Chapter Ten

MAGNETISM; ELECTROMAGNETISM AND ITS APPLICATIONS

KEY IDEAS

One of the phenomena associated with all substances is magnetism. Magnets have north and south poles, named for the way they orient themselves in the Earth's magnetic field. Unlike electric charges, single magnetic poles have not been discovered: A north pole is found in conjunction with a south pole. Like poles repel each other and unlike poles attract, a property similar to that observed in electric charges. The magnetic field around a magnetic configuration may be mapped using field lines in the same way an electric field is mapped.

Magnetic fields exist whenever an electric current is present. The direction of the magnetic field is always perpendicular to the electric field. Current-carrying wires and charges moving perpendicularly through a magnetic field experience forces that are perpendicular to both the direction of the magnetic field and the motion of the charges.

If a conductor is moved perpendicularly through a magnetic field, a potential difference is established across the conductor.

If a charge is accelerated, the changing electric and magnetic fields will give rise to electromagnetic waves that are carriers of energy.

KEY OBJECTIVES

At the conclusion of this chapter you will be able to:

- Define the terms *magnet, north pole, south pole, temporary magnet, permanent magnet.*
- Define the term *domain*, and describe how domains contribute to the magnetic properties of a metal such as iron.
- State the conventions for drawing magnetic field lines, and draw simple magnetic field configurations.
- Define the term *magnetic induction*, and state the SI unit for magnetic induction (field strength).
- Use an appropriate hand rule to describe the magnetic field around a current-carrying wire.
- Use an appropriate hand rule to determine the magnetic polarity of a current-carrying coil (solenoid).
- State the factors that influence the magnetic induction in a straight wire and in a solenoid.

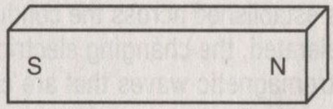
- Use an appropriate hand rule to determine the force on a current-carrying wire in an external magnetic field.
- Describe how a potential difference may be induced across a conductor moving in a magnetic field.
- Describe how electromagnetic waves may be produced from accelerating charges.

10.1 INTRODUCTION

The phenomenon of magnetism was known in ancient times, when it was observed that certain rocks (called lodestones) attracted iron. It was also observed that, when pieces of iron were rubbed with lodestones, the iron became magnetized and that, if a very thin magnet was floated on water, one end of the magnet always pointed in the northern direction. As a result of these discoveries, the Chinese used magnets to create compasses with which to navigate their waters.

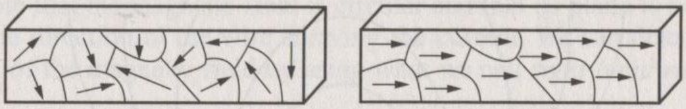
10.2 GENERAL PROPERTIES OF MAGNETS

A **magnet**, then, is any substance that possesses the properties discussed in Section 10.1. One common shape of a magnet is a rectangular bar, as shown in the diagram:



We know that magnets have "polarity." The end that points northward is the **north pole** of the magnet, and the end that points southward is the **south pole**. Also, when two magnets are brought near one another, it is observed that *like poles repel* and *unlike poles attract*. For these reasons we can conclude that the Earth itself behaves as a giant magnet. Earth's "North Pole" behaves like a magnetic south pole since it attracts the north pole of compass needles. If a piece of metal is placed in the vicinity of a magnet, the metal itself will become magnetized. If the metal retains its magnetism after the original magnet is removed, it is called a **permanent magnet**; otherwise it is a **temporary magnet**. Alloys such as ALNICO make good permanent magnets, while soft iron produces excellent temporary magnets.

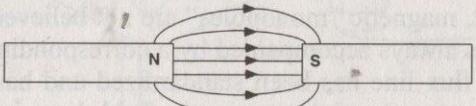
Why do certain substances, such as iron, have magnetic properties? It has been discovered that groups of atoms align their unpaired electrons so that they spin in the same direction, giving rise to microscopic magnets called **domains**. An external magnetic field causes all the domains to align in the same direction, as shown in the diagram on the right.

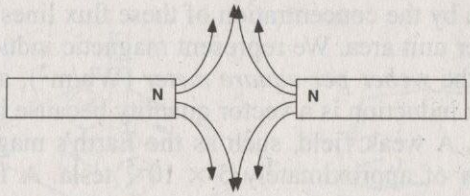


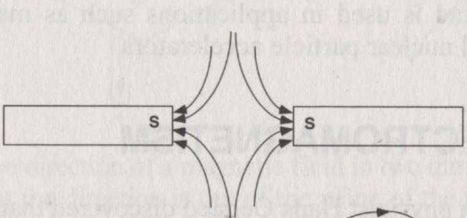
10.3 MAGNETIC FIELDS

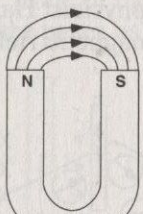
In the same way that electrostatic and gravitational forces can be explained by electric and gravitational fields, the existence of magnetic forces can be explained by the presence of magnetic fields. Also, just as field lines are used to visualize electric and gravitational fields, magnetic field lines (called *flux lines*) are used to visualize a magnetic field.

The magnetic fields between various poles of two adjacent magnets are shown in the diagrams, as well as the field around a horseshoe magnet, which is simply a bar magnet that has been bent so that the north and south poles are near each other. By agreement the field lines point away from the north and toward the south.









We can also draw the magnetic field around a single bar magnet, as shown below.

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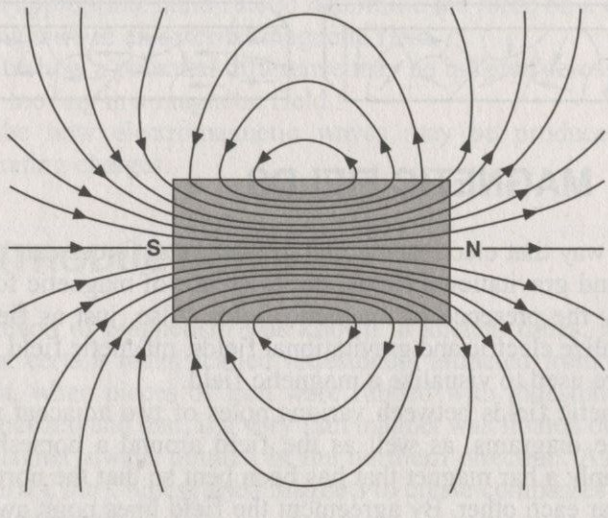
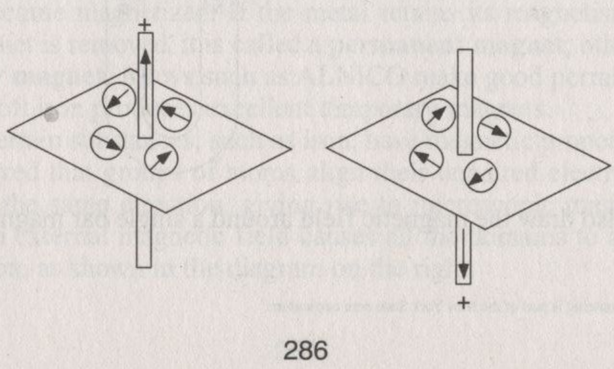


Note that the field lines form closed loops inside the magnet. As a consequence of this fact, magnetic "monopoles" are not believed to exist: a north pole of a magnet is always accompanied by a corresponding south pole.

Each magnetic flux line has been standardized and has the SI unit of 1 weber (Wb). The strength of the magnetic field, known as the **magnetic induction**, is given by the concentration of these flux lines, that is, the number of flux lines per unit area. We represent magnetic induction by the letter **B,** and its unit is the *weber per square meter* (Wb/m^2), also known as the tesla (T). Magnetic induction is a vector quantity because it has both magnitude and direction. A weak field, such as the Earth's magnetic field, has a magnetic induction of approximately 5×10^{-5} tesla. A field of 1 tesla is extremely strong and is used in applications such as magnetic resonance imaging (MRI) and nuclear particle accelerators.

10.4 ELECTROMAGNETISM

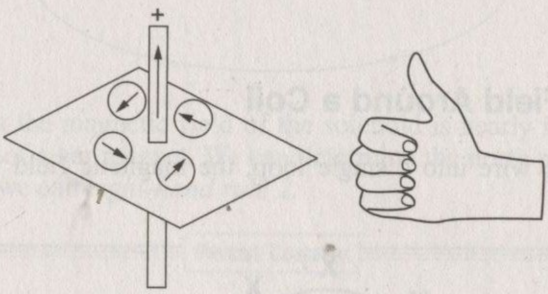
In 1820, the Danish physicist Hans Oersted discovered that a wire carrying a current produced a magnetic field as shown in the diagram.

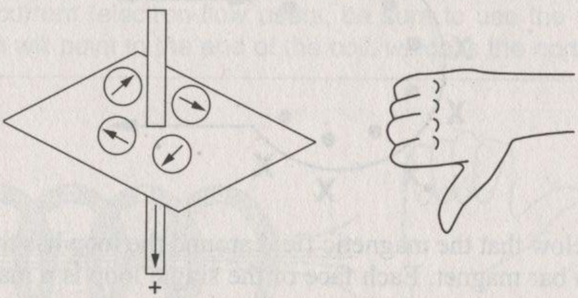


We note that the magnetic field is circular and that its plane is perpendicular to the direction of the wire carrying the current. We can determine the direction of the magnetic field by using what we call *right-hand rule 1:*

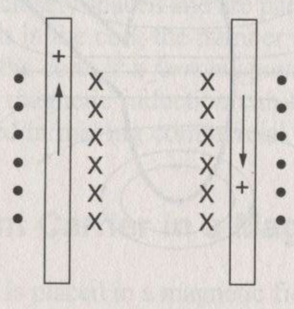
PHYSICS CONCEPTS

The thumb of the right hand is pointed in the direction of the conventional current. The fingers of the right hand (from wrist to fingertips) will curl in the direction of the magnetic field. (*Note*: If you use electron flow instead of conventional current, use your *left* hand instead of your right hand.)

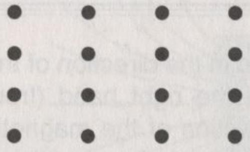




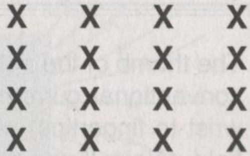
To represent the direction of a magnetic field in two dimensions, we use dots (•) to indicate that the direction is out of the plane of the paper and X's (X) to indicate that the direction is into the plane of the paper, as shown in the diagram.



The magnetic induction in the vicinity of a straight wire is directly proportional to the current in the wire and is inversely proportional to the distance from the wire. A uniform magnetic field into or out of the plane of the paper can be represented as shown below:



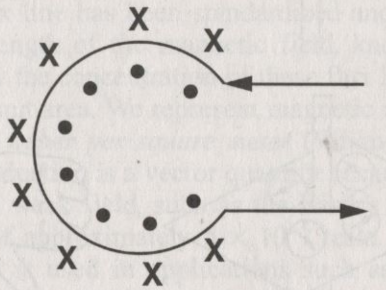
Uniform field out of the page



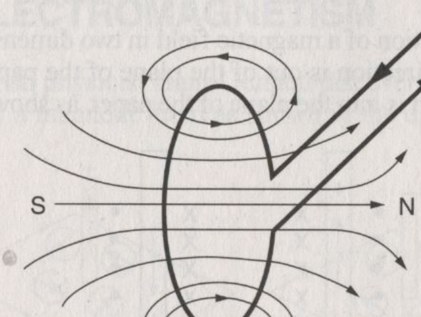
Uniform field into the page

Magnetic Field Around a Coil

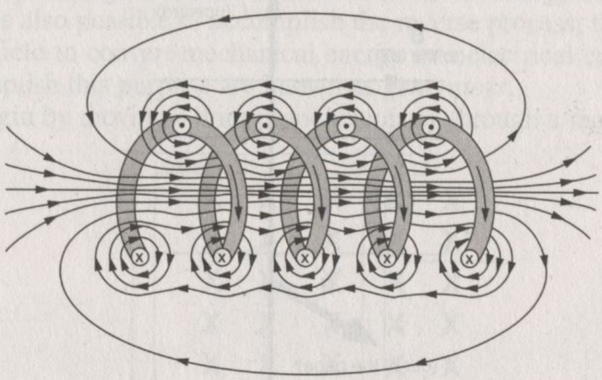
If we bend our wire into a single loop, the magnetic field will appear as illustrated.



We note below that the magnetic field around the loop has the appearance of a very thin bar magnet. Each face of the single loop is a magnetic pole.



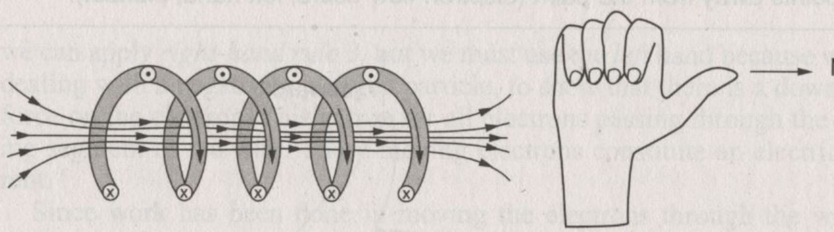
If we link a number of loops together, we produce a coil (or a *solenoid*) whose magnetic field is the result of the fields of the individual loops. The magnetic field around a solenoid is shown below.



We note that the magnetic field of the solenoid is nearly identical to the magnetic field of a bar magnet. We can determine the north pole of our coil by using what we call *right-hand rule 2:*

PHYSICS CONCEPTS

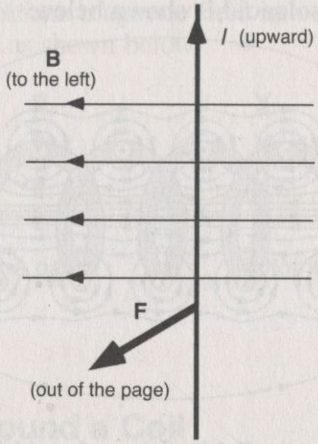
The fingers of the right hand are wrapped in the direction of the conventional current (electron-flow users, be sure to use the left hand). The thumb will point to the end of the coil, which is the north pole.



We note that the magnetic field is strongest inside the coil and is also uniform because the lines are closely spaced and are parallel. The magnetic induction depends on the current in the coil, the number of turns per unit length of the coil, and the nature of the core. If a *ferromagnetic* core such as soft iron is placed inside the coil, the magnetic induction can be increased thousands of times—a fact that is applied in making commercial electromagnets.

Forces on a Current Carrier in a Magnetic Field

If a wire carrying a current is placed in a magnetic field, so that the direction of the current is perpendicular to the direction of the magnetic field, the magnetic field of the wire will interact with the magnetic field of the magnet to produce a force on the wire. This is illustrated in the diagram.

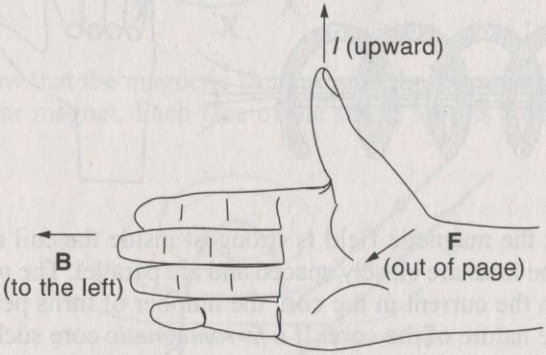


If, however, the current is parallel to the magnetic field, no force will be present on the wire.

To determine the direction of the force on the wire, we use what we call *right-hand rule 3,* illustrated in the diagram below.

PHYSICS CONCEPTS

The thumb points in the direction of conventional current, the fingers point in the direction of the magnetic field, and the direction of the force points away from the palm (electron-flow users, left hand, please!).

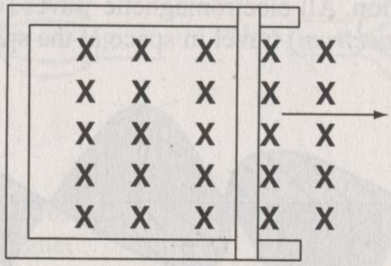


Suppose the wire was neither perpendicular nor parallel to the magnetic field. In that case, there would be a force on the wire but it would be less than the maximum force present when the wire is perpendicular, but greater than zero when the wire is parallel.

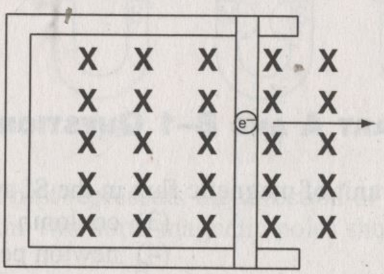
10.5 ELECTROMAGNETIC INDUCTION

A motor uses a magnetic field to convert electrical energy into mechanical energy. It is also possible to accomplish the reverse process, that is, to use a magnetic field to convert mechanical energy into electrical energy. Devices that accomplish this purpose are known as *generators*.

Let's begin by moving a wire perpendicularly through a magnetic field.



If we focus on one electron in the wire, indicated in the diagram below:



we can apply *right-hand rule 3,* but we must use the *left* hand because we are dealing with a negatively charged particle, to show that there is a downward force on the electron. This is true for all electrons passing through the moving segment of the wire. These moving electrons constitute an electric current.

Since work has been done in moving the electrons through the wire, a potential difference has been induced across the ends of the wire. This potential difference depends on the strength of the magnetic field, the length of the wire in the magnetic field, and the speed with which the wire is moved. It is important to note that in order to induce maximum voltage the wire needs to "cut" through the magnetic flux lines at a 90° angle. As the angle decreases, the voltage induced decreases. If the wire moves parallel to the magnetic flux lines, it doesn't "cut" through any flux lines, and so zero potential difference is induced.

Electromagnetic Waves

A changing electric field produces a changing magnetic field and vice versa. If the changing electric field is produced by an *accelerating* charge, energy will be radiated away from the charge in the form of *electromagnetic waves*. In an electromagnetic wave, both the electric field and the magnetic field vary as a sine wave and the two fields are perpendicular to each other and to their direction of motion. All electromagnetic waves (collectively known as the *electromagnetic spectrum*) travel in space at the speed of light.