Chapter 1

Magnetism and Electricity

Early experimenters dating back to the dawn of history discovered that certain hard black stones attracted small pieces of iron. Later, it was discovered that a *lodestone*, or leading stone, pointed north and south when freely suspended on a string, as shown in Figure 1-1. Lodestone is a magnetic ore that becomes magnetized if lightning happens to strike nearby. Today we use magnetized steel needles instead of lodestones in magnetic compasses. Figure 1-2 illustrates a typical pocket compass.

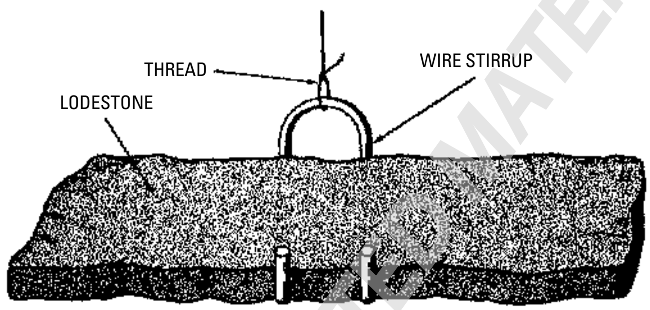


Figure 1-1 Lodestone is a magnetic ore.

Figure 1-2 A magnetic compass.

Magnetic Poles

Any magnet has a north and a south pole. We know that the earth is a huge, although weak, magnet. In Figure 1-1, the end of the lodestone that points toward the North Star is called its north-seeking pole; the opposite end of the lodestone is called its south-seeking pole. It is a basic law of magnetism that *like poles repel each other* and *unlike poles attract each other.* For example, a pair of north poles repel each other and a pair of south poles repel each other, but a north pole attracts a south pole.

Magnetic forces are invisible, but it is helpful to represent magnetic forces as imaginary lines. For example, we represent the earth's magnetism as shown in Figure 1-3. There are several important facts to be observed in this diagram. Since the north pole of a compass needle points toward the earth's geographical North Pole, we recognize that the earth's geographical North Pole has a magnetic south polarity. In other words, the north pole of a compass needle is attracted by magnetic south polarity.

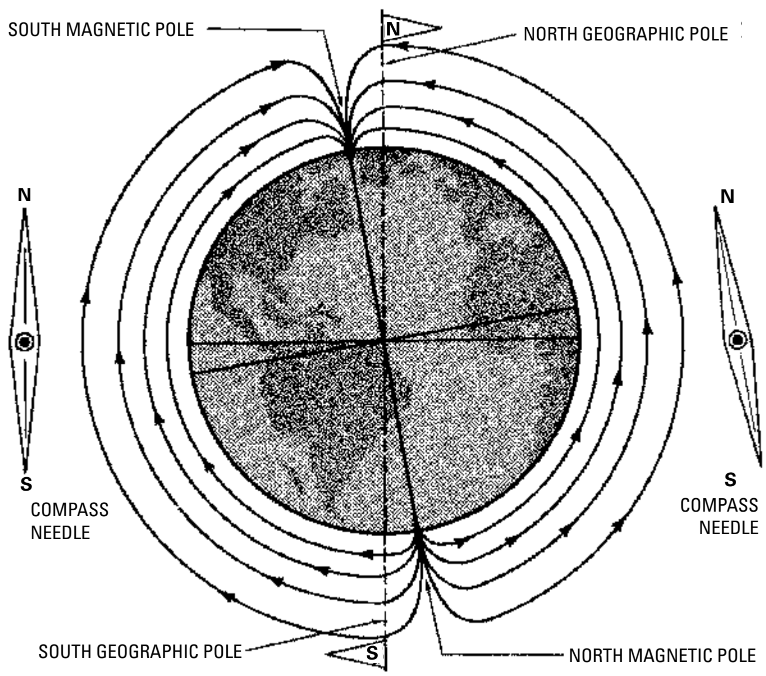


Figure 1-3 Earth's magnetic poles.

Another important fact shown in Figure 1-3 is the location of the earth's magnetic poles with respect to its geographic poles. The earth's magnetic poles are located some distance away from its geographic poles. Still another fact to be observed is that magnetic force lines have a direction, which can be indicated by arrows. Magnetic force lines are always directed out of the north pole of a magnet and directed into the south pole. Moreover, magnetic force lines are continuous; the lines always form closed paths. Thus, the earth's magnetic force lines in Figure 1-3 are continuous through the earth and around the outside of the earth.

The actual source of the earth's magnetism is still being debated by physicists. However, insofar as compass action is concerned, we may imagine that the earth contains a long lodestone along its axis. In turn, this imaginary lodestone will have its south pole near the earth's north geographic pole; the imaginary lodestone will have its north pole near the earth's south geographic pole.

Experiments with Magnets

If we bring the south pole of a magnet near the south pole of a suspended magnet, as shown in Figure 1-4, we know that the poles will repel each other. It can also be shown that magnetic attractive or repulsive forces vary inversely as the square of the distance between the poles. For example, if we double the distance between a pair of magnetic poles, the force between them will be decreased to one-fourth. It can also be shown that if the strength of the magnet in Figure 1-4 is doubled (as by holding a pair of similar magnets together with their south poles in the same direction), the force of repulsion is thereby doubled.

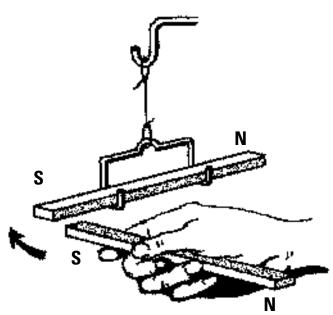


Figure 1-4 Showing repulsion between like magnetic poles.

The strength of a magnetic field is measured in *gauss* (G). For example, the strength of the earth's magnetic field is approximately

0.5 G. The gauss unit is a measurement of flux density—that is, it is a measure of the number of magnetic force lines that pass through a unit area. *One gauss is defined as one line of force per square centimeter.* In turn, one gauss is equal to 6.452 lines of force per square inch. For example, the strength of the earth's magnetic field is approximately 3.2 lines of force per square inch.

Note that there are 2.54 centimeters in 1 inch, or 0.3937 inches in 1 centimeter. Therefore, there are 6.452 square centimeters in 1 square inch, or 0.155 square inch in 1 square centimeter. Since one gauss is defined as one line of force per square centimeter, it follows that one gauss is also equal to 6.452 lines of force per square inch.

A unit of magnetic pole strength is measured in terms of force. That is, a *unit of magnetic force* is defined as one that exerts a force of one *dyne* on a similar magnetic pole at a distance of 1 centimeter. If we use a pair of like poles, this will be a repulsive force; if we use a pair of unlike poles, it will be an attractive force. There are 444,800 dynes in one pound; in other words, a dyne is equal to 1/444,800 of a pound. It is not necessary to remember these basic definitions and conversion factors. If you should need them at some future time, it is much more practical to look them up than to try to remember them.

Another important magnet experiment is shown in Figure 1-5. If we break a magnetized needle into two parts, each of the parts will become a complete magnet with north and south poles. No matter how many times we break a magnetized needle, we will not obtain a north pole by itself or a south pole by itself. This experiment leads us to another basic law of magnetism, which states that magnetic poles must always occur in opposite pairs. Many attempts have been made by scientists to find an isolated magnetic pole (called a *magnetic monopole*). All attempts to date have failed, though scientists are still trying.

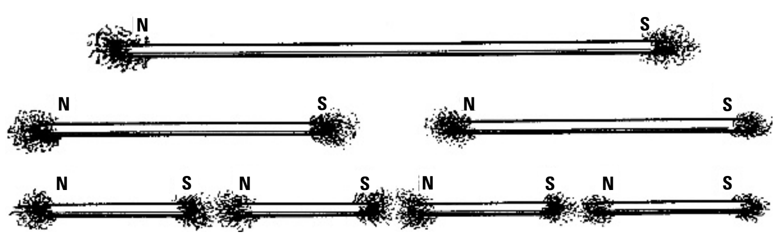


Figure 1-5 Showing the effects of breaking a magnet into several parts.

It has been found that iron and steel are the only substances that can be magnetized to any practical extent. However, certain *alloys,* such as *Alnico,* can be strongly magnetized. Substances such as hard steel and Alnico retain their magnetism after they have been magnetized and are called *permanent magnets.* Since a sewing needle is made from steel, it can be magnetized to form a permanent magnet. On the other hand, soft iron remains magnetized only as long as it is close to or in contact with a permanent magnet. The soft iron loses its magnetism as soon as it is removed from the vicinity of a permanent magnet. Therefore, soft iron is said to form a *temporary magnet.*

Permanent magnets for experimental work are commonly manufactured from hard steel or magnetic alloys in the form of *horseshoe magnets* and *bar magnets,* as shown in Figure 1-6. The space around the poles of a magnet is described as a *magnetic field* and is represented by magnetic lines of force. The space around a lodestone (Figure 1-1), around a compass needle (Figure 1-2), around the earth (Figure 1-3), and around a permanent magnet (Figure 1-4) are examples of magnetic fields. Since a magnetic field is invisible, we can demonstrate its presence only by its force of attraction for iron.

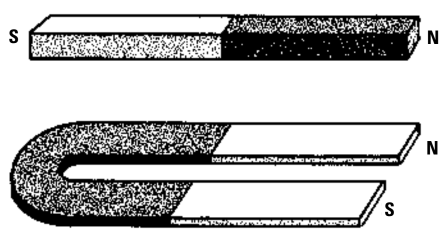


Figure 1-6 A bar magnet and a horseshoe magnet.

Consider the patterns formed by magnetic lines of force in various magnetic fields. One example has been shown in Figure 1-3. It can also be easily shown experimentally that when a bar magnet is held under a piece of cardboard and then iron filings are sprinkled on the cardboard, the filings will arrange themselves in curved-line patterns as shown in Figure 1-7. The pattern of iron filings formed provides a practical basis for our assumption of imaginary lines of force to describe a magnetic field. The total number of magnetic force lines surrounding a magnet, as shown in Figure 1-8, is called its *magnetic flux*.

A similar experiment with a horseshoe magnet is shown in Figure 1-9. The iron filings arrange themselves in curved lines that suggest the imaginary lines of force that we use to describe a magnetic field. Note that the magnetic field is strongest at the poles of the magnet in Figure 1-7. Since the field strength falls off as the square

P1: GDZ
GB034-01 GB034-Rosenberg-Sample May 6, 2004 21:40 Char Count= 0

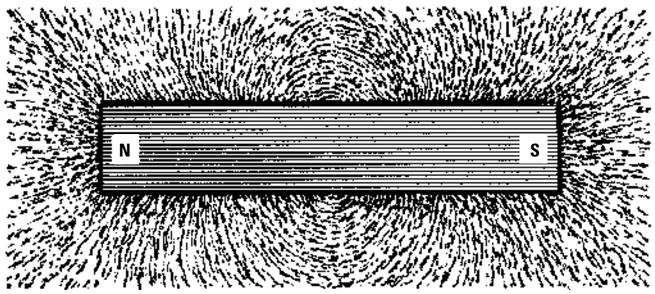


Figure 1-7 Pattern of iron filings around a bar magnet.

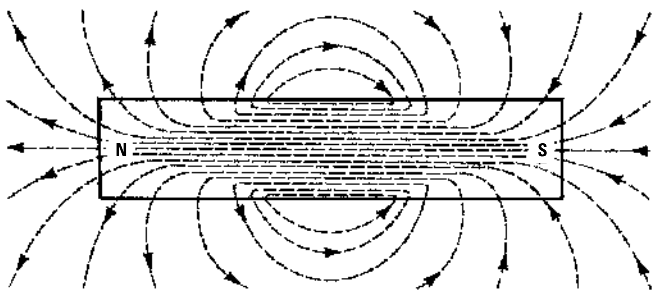


Figure 1-8 Field around a bar magnet represented by lines of force.

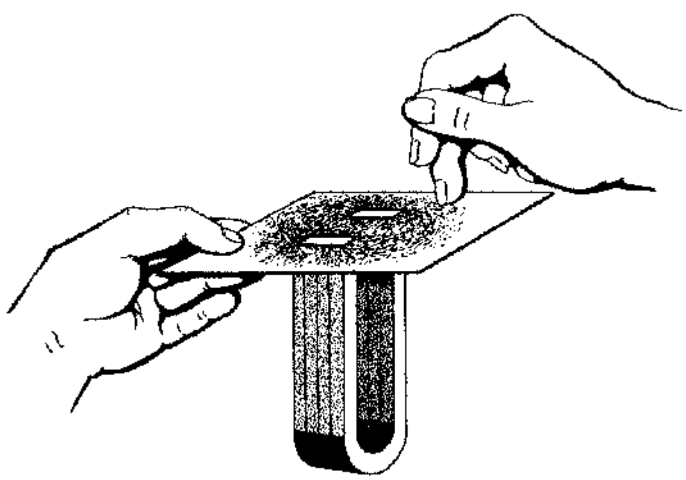


Figure 1-9 Pattern of iron filings in the space above a horseshoe magnet.

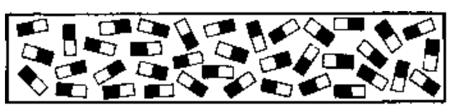
of the distance from a pole, a magnet exerts practically no force on a piece of iron at an appreciable distance. A magnet exerts its greatest force on a piece of iron when in direct contact.

Formation of Permanent Magnets

Another important and practical experiment is the magnetization of steel to form a permanent magnet. For example, if we wish to magnetize a steel needle, we may use any of the following methods:

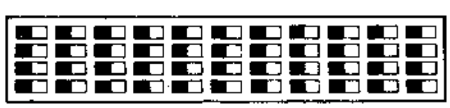
- The needle can be stroked with one pole of a permanent magnet. The needle can be stroked several times to increase its magnetic strength, but each stroke must be made in the same direction.
- If the needle is held in a magnetic field (such as between the poles of a horseshoe magnet) and the needle is tapped sharply, it will become magnetized.
- We can heat a needle to dull red heat and then quickly cool the needle with cold water while holding it in a magnetic field, and the needle will become magnetized.

The formation of permanent magnets is explained in terms of molecular magnets. Each molecule in a steel bar is regarded as a tiny permanent magnet. As shown in Figure 1-10, the poles of these molecular magnets are distributed at random in an unmagnetized



(A) Unmagnetized.

(B) Partially magnetized.



(C) Magnetized.

Figure 1-10 Representation of molecular magnets in a steel bar.

steel bar. Therefore, the fields of the molecular magnets cancel out on the average, and the steel bar does not act as a magnet. On the other hand, when we stroke an unmagnetized steel bar with the pole of a permanent magnet, some of the molecular magnets respond by lining up end-to-end. In turn, the lined-up molecular magnets have a combined field that makes the steel bar a magnet. If the steel bar is stroked a number of times, more of the molecular magnets are lined up end-to-end, and a stronger permanent magnet is formed, as shown in Figure 1-11A.

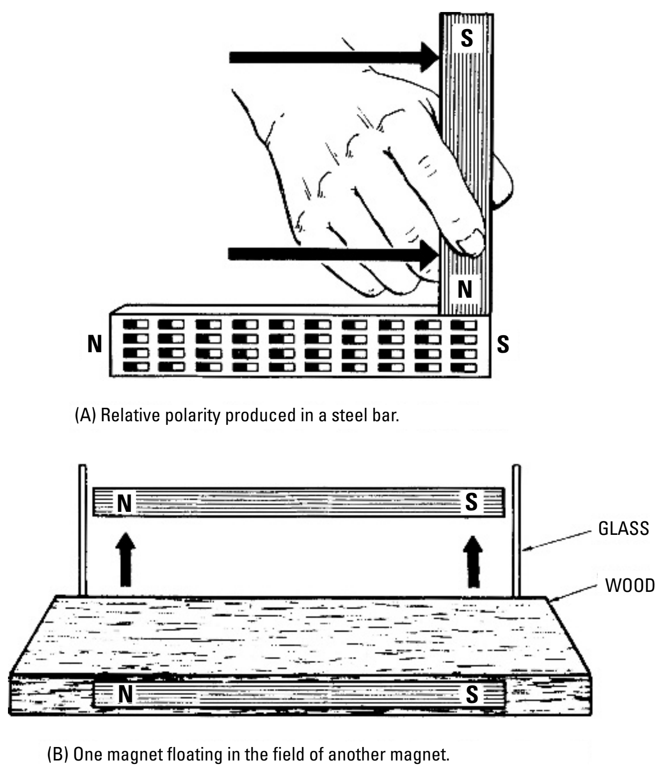


Figure 1-11 Magnet characteristics.

Steel is much harder than iron; therefore, it is more difficult to line up the molecular magnets in a steel bar than in a soft-iron bar. To make a strong permanent magnet from a steel bar, we must stroke the bar many times with a strong permanent magnet. A soft-iron bar becomes fully magnetized as soon as it is touched by a permanent magnet but will return to its unmagnetized state as soon as it is removed from the field of a permanent magnet. Once the molecular magnets have been lined up in a hard steel bar, however, they will retain their positions and provide a permanent magnet.

Although there are very large numbers of molecules in an iron or steel bar, the number of molecules to be lined up is not infinite. Therefore, there is a limit to which the bar can be magnetized, no matter how strong a field we use. When all the molecular magnets are aligned in the same direction, the bar cannot be magnetized further, and the iron or steel is said to be *magnetically saturated.* The ability of a magnetic substance to retain its magnetism after the magnetizing force has been removed is called its *retentivity.* Thus, retentivity is very large in hard steel and almost absent in soft iron. Magnetic alloys such as Alnico V have a very high retentivity and are widely used in modern electrical and electronic equipment. The Alnico alloys contain iron, aluminum, nickel, copper, and cobalt in various proportions depending on the requirements.

A permanent magnet that weighs $1^1/_2$ lbs may have a strength of 900 G and will lift approximately 50 lbs of iron. This type of magnet is constructed in a horseshoe form and is less than 3 in. long. A 5-lb magnet may have strength of 2000 G and will lift approximately 100 lbs of iron. A 16-lb magnet $5^1/_2$ in. long may have a strength of 4800 G and will lift about 250 lbs of iron.

Bar magnets can be magnetized with sufficient strength so that one of the magnets will float in the field of the other magnet, as shown in Figure 1-11B. A similar demonstration of magnetic forces is provided by circular ceramic magnets. Each circular magnet is about $2^1/_2$ in. in diameter and has a hole in the center that is 1 in. in diameter. One surface of the disc is a north pole, and the opposite surface is a south pole. When placed on a nonmagnetic restraining pole, with like poles adjacent, the circular magnets float in the air, being held in suspension by repelling magnetic forces.

Aiding and Opposing Magnetic Fields

An experiment that demonstrates the repulsion of like magnetic poles was illustrated in Figure 1-4. The question is often asked how magnetic force lines act in aiding or opposing magnetic fields. Figure 1-12 shows the answer to this question. Note that when unlike poles are brought near each other, the lines of force in the air gap are in the *same* direction. Therefore, these are aiding fields, and the lines concentrate between the unlike poles. It is a basic law of magnetism that lines of force tend to shorten as much as possible; lines of force

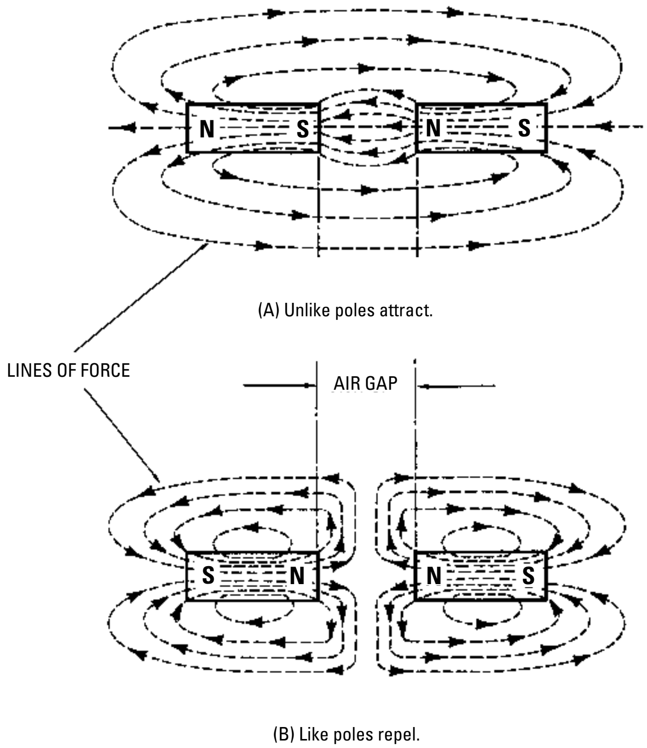


Figure 1-12 Lines of force between unlike and like poles.

have been compared to rubber bands in this respect. In turn, a force of attraction is exerted between the unlike poles in Figure 1-12A.

On the other hand, a pair of like poles have been brought near each other in Figure 1-12B. The lines of magnetic force are directed in opposition, and the lines from one pole oppose the lines from the other pole. In turn, none of the lines from one magnet enters the other magnet, and a force of repulsion is exerted between the magnets. We observe that the magnetic fields in Figure 1-12 are changed in shape, or are *distorted* with respect to the field shown in Figure 1-8. If the magnets in Figure 1-12 are brought more closely together, the fields become more distorted. Hence, we recognize that forces of attraction or repulsion between magnets are produced by distortion of their magnetic fields.

Electromagnetism

Electromagnetism is the production of magnetism by an electric current. An electric current is a flow of electrons; we can compare the flow of electrons in a wire to the flow of water in a pipe. Today we can read about electronics and electrons in newspapers, magazines, and many schoolbooks. However, the practical electrician needs to know more about electrons than a mechanic or machinist does. Therefore, let us see how electric current flows in a wire.

An atom is the smallest particle of any substance; thus, the smallest particle of copper is a copper atom. We often hear about *splitting the atom*. If a copper atom is split or broken down into smaller particles, we can almost say that it is built from extremely small particles of electricity. In other words, all substances, such as copper, iron, and wood, have the *same* building blocks, and these building blocks are particles of electricity. (This is technically not an entirely true statement, but it is close enough for our use here.) Copper and wood are different substances simply because these particles of electricity are arranged differently in their atoms. An atom can be compared to our solar system in which the planets revolve in orbits around the sun. For example, a copper atom has a *nucleus,* which consists of positive particles of electricity; electrons (negative particles of electricity) revolve in orbits around the nucleus.

Figure 1-13 shows three atoms in a metal wire. An electron in one atom can be transferred to the next atom under suitable conditions, and this movement of electrons from one end of the wire to the other end is called an electric current. Electric current is *electron flow.* To make electrons flow in a wire, an *electrical pressure* must be applied to the ends of the wire. This electrical pressure is a force called *electromotive force,* or *voltage*. For example, an ordinary dry cell is

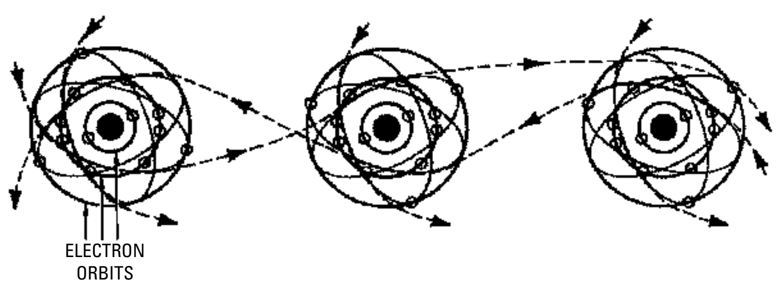


Figure 1-13 Atoms in a metal wire.

a source of electromotive force. A dry cell produces electromotive force by chemical action. If we connect a voltmeter across a dry cell, as shown in Figure 1-14, electrons flow through the voltmeter, which indicates the voltage of the cell.

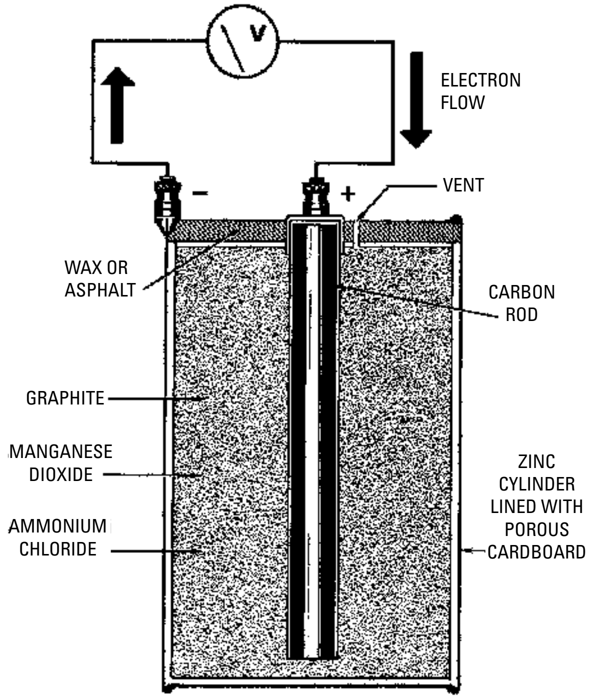


Figure 1-14 A dry cell produces electromotive force by chemical action.

We measure electromotive force (emf) in *volts* (V). If a dry cell is in good condition, it will have an emf of about 1.5 V. Note that a dry cell acts as a *charge separator.* In other words, the chemical action in the cell takes electrons away from the carbon rod and adds electrons to the zinc cylinder. Therefore, there is an electron pressure or emf at the zinc cylinder. When a voltmeter is connected across a dry cell (see Figure 1-14), this electron pressure forces electrons to flow in the connecting wire, as shown in Figure 1-13. We observe that electrons flow from the negative terminal of the dry cell, around the wire *circuit,* and back to the positive terminal of the dry cell.

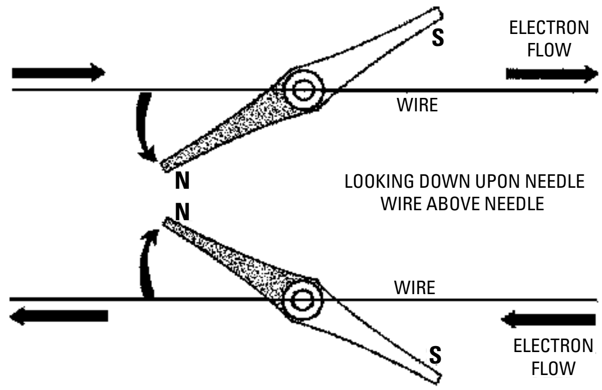


Figure 1-15 A compass needle is deflected in the vicinity of a current-carrying wire.

Next, we will find that an electric current produces a magnetic field. For example, if a compass needle is brought near a current-carrying wire, the compass needle turns, as shown in Figure 1-15. Since a compass needle is acted upon by a magnetic field, this experiment shows that the electric current is producing a magnetic field. This is the principle of electromagnetism. The magnetic lines of force surrounding a current-carrying wire can be demonstrated as shown in Figure 1-16. When iron filings are sprinkled over

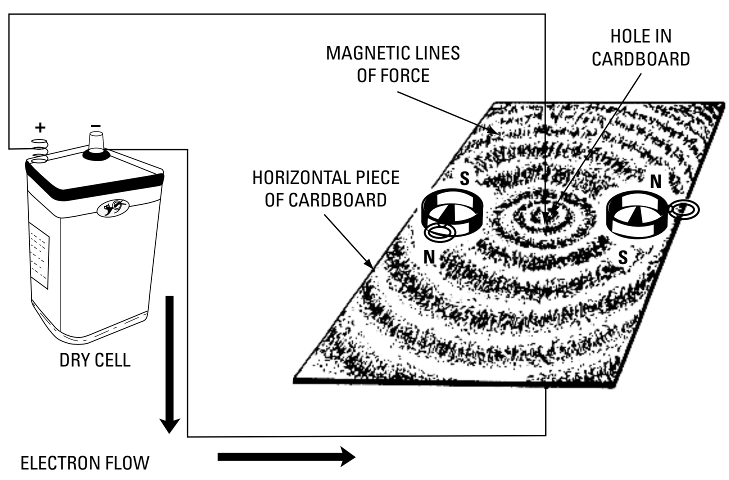


Figure 1-16 Demonstration of electromagnetism.

the cardboard, the filings arrange themselves in circles around the wire.

Although a current-carrying wire acts as a magnet, it is a form of *temporary magnet*. The magnetic field is not present until the wire is connected to the dry cell. Magnetic force lines are produced only while there is current in the wire. As soon as the circuit is opened (disconnected from the dry cell), the magnetic force lines disappear.

Let us observe the polarities of the compass needles in Figure 1-16. The magnetic lines of force are directed clockwise, looking down upon the cardboard. This experiment leads us to a basic rule of electricity called the *left-hand rule*. Figure 1-17 illustrates the left-hand rule; if a conductor is grasped with the left hand, with your thumb pointing in the direction of electron flow, then your fingers will point in the direction of the magnetic lines of force.

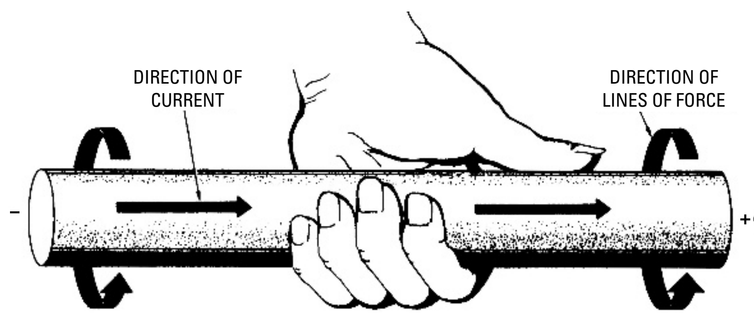


Figure 1-17 Left-hand rule used to determine direction of magnetic force lines around a current-carrying conductor.

Experiments show that the magnetic field around the wire in Figure 1-16 is weak, and we will now ask how the strength of an electromagnetic field can be increased. The magnetic field around a straight wire is comparatively weak because it is produced over a large volume of space. To reduce the space occupied by the magnetic field, a straight wire can be bent in the form of a loop, as shown in Figure 1-18. Now the magnetic flux lines are concentrated in the area enclosed by the loop. Therefore, the magnetic field strength is comparatively great inside the loop. This is an elementary form of *electromagnet*.

Next, to make an electromagnet with a much stronger magnetic field, we can wind a straight wire in the form of a helix with a number of turns, as shown in Figure 1-19. Since the field of one loop adds to the field of the next loop, the total field strength of

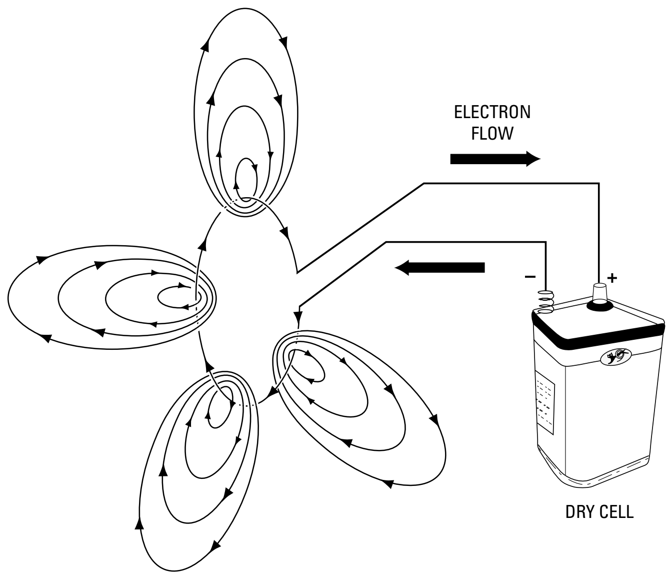


Figure 1-18 The magnetic field is concentrated by forming a conductor into a loop.

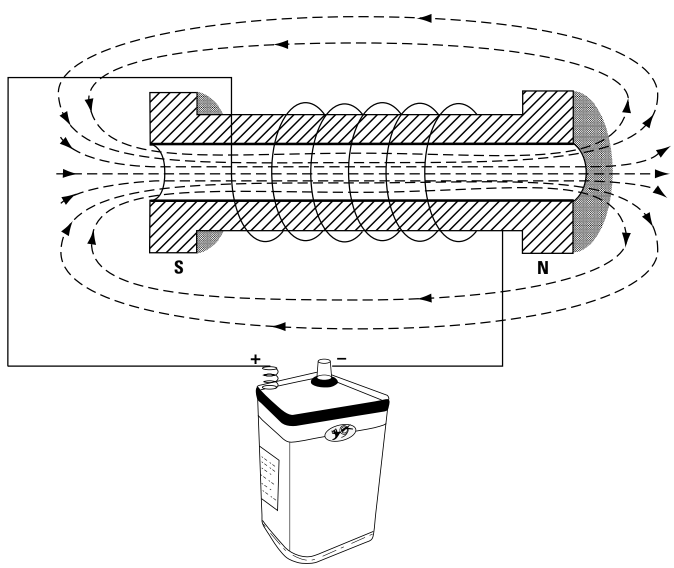


Figure 1-19 Magnetic field around an air-core solenoid.

the electromagnet is much greater than if a single turn were used. Note that if we use the same wire shown in Figure 1-16 to form the electromagnet in Figure 1-19, the current is the same in both circuits. That is, we have not changed the amount of current; we have merely concentrated the magnetic flux by winding the wire into a spiral. Electricians often call an electromagnet of this type a *solenoid*.

The name solenoid is applied to electromagnets that have an *air core*. For example, we might wind the coil in Figure 1-19 on a wooden spool. Since wood is not a magnetic substance, the electromagnet is essentially an air-core magnet. Note the polarity of the magnetic field in Figure 1-19 with respect to the direction of current flow. The left-hand rule applies to electromagnets, just as to straight wire. Thus, if we grasp an electromagnet as shown in Figure 1-20, with the fingers of the left hand in the direction of electron flow, then the thumb will point to the north pole of the electromagnet.

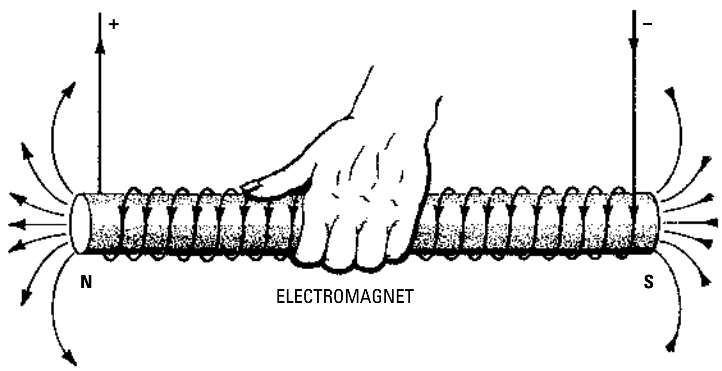


Figure 1-20 Method of finding the magnetic polarity of a coil by means of the left-hand rule.

Since iron is a magnetic substance, the strength of an electromagnet can be greatly increased by placing an iron core inside a solenoid. For example, if we place a soft-iron bar inside the wooden spool in Figure 1-19, we will find that the magnetic field strength becomes much greater. Let us see why this is so (with reference to Figure 1-10). The molecular magnets in the soft-iron bar, or *core,* are originally oriented in random directions. However, under the influence of the flux lines inside the electromagnet, these molecular magnets line up in the same direction. Therefore, the magnetic field of the molecular magnets is added to the magnetic field produced by the electric current, and the strength of the electromagnet is greatly increased.

Note that we have not changed the amount of current in the wire by placing an iron core in the solenoid. The magnetic field produced by the electric current remains unchanged. However, the electromagnet has a much greater field strength when an iron core is used because we then have two sources of magnetic field, which add up to produce the total field strength. If we open the circuit (shut off the current) of an iron-core electromagnet, both sources of magnetic field disappear. In other words, both solenoids and iron-core electromagnets are temporary magnets.

Volts, Amperes, and Ohms

To fully understand circuits such as the one shown in Figure 1-19, we must recognize another basic law of electricity, called *Ohm's law.* This is a simple law that states the relation between *voltage, current,* and *resistance.* We have become familiar with voltage, and we know that voltage (emf) is an electrical pressure. We also know that an electromotive force causes electric charges (electrons) to move through a wire. Electron flow is called an electric *current,* and a wire opposes (resists) electron flow. This opposition is called electrical *resistance.* We measure electromotive force (voltage) in *volts,* electric current in *amperes,* and resistance in *ohms.*

Figure 1-14 showed how the voltage of a dry cell is measured with a voltmeter. Current is measured with an *ammeter.* Resistance is measured with an *ohmmeter.* More electricians now use combination test instruments, such as the *multimeter* (a combination volt-ohm-milliammeter) shown in Figure 1-21. At this time, we are interested in the relation between voltage, current, and resistance. Ohm's law states that the current in a circuit is directly proportional to the applied voltage and inversely proportional to the circuit resistance. Thus, we write Ohm's law as follows:

$$\text{Electric current} = \frac{\text{electromotive force}}{\text{resistance}}$$

For example, Ohm's law states that if a wire has 1 ohm of resistance, an emf of 1 volt applied across the ends of the wire will cause 1 ampere of current to flow through the wire. Or, if we apply 2 volts across 1 ohm of resistance, 2 amperes of current will flow. Again,

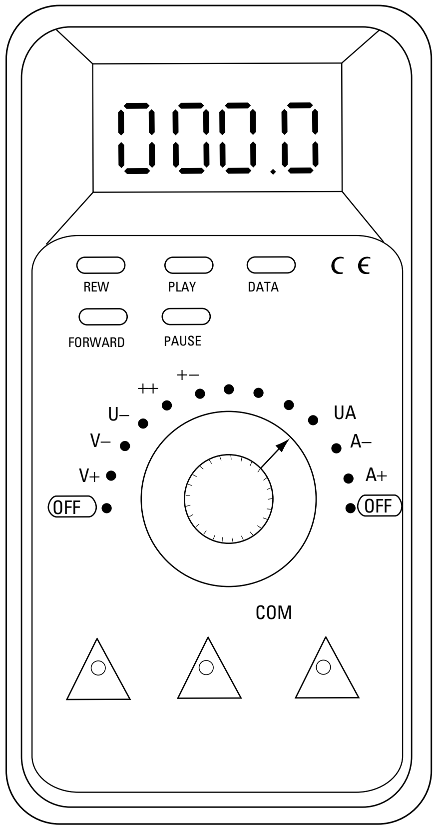


Figure 1-21 Electricians now use combination testing machines such as this digital multimeter.

if we apply 1 volt across 2 ohms of resistance, $1/2$ ampere of current will flow. We generally write Ohm's law with letters, as follows:

$$I = \frac{E}{R}$$

where I represents current in amperes,
E represents emf in volts,
R represents resistance in ohms.

Note that electrons (electric charges) flow in an electric circuit. On the other hand, voltage does not flow; resistance does not flow. Electric current is defined as the *rate* of charge flow. A current of 1 ampere consists of 6.24×10^{18} electrons (6,240,000,000,000,000,000

P1: GDZ
GB034-01 GB034-Rosenberg-Sample May 6, 2004 21:40 Char Count= 0

electrons). Therefore, a current of 1 ampere denotes the passage of 1 coulomb past a point in 1 second. Although we often speak of current flow, we really refer to charge flow, because current denotes the *rate of charge flow.* If electrons flow at the rate of 3.12×10^{18} electrons per second, the current value is $^1/_2$ ampere.

Electric and Magnetic Circuits

To measure the current in a circuit, we connect an ammeter into the circuit as shown in Figure 1-22. It is a basic law of electricity that the current is the same at any point in the circuit. Therefore, the ammeter indicates the amount of current that flows in *each turn* of the electromagnet. Each turn produces a certain amount of magnetism in the core. As we would expect, the amount of magnetism that is produced by each turn of wire depends on the amount of current in the wire. Therefore, we describe an electromagnet in terms of *ampere-turns*. If the ammeter in Figure 1-22 indicates a current of 1 ampere, each turn on the coil represents 1 ampere-turn.

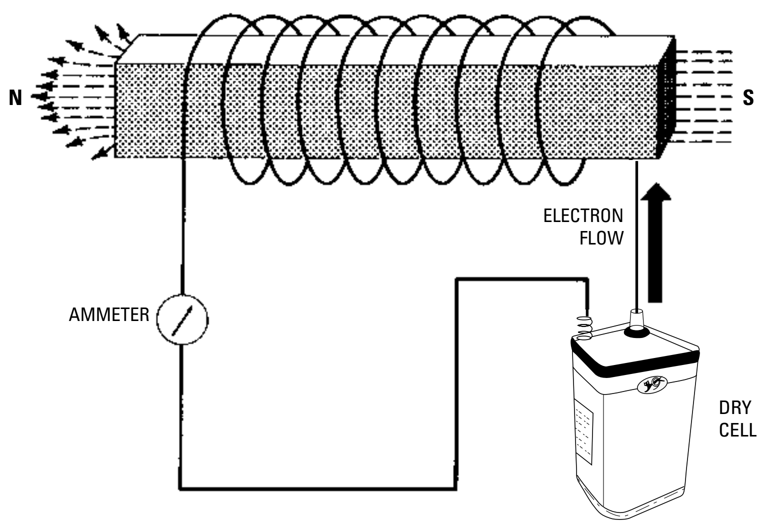


Figure 1-22 Measurement of current in the circuit.

The total number of ampere-turns on a coil is equal to the number of amperes times the number of turns. For example, with a current of 1 ampere in Figure 1-22, there will be a total of 9 ampere-turns. Next, let us suppose that we increase the current in Figure 1-22 to 2 amperes. Now 2 amperes of current flows in each turn of the coil, and we have a total of 18 ampere-turns. Since the strength of the electromagnet is proportional to the number of its ampere-turns, *we double the strength of the electromagnet by doubling the amount of current.*

Since each ampere-turn produces a certain amount of magnetism, the ampere-turn is taken as the unit of *magnetomotive force.* Magnetomotive force is measured in ampere-turns. We often compare magnetomotive force to electromotive force. In other words, electromotive force produces current in a wire, and magnetomotive force produces magnetic flux lines in a core. We will find that any core, such as air or iron, opposes the production of magnetic flux lines. This opposition is called the reluctance of the core. We often compare reluctance with resistance. In other words, production of magnetic flux lines is opposed by reluctance, and production of electric current is opposed by resistance. Therefore, we can also compare magnetic flux lines to electric current.

The foregoing comparisons lead us to the idea of a *magnetic circuit,* as shown in Figure 1-23. This diagram shows both an electric circuit and a magnetic circuit. The electric circuit consists of the 1-volt battery and the 1-ohm coil through which 1 ampere of current

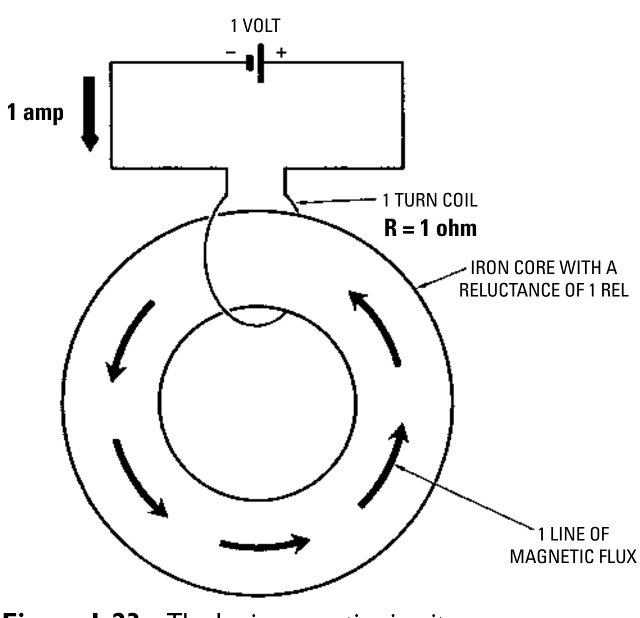


Figure 1-23 The basic magnetic circuit.

flows. The magnetic circuit in this example consists of a circular iron core. Reluctance is measured in *rels*. This core has a reluctance of 1 rel. A basic law of electromagnetism states that 1 ampere-turn produces 1 line of magnetic flux in a reluctance of 1 rel. Therefore, we write a law for magnetic circuits that is much the same as Ohm's law for electric circuits:

$$\text{magnetic flux} = \frac{\text{magnetomotive force}}{\text{reluctance}}$$

or,

$$\text{flux lines} = \frac{\text{ampere} - \text{turns}}{\text{rels}}$$

Next, suppose that we increase the current in Figure 1-23 to 2 amperes. Then, two lines of magnetic flux will be produced in the iron core. Another example is shown in Figure 1-24, where 5 amperes of current flows through 10 turns, providing a magnetomotive force of 50 ampere-turns. The number of flux lines that will be produced in Figure 1-24 depends on the reluctance of the magnetic circuit. Note that a continuous iron magnetic circuit is provided for the flux lines in Figure 1-23; the magnetic circuit in Figure 1-24 is more complicated, however, because part of the magnetic circuit is iron and the other part is air. From the previous discussion of electromagnets, we would expect air to have a much greater reluctance than iron.

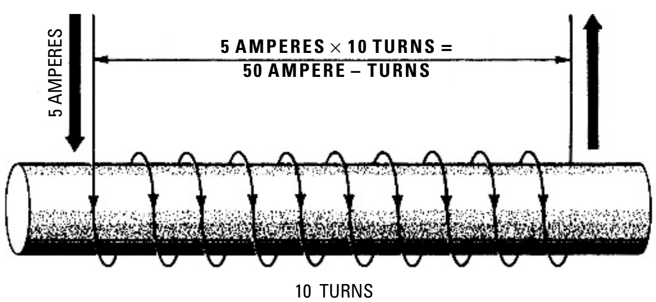


Figure 1-24 An electromagnet with 50 ampere-turns of magnetomotive force.

A volume of air that is 1 in. square and 3.19 in. long has a reluctance of 1 rel. This is 1500 times the reluctance of a typical iron core of the same size. If we place a closed iron core in a solenoid, the number of flux lines will increase 1500 times in a typical experiment.

However, the following are several facts that we must keep in mind when working with iron cores:

1. Different types of iron have different amounts of reluctance.
2. The reluctance of iron changes as the magnetomotive force is changed.
3. Since air has a much greater reluctance than iron, a magnetic circuit with a large air gap acts practically the same as an air core.

For example, cast iron has about 6 times as much reluctance as annealed sheet steel. To show the change in the reluctance of iron when the magnetomotive force is changed, we use charts such as that shown in Figure 1-25. The chart shows a magnetization curve. Note that the scales on the chart are marked off in terms of *magnetizing force* per inch and magnetic flux lines per square inch. Magnetizing force is equal to magnetomotive force per inch of core length. For example, let us consider the iron core shown in Figure 1-26. The length of this magnetic circuit is 16 in. If we apply a magnetomotive

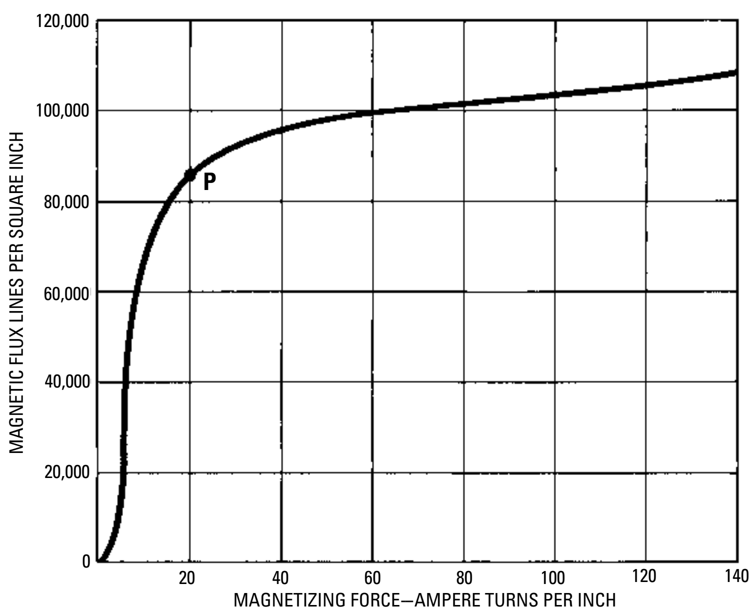


Figure 1-25 Magnetizing force versus flux density for annealed sheet steel.

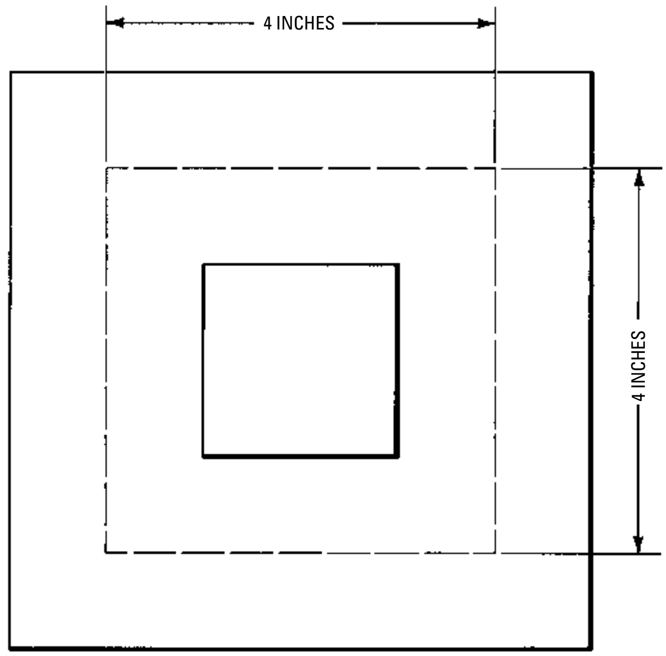


Figure 1-26 The length of this magnetic circuit is 16 in.

force of 320 ampere-turns to this core, we will have a magnetizing force of 20 ampere-turns per inch.

Let us find how many flux lines per square inch will be produced in the core (Figure 1-26) when a magnetizing force of 20 ampere-turns per inch is applied. At point P on the magnetization curve in Figure 1-25, we see that there will be about 83,000 lines per square inch produced in the core. Now, if the core of Figure 1-26 has a cross-sectional area of 1 square inch, there will be 83,000 lines of magnetic flux in the core. Or, if the core has a cross-sectional area of 2 square inches, there will be 166,000 lines of magnetic flux in the core. Again, if the core has a cross-sectional area of $^1/_2$ square inch, there will be 41,500 lines of magnetic flux in the core.

The number of magnetic flux lines per square inch is generally called the *flux density* in the core; flux density is represented by the letter B, and magnetizing force is represented by the letter H. Thus, a magnetization curve such as shown in Figure 1-25 is usually called a *B-H curve*. Note that the flux density in this example increases rapidly from 0 to 20 ampere-turns per inch. At higher values of magnetizing force, the B-H curve flattens off. This flattened-off portion of the curve is called the *saturation interval.* The curve will finally become horizontal, and the iron core will then have the same reluctance as air. When an iron core is completely saturated, we can remove the iron core from the electromagnet, and its magnetic field strength will remain the same.

Figure 1-27 shows some comparative B-H curves. We observe that an electromagnet with an annealed sheet-steel core will have a much stronger magnetic field than if cast iron is used for a core. Note also that if we wish to make a very strong electromagnet, it

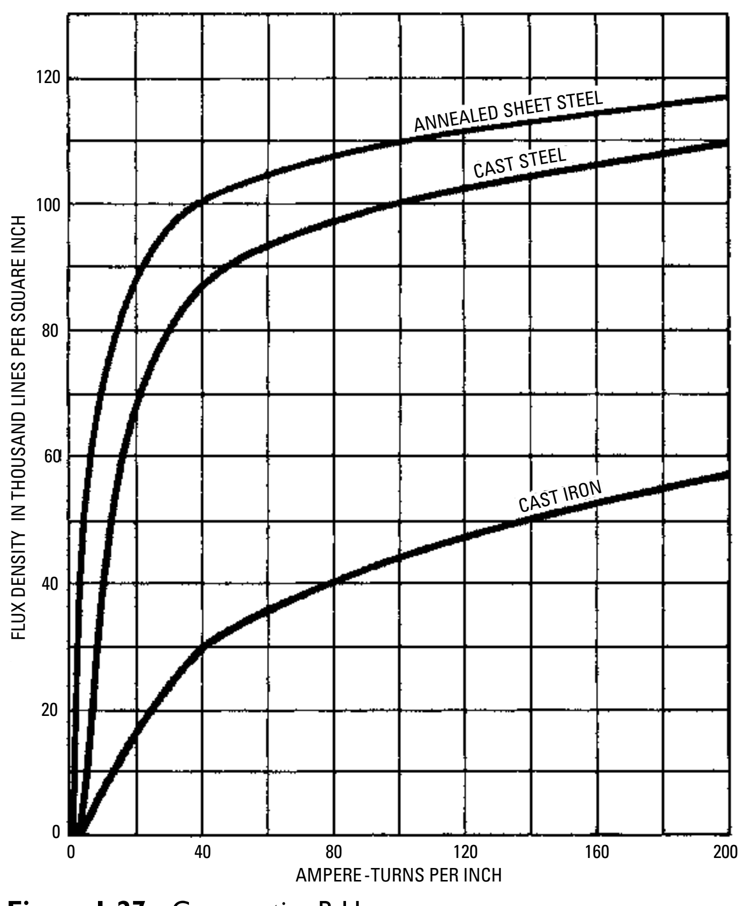
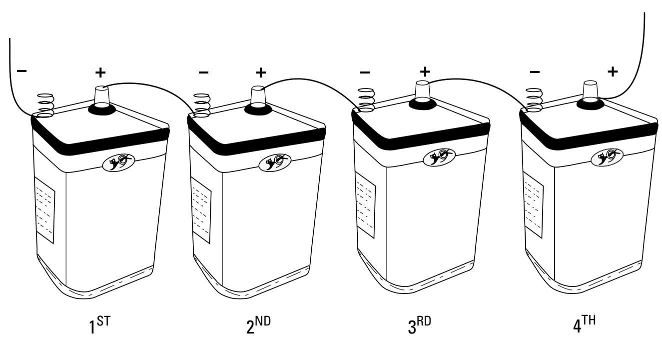


Figure 1-27 Comparative B-H curves.

is better to use a large cross-sectional area in the core instead of a large number of ampere-turns per inch. In other words, iron and steel start to saturate when more than 20 ampere-turns per inch are used, and core saturation corresponds to wasted electric current. Therefore, efficient operation requires that we use no more than 20 ampere-turns per inch and then make the cross-sectional area of the core as large as required to obtain the desired number of magnetic flux lines.

Understanding Electric Circuits

Any circuit must contain a voltage source to be of practical use. Source voltages may be very high, moderate, or very low. A dry cell is a familiar 1.5-volt source, as was shown in Figure 1-14. When a higher voltage is required, cells can be connected in *series* to form a *battery,* as shown in Figure 1-28. Note that the negative terminal of one cell is connected to the positive terminal of the next cell. This series connection causes the cell voltages to be added. Since there are four cells in the example, the battery voltage will be approximately 6 volts. New dry cells usually have an emf of slightly more than 1.5 volts. As a cell ages, its emf decreases.

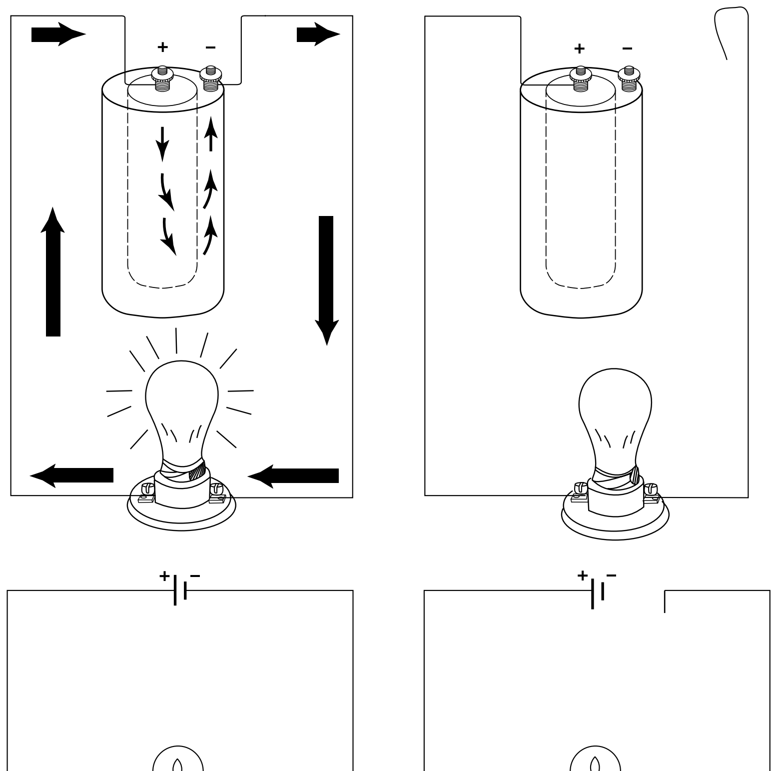


(A) A battery of four cells.

(B) Schematic representation.

Figure 1-28 Illustrating series-connected dry cells.

Current does not flow in a circuit unless the circuit is *closed*. Figure 1-29 shows the difference between a closed circuit and an open circuit. A flashlight bulb might draw 0.25 ampere from a 1.5-volt source. Let us apply Ohm's law to find the resistance of the bulb.

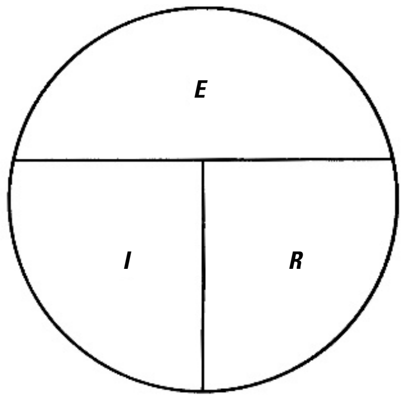


(A) Closed circuit. (B) Open circuit.

Figure 1-29 A simple electric circuit.

It is easy to see that there are three possible arrangements of Ohm's law, as shown in Figure 1-30. Since we are interested in finding the resistance of the bulb, we will use the second arrangement of Ohm's law. Accordingly, the resistance of the bulb is 1.5/0.25, or 6 ohms. Next, let us observe how the other two arrangements of Ohm's law are used.

In case we know the applied voltage (1.5 volts) and the resistance of the bulb (6 ohms), we will use the first arrangement of Ohm's law to find the current in the circuit. Thus, the current is equal to 1.5/6, or 0.25 ampere. On the other hand, in case we know the current through the bulb (0.25 ampere) and the resistance of the bulb (6 ohms), we will use the third arrangement of Ohm's law

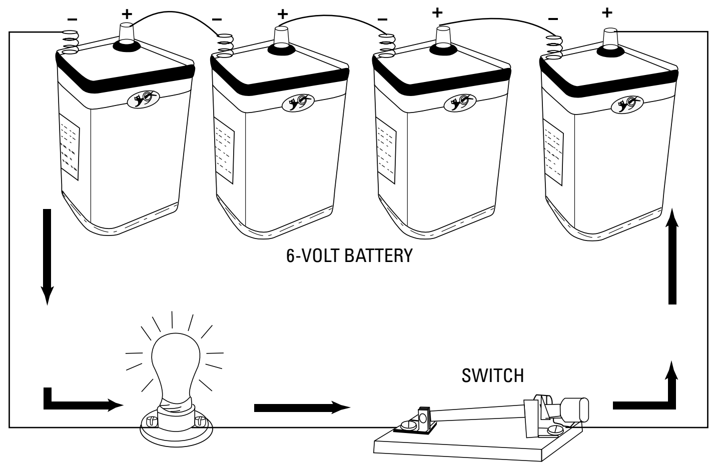


OHM'S LAW
CURRENT = $\frac{\text{ELECTROMOTIVE FORCE}}{\text{RESISTANCE}}$ $I = \frac{E}{R}$ AMPERES = $\frac{\text{VOLTS}}{\text{OHMS}}$
RESISTANCE = $\frac{\text{ELECTROMOTIVE FORCE}}{\text{CURRENT}}$ $R = \frac{E}{I}$ OHMS = $\frac{\text{VOLTS}}{\text{AMPERES}}$
ELECTROMOTIVE FORCE = CURRENT × RESISTANCE $E = IR$ VOLTS = AMPERES × OHMS

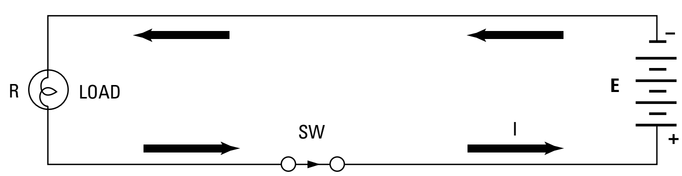
Figure 1-30 Ohm's law in diagram form.

to find the applied voltage. Thus, the applied voltage is equal to 0.25×6, or 1.5 volts. Figure 1-30 shows Ohm's law in diagram form. To find one of the quantities, first cover that quantity with a finger. The location of the other two letters in the circle will then show whether to divide or multiply. For example, to find I, we cover I and observe that E is to be divided by R. Again, to find E, we cover E and observe that I is to be multiplied by R.

A circuit can be opened by disconnecting a wire as shown in Figure 1-29B. To conveniently open and close a circuit, a switch is



(A) Pictorial diagram.



(B) Schematic representation.

Figure 1-31 A simple electric circuit.

used as shown in Figure 1-31. This type of switch is called a knife switch. Note that the lamp is called a *load resistance,* or simply a *load.* An electrical load in a circuit changes electricity into light and heat, as in this example; in other circuits, the load may change electricity into mechanical power or some other form of power. Let us consider the action of the *fuse* shown in Figure 1-32. A fuse is a type of automatic safety switch; the fuse blows and opens the circuit in case the load (R) should become short-circuited and draw excessive current from the battery.

Fuses are made from thin strips or wire of aluminum or other metal. The resistance of a fuse is comparatively low, but because of its small cross section, the fuse heats up and melts if a certain amount of current flows through it. For example, the fuse shown in Figure 1-32A has a resistance of 1 ohm (Ω). The load R has a resistance of 29 ohms, making a total of 30 ohms of circuit resistance. Since 6 volts is applied, 0.2 ampere will flow in accordance with Ohm's

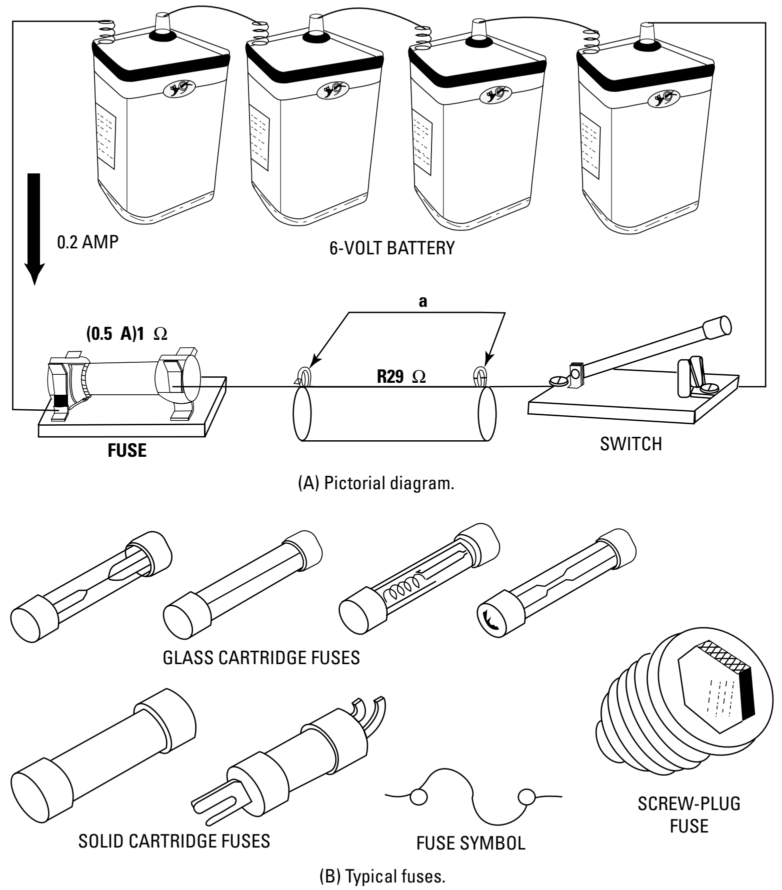


Figure 1-32 A fused circuit.

law. This fuse is made so that it will blow at a current of 0.5 ampere. Therefore, the fuse does not blow as long as R is not short-circuited.

We could short-circuit R by placing a screwdriver across the terminals. In such a case, the total circuit resistance would be reduced to 1 ohm, and 6 amperes of current would flow. Therefore, the fuse would immediately blow out and automatically open the circuit. Thereby, the battery is protected from damage due to excessive current drain. Note that after the fuse blows, the voltage between its terminals will be 6 volts. In normal circuit operation, the voltage across the load-resistor terminals (a) is 5.8 volts, in accordance with Ohm's law. The voltage across the fuse terminals is 0.2 volt, in accordance with Ohm's law. We call the voltage between the load-resistor terminals the *voltage drop* across the resistor; similarly, we call the voltage between the fuse terminals the *voltage drop* across the fuse.

When we speak of a voltage drop, we simply mean that this amount of voltage would be measured by a voltmeter connected across the terminals of resistance. It follows from the foregoing example that *Ohm's law applies to any part of a circuit, as well as to the complete circuit.* In other words, insofar as the load resistor is concerned in Figure 1-32A, 0.2 ampere is flowing through 29 ohms; therefore, the IR (current × resistance) drop across the load resistor is 5.8 volts. Insofar as the fuse is concerned, 0.2 ampere is flowing through 1 ohm; therefore, the IR drop across the fuse is 0.2 volt.

We have noted previously that both electromotive force (emf) and voltage are measured in volts. Electromotive force is often called a voltage. Nevertheless, there is a basic distinction between an emf and a voltage. For example, a dry cell is a chemical *source* of voltage, and we speak of the *emf produced by the source* of electricity. This emf is measured in volts. If a resistor is connected across a source of electricity, the current produces a voltage drop across the resistance in accordance with Ohm's law. This voltage drop is not called an emf but is called a voltage and is measured in volts. Even though the terms are normally used interchangeably, we should properly speak of the emf of a voltage source but of a voltage produced across a load resistor.

Kirchhoff's Voltage Law

The foregoing example also illustrates another basic law of electric circuits, called Kirchhoff's voltage law. This law states that *the sum of the voltage drops around a circuit is equal to the source voltage.* Note that the sum of the voltage drops across the load resistor and the fuse is equal to 6 volts (5.8 + 0.2) and that the source voltage (battery voltage) is also equal to 6 volts. We recognize that Kirchhoff's voltage law is simply a summary of Ohm's law as applied to all the resistance in a circuit. Although we do not need to use Kirchhoff's voltage law in describing the action of simple circuits, this law will be found very useful in solving complicated circuits.

Electrical Power

There are many forms of power. For example, an electric motor produces a certain amount of mechanical power, usually measured in horsepower. An electric heater produces heat (thermal) power. An electric light bulb produces both heat power and light power (usually measured in candlepower). Electrical power is measured in *watts;* electrical power is equal to volts times amperes. Thus we write

$$\text{watt} = \text{volts} \times \text{amperes}$$

or,

$$P = EI$$

With reference to Figure 1-32A, the battery supplies $6 \times 0.2 = 1.2$ watts to the circuit, the load resistor R takes $5.8 \times 0.2 = 1.16$ watts, and the fuse takes $0.2 \times 0.2 = 0.04$ watt. Note that the power taken by both resistances is equal to $1.16 + 0.04 = 1.2$ watts. In other words, the power supplied by the battery is exactly equal to the power taken by the circuit resistance. This fact leads us to another basic law called the *law of conservation of energy.* This law states that *energy cannot be created or destroyed but only changed into some other form of energy.* This is the same as saying that power can be changed only into some other form of power, because energy is equal to power multiplied by time.

In the example of Figure 1-32, electrical energy is changed into heat energy (or electrical power is changed into heat power) by the load resistor and the fuse. Since the load resistor takes 1.16 watts of electrical power, it produces 1.16 watts of heat power. With reference to Figure 1-31, light is measured in candlepower. An ordinary electric-light bulb produces approximately 1 candlepower for each watt of electrical power. For example, a 60-watt lamp normally takes 60 watts of electrical power and produces about 60 candlepower of light.

Since power is equal to *IE*, and $I = E/R$, we can write $P = E^2/R$. Since power is equal to *IE*, and $E = IR$, we can write $P = I^2R$. Thus, by substitution from Ohm's law into the basic power law and by rearranging these equations, we obtain the 12 important electrical formulas shown in Figure 1-33. In summary, these formulas state

$$I = \frac{E}{R} = \frac{P}{E} = \sqrt{\frac{P}{R}}$$

$$E = IR = \frac{P}{I} = \sqrt{PR}$$

$$R = \frac{E}{I} = \frac{P}{I} = \frac{E^2}{P}$$

$$P = IE = I^2R = \frac{E^2}{R}$$

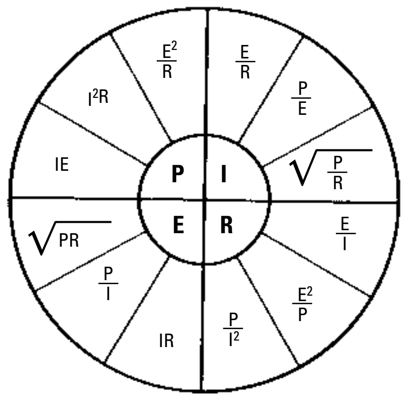


Figure 1-33 Summary of basic formulas.

These formulas are important because we may be working with a circuit in which the voltage and resistance are known, and we need to find the amount of current flow. Again, we may know the voltage and power in the circuit and need to find the amount of current flow. Or we may know the resistance and power in the circuit and need to find the amount of current flow. Similarly, we can find the voltage of a circuit if we know the current and resistance, or the current and the power, or the resistance and the power. We can find the resistance in a circuit if we know the voltage and current, or the current and power, or the voltage and power. We can find the power in a circuit if we know the voltage and current, or the current and resistance, or the voltage and resistance.

Next, let us consider the measurement of electrical energy. We measure electrical energy in watt-seconds, watt-hours, or kilowatt-hours. A watt-second is equal to the electrical energy produced by 1 watt in 1 second. In turn, a watt-hour is equal to the electrical energy produced by 1 watt during 1 hour; therefore, a watt-hour is equal to 3600 watt-seconds. A kilowatt-hour is equal to 1000 watt-hours. An instrument used to measure electrical energy is called a watt-hour meter. We are quite familiar with watt-hour meters because they are installed by public utility companies in every home, office, and shop.

Quick-Check Instruments for Troubleshooting

Electrical troubleshooting requires various tests. However, practical electricians generally make quick-checks with continuity testers and voltage indicators. Shop work often requires the use of voltmeters, ammeters, ohmmeters, wattmeters, and/or a continuity tester, which consists of a battery and some sort of signaling load (flashlight bulbs and small bells or chimes being the most common), along with a pair of test leads. Such devices are commonly used when connections are to be checked in a wiring system, or when a broken place in a wire is to be located. If the test leads are applied across a closed circuit, the bell rings. Note that if a poor connection is being checked, the bell may or may not ring, depending on the resistance of the bad connection.

A simple voltage indicator consists of a neon bulb with a built-in dropping resistor and a pair of test leads. This type of tester is usually preferred when circuits are being checked in a wiring system. If the test leads are applied across a circuit in which 70 volts or more are present, the neon bulb will glow. The bulb will glow much brighter across a 240-volt circuit than across a 120-volt circuit. However, the brightness of the glow cannot be used to estimate the voltage value accurately. A neon tester is essentially a quick-checker. However, it is a very practical tester in general troubleshooting procedures. Many of the tests formerly performed in a laborious fashion by these instruments are now superseded by multitesting instruments, such as the one shown in Figure 1-21, some of which have digital and analog displays.

Summary

A lodestone is a natural magnet consisting chiefly of a magnetic oxide of iron called magnetite. All magnets have a north and south pole. Magnetic lines of force are invisible but are always continuous, always forming a closed path. Like poles repel, unlike poles attract.

Iron and steel are the only materials that can be magnetized to any practical extent. Certain alloys, such as Alnico, can be strongly magnetized and are called permanent magnets. Permanent magnets are generally in the form of a horseshoe or bar. The space around the poles of a magnet is described as a magnetic field and is represented by magnetic lines of force. The total number of magnetic force lines surrounding a magnet is called its total magnetic flux.

Electromagnetism is the production of magnetism by an electric current. Electric current is a flow of electrons, which can be compared to the flow of water in a pipe. Electric current is electron flow; to make electrons flow, pressure must be applied to the end of the wire. This pressure applied is called the electromotive force or voltage. Electromotive force (emf) is measured in volts.

To fully understand electromagnetism or the basic laws of electricity, we must use Ohm's law. This is a law that states the relationship between voltage, current, and resistance. Voltage is the electrical pressure that causes electrons to move through a wire. Electron flow is called an electric current. Current is the movement of electrons through a conductor. A wire (or conductor) opposes the electron flow because of resistance.

Test Questions

1. What is a lodestone?
2. Do unlike magnetic poles attract or repel each other?
3. Why does a compass needle point in a north-south direction?
4. How does a permanent magnet differ from a temporary magnet?
5. Can a north pole exist without a south pole?
6. Are magnetic lines of force directed into or out of the north pole or magnet?
7. What is the definition of electromagnetism?
8. How do metals conduct electricity?
9. Is a dry cell a source of magnetism or of electricity?
10. In what way is electromotive force, or voltage, an electrical pressure?
11. Will a voltmeter measure the voltage or the current of a dry cell?
12. Why is a compass needle deflected in the vicinity of a current-carrying wire?
13. How is an electromagnet constructed?
14. Can you explain why a soft-iron core increases the strength of an electromagnet?
15. What is the name of the law that relates voltage, current, and resistance?
16. Is a magnetic circuit the same thing as an electric circuit?
17. How is an ampere-turn defined?
18. Does an ammeter measure current or voltage?
19. Can you state a law for magnetic circuits that is similar to Ohm's law?
20. Why are dry cells connected in series?
21. What is the meaning of a closed circuit? An open circuit?
22. In what way can a fuse be compared to a switch?