged, the force will be opposite to the direction the thumb points.

Figure 1.14 shows a positive charge $+q$ moving due north in a magnetic field pointing due west. The right-hand rule gives the force on the charge as out of the $V - B$ plane toward the reader. A negatively charged particle moving in the same direction would experience a force directed away from the reader, into the $V - B$ plane.

The force is always perpendicular to the plane formed by the velocity vector of the charge and the magnetic field direction.

For a practical example of how magnetic fields can be used with moving charges see the link below.

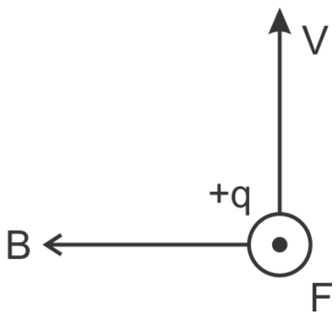

FIGURE 1.14

http://demonstrations.wolfram.com/TheMassSpectrometer/

Check Your Understanding

A proton moving with velocity $8.5 \times 10^{6}\ \frac{m}{s}$ enters a constant magnetic field of $2.15\ T$ at an angle of $30°$ to the field as shown in **Figure** 1.15. What is the magnitude and direction of the force acting on the proton?

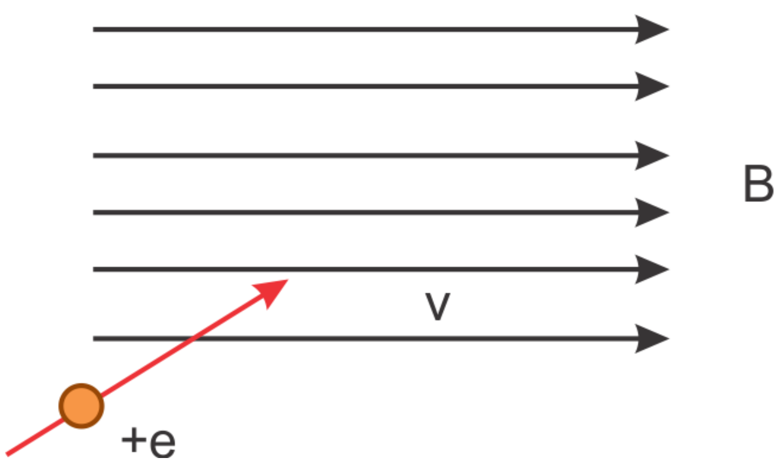

FIGURE 1.15

Answer:

The charge of the proton is $1.6 \times 10^{-19}\ C$.

$F = qvB\sin\theta = (1.6 \times 10^{-19}\ C)\left(8.50 \times 10^{6}\ \frac{m}{s}\right)(\sin 30°) = 6.8 \times 10^{-13}\ N$

The direction of the force is into the $v - B$ plane away from the reader (note that a proton is a positively charged particle, so we apply the right-hand rule without "flipping" the final result).

Illustrative Example 19.3.1

An electron moves in a plane perpendicular to a uniform magnetic field.

a. The magnitude of the force it experiences is:

1. Zero
2. Somewhere between $F = 0$ and a maximum of $F = qvB$

3. $F = qvB$

Answer:

The answer is 3.

Since the electron moves perpendicular to the magnetic field, it experience the maximum force because the angle between the velocity vector and the magnetic field is $90^\circ \rightarrow \sin 90^\circ = 1 \rightarrow F_{max} = qvB$.

b. What is the path of the electron as it moves through the magnetic field?

Answer:

Remember that since an electron is negatively charged, the force we determine from the right-hand rule must be reversed.

At any instant, the velocity and magnetic vectors are perpendicular to each other, as shown in **Figure** 1.16.

Since the magnetic field is uniform, the magnitude of the force on the electron is constant. The force, by the right-hand rule, remains perpendicular to the velocity of the electron and therefore cannot change the electron's speed-only its direction. When a constant force acts perpendicular to the velocity of an object, the object follows circular motion. The force shown below points toward the center of the circle in which the electron travels.

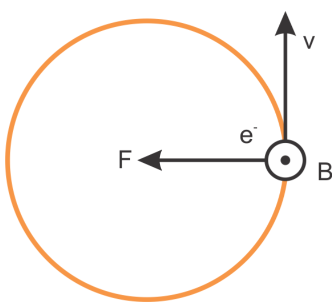

FIGURE 1.16

c. The magnetic field has magnitude 0.045 T, the velocity of the electron is $9.40 \times 10^6 \frac{m}{s}$, and its mass is 9.11×10^{-31} kg. Find the radius of the circle in which the electron travels.

Answer:

Since the electron travels in a circle, it experiences a force of

$F = ma_c = m\frac{v^2}{r}$.

This force is, of course, the force the electron experience due to the magnetic field $F_{max} = qvB$.

Thus, $m\frac{v^2}{r} = qvB \rightarrow r = \frac{mv}{qB} = \frac{(9.11\times10^{-31}\ kg)\left(9.40\times10^6\ \frac{m}{s}\right)}{(1.60\times10^{-19}\ C)(4.00\times10^{-2}\ T)} = 0.001338 \rightarrow 1.34 \times 10^{-3}\ m$.

1.4 A Practical Application of Magnetic Fields

Objectives

The student will:

- Understand the basic operation of an electric motor.

Vocabulary

- **brushes:**
- **commutator**
- **electric motor:** A device which converts electrical energy into mechanical work.

Introduction

The **electric motor** is arguably, the most important invention based on the understanding that a magnetic field could exert a force on a current-carrying wire. The average person uses many electrical appliances every day that depend upon an electric motor. There are motors in washing machines, dryers, air conditioners, electric lawn mowers and electric chain saws, electric blenders, electric can-openers, electric fans, DVD players, and in many children's toys, just to name a few.

How does an electric motor work?

The Rectangular Current Loop Revisited

In Example 19.2.1, a rectangular loop was placed perpendicular to the field lines of a uniform magnetic field. In such a position we showed that the net force on the loop was zero. We now consider the forces on a rectangular current-carrying loop of wire with constant current I, when placed in a uniform magnetic field B, such that the plane of the loop is parallel to the magnetic field. With such an arrangement, the magnetic field lines are perpendicular to the side (b) of the loop and parallel to the side (a) of the loop as seen in **Figure** 1.17.

By the right-hand rule, the force on the left side $\vec{F}_1$ of the loop is toward the reader, and the force on the right side $\vec{F}_2$ is away from the reader. We treat the result as a scalar quantity.

$F_1 = ILB\sin\theta = ILB\sin 90^\circ = ILB \rightarrow F_1 = ILB \; F_2 = ILB\sin\theta = ILB\sin 90^\circ = ILB \rightarrow F_2 = -ILB$

Since the forces are in opposite directions, $\vec{F}_1$ is taken as positive and $\vec{F}_2$ is taken as negative.

These are the only forces on the loop, since the angle between the magnetic field and the remaining sides of the current-carrying loop is zero degrees.

$F = ILB\sin\theta = ILB\sin 0^\circ = 0$

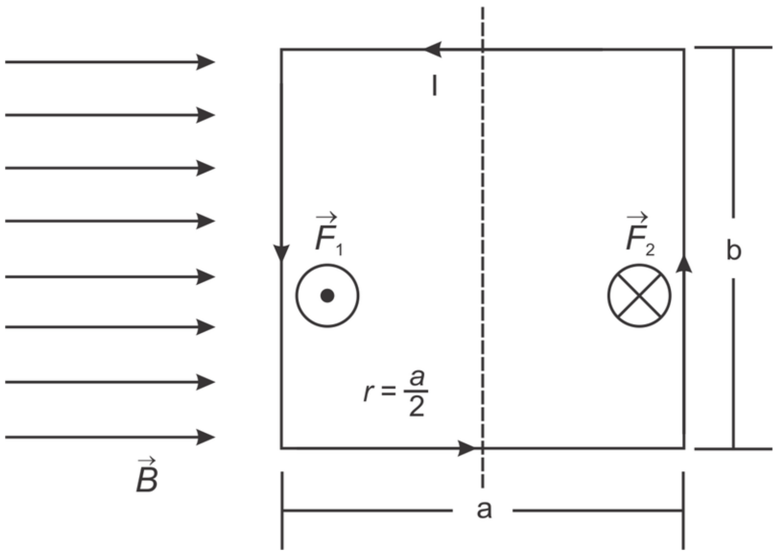

FIGURE 1.17

Let us imagine that the coil is free to rotate about the dotted line shown bisecting the coil in **Figure** 1.17. The forces $\vec{F}_1$ and $\vec{F}_2$ both place counterclockwise torques upon the loop.

Recall that the torque is defined as $\tau = rF \sin\theta$, where θ is the angle between the moment arm r and the force F.

The angle between r and F is $90°$, and therefore the net torque on the loop is

$\tau = rF \sin 90° + rF \sin 90° = 2rF \rightarrow \tau = 2rF$.

By substituting Equation 1 into Equation 2 the net torque can be expressed as:

Equation 1: $F = ILB$

Equation 2: $\tau = 2rF$

Equation 3: $\tau = 2rILB$

The moment arm has length $r = \frac{a}{2}$, and the side of the wire where the force is applied has length $L = b$.

Upon substitution into Equation 3 we have,

$\tau = 2rILB = 2\frac{a}{2}IbB = I(ab)B = IAB \rightarrow$

$\tau_{maximum} = IAB$, where A is the area of the loop.

This is the maximum torque that the loop experiences. Once the loop begins to rotate, the angle between the moment arm $\frac{a}{2}$ and the forces $\vec{F}_1$ and $\vec{F}_2$ is decreased until reaching zero degrees. This occurs when the loop in **Figure** 1.17 has rotated out of the page and is facing the reader. The forces $\vec{F}_1$ and $\vec{F}_2$ at this point are both parallel with the moment arm, and therefore the net torque on the loop is zero.

The torque the loop experiences as it turns is therefore $\tau = IAB \sin\theta$.

A DC Motor

In the situation above, once the loop has rotated ninety-degrees,3 the net torque is zero. The loop stops turning, see **Figure** 1.18.

If the loop could be kept in motion, we would have an electric motor.

This can be done if, at the moment the net torque on the loop is zero, the current is reversed. Then the forces $\vec{F}_1$ and

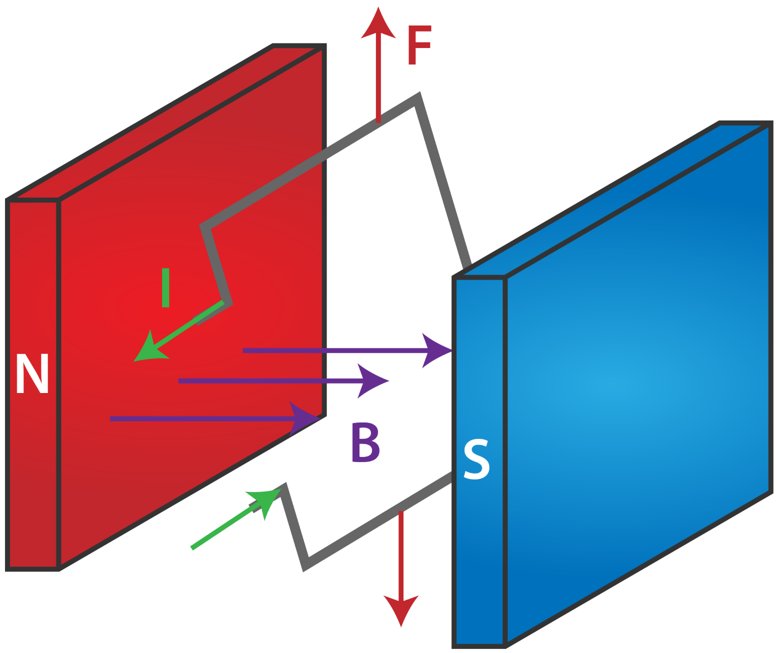

FIGURE 1.18
Once the loop is vertical it will no longer turn.

$\vec{F}_2$ would point inward. The loop's inertia carries it slightly past the point of zero net torque, but since the forces are now acting inward, the loop continues to turn. The process repeats thousands of times per second and we have a motor.

The secret to reversing the current is shown in **Figure** 1.19. After the loop rotates a quarter turn, it encounters a split ring commutator (see **Figure** 1.19). At this instant the voltage source (a battery) no longer provides current to the loop because of the split ring. But the inertia of the coil carries it farther around and a connection is immediately re-established with the battery. The right-hand side of the coil (which had been connected to the low side of the battery) is now connected to the high side of the battery and the current through the coil is reversed. The carbon brushes provide the contacts for the battery.

Attachments can be made to coil in order to perform mechanical work. Indeed, a motor is a device which converts electrical energy into mechanical work.

Motors typically have thousands of coils. A greater torque can be established with numerous coils. The motor, in turn, can perform more mechanical work.

1. The magnitude of the force on a straight current-carrying wire within a magnetic field is given by the equation $F = ILB \sin\theta$.

The direction of the force is found using the right-hand rule: The force is perpendicular to the plane formed by the current-carrying wire and the magnetic field direction.

2. The force experienced by a charged particle moving through a magnetic field is given by the equation $F = qvB \sin\theta$.

The direction of the force is found using the right-hand rule but must be reversed if the particle is negatively charged. The force is perpendicular to the plane formed by the velocity vector of the charge and the magnetic field direction.

3. A charge traveling in a uniform magnetic field moves in a circle of radius

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

4. The torque a current-carrying loop experiences in a uniform magnetic field is given by the equation

$\tau = IAB \sin\theta$

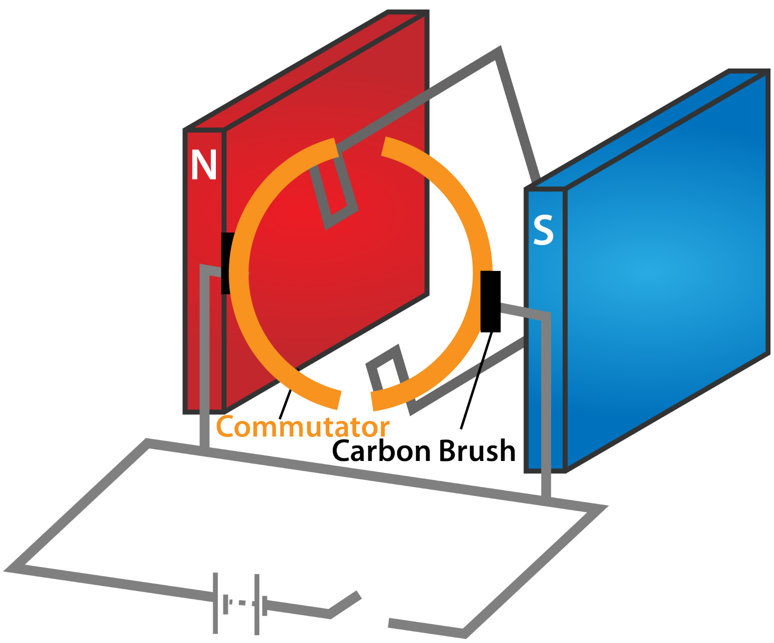

FIGURE 1.19

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