Electromagnets

A. Electromagnets

1. Magnets

   a. Material with the ability to attract iron or iron alloys is called a magnet. Materials attracted by magnets are called magnetic materials. Examples of magnetic materials are iron, nickel, cobalt, and alloys of these basic materials. Materials not attracted by magnets, wood, paper, glass, copper, or tin, are nonmagnetic materials. A magnet attracts magnetic material by contact, at a distance, or through a nonmagnetic material.

2. Natural Magnets

   a. The phenomenon of magnetism was first observed in nature with the discovery of a type of stone (iron ore) near the town of Magnesia in Asia Minor. This stone was called magnetite, from which magnet was derived. Today magnetite is iron ore possessing magnetic qualities found in its natural, unrefined form. For this reason, magnetite is said to be a natural magnet.

3. Artificial Magnets

   a. Magnets produced from ordinarily unmagnetized magnetic materials are called artificial magnets. Such magnets are produced either by bringing a magnetic material in contact with a natural magnet or by electrical means. Artificial magnets produced by contact or stroking with a natural magnet are weak in terms of modern standards. Much stronger artificial magnets are produced by electrical means.

   b. The process of producing artificial magnets by stroking the magnetic material, or bringing a material in contact with a natural magnet is called inducing magnetism. Magnetic materials have different abilities to become magnetized, and to retain this condition once they are magnetized. The ability of a material to retain its magnetism is called retentivity. Artificial magnets are classified as “permanent” or “temporary”, depending on their ability to retain magnetic strength after the magnetizing force has been removed.

c. Hardened steel and certain alloys are relatively difficult to magnetize. Once magnetized, however, these materials retain a large part of their magnetic strength and are called permanent magnets. Permanent magnets are used extensively in electric measurement instruments, permanent magnet loud speakers, and magnetos.

d. Substances that are relatively easy to magnetize, such as soft iron and annealed silicon steel, but retain only a very small portion of their magnetism after the magnetizing force is removed, are called temporary magnets. Paper clips, for example, can be connected in a string to a permanent magnet, but when the magnet is removed, the clips fall and separate. Silicon steel and similar materials are used in transformers with constantly changing magnetism and in generators and motors with field strengths that can be readily changed. Magnetism that remains after the magnetizing force is removed is called residual magnetism.

4. Theory of Magnetism

a. Magnetic Poles

1) The effects of magnetism are not distributed uniformly over the entire surface of a magnet. They are strong at the ends (poles) and weak in the middle. This is illustrated by suspending a bar magnet, free to swing in a horizontal plane. The magnet swings around and comes to rest with one end pointing toward north. Regardless of number of times this experiment is repeated, the same end of the magnet comes to rest pointing toward the north. When this fact was first established, the north-seeking end of the magnet was called the north pole, and the south-seeking end of the magnet was called the

south pole. These designations are still used. Permanent magnets are marked “N” or “(+)” at the north pole, and “S” or “(-)” at the south pole.

b. Domain Theory

1) Various theories have been developed to explain magnetism. One of the most popular is domain theory.

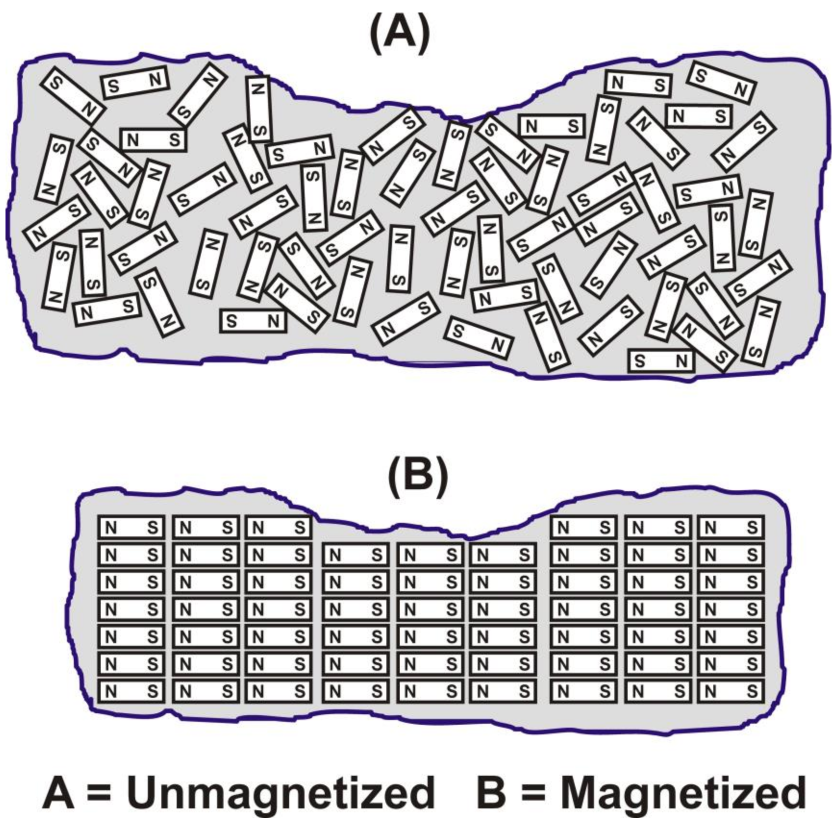
2) When a bar magnet is broken in two, each part becomes a magnet with a north pole and south pole. If these parts are again broken in two, four magnets are formed. Regardless of divisions, parts of the original magnet are always magnets themselves.

3) All properties of magnetization are based on certain alignments of large numbers of atoms called domains. In magnetic materials, the “spin” of an atom's orbital electrons is such that it sets up a north and south pole. A domain is a group of atoms (approx.), with similar electron spins and magnetic poles. This causes the atoms to line up with one another.

4) When a magnetic material is demagnetized, its domains are oriented in random fashion (Picture 1A). The result is a cancellation of magnetic effects of individual domains. No overall magnetic field exists. When the material is brought under the influence of a strong magnetic field, the domains begin to align themselves in a definite direction. As the strength of the magnetic field is increased, more and more domains align themselves (Picture 1B). At one end of the iron bar are many tiny north (N) poles, and at the other end are many tiny south (S) poles. These small poles acting together produce strong external magnetic effects at each end. Along the sides of the bar, magnetic effects exerted on external magnetic material is

reduced by the interaction of north and south poles of individual domains.

5) The reason each piece of magnet always has two poles when broken in two is easily seen in Picture 1B. No matter where the magnet is broken, north and south poles are always exposed at the ends of each piece.



Picture 1, Arrangement of Molecules on a Piece of Magnetic Material

6) When all domains are aligned, the material is saturated. Therefore, there is a definite limit to the magnetism a material can have. When all domains have been lined up in perfect order, nothing more can be done to increase the magnetism.

c. First Law of Magnetism

1) The first law of magnetism states that like magnetic poles repel, and unlike magnetic poles attract. This can be observed when a suspended bar magnet is free to swing about in a horizontal plane. When the north pole of a second magnet is brought toward the north pole of the suspended magnet, the suspended magnet is pushed away (repelled).

2) The same results are obtained if the south pole of the second magnet is brought toward the south pole of the suspended magnet. But when the south pole of the second magnet is brought close to the north pole of the suspended magnet, it is pulled toward (attracted by) the second magnet. The same results are obtained if the north pole of the second magnet is brought close to the south pole of the suspended magnet.

d. Second Law of Magnetism

1) Strength of attraction or repulsion between two magnetic poles is dependent upon distance and individual magnetic strength. Magnetic force of attraction and repulsion is similar to the force of attraction and repulsion between two electric charges. Charles Coulomb used a torsion balance and established the inverse square law of force between magnetic poles. This second law of magnetism states that the force between magnetic poles is directly proportional to the product of the magnetic pole field strengths and inversely proportional to the square of the distance between the magnetic poles.

2) When magnetic poles are separated by a considerable distance, no visible effects are apparent between them. The force of attraction or repulsion between magnetic poles varies inversely with the distance squared. Thus, if the distance between the two poles is reduced by a

factor of three, the force becomes nine times as great. If the distance between the poles is tripled, the force becomes one ninth the original amount.

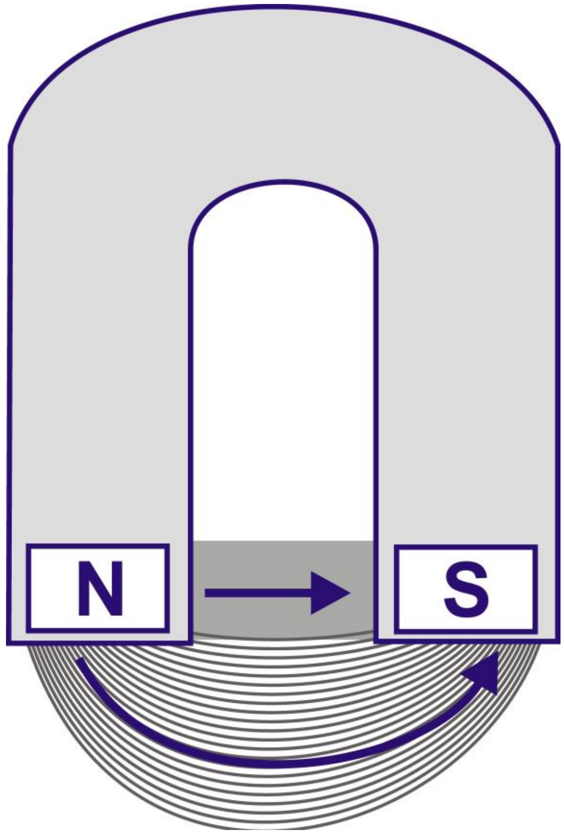
3) Force of attraction and repulsion between magnetic poles directly varies with the amount of force the individual magnetic poles are capable of exerting. The strength of a magnetic pole varies with size, material, and degree of magnetization (i.e., the number of domains which are aligned).

e. Lines of Magnetic Flux

1) Magnetic Field

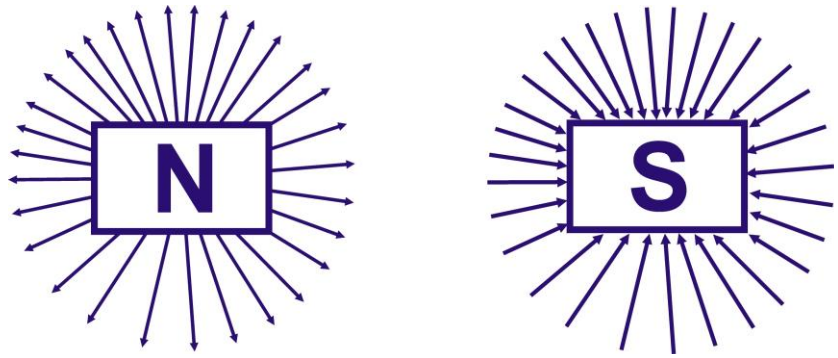
a) A magnetic pole acts at a distance upon other magnetic poles and magnetic materials, because an invisible force exists in the space surrounding the pole. This invisible magnetic force is called the external magnetic field. The complete magnetic field consists of the external field plus the field through the material of the magnet. A magnetic field is considered a vector since, like a vector, it has direction as well as magnitude.

b) A magnet placed in a magnetic field will move as a consequence of this force. North pole moves in one direction, south pole moves in the opposite direction. These forces have been given the name, “lines of force” (Picture 2). Arrowheads are placed on each line to indicate that it leaves the magnet at the north pole and enters at the south pole. Within the magnet, the direction of the lines of force is from south pole to north pole, so a continuous loop is formed by each line of force. The direction of these lines is arbitrarily defined as the direction in which the north pole of a compass needle points when placed along a line of force inside the magnet.



Picture 2, Magnetic Lines of Force

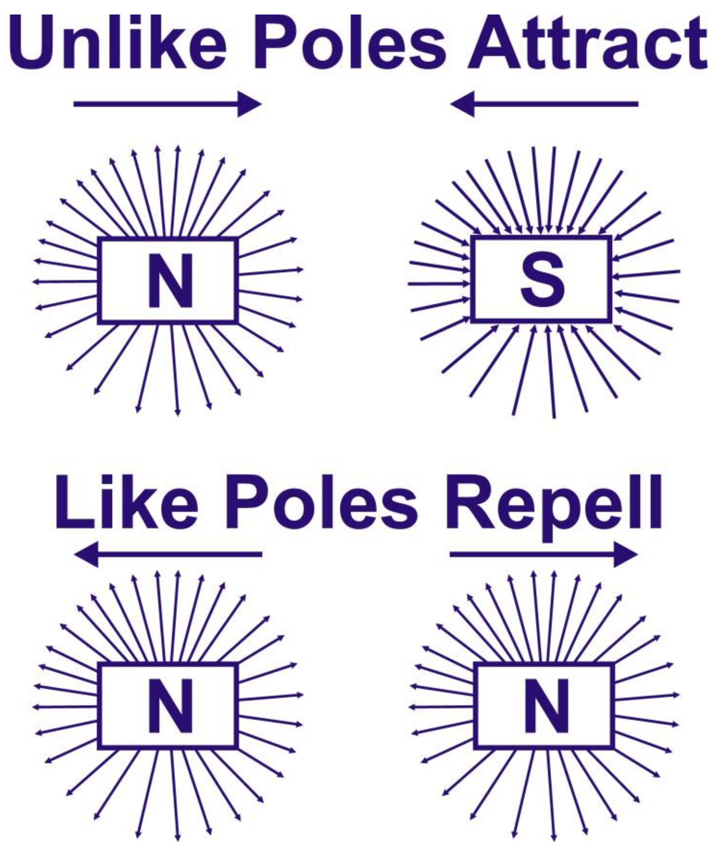
c) Various terms are used to distinguish lines of force inside and outside the magnet. For this text, only the term magnetic lines of force will be used. The magnetic field completely fills space surrounding a magnet. This field extends great distances, with intensity decreasing rapidly as distance is increased. Picture 3 illustrates a magnetic field extending from the ends in all directions around a bar magnet.



Picture 3, End View Representation of the Lines of Force

d) Although lines of force are invisible, they have certain properties (Picture 4) and are summarized as follows:

- Magnetic lines of force are continuous and always form closed loops.
- Magnetic lines of force never cross one another.
- Magnetic lines of force pass through all materials, although not all materials have magnetic properties.
- Magnetic lines of force of the same polarities (like poles) push apart.
- Magnetic lines of force of different polarities (unlike poles) pull together.



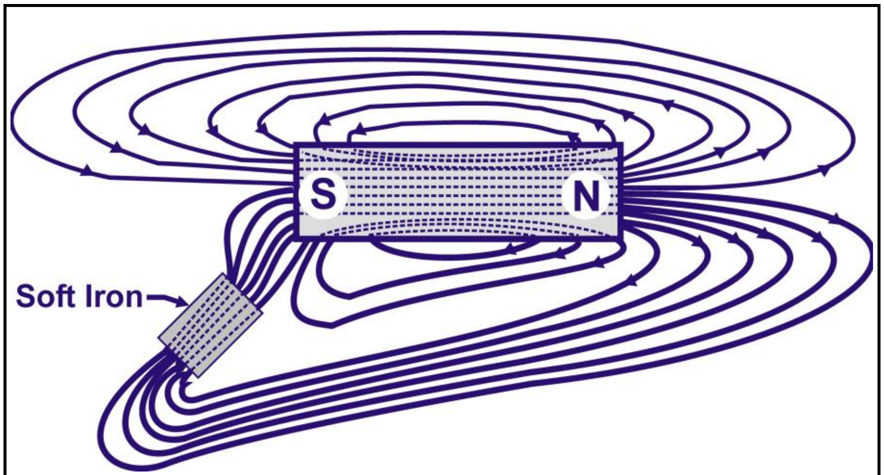
Picture 4, Lines of Force Between Poles

2) Permeability

   a) Modern theory considers lines of force as an imaginary, but highly useful concept for mapping magnetic fields and calculating effects. A single line of force represents a unit of magnetic force. The closer together these lines of force, the stronger the magnetic flux in that area. The ability of these lines to pass through a material, compared to air, is called permeability.

   b) There is no known insulator for magnetic flux. If a nonmagnetic material, such as air, is placed in a magnetic field, there is no appreciable change in flux. Flux penetrates the nonmagnetic material. For example, a glass plate between poles of a horseshoe magnet will have no appreciable effect on the field although glass is a good insulator in an electric circuit.

c) The permeability of magnetic materials is several thousand times that of air, permitting a flux density far greater than in air. A good magnetic material with high permeability can concentrate flux and produce a large value of flux density (Picture 5). For this reason, magnetic materials, such as iron, are used to guide and concentrate flux in such magnetic circuits as transformers.

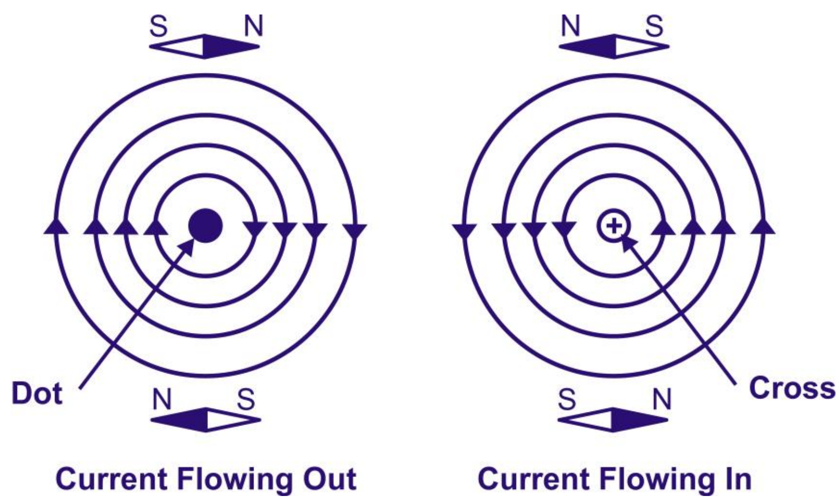


Picture 5, Effects of a Magnetic Substance on a Magnetic Field

f. Electromagnetic Flux

1) Current Carrying Conductors

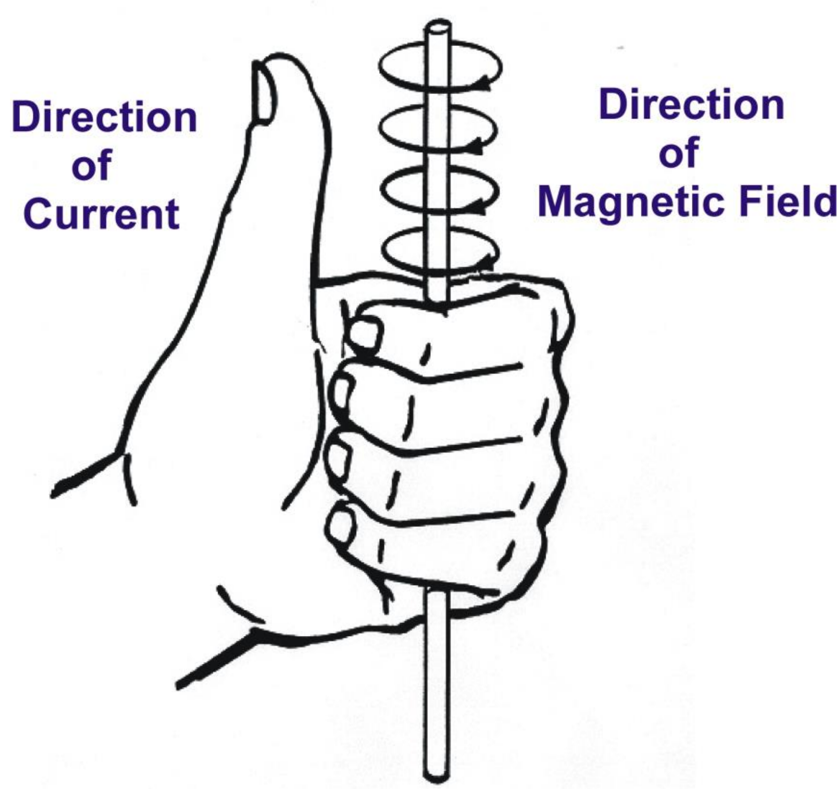
a) When a conductor of electricity has current flowing through it, a magnetic field exists about the conductor (Picture 6). In this figure, current in the conductor flowing out of the page, as indicated by the symbol, X, representing the pointed end of the arrow. The end of the conductor with current flowing into the page is shown by the symbol, +, representing the tail of an arrow. Magnetic fields produced by an electrical current are always at right angles to the current that produces it. Since magnetic fields have both intensity and direction, lines of force are closely concentrated (stronger) near the conductor and become less dense as the distance from the conductor increases. Strength of magnetic fields around a current-carrying conductor increases when current increases, and decreases when current decreases. Similar to field strength of a permanent magnet, magnetic field strength of a current-carrying conductor also varies inversely with the square of the distance.



Picture 6, Magnetic Fields Around Current-Carrying Conductors

b) After the discovery of the relationship between current through a wire and direction of magnetic field, caused by current flow, a simple rule was established for determining direction of magnetic field around a current-carrying conductor. This rule, known as the left-hand rule for conductors, is based on the electron theory of current flow. The left-hand rule is stated as follows:

Grasp the conductor in the left hand, with the thumb pointing in the direction of electron current flow. The direction of the fingers will indicate the direction of magnetic lines of force (Picture 7).



Picture 7, Left Hand Rule for Conductors

c) Using this rule, if direction of the magnetic field or current is known, the other may be obtained.

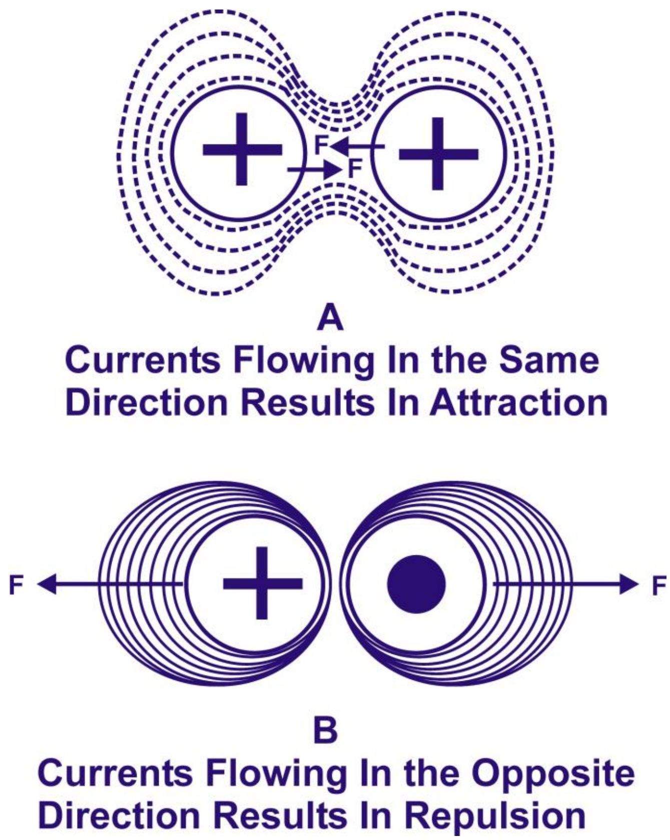
g. Multiple Conductor Interaction

1) The magnetic field produced by electric currents in separate conductors cause attraction or repulsion, as in permanent magnetic fields, and depends on the direction of current flow. The effects of parallel conductors with current flowing in the same direction is shown in Picture 8A. In the area between conductors, lines of force

oppose each other causing the field to be weakened. In the area outside the conductor, the field is strengthened. Because of the weakened field, the lines of force tend to encircle both conductors, and the conductors are attracted to each other. Thus, it is stated that parallel currents flowing in the same direction cause attraction. Picture 8B shows the effects of parallel conductors with currents flowing in opposite directions. By application of the left-hand rule, the directions of the lines of force indicate that the two magnetic fields aid each other in the region between the conductors. This field is now strengthened as compared with the field outside of the conductors, so it tends to push the conductors apart; they repel each other. Thus, parallel currents flowing in opposite directions cause repulsion.

2) Currents Flowing in the Same Direction Result in an attraction (A)

3) Current Flowing in the Opposite Direction Result in a repulsion (B)



Picture 8, Magnetic Field and Forces Resulting from Two Parallel Conductors

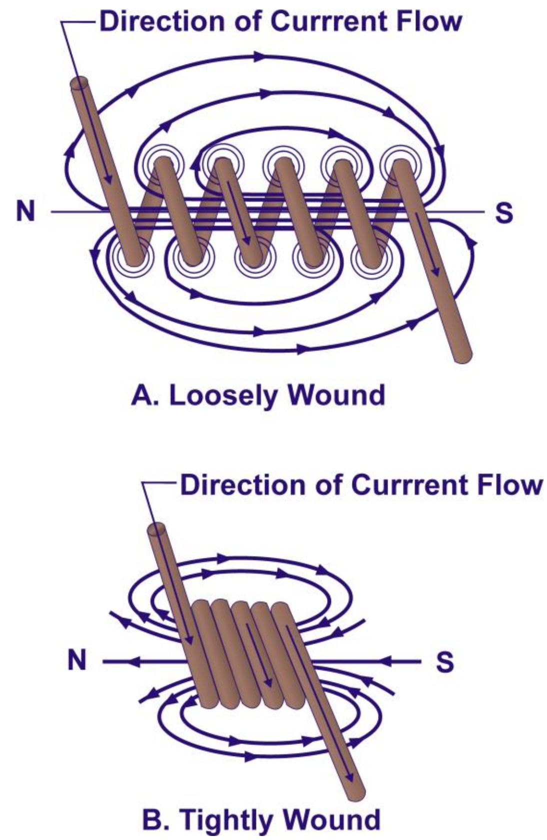
h. Solenoid

1) If a straight current-carrying conductor is formed into a loop, the same circular lines of force surround the conductor. When the conductor is formed into a loop, all lines of force enter on one side of the loop and leave on the other side. This is in accordance with the Left-Hand Rule.

2) Several loops or turns of wire are wound to form a coil, called a Helix or Solenoid. Any coil of wire is a helix, while a solenoid is a coil that has considerable length compared with its diameter. The magnetic field surrounding a loosely wound solenoid is shown in Picture 9A. Since current is flowing in the same direction in all loops, the

magnetic field produced between loops is similar to that of parallel conductors with currents flowing in the same direction. The field between individual turns is weakened by flux opposition between the turns. Some lines of force encircle several turns of the entire solenoid. These lines of force produce a magnetic field similar to the magnetic field of a bar magnet, making a north pole at one end of the solenoid and a south pole at the other.

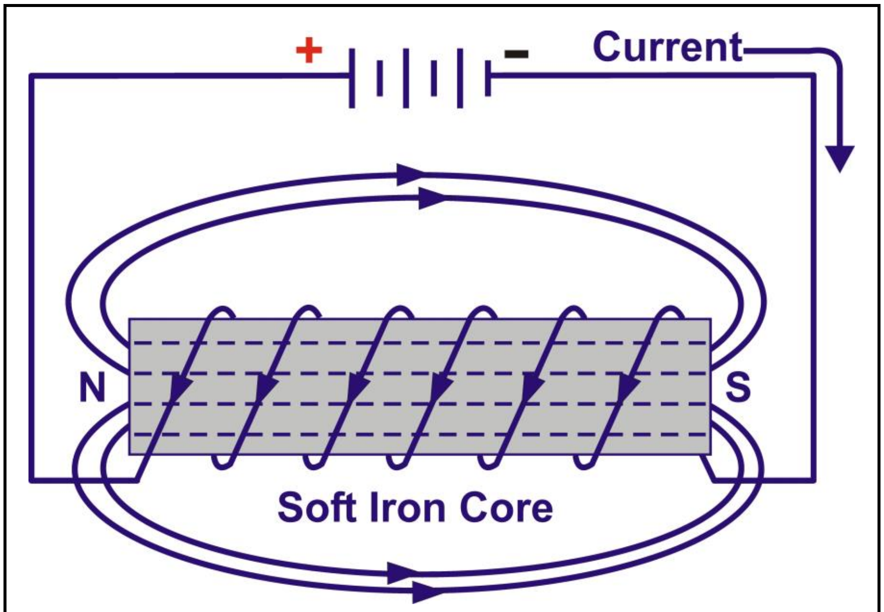
3) The magnetic field around a solenoid is made apparent by studying direction of magnetic lines of force in Picture 9A. In the upper conductor of each loop, current flows in a direction out of the paper and produces a clockwise magnetic field around each conductor. Since adjacent upper conductors have magnetic fields of the same direction, individual magnetic fields combine to form one continuous magnetic field with a clockwise direction. In the lower part of the conductor, the current flows opposite to current in the upper section. Therefore, magnetic fields around the lower portion combines to form a continuous counterclockwise magnetic field. If loops of the solenoid are pushed together as close as possible (Picture 9B), many more lines of force encircle the entire solenoid since distance between the magnetic fields has decreased. Because of this, magnetic field within the coil and at the poles is much stronger than the field of the loosely wound solenoid, since practically all lines of force previously encircling individual loops now encircle the entire solenoid. Therefore, while current is flowing, the solenoid has properties of a permanent magnet.



Picture 9, Magnetic Fields Around Coils

4) When a piece of magnetic material, usually soft iron, is placed within the solenoid, magnetic properties of the solenoid are greatly increased. This increased magnetic strength is due to the better magnetic path provided by the soft iron. Whatever is enclosed by a coil, whether it be air or a magnetic material, is the core of the magnet. A coil wound on a core of magnetic material is called an electromagnet (Picture 10). The coil is wound with one or more layers of wire extending from one end of the core to the other. Current flows around the core continuously in the same direction. The left-hand rule for determining the direction of the magnetic field of a solenoid, or coil, is also used to determine direction of the magnetic field of an electromagnet. Wrap the fingers of the left hand

around the solenoid in the direction of current through the coil, the thumb points to the north pole.



Picture 10, Typical Electromagnet

i. Force On A Conductor

a) A current-carrying conductor is surrounded by a magnetic field. A magnetic field exerts a force on a magnet within that field, so it exerts a force on a current carrying conductor. Interaction between the field of the current-carrying conductor and an external field actually exerts a force of attraction or repulsion on the conductor. This effect was discovered by the French scientist André Ampere, who formulated it into Ampere's Law.

b) Ampere's Law states: Any current-carrying conductor located at right angles to lines of force in a magnetic field will be pushed by a force directly proportional to three things:

(1) the flux density

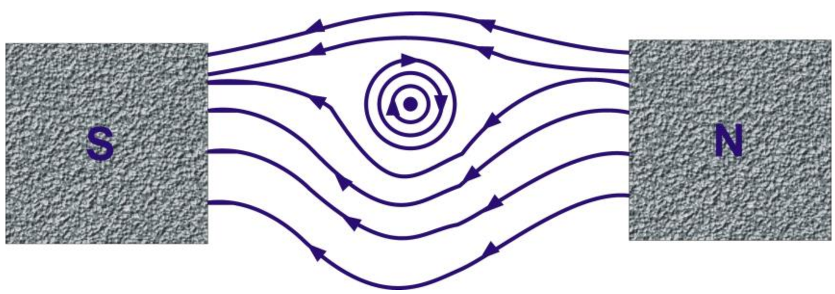
(2) the amount of current flow

(3) the length of the conductor

c) If any of the three increase, strength of the force on the conductor will increase proportionally.

d) Interaction between the magnetic field of a magnet and a current-carrying conductor produces a force on the conductor; this is the basis of operation behind many electrical devices, such as motors.

e) The interaction between fields when a current-carrying wire is inserted between poles of a magnet is illustrated in Picture 11.



Picture 11, Composite Magnetic Field of Magnet and Current-Carrying Conductor

f) The cross section of wire in Picture 11 is shown by the heavy circle and direction of current (out of the page) is indicated by the dot within the circle. The left-hand rule for a conductor, given earlier in this chapter, states the direction of the field produced by current in the wire will be clockwise, as indicated by the arrows. Magnetic flux above the wire is thus aided by the field surrounding the wire, while flux below the wire is opposed by the field of the wire. Lines of flux are concentrated above the wire and weakened below the wire. Thus, there is a relatively strong magnetic force above the wire and a relatively weak magnetic force below the wire. The stronger force prevails and the wire will be pushed downward into the weaker field. Imagine lines of force as elastic rubber bands which tend to straighten themselves out and become as short as possible. The many stretched lines above the conductor will push the conductor downward toward the fewer, straightened lines. If the direction of current flow were reversed into the page, the effect between the two magnetic fields would be opposite from that of Picture 11, causing lines of flux to concentrate below the wire. This would force the wire upward. These results can be obtained more simply by using the right-hand motor rule.

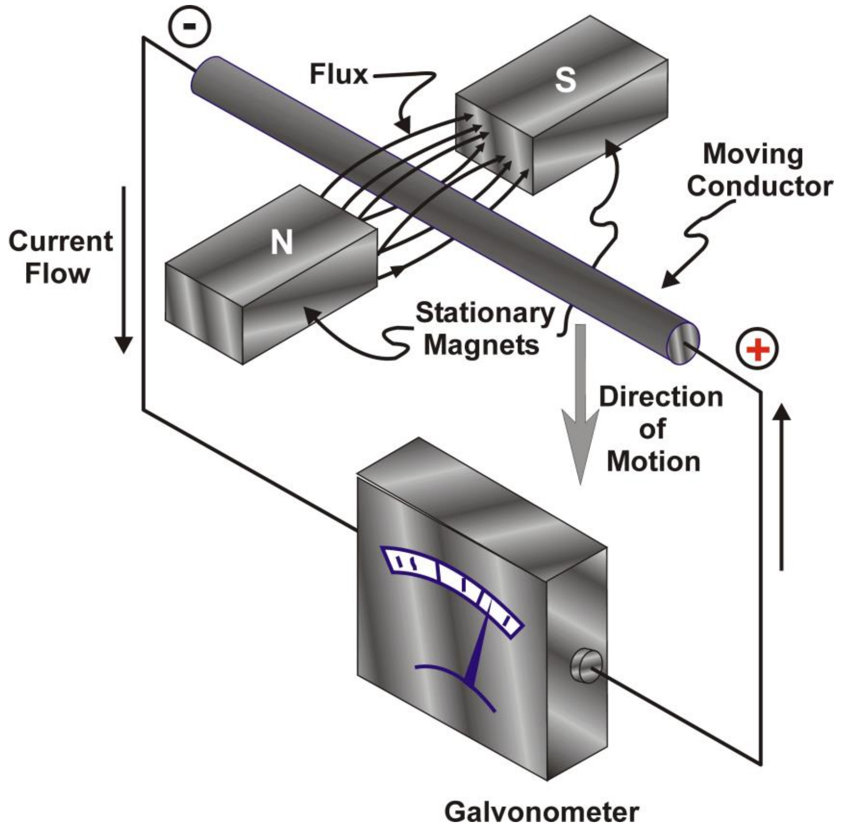
5. Electromagnetic Induction

   a. Electromagnetic Induction Process

      1) Electromagnetic induction is the act of producing voltage, or emf, by relative motion of a magnetic field across a conductor (magnetic lines of force passing through the conductor). This is called induction because there is no physical connection between magnet and conductor.

   b. Since we know that current flow in a conductor generates a magnetic field around the conductor, it is reasonable to assume that the movement of a conductor in a magnetic field or the movement of a magnetic field across a conductor will generate a potential and a resultant current flow, if circuit is closed, in the conductor.

   c. Potential difference is maintained as long as the conductor continues to move downward. If motion stops, magnetic field interactions stop and no emf is produced. Because voltage exists, if a closed circuit is connected between the ends of the conductor, it can supply electrons just as a battery does. If an external circuit, such as a galvonometer or current measuring device, is connected to the ends of the conductor (Picture 12), a current is measured. The polarity of voltage and direction of current flow are easily determined using the left-hand rule for generators.



Picture 12, Magnetically Induced Current

d. The reverse is also true. If the conductor is held stationary and the magnet is moved so that its field cuts the conductor, voltage is induced in the conductor. Whenever there is relative motion between a conductor, and a magnetic field, voltage is induced in the conductor.

6. Factors Affecting Electromagnetic Induction

a. Three factors affect the value of induced voltage and current:

1) a stronger magnetic field produces more induced voltage and current.

2) a larger number of conductors cutting the magnetic field produces more induced voltage and current (i.e., coil vs. straight conductor)

3) a faster relative motion between the magnetic field and conductors produces more induced voltage and current.

B. In Summary

1. Principles of magnetism and magnetic interactions are used throughout the plant in motors (on pumps and valves), generators (on turbines and diesels), and electrical transformers.

2. Magnets can be classified into two groups: natural and artificial. Artificial magnets are strongest (for their size) and most commonly seen. When magnetic material is exposed to an external magnetic force, it sets up its own magnetic field. If the external magnetic force is removed, magnetic material may remain magnetic (permanent magnet) or lose magnetism (temporary magnet), depending on its retentivity.

3. Magnetized material is composed of billions and billions of tiny molecular magnets (domains), each with its own north and south pole. In unmagnetized magnetic material, domains are randomly aligned and have no resulting magnetic force. If an external magnetic force is applied, domains begin to align, resulting in a definite overall magnetic field with a north and south pole. When all domains are aligned, increasing the external magnetic field does not increase the magnetic strength. The upper limit to magnetic strength is called saturation.

4. Magnetic force is strongest at the magnetic poles and must follow the two laws of magnetism. The first law states that like magnetic poles repel and unlike magnetic poles attract. The second law states that force between two

magnetic poles is directly proportional to the product of their strengths and inversely proportional to the square of the distance between them.

5. A common way to explain magnetic force is as imaginary lines of force. These lines originate from the north pole and return to the south pole through the path of least magnetic resistance.

6. Lines of force are continuous and always form closed loops. They never cross one another and can pass through all materials. Since lines of force travel the path of least magnetic resistance, certain materials, such as iron, which pass magnetic flux better than air, can be used to guide magnetic flux and concentrate it. These low magnetic resistance materials are said to have a high permeability.

7. When a conductor has a current flow, magnetic flux exists around that conductor. The direction of lines of flux can be determined by the left-hand rule for conductors. If a current carrying conductor is coiled, individual magnetic fields interact with one another allowing all lines of force to enter the coil. This causes the density of lines of force to be greatest through the center of the coil, forming strong north and south poles at the ends.

8. When magnetic material is placed into the center (core) of the coil, the strength becomes greater than one with an air core. This is called an electromagnet.

9. When a current-carrying conductor exists in an external magnetic field, the two magnetic fields interact so that force is developed on the conductor. Relative motion between a conductor and a magnetic field, develops an electromotive force across the conductor. If the electrical circuit is closed, current will flow. If this relative motion stops, induction of emf is stopped and current will cease to flow.

10. Magnetism is used to regulate output from the main electrical generator, change speed of a pump, and (when a control rod is moved), the rod position indication system to determine the rods height.
11. These concepts will be used extensively in the next chapters to develop AC voltage and operate motors, generators, and transformers.

Electromagnets

PRACTICE:

1 What is a magnet?

2. What is an artificial magnet?