Understanding Basic Electricity and Electronics

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Terminology

Electromagnetism: The relationship between an electric current and a magnetic field

Compound: Matter consisting of two or more different kinds of atoms chemically joined

Element: Matter consisting of only one kind of atom

Inert Element: An element that does not combine chemically with other elements

Circuit: Path for electric current

Potential difference: The potential energy of an electron in one place compared to another place

Cell: Combination of materials that produces a potential difference between two points

Battery: Two or more cells connected together

Electricity, once a scientific curiosity, is a necessity in the modern world of sophisticated equipment and machinery. Without electricity, industry as we know it would not exist. Production equipment, communications systems, and utilities operate on electricity.

The language of electricity may confuse the layman, but electrical and electronics specialists must know the specific meaning of each word and term. In this Lesson, we define electrical terms used by electrical craftsmen. We also describe matter, molecules, atoms, and their relationship to electricity.

Electrical force is also explained in this Lesson. We describe how objects attract and repel each other depending on their electrical charge. You may want to experiment with forces after studying this Lesson.

History of Electricity

1-1 Electricity is one of our most useful sources of energy today. It is hard to imagine how a modern industrial society could exist without electricity. But until the mid-1800s, no one knew much about electricity or how to use it. Until then, electricity was nothing more than a scientific curiosity.

1-2 When scientists first began studying electricity, they discovered that *electricity* and *magnetism* are related. For example, they discovered that when an electric current flows in a wire, it creates a magnetic field. The magnetic field is exactly like the field produced by an ordinary magnet. It produces the same effects on a compass and on iron filings. They also discovered that you can make an electric current flow in a wire if you move the wire rapidly through a magnetic field.

1-3 These experiments led to an understanding of **electromagnetism** which is the relationship between an electric current and a magnetic field. Electromagnetism is the foundation of all our modern electrical machinery and equipment.

1-4 Understanding the relationship between electricity and magnetism has made it possible to invent machines that generate large amounts of electricity at low cost. Electricity from these generators drives countless kinds of industrial machinery and provides mass transportation in our cities. It also provides the power for light, heat, communications, and data processing.

Language of Electricity

1.5 Electrical and electronics craftsmen use special words and phrases just as carpenters and mechanics do. The workers in each trade have their own special ways of communicating to other workers in the trade. When you use electrical terms, make sure you understand what each term means.

1-6 For example, you may hear someone say, "The power output is low." You may think you know what the statement means. But the word *power* has a very special meaning. Low power is not necessarily the same as too little electricity.

1-7 Almost every electrical machine or appliance has a tag or nameplate stating the operating *voltage* and *current* of the unit. These terms also have special meanings. You must understand those meanings in order to make use of the information they provide.

1-8 Electrical *voltage* is often compared to *pressure* in a water system. The two ideas are not exactly the same. But they are enough alike to make the comparison useful. You may find electricity easier to understand at first if you think of voltage as a sort of "electrical pressure" that pushes electric current through a wire or through a piece of equipment.

1-9 Another common name for voltage is *electromotive* force, abbreviated *emf*. This term is used by many people, but it is misleading. Electromotive force is not the same as the force of gravity or the force that a tool exerts on a workpiece. It refers to the same "electrical pressure" as *voltage*, and it is measured in *volts*.

Language of Electricity (continued)

1-10 Electricity in motion is called *current electricity*. You can think of electric current as being similar to a current of water in a pipe or in a stream. But there are some important differences you must learn about in order to avoid confusion. Electric current is measured in *amperes*, often abbreviated *amps*.

1-11 Electricity that does not move is called *static electricity*. You probably have had first-hand experience with static electricity. If you walk across a carpet when the surrounding air is fairly dry, static electricity may build up on your body. If you then touch a door knob, a water faucet, or some other metal object, the static electricity flows into the metal.

1-12 If you have built up enough static electricity on your body, the electricity may suddenly jump from your hand to the metal. It jumps just before you touch the metal. Then you can feel the electricity flowing for an instant. You call the feeling a "shock." The shock may startle you, and it may cause a little pain, but it is harmless.

1-13 If you connect a wire across the terminals of a dry cell or a storage battery, electric current flows through the wire. The flowing electricity raises the temperature of the wire. The wire may become hot enough to glow, or even melt.

1-14 This effect demonstrates another important idea concerning electricity. Electricity has *energy*. When it flows, its energy decreases, and the energy of something else increases. A wire increases its thermal energy when it gets hot. A motor increases its rotational energy when the armature and shaft start spinning.

Structure of Matter

1-15 To understand electricity, you must understand the structure of matter. Electricity is related to some of the most basic building blocks of matter— atoms, electrons, and protons. All matter is made of these electrical building blocks, and therefore all matter is said to be "electrical."

1-16 **Matter** is defined as anything that has mass and occupies *space*. All matter is made of tiny, invisible particles called *molecules*. A **molecule** is the smallest particle of a substance that has the properties of the substance. Each molecule can be divided into simpler parts by chemical means. The simplest parts of a molecule are called **atoms**.

1-17 Matter consisting of two or more different kinds of atoms is called a **compound**. Water, table salt, and alcohol are examples of compounds. The smallest particle of a compound is a molecule. Each molecule of a compound consists of the same number and kind of atoms, joined chemically into a single unit.

1-18 If you separate the atoms of a molecule into smaller groups, or into individual atoms, you no longer have the same compound. The simpler molecules or atoms make up a different material having different properties.

Structure of Matter (continued)

1-19 For example, a molecule of water is made of two atoms of hydrogen and one atom of oxygen, as shown in Figure 1.1 below. This molecule is the smallest bit of water that still has the properties of water. If you break the atoms apart, you no longer have water. Instead you have two gases, hydrogen and oxygen, with properties entirely different from those of water. They have different densities, boiling temperatures, and chemical properties.

1-20 When all of the atoms in a given piece of matter are of the same kind, the matter is called an **element**. More than 100 different elements are known today. Ninety-two of them are stable and occur in nature. Examples include *nitrogen* and *oxygen* in the air, *carbon* in living things, and *silicon* in sand.

1-21 About a dozen elements are unstable. Each atom of such an element exists for only a fraction of a second during a nuclear reaction. No one has ever seen material made of one of these elements.

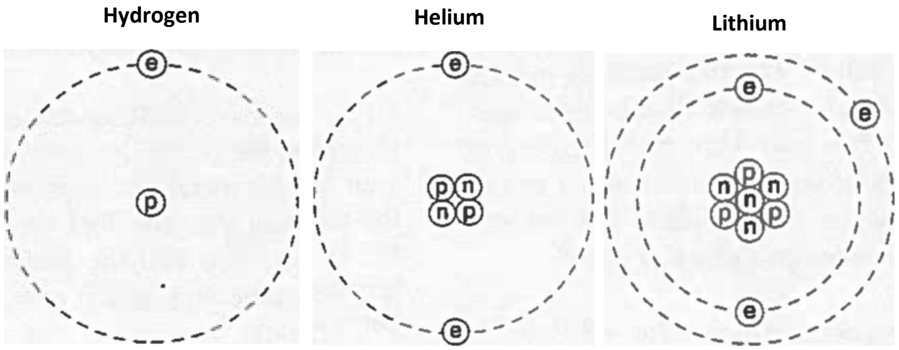
Structure of Atoms

1-22 Most of the mass of an atom is concentrated in a tiny spot at the center, called the **nucleus**. The nucleus is not a single particle, however. It is a collection of two kinds of particles called *protons* and *neutrons*. The **proton** has a *positive* electrical charge. The **neutron** has *no* electrical charge. It is neutral.

1-23 The positive charge of each proton equals the negative charge of each electron. The two opposite charges cause a force of attraction between the proton and the electron. The proton pulls inward on the electron, and the electron pulls outward on the proton.

1-24 If the proton and electron had the same mass, or nearly the same mass, they would rotate around a central point located somewhere between them. But the proton has about 1840 times as much mass as the electron. Therefore, the proton hardly moves. The electron moves around it, somewhat like a planet in orbit around the sun.

1-25 The protons, neutrons, and electrons in every element are identical. But the *numbers* of protons, neutrons, and electrons differ, as shown in Figure 1.2 below. These differences make one element different from another.



1 Proton
0 Neutrons
1 Electron

2 Protons
2 Neutrons
2 Electrons

3 Protons
4 Neutrons
3 Electrons

Figure 1.2: Atomic Structures

Structure of Atoms (continued)

1-26 When the number of protons in the nucleus equals the number of orbiting electrons, the atom is electrically *neutral*. That is, the atom as a whole has no electrical charge. But in some atoms, the outermost electrons are attracted to the nucleus only weakly. The force of attraction is weak because of the inner electrons. The inner electrons repel the outer electrons. This force combines with the attraction of the protons, creating a weak force on the outer electrons.

1-27 In such an atom, one or more of the outermost electrons can escape from the atom. Each electron that escapes removes one unit of negative charge from the atom, leaving the remainder of the atom with a net positive charge.

Electron Shells

1-28 If it were possible to see the electrons around the nucleus of an atom, you would see a sort of cloud in the shape of a hollow sphere. The drawing in Figure 1.3 below is a rough idea of how an atom of oxygen might look. If you could look very closely at the electron cloud in a real atom, you might see a few layers within the cloud. The 16 electrons of an oxygen atom exist within this cloud, but not as compact objects moving on simple paths. You would *not* see individual electrons moving like planets in orbit around a sun.

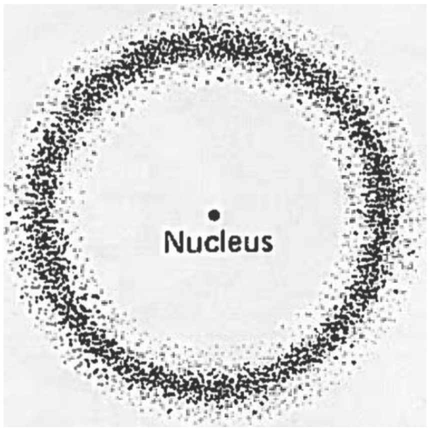


Figure 1.3: Electron Cloud

Electron Shells (continued)

1-29 To understand the behavior of an atom, it helps to think of the electrons in a rather simple way. You should think of the electrons as being arranged around the nucleus in shells of different size. You can picture each shell as a thin, hollow sphere. Several shells can surround the nucleus of the atom, the larger ones surrounding the smaller ones, as shown in Figure 1.4 below.

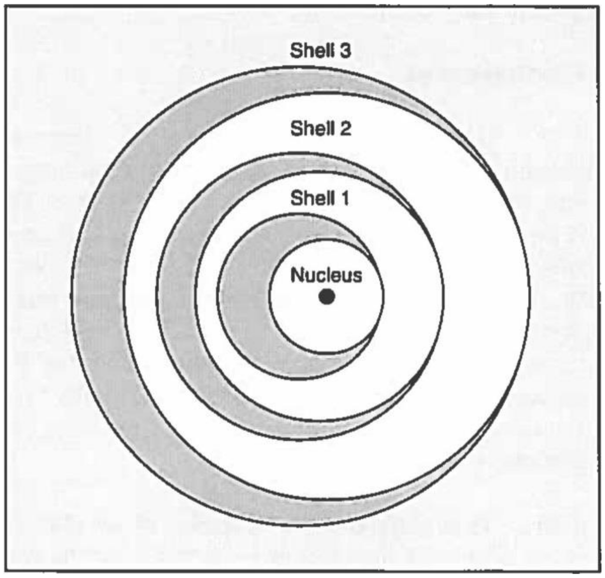


Figure 1.4: Electron Shells

1-30 Each "shell" can contain only a certain maximum number of electrons. The innermost shell, the one closest to the nucleus, can contain a maximum of only two electrons. That is, it can contain either one electron, or two. In the hydrogen atom, this shell contains only one electron. In all other atoms, it contains a full set of two electrons.

1-31 The second shell is larger than the first. It can contain up to eight electrons. The third shell is still larger, and can contain up to 18 electrons. The fourth shell can contain 32.

Electron Shells (continued)

1-32 If you "look" at the electron shells a little closer, the picture is a little more complicated. All shells except the innermost one are divided into *subshells*. The second shell is divided into *two* subshells, the third into *three* subshells, and the fourth into *four* subshells. In each case, the innermost subshell can contain up to two electrons, the second can contain up to six electrons, the third can contain up to ten, and the fourth can contain up to 14. Figure 1.5 shows the subshells for the first three electron shells.

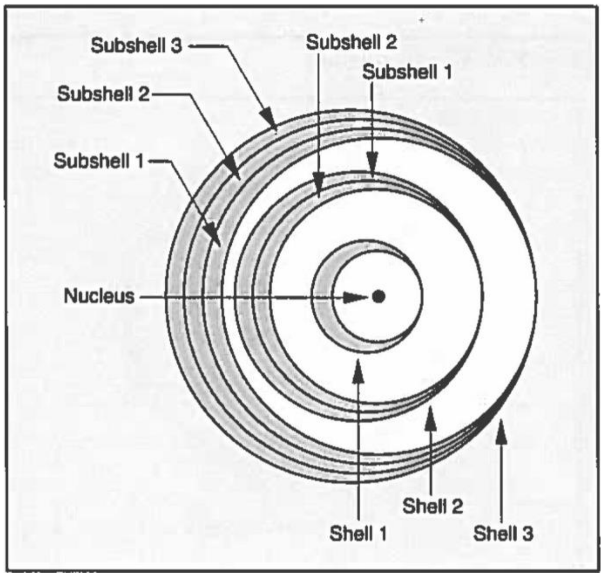


Figure 1.5: Electron Subshells

1-33 Table 1-1 on the following page shows the electron distribution of the first 55 atoms. You can see that the first ten atoms make up a simple pattern as the electrons fill the first two shells. The inner shell fills up first with two electrons, and then the second shell fills up with eight. When the second shell fills, the first two go into the inner subshell and the next six go into the outer subshell.

1-34 As the third shell begins filling, the pattern becomes more complicated. The first subshell fills first with two electrons. Then the second subshell fills with six. But before the third subshell begins to fill, the first subshell of the fourth shell fills. Notice that another odd series begins with element 37.

1-35 The chemical and the electrical behavior of atoms depends on how completely the various shells and subshells are filled. The atoms that are most active chemically are those that have one electron more or one electron less than a completely-filled shell. Atoms that have the outer shell exactly filled are chemically inactive. They are all gases that do not combine chemically with other elements. These gases are called inert elements. You can identify these **inert elements** in Table 1-1 on the following page.

Element	No. of Protons	Number of Electrons																		
		Shell 1	Shell 2		Shell 3			Shell 4				Shell 5				Shell 6				
			1	2	1	2	3	1	2	3	4	1	2	3	4	1	2	3	4	
Hydrogen	1	1																		Very Active Element
Helium	2	2																		Inert Element
*Lithium	3	2	1																	Very Active Element
*Beryllium	4	2	2																	
Boron	5	2	2	1																
Carbon	6	2	2	2																
Nitrogen	7	2	2	3																
Oxygen	8	2	2	4																
Fluorine	9	2	2	5																Very Active Element
Neon	10	2	2	6																Inert Element
*Sodium	11	2	2	6	1															Very Active Element
*Magnesium	12	2	2	6	2															
*Aluminum	13	2	2	6	2	1														
Silicon	14	2	2	6	2	2														
Phosphorous	15	2	2	6	2	3														
Sulfur	16	2	2	6	2	4														
Chlorine	17	2	2	6	2	5														Very Active Element
Argon	18	2	2	6	2	6														Inert Element
*Potassium	19	2	2	6	2	6		1												Very Active Element
*Calcium	20	2	2	6	2	6		2												
*Scandium	21	2	2	6	2	6	1	2												
*Titanium	22	2	2	6	2	6	2	2												
*Vanadium	23	2	2	6	2	6	3	2												
*Chromium	24	2	2	6	2	6	4	1												
*Manganese	25	2	2	6	2	6	5	2												
*Iron	26	2	2	6	2	6	6	2												
*Cobalt	27	2	2	6	2	6	7	2												
*Nickel	28	2	2	6	2	6	8	2												
*Copper	29	2	2	6	2	6	10	1												
*Zinc	30	2	2	6	2	6	10	2												
*Gallium	31	2	2	6	2	6	10	2	1											
Germanium	32	2	2	6	2	6	10	2	2											
Arsenic	33	2	2	6	2	6	10	2	3											
Selenium	34	2	2	6	2	6	10	2	4											
Bromine	35	2	2	6	2	6	10	2	5											Very Active Element
Krypton	36	2	2	6	2	6	10	2	6											Inert Element
*Rubidium	37	2	2	6	2	6	10	2	6			1								Active Element
*Strontium	38	2	2	6	2	6	10	2	6			2								
*Yttrium	39	2	2	6	2	6	10	2	6	1		2								
*Zirconium	40	2	2	6	2	6	10	2	6	2		2								
*Niobium	41	2	2	6	2	6	10	2	6	4		1								
*Molybdenum	42	2	2	6	2	6	10	2	6	5		1								
*Technitium	43	2	2	6	2	6	10	2	6	6		1								
*Ruthenium	44	2	2	6	2	6	10	2	6	7		1								
*Rhodium	45	2	2	6	2	6	10	2	6	8		1								
*Palladium	46	2	2	6	2	6	10	2	6	10										
*Silver	47	2	2	6	2	6	10	2	6	10		1								
*Cadmium	48	2	2	6	2	6	10	2	6	10		2								Active Element
*Indium	49	2	2	6	2	6	10	2	6	10		2	1							
*Tin	50	2	2	6	2	6	10	2	6	10		2	2							Inert Element
Antimony	51	2	2	6	2	6	10	2	6	10		2	3							
Tellurium	52	2	2	6	2	6	10	2	6	10		2	4							Active Element
Iodine	53	2	2	6	2	6	10	2	6	10		2	5							
Xenon	54	2	2	6	2	6	10	2	6	10		2	6							
*Cesium	55	2	2	6	2	6	10	2	6	10						1				

*Indicates the elements that are metal

Table 1-1

Electron Shells (continued)

1-36 Elements that belong to the class called *metals* are good electrical conductors. In these elements, the electrons in the outer shells and subshells can easily move from one atom to another. In moving from atom to atom, they carry charge through the material.

1-37 You can see which atoms in Table 1-1 are classified as metals. They are marked with an asterisk (*) in front of the element name. Many of these elements have "gaps" in their electron shells and subshells. The first group with gaps consists of atoms 19-28.

1-38 As you can see from studying Table 1-1, some elements *without* gaps are among the best conductors, for example, aluminum (No. 13) and copper (No. 29). And some elements *with* gaps are not good conductors, for example, iodine (No. 53), which is missing subshell 4 of shell 4. But in general, most elements that have gaps in their electron shells and subshells are good conductors of electricity.

Transferring Charges

1-39 Under certain conditions, one or two of the outermost electrons of an atom can be stripped away from an atom and transferred somewhere else. This process leaves the atom with a net positive charge. Something else in the universe then has a net negative charge.

1-40 For example, if you rub a piece of plastic with fur or wool, electrons are stripped away from some of the atoms in the wool and transferred to the plastic. The plastic then becomes *negatively* charged, because it has an excess of electrons. The fur or wool becomes *positively* charged, because it has a deficiency of electrons. Figure 1.6 shows this redistribution of charge.

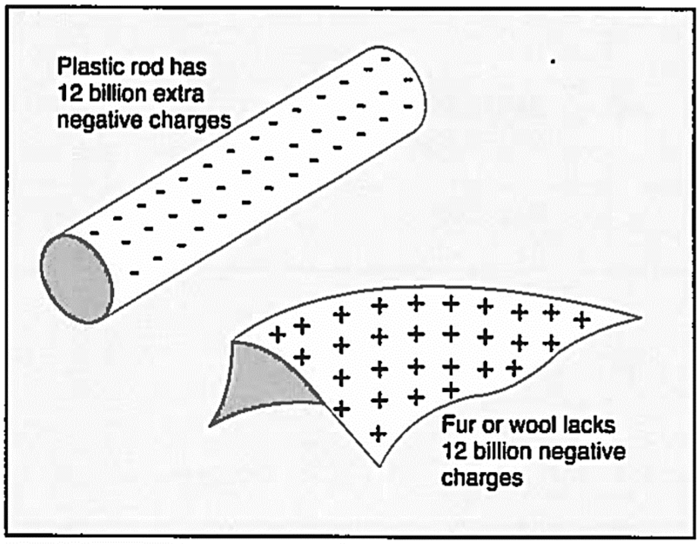


Figure 1.6: Charge Redistribution on a Plastic Rod

Transferring Charges (continued)

1-41 Likewise if you rub a glass rod with silk, electrons are stripped away from some of the atoms in the glass. The glass rod then becomes *positively* charged, because it has lost electrons. The silk becomes *negatively* charged, because it has gained electrons. Figure 1.7 shows how the charges are redistributed on the glass and silk.

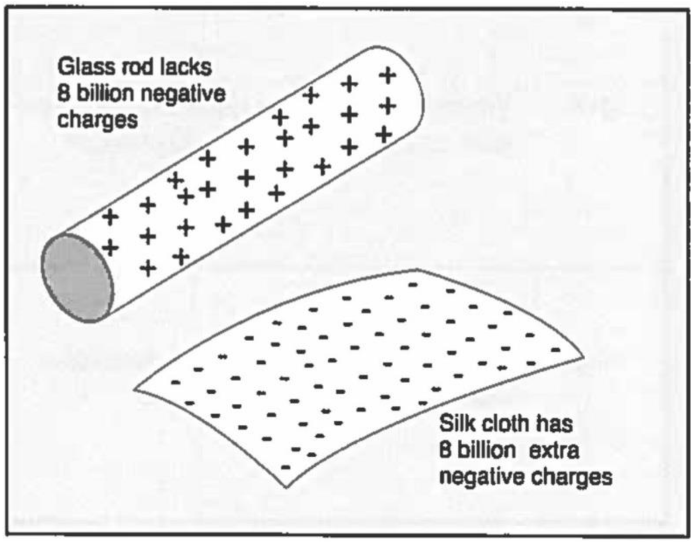


Figure 1.7: Charge Redistribution on a Glass Rod

1-42 You should note that electricity is not *created* in either of these examples. The total number of electrons in the universe always remains unchanged. Some electrons are moved from one place to another, but the excess in one place equals the deficiency in the other. The balance remains perfect.

1-43 The balance for the universe as a whole always remains perfect. For every extra electron in one place, there is an electron missing somewhere else. Thus, for every *positively-charged* object, there is a net negative charge of exactly the same amount in the remainder of the universe. For every *negatively-charged object*, there is a net positive charge of exactly the same amount in the remainder of the universe.

Electrical Forces

1-44 Objects having electrical charges can exert forces on each other. These forces are the strongest forces known in nature. No other forces—magnetic, gravitational, or nuclear forces— are as strong as electrical forces for objects of the same size or separated by the same distance. Electrical forces *attract* two objects that have opposite charges (one positive and one negative). They *repel* two objects that have identical charges (both positive or both negative).

1-45 Figure 1.8 shows a common way to demonstrate the forces of attraction and repulsion. The plastic ball shown at the far left has no charge. It is then given a negative charge by rubbing it with fur. A plastic rod, also charged negatively, is then brought near the ball. The ball swings away from the rod, because the two objects have the same charge. The same thing would happen if the ball and the rod both had a positive charge.

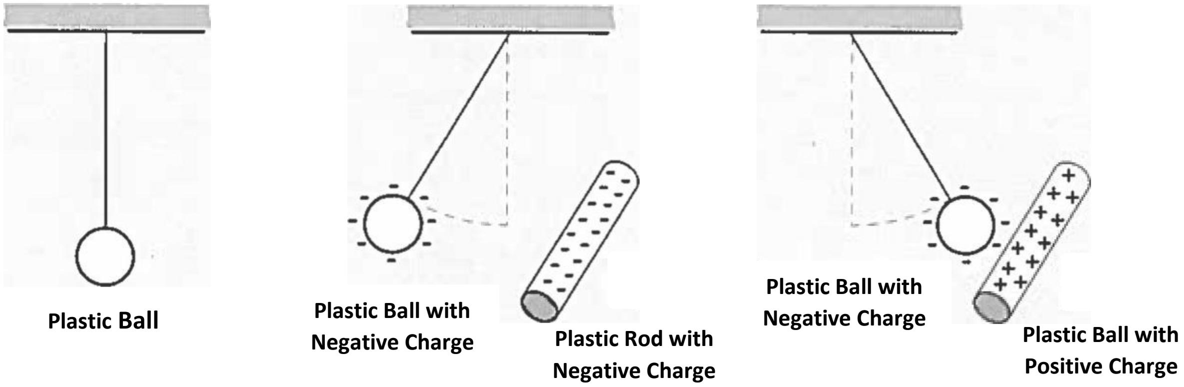


Figure 1.8: Forces Between Charged Objects

1-46 Next, a positively-charged glass rod is brought near the negatively-charged ball. The ball swings *toward* the glass rod because of the attraction between the opposite charges. A negative rod would attract a positive ball for the same reason.

1-47 The forces of attraction and repulsion between electrical charges give shape and substance to the world. Atoms that share electrons in chemical bonds are held together by the forces of attraction between unlike charges.

1-48 When you press your hand against something solid, there is an electrical force repelling your hand from the object. This force exists because electrons in the atoms of your hand repel the electrons of the object. If the electrical force of repulsion did not exist, your hand would pass right through the solid object, because every atom is mostly empty space.

Electrical Terms

1-49 As you study electricity in your training program, and as you work with electricity in the plant, you will hear, read, and use various electrical terms. These terms have very exact meanings. You must know what each one means if you are to understand other people and make them understand you. The following paragraphs explain the meaning of the most basic electrical terms. Other terms will be explained in other Lessons and Units as you need them.

1-50 **Electric current**. When electrons flow from one place to another, they make a *current*. The electrons always flow from a negative point to a positive (or less negative) point, because electrons have a negative charge.

1-51 Unfortunately, the direction of current flow can be confusing. Some people think of a *positive current* that is in the opposite direction from the *electron flow*. That is, from positive to negative instead of from negative to positive. You must be careful to distinguish between the two kinds of flow. Both kinds are commonly used, both in words and in diagrams.

1-52 The so-called "positive current" is from positive to negative. The "electron flow" is from negative to positive. In these training manuals, we will always use the word "current" to mean *electron flow*—from negative to positive. Figure 1.9 shows the difference between positive current and electron flow.

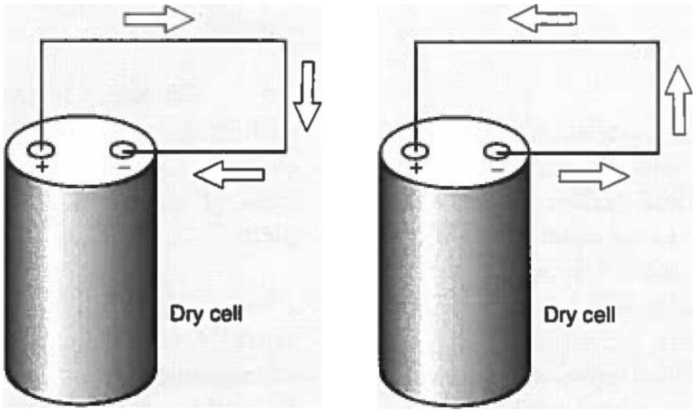


Figure 1.9: Two Directions of Electric Current

1-53 **Circuit**. Electrons flow along some kind of path in going from one point to another. This path is called a *circuit*. If the path has no gaps to stop the flow of electrons, the circuit is said to be "complete."

Electrical Terms (continued)

1-54 If the path has a gap that the electrons cannot cross, such as a break in a wire where the ends are separated by air, the circuit is said to be "open." If another pathway provides an easier way or a shortcut for the electrons to go from one point to another, that part of the circuit is said to be "shorted." Figure 1.10 shows circuits that are complete, open, and shorted.

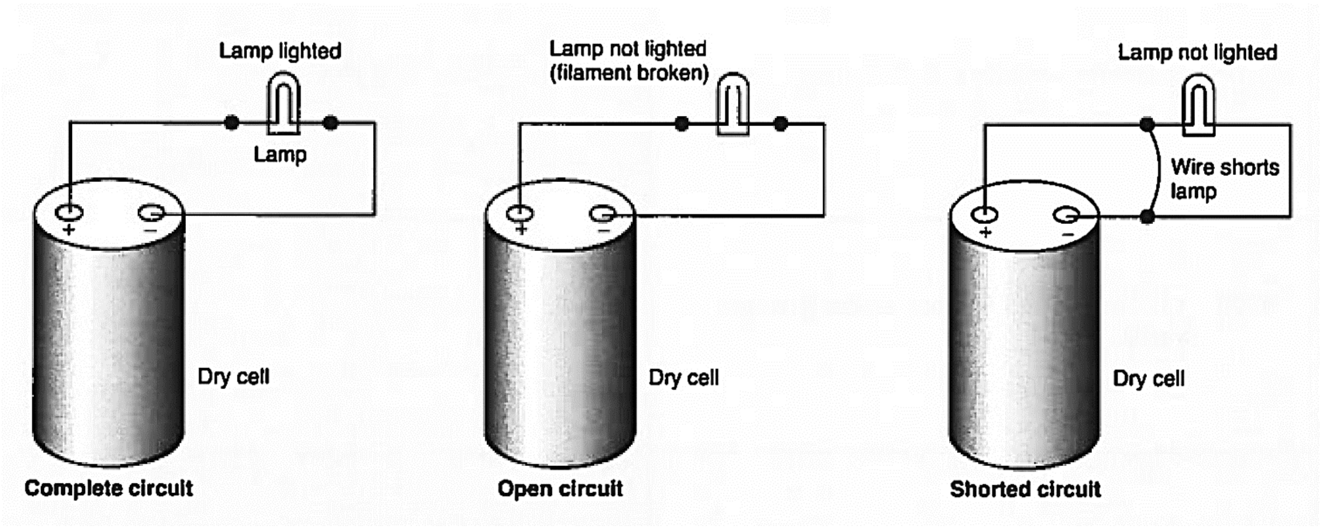


Figure 1.10: Electric Circuits

1-55 **Potential difference**. This term is the correct name for what is often called "voltage" or "electromotive force." Potential difference is a measure of how much potential energy an electron has in one place compared to another place.

1-56 The greater the potential energy, the more work an electron can do in going from one place to the other. The potential energy of each electron also determines how much current will flow from one point to another in a given circuit.

1-57 **Resistance**. Every electrical pathway from one place to another has the property of resisting the flow of electrons. Some pathways resist the flow only slightly. For example, a thick copper wire offers very little resistance. Other pathways—for example, an air gap—offer great resistance. The greater the resistance, the less the current for a given potential difference.

1-58 **Cell**. Electricity can be produced by chemical means. The arrangement of materials that produces a potential difference between two points by chemical means is called a *cell*. Familiar cells include the "dry cells" used in flashlights, calculators, and radio.

Electrical Terms (continued)

1-59 **Battery**. When you connect two or more cells together, the combination is called a *battery*. If your calculator takes two dry cells, the combination is called a "two-cell battery."

1-60 The storage battery in a car or truck is usually a six-cell battery that produces a potential difference of 12 volts between the terminals. Each cell in such a battery produces a potential difference of two volts between its internal terminals. The terminals of the cells are connected in such a way that their potential differences add together between the external terminals.

1-61 As you study the remaining Lessons in this Unit, and the other Units in your course, make sure you learn the proper terms to use in discussing electricity, and the exact meaning of each term. Always use the correct terms, even if other people do not. If you use the wrong terms, you are likely to be misunderstood. In addition, other people will think you know less about electricity than you actually do.

Chapter 1 Exercise

Circle the appropriate letter next to the correct answer.

1. The foundation of all our modern electrical machinery and equipment is ______________________________________.

   a. Science
   b. Physics
   c. Electricity
   d. Electromagnetism

2. What is the name for electricity in motion?

   a. Static electricity
   b. Current flow
   c. Flowing electricity
   d. Electromagnetism

3. Anything that has mass and occupies space is called _________________________________.

   a. Fluid
   b. An electron
   c. Protons
   d. Matter

4. Each molecule of a compound consists of the same number and kind of ______________________________________.

   a. Elements
   b. Atoms
   c. Protons
   d. Neutrons

5. Most of the mass of an atom is concentrated in the _____________________________.

   a. Nucleus
   b. Core
   c. Electron
   d. Proton

Chapter 1 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. When the number of protons in the nucleus equals the number of orbiting electrons, the atom is electrically ________.

   a. Charged
   b. Complete
   c. Neutral
   d. Inert

7. The strongest forces for objects of the same size and separated by the same distance are ________________________.

   a. Electrical
   b. Gravitational
   c. Magnetic
   d. Nuclear

8. Two objects having the same charge will ____.

   a. Attract each other
   b. Repel each other
   c. Not affect each other
   d. Either attract or repel each other

9. Electrons flowing from one place to another make a(n) ____________________.

   a. Track
   b. Channel
   c. Circuit
   d. Current

10. Two or more cells connected together make a combination called (n) ___________________________.

    a. Coulomb
    b. Battery
    c. Engine
    d. Motor

Summary

The industrial world is largely an electrical world. Most equipment and machinery operates on electricity. It is matter, molecules made up of atoms, that makes electricity possible. Atoms are made up of electrons, protons, and neutrons.

The center of the atom is called the nucleus. It contains protons and neutrons. Electrons revolve around the nucleus. The relationship between the protons and the electrons creates force. This force attracts or repels objects depending on whether the objects have opposite charges or the same charge. Objects with opposite charges attract each other. Objects with the same charge repel each other.

Electricity in motion is called current electricity. Electricity that does not move is called static electricity. When electrons flow, they create a current. The path they flow along is called a circuit. The measure of how much potential energy an electron has in one place compared to another place is called potential difference.

Electricity can also be created by chemical means. A cell is an arrangement of materials that produces a potential difference between two points. Cells are used in combination to make batteries.

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Chapter 2: Static Electricity

In This Chapter:

- **Nature of Static Electricity**
- **Generating Static Electricity**
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- **Effects of Humidity**
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- **Static Charges on Dusts and Fibers**
- **Static Charges in Process Machinery**
- **Using Static Electricity**
- **Measuring Static Electricity**

Terminology

Static electricity: Electricity that does not move

Bonding: Electrical connection between two or more metallic objects

Grounding: Connection of an object to the earth

Ion: An electrically-charged atom

Purge: To replace one gas with another

Electroscope: An instrument for detecting static electricity

Electrostatic voltmeter: A precise electroscope used for measuring large static charges

Electrostatic amplifier: A sensitive instrument for measuring small static charges

Static electricity can be a help or a hazard. Your understanding of the nature of static electricity may determine your safety and that of other employees in the plant.

In this Lesson, we explain what static electricity is, what causes it, and steps you can take to reduce or prevent it in the plant. We explain bonding and grounding techniques, and when and where they should be used. We also list static eliminators that can be attached or applied to materials, machinery, and equipment.

This Lesson also includes the practical applications of static electricity in the plant. Finally, it explains the use of instruments for measuring static electricity.

Nature of Static Electricity

2-1 Static Electricity is electricity that does not move. The word static comes from the Greek word statikos, meaning the act of making something stand still. Static electricity consists of electrical charges that remain unmoving on an object.

2-2 Static electricity usually is generated by the physical contact and separation of different kinds of materials. Various effects result from the formation of positive and negative charges. Static electricity cannot be avoided, because electric charges are naturally present in all objects.

2-3 Static electricity can cause problems in industrial equipment. It can interfere with the operation of electronic equipment, and it can cause sparks that ignite flammable liquids and vapors. In order to prevent these problems, you must understand the nature of static electricity.

2-4 Electrical charges themselves cannot cause a fire or explosion. In order for static electricity to cause ignition, four conditions must exist.

- There must be a means of generating static charges.
- There must be a means of maintaining a potential difference.
- The potential difference between the charges must be great enough to cause breakdown of the resistance of the air between them.
- The spark must occur in a flammable atmosphere.

2-5 Some of the most common causes of static electricity are listed here.

- Pulverized materials passing through chutes or pneumatic conveyors
- Steam, air, gases, or nonconductive liquids discharging from a pipe or hose
- Nonconductive powered conveyor belts in motion
- Moving vehicles
- People walking on nonconductive carpeting or waxed floors

Generating Static Electricity

2-6 When two unlike materials are pressed together, some of the electrons at the surfaces transfer from one material to the other. When the two materials are then separated, more of the electrons remain with one material than with the other. As a result, the material having more electrons has a negative charge. The other material has an equal positive charge, because it lacks the same number of electrons.

2-7 If a conductive path becomes available, the extra electrons on one material will rush to the other material. Then both materials will become electrically neutral again, or nearly so. If there is no conductive path between them, the two materials may remain charged even if the potential difference between them builds up to several thousand volts.

2-8 On some materials, for example concrete and asphalt, the charges are somewhat mobile. After these materials become charged, they will slowly discharge until they become electrically neutral again.

Generating Static Electricity (continued)

2-9 On insulating materials, for example plastic or rubber, the charges are unable to move freely. These materials can remain charged for a long time, even if the potential difference becomes fairly high.

Effects of Static Electricity

2-10 The human body is a good electrical conductor. In a dry atmosphere, you can pick up static charges from certain manufacturing operations. You can also pick up a charge as your shoes make and break contact with floor coverings, especially carpeting.

2-11 These charges become distributed over the entire surface of your body. The potential difference between your body and other objects in the plant may reach several thousand volts. Yet you may feel nothing unusual.

2-12 If your clothing and shoes are moist enough, for example, when the humidity is high, static charges will drain away quickly into the air. They will never build up and produce a large potential difference between your body and other objects in the plant. But if the air is very dry, the potential difference may become large enough to make a spark jump when you come near an object.

2-13 If you work in an area filled with flammable liquids, explosive gases, or fine dusts, you must take special precautions to prevent sparks from occurring. Do not wear rubber shoes or boots when handling flammable liquids. Wear shoes with soles made of leather or other conductive material. Leather absorbs moisture, so that it provides a conductive path to drain away static charges as they occur.

2-14 If your shoes have steel toe protectors, heel plates, or nails, then they are conductive, no matter what other materials they are made of.

2-15 The shock from a static charge may sting, and under some circumstances it may lead to an injury. The injury will probably not come from the shock itself, but from your reaction to the shock.

2-16 For example, the normal human reaction to a shock on the hand is to pull your hand away quickly. This action is an automatic reflex action that you do not even think about. But the rapid, uncontrolled action may cause your hand to strike another object or to enter a hazardous area on a machine, leading to a serious injury.

2-17 Some clothing materials can build up a large static charge. Removing a jacket, a sweater, or other garment can be dangerous in an area where the atmosphere is flammable or explosive.

Eliminating Static Electricity

2-18 Static electricity can be eliminated from metal equipment by *bonding* and by *grounding*. These two techniques are shown in Figure 2.1.

- Bonding is the creation of an electrical connection between two or more metallic objects. The connection is usually made by means of a metal wire or a metal strap.
- Grounding is the electrical connection of an object to the earth by means of a grounding device.

Bonding minimizes the potential difference between two objects. Grounding minimizes the potential difference between an object and the earth.

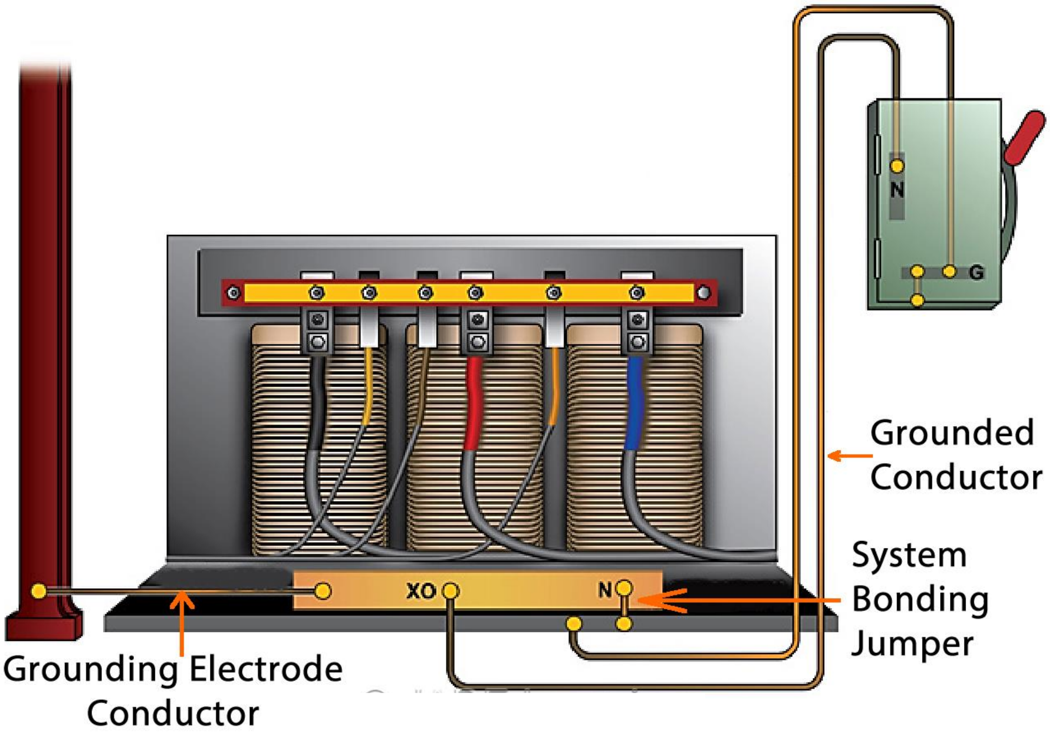


Figure 2.1: Bonding and Grounding

2-19 A metal object can be grounded by bonding it to another metal object that is grounded. Some metal objects are bonded or grounded simply by touching another metal object that is connected to the earth. Common examples of good grounds include underground metal piping and large storage tanks resting on the ground.

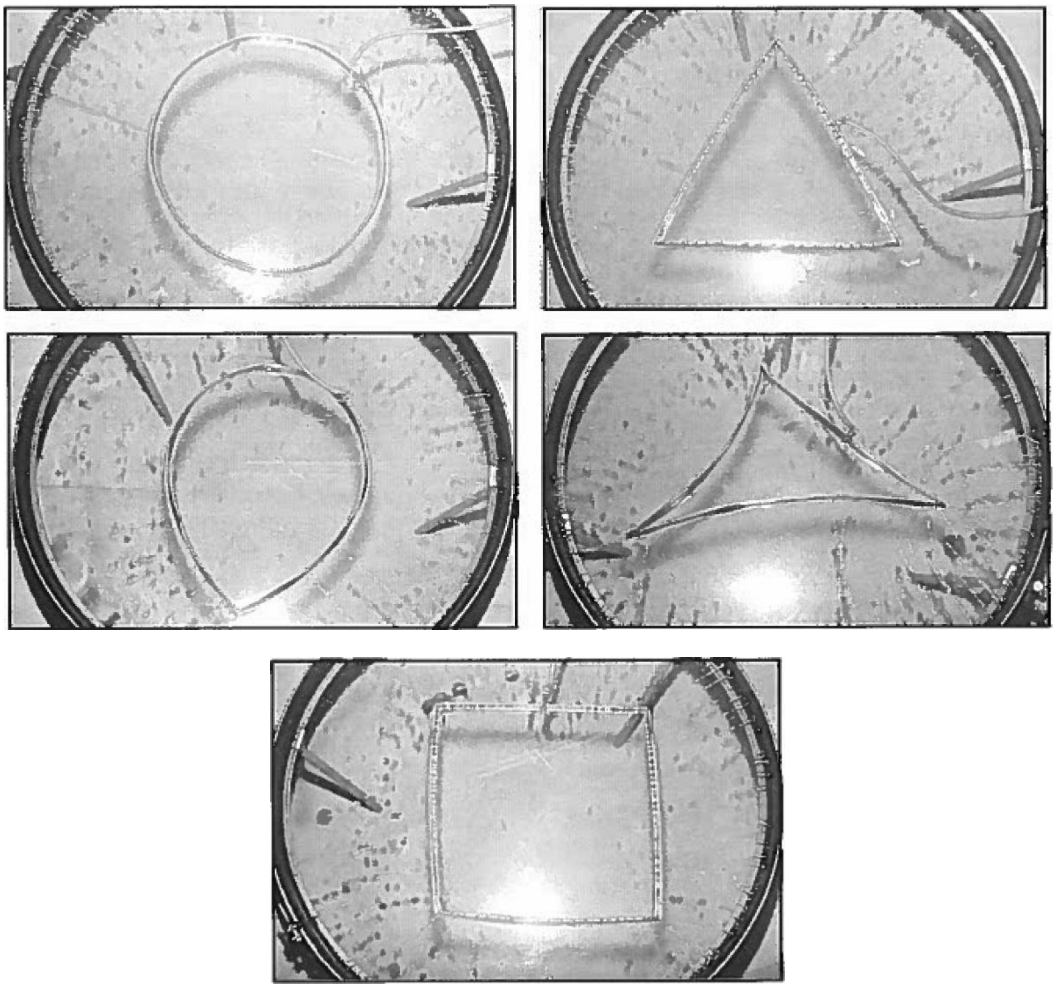
2-20 Bonding and grounding wires should be large enough to handle the largest currents that are likely to occur. A grounding wire should be no smaller than AWG No. 8. This size is large enough to provide mechanical strength as well as a large current-carrying capacity.

2-21 Solid wire is good enough for permanent, stationary connections. A flexible conductor should be used if the objects are to be connected and disconnected often, or if they can move relative to each other.

Static Eliminators

2-22 Static charges distribute themselves on objects according to definite rules. For example, the charges distribute themselves *evenly* on the surface of a perfect sphere. On objects with sharp points, the charges become *concentrated* at the points.

2-23 The photographs in Figure 2.2 show how static charges are distributed on two-dimensional models of several basic shapes. The particles surrounding these models are distributed in the same way as the electrical charges on the model. The particles show that the charges are concentrated at points where two surfaces meet at a sharp angle. The sharper the angle, the more charge is concentrated in that area.



NOTE: To make these photographs, grass seeds were floated on a shallow pool of clear vegetable oil in a small glass-bottomed tank. The shaped electrodes were made of brass strips soldered together at the joints. The wire clipped to each electrode was connected to a static generator that produced many thousands of volts. The grass seeds formed "chains" perpendicular to the charged electrode. They did not necessarily touch the electrode.

The grass seeds appear white on the surface of the oil. The dark spots are shadows cast by the seeds onto the laboratory floor under the tank.

Figure 2.2: Static Charge Distribution

Static Eliminators

2-24 A **static comb** is a metal bar having many points. It may be a bar with metal flaps hanging from it, or it may be a wire rod covered with metal tinsel. Both forms are shown in Figure 2.3.

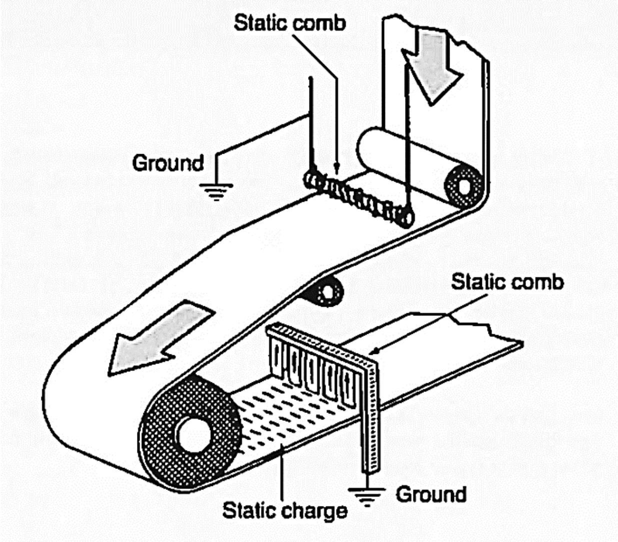


Figure 2.3: Static Eliminators

2-25 When a grounded static comb is brought close to a charged surface, as shown in Figure 2.3, the charge on the surface induces the opposite charge on the comb. The induced charge becomes highly concentrated at the points on the comb, just as shown in Figure 2.2.

2-26 The high concentration of charge around the points breaks down some of the air molecules, producing electrically-charged atoms called *ions*. These ions are repelled by the charge on the points, and conduct charges away from the charged surface. Thus, the charge can be removed from fabrics, belts, paper, and other surfaces.

Effects of Humidity

2-27 You probably have noticed that you often get a shock after walking across a carpet in *dry* weather. But if the air is *moist*, you do not get a shock. The difference is caused by the difference in the moisture content of the air.

2-28 Cloth, wood, paper, concrete, and other non-conducting materials contain moisture that affects their ability to get rid of static charges. The amount of moisture they contain depends on the humidity of the air.

2-29 When the humidity is high, materials absorb moisture from the air. The moisture they absorb forms a conducting film on the surface of the fibers and grains of the material. This film conducts electric charges easily.

2-30 When static electricity causes problems in materials-processing equipment, adding moisture to the air may be the solution. The material going through the machine absorbs moisture, and the moisture drains off the static charges. By eliminating the charge, you can often solve the problems.

2-31 Sometimes it is not practical to humidify the air where static electricity might cause problems. High humidity can damage some materials, and it can cause other problems in the processing machinery.

Effects of Humidity (continued)

2-32 Furthermore, raising the humidity will not reduce the buildup of static charges on an oily solid or on an oily liquid. Oily surfaces do not absorb water, and therefore cannot acquire a conductive path for electric charges. Such a material can accumulate a static charge even with 100 percent relative humidity in the air. The charges must be removed in other ways.

Static Charges on a Liquid Surface

2-33 A static charge is generated when a liquid flows and makes contact with other materials. Static charges occur commonly when liquids flow through pipes. They also occur during mixing, pouring, pumping, filtering, and agitating. Micro-filters and filters made of clay increase the ability of some liquids to develop static charges.

2-34 Under certain conditions, enough static charge may build up to cause a spark in a product or other flammable liquid. However, crude oils do not produce enough static electricity to cause self-ignition.

2-35 The electrical *resistance* of a liquid is a measure of its ability to hold a charge. The higher the resistance, the greater the ability of the liquid to hold a charge.

2-36 Very pure water has high resistance, and is capable of holding an electrical charge. Ordinary tap water contains dissolved minerals that are good conductors of electricity. Static charges leak off tap water as rapidly as they are formed.

2-37 When an electrically-charged liquid is poured, pumped, or transferred to a container, static charges become distributed on the outer surfaces of the liquid. These surfaces are in contact with the container or with the air-space above the liquid. These "surface charges" are usually responsible for any problems that occur.

2-38 Most large containers are made of metal, Therefore they can conduct electricity, regardless of whether they make electrical contact with the earth or not. If the container is grounded, any charges in the liquid flow to the earth very quickly.

2-39 If the container is not grounded, the charge on the metal wall is opposite the charge on the liquid. The two charges partially neutralize each other until the liquid and the container become stable.

2-40 The time required for stabilization can range from a fraction of a second to a few minutes. After stabilization, there is usually a potential difference between the earth and the tank, and also between the earth and the liquid.

2-41 If there is a potential difference between any part of the liquid surface and the metal tank, a spark may jump to the container wall. Such a spark is likely to cause ignition if a flammable mixture of vapor and air is present above the liquid. For this reason, the danger of explosion is greater in a partially-filled tank than in one that is completely filled.

Static Charges on a Liquid Surface

2-42 Surface charges can be generated in several ways inside a tank.

- by spraying or splashing of the liquid
- by air or gas bubbling through the liquid
- by jet or propeller action
- by convection currents within the liquid

2-43 Grounding of a very large container may not be sufficient to remove all the electrical charges. In addition to grounding, a further precaution can be taken against spark ignition by "purging" the container.

2-44 To **purge** a container, the vapor above the liquid is replaced with nitrogen, carbon dioxide, or some other nonflammable gas. Purging also eliminates the oxygen necessary for combustion. Even if a spark occurs, it cannot ignite the vapor in the absence of oxygen.

Static Charges on Rubber-Tired Vehicles

2-45 Vehicles with rubber tires can accumulate static electricity, especially when the tires and the pavement are dry. The static charges are generated as the tires roll on the pavement and during filling of the tank with liquid.

2-46 A significant static charge can develop when tank trucks are loaded through open domes. If the tires are dry, a potential difference can develop between the vehicle and a grounded piping system. Then a spark may jump between the edge of the tank opening and the fill pipe.

2-47 To avoid sparking when filling a tank truck, an electrical bond should be made between the fill pipe and the tank, as shown in Figure 2.4. The connection should be made before the dome is opened. It should not be removed until after the dome is closed.

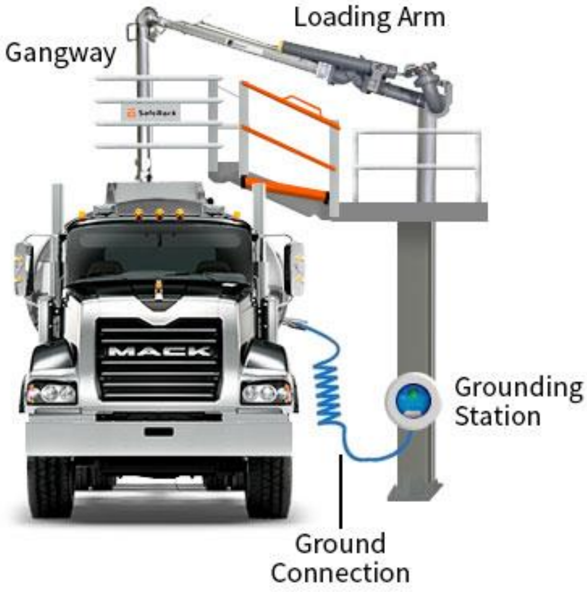


Figure 2.4: Bonding for Filling a Tank Truck

Static Charges on Rubber-Tired Vehicles (continued)

2-48 One end of the bonding wire should be permanently connected to the fill pipe, which in turn is connected to ground. The other end of the bonding wire should have an attachment clip that will pull away easily if the truck drives off before the bonding wire is removed.

2-49 No external bonding wire is needed for unloading flammable liquids into an underground tank, as shown in Figure 2.5. Any charge in the liquid is removed as it flows through the metal nozzle, because the nozzle is grounded by its contact with the metal opening in the tank.

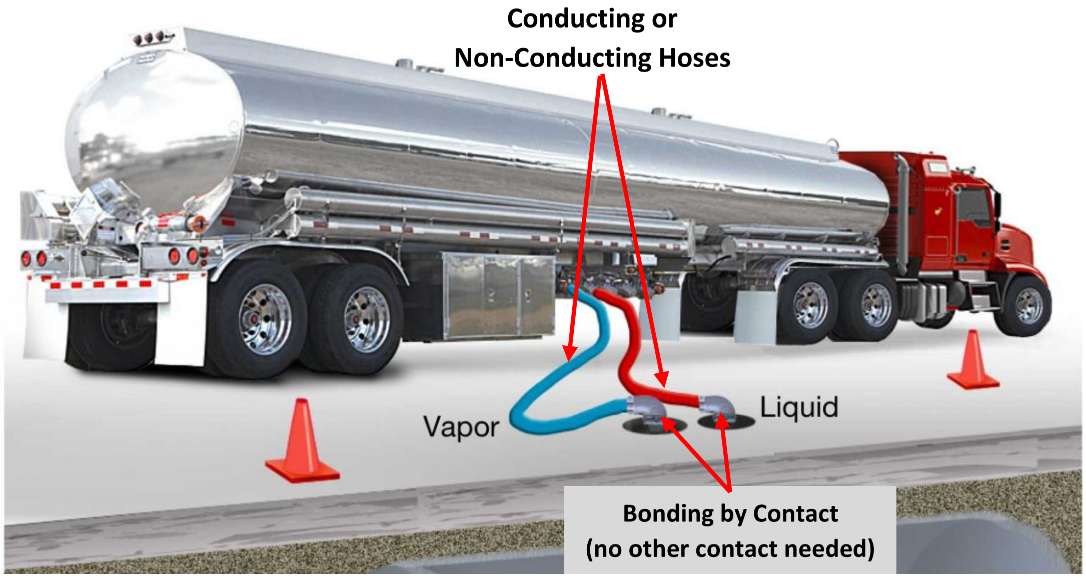


Figure 2.5: Bonding for Emptying a Tank Truck

Static Charges on Rubber-Tired Vehicles (continued)

2-50 When filling a portable container, the same grounding rules apply as when filling a truck.

- Keep the metal fill spout, nozzle, or pipe in contact with the opening in the container.
- Keep any metal funnels or strainers in contact with the nozzle and the container.
- If electrical contact cannot be maintained between the fill pipe and container, a bonding wire should be used between them.

Two protective measures used in filling a container are shown in Fig. 2-6.

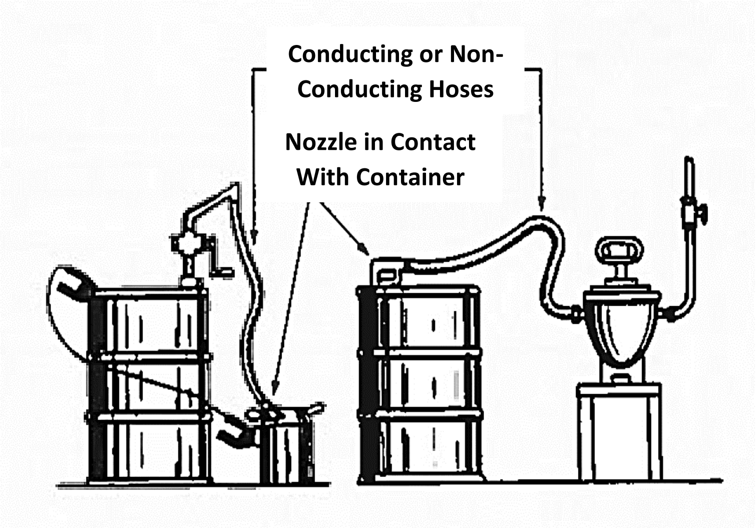


Figure 2.6: Bonding for Filling Containers

Static Charges on Dusts and Fibers

2-51 Dust removed from a surface can develop an electric charge. The kind and amount of charge depends on the properties of the material, the size of the particles, the amount of contact, and how well the material conducts electricity.

2-52 You cannot prevent the generation of an electrostatic charge when you move dust. High humidity or grounding the surface from which the dust is moved will not eliminate the charge. Also, the method used in removing the dust does not affect the intensity of the charges or how they are distributed.

2-53 Combustible dust can be ignited by a static discharge. Dusts of aluminum, magnesium, titanium, zirconium, and other metals require less energy for ignition than do dusts that contain carbon.

2-54 Mixing, blending, grinding, and screening solid, nonconductive materials can generate static electricity. The strength of the charge determines whether or not a spark can be produced.

2-55 Bonding and grounding all metal parts are common methods of draining off static charges accumulated when solid materials are processed. This method may not prevent a static charge on the dust produced during processing, but it reduces the overall charge.

Static Charges in Process Machinery

2-56 Coating, spreading, and impregnating operations are quite similar. Each operation involves the application of solutions to fabrics, paper, and other materials, often with knives or rollers. Static charges are often produced in each of these operations.

2-57 The material to be processed usually comes off a roll at one end of the machine. In processing, the material either passes over a series of rollers, under a spreader, or through a tank between squeeze rollers.

2-58 The material may then pass over a steam table or drying table, a belt, or an oven. Then it may be wound on a reel or stacked on skids. At each step, static electricity can be generated by the movement of the material over or between parts of the machine.

2-59 When flammable liquids are used in a process, you must take special precautions against ignition of the liquid or its vapors. Static eliminators can be installed where the roll of material is unwound and where it passes over rollers or under spreading knives. The frame of the machine should be grounded by a conductor that cannot easily be removed or broken. Figure 2.7 shows the installation of static eliminators and grounding wires on a typical process machine.

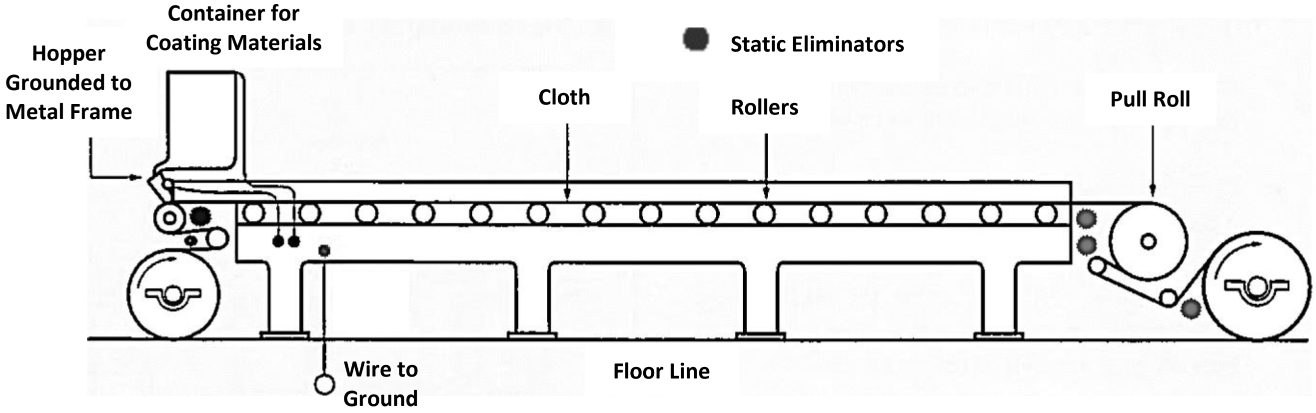


Figure 2.7: Static Controls on a Coating Machine

2-60 A flat belt made of rubber or leather running at moderate or high speed can generate a very high static charge. It can cause sparks several inches long. These belts are usually good insulators, because they are dry.

2-61 The belt generates static charges at the point where it separates from the pulley. The charge can develop regardless of whether the pulleys or other machinery parts are conductive or nonconductive.

Static Charges in Process Machinery (continued)

2-62 A conductive dressing applied to the belt can prevent the generation of static charges. However, the coating must be applied frequently to remain effective. Grounded metal combs placed close to the inside of the belt are effective in removing most of the static charges. Figure 2.8 shows examples of where static eliminators may be located on a belt drive.

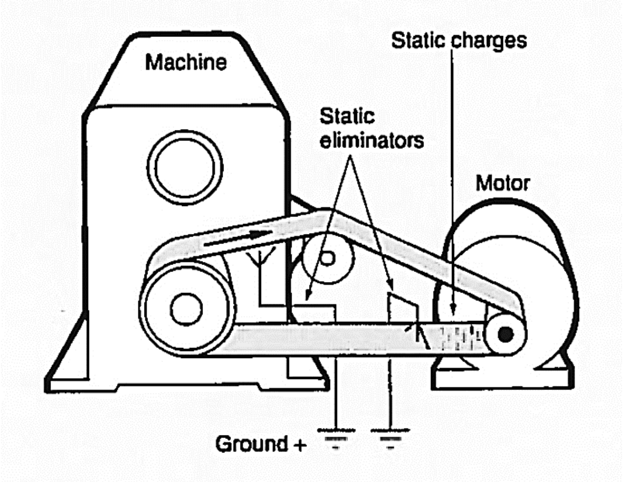


Figure 2.8: Static Eliminators on a Belt Drive

2-63 Special conducting belts can be used in areas where there is a danger of fire or explosion. These belts eliminate most of the static charge as it is generated.

2-64 Conveyor belts usually run at low speeds. At these speeds, they do not normally generate static charges. However, if the materials being transported are very dry, or if the belt runs at a speed higher than normal, it can generate static electricity.

2-65 Materials dropping from the end of a conveyor belt into a hopper or chute may be charged with static electricity. The belt supports and pulleys should be electrically bonded to the hopper or chute if these static charges are likely to cause problems.

2-66 If the machinery frame is not grounded, the metal pulleys acquire a charge opposite to the charge on the belt. Grounding the frame drains these charges from the pulley through the shaft and bearing, and thus to ground. Machinery frames are usually conductive to prevent isolated metal parts from holding static charges.

2-67 Ball bearings and journal bearings conduct electricity well enough to remove static charges from the shaft and other rotating equipment. But the discharge of static electricity through the oil film on a bearing sometimes roughens and pits the bearing surfaces, shortening its life.

2-68 In situations where the bearings are damaged by static discharges, you can bond the pulley shaft to the journal housing by means of a brush made of metal or carbon.

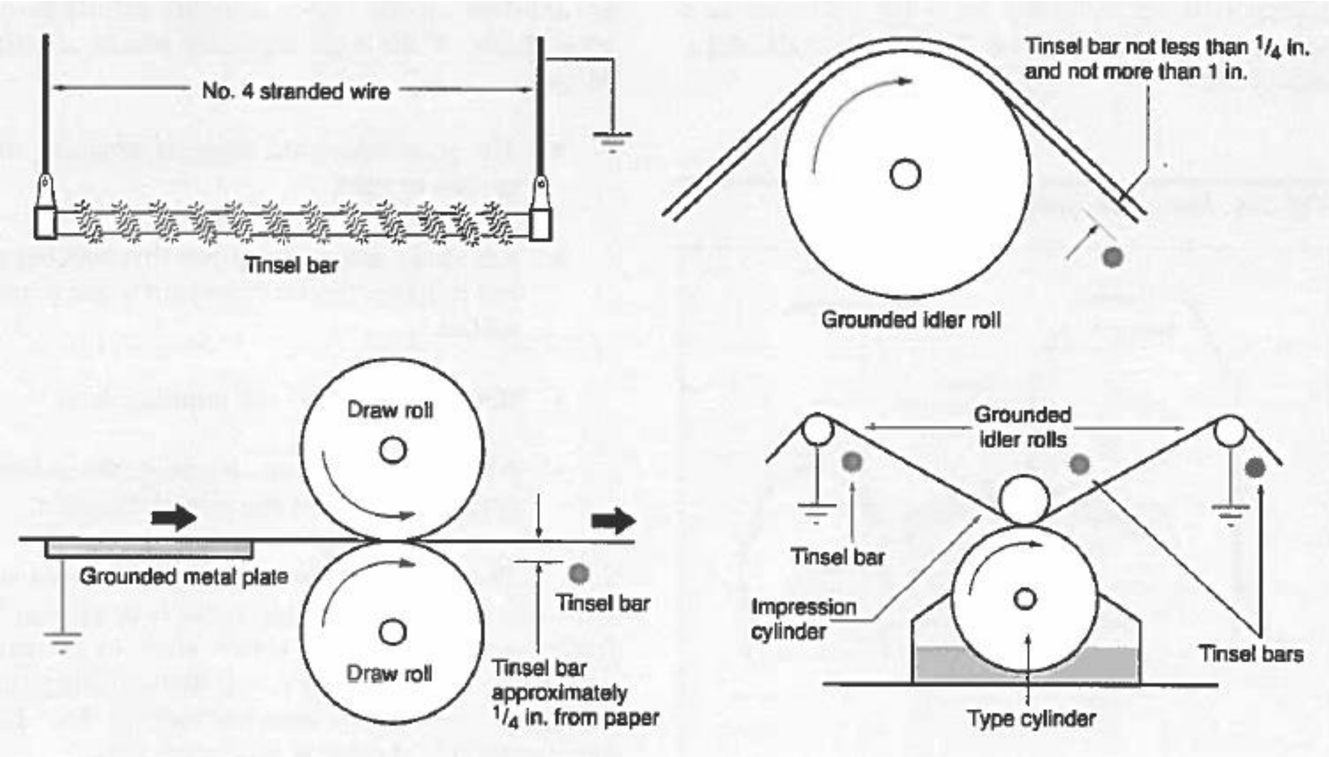
Static Charges in Process Machinery (continued)

2-69 In a printing plant, paper running through a press generates static charges. The charges can accumulate on the paper at many points on the press. Some of the most important places are listed below.

- The point where the paper is removed from the roll or stack
- The point where the paper first touches the roll or feeder device carrying it to the printing surface
- Between the rollers and printing plates
- At handling stations between the printing plates and the final delivery of the paper

2-70 The most common method of removing static electricity from a printing press is to ground the frame. Static eliminators placed close to the paper will help remove the charges. But eliminating static charges at *some* points does not prevent them from being generated at *other* points on the press.

2-71 Even removing the static charge from one side of the paper may not remove the charge from the other side. Static eliminators are needed at various places, as shown in Figure 2.9.



2-72 Spraying paints, varnishes, lacquers, and other coatings with air often generates static electricity. But the charges generated are not high, and therefore the hazard is not serious.

2-73 However, *airless* spraying generates high static charges, and does create an important hazard. Static charges accumulate on the object being sprayed, and also on the spray gun. When liquid being sprayed is flammable, a serious hazard exists.

Static Charges in Process Machinery (continued)

2-74 If the object being sprayed is conductive, it should be bonded to the spraying equipment. In addition, the spray equipment should be grounded.

2-75 Steam released into the air can also carry static charges. If the steam condenses on a cool surface, the surface may acquire a charge from the steam.

2-76 You should be careful in using a steam jet around flammable materials. If steam cleaning presents a hazard, the steam pipes and nozzles should be grounded, and the object being cleaned should also be grounded.

Using Static Electricity

2-77 So far in this Lesson, we have discussed only how to remove, reduce, or prevent static electricity. However, there are many practical uses for static electricity. For example, static electricity attracts ink to the paper in an electrostatic copying machine.

2-78 Electrostatic filters remove dust and other solid materials from the air in plants and offices. In an electrostatic filter, the air passes through wire grids that have a high electric charge. The air becomes ionized in passing through these grids, and the ions transfer charges to the particles of dust.

2-79 Then the air passes over a second set of grids. These grids carry a charge opposite to the charge on the first set. The dust particles are attracted to these grids, as shown in Figure 2.10.

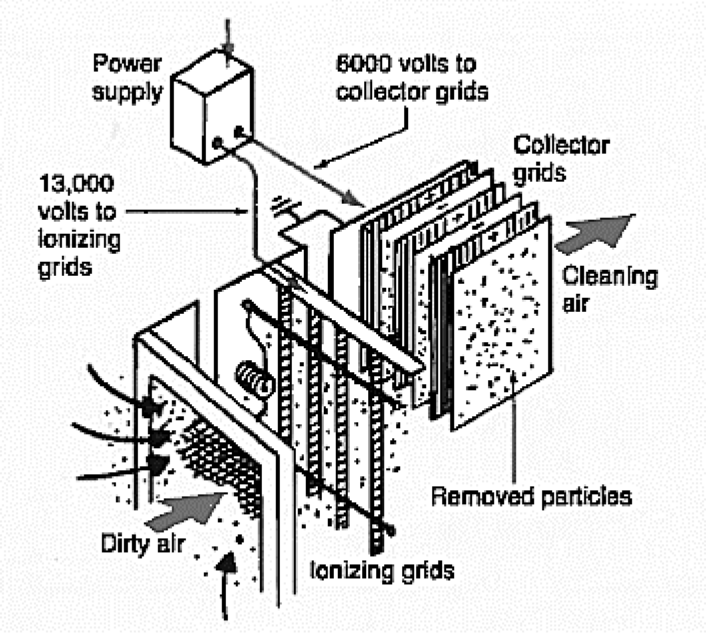


Figure 2.10: Electrostatic Filter

Measuring Static Electricity

2-80 Another use of static electricity is in spraying paint. It is almost impossible to spray an even coat of paint on some objects, because they have a complicated shape. This problem can be solved by using static electricity.

2-81 The object to be painted is charged either positively or negatively. The paint is given the opposite charge as seen in Figure 2.11. The paint is then attracted to the object, and covers it evenly.

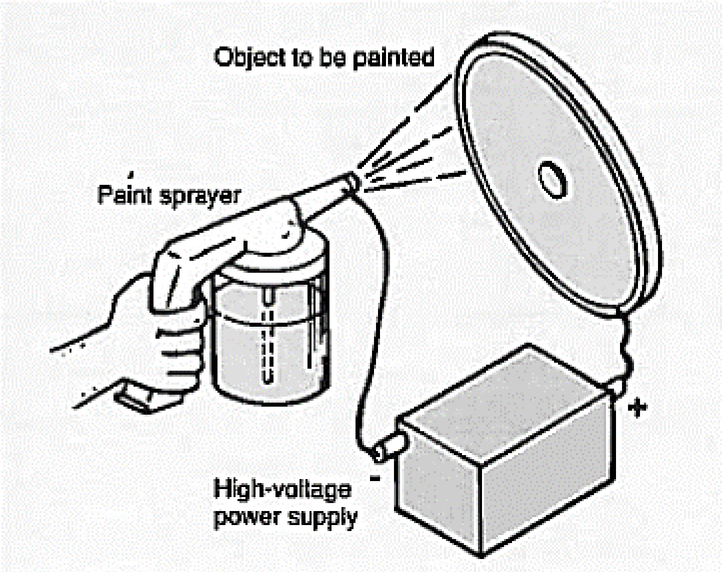


Figure 2.11: Electrostatic Paint Spraying

2-82 The simplest instrument for detecting static electricity is the *electroscope*, shown in Figure 2.12. When a charged object comes near the plate on top of the electroscope, the pivoted arm rotates away from the vertical position.

Figure 2.12: Electroscope

Measuring Static Electricity (continued)

2-83 The *electrostatic voltmeter* is a more precise version of the leaf electroscope. It operates by electrostatic attraction between movable and stationary metal vanes. No current passes through the meter because the vanes are insulated from the charged object. Electrostatic voltmeters can measure potential differences of 100 to 5,000 volts.

2-84 The most sensitive instrument for measuring static electricity is an *electrostatic amplifier*. This instrument can measure potential differences as low as 0.1 volts. It can measure static charges accurately because it drains almost no charge from the object during measurement.

Chapter 2 Exercise

Circle the appropriate letter next to the correct answer.

1. When working in an area filled with flammable liquids and vapors, you must wear shoes with ________________.

   a. Steel toe protectors
   b. Leather soles
   c. Rubber heels
   d. Steel heel plates

2. Bonding minimizes the potential difference between ____________________________.

   a. Two objects
   b. An object and the earth
   c. Static and current electricity
   d. Protons and neutrons

3. A grounding wire should be ________________________.

   a. Solid
   b. Flexible
   c. AWG No. 8 or smaller
   d. At least AWG No. 8 or larger

4. Electrically-charged atoms are called ____________.

   a. Neutrons
   b. Protons
   c. Ions
   d. Eons

5. To guard against spark ignition in a tank, you should ________________.

   a. Bond it
   b. Ground it
   c. Purge it
   d. Ground it and purge it

Chapter 2 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. The kind and amount of charge generated when removing dust does NOT depend on the ___________________.

   a. Properties of the surface material
   b. Size of the particles
   c. Amount of contact
   d. Humidity

7. If you use conductive dressing on a belt, you must apply it ___________________.

   a. Sparingly
   b. Thickly
   c. Frequently
   d. Infrequently

8. To prevent damage to a bearing by static discharges, you can bond the shaft to the bearing by means of a ________________________________.

   a. Grounding wire
   b. Conductive dressing
   c. Metal or carbon brush
   d. Metal comb

9. When using static electricity in spray painting, what kind of charge is given to the object being painted?

   a. Positive
   b. Negative
   c. Either positive or negative
   d. Neither positive nor negative

10. The most sensitive instrument for measuring static electricity is the _________________________.

    a. Electrostatic amplifier
    b. Electrostatic voltmeter
    c. Electroscope
    d. Staticscope

Summary

Static electricity is electricity that does not move. Its accumulation can cause problems in the plant if steps are not taken to prevent or reduce static charges. The charges themselves are not dangerous. But under the right conditions they can jump a gap and cause an explosion.

You can help reduce the danger of static electricity in the plant by wearing shoes with soles made of leather. Do not wear rubber shoes or boots, shoes with steel toe protectors, heel plates, or nails, especially near flammables.

Static electricity can be eliminated from metal equipment by bonding and grounding. Other static eliminators include static combs, conductive dressings, and the use of humidity.

There are times when you can use static electricity in your work. Certain printing and spray painting operations require the use of static charges, for example.

Static electricity can be measured with instruments ranging from simple to very sensitive. These include the electroscope, the electrostatic voltmeter, and the electrostatic amplifier.

Chapter 3: Current Electricity

In This Chapter

Electric Current and Energy

Electricity from Chemical Action

Primary Cells

Secondary Cells

Batteries

Electricity from Electromagnetism

Electricity from Contact

Electricity from Heat

Electricity from Light

Electricity from Deformation

Terminology

Current electricity: electricity in motion

Energy: a measure of the ability to do work

Cell: Device for making electricity by chemical means

Battery: Two or more cells connected together

Cathode: Negative plate in a cell

Anode: Positive plate in a cell

Primary cell: Cell that cannot be recharged

Secondary cell: A cell that can be recharged

Thermocouple: Two different metals welded together that produces electricity when heated

Thermopile: Several thermocouples connected in series

Photoelectric device: A device that produces a potential difference when it receives light

Piezoelectric crystal: Crystal that produces a potential difference as it is deformed

Potential difference is what makes electrons flow. This flow of electrons produces the electricity that operates the machines and equipment in the plant. However, there is more to electricity than simply flipping a switch or pressing a button.

In this Lesson, we explain the six main ways in which a potential difference is produced, and present examples of each method. Because cells are an important means of producing electricity, we explain the different types of cells and batteries.

Cells are just one important category of electricity-producing devices commonly used in industrial applications. In this Lesson, we explain how electricity is created from electromagnetism, contact, heat, light, and deformation.

Electric Current and Energy

3-1 Electricity in motion is called **current electricity**. It occurs whenever electrons are in motion. As the electrons move, they transfer energy from one place to another. For this reason, current electricity is extremely useful.

3-2 **Energy** is a measure of the ability to do work. Many things in nature have this ability, in different ways. Examples include chemical bonds between atoms, electrons at the terminals of a battery or generator, moving molecules, and radiation from hot materials or from a nuclear reaction.

3-3 The amount of energy in a closed system is constant. It neither increases nor decreases. But specific parts of the system may increase or decrease in energy. For example, think about what happens in a coal-fired power plant.

3-4 As the coal burns, certain chemical bonds are broken and others are formed, resulting in an overall decrease in the amount of chemical energy in the coal. At the same time, the molecules of gas in the furnace move faster than before, increasing their energy of motion.

3-5 The rapidly-moving molecules of gas strike the walls of the boiler tubes, making the atoms of metal vibrate harder. After a gas molecule hits the wall, it rebounds at a lower speed. Therefore, the energy of the gas molecule is reduced. The metal atoms in the boiler tubes vibrate faster, so their energy is increased.

3-6 The vibrating atoms on the inside surface of the tube strike water molecules, making the water molecules move faster. The metal atoms decrease in motion and energy, and the water increases in motion and energy. The increase in motion turns the water into steam. A molecule of water in steam has much more energy than a molecule in liquid water, because it is moving much faster.

3-7 It is possible to continue this step-by-step analysis of what happens in the system. But you need only recognize that in each step one part of the system *decreases* in energy as another part *increases* in energy. The final step is an increase in the energy of electrons at the output terminals of the generator.

3-8 All matter is electrical, because it contains electrons. But the electrons do not move through a conductor unless there is a potential difference between the ends of the conductor.

3-9 The six main methods of producing the required potential difference are listed below. Each method is explained in this chapter.

Method	**Examples**
Chemical action	Dry cell, storage battery
Electromagnetism	Generator, alternator
Contact	Static charges
Heat	Thermocouple
Light	Photovoltaic cell
Deformation	Quartz crystals

Electricity from Chemical Action

3-10 The basic device for making electricity by chemical action is the **electrochemical cell**. Two or more of these cells can be connected together to make a **battery**. Figure 3.1 shows the basic construction of an electrochemical cell. Two *plates*, made of different materials, are immersed in a special solution called an *electrolyte*. Sulfuric acid is often used as an electrolyte.

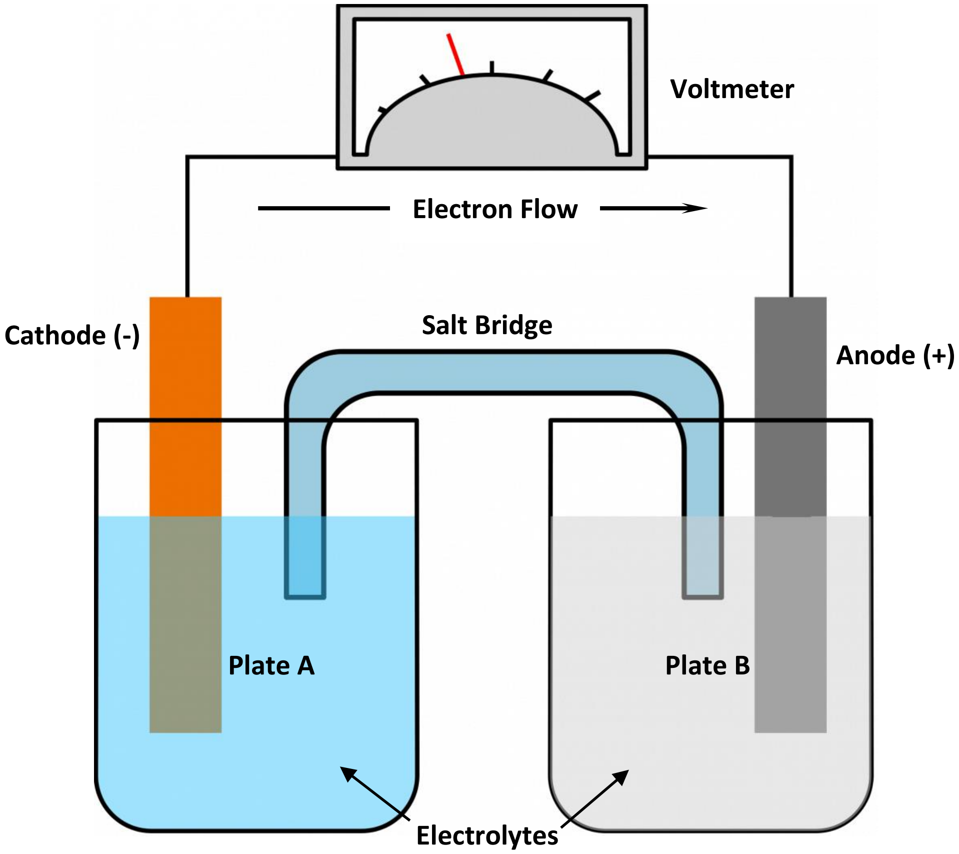


Figure 3.1: Electrochemical Cell

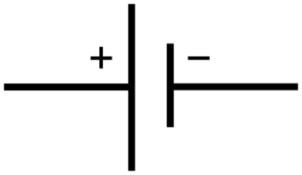
3-11 Chemical reactions take place between the electrolyte and the two plates. As a result of these reactions, electrons leave one plate, pass through the electrolyte, and enter the other plate. In this way a potential difference is created between the two plates. The plate where the electrons collect becomes the *negative* plate, called the **cathode**. The other plate becomes the *positive* plate, called the **anode**.

3-12 Electricians are responsible for a variety of equipment that use batteries as a normal or emergency power source. Therefore, they must understand how batteries work, where they are located, and how to care for them. A "dead" or *discharged* battery can cause serious problems.

Primary Cells

3-13 While an electrochemical cell produces electricity, the negative plate is slowly used up by the chemical reaction with the electrolyte. When the chemical action has completely destroyed the negative plate, the cell stops working.

3-14 A one-use cell is called a **primary cell**. Once it stops working, it cannot be charged again. You must either replace the cell with a new one, or you must replace the negative plate and the electrolyte. The symbol below stands for a cell.



3-15 There are many kinds of primary cells for special uses. The common dry cell is the most familiar. The materials in this cell produce a potential difference of I .5 volts between the terminals.

3-16 Dry cells are manufactured in various shapes, sizes, and weights. Small dry cells are used in a pencil-size flashlight. Larger cells are used in equipment that requires a higher amount of current. Four 1.5-volt cells can be connected to produce a potential difference of 6.0 volts when needed.

3-17 In a dry cell, the negative "plate" is made in the shape of a container that holds the electrolyte. It is made of zinc. The positive plate is a carbon rod suspended in the center of the case, shown in Figure 3.2.

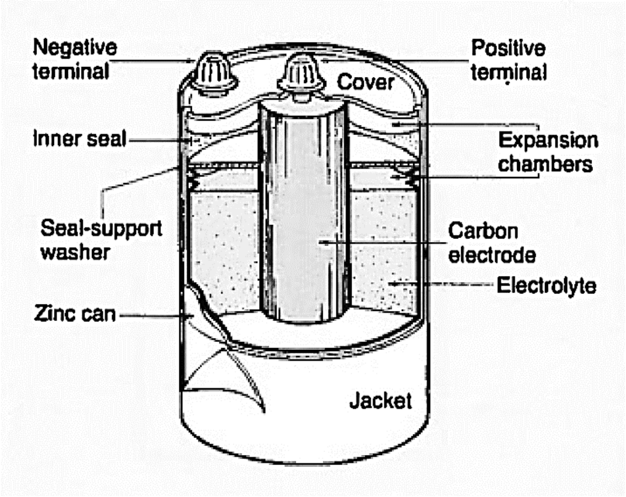


Figure 3.2: Dry Cell

3-18 The electrolyte is a paste made of ammonium chloride. The fact that the electrolyte is not a liquid is the reason for calling the cell a *dry cell*. The cell is not actually dry.

3-19 A tar-paper washer on the bottom of the zinc case prevents the carbon rod from touching the case. The top of the case is sealed by layers of sawdust, sand, and pitch to hold the carbon rod in position and prevent the electrolyte from leaking out. The positive plate in a primary cell is usually made of carbon, but metals are used in some cells.

Primary Cells (continued)

3-20 When a dry cell becomes discharged in use, the electrolyte may swell, crack the case, and leak out. The paste causes corrosion that can ruin a flashlight or an electronic instrument. To prevent such damage, some dry-cell manufacturers fit a strong steel jacket around the zinc container.

3-21 A dry cell in storage gradually discharges. A slow chemical action, called "local action," occurs inside. In addition, the moisture content of the cell changes. This process occurs very slowly if the cell is stored in a cool, dry place. Large cells have a shelf life of a year or longer. Small cells have a shorter shelf life.

Secondary Cells

3-22 A **secondary cell** works just like a primary cell, except that it can be recharged. The electrodes and the electrolyte are changed by chemical action as the cell delivers electric current. But these changes can be reversed by sending electric current back into the cell in the opposite direction. An automotive storage battery like the one shown in Figure 3.3, consists of six secondary cells.

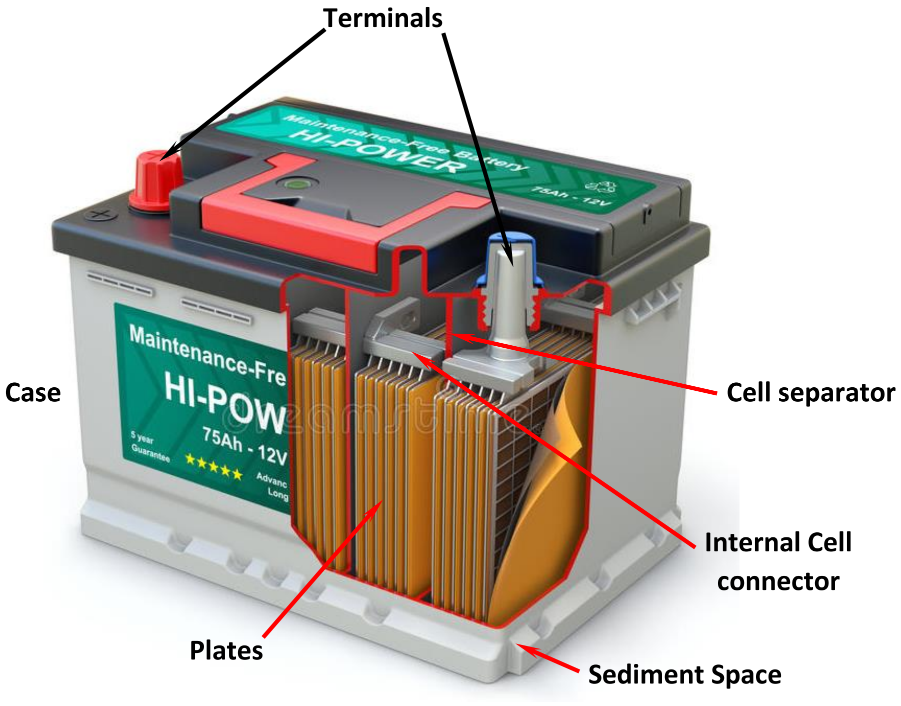


Figure 3.3: Automotive Storage Battery

3-23 The secondary cell is a very common device for producing electricity by chemical action. Three kinds of secondary cells are in common use. In the cells of an automotive battery, the positive and negative plates are both made of lead, and the electrolyte is sulfuric acid.

3-24 In another kind of secondary cell, rechargeable batteries, the plates are made of nickel and iron, and the electrolyte is an alkali instead of an acid. In a third kind of secondary cell, the plates are made of nickel and cadmium, and the electrolyte is an alkali.

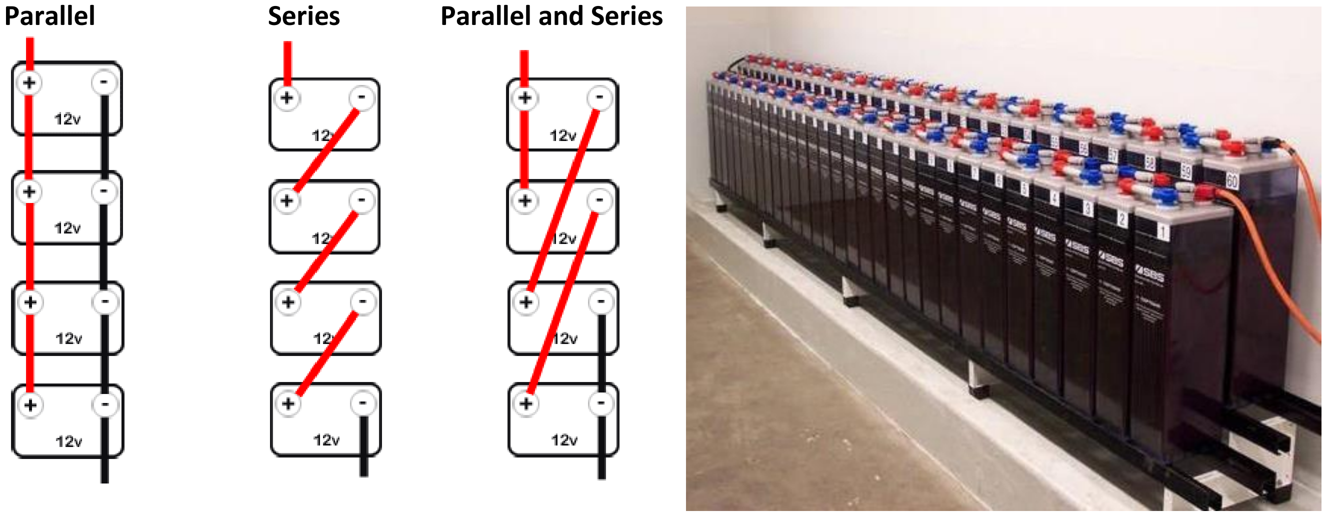
Batteries

3-25 Cells can be connected together to make a battery that is better than a single cell. The cells can be connected in two basic ways. One way produces a battery with a greater capacity for delivering *current*. The other way produces a battery with a greater *potential difference*.

3-26 To produce a battery with a greater current capacity, the negative (-) terminals of all the cells should be connected together. All the positive (+) terminals should also be connected together. These connections are shown by the diagram at the far left in Figure 3.4. Cells connected in this way are said to be connected in **parallel**. The potential difference of the battery is the same as the potential difference of a single cell.

3-27 To increase potential difference, the positive electrode of one cell is connected to the negative electrode of the next, as shown by the center diagram in Figure 3.4. These cells are said to be connected in **series**.

3-28 Both the potential difference and the current capacity can be increased by connecting the cells as shown by the diagram at the far right in Figure 3.4. In this arrangement, groups of cells are first connected in *series* to provide the desired potential difference in each group. Then the groups are connected in *parallel* to provide a battery with the desired current capacity. The photograph in Figure 3.4 shows a large battery with the cells connected in this way.



Parallel

Series

Parallel and Series

Figure 3.4: Connecting Cells to make a Battery

Batteries (continued)

3-29 The chemical conditions in a charged storage battery are shown in Figure 3.5. The negative plate consists of lead, and the positive plate consists of lead oxide, a compound of oxygen and lead. The electrolyte is sulfuric acid, which consists of oxygen, hydrogen, and sulfur.

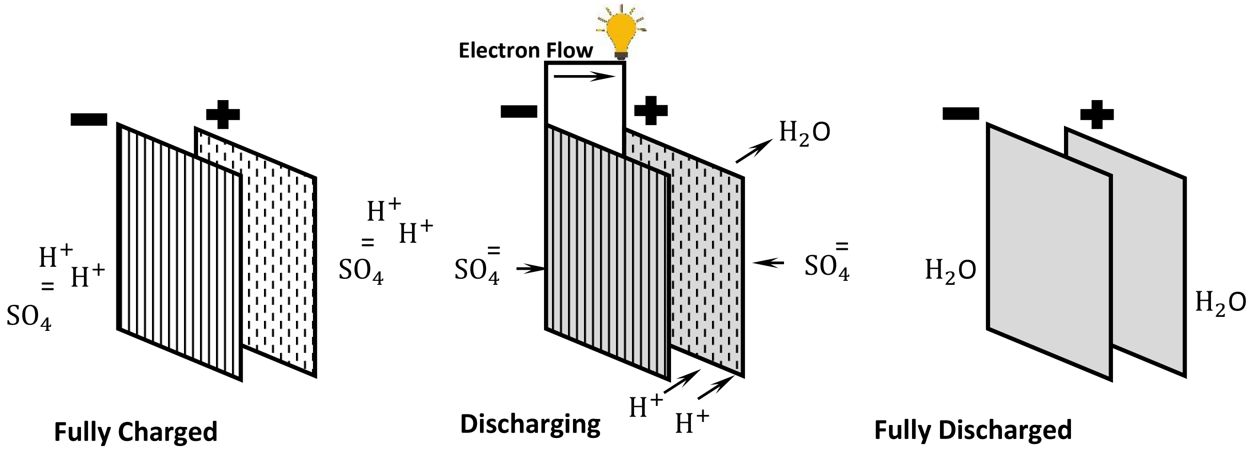


Figure 3.5: Discharging a Secondary Cell

3-30 As the storage battery delivers current, oxygen from the positive plate goes into the electrolyte. Sulfur in the electrolyte goes to both plates, where it combines with the lead and oxygen to form lead sulfate. As a result, both plates become chemically identical.

3-31 Keeping the external circuit connected to the battery will eventually cause the battery plates to change to lead sulfate and the electrolyte to water. The battery is then completely discharged, and electricity stops flowing in the external circuit.

3-32 To recharge a storage battery, an external power source must force electricity to flow through the battery in the opposite direction, as shown in Figure 3.6. The electrical current forces oxygen to leave the electrolyte and reform lead oxide on the positive plate. At the same time, it forces sulfur to leave both plates and return to the electrolyte, changing the water back into sulfuric acid.

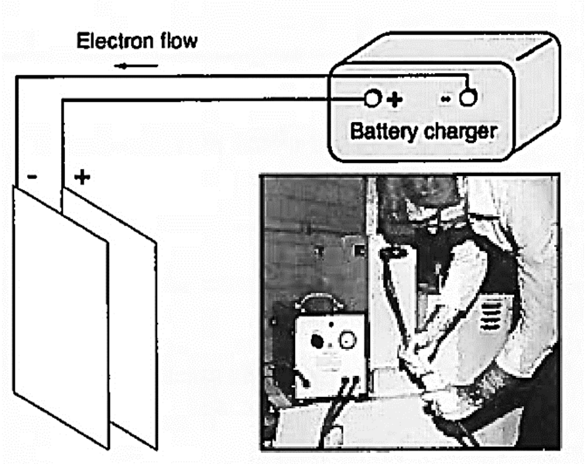


Figure 3.6: Recharging a storage Battery

Batteries (continued)

3-33 The charging action continues until the battery is fully recharged. The battery is then ready for service again. The cycle of discharging and recharging can be repeated many times.

3-34 Storage batteries have many uses in industrial plants. For example, they provide power for lift trucks and for emergency lighting systems, they start engines, and they operate many DC devices. Therefore, it is important to keep these batteries fully charged and ready for use at all times.

3-35 You must be careful when recharging lead-acid batteries. They produce flammable gases during charging. An accidental spark can ignite these gases, causing an explosion inside the battery. Such an explosion can break the battery case and throw acid on you, on other people, and on equipment in the area.

Electricity from Electromagnetism

3-36 Most of the electricity in use every day is produced by *generators* and used by *motors*. Motors and generators take advantage of the close relationship between electricity and magnetism. An electric current produces a magnetic field, and moving a conductor through a magnetic field produces an electric current. These two effects form the basis for the operation of almost every piece of electrical machinery.

3-37 Other Lessons in this Unit and in other Units describe magnetism and generators in detail. Therefore, we will not describe them further in this Lesson.

Electricity from Contact

3-38 Lessons One and Two of this Unit explained static electricity in detail. It explained how objects acquire electrical charges by coming into contact with other objects and then being separated from them. For example, rubbing a plastic rod with fur or wool creates an electric charge on the rod. It also creates the opposite electric charge on the fur or wool.

3-39 Likewise, truck tires making and breaking contact with the road can produce a static charge on the truck. Trucks that carry flammable materials, gasoline for example, must be carefully grounded before loading or unloading to avoid the possibility of igniting the fuel or its fumes with an unexpected spark.

3-40 The development of static charges creates a potential difference between two objects, or between each object and the ground. If a conducting path then forms between the objects, current can flow from one to the other. This current may be very high, as in lightning, but it lasts for an extremely short time.

Electricity from Heat

3-41 Another method of producing a potential difference between two points involves a device called a *thermocouple*. The beginning of the word comes from the Greek word *therme*, meaning "heat." A thermocouple consists of two different metals welded together as shown in Fig. 3.7.

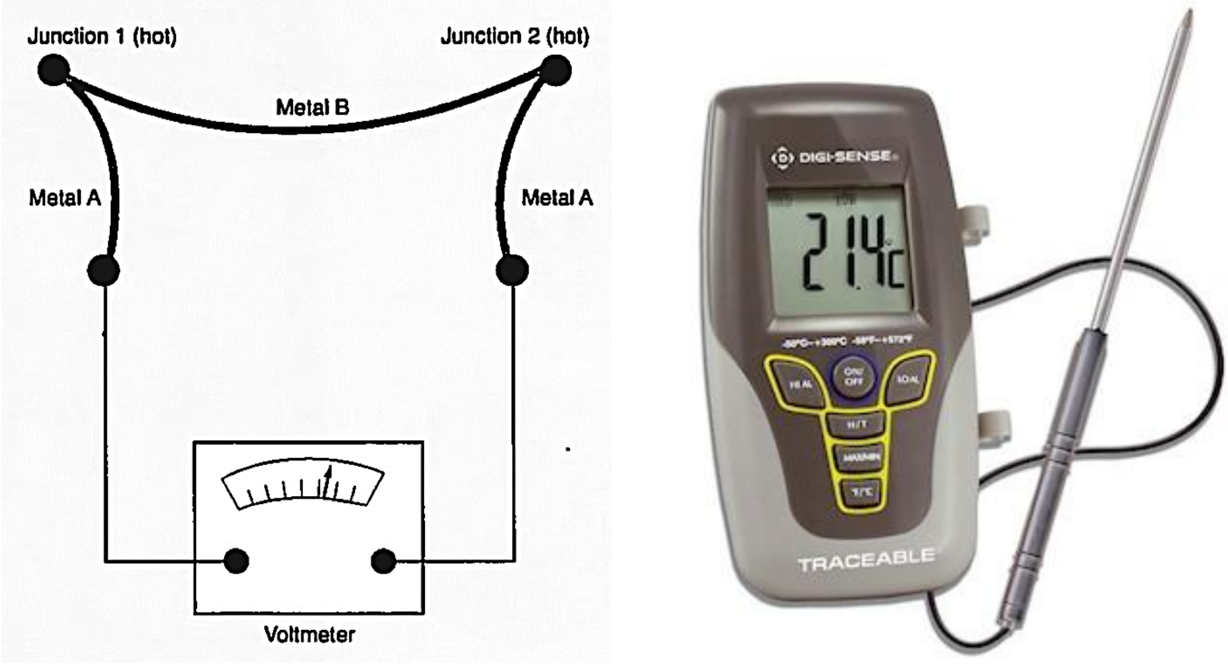


Figure 3.7: Thermocouple

3-42 When one end of a metal wire is heated, electrons usually move away from the warm end toward the cool end. However, in some metals the electrons move from the cool end toward the warm end. If two different metals are welded together at each end, and then one end is heated, a potential difference is created between the two ends. The potential difference is small, but it can be measured with a sensitive voltmeter. The amount of potential difference between the junctions becomes larger if the difference in temperature becomes larger.

3-43 This potential difference can produce a small current through a very high resistance. A measurement of this current with a sensitive ammeter can be translated into a measurement of the temperature difference between the two junctions of the thermocouple.

Electricity from Heat (continued)

3-44 A *thermopile* is made by connecting several thermocouples together in series. The combination produces a larger potential difference for a given temperature difference, increasing the accuracy of a temperature-measuring instrument. Figure 3.8 shows a thermopile connected to a voltmeter. The voltmeter is usually calibrated in *degrees* of temperature rather than in *volts* of potential difference.

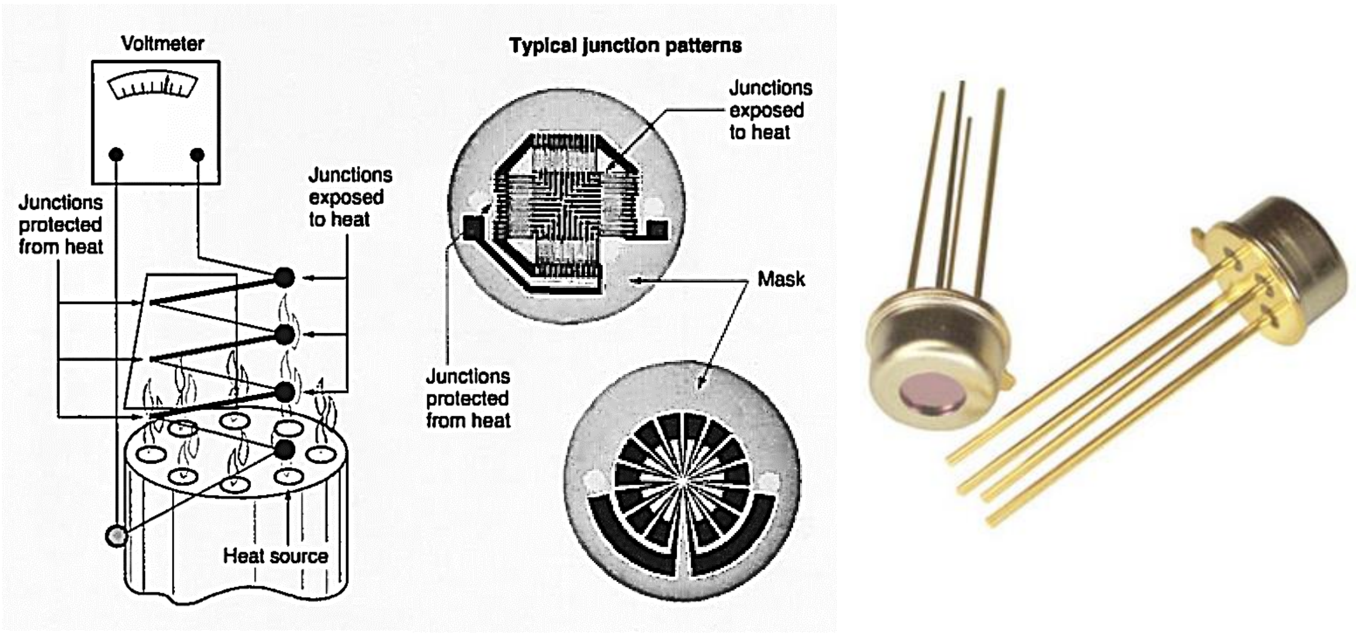


Figure 3.8: Thermopile

Electricity from Light

3-45 When light strikes certain materials, the material ejects electrons. By ejecting these charges, the material produces a potential difference between its front and back surfaces. This potential difference can cause current to flow in a circuit.

3-46 Devices that receive light and produce a potential difference are called *photoelectric* devices. The word *photoelectric* comes from the Greek word *phot*, meaning "light," and the word *electric*. The following paragraphs describe three kinds of photoelectric devices.

3-47 Photovoltaic devices consist of a transparent electrode and a base of selenium or silicon, separated by a barrier. The construction of the devices is shown in Figure 3.9. Light shines through the transparent electrode and the barrier to the base. Electrons then leave the base and move through the barrier to the transparent electrode. This redistribution produces a potential difference

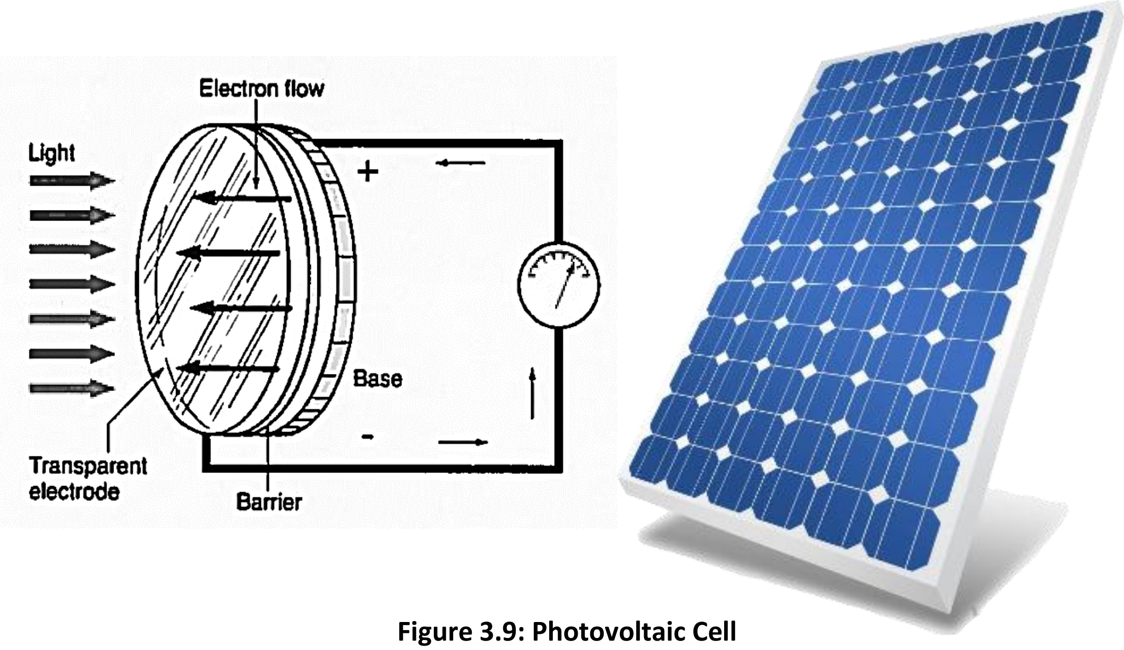


Figure 3.9: Photovoltaic Cell

3-48 The photovoltaic cell is also called a *solar cell*. Exposing it to light from the sun can produce electricity to charge small batteries and operate electronic equipment. Photovoltaic cells are also used in photographic light meters.

3-49 **Photoconductive cells** are similar to resistors, but their resistance varies according to the amount of light striking them. A photoconductive cell has a high resistance in the dark. As the amount of light increases, the cell's resistance decreases.

Electricity from Light (continued)

3-50 One common kind of photoconductive cell is the cadmium sulfide cell. Figure 3.10 shows such a cell. As light shines on the device, the cadmium sulfide element decreases in resistance. Then more current can flow through the element from one metal grid to the other. This current can operate a relay or other electrical device.

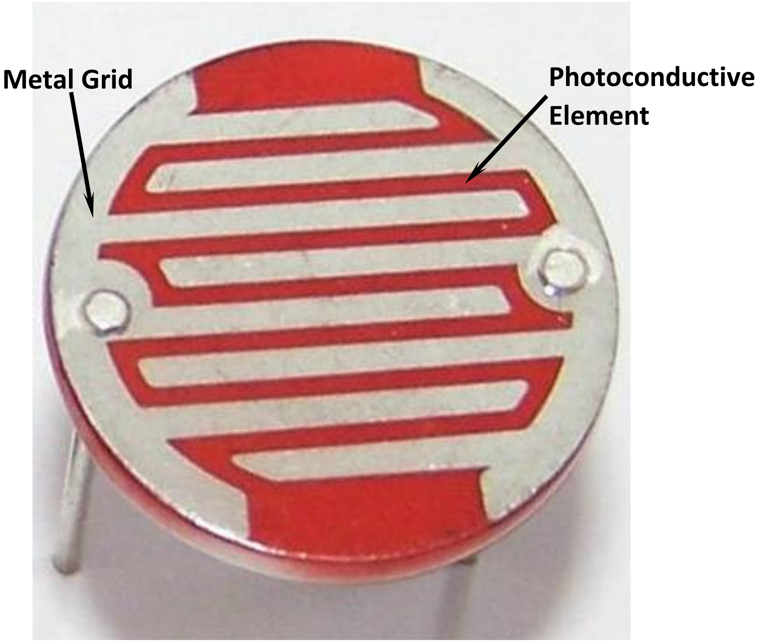


Figure 3.10: Photoconductive Cell

Electricity from Light (continued)

3-51 **Photoemission cells** are electronic vacuum tubes. The cathode (negative electrode) is a curved metal plate coated with sodium, cesium, or barium. These materials eject electrons when light strikes them. The rate of electron emission increases as the intensity of the light increases. the anode (positive electrode) is a wire coated with sodium, cesium, or barium. Figure 3.11 shows the construction of a photoemisson cell.

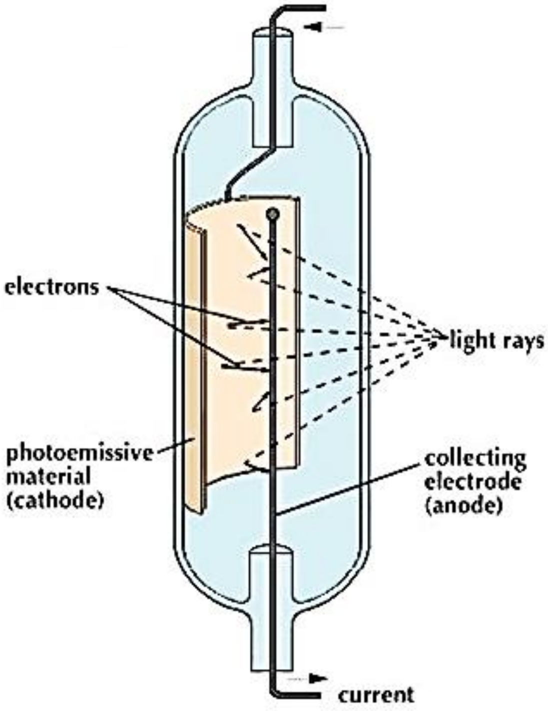


Figure 3.11: Photoemissive Cell

3-52 The electrons emitted by the cathode are repelled by the negative charge on the cathode and attracted by the positive charge on the anode. Therefore, they move through the vacuum to the anode. The current increases as the intensity of light increases.

3-53 The crystals of certain materials produce a small potential difference between one side and the other when they are suddenly deformed. Crystals that behave in this way are called piezoelectric crystals. They include crystals of barium titanate, quartz, and Rochelle salts.

3-54 These crystals produce a potential difference only while deformation is occurring. If the crystal stops deforming, the potential difference returns to zero, even if the crystal is held in its deformed condition. As the crystal returns to its un-deformed shape, it produces another potential difference. This potential difference is the opposite of the first. Figure 3.12 on page 56 shows these effects.

Electricity from Light (continued)

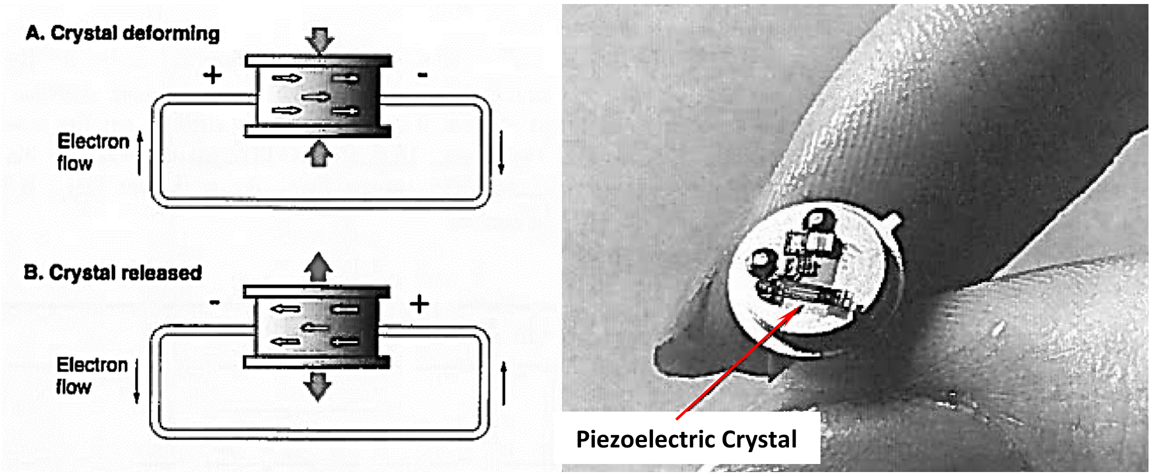


Figure 3.12: Piezoelectric Crystal

3-55 Piezoelectric crystals also work in "reverse." That is, they undergo sudden deformation if a potential difference is applied from one side to the other. You can make such a crystal vibrate by applying a rapidly-alternating potential difference across it.

3-56 Piezoelectric crystals have two important uses. Quartz crystals are widely used in devices that must operate at precisely controlled frequencies. Timing devices and radio equipment are two examples of such devices. You have probably seen wristwatches and clocks that are controlled by quartz crystals.

3-57 The second important use is in turntable pickup cartridges, like the one shown in Figure 3.13. The stylus vibrates as it rides in the groove of a record. The diamond stylus is connected to a small crystal of Rochelle salt in the pickup cartridge. As the crystal vibrates, it produces a changing potential difference that matches the motion of the stylus. The small potential difference is then amplified, and the stronger electrical signal drives speakers to produce sound.

Figure 3.13: Turntable Pickup Cartridge

Chapter 3 Exercise

Circle the appropriate letter next to the correct answer.

1. The basic device for making electricity by chemical action is the ____.

   a. Battery
   b. Electrolyte
   c. Thermocouple
   d. Cell

2. The positive plate in a cell is called the ___________________________.

   a. Anode
   b. Cathode
   c. Primary Cell
   d. Secondary cell

3. Four 1.5 volt cells can be connected to produce a potential difference of ________________________.

   a. 0.15 volts
   b. 4.0 volts
   c. 6.0 volts
   d. 8.0 volts

4. In the cells of an automotive battery, the electrolyte is ________________________.

   a. Ammonium chloride
   b. Alkali
   c. Sulfuric acid
   d. Barium titanite

5. If the positive electrode of one cell is connected to the negative electrode in the next, the cells are connected in _______________________.

   a. Pairs
   b. Tandem
   c. Parallel
   d. Series

Chapter 3 Exercise (continued)

6. You must be careful when recharging a lead-acid battery because it can do any of the following EXCEPT:

   a. Explode
   b. Produce flammable gas
   c. Break and throw acid on you
   d. Overheat and meltdown

7. Motors and generators take advantage of the close relationship between ________________________.

   a. Gears and ratios
   b. Cells and batteries
   c. Electricity and magnetism
   d. Static and current electricity

8. A voltmeter connected to a thermopile is usually calibrated in _____________________.

   a. Degrees
   b. Volts
   c. Meters
   d. Seconds

9. Photovoltaic, photoconductive, and photoemission devices are types of _______________________.

   a. Batteries
   b. Thermopiles
   c. Electronic tubes
   d. Photoelectric devices

10. Devices that must operate at precisely controlled frequencies have crystals made of ________________________.

    a. Barium titanate
    b. Quartz
    c. Rochelle salts
    d. Salt

Summary

Current electricity is a vital part of industry. For current to flow, there must be a potential difference between the ends of the conductor. The six main methods of producing a potential difference are by chemical action, electromagnetism, contact, heat, light, and deformation.

Cells are devices for producing electricity by chemical means. A one-use cell is called a primary cell. It cannot be recharged. The dry cell is a common primary cell. Secondary cells are rechargeable. When two or more cells are connected they make up a battery.

The current capacity of a battery can be increased by connecting the cells in parallel. To increase potential difference, cells should be connected in series.

Generators and alternators are devices whose electricity is produced by electromagnetism. Static charges are produced by contact.

Devices that receive light and produce a potential difference are called photoelectric devices. These include photovoltaic devices, photoconductive cells, and photoemission cells.

Chapter 4: Magnetism

In This Chapter

Discovery of Magnetism
Definition of a Magnet
Magnetic Forces
Molecular Theory of Magnetism
Magnetic Fields
Magnetism and Electricity
Left-Hand Rules
Using the Left-Hand Rules
Electromagnets
Industrial Uses of Magnets

Terminology

Magnet: A substance that attracts magnetic materials

Magnetic pole: A point on a magnet where the magnetic attraction is greatest

North pole: Pole that points north in the earth's magnetic field

South pole: Pole that points south in the earth's magnetic field

Electromagnet: Coil of wire that carries an electric current

Magnets have many uses in industry. Magnetism is closely related to electricity, the source of tool, equipment, and machine power. Magnetic materials are used in all types of electrical devices and equipment.

To understand electricity, you must first understand the basic principles of magnetism. In this Lesson, we explain magnetic force and the erects of magnetic poles, the molecular theory of magnetism, and magnetic fields. We also explain the left-hand rules.

We also explain what an electromagnet is and its function in such pieces of plant equipment as lifting, holding, and separating devices.

Discovery of Magnetism

4-1 About 3000 years ago, people discovered an unusual mineral in Asia Minor. The mineral had the ability to attract iron objects. The mineral was found near the ancient city of *Magnesia*, and so it was called *magnetite*. It was the first known magnetic material.

4-2 Even before the discovery of magnetite in Asia Minor, the Chinese had discovered that if certain stones were suspended by a thread, they generally lined up in a north-south direction. Early Chinese navigators are said to have made crude compasses from these stones. The stones used as compasses were called "lodestones," meaning *leading stones*. The stones contained magnetite.

4-3 Man-made magnets were put to practical use for the first time in about the 12th century. At that time, people discovered that a magnet which was free to rotate would swing until it came to rest in a north-south direction. Thus, the magnet came into regular use as a compass. Early explorers used them in navigation.

4-4 The magnets used in the first compasses were made of iron. Ordinary pieces of iron were made magnetic by stroking them with a natural magnet. This method is not used anymore, because other methods are easier and they produce stronger magnets.

4-5 A substance is called a **magnet** if it has the property of attracting *magnetic materials* such as iron. A bar-shaped magnet generally produces its strongest effect at each end. It produces very little effect at its center.

4-6 The points of maximum attraction are called **magnetic poles**. Magnets always have two kinds of poles. One kind points toward the north when the magnet is suspended by a thread, and the other points toward the south.

4-7 The pole that points toward the north is called the "north-seeking pole," or simply the *north pole*. The pole that points toward the south is called the "south-seeking pole," or simply the *south pole*.

4-8 A magnet can be used as a compass because the earth itself is a huge magnet. One pole is located in northern Canada. The other pole is located in Antarctica. The *magnetic* poles are not located at the same points as the *geographic* poles.

4-9 Magnets are essential parts of many instruments and machines. Without magnetism, electric motors, generators, telephone receivers, and many other common devices could not work as they do. In addition, certain kinds of electronic equipment could not exist.

4-10 The *causes* of magnetism can be explained only by complex scientific theories. But the basic laws of magnets are well-known by nearly everyone. They are used every day.

Magnetic Forces

4-11 The most basic law of magnetic force is that *unlike* poles *attract* each other, and *like* poles *repel* each other. For example, suppose you suspend a bar magnet in the air and allow it to turn freely. Then suppose you hold another bar magnet in your hand, and bring its *north* pole near the *north* pole of the suspended magnet. What will happen? The suspended magnet will turn away from the magnet in your hand, because two like poles always repel each other.

4-12 The same thing will happen if you hold the *south* pole of your magnet near the *south* pole of the suspended magnet. An invisible "magnetic force" pushes any two "like" poles of the magnets away from each other. In this respect, "like" magnetic poles react to each other in the same way as "like" electric charges.

4-13 When you bring the *south* pole of the magnet in your hand near the *north* pole of the suspended magnet, the two "unlike" poles attract each other. The reverse is also true. When you bring the *north* pole of your magnet near the *south* pole of the suspended magnet, these two poles also attract each other. "Unlike" magnetic poles react to each other in the same way as "unlike" electric charges.

Molecular Theory of Magnetism

4-14 The molecular theory of magnetism is based on the idea that each molecule of a magnet is itself a tiny magnet. The molecules in an un-magnetized bar of iron or steel are arranged at random, as shown in Figure 4.1. The overall effect of this random arrangement is to produce no magnetic effect at all.

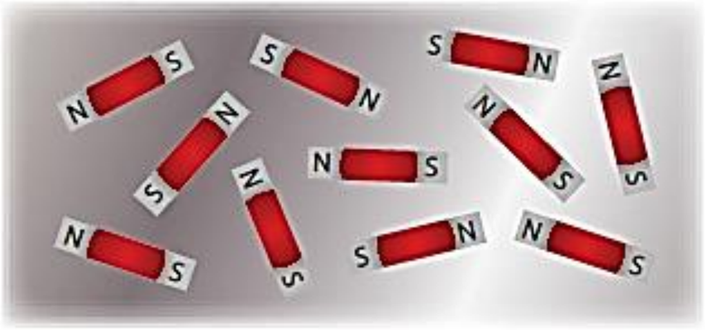


Figure 4.1: Molecules in Un-Magnetized Iron

Molecular Theory of Magnetism (continued)

4-15 When a magnetizing force is applied to an un-magnetized bar of iron or steel, the molecules become aligned. Most of the north poles point in one direction, and most of the south poles point in the opposite direction. Figure 4.2 shows this alignment.

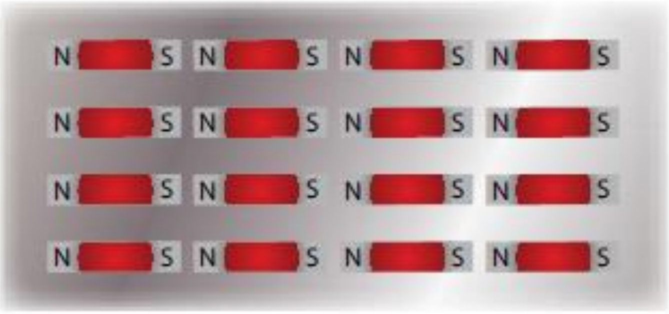


Figure 4.2: Molecules in Magnetized Iron

4-16 If you break a bar magnet, each part becomes a complete magnet with a north pole and a south pole, as shown in Figure 4.3. The poles of these small magnets are lined up in the same directions as the poles of the unbroken magnet. If you continue breaking the parts, the resulting pieces will all have two poles. Even if the magnet is reduced to molecules, all the pieces will have two poles just like the original magnet.

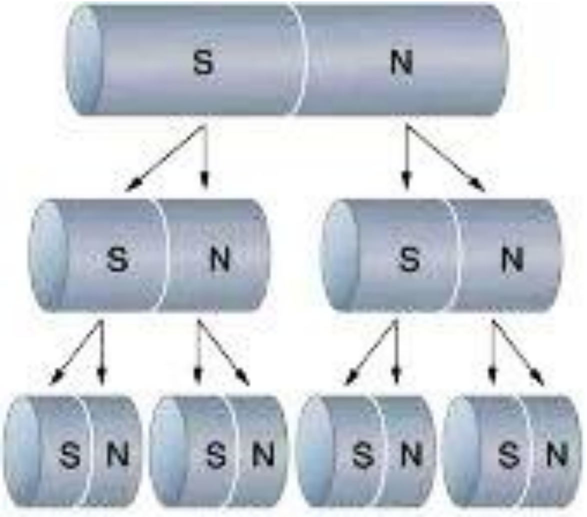


Figure 4.3: Breaking a Bar Magnet

4-17 If a bar magnet is repeatedly hit, heated, or exposed to a strong alternating magnetic field, the molecular structure becomes disarranged and the bar loses some of its magnetic properties. Electric meters that depend on magnets become inaccurate if their permanent magnets are heated, struck, or exposed to a strong external magnetic field.

Magnetic Fields

4-18 Whenever two objects are able to exert forces on each other from a distance, without touching each other, you can use the term **field** in describing the forces. One example of a field force is *gravity*. It acts on objects that have mass. Another is the *electric* force that acts on objects that carry an *electric* charge.

4-19 You know that the force of the earth's *gravitational* field pulls you down. It does so because you have *mass*.

4-20 You do not need to touch the earth in order for the earth's gravitational field to apply force to you. The field pulls on you with the same force if you fall or jump off a platform.

4-21 The earth's gravitational field also keeps a spacecraft in orbit, because the spacecraft has mass. Without the gravitational field of the earth, a spacecraft could not travel in orbit. It would move on a straight line into outer space. Figure 4.4 shows a satellite in orbit approximately 22,000 miles above the earth's surface.

Figure 4.4: Satellite Drawn by Earth's Gravity

4-22 The moon stays in orbit around the earth, because the earth's gravitational field pulls on the mass of the moon. The force acts even though the moon is about 250,000 miles from the earth.

4-23 Likewise, the earth keeps going around the sun because of the sun's gravitational field pulling on the mass of the earth. This force acts over a distance of 93 million miles. The sun's gravitational field pulls on other planets that are even farther away.

Magnetic Fields (continued)

4-24 In a similar way, an *electric* field exerts a force on a *charged* object from a distance. For example, in a leaf electroscope each leaf produces its own electric field. The field produced by *one* leaf exerts a force on the charge carried by the *second* leaf. Likewise, the field produced by the *second* leaf exerts a force on the charge carried by the *first* leaf.

4-25 In other words, the *charge* on each leaf is acted upon by a force caused by the *electrical field* of the other leaf. The force on each leaf of the electroscope keeps it suspended at an angle. The size of the angle is such that the *electrical* force just balances the force of the earth's *gravitational* field acting on the mass of the leaf, as shown in Figure 4.5.

Figure 4.5: Charged Electroscope

4-26 A *magnetic field* is very similar to a gravitational field and an electrical field. But it acts on objects because of their *magnetic* properties rather than their *mass* or their *charge*. Just as in the case of gravity and electrical forces, you must keep two ideas in mind when you deal with magnetic forces.

- Every magnetic object *creates* a *magnetic field* that can affect other magnetic objects.
- Every magnetic object *can be acted upon* by the magnetic field of another object.

Magnetic Fields (continued)

4-27 Try to keep the idea of the field separate from the idea of the force produced by the field on a magnetic object. Also remember that forces always come in pairs. In every pair, each force is produced by one object and acts on another object. If you can avoid confusing these forces, you will find it easier to understand all field forces, including magnetic forces.

4-28 Every field has a direction. The direction may be different at different places. The direction of a magnetic field at any place is defined as the direction in which a compass needle points if the compass is placed at that spot.

4-29 Figure 4.6 shows how the direction of a magnetic field is defined. Compare the pattern of iron filings in the photograph to the lines in the diagram showing the field directions.

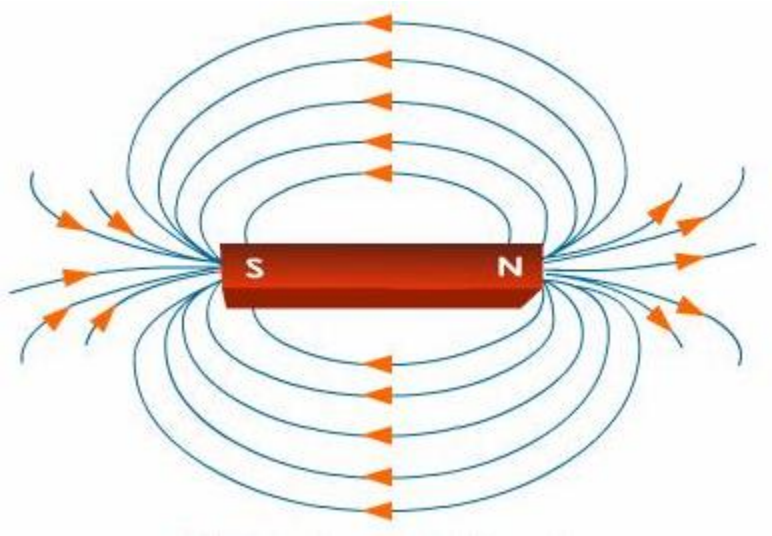


Figure 4.6: Magnetic Field of a Bar Magnet

4-30 Notice that the lines in the diagram are curved, just like the lines of iron filings in the photograph. The arrows on the lines show the direction of the field along the lines. Compare these arrows to the direction of the needles on the compasses in the diagram.

Magnetism and Electricity

4-31 Magnetic fields are important because of the relationship between *magnetism* and *electricity*.

- A moving charge *produces* a *magnetic field*
- A magnetic field *exerts force on a moving charge*

4-32 These two parts of the relationship between magnetism and electricity have great practical value. They form the basis for understanding motors, generators, solenoids, and many other electrical devices.

4-33 Every moving electric charge produces a magnetic field. The charge may be moving along a conductor, or it may be moving through a vacuum. The strength of the magnetic field depends on the *speed* and the *strength* of the charge.

4-34 The magnetic field is strong when the charge is moving *rapidly* and when the charge is *strong*. The field is weak when the charge is moving slowly and when the charge is weak.

Left-Hand Rules

4-35 You can use two "left-hand rules" that make it easy to keep track of various directions when you work with electricity and magnetism. These rules show you the relationships among the following directions.

- The direction the electric charge moves
- The direction of the magnetic field
- The direction of the force on the moving charge

These directions are always at right angles to one another.

4-36 In both left-hand rules, your left thumb always points in the direction the *negative* charges move. The fingers on your left hand always point in the direction of the magnetic field.

4-37 The first "left-hand rule" concerns the magnetic field produced by a moving electric charge. Figure 4.7 shows how this rule works. You point your left thumb in the direction the *electrons* are moving. At the same time, you curl the fingers of your left hand around the path of the electrons.

Figure 4.7: Left-Hand Rule for Field Direction

Left-Hand Rules (continued)

4-38 When your left hand is in this position, your fingers point in the direction of the magnetic field produced by the moving electrons. The field is circular, around the path of the electrons. Figure 4.7 shows how the field would look if you could see it.

4-39 If the moving particles have a *positive* charge instead of a *negative* charge, the magnetic field will be in the opposite direction. You can still use the left-hand rule. But you must either point your thumb in the direction *opposite* the motion of the positive charges, or you must remember that the magnetic field is in the *opposite* direction from your fingers.

4-40 The second "left-hand rule" concerns the force exerted on an electric charge as it moves through a magnetic field. This magnetic field is not produced by the moving charge, but by a magnet or some other device.

4-41 Figure 4.8 shows the second left-hand rule. To use it, you hold your left hand flat, with your thumb pointing sideways. You position your hand so that your fingers point in the direction of the magnetic field and your thumb points in the direction the electrons are moving. The palm of your hand then "pushes" in the same direction as the force the magnetic field exerts on the moving electrons.

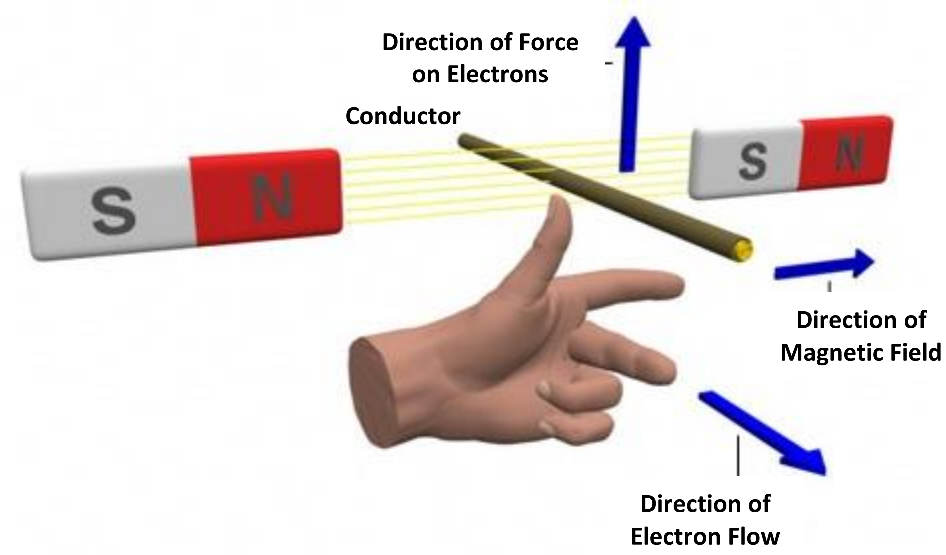


Figure 4.8: Left-Hand Rule for Force

4-42 If the moving particles have a positive charge instead of a negative charge, the force will be in the opposite direction. You can still use the left-hand rule. But you must either point your thumb in the direction opposite the motion of the positive charges, or you must reverse the direction of the force shown by your palm.

4-43 Another use for the second left-hand rule concerns the production of an electric current in a generator. Figure 4.9 shows the simplest possible generator. It consists of a conductor moving through a magnetic field. As the conductor moves, the magnetic field forces electrons to move along the conductor.

Left-Hand Rules (continued)

4-43 Another use for the second left-hand rule concerns the production of an electric current in a generator. Figure 4.9 shows the simplest possible generator. It consists of a conductor moving through a magnetic field. As the conductor moves, the magnetic field forces electrons to move along the conductor.

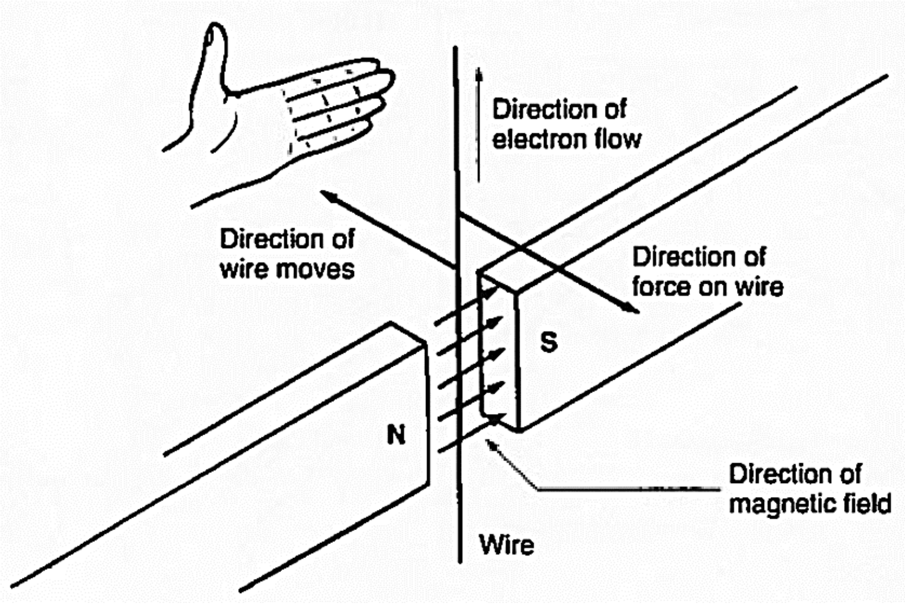


Figure 4.9: Left-Hand Rule for Generators

4-44 To figure out which way the electrons move, you first point the fingers of your left hand in the direction of the magnetic field, as shown in Figure 4.9. Then you turn your palm so that it "pushes" in the direction of the force exerted by the field on the conductor.

4-45 The direction of your palm must be *opposite* the direction of the conductor's motion, because the magnetic field resists the motion of the conductor. With your hand in this position, your left thumb will point in the direction of the electron flow in the wire.

Using the Left-Hand Rules

4-46 An example of how to apply both these rules is shown in Figure 4.10. This example shows the two conductors carrying alternating current to a motor. The conductors are not attached to each other, so they are free to move. How will the current in these conductors move them, if at all?

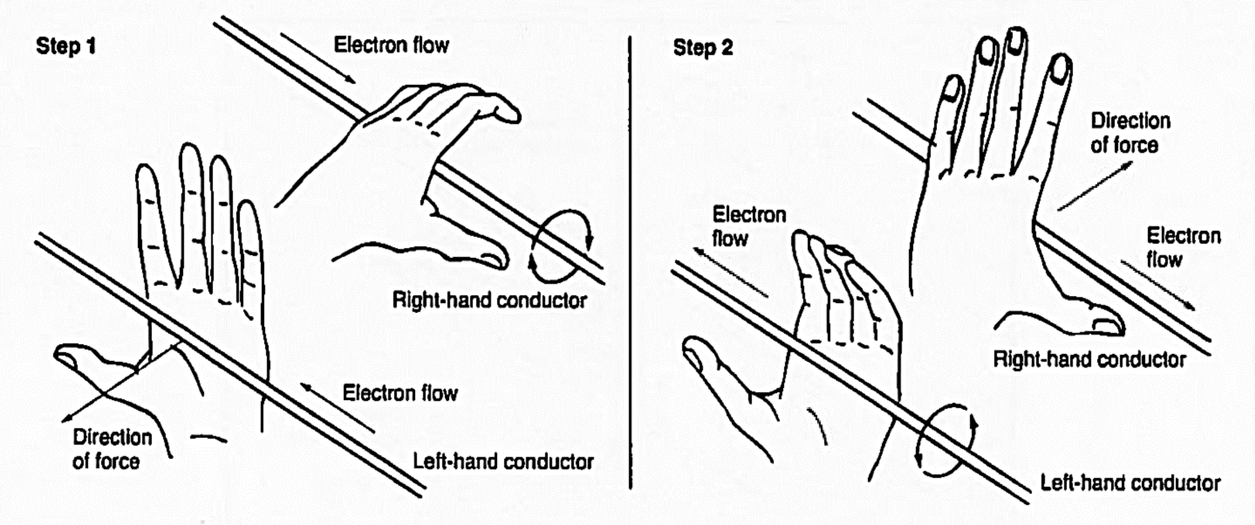


Figure 4.10: Forces on Parallel Conductors Carrying Alternating Current

4-47 Because you want to analyze *two* forces on *two* different conductors, you must use *two* steps. It does not matter which one you analyze first, but you cannot analyze both forces at the same time.

Step 1: In one step, you analyze the force exerted on the electrons moving through the *left-hand* conductor. This force is exerted by the magnetic field produced by the *right-hand* conductor. Figure 4.10 shows this step.

You start by using one left-hand rule to find the direction of the magnetic field around the right-hand conductor. In Figure 4.10, this field is shown by the circles around the conductor. The direction of the magnetic field is upward through the left-hand conductor.

Using the other left-hand rule, you can find the direction of the force on the left-hand conductor. The rule shows that the force is *away* from the right-hand conductor.

Step 2: In the second step, you look at the force exerted on electrons moving through the *right-hand* conductor by the magnetic field produced by the *left-hand* conductor.

Using the first left-hand rule, you can see that the direction of the magnetic field is upward where the right-hand conductor passes through it. Figure 4.10 shows this step.

Then using the other left-hand rule, you can see that the force on the right-hand conductor is *away* from the left-hand conductor.

Using the Left-Hand Rules (continued)

4-48 When the alternating current reverses, two changes occur:

- The electron flow reverses in each conductor.
- The reversal in electron flow also reverses the direction of the magnetic field around each conductor.

4-49 If you use the left-hand rules, you can see that the force on each conductor continues to be directed away from the other conductor. In other words, when two conductors carry electricity in opposite directions, there is a force on each conductor directed away from the other. It does not matter whether the electrons reverse direction, provided they *both* reverse.

Electromagnets

4-50 One of the most important magnetic devices using electricity is the **electromagnet**. An *electromagnet* consists of a coil of wire that carries an electric current. The electrons move many times in a circular path around a center.

4-51 You can use the first left-hand rule to figure out the direction of the magnetic field produced by an electromagnet. Examine Figure 4.11. Notice that the direction of the electron flow is the same for all pieces of the wire positioned side-by-side.

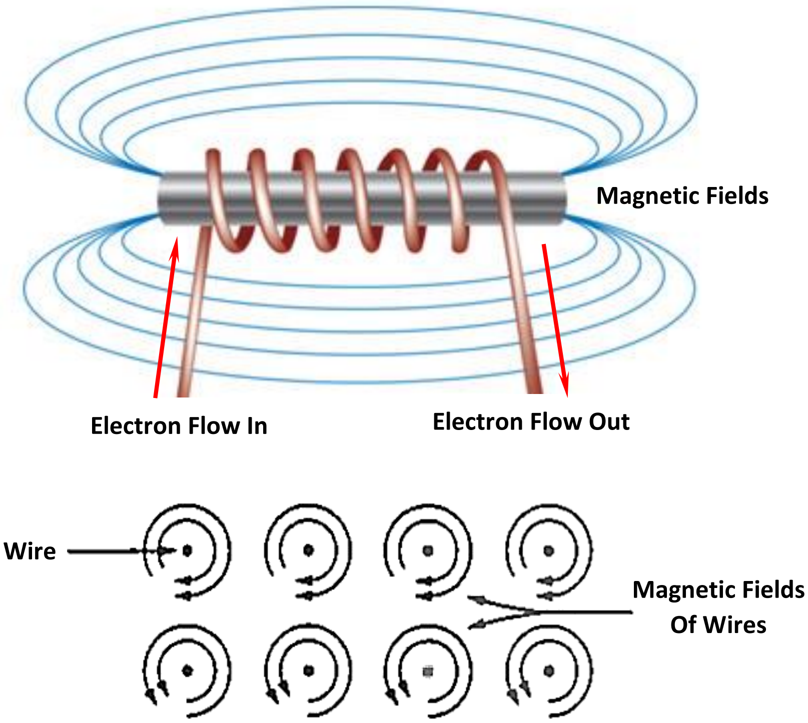


Figure 4.11: Magnetic Field of an Electromagnet

Electromagnets (continued)

4-52 The magnetic field produced by each piece of wire combines with the magnetic field produced by the piece next to it. The effect is to create a magnetic field inside the coil that has the combined strength of the fields from all the turns of wire. The more turns of wire in the coil, the stronger the magnetic field.

4-53 If you place a bar of iron or steel inside the coil, the coil's magnetic field will align the molecular magnets in the metal. Then the magnetic field of the device is increased by the amount of the bar's field. If a large fraction of the molecular magnets line up with the coil's field, the combined effect can be much stronger than the field of the coil alone. When the electric current stops flowing in the coil of the electromagnet, the molecular magnets of the iron core are allowed to return to their random arrangement.

4-54 To practice using the left-hand rules, try applying them to the examples shown in Figure 4.12. In each example in the upper row, draw arrows to show the direction of the magnetic field produced by the electric current. In the lower row, draw arrows to show the direction of the force acting on the moving charge. The correct answers are shown at the top of the following page.

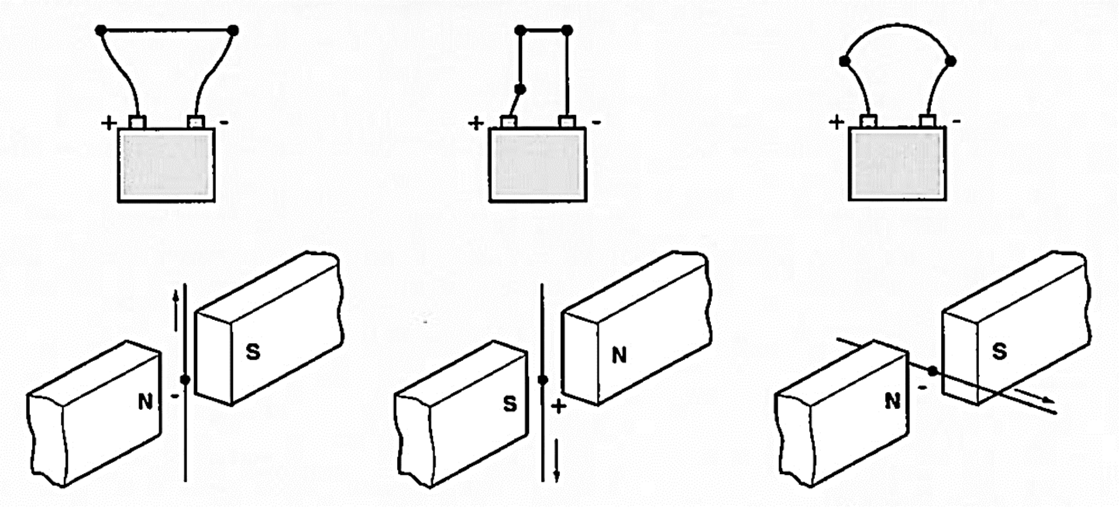
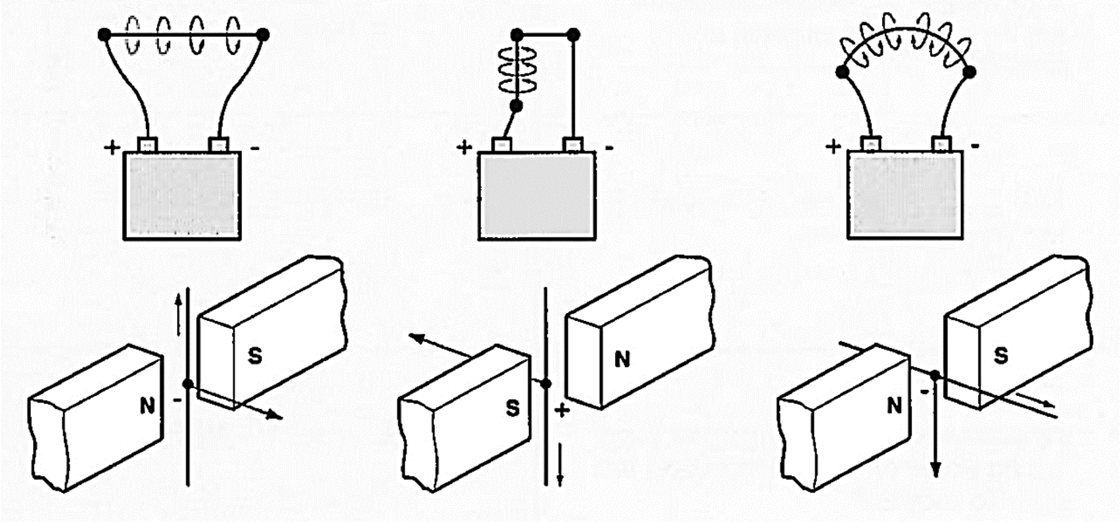


Figure 4.12: Practice Exercises

Electromagnets (continued)



Answers to Chapter Exercises

Industrial Uses of Magnets

4-55 Some of the most common industrial uses of magnets are in lifting devices, chucks, clutches, brakes, and pulleys.

4-56 *Lifting magnets* are used in transferring pieces of iron and steel from one place to another. Many pieces of iron and steel have odd shapes, making them difficult to handle. But a magnet can lift odd-shaped pieces easily, hold them securely, and release them at the proper time. The magnet lifts without chains or slings, so it saves time and effort.

4-57 Figure 4.13 shows a lifting magnet in use. The magnet is a large coil of wire surrounded by a steel frame. The frame protects the coil, and also improves the lifting ability of the magnet.

Figure 4.13: Lifting Magnet

Industrial Uses of Magnets (continued)

4-58 To pick up a load, the operator lowers the magnet onto the metal. Closing a switch sends an electric current through the coil, creating a magnetic field. The magnetic field attracts the magnetic molecules in the metal, and holds the metal firmly against the steel base of the magnet. To release the load, the operator opens the switch. When the current stops, the electromagnet loses its magnetic field.

4-59 A *magnetic chuck* is a machine-tool bed with an electromagnet built into it. The electromagnet holds iron and steel parts down during machining, eliminating the need for clamps. The entire surface of each part can be machined without obstruction. Figure 4.14 shows a shaft held in a V-shaped magnetic chuck while a deep keyway is milled.

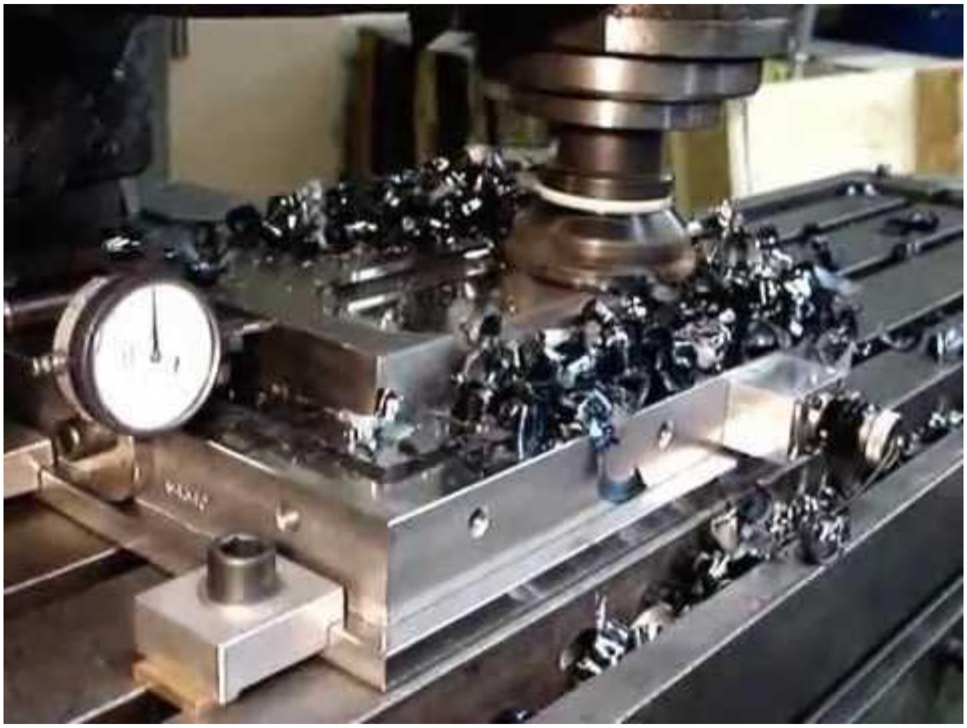


Figure 4.13: Lifting Magnet

Industrial Uses of Magnets (continued)

4-60 A *magnetic pulley* removes pieces of iron and steel from other materials—for example, wood chips, grain, coal, or sand. The material flows onto a moving belt which passes over a magnetized pulley, as shown in Figure 4.15.

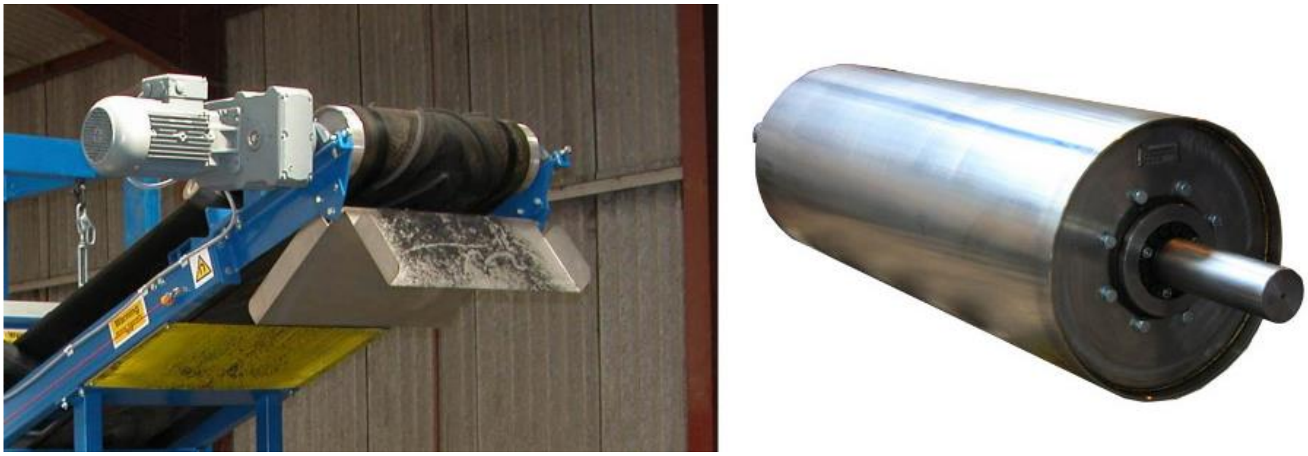


Figure 4.14: Lifting Pulley

4-61 The iron or steel is held onto the belt as it passes over the magnetic pulley. The magnetic field of the pulley holds the metal on the belt longer than the nonmagnetic material, so that it drops off later. The magnetic and nonmagnetic materials drop into separate containers.

Chapter 4 Exercise

Circle the appropriate letter next to the correct answer.

1. A bar-shaped magnet generally produces its strongest effect at __________________________.

    a. Its north pole
    b. Its south pole
    c. Both poles
    d. Its center

2. Two like magnetic poles always ________________________________.

    a. Attract each other
    b. Repel each other
    c. Cancel each other
    d. Reinforce each other

3. The earth’s gravitational field pulls you down because you have ___________________________.

    a. Weight
    b. Mass
    c. Force
    d. Attraction

4. A magnetic field acts on other objects because the objects have ________________________.

    a. Charge
    b. Mass
    c. Substance
    d. Magnetic properties

5. A moving charge creates a magnetic field. The strength of the field depends on the ________________________.

    a. Speed and strength of the charge
    b. Distance between magnetic poles
    c. Direction the charge is moving
    d. Whether the charge is positive or negative

Chapter 4 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. In both left-hand rules, your left thumb points in the direction in which ___________________________________.

   a. The positive charges move
   b. The negative charges move
   c. The magnetic field moves
   d. The north magnetic pole moves

7. A coil that carries an electric current is called a(n) _____________________.

   a. Conductor
   b. Thermocouple
   c. Electrocurrent
   d. Electromagnet

8. One advantage of a lifting magnet is that it can lift ____________________.

   a. Odd-shaped pieces
   b. All kinds of materials
   c. Other magnets
   d. With very little force

9. A magnetic chuck ____.

   a. Holds a tool in place
   b. Should not be used near iron or steel
   c. Is an electromagnet
   d. Is a permanent magnet

10. Pieces of iron and steel can be removed from other materials on a belt by means of a ______________________.

    a. Magnetic pulley
    b. Lifting magnet
    c. Magnetic chuck
    d. Metal separator

Summary

A magnet is any substance that attracts magnetic materials. The points of maximum attraction are called poles. Every magnet has a north pole and a south pole. Magnetic poles and electrical charges react in the same way. Unlike poles or electrical charges attract each other while like poles or charges repel each other.

When two objects exert force on each other from a distance without touching each other, the forces are called a field. The strength of the magnetic field is determined by the speed and the strength of the electric charge.

When you work with electricity and magnetism you may use the left-hand rules. These rules are used in determining the direction of the electric charge, the direction of the magnetic field, and the direction of the force on the moving charge. When you use the left-hand rules, remember that these directions are always at right angles to one another.

A coil of wire that carries an electric current is called an electromagnet. Electromagnets are used in lifting devices, chucks, clutches, brakes, and pulleys.

Chapter 5: Current, Resistance, and Potential Difference

In This Chapter

Electric Current

Resistance

Potential Difference

Ohm's Law

Resistance and Voltage Drop

Measuring Current

Measuring Potential Difference

Measuring Resistance

Terminology

Free electrons: Electrons not bound tightly to atoms

Electric current: The result when many free electrons move in the same direction

Electrical conductor: A material having many free electrons that can move easily

Electrical insulator: A material having few free electrons that cannot move freely

Resistance: Opposition to the movement of free electrons

Potential difference: Difference in potential energy per unit of charge between two points

Voltage drop: Decrease in potential difference across part of a path

Electricity is a complex science with many terms that must be understood by the trainee. To work with electricity, you must know the meanings of such terms as ampere, volt, ohm, potential difference, and resistance. In this chapter, we define these terms and explain the role of these units in electricity.

In order to work safely with electricity, you must also know the difference between an electrical conductor and an electrical insulator. This chapter explains the function of each and lists materials commonly found in the plant that conduct or insulate against electric current now.

Personnel who must measure current flow, potential difference, and resistance can use various measuring devices. These include ammeters, voltmeters, and ohmmeters.

Electric Current

5-1 Many materials have *free electrons*. These electrons are not bound tightly to the atoms. They are free to move from one atom to another. When large numbers of these electrons move in one direction, the result is called an **electric current**.

5-2 In metals such as copper, the free electrons can move very easily. These materials are called electrical conductors. The most common **electrical conductors** in the plant are made of metals or carbon.

5-3 Materials known as **electrical insulators** have few free electrons. It is difficult to force any of the electrons to move from atom to atom. Therefore, it is difficult to produce an electric current in these materials. Some of the best electrical insulators are mica, porcelain, glass, rubber, silk, air, slate, paper, and certain synthetic materials, including plastics, silicone, and neoprene.

5-4 There is no sharp dividing line between conductors and insulators. Impure water is a conductor, but chemically pure water is an insulator. In fact, the ability of water to resist the flow of electricity is used as a measure of high purity. Many nonmetallic crystalline materials are good insulators. Examples include diamond and quartz.

5-5 Cotton, wood, and paper are good insulators, but only if they are dry. Any water in the material coats the fibers and conducts electricity. These fibrous materials must be saturated with mineral oil, tar, pitch, or some other moisture repellent in order to be used as insulators.

5-6 According to the *kinetic theory of matter*, the particles that make up a material are never completely at rest. The atoms, molecules, and free electrons move constantly in a random manner. If you connect the ends of a copper wire to the terminals of a battery, the random motion of the electrons changes to a motion directed toward the positive terminal.

5-7 Electrons at one end of a conductor respond very quickly to changes at the other end. But the electrons do not move through the conductor at high speed. In fact, each electron moves quite slowly. But as soon as the first electron moves toward the positive terminal, it displaces the next one, causing it to move forward. This electron in turn forces the next one to move, and so on.

5-8 These changes occur very rapidly. As a result, the last electrons at the far end of the wire are forced to move almost instantly when the first ones move.

5-9 This action is similar to the flow of water through a pipe. Water is not compressible, so water starts flowing from one end of a pipe as soon as you start forcing water into the opposite end (provided the pipe is already filled with water when you start).

5-10 Another simple way to picture electric current is to compare the conducting path to a freight train. The cars of the train are like the free electrons in the conductor, and the locomotive is like the battery.

5-11 When the locomotive starts the train moving, it pulls suddenly against the first car in the line. This slight motion takes the slack out of the couplers, car after car, down the line. Each car moves only a short distance, but the shock runs down the entire line of cars at very high speed. You can *hear* the shock better than you can *see* it.

Electric Current (continued)

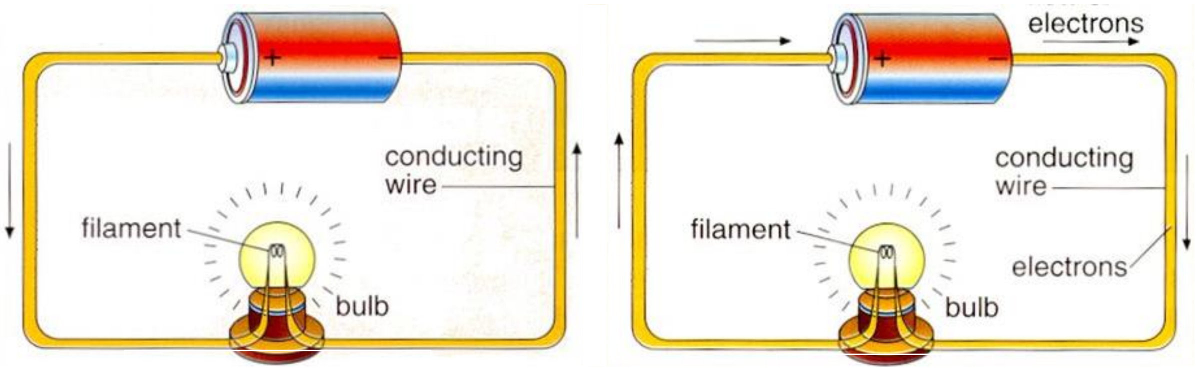
5-12 An electric current is like that shock wave. Each electron in the conductor moves only a short distance. But the effect at one end of the conductor produces an effect at the other end very quickly.

5-13 The movement of electrons from atom to atom is the same everywhere along a wire. The distribution does not change as the electrons move. When you disconnect the battery, each atom is left with its proper number of electrons. The number of electrons that came out of the wire at the positive terminal is exactly equal to the number that entered the wire at the negative terminal.

5-14 Today, everyone knows that an electric current is the flow of negatively-charged electrons. The electrons flow from the negative terminal of a battery to the positive terminal. That is, the current flows from *negative* to *positive*.

5-15 Only a hundred years ago, no one knew what electricity was. Scientists thought *something* was flowing between the terminals of a battery. But they did not know what the "something" was. They did not know about electrons or that the moving material carried a negative charge.

5-16 The early scientists labeled the terminals of a battery "+" and "-". Then they incorrectly guessed that something was flowing *out* of the positive terminal and *into* the negative terminal. That is, they assumed the current flowed from positive to negative, as shown at the left in Figure 5.1.



Positive Current Flow **Electron Flow**

Figure 5.1: Two Kinds of Electrical Current

5-17 This incorrect assumption causes a certain amount of confusion today. Many people still think of electricity as a "positive current." But most people think of it as the flow of electrons. In order to avoid confusion in these chapters, the term *electric current* will always mean the flow of electrons.

5-18 An electric current is defined as the amount of electrical charge moving past a given point in a unit of time. The amount of charge is measured in *coulombs*, and the time is measured in *seconds*. A rate of flow of one coulomb per second is called one **ampere**.

Electric Current (continued)

5-19 It takes 6.28×10^{18} (628 billion billion) electrons to make up a charge of one coulomb. Therefore, a current of one ampere consists of 6.28×10^{18} electrons flowing past a given point in one second. The current through an ordinary 100-watt light bulb is almost one ampere. The current through an industrial motor may be 100 amperes or more.

5-20 The rate that electrons move through a conductor is beyond the ability of the human mind to imagine it, even if the current is only one ampere. For example, suppose a conductor carries a current of one ampere. The number of electrons that pass a given point in this conductor in just *one billionth* of a second is greater than the total number of people living on the earth today.

5-21 Looking at this current another way, suppose you divide the distance around the earth, approximately 25,000 miles, into one-inch parts, as shown in Figure 5.2. A current of one ampere, lasting for only *one billionth* of a second, would consist of four electrons for every inch in the earth's circumference.

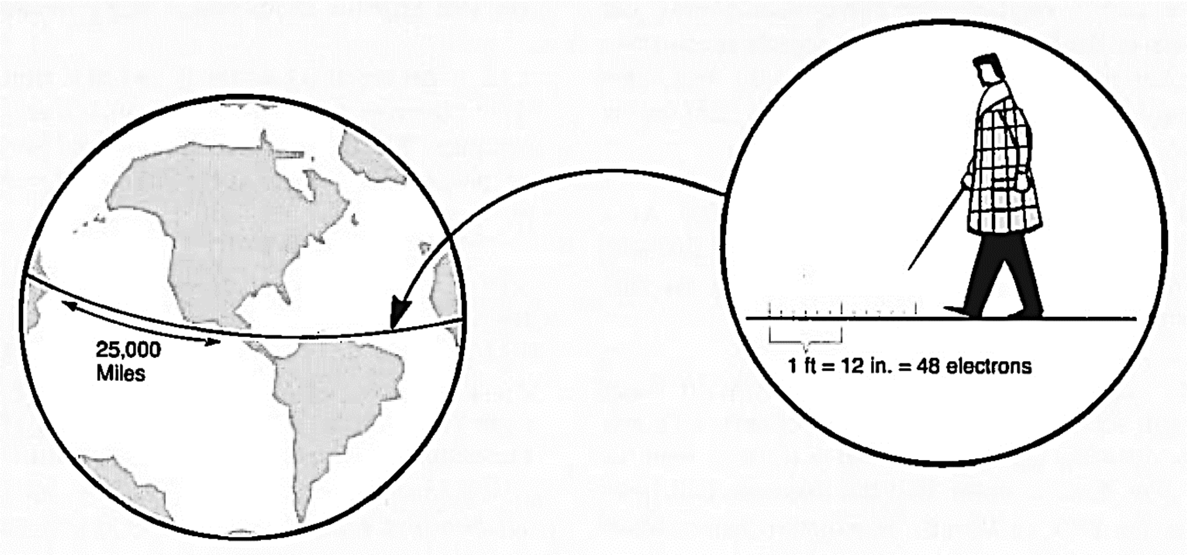


Figure 5.2: Circumference of the Earth Equals 1.5 Billion Inches

Resistance

5-22 When any material flows through a pipe, it meets opposition. The opposition comes from friction between the material and the inner surface of the pipe. The friction resists the flow of the material, and it produces heat.

5-23 The same is true of electricity flowing in a conductor. The moving electrons meet opposition, and the opposition produces heat. This opposition is called the **resistance** of the conductor.

5-24 Resistance is a property of the *material*, its *size*, and its *temperature*. Some materials have a greater resistance to the flow of electricity than other materials of the same cross-sectional area and at the same temperature. For example, metals generally have lower resistance than nonmetals. For most conductors, increasing the cross-sectional area decreases the resistance. Raising the temperature generally increases the resistance.

Potential Difference

5-25 If electrons have greater potential energy at one place than at another, then a *potential difference* is said to exist between the two places. **Potential difference** is the difference in potential energy, per unit of charge, between two points.

5-26 In the metric system, potential energy is measured in *joules*. Charge is measured in *coulombs*. If the difference in potential energy between two places is one joule for every coulomb of charge, then there is a *potential difference* of one joule per coulomb. This amount of potential difference is called *one volt*.

$$\textbf{1 Volt} = \frac{\text{One Joule of Potential Energy}}{\text{Coulomb of Charge}}$$

5-27 Figure 5.3 shows the idea of a volt. Suppose you place a small electric heater in approximately one gram of water which occupies a volume of one cubic centimeter. Suppose further that the resistance of the heater allows current of one ampere to flow when the heater is connected to a one-volt cell.

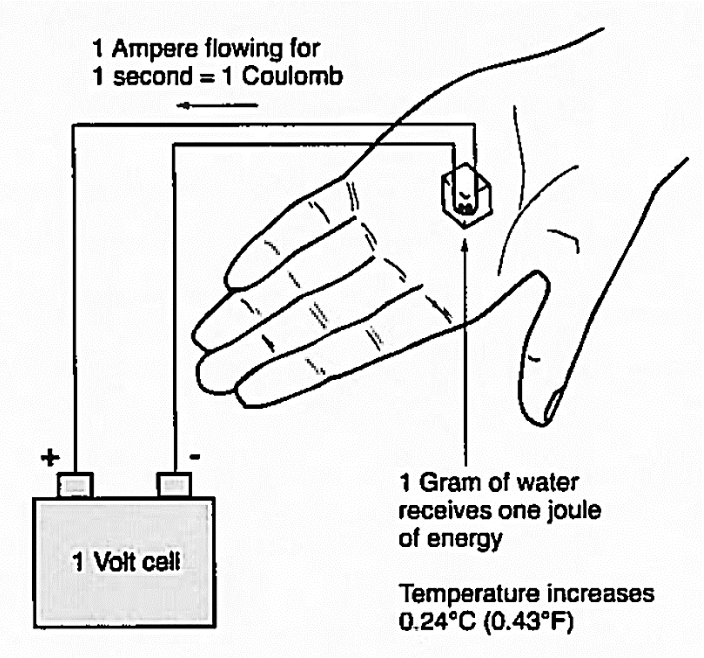


Figure 5.3: Electricity Heating Water

5-28 If you let the current flow for exactly one second, one coulomb of charge will flow through the heater. As it flows, the electrons will lose energy to the water through the heater. The temperature of the water will rise by slightly less than one-fourth of a degree Celsius.

5-29 In general, if a conductive path exists between any two points, charge will flow between the points as long as the potential difference exists. But the current reduces the charge at one point, and increases the charge at the other. The effect is to reduce the potential difference between the two places.

Potential Difference

5-30 If the potential difference decreases to zero, the current stops. Therefore, to maintain a current between two points, you must maintain the potential difference as the charge flows.

5-31 A battery or generator acts like a "pump," moving electrons through itself to maintain a potential difference between two points. The electrical utility runs wires to your plant from its generators. The utility maintains a certain potential difference between these wires to keep the equipment running in the plant.

5-32 Potential difference can vary from zero to several million volts. The potential difference between the terminals of a dry cell is about 1.5 volts. The potential difference between the terminals of an automobile storage battery is about 12 volts. The potential differences commonly applied to the terminals of industrial electric motors are 120, 200, 240, 480, 2400, and 4000 volts.

Ohm's Law

5-33 There is a simple relationship between the current that flows through a conducting path and the potential difference between the ends of the path. As you increase the potential difference, the current increases, as shown in Figure 5.4.

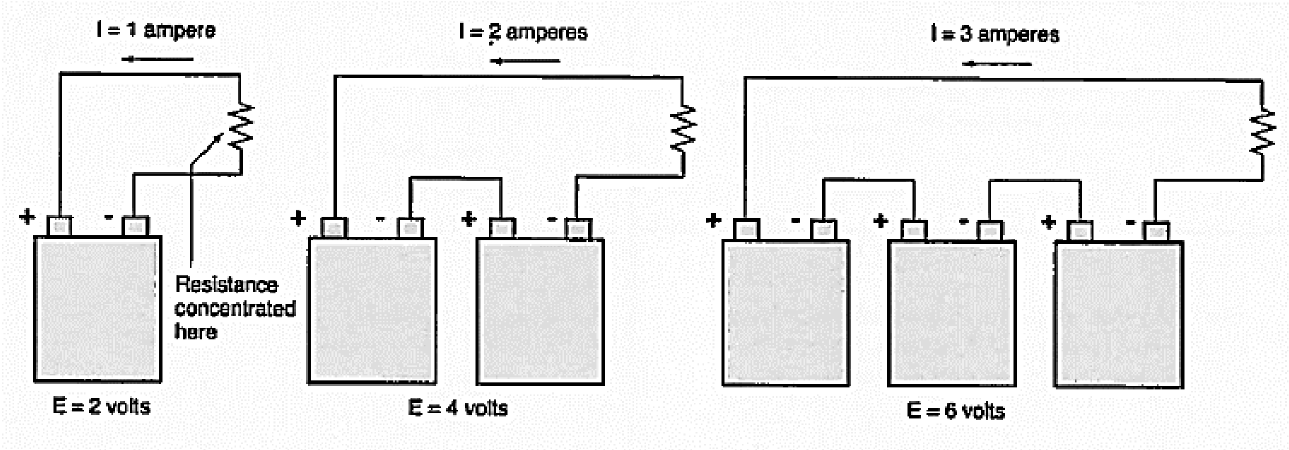


Figure 5.4: Effect of Potential Difference on Current

5-34 The two values are proportional. That is, doubling the potential difference doubles the current. Tripling the potential difference triples the current, and so on. This proportional relationship between potential difference and current is called **Ohm's law** in honor of George Ohm. He was a German scientist who discovered the relationship in the early 1800s.

Ohm's Law (continued)

5-35 Ohm's law is usually expressed in mathematical form. The equation is written in the following way.

$E = I \times R$

Where E = Potential difference between the ends of the conductor

I = Current through the conductor

R = The constant of proportionality between E and I

5-36 The value R is called the *resistance* of the conductor. It is measured in units called **ohms**. One *ohm* is defined as the resistance of a conductor that carries a current of one ampere when the potential difference between its ends is one volt.

5-37 The Greek letter Ω (*omega*) is used as a symbol to stand for the unit *ohms*. For example, 40 Ω means a resistance of 40 ohms. When you write large or small values of resistance, you can use prefixes to simplify your writing. Table 5-1 shows several examples using the common prefixes.

Table 5-1: Common Prefixes

Symbol	Prefix Meaning	Example
µ	Micro- One millionth	1 µΩ = 0.000001 ohms
m	Milli- One thousandth	1 mΩ = 0.001 ohms
k	Kilo - Thousand	1 kΩ = 1000 ohms
M	Mega - Million	1 MΩ = 1,000,000 ohms

5-38 You can use Ohm's law to calculate the third value in the equation when you know any two values. For example, suppose you know that a conductor carries a current of 0.50 amperes when the potential difference between its ends is 25 volts. What will the current be if you raise the potential difference to 35 volts?

5-39 To answer this question, you can use Ohm's law in two steps. First you calculate the resistance of the conductor, using the current and potential difference given. Then you use that value of the resistance to calculate the current when the potential difference is raised to 35 volts. These calculations are shown in Figure 5.5.

5-40 Notice in Figure 5.5 that the *units* are included in the calculations. You should do the same when you solve problems. The equation is a *physical equation*. The letters stand for *physical* quantities, not just *numbers*.

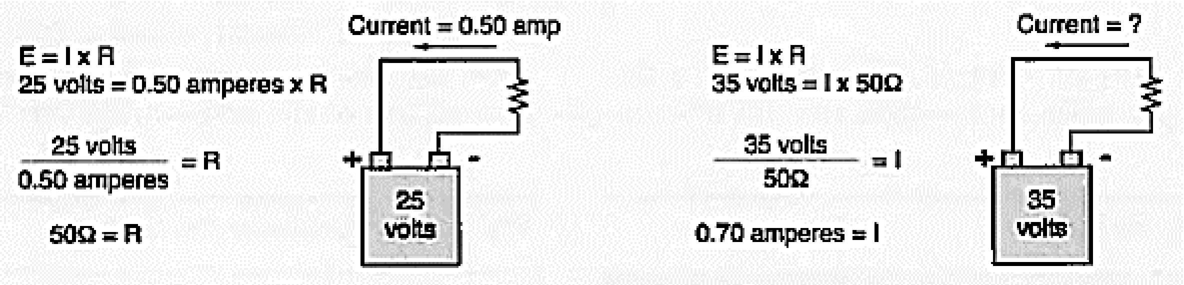


Figure 5.5: Using Ohm's Law

Resistance and Voltage Drop

5-41 The potential difference from one end of a conductive path to the other depends on what the ends are connected to. But the potential difference between other pairs of points depends only partly on what the ends of the path are connected to. It also depends on the resistance between the points compared to the total resistance.

5-42 An example will help you understand this point. Suppose a conductive path consists of three sections, each having a different resistance. These sections are connected in *series* or end-to-end as shown in Figure 5.6. All the current in the path flows through each resistor.

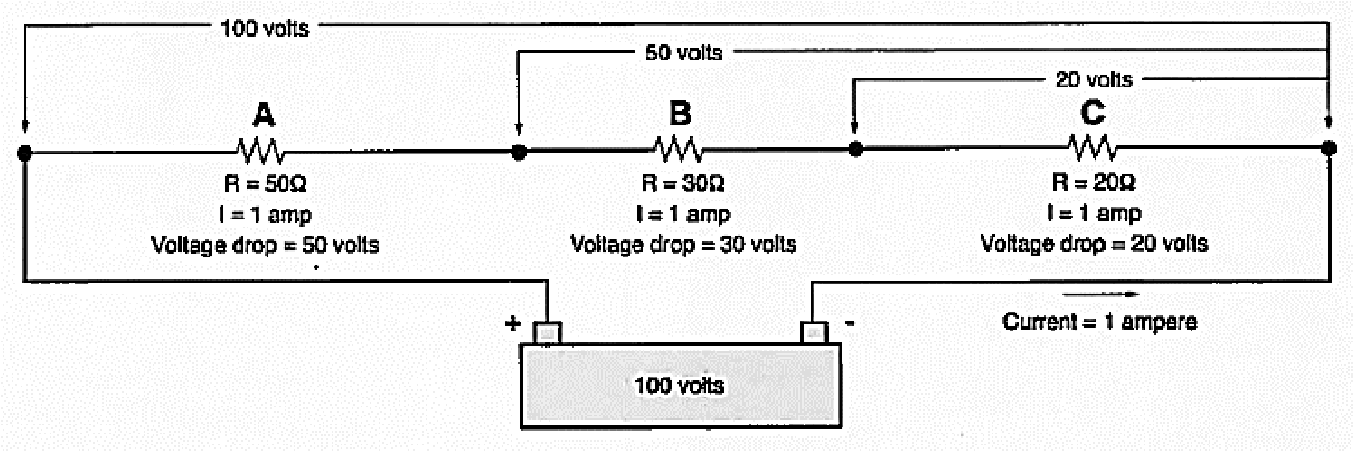


Figure 5.6: Voltage Drop

5-43 Suppose the three sections have a combined resistance of 100 Ω. Suppose further that the potential difference between the ends of the path is 100 volts. Using Ohm's law, you can calculate that the current is one ampere.

5-44 If you measure the potential difference from *one end* of the path to various points *between* sections, you will find that the potential difference is lower than 100 volts. If your measuring instrument spans only *one* section, the potential difference is even less. And if it spans *no* sections, the potential difference is zero.

5-45 You can think of this reduction as a *decrease* in potential difference as you span less and less of the total path. The common name for this decrease in potential difference over the path is "voltage drop."

5-46 You can use Ohm's law to see why the potential difference decreases when you measure it across only part of the path. Each resistor carries the same amount of current as the whole path. Therefore, according to Ohm's law, the potential difference across each section equals the product of this current and the resistance of the section.

5-47 For example, the potential difference across section A in Figure 5.6 is 50 volts, because the current is one ampere (l ampere x 50 Ω = 50 volts). If you calculate the potential difference across all three sections, and add the three results together, the total will equal the potential difference across the total path.

5-48 The voltage drop is proportional to the amount of resistance in the span you are measuring. If half the total resistance is included in the span, the voltage drop is half the potential difference across the whole path. If 80 percent of the total resistance is included, the voltage drop is 80 percent of the potential difference across the whole path.

Measuring Current

5-49 On certain troubleshooting jobs, you will need to know how much current is flowing in part of a circuit. Measuring the current establishes part of the basis for analyzing the circuit, which can lead you to the cause of the problem. To measure the current, you use an *ammeter*.

5-50 Two basic kinds of meters are in common use. The simplest kind to read is the modern *digital* meter. It displays values as numerals. Figure 5.7 shows a digital meter. This instrument can measure current, resistance, and potential difference. You select the kind of measurement and the range by means of controls on the front of the instrument.

Figure 5.7: Digital multimeter

Measuring Current (continued)

5-51 The older kind of meter has an electromechanical movement, called a *D'Arsonval movement*, that displays values. This movement works by making use of the relationship between electricity and magnetism. Figure 5.8 shows the basic construction of the D'Arsonval movement.

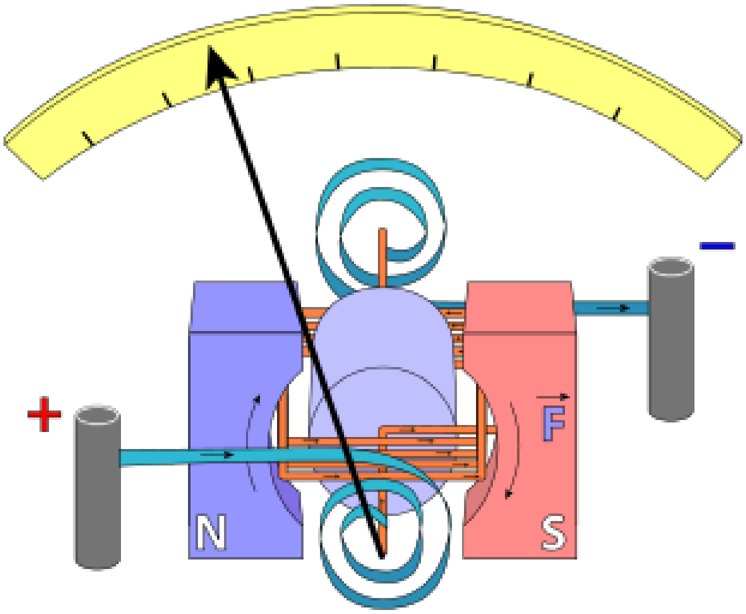


Figure 5.8: D'Arsonval movement

5-52 The movement is designed so that a small current flows through a coil of wire suspended in a strong magnetic field. The magnetic field exerts force on the electrons as they move through the coil. The force is in opposite directions in the two sides of the coil. Thus, the two forces, acting on opposite sides of the coil, produce the same twisting effect on the coil.

5-53 The coil is suspended so that it can rotate in response to the twisting effect of the magnetic field. But in order to rotate, the coil must partly wind up a small spring. The spring exerts another twisting effect on the coil. This effect opposes the twisting effect of the magnetic field. The more the coil rotates, the more it must wind up the spring, increasing the twisting effect of the spring.

5-54 The coil reaches a position where the twisting effect of the magnetic field exactly balances the twisting effect of the spring. This position serves as a measure of the amount of current flowing through the coil.

5-55 A pointer attached to the coil shows how far the coil has rotated in relation to a fixed scale. The scale can indicate current, resistance, or potential difference, depending on how the meter is connected to the circuit and to other devices inside. The scale can be calibrated in amperes, ohms, or volts.

Measuring Current (continued)

5-56 In an ammeter, most of the current flowing through the meter goes *around* the meter movement. It goes through a special resistor, called the *shunt*, as shown in Figure 5.9. The resistance of the shunt is quite low. Yet it is precisely set, so that a known fraction of the current flows through the D'Arsonval movement. The accuracy of the shunt resistor determines the accuracy of the readings on the ammeter.

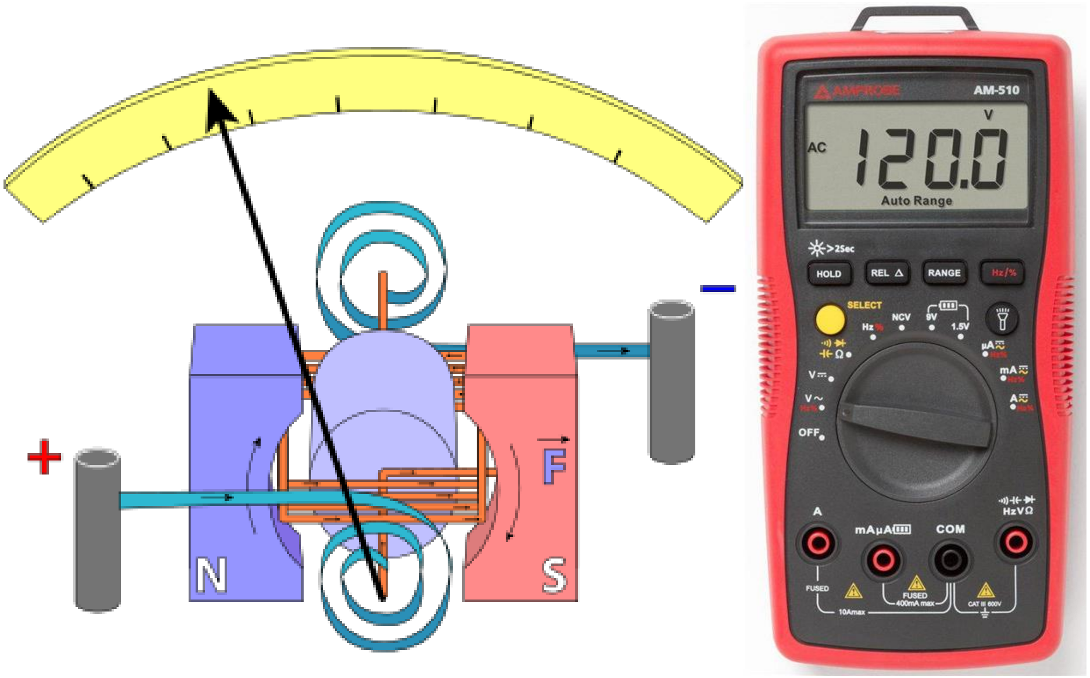


Figure 5.9 Ammeter

5-57 The resistance of the shunt determines the sensitivity and the range of the ammeter. The *higher* the resistance of the shunt, the greater the fraction of the current that flows through the meter movement. Increasing this fraction increases the *sensitivity* of the meter and reduces the amount of *current* required to produce a full-scale deflection of the meter movement.

5-58 In most ammeters, you can turn a rotary switch to select any one of several shunts. In this way, you can choose the sensitivity and the range of the meter.

5-59 The meter used for measuring potential difference is called a *voltmeter*, because it measures potential difference in *volts*. A digital voltmeter displays the value as a numeral. A D'Arsonval voltmeter displays the value as the position of a pointer on a scale.

5-60 A D'Arsonval *voltmeter* is connected internally much like a D'Arsonval *ammeter*. But instead of a *shunt* to carry most of the current around the meter movement, it has a *series resistor* connected to the movement, as shown in Figure 5.10.

Figure 5.10: Voltmeter

5-61 The series resistor has a very high resistance. Therefore, the amount of current flowing through the meter movement is very low. The value of the resistor determines the sensitivity and the range of the voltmeter.

5-62 The *higher* the resistance, the *lower* the current that flows through the meter movement for a given potential difference. Decreasing the current lowers the *sensitivity* of the meter and increases the *potential difference* required to produce a full-scale deflection of the meter movement.

Measuring Resistance

5-63 The instrument for measuring resistance is a combination of an electrical source (usually a dry cell) and an ammeter, as shown in Figure 5.11. The electrical source applies a known potential difference between two points in a circuit. The ammeter measures the amount of current produced by this potential difference. A special *limiting resistor* is included to protect the meter in case the resistance of the circuit is very low.

Figure 5.10: Ohmmeter

5-64 You can calculate the resistance of the circuit by dividing the potential difference by the current. But the meter solves this problem for you, and shows the result in ohms. A digital ohmmeter displays the result as a numeral. A D'Arsonval ohmmeter displays the result as the position of a pointer on a scale. The scale is usually "backward," with zero at the right.

Chapter 5 Exercise

Circle the appropriate letter next to the correct answer.

1. Free electrons can move easily in ___________________.

   a. Conductors
   b. Atoms
   c. Materials
   d. Insulators

2. A rate of one coulomb per second is called one ___________________.

   a. Ampere
   b. Joule
   c. Volt
   d. Ohm

3. For most conductors, increasing the temperature increases the __________________.

   a. Number of free electrons
   b. Current
   c. Voltage drop
   d. Resistance

4. The difference in potential energy, per unit of charge, is called __________________.

   a. Voltage
   b. Voltage drop
   c. Potential
   d. Potential difference

5. To maintain a current between two points, you must maintain the__________________.

   a. Voltage source
   b. Battery
   c. Potential difference
   d. Amperage

Chapter 5 Exercise (continued)

6. Resistance is measured in ____________________.

   a. Amperes
   b. Volts
   c. Watts
   d. Ohms

7. If a path has two resistors, one 20Ω and the other 30Ω, and a potential difference of 50 volts is applied across the whole path, what is the voltage drop across the 30Ω resistor?

   a. 50 volts
   b. 30 volts
   c. 20 volts
   d. 15 volts

8. The simplest kind of electrical meter to read is the ____________________.

   a. D'Arsonval meter
   b. Digital meter
   c. Pointer meter
   d. Dial meter

9. In an ammeter, most of the current going through the meter goes through a special resistor called the _______.

   a. Shunt
   b. Shoot
   c. Shuttle
   d. Slope

10. A voltmeter includes a special resistor called the _________________.

    a. Limiting resistor
    b. Series resistor
    c. Parallel resistor
    d. Shunt

Summary

Electric current is the flow of electrons from a negative point to a positive point. The flow of electric current is measured in units called amperes. For current to now, a potential difference must exist between two points. Potential difference is measured in units called volts.

Electrons flow very easily through some materials—metals and carbon, for example. Such materials are called conductors. Other materials—rubber, plastic, and glass, for example—inhibit the flow of electrons. Such materials are called insulators. Conducting and insulating materials are used in construction, equipment, and machines.

When you work with electric current, you should remember Ohm's law. Simply put, it says the amount of current flow is proportionate to the amount of potential difference between the ends of the path. In other words, increasing or decreasing the potential difference increases or decreases the amount of current flowing along the path.

You can use an instrument called an ammeter to measure electric current. A voltmeter is used in measuring potential difference.

Chapter 6: Electrical Components

In This Chapter

Resistance

Resistors

Fixed Resistors

Resistor Color Code

Resistor Power Rating

Tapped Resistors

Capacitance

Types of Capacitors

Connecting Capacitors

Induction

Mutual Induction

Inductance

Terminology

Superconductor: A material that loses all its electrical resistance at temperatures near absolute zero

Fixed resistor: A resistor with a resistance that cannot change

Power: Rate of energy production or consumption

Rheostat: Variable resistor having a low resistance

Potentiometer: Variable resistor having high resistance

Capacitor: Device that can store electric charge

Farad: Unit of capacitance

Induction: Magnetic effect that occurs in a coil of wire when the current changes

Solenoid: Coil of wire with a movable magnetic core

Relay: A switch that operates by electricity

When you work with electricity, it is important to know about the materials used in wiring, insulating, and other electrical components. Such materials are selected for their ability to conduct or resist the flow of electrons.

Capacitors, inductors, solenoids, and relays are important electrical components. In this Lesson, we explain the uses of conducting and insulating materials in electrical components commonly used in plant equipment and machinery.

Resistance

6-1 Various materials have different atomic structures. The number of free electrons differs in each material. The more free electrons a material has, the easier it is for electric current to flow through it. The fewer free electrons, the more difficult it is for electricity to flow.

6-2 The opposition to electric current is called **resistance**. Resistance is a physical quantity—a property of a material. Materials that conduct electric current have definite values of resistance ranging from zero to very high values. The resistance also depends on the length, the cross-sectional area, and the temperature of the material.

6-3 Certain materials lose their electrical resistance completely at temperatures near absolute zero. These materials are called *superconductors*. If an electric current is started in a loop of wire made of superconducting material, the current will continue to flow even after the power source is removed.

6-4 An "ideal" conductor, used for carrying electricity from a power source to a load, should have no electrical resistance. However, the ideal conductor does not exist at ordinary temperatures. Therefore, electrical wires are made of materials having the lowest possible resistance at a reasonable cost.

6-5 Copper is the material used most often for electrical conductors. Where it is important to save weight, aluminum is used instead. Aluminum wiring is used in aircraft wiring and in long-distance power transmission lines that are suspended from towers.

6-6 In some applications, even the slight resistance of the wires connecting parts of a sensitive electronic circuit can affect the performance of the circuit. In such applications, silver wires keep the circuit resistance to a minimum. Silver has the lowest resistance of all metals at ordinary temperatures.

6-7 High resistance is needed for electric heating elements and for the filaments of light bulbs. These elements must have high resistance to control their temperature during use.

6-8 The heating element in an electric heater is usually made of high-resistance *nichrome* (nickel-chromium) wire. The cable supplying power to the heater is made of low-resistance copper wire.

6-9 The high-resistance wire becomes hot when electric current passes through it because of its high resistance. The copper wire remains cool because its resistance is much lower than that of the nichrome element.

6-10 Another purpose of high resistance is to limit the current in a circuit. All electrical equipment has some resistance, but sometimes resistance must be added to control the current. Most dc motors require extra resistance in the circuit during starting to prevent too much current from flowing through the motor windings.

6-11 The most effective method of controlling the current during starting is to add several units of resistance in series with the motor windings. These units are then gradually disconnected during the starting period until all the extra resistance has been removed.

Resistors

6-12 Components that add resistance to a circuit are called **resistors**. There are many types of resistors. Some have a fixed value of resistance, and others are variable. Many resistors are made of high-resistance wire wound around a ceramic form. Others are made of cast iron, punched steel sheet, or carbon. Resistors can differ in size and construction, even if their resistance values are the same.

6-13 Electricity flowing through a resistor produces heat. The rate of heat production is proportional to the product of the *potential difference* across the resistor and the current passing through it. That is, you multiply E x I for the resistor, and the product is a measure of how fast heat is produced.

6-14 For example, suppose you connect two resistors in two circuits so that the potential difference is the same across both resistors. Suppose further that one resistor has only half as much resistance as the other, and therefore carries twice the current.

6-15 The resistor that carries twice as much current will produce heat twice as fast. When you multiply the current times the potential difference for each resistor, you get a product twice as high for the resistor carrying twice the current.

6-16 But suppose you double the potential difference across the resistor in just one of these circuits. Doing so will multiply the rate of heat production in that resistor by *four*, not by two. The reason has to do with Ohm's law. Doubling the potential difference also doubles the current flowing through the resistor. Therefore, the product is multiplied by four.

6-17 Resistors that must carry high currents are physically large so the heat can be released quickly into the surrounding air. If a resistor does not get rid of its heat fast enough, the temperature can rise so high that it damages or even melts the resistor.

Fixed Resistors

6-18 The simplest kind of resistor is the *fixed resistor*. It is a unit constructed so that its resistance value cannot be changed. Some examples of fixed carbon resistors are shown in Figure 6.1.

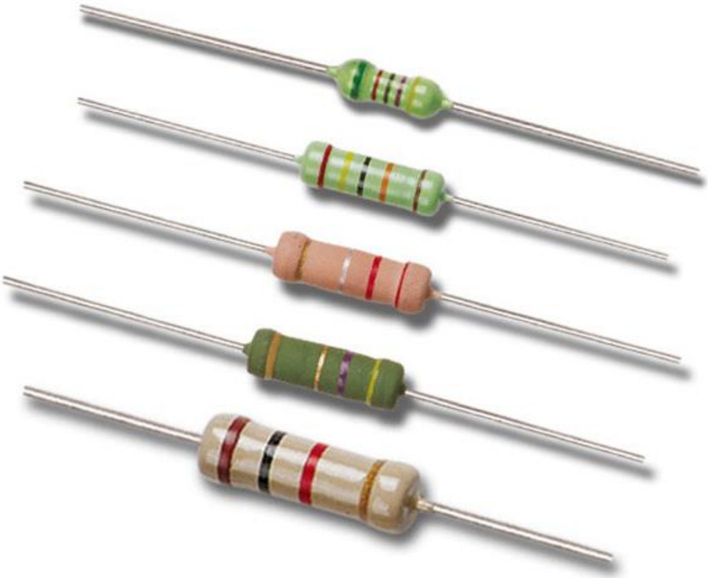


Figure 6.1: Fixed Carbon Resistors

6-19 The resistance of the resistor is determined by the composition of the material used in making it. Carbon is commonly used for resistors of low power rating. Resistors for high-power use are made of high-resistance wire wound on an insulated core. They are covered with a protective coating, as shown in Figure 6.2.

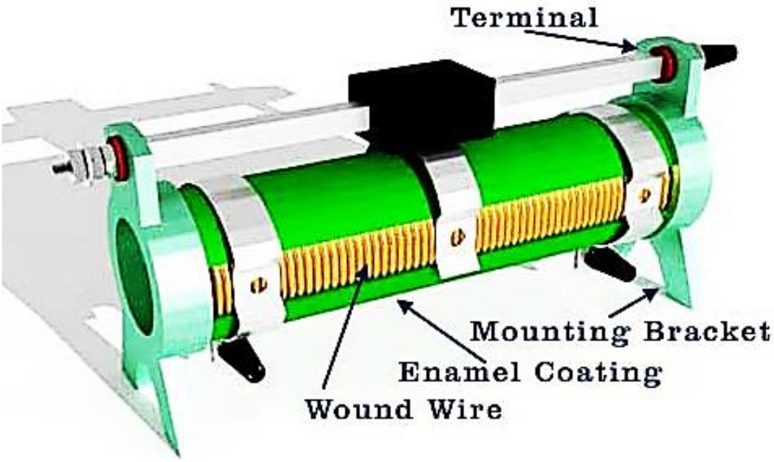


Figure 6.2: Fixed Wire Wound Resistors

Fixed Resistors (continued)

6-20 Schematic symbols for fixed resistors are shown in Figure 6.3. The Joint Industrial Council (JIC) symbol for a resistor is a rectangle. A zigzag line is the symbol used on the diagrams in electronics.

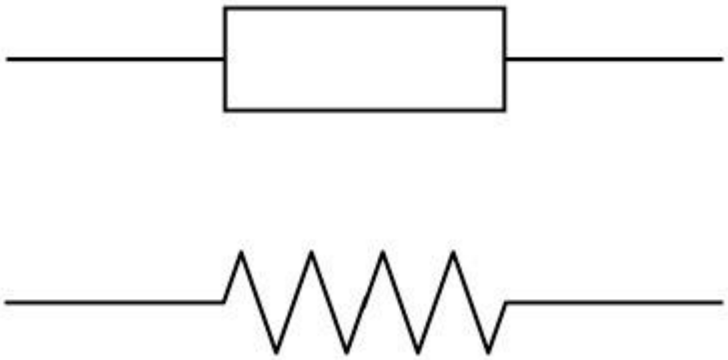


Figure 6.3: Symbols for Resistors

6-21 Fixed resistors are marked to show the value of their resistance. Carbon resistors are generally quite small. They are marked by a special code, consisting of a system of colored rings. Larger wire-wound resistors have numbers stamped on them to show the value of their resistance in ohms.

Resistor Color Code

6-22 The resistor color code is a system of bands painted around the body of a resistor. To read the color code, you start with the band at the *end* and read toward the *center* of the resistor. The meanings of these bands are listed below.

First band: First digit of the resistance value

Second band: Second digit of the resistance value

Third band: Multiplier or the number of zeros that follow the first two digits

Fourth band: Tolerance in the resistance value

6-23 It is impossible to manufacture millions of resistors at low cost and have their resistance values all turn out identical. But the resistance values can be maintained within certain upper and lower limits. This tolerance may be wide or narrow, depending on the manufacturing methods.

6-24 If the fourth color band is missing, it means the measured value of the resistance is within 20 percent of the marked value. For example, a resistor marked 1000Ω would have a measured value of IOOOΩ ± 200Ω, which is 800 - 1200Ω.

Resistor Color Code (continued)

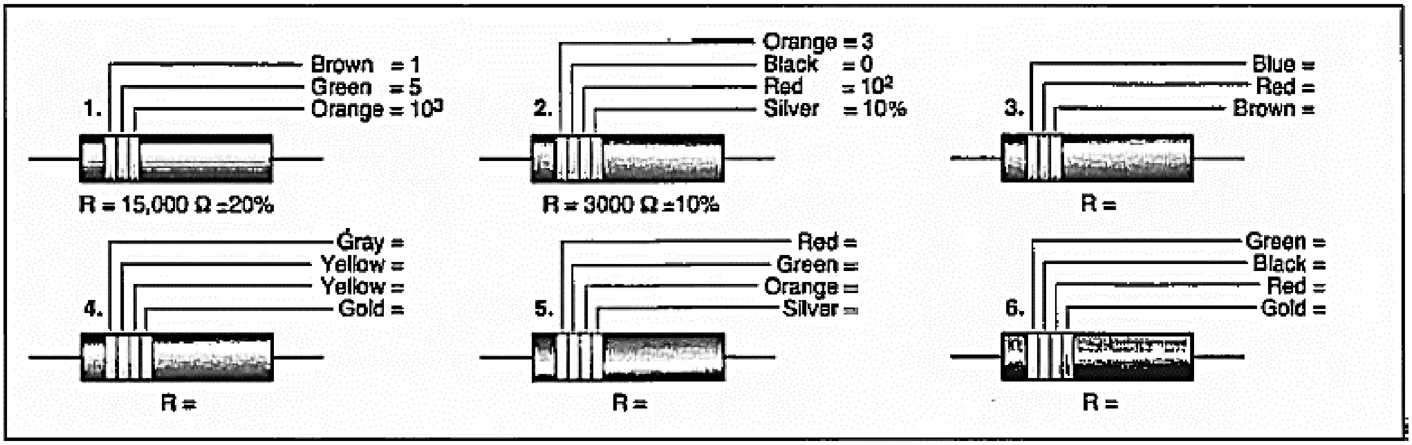
6-25 If the resistor has a fourth band that is *silver*, the tolerance is ten percent. A *gold* band indicates the tolerance is five percent.

6-26 Table 6-1 lists the color bands and their meaning. You should memorize this table. To check your memory, figure out the resistance values of the resistors shown in figure 6.4. the first two examples have been done for you.

6-27 In the remaining four cases, figure out what each color band means and then write the resistance values in the spaces provided. Make sure you include the tolerance for each value. Then check your answers against the values provided on the following page.

Table 6-1: Resistor Color Code

Color	**First Band** (First Digit)	**Second Band** (Second Digit)	**Third Band** (Multiplier)	**Fourth Band** (Tolerance)
Black	0	0	$10^0 = 1$	
Brown	1	1	$10^1 = 10$	
Red	2	2	$10^2 = 100$	
Orange	3	3	$10^3 = 1000$	
Yellow	4	4	$10^4 = 10,000$	
Green	5	5	$10^5 = 100,000$	
Blue	6	6	$10^6 = 1,000,000$	
Violet	7	7	$10^7 = 10,000,000$	
Gray	8	8		
White	9	9		
Gold			$10^{-1} = 0.1$	± 5%
Silver			$10^{-2} = 0.01$	± 10%
(None)				± 20%



Resistor Color Code (continued)

3. Blue = 6
Red = 2
Brown = 10^1

R = 620Ω ± 20%

4. Gray = 8
Yellow = 4
Yellow = 10^4
Gold = 5

R = 840,000Ω ± 5%

5. Red = 2
Green = 5
Orange = 10^3
Silver = 10%

R = 25,000Ω ± 10%

6. Green = 5
Black = 0
Red = 10^2
Gold = 5%

R = 5000Ω ± 5%

Resistor Power Rating

6-28 When choosing a resistor for a given purpose, you must consider two factors.

- The required resistance
- The amount of power the resistor will be required to carry

6-29 The current passing through a resistor produces heat. The rate at which heat is produced depends on the *current* and on the *potential difference* across the resistor. The higher the product of these two values, the faster heat is produced. The rate of heat production is called **power**. It is measured in watts.

6-30 Typical power ratings for carbon resistors are ¼ watt, ½ watt, 1 watt, and 2 watts. The greater the power rating, the larger the size of the resistor, as shown in Figure 6.1 on page 100.

6-31 Resistors in motor circuits carry large currents, especially during starting. The high current produces heat at a very high rate. The power rating of such a resistor must therefore be quite high— 1000 watts or more.

6-32 These high-power resistors are made of cast iron or punched steel sheets. They are sometimes called *grids*, because of the way they are assembled. Grid-type resistors are used in controlling the speed of large dc motors. An example of this type of resistor is shown in Figure 6.5.

Figure 6.5: Grid Resistor

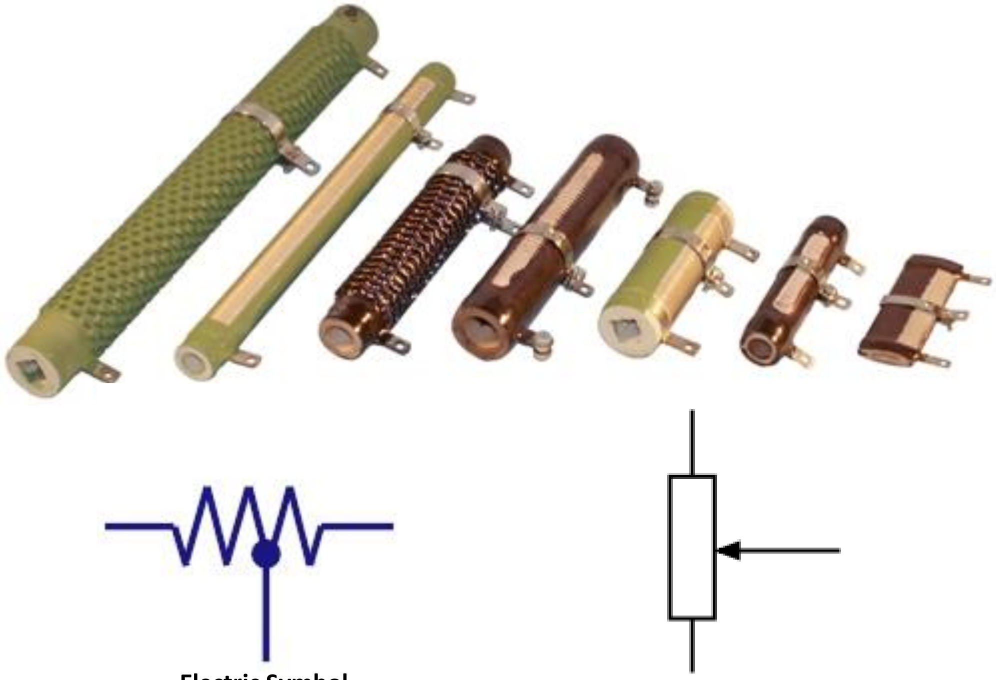
6-33 Grid-resistor elements are made of cast iron or a similar alloy of uniform thickness. Individual elements are assembled on metal tie rods. The elements are insulated from the tie rods by mica. The grids are securely supported for protection against mechanical stresses.

6-34 Grid sections are connected to form an electrical path. The grid construction also serves to dissipate heat very efficiently. These resistors usually have low resistance and carry high currents. They sometimes become red hot in operation.

Tapped Resistors

6-35 Fixed resistors sometimes have one or more connections, called **taps**, between the ends of the resistance material. Most tapped resistors consist of resistance wire wrapped around a ceramic core. There is a separate terminal attached to the resistance wire for each tap.

6-36 On some units, a section of the resistance wire is exposed all along one side of the resistor. A sliding lug can be set to make contact with the wire at any of the exposed points. Figure 6.6 shows several sizes of these adjustable tapped resistors.



Electric Symbol **JIC Symbol**

Figure 6.6: Adjustable Tapped Resistors

6-37 Figure 6.6 also shows the symbols for tapped resistors. The zigzag line appears mostly on the schematics for electronic equipment. The rectangle is the standard JIC symbol used on machine tool wiring diagrams.

Variable Resistors

6-38 Often it is necessary to be able to vary the resistance in an electrical circuit in order to get the desired output from the equipment. Variable resistors have a movable contact mounted on a shaft, a slide, or some other control mechanism. You can operate the mechanism to vary the resistance of the device.

6-39 The volume control on a radio and a variable-speed control on a portable electric drill are common examples of variable resistors. The volume control is called a *potentiometer*, or sometimes simply a "pot." The variable resistor in the speed control of the drill is called a *rheostat*.

6-40 Potentiometers and rheostats are similar in construction. The resistance element is usually arranged in a circular arc, making a circular component like the ones shown in Figure 6.7. But sometimes the resistance element is in a straight line. A sliding contact changes the resistance between the contact and the end of the element.

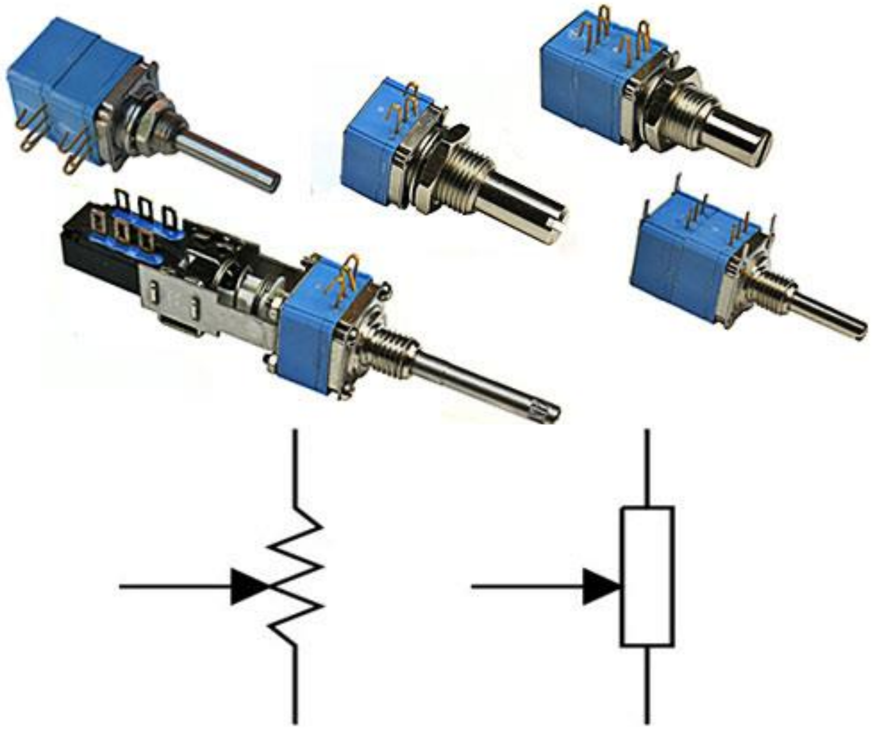


Figure 6.7: Potentiometers

6-41 Rheostats are usually wire-wound. Potentiometers can have either wire or carbon resistive elements. Both devices have *three* terminals. One at each end of the resistance element, and one for the sliding contact. The two devices differ in their resistance and in the way they are connected in a circuit.

Variable Resistors (continued)

6-42 A potentiometer has high resistance. Usually on the order of 10,000 - 50,000Ω. A rheostat has much lower resistance. The potentiometer is usually quite small. About as big as a quarter or a half-dollar. You can easily hold one in the palm of your hand. A rheostat may be quite large, as shown in Figure 6.8.

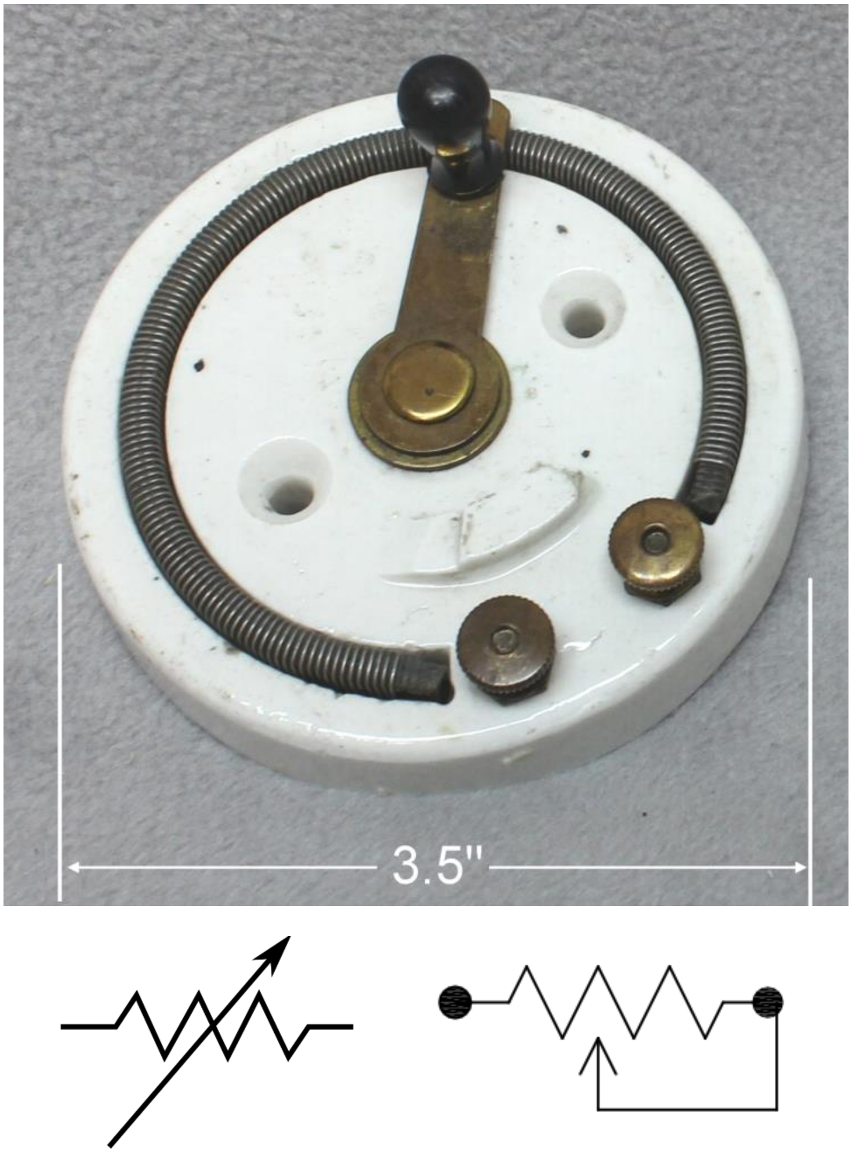


Figure 6.8: Rheostat

6-43 A potentiometer conducts very little current. Its purpose is to divide a fixed potential difference into two parts. The fixed potential difference is applied across the end-terminals of the device. As you move the sliding contact, the potential difference *increases* between one end-terminal and the sliding contact. It *decreases* between the other end-terminal and the contact.

6-44 The purpose of a rheostat is to vary the amount of current passing through it. Normally, one end-terminal is left unconnected. When you adjust the rheostat, you vary the resistance between the sliding contact and the other and terminal. Therefore, you vary the amount of current passing through the rheostat.

Variable Resistors (continued)

6-45 Potentiometers and rheostats are rated according to the amount of power they can handle. Potentiometers with carbon resistive elements have power ratings of ½ - 2 watts. Rheostats with wire-wound resistive elements can handle power in the range of 5 - 1000 watts.

Capacitors

6-46 A **capacitor** is a device that can store electrical charge. It is also sometimes called a *condenser*. It consists of two conducting surfaces separated by insulation. The insulation is called a *dielectric*. Figure 6.9 shows the basic construction of a capacitor.

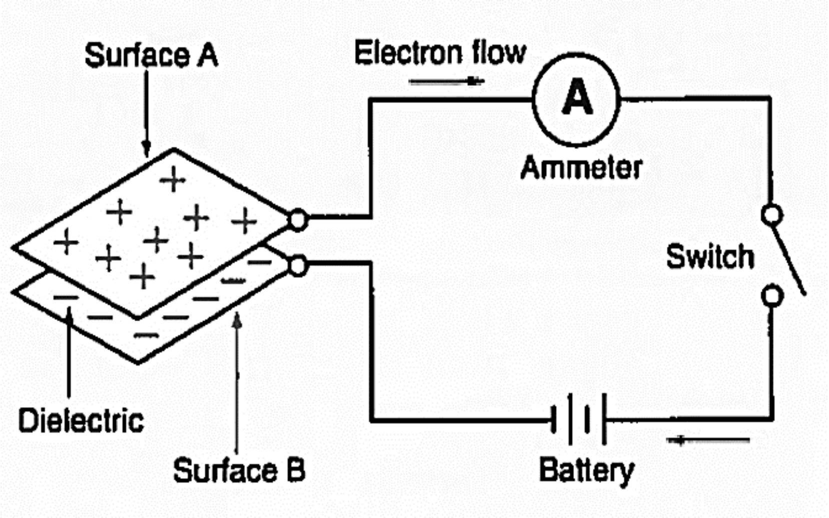


Figure 6.9: Basic Construction of a Capacitor

6-47 When connected to a battery or to another dc source, one conducting surface acquires a positive charge, and the other acquires an equal negative charge. The dc source acts like an "electron pump." It removes electrons from one surface, giving it a positive charge. It delivers an equal number of electrons to the other surface, giving it a negative charge. The electrons cannot flow from one surface to the other inside the capacitor, because the dielectric will not conduct them.

6-48 When the switch is first closed, there is a momentary surge of electrons flowing *off* the positive plate. There is an equal surge of electrons flowing *onto* the negative plate. An ammeter shows that current flows immediately after the switch is closed, and then decreases to zero.

6-49 When a capacitor begins charging, it behaves as though the electrical path were complete inside. But when the potential difference between the terminals of the capacitor equals the potential difference between the terminals of the dc source, the current stops. At this point, no more current can flow to or from the capacitor.

Capacitors (continued)

6-50 After the terminals of the capacitor are disconnected from the dc source, the charge may remain on the two conducting surfaces for several minutes, an hour, or even longer.

6-51 If you are working on a machine that includes a capacitor charged at a high potential difference, you may be in danger of receiving a serious electric shock from it. You can discharge the capacitor by shorting the terminals with an insulated wire or with a screwdriver with an insulated handle. Electrons will then flow from one surface to the other until both surfaces are electrically neutral.

Capacitance

6-52 Just as *resistance* is the ability of a resistor to resist the flow of electric current, **capacitance** is the ability of a capacitor to store electric charge. *Capacitance* is the amount of charge a capacitor can store compared to the potential difference between its terminals.

6-53 In order to calculate capacitance, you divide the stored charge (measured in *coulombs*) by the potential difference between the terminals (measured in *volts*). A capacitance of one coulomb per volt is called one **farad**, abbreviated F. This unit is named for Michael Faraday, an English scientist who made important discoveries about the nature of electricity during the 1800s.

6-54 The farad is too large a unit for practical applications. A smaller unit, the *microfarad*, is used in measuring capacitance in both electrical and electronics applications. The prefix *micro-* means *one-millionth*. A microfarad is one-millionth of a farad. It is abbreviated μF.

6-55 The *micro-microfarad*, also called the **picofarad**, is a smaller unit used mostly in electronics. A *picofarad* is one-millionth of a microfarad. It is abbreviated pF or μμF.

6-56 Capacitance is determined by the area of the conductive surfaces inside the capacitor and by the spacing between the surfaces. The larger the area of the surfaces, and the closer together they are, the higher the capacitance.

6-57 Capacitance also depends on what kind of dielectric material is placed between the conducting surfaces. The capacitance is lowest when the dielectric is air. Substituting other insulating materials for air greatly increases the capacitance.

6-58 The ratio of capacitance with a given dielectric material to the capacitance of the same capacitor with air as the dielectric is called the *dielectric constant* of the given material. The dielectric constant of air is one, because of this definition. If the air in a capacitor is replaced by a sheet of glass, the capacitance is multiplied by 7.5. Therefore, the dielectric constant of glass is said to be 7.5.

Types of Capacitors

6-59 Capacitors used in electrical and electronic circuits differ considerably in physical size, construction, and capacitance. Several common shapes are shown in Figure 6.10.

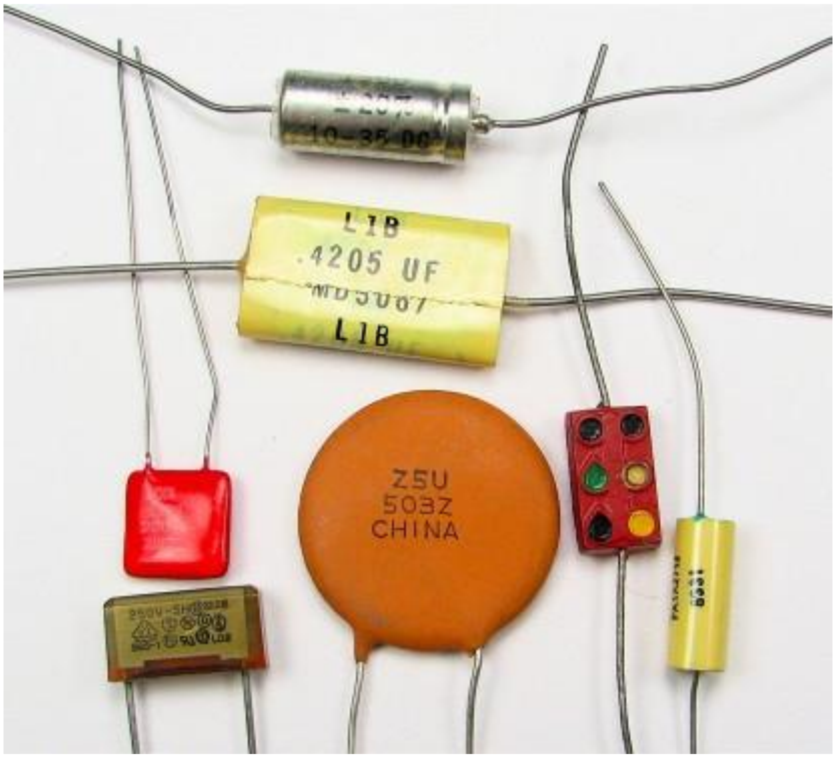


Figure 6.10: Common Capacitor Types

6-60 A *fixed* capacitor has a constant value of capacitance. It may be made of metal plates separated by air, but most fixed capacitors are made of metal foil separated by a solid or liquid dielectric. With this "sandwich" construction, a high capacitance can be obtained in a small unit. The most commonly-used solid dielectrics are paper, ceramic, mica, and plastic. The liquid dielectric is either mineral oil or a synthetic material.

6-61 An electrolytic capacitor has plates made of aluminum foil, and a moist, conducting chemical paste between them. The dielectric is a thin film that forms on one plate when a potential difference is applied across the plates. The capacitance of an electrolytic capacitor is very high for a given plate area.

6-62 A variable capacitor is usually made with air as the dielectric. One set of metal plates, called the rotor, can rotate on a shaft. The plates of the rotor mesh with a set of stationary plates, called the stator. The capacitance is varied by turning the rotor to vary the overlap of the plates on the rotor and stator.

Types of Capacitors (continued)

6-63 Two variable capacitors are often mounted on the same structure so that they will always work together. This device is called a ganged variable capacitor. The symbols for single and ganged variable capacitors are shown in Fig. 6.11.

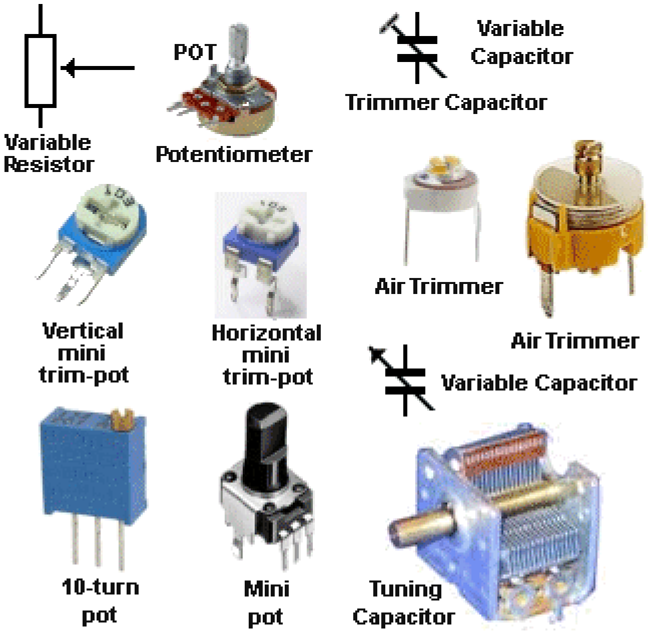


Figure 6.11: Variable Capacitors

6-64 When a potential difference is applied across the plates of a capacitor, the plates apply compression forces to the dielectric. These forces come from the attraction between the oppositely charged plates.

6-65 If the potential difference between the plates gets too high, electrons can "punch through" the dielectric, breaking it down and providing a path for electrons to flow easily between the plates. This path remains even after the potential difference is reduced to its normal level. The capacitor is therefore permanently damaged. The potential difference required for this kind of breakdown is called the **breakdown voltage**.

6-66 The maximum potential difference that can be applied to a capacitor without damaging it is usually printed on the capacitor. Exceeding this value can destroy the capacitor. Once dielectric breakdown occurs, most capacitors are useless. However, some electrolytic capacitors can "heal" themselves if the breakdown is not severe. The electrolytic reforms the damaged insulation.

Connecting Capacitors

6-67 Capacitors are connected in a circuit either in parallel or in series.

- When capacitors are connected in *parallel*, as shown at the left in Figure 6.12, their combined capacitance equals the sum of the capacitances of all the individual capacitors.
- When capacitors are connected in *series*, as shown at the right in Figure 6.12, their combined capacitance is less than that of the lowest-value capacitor in the group.

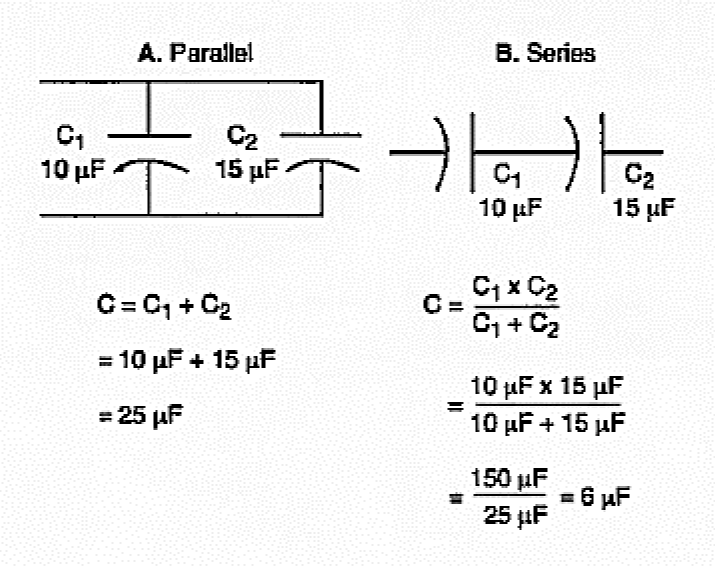


Figure 6.12: Connecting Capacitors

6-68 Capacitors are connected in parallel to achieve higher capacitance than is available in one unit. The potential difference applied to a group must not exceed the lowest breakdown voltage for all the capacitors in the group.

6-69 For example, suppose three capacitors are connected in parallel. Two have a breakdown voltage of 450 volts, and one has a breakdown voltage of 300 volts. The maximum potential difference you can apply to the group without damaging any capacitor is 300 volts.

6-70 One reason capacitors are connected in series is to reduce the total capacitance in the circuit. Another reason is that two or more capacitors in series can withstand a higher potential difference than any individual capacitor can withstand.

6-71 For example, two identical capacitors with breakdown voltages of 450 volts can withstand up to 900 volts when they are connected in series. In this case, the potential difference is divided equally because the capacitances are equal.

6-72 The potential difference does not divide equally if the capacitances are unequal. If the capacitances are unequal, you must be careful not to exceed the breakdown voltage of any capacitor.

Induction

6-73 *Induction* is a magnetic effect that occurs when the current changes in a coil of wire. The changing current produces a changing magnetic field around the coil. The changing magnetic field *opposes* the change in the current.

6-74 The coil acts like a resistor while the magnetic field is building up. When the magnetic field is disappearing, the coil acts like a power source. While the current remains steady, the coil does not interfere with the flow of electricity. It affects the current only while the magnetic field is changing.

6-75 The magnetic field does not appear instantly when current starts flowing in the coil. It takes time to build up. Likewise, when the current stops, the field does not disappear instantly. It takes a certain amount of time to disappear.

6-76 As the field disappears, it develops a potential difference between the ends of the coil. If the field disappears very rapidly, this potential difference may be very high—high enough to cause a large spark in the coil or in the switch controlling the current. As soon as the field disappears, this potential difference disappears.

Mutual Induction

6-77 The magnetic field produced by one coil or conductor can create a current or a potential difference in another coil or conductor. This effect is called **mutual induction**. The direction of the current in the second coil is opposite the direction of the current in the first coil.

6-78 Figure 6.13 shows a simple example of mutual induction. A loop of wire is connected to battery through a switch. While the switch is open, no current flows in the loop, and there is no magnetic field. When the switch closes, the loop begins to carry a current, and this current creates a magnetic field.

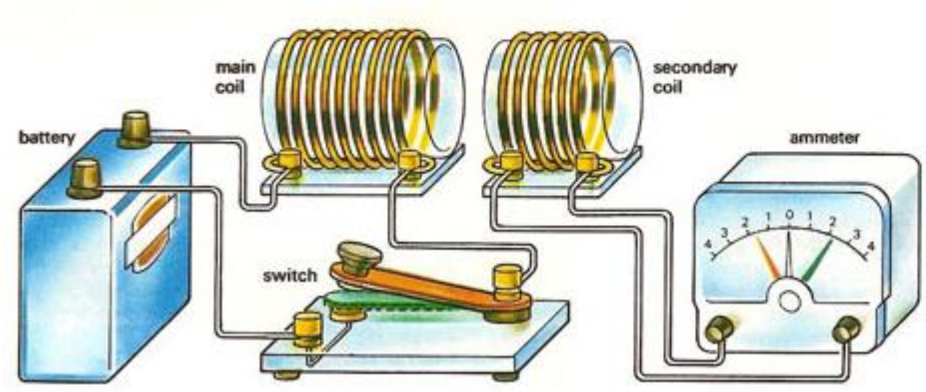


Figure 6.13: Mutual Induction

Mutual Induction (continued)

6-79 As the magnetic field builds up, its strength changes from zero to a maximum value. This changing field produces a current in the lowest loop. If the lower loop were not closed, the magnetic field would produce a potential difference between the ends of the wire. After the magnetic field reaches its maximum value, it no longer produces either a current or a potential difference in the lower loop.

6-80 When the switch in the circuit of Figure 6.13 is opened, current stops flowing in the upper loop. The magnetic field then changes in strength from its maximum value to zero. This change produces the reverse effects in the lower loop.

Inductance

6-81 The measurement of induction is called inductance. The unit of inductance is the **henry**, named for the American scientist Joseph Henry. Henry made electrical discoveries similar to those of Faraday in England at almost the same time. One *henry* is defined as the inductance that produces a potential difference of one volt in an open circuit when the current changes in the other circuit at the rate of one ampere per second. The symbol for the henry is *H*.

6-82 The henry is too large a unit for measuring inductance in most circuits. Smaller units are usually used instead, especially the millihenry (mH, one thousandth of a henry) and the microhenry (µH, one millionth of a henry).

6-83 Inductance is not as important in dc circuits as it is in ac circuits. A coil in a dc circuit opposes current flow only when the current changes. For example, when it *starts* flowing and when it *stops* flowing. In an AC circuit, the current is continually changing. Therefore, the coil opposes the flow of current continually.

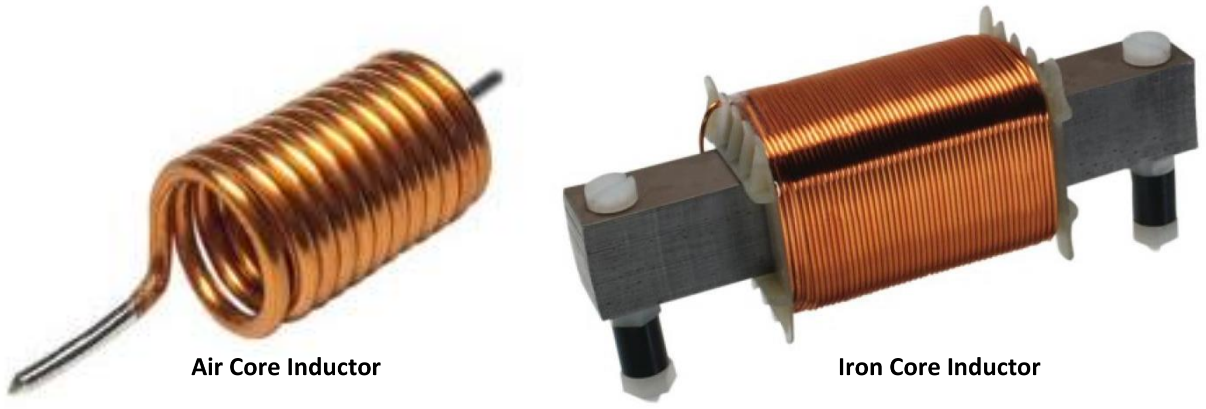
6-84 A coil or a capacitor in an ac circuit acts like a resistor, but without producing the heat a resistor would produce. This kind of opposition to the flow of alternating current is called *reactance*. When caused by a capacitor, it is called *capacitive reactance*. When caused by a coil, it is called *inductive reactance*.

6-85 The unit for measuring reactance is the same as the unit for resistance, the *ohm*. But reactance cannot be measured with an ohmmeter, because the ohmmeter applies *direct* current to the circuit rather than *alternating* current. Therefore, capacitors and coils do not resist the current, except when you first connect the ohmmeter.

Inductors

6-86 An *inductor* is an electrical component that opposes any change in the current flowing in a circuit. The inductor *resists* the current when the current increases, and it *aids* the current when the current decreases.

6-87 An inductor is made by winding wire around a "core." The core may be made of either a *magnetic* material or a *nonmagnetic* material. Most conductors have cores of iron, but some have an "air core." The wire in an air core inductor is wound around a tube of paper or plastic. Figure 6.14 shows both kinds of inductors and their symbols.



Air Core Inductor

Iron Core Inductor

Figure 6.14: Inductors

6-88 An inductor is often called a *choke* or a *coil*. The name "choke" is based on the specific effect of the inductor in certain circuits. The name "coil" comes from the construction of the conductor.

Solenoids and Relays

6-89 Solenoids and relays are electromagnetic coils used as *transducers*. A **transducer** is a device that uses one kind of effect to produce another kind of effect. For example, the solenoid uses an *electromagnetic* effect to produce a *mechanical* effect.

6-90 A **solenoid** is a coil of wire with a movable magnetic core. When current flows through the coil, the magnetic field pulls the core into the coil. When the current stops, a spring pulls the core back out of the coil. The core can operate a valve or some other mechanical device.

6-91 A **relay** is a switch that operates by electricity. It consists of a magnetic armature mounted over the core of an electromagnet, as shown in Figure 6.15. When current flows through the electromagnet, it pulls the armature down, opening the normally-closed (NC) contacts and closing the normally-open (NO) contacts. When the current stops flowing through the coil, a spring returns the armature to its original position.

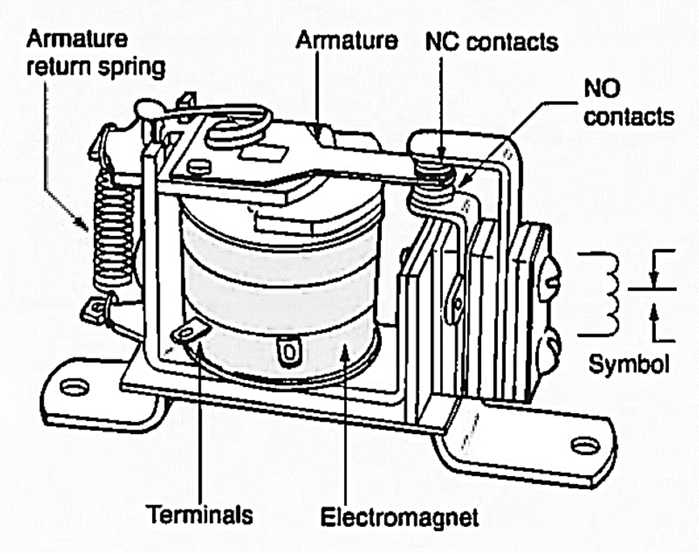


Figure 6.14: Relay

6-92 A relay can provide switching control for machinery and other equipment from a remote location. The relay provides safety for the operator, because it usually operates at a low potential difference. For example, a relay coil operating on 6 volts can control a 240-volt motor.

Chapter 6 Exercise

Circle the appropriate letter next to the correct answer.

1. Which of the following resistors can NOT be adjusted to change the resistance?

   a. Fixed resistor
   b. Variable resistor
   c. Potentiometer
   d. Rheostat

2. If a resistor is marked with only three color bands, what is the tolerance of the resistor?

   a. 5 percent
   b. 10 percent
   c. 20 percent
   d. 30 percent

3. Dividing a potential difference into two parts is the purpose of a high-resistance device called a _____________.

   a. Rheostat
   b. Tapped resistor
   c. Fixed resistor
   d. Potentiometer

4. The insulation in a capacitor is called a(n) __________________.

   a. Condenser
   b. Farad
   c. Dielectric
   d. Electrolyte

5. Capacitance is determined in part by the area of the __________________ inside the capacitor.

   a. Dielectric
   b. Insulation
   c. Conductive surfaces
   d. Taps

Chapter 6 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. Two variable capacitors that work together make up a ____________________.

   a. Rotor
   b. Stator
   c. Variable capacitor
   d. Ganged capacitor

7. To achieve higher capacitance than is available in one capacitor, two capacitors can be connected in _________.

   a. Series
   b. Parallel
   c. A gang
   d. A column

8. The magnetic effect that occurs when the current changes in a coil of wire is called _______________________.

   a. Induction
   b. Reactance
   c. Capacitance
   d. Power

9. An electrical component that opposes any change in the current is called a(n) ________________________.

   a. Resistor
   b. Capacitor
   c. Inductor
   d. Transducer

10. A device that uses one kind of effect to produce another kind of effect is called a(n) ___________________.

   a. Capacitor
   b. Inductor
   c. Resistor
   d. Transducer

Summary

The ease or difficulty with which electric current flows is determined by the number of free electrons in the material the current must flow through. Materials having few free electrons are called resistors. Materials with many free electrons are called conductors.

The simplest type of resistor is the fixed resistor. Its resistance value cannot be changed. Variable resistors allow the resistance value to change as needed.

A capacitor is an electrical component that can store a charge. The ability to store a charge is called capacitance. Capacitance is measured in units called farads. Types of capacitors include fixed, electrolytic, and variable.

When the current changes in a coil of wire, a magnetic effect called induction is produced. The measurement of induction is called inductance, and is measured in units called henrys.

Other components that alter electric current include solenoids and relays. They are devices that use one kind of effect to produce another kind of effect.

Chapter 7: Conductors

In This Chapter

Conductors and Insulators

Conductors

Conductor Sizes

Conductor Classification

Insulation Properties

Insulating Tape

Protecting Conductors

Flexible Conduit

Conduit Fill

Splicing Conductors

Terminology

Conductor: A material having many free electrons, able to carry an electric current

Insulator: A material having few free electrons

Dielectric: An insulating material

Gauge Number: A measure of wire diameter

Dielectric Strength: Potential difference a layer of insulation can withstand without breaking down

Raceway: An enclosed channel designed for holding conductors

Ampacity: Current-carrying capacity of a conductor

All electrical devices are made up of materials that conduct and resist the flow of electrons. The trainee must be familiar with these materials.

When you work with conductors, you must know how to determine conductor size. In this Lesson, we explain the basic units of conductor measurement.

Electrical devices are often insulated with tape. You should be familiar with the different tapes and their uses.

You may need to protect the conductors in your plant. This Lesson explains how to do so as well as the materials and tools to use. It also describes special tools used in stripping insulation, and explains how to splice wires.

Conductor and Insulators

7-1 A material that contains many free electrons is capable of carrying an electric current and is called a **conductor**. *Free electrons* are electrons that are not tightly bound to the atoms of the material. These electrons make up the electric current in metal wires, transistors, microprocessors, and all other kinds of devices that depend on the flow of electricity.

7-2 Some materials are better conductors of electricity than others. The more free electrons a material has, the better it will conduct. In good conductors, there is a *weak* attraction between the *positive* charge of the nucleus in each atom and the *negative* charge of the outer electrons surrounding the nucleus. Silver, copper, aluminum, and most other metals are good conductors, because they contain many free electrons.

7-3 A material that has only a few free electrons is called an **insulator**. In an insulator, there is a strong attraction between the positive charge of the nucleus and the negative charge of the outer electrons. Wood, rubber, porcelain, clay, and other nonmetallic materials are good insulators, because they have very few free electrons.

7-4 Materials that conduct electricity easily such as copper or aluminum, make up the main *conducting* parts of electrical equipment. But the equipment requires *nonconducting* materials as well. These nonconducting materials are called **dielectrics** as well as *insulators*.

7-5 Dielectrics prevent electricity from flowing where it should not flow. In this way, they help ensure the proper operation of electrical circuits, and they minimize the electrical hazards of motors and other equipment.

Conductors

7-6 The use of conductors and their insulation is regulated mainly by the *National Electrical Code* (NEC). The NEC consists of a book of regulations listing the minimum safety precautions needed to safeguard people, buildings, and materials from the hazards of using electricity.

7-7 The NEC covers the electrical conductors and equipment serving public and private buildings and industrial plants. It also covers the conductors that connect buildings and equipment to a source of electricity. Installing and maintaining equipment in compliance with the NEC will result in installations that are generally free of electrical hazards.

Conductors (continued)

7-8 Wires and cables are the most common forms of conductors. They carry electric current through all kinds of circuits and systems. Wires and cables are made in a wide variety of forms suited to many different applications. Figure 7.1 shows some of the differences among wires and cables.

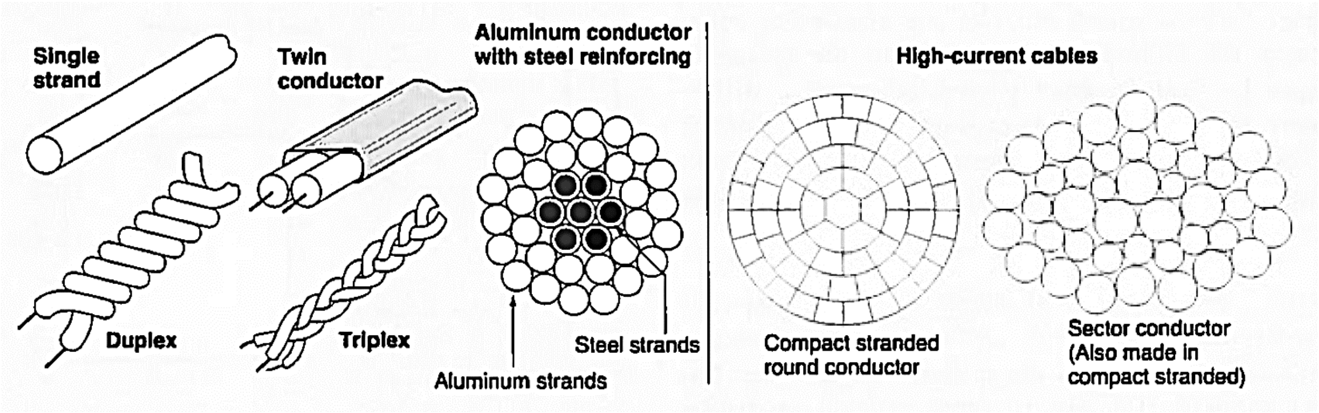


Figure 7.1: Wires and Cables

7-9 Conductors form an unbroken line carrying electricity from the generating plant to the point where it is used. The conductors are usually copper. The NEC defines a *conductor* as "a wire or cable or other form of metal suitable for carrying current."

7-10 All wires are conductors, but not all conductors are wires. Copper *busbars*, for example, are conductors but not wires. They are rigid rectangular bars rather than flexible wires.

7-11 The current passing through a conductor generates heat. The rate at which heat is generated depends on the amount of current in the conductor and on the potential difference between its ends. To calculate the rate of heat production (in watts), you multiply the current (in amperes) by the potential difference (in volts).

7-12 The potential difference in turn depends on the current through the conductor and on the resistance from end to end. The greater the resistance, the greater the potential difference and the faster heat is produced. The rate of heat production in the conductor equals the amount of power lost by the electricity in passing through the conductor.

7-13 A conductor must have a *large* enough cross-sectional area to give it a low resistance. But the cross-sectional area must also be *small* enough to keep the cost and the weight of the conductor as low as possible. For every conductor, there is a balance point between these two opposing goals.

7-14 The best cross-sectional area depends in part on how much current the conductor must carry. If it must carry a large current, the resistance must be small in order to keep the potential difference and the power loss as small as possible. If the current is small, the resistance can be higher without increasing the potential difference or the loss in power.

Conductors (continued)

7-15 Every electrical device operates most efficiently when the potential difference between its terminals is the amount the device was designed for. For example, if an electric motor runs on a potential difference below its design rating, its efficiency drops.

7-16 The rate of heat production in a conductor increases with the *square* of the current. As heat is produced, the conductor gets hotter. As it does so, it releases heat to the surroundings at a faster rate.

7-17 The temperature rises until the rate at which the conductor releases heat to the surroundings matches the rate at which heat is produced within the conductor. The temperature of the conductor then remains steady. This steady temperature is called the *equilibrium temperature*.

7-18 There is a limit to the temperature each kind of insulation can safely withstand. There is also a limit to the temperature the surroundings can withstand. Even a bare wire must not be allowed to get hot enough to cause a fire in the surrounding materials. The NEC specifies the maximum current considered safe for conductors of different *sizes*, having different *insulations*, and installed in different *surroundings*.

Conductor Sizes

7-19 To understand the different sizes of conductors, you must first understand the system for numbering these sizes. The basic unit is the **mil**. A *mil* is one thousandth (0.001) of an inch. A **circular mil** (abbreviated *cir mil*) is the area of a circle one mil in diameter.

7-20 For example, a wire measuring one mill (0.001 in.) in diameter has a cross-sectional area of one circular mil. The drawing on the left in Figure 7.2 shows the relationship between a mil and a circular mil.

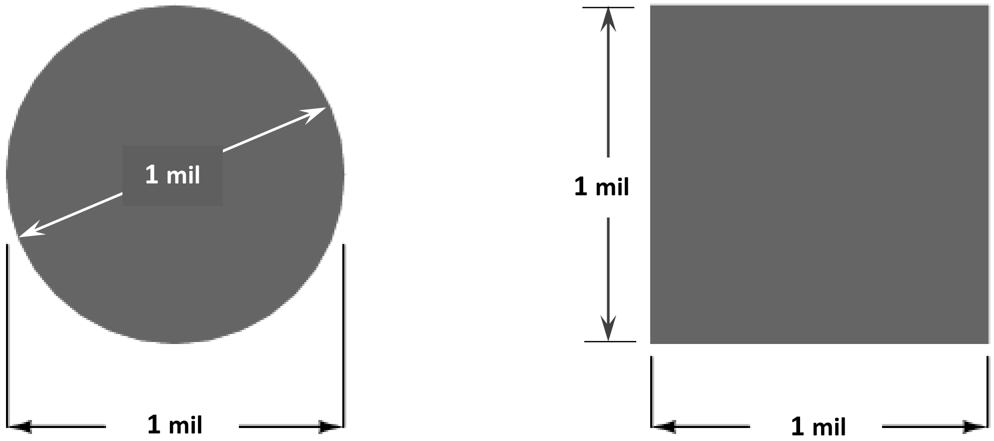


Figure 7.2: Conductor Measurements

7-21 The circular mil is the standard unit of wire cross-sectional area used in American and English wire tables. The diameter of a round wire is only a small fraction of an inch. By expressing these diameters in mils, you can avoid using decimals.

Conductor Sizes (continued)

7-22 For example, the diameter of a wire can be expressed as 25 mils instead of 0.025 in. The cross-sectional area in circular mils of a round conductor equals the *square* of the diameter measured in mils. Thus a wire with a diameter of 25 mils has a cross-sectional area of 625 cir mil, because 25 x 25 = 625.

7-23 The *square mil* (abbreviated *sq mil*) is a convenient unit for measuring the cross-sectional area of square and rectangular conductors. A **square mil** is defined as the area of a square measuring one mil on each side. The drawing at the right in Figure 7.2 shows the relationship between a mil and a square mil.

7-24 To calculate a cross-sectional area in square mils, you multiply the height by the width—both measured in mils. For example, suppose a rectangular busbar measures $^{3}/8$ inch by 4 inch. In decimal form, the thickness is 0.375 in. or 375 mils. The width of 4 in. equals 4000 mils. Therefore, the area is 1,500,000 sq mil, because 375 x 4000 = 1,500,000.

7-25 The resistance of a material *increases* as the length of the conductor increases. The resistance *decreases* as the cross-sectional area of the conductor increases. You can compare a material to others by measuring the resistance of a sample, multiplying by the cross-sectional area, and dividing by the length of the conductor. The result is called the **resistivity** of the material.

$$\text{Resistivity} = \frac{\text{Resistance x Area}}{\text{Length}}$$

7-26 You can measure the resistance in ohms, the cross-sectional area in sq mils or cir mils, and the length in feet. Then the resistivity is in *ohms sq mils per foot*, or in *ohms cir mils per foot*.

7-27 A common measure of wire diameter is the *gauge number*. The gauge commonly used in the United States is the American wire gauge (abbreviated *AWG*). Two typical AWG wire gauges are shown in Figure 7.3. The gauge at the left measures wires ranging in diameter from No. 30 (the smallest) to No. O (the largest). The gauge at the right measures sizes 15-0000.

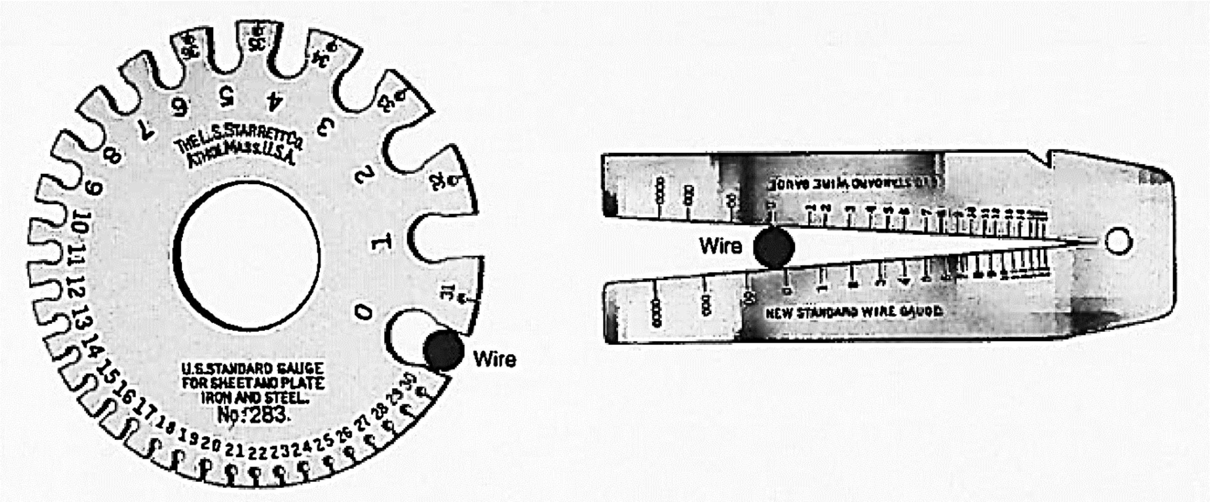


Figure 7.3: Wire Gauges

Conductor Sizes (continued)

7-28 To measure the size of a wire with a wire gauge, you fit the bare wire into the smallest opening that will accept it. The number corresponding to that slot tells you the size of the wire.

Conductor Classification

7-29 Wires and cables can be classified according to the kind of covering they have.

- *Bare conductors* have no covering. The most common use of bare conductors is in high voltage electrical transmission lines suspended from towers.

- *Covered conductors* are not insulated. However, they have a covering that provides protection against the weather and against heat from the surroundings. Covered conductors are used for outdoor low-voltage overhead circuits and for exposed interior wiring.

- *Insulated conductors* have a coating of insulation over the metal. The insulation separates the conductor electrically from other conductors and from the surroundings. It allows conductors to be grouped without danger. Additional covering over the insulation adds mechanical strength plus protection against weather, moisture, and abrasion.

- *Stranded conductors* consist of many strands of fine wire, as shown in Figure 7.4. The wires in a stranded conductor are usually twisted together.

- *Cable* consists of two or more conductors inside a single covering. The conductors in the cable may be either bare or insulated. The term "cable" is a general term for any conductor consisting of two or more conductors. In practice, it refers only to large conductors. A small cable is called a cord.

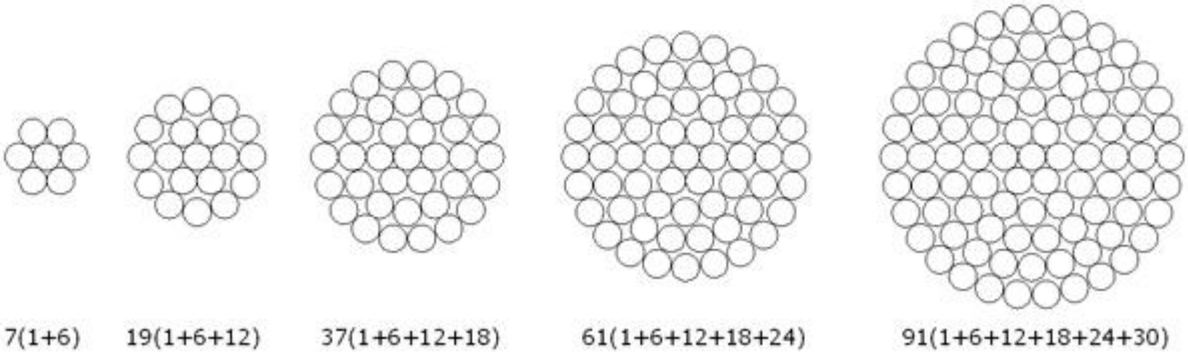


Figure 7.3: Wire Gauges

Insulation Properties

7-30 Two fundamental properties of insulation materials are called *insulation resistance* and *dielectric strength*. They are entirely different from each other, and they are measured in different ways.

7-31 **Insulation resistance** is the electrical resistance of the insulation against the flow of current. The instrument used for measuring insulation resistance is the *megohmmeter*. It measures high resistance values (in millions of ohms, called *megohms*), and it does not damage the insulation in making the measurement.

7-32 To understand the measurement of insulation resistance you need to know only one basic relationship—Ohm's law. Understanding the meaning of this law will help you in all kinds of electrical work. The equation expressing Ohm's law is very simple.

$$E = I \times R$$

where E = Potential difference across a conductor, measured in *volts*
I = Current through the conductor, measured in *amperes*
R = Resistance of the conductor, measured in *ohms*

7-33 The measurement of insulation resistance serves as a guide in evaluating the condition of insulation. However, it may not give a complete picture of the condition of the insulation. Clean, dry insulation may have a high insulation resistance, even if it is cracked and has other faults. Insulation in this condition is not safe to use, because the conductor is exposed wherever there are gaps in the insulation.

7-34 **Dielectric strength** is a measure of how much potential difference the insulation layer can withstand without breaking down. If the potential difference gets high enough, any insulation will fail suddenly and allow a large current to flow. The potential difference that causes breakdown is called the *breakdown voltage* of the insulation.

7-35 Every electrical device, whether it is a motor, generator, cable, switch, or transformer, is protected by some kind of electrical insulation. The insulation should be in good condition. Current must not leak through it slowly, and the material must not suddenly break down and allow a large current to flow.

7-36 With few exceptions, wires and cables used in all interior electrical systems are insulated. The insulating material varies in composition, form, and thickness, according to the needs of each application. The desirable characteristics of electrical insulation include the following.

- High dielectric strength
- Temperature resistance
- Flexibility
- Mechanical strength
- Moisture resistance

7-37 No single insulating material has all the characteristics required for every application. Therefore, many different kinds of insulating materials have been developed. Engineers can select the best combination of materials to provide the proper protection under various conditions of service.

Insulating Tapes

7-38 Various tapes are used for insulating electrical equipment, conductors, and components. Some of these tapes are adhesive. The tapes commonly used include *friction*, *rubber*, and *plastic* tape.

7-39 Rubber tape is made for insulating electrical splices. The tape is applied to the splice under slight tension, so that each layer presses tightly against the one underneath. The pressure causes the layers to bond together in a solid mass.

7-40 Applying rubber tape to a splice restores the *insulation* that was removed. But the outer *protective covering* must be restored with friction tape applied over the rubber tape. Friction tape consists of cotton cloth impregnated with an adhesive. It does not stretch like rubber tape does, and it does not have the insulating qualities of rubber tape. For these reasons, friction tape should not be used alone for insulation.

7-41 Plastic electrical tape is being used more than rubber or friction tape today. The plastic has several advantages over the materials used in other tapes.

- It has high dielectric strength. It can withstand several thousand volts without breaking down.
- It is very thin compared to rubber tape and friction tape. Extra layers add extra protection, but add very little to the size of the splice.
- It can stretch, so it easily conforms to the contour of the splice.

7-42 Varnished-cambric tape is also commonly used in electrical work. This tape is made of cloth impregnated with varnish. It usually has no adhesive coating. The tape is manufactured in sheets and in rolls.

7-43 Varnished-cambric tape is ideal for use on motor connections. Motor leads are disconnected more often than any other kind of electrical connection, because motors burn out, need repair, or are moved more frequently.

7-44 Removing rubber or plastic tape from a motor lead is difficult and time-consuming, because heat from the motor often fuses the tape onto the lead. To eliminate this problem, the motor lead connection is first wrapped with varnished-cambric tape. Then it is wrapped with plastic or friction tape. The varnished-cambric tape does not stick to the lead. You remove it simply by cutting through the layers and laying the tape open.

Protecting Conductors

7-45 Conductors are often installed in places where they need protection from damage. The kind and amount of protection required depends on how and where they are installed, and on how they are used.

7-46 Cables buried in the ground must resist moisture, chemical action, and abrasion. Abrasion is caused by movement of stones, gravel, or other rough materials against the cable.

7-47 Conductors installed in buildings must be protected against mechanical damage as the building is used. Conductors strung on cross arms of poles must have a high tensile strength. They must also be supported well in order to withstand the forces of heavy ice and snow, and of strong winds.

7-48 The best way to protect electrical conductors from physical damage is to enclose them in a solid protective channel. Such a channel is called a **raceway**. The NEC defines a *raceway* as any enclosed channel designed specifically for holding wires, cables, or busbars. A raceway can be made of metal or of an insulating material. It serves several purposes.

- It prevents mechanical damage to the wiring.
- It protects the wiring against harmful chemicals, vapors, and other materials.
- It protects people and property from the hazards

7-49 The most familiar raceway used in industrial plants is *rigid metal conduit*. This kind of conduit provides excellent physical protection for conductors. It also serves as an effective electrical ground for equipment.

7-50 Rigid conduit is a standard type of protection for wiring. It can be used in many different kinds of situations. It is used for concealed wiring in frame buildings and in solid masonry buildings. It provides good protection to exposed wiring subject to damage in hazardous locations.

7-51 Rigid conduit is steel pipe that encloses all wires. Conduit differs in several ways from the pipe used for carrying water, gas, and other materials.

- It is annealed to permit easy bending.
- The inside surface is prepared so the wires can be pulled into it with minimum effort and without damaging the insulation.
- It has a corrosion-resistant finish, usually galvanized, so the installation can be permanent without special care.

7-52 All conduit sizes have the same standard dimensions as the corresponding sizes of steel pipe. The range of external sizes is ½ to 6 inches. Conduit is sold in 10-foot lengths, which are threaded on both ends. A threaded coupling is furnished with each 10-foot length.

7-53 Elbows are made for all diameters of rigid conduit, but most electricians bend the conduit on the job. Small diameters are bent with hand benders and "hickeys." Large diameters are bent with hydraulic machines. Rigid conduit is fastened to junction boxes with locknuts and end-bushings.

Protecting Conductors

7-54 Junction boxes protect wire splices. They are used wherever connections are made to electrical devices. There is little danger of overheating in continuous conductors, but poorly-made splices can cause short circuits, grounds, or overheating. To prevent fires, splices should always be enclosed in a metal junction box. The box also provides ground continuity.

7-55 Another kind of conduit is *electrical metallic tubing*, abbreviated as *EMT*. This conduit is made of thin-walled, semi-rigid metal. The walls are thinner than rigid conduit. The difference is shown in Figure 7.5. EMT has no threads, it is light in weight and easy to handle, and it can be used for both exposed and concealed wiring.

EMT **Rigid Conduit**

Figure 7.5: Metal Conduit

7-56 EMT is not as strong as rigid conduit, and it does not protect wiring as well against mechanical damage or corrosion. *Couplings* are used in joining lengths of EMT. *Connectors* secure EMT to junction boxes. The smallest trade size of EMT is ½ inch internal diameter and the largest is 4 inches.

7-57 EMT is easy to bend with an EMT bender, as shown in Figure 7.6. Using this type of bender, you can make bends and offsets to fit the contours of the building when installing EMT. However, elbows are also available. They are especially useful for installing large-diameter EMT.

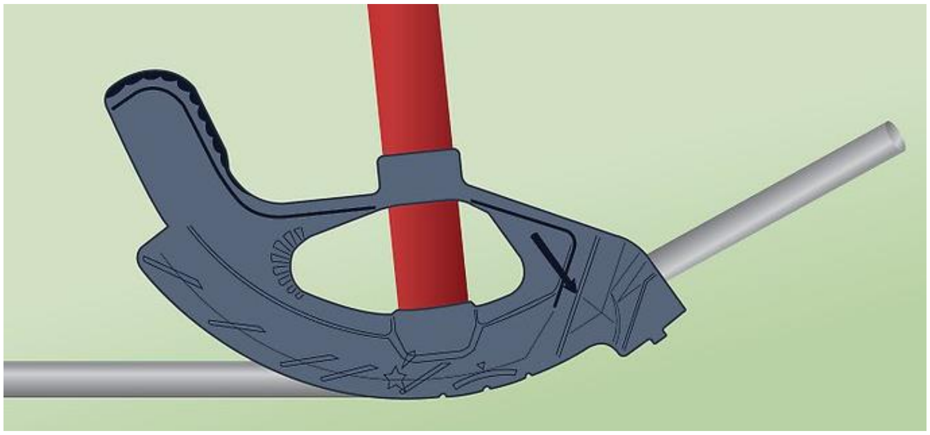


Figure 7.6: Bending EMT

Flexible Conduit

7-58 Flexible conduit, often called *Greenfield conduit*, is used where it is not practical to install either rigid conduit or EMT. This conduit is made of a single strip of galvanized steel. The strip is wound in a spiral upon itself, and interlocked to provide strength and flexibility. Figure 7.7 shows this kind of conduit. Flexible conduit is available in continuous lengths of up to 250 feet.

Figure 7.7: Flexible Conduit

7-59 Flexible metal conduit is better than rigid conduit for runs through spaces that contain obstructions or that require many bends. It is also commonly used instead of rigid conduit for connecting the wiring leading to motors or other vibrating machinery. Flexible conduit absorbs vibrations which would cause noise and also possibly loosen rigid conduit. Flexible conduit also makes it easier to shift a motor slightly.

7-60 Flexible conduit is recommended for temporary wiring where local codes require wiring to be enclosed in metal conduit. It can be used for most locations, except where conditions are wet and hazardous, or would cause deterioration of the conductor insulation.

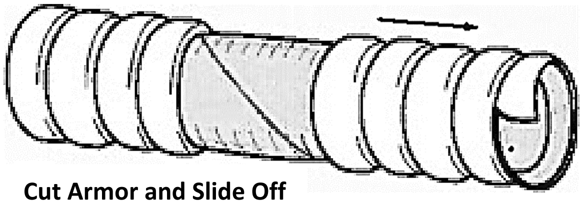
7-61 Liquid-tight, flexible metal conduit, often called by its trade name, Sealtight™, is suitable where oil, water, certain chemicals, and corrosive gases might be present. This conduit has an outer liquid-tight jacket over the flexible armor. It requires special compression connectors to join it to other conduit or to a junction box.

7-62 Armored cable, generally known as **BX**, consists of insulated wire inside a flexible conduit. The armor protects the wire from physical damage. BX is installed in a manner similar to flexible conduit.

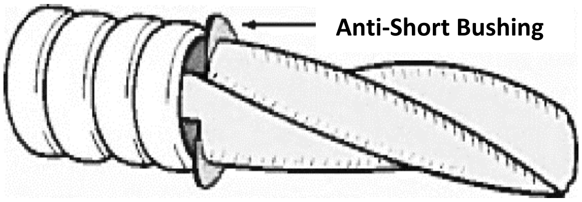
7-63 The armor must be stripped back about eight inches from the end before BX can be attached to a junction box. This is done by cutting through the armor at an angle with a fine-tooth hacksaw blade. You must be careful not to damage the insulation on the wire. The end of the armor is then twisted off.

Flexible Conduit (continued)

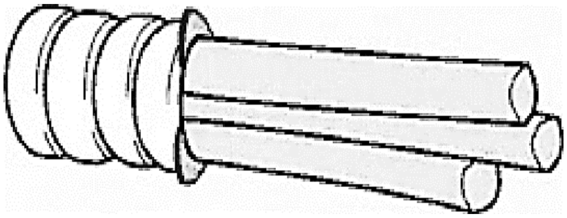
7-64 The sharp edge of the cut armor is covered by a fiber bushing, called an *anti-short* bushing, as shown in Figure 7.8. A special BX connector is then used to grip the end of the armor and allow for a secure connection to a junction box.



Cut Armor and Slide Off



Insert Bushing Between Armor and Conductors



Straighten Conductors and Remove Paper

Figure 7.8: Preparing an End on BX Cable

Conduit Fill

7-65 The number of conductors allowed in a conduit is specified by the NEC. The conduit cannot be filled to more than 40 percent of its cross-sectional area. The number of conductors occupying the conduit depends on the sizes of the conductors and type of insulation. Tables in Lesson 9 of the NEC show the number of conductors for various kinds of wire in various sizes of conduit.

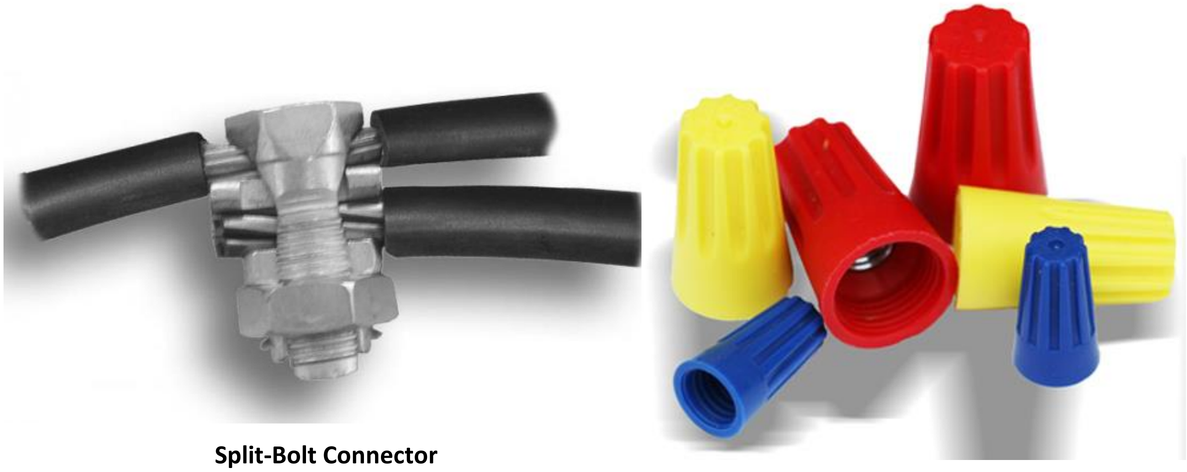
7-66 The NEC also specifies how mixed sizes may be used in a conduit, and how more than three conductors may be used. The current-carrying capacity of a conductor, often called *ampacity*, is specified in other tables in the NEC.

Splicing Conductors

7-67 Before making a splice, always make sure the power is turned off. Then remove the insulation from the end of the conductor to expose the metal. If you use a knife, cut the insulation away in the same way you cut away the wood when you sharpen a pencil with a knife. Be careful not to nick the wire.

7-68 Special insulation strippers are available that will cut through the insulation without nicking the wire. The tool then slides the insulation off the end, exposing the bare wire.

7-69 Wires are often connected with solderless connectors instead of by splicing. These connectors make the job of joining wires quite simple. Large wires that are difficult to twist are joined with *split-bolt* connectors, as shown in Figure 7.9. Smaller wires that are easy to twist together can be joined with *wire nuts*.



Split-Bolt Connector

Wire Nuts

Figure 7.9: Solderless Connectors

7-70 A *pigtail splice*, shown in Figure 7.10, is one of the most common splices. It is used mostly in junction boxes and pull boxes. The ends of the wires are stripped about 1½ - 2 inches and twisted together to make the splice. Sometimes the pigtail is bent over so the ends of the wire will not puncture the tape as it is applied.

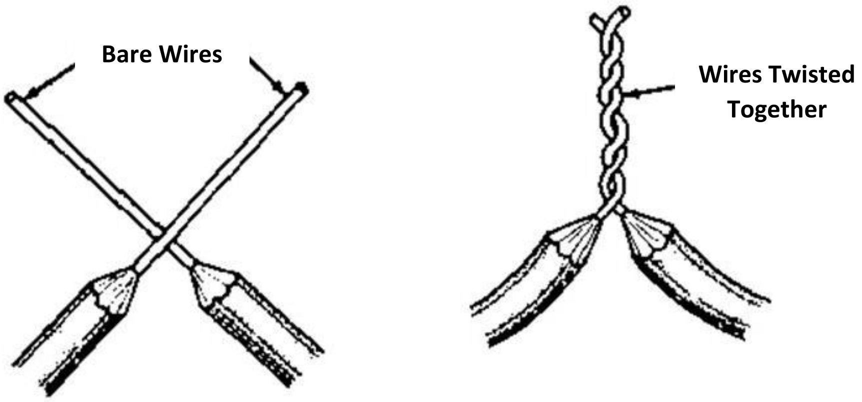


Figure 7.10: Pigtail Splice

Splicing Conductors (continued)

7-71 A lighting fixture can be connected to a branch circuit wire with a *fixture splice*, if the fixture wire is smaller than the branch wire. Start by winding the fixture wire around the branch wire, as shown in Figure 7.11. Then bend the end of the branch wire back, and continue wrapping the fixture wire over the bent branch wire.

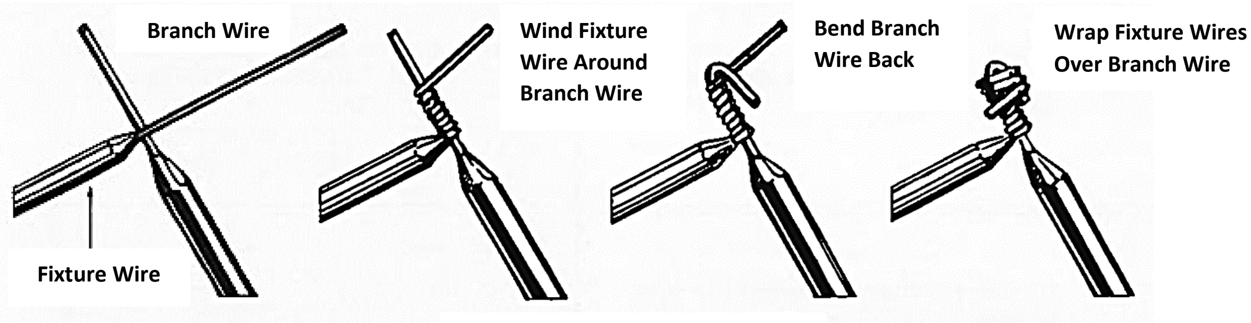


Figure 7.11: Fixture Splice

7-72 When a splice is complete, you should solder it and tape it with plastic tape and friction tape. Soldering adds some strength to the splice, but you should not rely on soldering for mechanical strength. The main purpose of soldering is to make a good electrical contact. A soldered splice will last for many years.

Chapter 7 Exercise

Circle the appropriate letter next to the correct answer.

1. Which of the following materials is NOT a good conductor?

   a. Aluminum
   b. Copper
   c. Porcelain
   d. Silver

2. Which of the following materials is NOT a good insulator?

   a. Clay
   b. Copper
   c. Rubber
   d. Porcelain

3. A wire measuring one mil in diameter has a cross-sectional area of one ____________________.

   a. Inch
   b. mil
   c. circular mil
   d. Square mil

4. The potential difference that causes the breakdown of insulation is called the ___________________.

   a. Breakdown voltage
   b. Dielectric strength
   c. Insulation resistance
   d. Ampacity

5. Which of the following tapes is best for use on motor connections?

   a. Rubber
   b. Friction
   c. Plastic
   d. Varnished-cambric

Chapter 7 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. When installing conductors, the kind and amount of protection required does NOT depend on _______________.

   a. How the conductors are installed
   b. Where the conductors are installed
   c. The kind of conductors being installed
   d. How the conductors are used

7. Which of the following is NOT a purpose of a raceway?

   a. To prevent physical damage to the wiring
   b. To allow electrons to flow easily
   c. To prevent chemical damage
   d. To protect people and property

8. Where oil, water, certain chemicals, and corrosive gases might be present, you can use _____________________.

   a. Sealtight™ conduit
   b. Greenfield conduit
   c. Rigid conduit
   d. EMT conduit

9. The NEC specifies that conduit is not to be filled to more than what percentage of its cross-sectional area?

   a. 20
   b. 30
   c. 40
   d. 50

10. What is the main purpose of soldering an electrical splice?

    a. To increase its strength
    b. To eliminate the need for tape
    c. To make good electrical contact
    d. To increase its resistance

Summary

Metal wires, transistors, microprocessors, and many other devices that depend on the flow of electricity are constructed from materials with many free electrons. These materials are called conductors. Most metals are good conductors.

Non-conducting materials are also important to the proper operation of electrical equipment. These materials are called insulators or dielectrics. Many nonmetallic materials are good insulators.

The basic unit of measurement for a conductor is the mil – 0.001 inches. A circular mil is the area of a circle one mil in diameter. Wire diameter is designated by a gauge number.

In selecting an insulating material, you should look for materials that possess high dielectric strength, temperature resistance, flexibility, mechanical strength, and moisture resistance. No one material will have all these qualities.

Friction, rubber, and plastic tapes are useful for insulating. Varnished-cambric tape is superior in some areas because it does not melt.

Conductors may need protection depending on how and where they are installed, and how they are used. They are usually enclosed in solid protective channels called raceways. Common raceways include various types of conduit.

Chapter 8: DC Circuits

In This Chapter

DC Characteristics

Ohm's Law

Applying Ohm's Law

Circuit Power

Series Circuit

Parallel Circuits

Series-Parallel Circuits

Open and Short Circuits

Terminology

Direct Current: Electric current that flows in only one direction

Power: The rate of doing work

Series Circuit: A circuit having only one path for electricity to follow

Parallel Circuit: A circuit having two or more paths for electricity to follow

Direct current is widely used in industry. Because its use is so common, the trainee should be well acquainted with DC characteristics.

In this Lesson, we explain Ohm's Law and how to apply it in solving problems in dc circuits. We also explain how to calculate the amount of power consumed by an electrical load.

Depending on the needs in your plant, dc circuits may be connected in series, in parallel, or in series-parallel. This Lesson includes examples of each type of connection for you to study and follow when working with dc circuits.

To troubleshoot a faulty circuit, you must be familiar with electrical test equipment. Always follow the warnings and safety information given in this Lesson when using such devices.

DC Characteristics

8-1 Electric current that flows in only one direction is called **Direct Current** (abbreviated dc). In order to achieve direct current, the potential difference across a load must not change direction.

8-2 In some dc applications, the potential difference may change in magnitude. But in most the potential difference remains fairly constant. Then, if the resistance of the load does not change, the current through the load remains constant. If the current remains constant and in one direction, the electromagnetic field around each conductor also remains constant.

8-3 To help you "see" how a simple dc circuit works, you can compare it to a simple water system. In the water system, a pump produces a difference in pressure between its intake and outlet ports. If a continuous pipe connects the two ports, leading through a restriction, the difference in pressure makes water flow, as shown on the left in Figure 8.1.

8-4 In an electrical circuit, a generator may be used to produce a difference in potential between its positive and negative terminals. If a continuous conductor connects the two terminals, leading through a resistor, the difference in potential makes electrons flow as shown at the right in Figure 8.1.

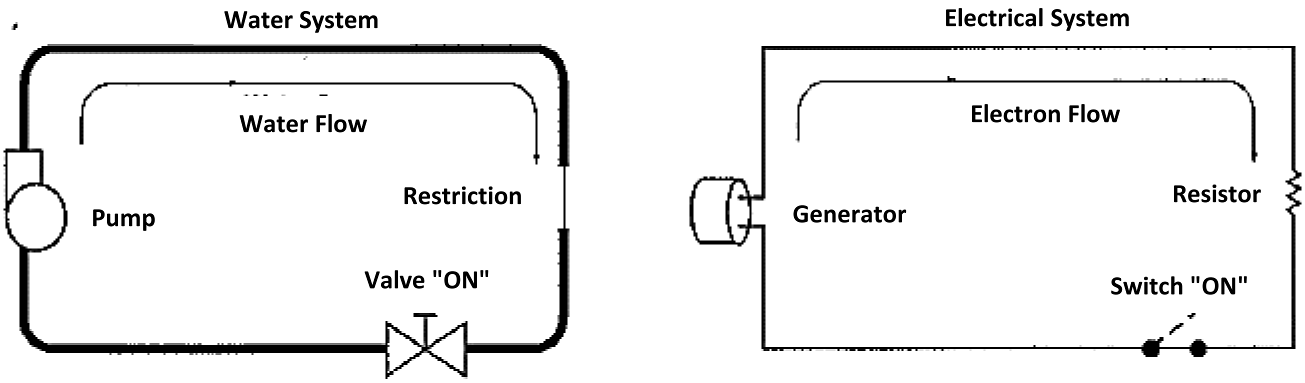


Figure 8.1: Comparison of a Water System and an Electrical System

8-5 In the water system, the pump rotates in only *one* direction and water flows through the pipe in only *one* direction. The same is true in the electrical system. If the generator rotates in only one direction, the current flows in only one direction.

8-6 In the water system, the flow of water depends on two factors:

- The difference in pressure between the ports of the pump, and
- The amount of resistance in the restriction.

Likewise, in the electrical system the flow of electrons depends on two factors:

- The difference in potential between the terminals of the generator, and
- The resistance of the resistor.

DC Characteristics (continued)

8-7 If the pump produces a greater difference in pressure between its ports, water will flow faster through the pipes and the restriction. Similarly, if the generator produces a greater difference in potential between its terminals, electrons will flow faster through the conductors and the resistor.

8-8 The restriction in the water system interferes with the flow of water. Likewise, the resistor in the electrical system interferes with the flow of electrons.

8-9 In the water system, water cannot flow unless there is a complete pathway from the outlet port to the inlet port. If the valve is turned in the **OFF** direction, the pathway is broken by a solid wall of metal, and the water cannot flow. In the electrical system, the switch performs the same function as the valve. If it is turned in the OFF direction, the electrical pathway is broken by an air gap, and electrons cannot flow.

8-10 The flow of water is defined as the amount of water passing a specific point in a standard interval of time. The volume is usually measured in *gallons*, and the time interval is usually *one minute*. That is, the flow of water is usually measured in *gallons per minute*.

8-11 The flow of electricity is defined as the amount of charge passing a specific point in a standard interval of time. The charge is usually measured in *coulombs*, and the time interval is usually *one second*. That is, electric current is usually measured in *coulombs per second*. One coulomb per second is defined as one **ampere**.

Ohm's Law

8-12 Ohm's law describes the relationship among the *potential difference* across a load, the *current* through the load, and the *resistance* of the load. The law looks very simple in mathematical form.

$$E = I \times R$$

where E = Potential difference measured in *volts*

I = Current measured in *amperes*

R = Resistance measured in *ohms*

8-13 You can see from the mathematical expression that Ohm's law combines two simple ideas.

- Current in a load *increases* if the potential difference across the load increases and the resistance stays the same.
- Current in a load *decreases* if the resistance of the load increases and the potential difference across it stays the same.

8-14 This law is the most important electrical relationship, and the one you will use most in working with electricity. To understand electricity, you must understand Ohm's law and how to apply it effectively in solving electrical problems. With Ohm's law you can calculate any one of the three quantities if you know the other two.

Ohm's Law (continued)

8-15 You can use Ohm's law in three different ways. You can use it to find:

E when you know *I* and *R*: $E = I \times R$

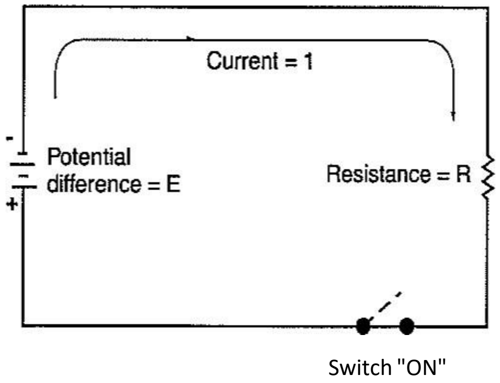
I when you know *E* and *R*: $I = E/R$

R when you know *E* and *I*: $R = E/I$

All these equations express the same relationship among the three variables. If you can remember the first one, you can figure out the other two by simple algebra.

8-16 For practice in using Ohm's law, examine the diagram in Figure 8.2. The table lists five combinations of potential difference across the load, current through the load, and resistance of the load. In each case, one of the values is missing.

8-17 Calculate the missing value for each case, and write it in the proper blank space in the table. The correct answers appear on page 159 of this Chapter.



	E	I	R
1.	150 Volts	15 Amperes	
2.	240 Volts		20Ω
3.		4 Amperes	30Ω
4.		25 Amperes	80Ω
5.	480 Volts	5 Amperes	

Figure 8.2: Practice Problem got Using Ohm's Law

Applying Ohm's Law.

8-18 Ohm's law can be applied to an electric circuit as a whole, or it can be applied to any part of it. Once you understand the basic idea expressed by Ohm's law, you will be able to solve many electrical problems.

8-19 For example, you will be able to calculate the potential difference across a single resistor, if you know its resistance and the current passing through it. You will be able to calculate the current flowing through a resistor if you know its resistance and the potential difference across it.

8-20 Your work will be simplified if you remember to apply all parts of Ohm's law to the same section of the circuit.

- When applying Ohm's law to the *entire circuit*, the potential difference across the *entire circuit* equals the current in the *entire circuit* multiplied by the resistance of the entire circuit. Note that the phrase "entire circuit" applies to all three parts of Ohm's law.
- When applying Ohm's law to only *one part* of a circuit, the potential difference across *that part* of the circuit equals the current in *that part* of the circuit multiplied by the resistance of *that part*.

Circuit Power

8-21 **Power** is defined as the *rate of doing work*. The usual symbol for power is *P*. The standard unit for measuring work is the *joule*, and the standard unit for measuring time is the *second*. Doing work at the rate of one joule per second is defined as a power of one **watt**.

8-22 To calculate the amount of power consumed by an electrical load, you can just multiply the potential difference across the load, measured in *volts* (joules per coulomb) by the current flowing through it measured in *amperes* (coulombs per second). That is,

$$P = E \times I = \frac{\text{Joules}}{\text{Coulomb}} \times \frac{\text{Coulombs}}{\text{Second}} = \frac{\text{Joules}}{\text{Second}}$$

where *P* = Power consumed by the load measured in *watts*

E = Potential difference across the load measured in *volts*

I = Current through the load measured in *amperes*

8-23 You can see from Ohm's law that you can calculate the amount of power consumed by a load if you know any two of the three basic electrical values—potential difference across the load, current through the load, and the resistance of the load. You just use Ohm's law to replace either *E* or *I*, whichever one you do *not* know.

8-24 For example, suppose you know the *potential difference* across a load is 120 volts and the resistance of the load is 10Ω. You do not know the *current*. You use Ohm's law to substitute for *I* (*E = I x R so I = E/R*).

$$P = E \times I$$

$$= E \times (E/R)$$

$$= E^2/R$$

8-25 You can now calculate the power by substituting the actual values for *E* and *R*.

$$\text{P} = E^2/R$$

$$= \frac{(120\text{ Volts})^2}{10\Omega}$$

$$= \frac{14{,}400\text{ Volts}}{10\Omega}$$

$$= 1440\text{ watts}$$

Circuit Power (continued)

8.26 When you are solving an electrical problem, following the seven steps listed below will help simplify the process.

1. Draw a diagram of the circuit.
2. Label all parts.
3. Write all known values on the diagram.
4. Draw arrows to show the directions of electron flow.
5. Write the equations you will need.
6. Substitute the proper values for the letters in the equations.
7. Solve the equations for the unknown values. Use a calculator if possible.

Series Circuits

8-27 If a circuit has only *one* path for electricity to follow in passing through two or more loads, the circuit is called a **series circuit**. This name comes from the fact that all the current flows through all the resistors, one after another, in series. Electrons leave the negative terminal of the battery or generator, pass through every load, and return to the positive terminal. An example of a series circuit is shown in Figure 8.3.

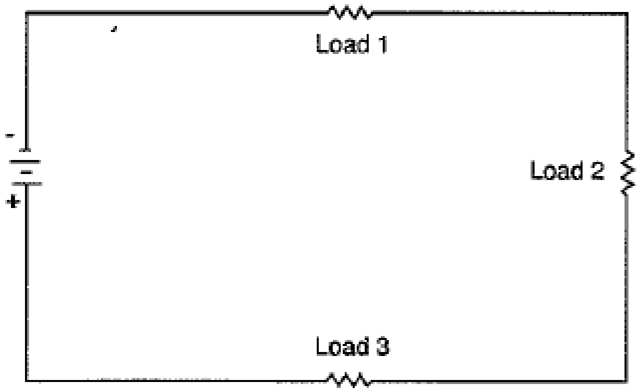


Figure 8.3: Series Circuit

Series Circuits (continued)

8-28 The total resistance in a series circuit equals the sum of all the individual resistances in the circuit. In Figure 8.3, the total resistance equals the sum of, R_1, R_2, and R_3 as expressed by the following equation.

$$R_T = R_1 + R_2 + R_3$$

where R_T = Total resistance of all the loads in the circuit

R_1 = Resistance of Load 1

R_2 = Resistance of Load 2

R_3 = Resistance of Load 3

8-29 The current in a series circuit is the same at all points in the circuit. If six amperes of current flow from the battery, six amperes also flow through loads 1, 2, and 3. This idea is expressed by the following equation.

$$I_T = I_1 + I_2 + I_3$$

where I_T = Total current

I_1 = Current through Load 1

I_2 = Current through Load 2

I_3 = Current through Load 3

8-30 When current flows through two or more loads, the potential difference across the terminals of the battery or generator is divided into smaller potential differences across the individual loads. Each smaller potential difference is called the *voltage drop* across that load. The ratio of voltage drops equals the ratio of the resistances of the loads.

8-31 The voltage drop across each load equals the product of the *current* through the load and the *resistance* of the load, following Ohm's law. The higher the resistance of any one load, the greater the potential difference across it and the lower the potential difference across other loads in the series.

$$E_T = IE_1 + E_2 + E_3$$

where E_T = Potential difference between the terminals of the battery or generator

E_1 = Voltage drop across Load 1

E_2 = Voltage drop across Load 2

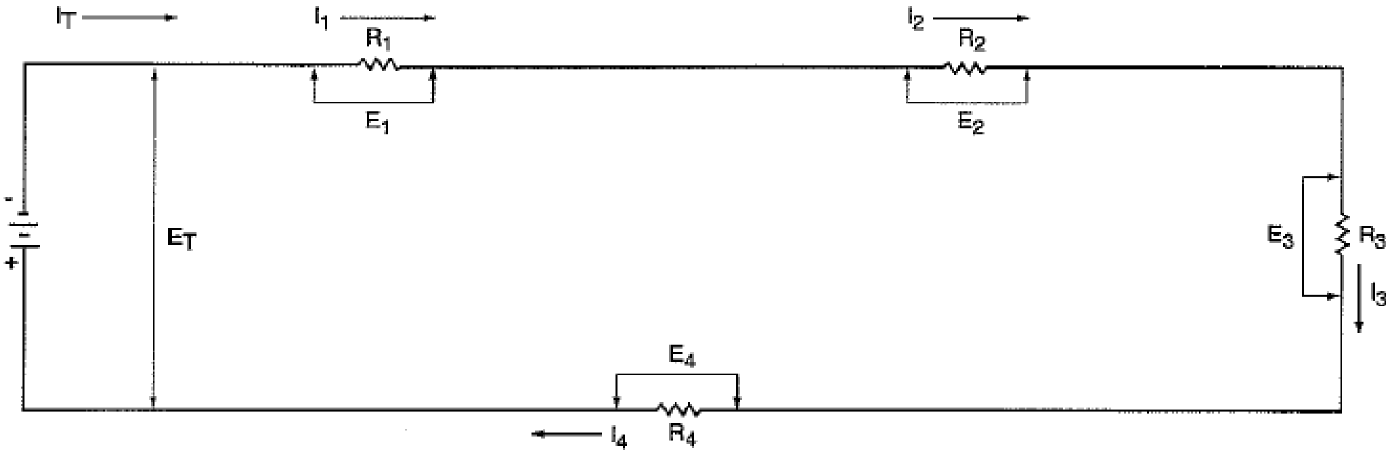
E_3 = Voltage drop across Load 3

Series Circuits (continued)

8-32 If you add the voltage drops for all the loads, the total equals the potential difference across the terminals of the battery or generator. Expressed in mathematical terms, this relationship can be written in the following way.

8-33 Figure 8.4 is a diagram of a simple series circuit. Some of the values are written on the diagram. Other values are missing. Use Ohm's law and the other equations for series circuits to calculate the missing values of potential difference, current, and resistance.

8-34 As you solve the problems in Figure 8.4, work carefully and slowly. Do not let the large number of unknowns confuse you. Solve the problems one at a time. As you work, write each answer on the diagram in the space provided. When you are finished, turn to page 159 of this Lesson and check your answers.



E_T = 240 Volts I_T = __________ R_T = __________ E_3 = __________ I_3 = __________ R_3 = 10Ω

E_1 = __________ I_1 = __________ R_1 = 20Ω E_4 = __________ I_{41} = __________ R_4 = 40Ω

E_2 = __________ I_2 = __________ R_2 = 30Ω

Figure 8.4: Practice Problem for a Series Circuit

Parallel Circuits

8-35 Some circuits have two or more paths for the current to follow. Such a circuit is called a **parallel circuit**. The path branches, as shown in Figure 8.5. When current leaves the source, it divides among the branches according to the resistances of the loads in the branches.

8-36 In a parallel circuit, the potential difference is the same across all the branches. The current in any single branch is always less than the total current from the battery or generator. The current in one branch does not affect the current in the other branches.

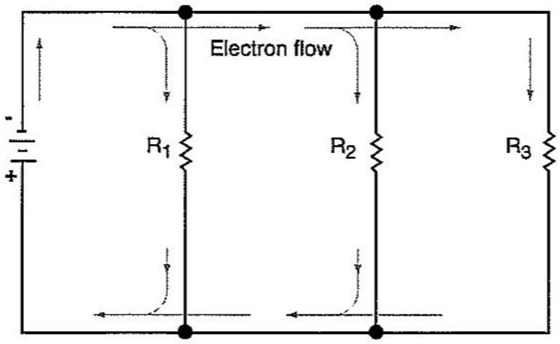


Figure 8.5: Parallel Circuit

8-37 A break in a parallel circuit stops the current only in the branch with the break. The current from the battery or generator is then reduced by that amount.

8-38 In the circuit shown in Figure 8.6, the battery produces a potential difference of 12 volts between its terminals. This potential difference exists across all three loads—the heater fan, the starter motor, and the lamp. If the fan is turned off, the other equipment still works because the current continues in these branches.

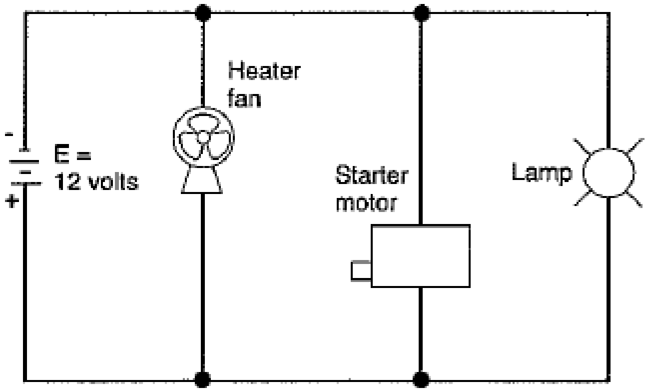


Figure 8.6: Parallel Circuit in an Automobile

Parallel Circuits (continued)

8-39 The lamps on a string of Christmas tree lights may be connected either in series or in parallel. If they are connected in *parallel*, one lamp may burn out without affecting the others. If they are connected in *series*, all the lamps go out when one burns out.

8-40 The current may not be the same in all branches of a parallel circuit. In fact, the current cannot be the same unless all branches have the same resistance.

8.41 Total current from a battery or generator is the sum of the currents in all the branches of a parallel circuit. The following equation expresses this relationship for the circuit shown in Figure 8.7.

$$I_T = I_1 + I_2 + I_3$$

where I_T = Total current flowing from the source

I_1 = Current flowing through Load 1

I_2 = Current flowing through Load 2

I_3 = Current flowing through Load 3

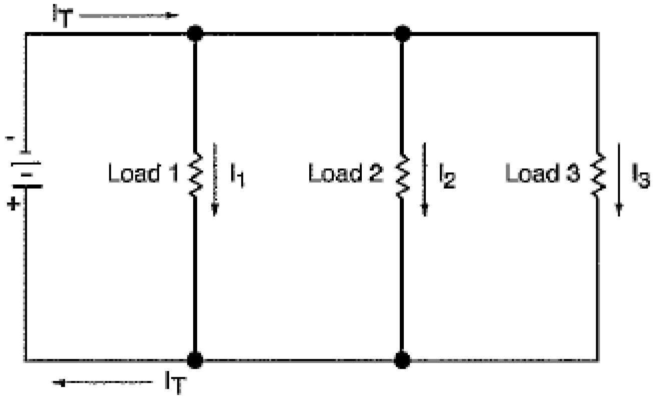


Figure 8.7: Branch Currents in a Parallel

8-42 You can calculate the resistance of a parallel circuit quite easily, but the result may surprise you the first time. You calculate the resistance in two steps.

- In the first step, you calculate the total current flowing in each branch, using Ohm's law, and then add the currents to find the total for the circuit.
- In the second step, you use Ohm's law again, dividing the potential difference across the branches by the total current to find the resistance of the circuit.

Parallel Circuits (continued)

8-43 Suppose you have a three-branch parallel circuit like the sample shown in Figure 8.8. The resistance in each branch differs from the resistance in the other two branches. What is the resistance of the circuit as a whole?

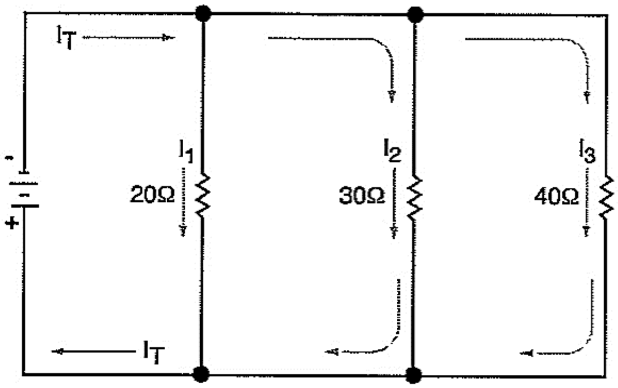


Figure 8.8: Sample Parallel Circuit

8-44 You begin by calculating the current that will flow through each branch if a potential difference is applied across the ends of the circuit. To do so, you must *assume* a value for the potential difference.

8-45 You can assume any value you want for the potential difference, *E*. The final result – the resistance of the circuit – will be the same no matter what value you choose. We will choose a value of 120 volts, because that value makes the arithmetic simple. Any other value would give the same result, but the arithmetic might be more difficult.

8-46 In the first step, you calculate the total current flowing in the circuit. To do so, you calculate the current in each branch, and then add those values together to find the total current, I_T. To calculate the current in each branch, you use Ohm's law, dividing the potential difference across the branch by the resistance of the branch.

$$\text{Branch 1: } I_1 = \frac{E}{R_1} = \frac{120 \text{ Volts}}{20\Omega} = 6 \text{ Amperes}$$

$$\text{Branch 2: } I_2 = \frac{E}{R_2} = \frac{120 \text{ Volts}}{30\Omega} = 4 \text{ Amperes}$$

$$\text{Branch 3: } I_3 = \frac{E}{R_3} = \frac{120 \text{ Volts}}{40\Omega} = 3 \text{ Amperes}$$

$$\text{Total: } I_T = 6 \text{ Amperes} + 4 \text{ Amperes} + 3 \text{ Amperes} = 13 \text{ Amperes}$$

8-47 In the second step, you use Ohm's law again. This time you divide the potential difference across the whole circuit by the total amount of current through the whole circuit to find the resistance.

$$R_T = \frac{E}{I_1} = \frac{120 \text{ Volts}}{13 \text{ Amperes}} = 9.23\Omega$$

Parallel Circuits (continued)

8-48 The surprising part of this result is that the resistance of the total circuit is less than the resistance of any one branch. This result occurs in all parallel circuits. In fact, the more branches a parallel circuit has, the lower its resistance.

8-49 The reason a parallel circuit has lower resistance than any of its branches is that each branch provides another path for electricity. Each additional path increases the amount of current that can flow through the circuit for any given potential difference applied across its ends. The greater the current, the lower the overall resistance of the circuit.

8-50 The general method for calculating the resistance of a parallel circuit is to use the equation shown below. You do not need to choose a value for E when you use this equation.

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \ldots\ldots \frac{1}{R_n}}$$

where R_T = Total resistance

R_1 = Resistance in Branch 1

R_2 = Resistance in Branch 2

R_3 = Resistance in Branch 3

R_n = Resistance in Branch *n*

8-51 You can see how this equation works by using it on the example in Figure 8.8. When you substitute the three resistance values into the equation, you get the results shown below.

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \ldots\ldots \frac{1}{R_n}} = \frac{1}{\frac{1}{20\Omega} + \frac{1}{30\Omega} + \frac{1}{40\Omega}} = \frac{1}{0.05 + 0.0333 + 0.025}\,\Omega = \frac{1}{0.1038}\,\Omega = 9.23\Omega$$

This result matches the result obtained in paragraph 8-47.

Series-Parallel Circuits

8-52 Many electrical circuits are combinations of series and parallel circuits. It is not difficult to figure out the values of potential differences, currents, and resistances in these combination circuits. All you need to remember is Ohm's law, plus the ideas of simple series and parallel circuits. Then you go through the combination circuit step-by-step and figure out what you need to know.

8-53 Before trying to solve a series-parallel problem, look at the circuit to see how you can divide it into simpler parts. Try to simplify these parts in one of the following ways.

- If you see two or more resistors in *series*, treat them as a single resistor equal to the sum of the individual resistances.
- If you see two or more resistors in *parallel*, treat them as a single resistor equal to the value of the combination.

8-54 The example in Figure 8.9 shows a circuit with resistors connected in both series and parallel. Read the following paragraphs and perform the calculations described. If you have a calculator, you should use it.

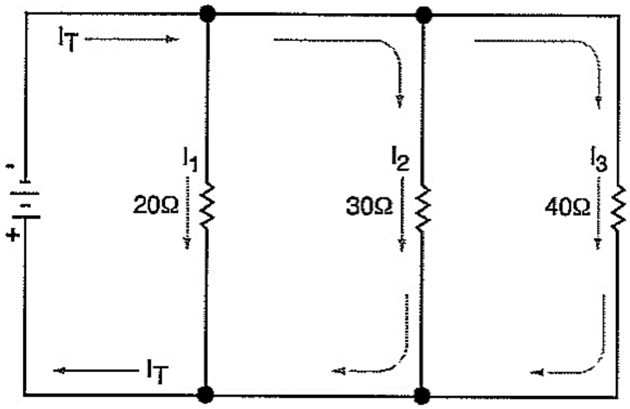


Figure 8.9: Sample Parallel Circuit

8-55 Begin by finding the total resistance for Branch 3. This branch consists of two resistors in parallel, and two others in series with the combination. The total resistance is the sum of three parts – R_5 + R_6 + the parallel combination of R_7 and R_8. You should calculate a value of 10Ω for the two parallel resistors, and a total of 35Ω for the entire branch.

8-56 Next, you can combine Branch 3 with Branch 2, and calculate the total resistance of this parallel combination. Branch 3 has been reduced to a single resistor, with a value of 35Ω. But Branch 2 consists of two resistors in series. The total resistance in Branch 2 is 30Ω.

8-57 To combine Branch 2 and Branch 3, you can again use the equation for parallel resistors. The calculation is quite easy if you use a calculator. You should find that the total resistance of these two branches is 16.16Ω.

Series-Parallel Circuits (continued)

8-58 The next step is to combine Branch 1 with resistor R_9 and the equivalent for Branches 2 and 3. You can again use the equation for parallel resistors. Note that R_9 is in series with the equivalent of Branches 2 and 3. Use the equation below and finish the calculation. You should find a value of 953Ω. This value is the resistance of the combination of all resistors in the circuit except R_1.

$$R_T = \frac{1}{\frac{1}{15\Omega} + \frac{1}{10\Omega + 16.16\Omega}}$$

8-59 Finally, you can combine RI with the equivalent of all the other resistors, and get a value for the total resistance of the entire circuit. Then you can use Ohm's law to calculate any currents and potential differences you may need to know.

8-60 Calculate the following values for the circuit shown in Figure 8.9, and write your answers in the spaces below. When you finish, check your answers on page 159 of this Lesson.

R_T = ________________

Reading on A_1 = ________________

Reading on A_3 = ________________

Reading on V_1 = ________________

Reading on V_2 = ________________

Reading on A_2 = ________________

Reading on V_3 = ________________

Reading on V_9 = ________________

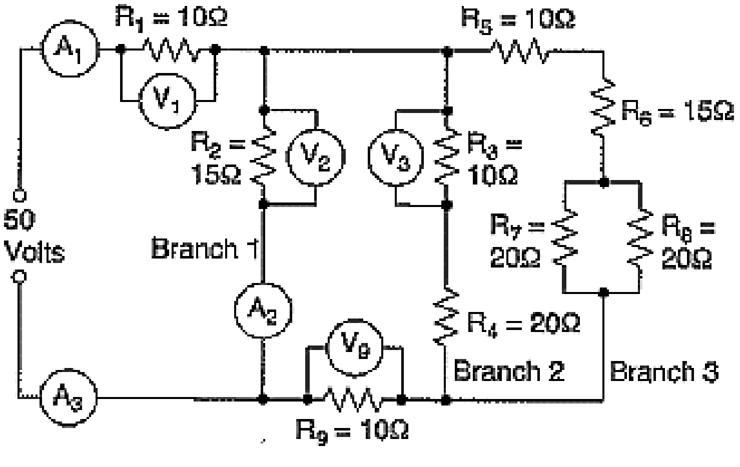


Figure 8.9: Example of a Series-Parallel Circuit

Series-Parallel Circuits (continued)

8-61 Figure 8.10 shows three circuits. The resistors in these circuits are connected in series, in parallel, and in series-parallel combinations. Use the methods described in this Lesson to calculate the total resistance of each circuit. Write your answers in the spaces provided in Figure 8.10. When you have finished, check your answers on page 159 of this Lesson.

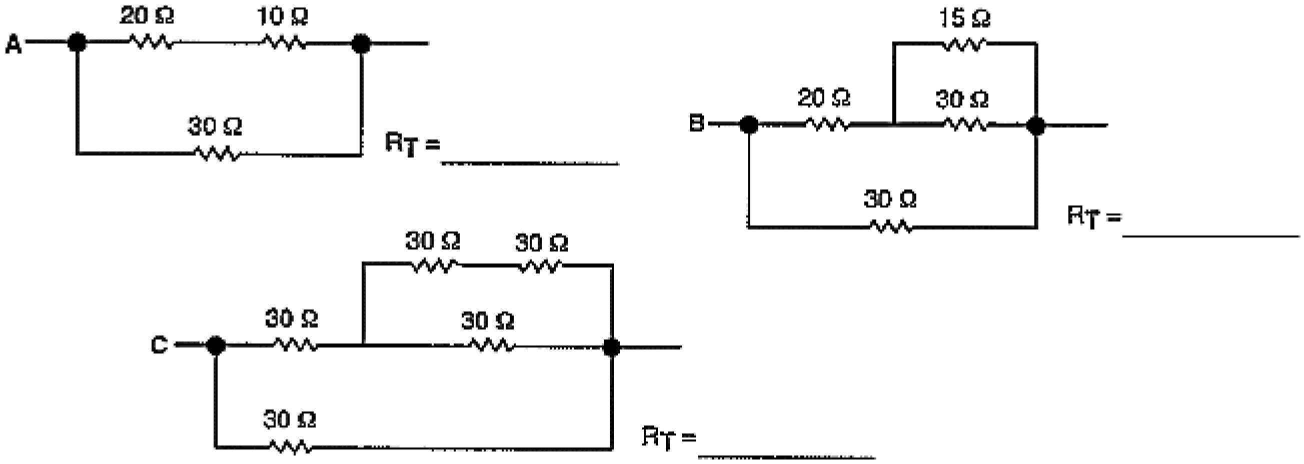


Figure 8.10: Series-Parallel Problems

Open and Short Circuits

8-62 An **open circuit** occurs when a current path in a circuit is broken. An open circuit can be caused intentionally, as when you open a switch. It can also be caused accidentally by a break in a conductor or a faulty connection.

8-63 A **short circuit** occurs when the current can avoid flowing through part of the circuit by flowing around it through a parallel low-resistance path. When two parallel paths are available, the path having the lower resistance carries the larger fraction of the current. The greater the difference in resistance, the greater the difference in current.

8-64 Short circuits can occur because of improper wiring or because two bare conductors touch. A short circuit usually provides a very low-resistance path that carries nearly all the current. It effectively prevents the current from flowing to electrical components beyond the point where the "short" occurs.

8-65 In the series circuit shown in Figure 8.11, a short has occurred after resistance R_1. This short has the effect of removing R_2 and R_3 from the circuit, because almost no current flows through them.

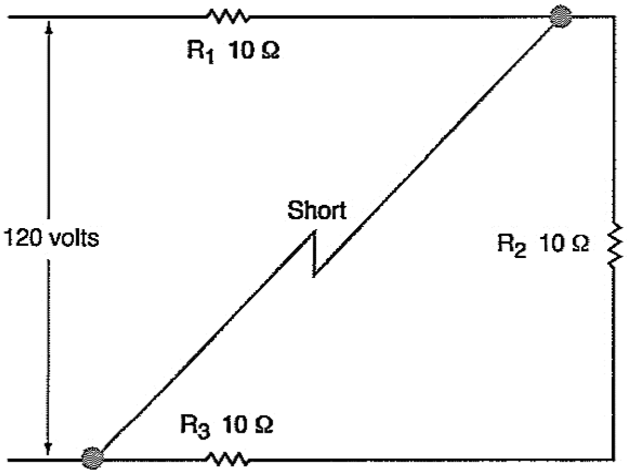


Figure 8.11: Shorted Series Circuit

8-66 Before the short occurred, the current in the circuit was 4 amperes (120 volts / 30Ω = 4 amperes). The potential difference across R_1 is 40 volts (4 amperes x 10Ω = 40 volts).

8-67 After the short, the full potential difference—120 volts—is applied across R_1. Using Ohm's law, you can calculate that the current through R_1 increases to 12 amperes.

Open and Short Circuits (continued)

8-68 Compare the series circuit in Figure 8.11 with the parallel circuit in Figure 8.12, which has a short at a similar location. The low-resistance short carries a large additional current in the circuit.

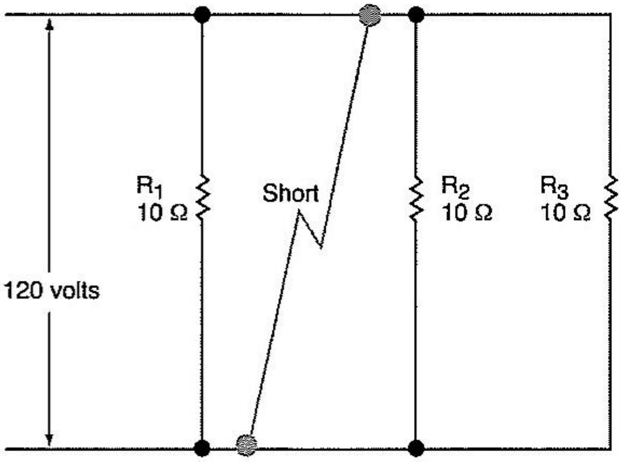


Figure 8.12: Shorted Parallel Circuit

8-69 Unlike the short in the series circuit in Figure 8.11, the short in the parallel circuit in Figure 8.12 does not change the current in R_1, R_2, or R_3. Neither does it change the potential difference across these resistors.

8-70 If the short has a resistance of 0.1Ω, it will carry 1200 amperes (*I* = *E/R* = 120 volts / 0.1Ω = 1200 amperes). This current is 100 times the current that normally flows through each branch of the circuit. The short will almost certainly overheat, and may cause a fire or other damage unless a fuse or circuit breaker interrupts the current.

8-71 You can see the area of trouble in Figures 8.11 and 8.12. But what if you had to work on an actual installation where the source of the trouble is not so apparent? Is the trouble a short circuit? Or is it an open circuit? And exactly where is the point of trouble?

8-72 Both open circuits and short circuits affect the total circuit resistance. The logical thing to do in either event is to measure the resistance. You can make the measurement with an ohmmeter.

WARNING

Never use an ohmmeter without first disconnecting the circuit from the power source. Using an ohmmeter on an energized circuit can destroy the meter mechanism and cause injury to you.

8-73 In general, you should open the circuit switch before troubleshooting a circuit. If necessary, you can use a voltmeter to find whether there is a potential difference across each resistor. But measuring potential difference requires that the circuit be energized, so use extreme care to avoid a shock.

Chapter 8 Exercise

Circle the appropriate letter next to the correct answer.

1. Electric current that flows in only one direction is called _________________.
   - a. Alternating current
   - b. Direct current
   - c. Parallel current
   - d. Series current

2. If the current remains constant and in one direction, the current produces constant ________________.
   - a. Potential difference
   - b. Number of electrons
   - c. Electromagnetic field
   - d. Resistance

3. One coulomb per second is defined as one ___________________.
   - a. Ampere
   - b. Ohm
   - c. Volt
   - d. Watt

4. Doing work at the rate of one joule per second is defined as a power of one __________________.
   - a. Ampere
   - b. Ohm
   - c. Volt
   - d. Watt

5. If a circuit has only one path for electricity, the circuit is called a(n) __________________.
   - a. Alternating-current circuit
   - b. Direct-current circuit
   - c. Parallel circuit
   - d. Series circuit

Chapter 8 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. When current flows through two or more loads, the potential difference across one load is called ___________.

   a. Voltage breakdown
   b. Voltage drop
   c. Resistance decrease
   d. Current decline

7. In a parallel circuit, each additional branch increases the current and decreases the circuit's ________________.

   a. Resistance
   b. Potential difference
   c. Conductance
   d. Voltage breakdown

8. Before trying to solve a series-parallel problem, you should try to divide the circuit into ____________________.

   a. Two sections
   b. Units
   c. Series
   d. Simpler parts

9. When two parallel paths are available, the path having the lower resistance carries _________________.

   a. No current
   b. Half the current
   c. More than half the current
   d. All the current

10. When making measurements on an energized circuit, you must use extreme care to ________________.

   a. Get the correct reading
   b. Avoid electrical shock
   c. Open the circuit
   d. Use the meter correctly

Summary

Direct current is electric current that flows in one direction only. In dc, the direction of the potential difference also remains the same. The relationship between the potential difference, the current, and the resistance is explained by Ohm's law.

Any electrical problem is easier to solve if you follow sequential steps. First, draw a diagram of the circuit and label all parts. Next, write all known values on the diagram. Draw arrows to show the directions of electron flow. Then, write the equations you will need and substitute the proper values for the letters in the equations. Finally, solve the equations for the unknown values. Use a calculator if you have one.

DC circuits can be connected in series, in parallel, or in series-parallel. A series circuit has only one path for electricity to follow in passing through two or more loads. Parallel circuits have two or more paths for the current to follow. Series-parallel circuits have resistors connected both in series and in parallel.

Both open and short circuits are potentially dangerous because the current flows along a low-resistance path. If you are using an ohmmeter to measure the resistance, first make sure to disconnect the circuit from the power source.

Answers to Problems

Figure 8.2:

1. R = 10Ω
2. I = 12 Amperes
3. E = 120 Volts
4. E = 2000 Volts
5. R = 96Ω

I_2 = 2.4 Amperes

Figure 8.4:

E_1 = 48 Volts

I_T = 2.4 Amperes

E_2 = 72 Volts

I_1 = 2.4 Amperes

E_3 = 24 Volts

I_3 = 2.4 Amperes

E_4 = 96 Volts

R_T = 100Ω

I_4 = 2.4 Amperes

Paragraph 8-60

R_T = 19.53Ω

Reading on A_1 = 2.56 Amperes

Reading on A_3 = 2.56 Amperes

Reading on V_1 = 25.6 Volts

Reading on V_2 = 24.4 Volts

Reading on A_2 = 1.63 Amperes

Reading on V_3 = 5.03 Volts

Reading on V_9 = 9.33 Volts

Figure 8.10

A. R_T = 15Ω

B. R_T = 15Ω

C. R_T = 18.75Ω

Chapter 9: AC Circuits

In This Chapter

Terminology

Alternating Current (AC): Electricity that changes direction at a regular rate

Inductance: Property of a coil of wire that opposes any change in current

Henry: Unit of inductance

Inductive Reactance: Opposition to the flow of current in an AC circuit due to inductance in the circuit

Capacitance: Property of a capacitor that opposes any change in potential difference between two points

Farad: Unit of capacitance

Capacitive Reactance: Opposition to the flow of current in an AC circuit due to capacitance in the circuit

Impedance: Sum of the inductive reactance, capacitive reactance and resistance in a circuit

Alternating current is the form of electrical power most widely used throughout the world. As more devices using electrical and electronic controls are developed, the need for knowledge about ac circuits increases. Today's trainee must continually expand his understanding of ac circuits if he is to keep up with industry's use of electrical equipment.

In this Lesson, we explain the basic principles of ac, the advantages of alternating current, and basic characteristics of ac circuits.

As you study this Lesson, pay special attention to the terms. Some have been defined in previous Lessons in this Unit. If any terms are confusing, refer back to the previous Lessons.

Advantages of Alternating Current

9-1 Direct current (dc) flows continuously in one direction. It does so because the potential difference across the terminals of the source never changes direction. But with **alternating current** (abbreviated *ac*), the potential difference and the current both change direction at a regular rate.

9-2 In the United States, the standard alternating rate for electric power is 60 hertz (abbreviated Hz). Sixty Hz means the current goes through 60 complete cycles of directional change, from one direction to the other and back again, every second. In Canada, the standard rate is also 60 Hz. Throughout the world, the standard rate for ac power is either 50 Hz or 60 Hz.

9-3 Power companies use *ac generators*, also called *alternators*, instead of *dc generators* to produce electric power. They do so because the alternating current can be transmitted over long distances at low cost. The main reason for the low cost is that alternating current can be "transformed." That is, the potential difference can be raised or lowered, depending on need.

9-4 A transformer can increase or decrease the potential difference of ac electricity with almost no loss of power. The cost is therefore very low. Direct current cannot be transformed from one potential difference to another.

9-5 Transforming is important in keeping costs low, because of the nature of electric *power*. Remember that electric power is defined as the product of the potential difference across a circuit element and the current through it. This relationship is expressed by the first equation below.

9-6 From this definition and Ohm's law, you can see that the loss in power as current passes through a resistor depends strongly on the amount of current in the resistor. This relationship is expressed by the second equation below.

$$P = E \times I$$

$$P_L = I^2 \times R$$

where P = Electric power entering or leaving a transmission line in *watts*

P_L = Power lost in passing through the line in *watts*

E = Potential difference between the line and electrical ground in *volts*

I = Electric current in the line in *amperes*

R = Resistance if the line in *ohms*

9-7 You can see from the second equation above that multiplying the current by ten increases the power loss by a factor of 100, because the power loss varies with the square of the current.

9-8 A transformer changes alternating current from one combination of potential difference and current to another combination. The amount of power neither increases nor decreases. The power that goes into a transformer equals the power coming out.

Advantages of Alternating Current (continued)

9-9 For example, a transformer might receive electricity from the generator at 10,000 volts and 50 amperes. It might deliver electricity into the transmission line at 250,000 volts and 2 amperes. The power going into the transformer equals the power coming out (10,000 volts x 50 amperes = 250,000 volts x 2 amperes = 500,000 watts).

9-10 The transformer has multiplied the potential difference by 25, and it has divided the current by 25. This reduction in current from 50 amperes to 2 amperes cuts the power loss (I^2 x R) in the transmission line by 99.84 percent.

9-11 Direct current cannot be transformed to higher or lower potential differences. If it is transmitted over a long distance line at a potential difference low enough to be useful at the destination, the current required is very high. The high current produces heat in the transmission line, and greatly reduces the power delivered at the destination.

Generating Alternating Current

9-12 The manner of generating alternating current is shown in Figure 9.1. A two-pole alternator is shown with a wire loop rotating through a magnetic field. The loop is "open." That is, the ends are not connected to each other or to anything else.

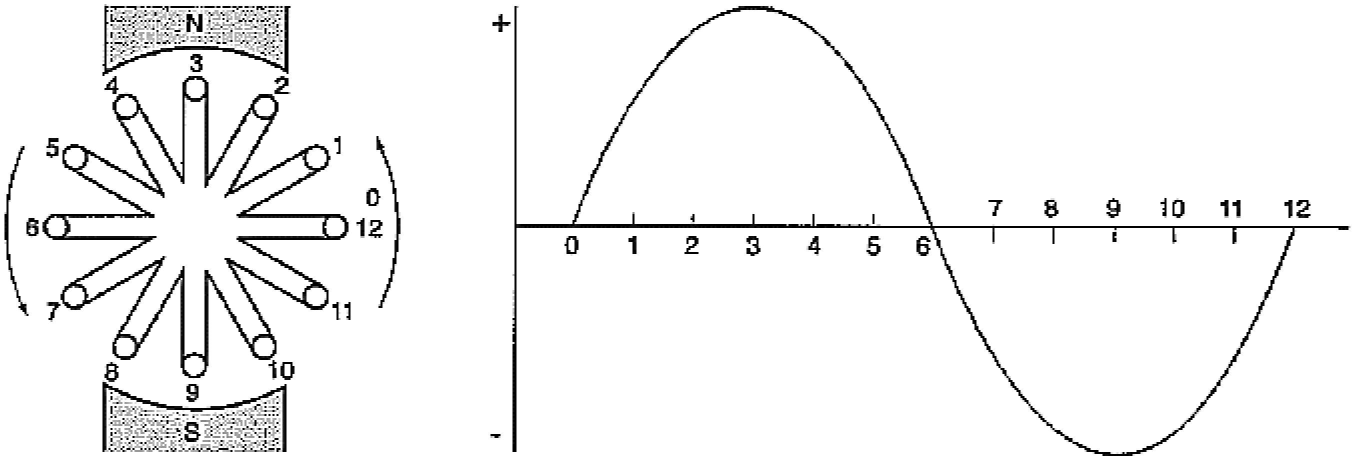


Figure 9.1: Potential Difference Generated in a Two-Pole Alternator

Generating Alternating Current (continued)

9-13 The following paragraphs describe variations through the magnetic field.

- **Position 0 - 0°**: Note that the loop is moving *parallel* to the magnetic field. Therefore, no potential difference is generated between the ends of the loop. The graph at the right shows a value of zero at Position 0 on the horizontal axis.

- **Position 1 - 30°**: In this position, the loop is crossing the magnetic field at an angle of 30° going toward the *left*. As a result, a potential difference is generated between the ends of the loop. This potential difference is represented in the graph by the positive value at Position 1.

- **Position 2 - 60°**: The loop is now cutting the magnetic field at an angle of 60°. The potential difference between the ends is higher as a result of the increased angle. The graph at the right shows a higher positive value at Position 2.

- **Position 3 - 90°**: The loop is cutting the magnetic field at an angle of 90° in this position. The potential difference produced between the ends of the loop is therefore at its maximum. The graph shows this peak value at Position 3.

- **Position 4 - 120°**: The loop is now cutting through the magnetic field at an angle of 60° again. The potential difference is still positive, as when the loop was in Position 2 but the value is dropping. You can see this decrease on the graph.

- **Position 5 - 150°**: Now the loop is cutting through the field at an angle of 30°, just as when it was in Position 1. The potential difference shown on the graph has dropped to the same value as at Position 1.

- **Position 6 - 180°**: In this position the loop is again moving parallel to the magnetic field. Therefore, no potential difference is generated between the ends of the loop. The graph shows a value of zero at Position 6.

- **Position 7 - 210°**: The loop is now cutting across the magnetic field at an angle of 30° again but it is moving toward the *right* instead of the left. Therefore, the potential difference between the ends of the loop is in the opposite direction. On the graph, this reversal appears as a negative value.
- **Position 8 - 240°:** The angle at which the loop cuts the field is 60^0 and the potential difference is higher again. However, the graph shows that the direction is still opposite the original direction, because the loop is moving toward the right instead of the left.

- **Position 9 - 270°**: The loop now cuts the magnetic field at an angle of 90°. The potential difference is at its maximum value, but in the "negative" direction.

- **Position 10 - 300°**: The cutting angle has been reduced to 60° again, and the graph shows that the potential difference is returning toward zero. However, the direction is still negative.

Generating Alternating Current (continued)

- **Position 11 - 330°**. The loop now cuts the magnetic field at only 30°. The potential difference is reduced still further, and it is still in the negative direction.

- **Position 12 - 360°**. The loop is now back in its starting position. Its motion is again parallel to the direction of the magnetic field. Therefore, the potential difference between the ends of the loop is again zero for an instant.

9-14 One complete revolution of the loop produces one complete alternation in the value and direction of the potential difference generated, as shown by the graph in Figure 9.1. The number of cycles completed every second is called the **frequency** of the alternation, measured in *hertz*.

Effective and Average Values

9-15 You may wonder how to express the current and potential difference for alternating current. Both values are continually changing.

- You could measure the value at any *instant*, but the value would be different at every instant.
- You might realize that the *average* value for a full cycle is zero, for either current or potential difference, because for every positive value there is an equal negative value.

9-16 The average value over *half* a cycle is not zero. To understand how such an average is calculated, think of a graph for half a cycle, as shown in Figure 9.2. This graph has the shape of half a sine curve. You can measure the area under the curve. Then to calculate an average, you find a *constant* value that has an area underneath it that equals the area under the sine curve.

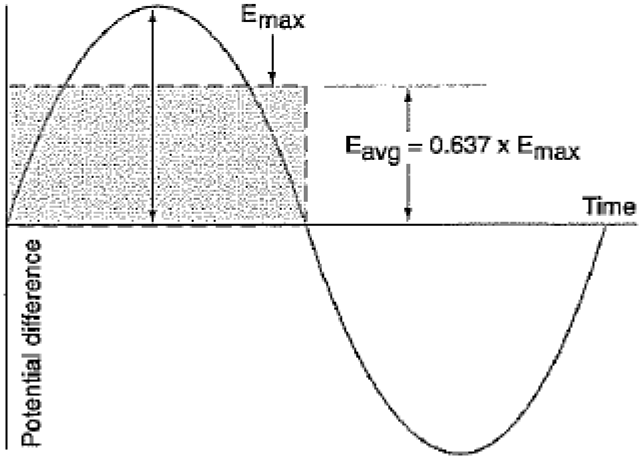


Figure 9.2: Average Potential Difference

Effective and Average Values (continued)

9-17 Figure 9.2 shows this average for *potential difference*. The average equals 0.637 times the maximum value, represented by the peak of the sine curve. The graph of *current* is also a sine curve, so the average current equals 0.637 times the maximum value of current.

9-18 One ampere of average alternating current has less effect than one ampere of direct current. Therefore, you should not use the *average* current or potential difference in making electrical calculations involving alternating current. You should use the *effective* value instead.

9-19 To compare the effects of ac and dc, you should equate their *heating effects*. Alternating current is said to have an effective value of one ampere when it produces heat in a given resistor at the same rate as one ampere of direct current.

9-20 The effective value of alternating current can be figured out without actually passing electricity through a resistor. It can be determined either by graphing or by calculating it mathematically. The result is the same for both methods. The effective value of current or potential difference in ac is 0.707 times the maximum value, if the graph has the shape of a sine curve. This effective value is called the **root-mean-square** value (abbreviated *RMS*). The value 0.707 equals half the square root of two ($\sqrt{2} / 2$).

9-21 Examples of AC values are shown in Figure 9.3. The maximum potential difference, E_{max}, is 170 volts. The effective and average values are calculated below.

$$
\begin{aligned}
E_{max} &= 0.707E_{max} \\
&= 0.707 \text{ x } 170 \text{ Volts} \\
&= 120 \text{ Volts} \\
E_{avg} &= 0.637E_{max} \\
&= 0.637 \text{ x } 170 \text{ Volts} \\
&= 108 \text{ Volts}
\end{aligned}
$$

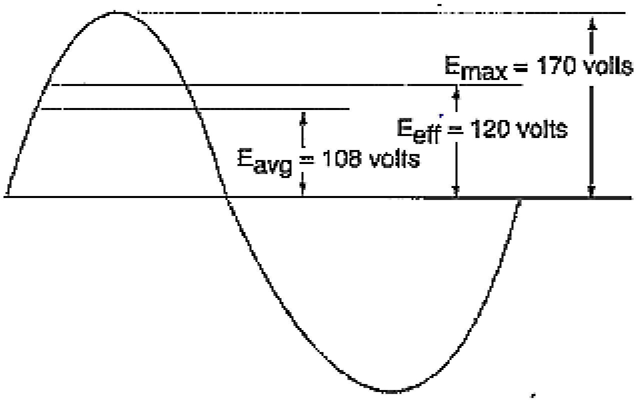


Figure 9.3: Values on a Sine Curve

Effective and Average Values (continued)

9-22 The RMS values are always used for electrical calculations. AC meters measure RMS values for potential differences and currents. You should assume all values of current or potential difference are RMS values, unless stated otherwise.

Electrical Degrees

9-23 One complete cycle of ac consists of 360 *electrical degrees*. The cycle is shown by the graph in Figure 9.4. The electrical degrees are printed along the horizontal axis. The cycle begins in a positive direction at 0° (at the far left on the graph). The potential difference there is zero.

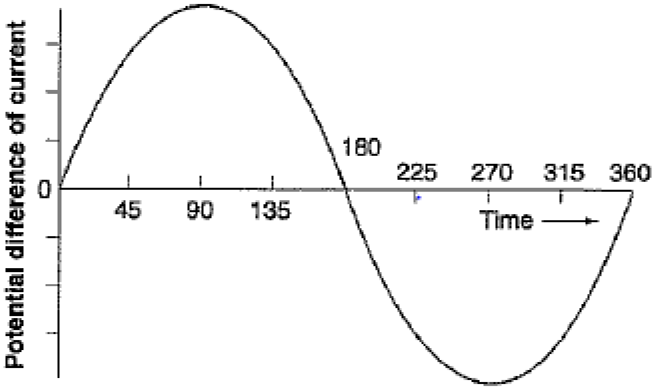


Figure 9.4: Electrical Degrees

9-24 The value rises until it reaches a maximum at 90°. From 90°, the value decreases, passing through zero at 180°. It continues to decrease, taking on negative values until it reaches a minimum value (meaning a maximum negative value) at 270°. Then the potential difference begins increasing again, and it returns to zero at 360°. You can see that 360° is the starting position, the same position as 0°.

9-25 A complete cycle occurs when a conductor passes one pair of magnetic poles (a north pole and a south pole). How far the conductor must rotate to generate one complete electrical cycle depends on how many north and south magnetic poles are in the generator.

Electrical Degrees (continued)

9-26 How far the conductor rotates is measured in *mechanical degrees* of rotation. How much of a complete electrical cycle the conductor generates is measured in *electrical degrees* of rotation. One complete rotation of the conductor equals 360 mechanical degrees. One complete electrical cycle equals 360 electrical degrees.

- In a two-pole generator, the conductor makes one complete revolution (360 mechanical degrees) to produce one complete electrical cycle (360 electrical degrees), as shown at the left in Figure 9.5.
- In a four-pole generator, the conductor makes only half a revolution (180 mechanical degrees) to produce one complete electrical cycle (360 electrical degrees), as shown at the right in Figure 9.5.

The more poles a generator has, the fewer mechanical degrees are required to generate a complete cycle of 360 electrical degrees.

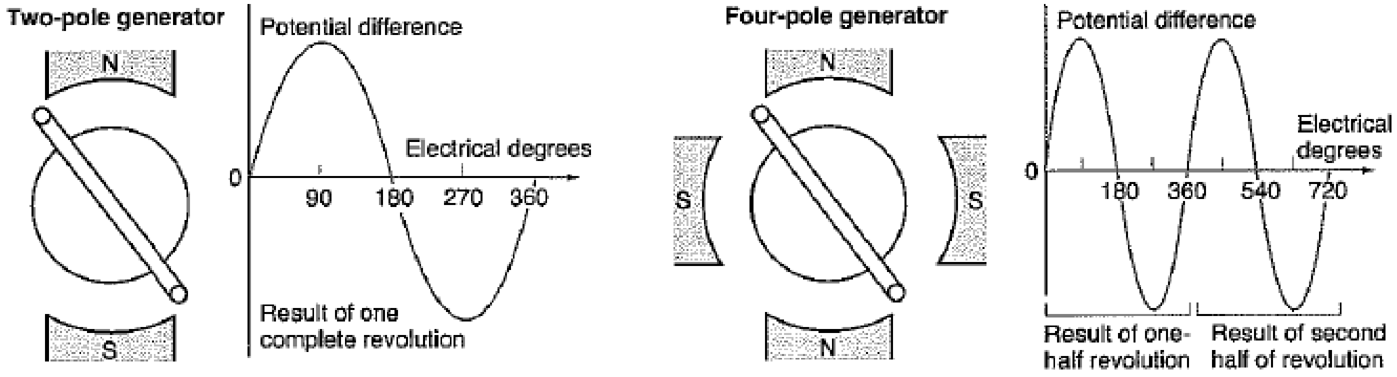


Figure 9.5: Electrical Degrees Compared to Mechanical Degrees

9-27 The frequency of electricity generated depends on the number of magnetic poles in the generator and on the rate at which the conductor rotates. You can calculate the frequency of an AC generator by placing the proper values in the following equation.

$$f = \frac{1}{15\Omega} x \frac{N}{60} = \frac{PN}{120}$$

Where f = Frequency of the alternating current in hertz

P = Number of north and south magnetic poles in the generator

N = Number of times the conductor rotates per minute (RPM)

9-28 For example, suppose you need to calculate the frequency generated by an 8-pole alternator that runs at 900 revolutions per minute. You simply enter these values into the equation, and use simple arithmetic to calculate the result. You should use a calculator, if you have one.

$$f = \frac{8\,Poles\ x\ \ 900\ RPM}{120}$$

Resistance in AC Circuits

9-29 Many ac circuits are mainly *resistive*. That is, they consist mainly of resistors, without inductors or capacitors. For example, resistors, lamps, heating elements, and other simple electrical devices have very little inductance or capacitance. In practice, they are considered to be purely resistive, with little or no inductance or capacitance. The effect of inductance and capacitance in ac circuits will be explained in later paragraphs.

9-30 When only resistive devices occur in an ac circuit, you can use Ohm's law exactly as in a dc circuit. The equation for Ohm's law (*E = I x R*), and the equation for power (*P = E x I*) also apply to all resistive ac circuits.

9-31 When you connect an ac power source to a resistor, the potential difference rises and falls, reaching a maximum value first in one direction and then in another. The current in the resistor changes at the same time and in the same direction as the potential difference. Therefore, voltage and current are said to be *in phase* in a resistive ac circuit. The relationship between potential difference and current is shown by the graph in Figure 9.6.

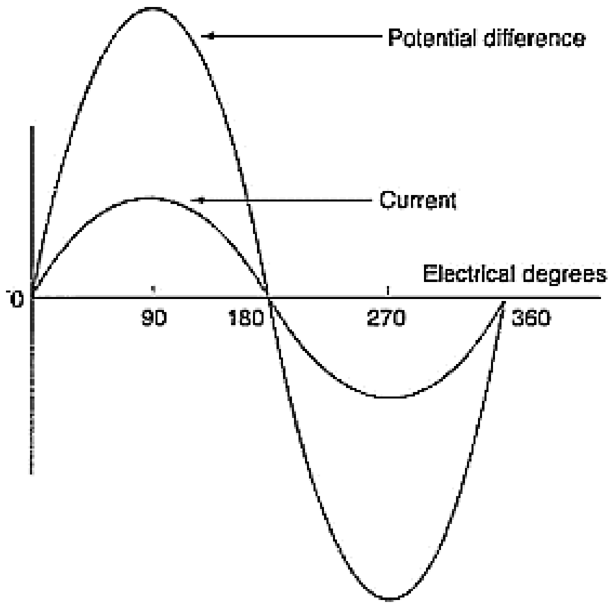


Figure 9.6: Current in Phase with Potential Difference

Inductance in AC Circuits

9-32 Inductance is the property of a coil of wire that *opposes* any change in the current flowing through the coil. The opposition to changes in current is an electromagnetic effect. A potential difference is induced in a conductor whenever the conductor moves across a magnetic field and whenever the magnetic field changes around a conductor.

9-33 In addition to *opposing* a change in current, a coil *delays* the change. Figure 9.7 shows the delay. Notice that the frequency of the current equals the frequency of the potential difference. That is, the time between peaks is the same for both curves in Figure 9.7. But the curve for current is delayed 90° compared to the curve for potential difference.

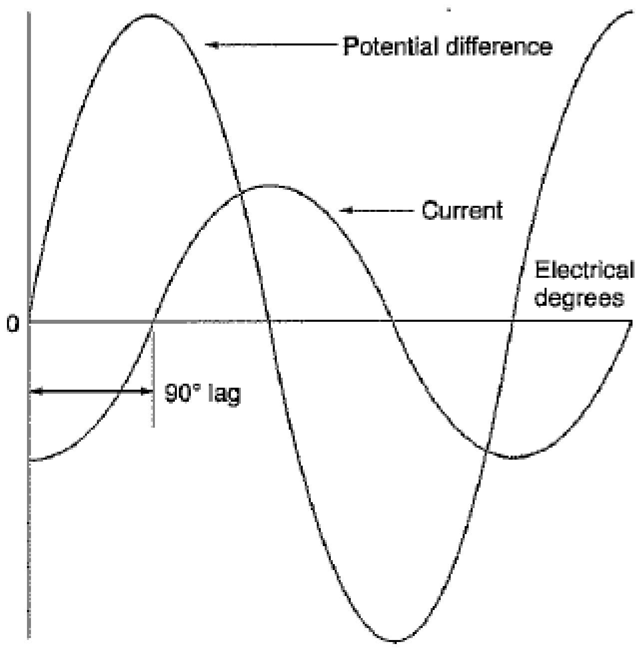


Figure 9.7: Current lagging Potential Difference

9-34 When the current is constant, as in a dc circuit, the magnetic field around the conductor is also constant. But when the current changes continuously, as in an ac circuit, the magnetic field around the conductor also changes continuously. As current increases from zero to a maximum value, the magnetic field around the conductor increases from zero to a maximum value. As the current returns to zero, the magnetic field around the conductor also decreases.

9-35 In any conductor, an increasing or decreasing magnetic field generates its own potential difference across the conductor. This *induced* potential difference opposes the potential difference of the source.

9-36 If potential difference of the source increases in the *positive* direction, the increasing current in the coil generates a second potential difference in the *negative* direction. The combined effect of these two potential differences produces a current that is reduced and delayed from what it would be without inductance in the circuit.

Inductance in AC Circuits (continued)

9-37 This effect is summarized in a statement known as *Lenz's law* as stated below.

> "The induced potential difference in any circuit is always in a direction that opposes the effect that produced it."

9-38 The inductance of a coil depends on several factors, including the number of turns of wire, the shape and size of the coil, how the wire is wound, and the material used in the core of the coil. Figure 9.8 shows the variations in coils.

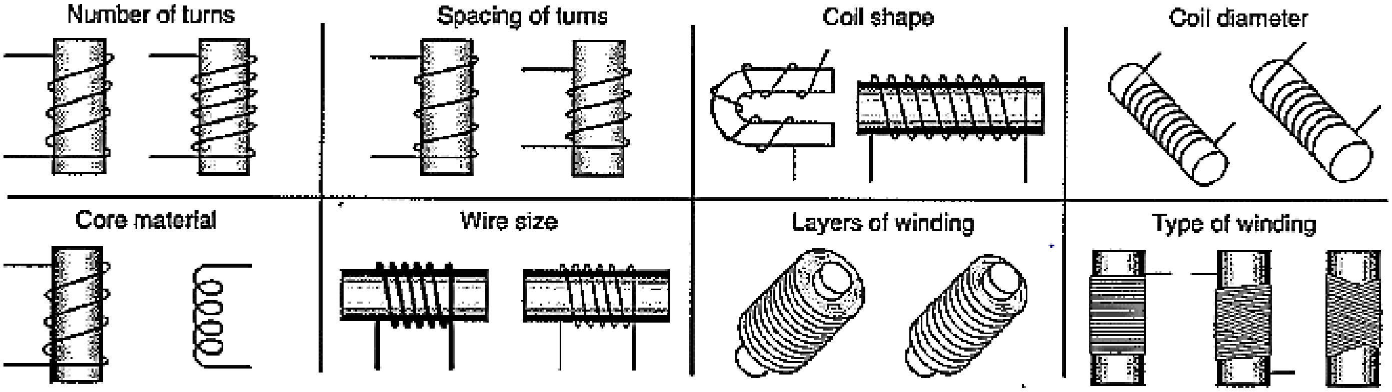


Figure 9.8: Variations in Coil Shapes and Windings

9-39 Another important factor in inductance is the "linkage" among the magnetic fields produced at various points along the conductor. Inductance is very small in a straight conductor, because there is little linkage of the magnetic fields from various points on the conductor. Inductance increases when the conductor is wound in the shape of a coil, because there is more linkage.

9-40 In equations, the value of inductance is usually represented by the letter *L*. The unit of measurement for inductance is the *henry*. A conductor has an inductance of **one henry** when current changing at the rate of one ampere per second in the conductor causes an induced potential difference of one volt.

9-41 An inductance smaller than one henry may be measured in smaller units. The *millihenry* equals one thousandth of a henry, and the *microhenry* equals one millionth of a henry.

9-42 When an inductor opposes changes in the current in an ac circuit, the opposition is called **inductive reactance**. Inductive reactance is measured in *ohms*, like resistance, but it differs from resistance in two important ways.

- Inductive reactance has no effect on a steady dc circuit.
- The amount of inductive reactance depends on the *frequency* of the alternating current. The higher the frequency, the higher the inductive reactance of a given inductor.

Capacitance in AC Circuits

9-43 Capacitance in an ac circuit causes the current to *lead* the potential difference, rather than to lag behind. In this respect, capacitance counteracts the inductance in a circuit. Capacitance is useful in overcoming the inductive lag common to most ac motors.

9-44 Capacitance is the property of an electric circuit that opposes any change in potential difference between two points.

- When the power supply tries to *increase* the potential difference between the points, a capacitor builds up a charge internally. By absorbing charge, the capacitor delays the increase in potential difference. As the charge builds up, current flows into one terminal of the capacitor and out the other.
- When the power supply tries to *decrease* the potential difference, the capacitor releases charge and delays the decrease. As the capacitor releases charge, current flows out one terminal and into the other.

9-45 In an ac circuit, the potential difference across a capacitor is always changing. Electric current always flows, because the capacitor is either giving up or collecting charge.

9-46 The capacitance of a capacitor is represented in equations by the letter C. Capacitance is measured in units called *farads*. One **farad** is the capacitance of a capacitor that stores one coulomb of charge when the potential difference across its terminals is one volt.

9-47 Most capacitors have capacitance measured in small fractions of a farad. The units for measuring these small capacitances are *microfarads* (millionths of a farad) and *picofarads* (millionths of a microfarad).

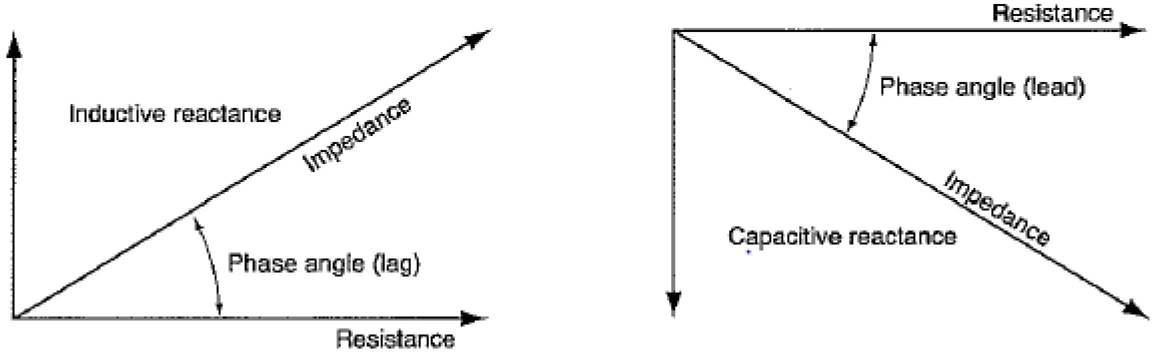
9-48 A capacitor opposes the flow of current in an ac circuit, just as an inductor does. This opposition is called **capacitive reactance**. It is measured in ohms, just as resistance and inductive reactance are. But capacitive reactance is different from either one.

- In a steady dc circuit, the capacitive reactance of a capacitor is infinitely large—the capacitor completely stops the current.
- In an ac circuit, the capacitive reactance depends on the frequency of the source. As the frequency increases, the capacitive reactance decreases.

9-49 Inductive reactance, capacitive reactance, and resistance are all measured in ohms. The total opposition to current in a circuit depends on all three values. However, the three values cannot be added together as simply as when the circuit contains only resistance.

Capacitance in AC Circuits

9-50 When you add together the inductive reactance, the capacitive reactance, and the resistance in a circuit, you must add them by vector addition, as shown in Figure 9.9. The resulting value is called the **impedance** of the circuit.



Adding resistance and inductive reactance **Adding resistance and capacitive reactance**

Figure 9.9: Vector Addition of Resistance and Reactance

9-51 Vector addition is explained in detail in another unit on ac circuits. For now, you should understand only that you will need to use a special method for such an addition. You will need this method when you evaluate an ac circuit that contains capacitors and coils.

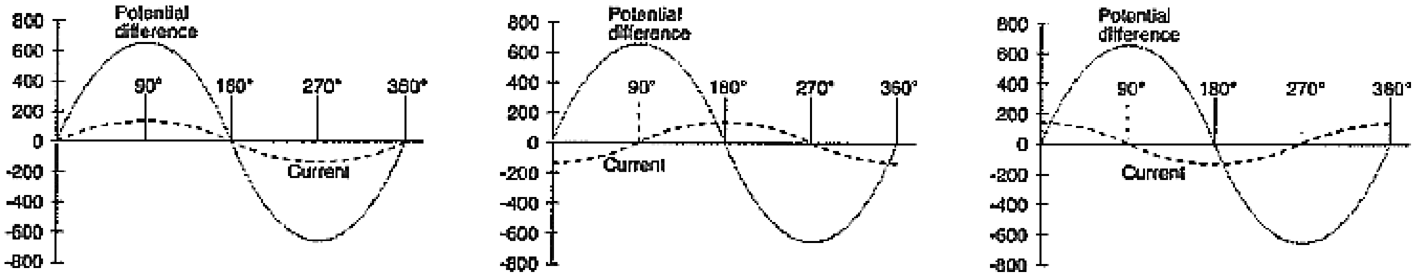
Current in AC Circuits

9-52 When the current and potential difference in a circuit alternate "in step" with each other, the current is said to be *in phase* with the potential difference. In some circuits, the current alternates a little ahead or a little behind the potential difference. The current is then said to be *out of phase* with the potential difference.

9-53 A difference in phase is commonly expressed in electrical degrees. The value is called the *phase angle*.

9-54 There are three possible phase relationships between current and potential difference in an ac circuit.

- The current may be exactly *in phase* with the potential difference as shown at the left in Figure 9.10. This condition occurs when the circuit contains resistance but no inductance or capacitance.
- The current may *lag* behind the potential difference as shown in the middle portion of Figure 9.10. The phase angle can be as large as 90°. This maximum phase angle occurs in a circuit that contains inductance but no resistance or capacitance.
- The current may *lead* the potential difference as shown at the right in Figure 9.10. The phase angle can be as great as 90° if the circuit contains capacitance but no resistance or inductance.



In phase
No capacitance or inductance

90° out of phase
Inductance, but no capacitance.
Current lags potential difference.

90° out of phase
Capacitance, but no inductance.
Current leads potential difference.

Figure 9.10: Phase Relationships Between Current and Potential Difference

Power in AC Circuits

9-55 When you calculate power in a dc circuit, you measure the potential difference across a circuit power in a dc circuit, you measure the potential difference across a circuit element and multiply by the current through the element. You do not need to be concerned about any changes in these measurements with time, because in a dc circuit both the potential difference and the current remain steady.

9-56 In an ac circuit, you start from the same idea that power is the product of potential difference and current. However, you cannot simply multiply the two values, because both values are always changing.

9-57 Power at any instant of time in an ac circuit is the product of the *instantaneous* values of potential difference and current, taken from the two sine curves. Power is positive whenever the potential difference and the current are both positive or both negative. Power is negative whenever the potential difference and the current have opposite signs. Three examples are shown in Figure 9.11.

9-58 *Average power* is a constant value that defines a rectangle on the graph. The rectangle has an area equal to the area enclosed by the positive portion of the power graph minus the area enclosed by the negative portion. This average power is also called the *effective power* in the circuit.

9-59 When the potential difference and the current are in phase, the average power can be calculated by multiplying the RMS potential difference and the RMS current. But if the potential difference is out of phase with the current, the average power will be lower in value. If they are 90° out of phase, the average power is zero.

9-60 The ratio of the average power to the in-phase power is called the *power factor*. It is expressed by the following equation:

$$\text{Power Factor} = \frac{\text{Average Power}}{\text{In-Phase Power}}$$

9-61 You can see from this equation that the power factor equals one only when the potential difference and the current are in phase. When they are 90° out of phase, the power factor is zero. The power factor is always equal to the cosine of the phase angle.

Chapter 9 Exercise

Circle the appropriate letter next to the correct answer.

1. The potential difference and the current both change direction at a regular rate in _________________.

   a. Alternating current
   b. Direct Current
   c. Electric current
   d. Electromagnetic current

2. In the United States and Canada, the standard alternating rate for electric power is _________________.

   a. 40 Hz
   b. 50 Hz
   c. 60 Hz
   d. 120 Hz

3. Alternating current is changed from one combination of potential difference and current to another by a(n) ___________________.

   a. Generator
   b. Alternator
   c. Capacitor
   d. Transformer

4. In making calculations involving alternating current, you should use the __________________.

   a. Highest value
   b. Effective value
   c. Constant value
   d. Instantaneous value

5. How many electrical degrees are in one complete electrical cycle?

   a. 90
   b. 180
   c. 270
   d. 360

Chapter 9 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. Resistive ac circuits consist mainly of ___________________.

   a. Capacitors
   b. Inductors
   c. Resistors
   d. Transistors

7. In addition to opposing a change in current, a coil ________________.

   a. Delays the change
   b. Hastens the change
   c. Decreases the change
   d. Increases the change

8. Which of the following is NOT a factor in the inductance of a coil?

   a. The number of turns of wire
   b. The size and shape of the coil
   c. The material in the coil's core
   d. Potential difference on the coil

9. The total opposition to the flow of current in an ac circuit is called _________________.

   a. Inductive reactance
   b. Capacitive reactance
   c. Resistance
   d. Impedance

10. A difference in phase between the current and the potential difference is commonly called _________________.

   a. Phase angle
   b. Phase difference
   c. AC difference
   d. lead or lag

Summary

Alternating current is widely used in industry. In ac circuits, both the potential difference and the current change direction at a regular rate. The main advantage of ac is that it can be generated, transmitted, and transformed at low cost.

The standard alternating rate of power in the United States is 60 hertz or 60 complete back and forth cycles every second.

Many ac circuits consist mainly of resistors. Connecting an ac power source to a resistor causes the potential difference to rise and fall. The current in the resistor changes at the same time and in the same direction. The voltage and current are said to operate in phase. If the current is not in phase with the potential difference, the current is said to be out of phase.

Inductance in an ac circuit is the property of a coil of wire that opposes any change in the current flowing through the wire. The coil also delays the change. The unit of measurement for inductance is the henry.

Capacitance in an ac circuit causes the current to lead the potential difference. Therefore, capacitance counteracts the lag caused by inductance. Capacitance is measured in farads.

Chapter 10: Electronics

In This Chapter

- **Development of Electronics**
- **Electron Motion in a Vacuum Tube**
- **Kinds of Cathodes**
- **Vacuum-Tube Diode**
- **Vacuum-Tube Triode**
- **How a Triode Amplifies**
- **A Vacuum-Tube Circuit**
- **Semiconductors**
- **Semiconductor Junctions**
- **Kinds of Semiconductor Diodes**
- **Transistors**
- **Kinds of Transistors**
- **Microprocessors**

Terminology

Filament: Heating element for the cathode in a vacuum tube

Anode: Positively-charged element in a vacuum tube

Cathode: Negatively-charged element in a vacuum tube

Directly-heated cathode: Filament that also serves as a cathode

Indirectly-heated cathode: Cathode separate from its heating element

Diode: Electron tube containing only two elements, a cathode and an anode

Triode: Electron tube containing three elements, a cathode, an anode, and a control grid

Semiconductor material: A material with properties between those of a conductor and an insulator

Transistor: Two junction diodes connected back-to-back

Integrated circuit: A circuit manufactured as a single unit

Probably the greatest change in electronics technology was the development of the transistor 30 years ago. Since that time the vacuum tube, once the basis of all electronic devices, has largely been replaced by the transistor. And even the transistor has been replaced by the integrated circuit in many electronic instruments.

This Lesson explains all three kinds of electronic devices. Information on the vacuum tube is included because it was the forerunner of modern electronics. It is also the most easily understood of the three devices.

This Lesson is intended as an introduction to electronics. Other units are available which deal specifically with the details of this technology.

Development of Electronics

10-1 Until 1960, the word *electronics* meant the technology of *vacuum tubes*. But within ten years after the invention of the transistor, in 1951, electronic systems with vacuum tubes were obsolete. The transistor replaced the vacuum tube as the basic electronic device, except for certain special uses. Transistors are cheaper to manufacture, less fragile, use less electricity, and last longer than vacuum tubes.

10-2 In the late 1970s, the technology of manufacturing electronic devices had advanced to the point where a whole circuit could be manufactured as a single unit, called an *integrated circuit*. The most complex of the early integrated circuits contained several hundred components, including transistors, resistors, and capacitors all properly connected together.

10-3 Within a few years, the maximum number of circuit components possible in a single integrated circuit had increased to several thousand. Today the number in some integrated circuits is over one million. Integrated circuits are widely used in calculators, computers, machine-control systems, automobiles, and countless other devices.

10-4 In this Lesson, we describe all three kinds of electronic devices. We start with the vacuum tube, because of its historical importance and because it is the easiest to understand. Then we describe transistors and integrated circuits.

10-5 This Lesson is not intended to make you an expert in electronics. It is only an introduction to the subject. If you are interested, or if your job requires you to know more about electronics, you should study other manuals that deal specifically with the details of electronics.

Electron Motion in a Vacuum Tube

10-6 The difference between a vacuum tube and other electrical devices is that in the vacuum tube, electrons do not move from atom to atom, as in a conductor. Instead the electrons fly freely through empty space called a vacuum.

10-7 Free electrons are "boiled out" of hot metal. The electrons are then repelled by a negative charge applied to the metal by an external power supply. The negatively-charged electrons are also attracted by a positively-charged plate inside the tube. The attraction and repulsion of the electrons produce the electric current in a vacuum.

10-8 A practical way to get large numbers of free electrons in a vacuum is by *thermionic emission*. Thermionic emission takes place when some of the electrons in a hot metal gain enough energy to escape from the surface into the vacuum.

Electron Motion in a Vacuum Tube (continued)

10-9 In a vacuum tube, a thin wire is heated electrically until it glows bright orange, as shown in Figure 10.1. At this temperature, electrons at the surface of the wire fly off into the space around it. If the temperature of the wire is increased, electrons escape from the surface at a faster rate.

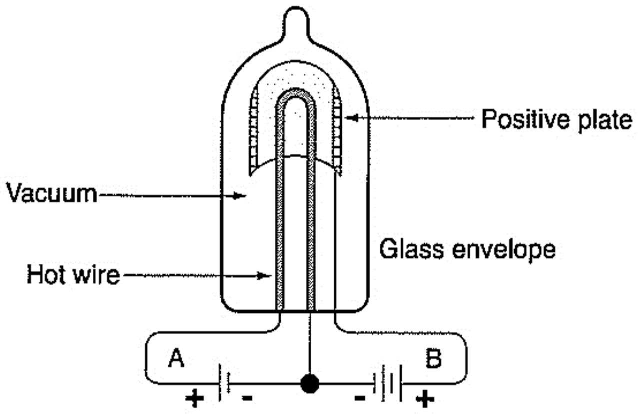


Figure 10.1: Thermionic Emission

10-10 If the hot wire is not given a negative charge, most of the emitted electrons stay close by. They form an electron cloud around the wire. The cloud has a negative charge, because the electrons are negatively charged. The charge of the cloud repels other electrons in the hot wire, hindering their entry into the vacuum.

10-11 The electrons around the wire do not produce an electric current, even if the wire is given a negative charge. A second conductor, in the shape of a curved plate, must be placed in the vacuum tube at a distance from the wire. A positive charge is applied to the plate.

10-12 The electrons from the hot wire are attracted to the positively-charged plate. A stream of electrons then flows from the hot wire to the plate. An external power supply delivers electrons to the hot wire and removes them from the positive plate, maintaining the plate's positive charge.

10-13 The parts of the vacuum tube described so far have special names. You should memorize these names.

Filament: Heating element that produces the temperature required to "boil" electrons out of the cathode

Anode: Curved metal plate with a positive charge

Cathode: Metal with a negative charge

Electron Motion in a Vacuum Tube (continued)

10-14 In Figure 10.1, a single wire serves as both the filament and the cathode. The "A" battery heats the filament to proper temperature. The "B" battery produces a potential difference between the cathode and the anode. It supplies electrons to the cathode, and puts a positive charge on the anode.

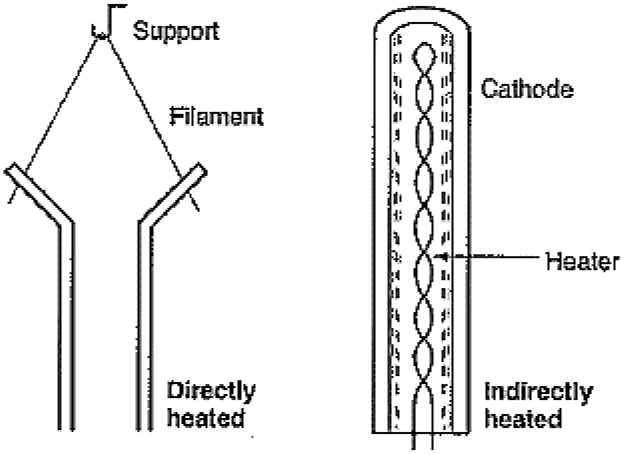


Figure 10.2: Cathodes for Vacuum Tubes

10-15 The negatively-charged electrons are attracted to the anode only when the anode is positive with respect to the cathode. If you reverse battery "B," making the anode negative with respect to the cathode, no current will flow. This effect is an important part of the behavior of a vacuum tube. Electrons can flow in one direction only—from cathode to anode.

Kinds of Cathodes

10-16 The cathodes used in vacuum tubes are classified into two groups.

- **Directly-heated cathodes**, also called *filament cathodes*, are heating elements that also serve as cathodes.
- **Indirectly-heated' cathodes**, also called *heater cathodes*, are separate from their heating elements.

Most vacuum tubes have indirectly-heated cathodes.

10-17 The directly-heated cathode is usually shaped like an inverted V, as shown at the left in Figure 10.2. The supporting wires are connected to pins in the tube base. A potential difference between the two pins produces a current that heats the filament to the proper temperature.

10-18 Filament cathodes reach operating temperature very quickly when the current starts. If the filament is connected to an ac source, the emission of electrons varies because of the varying current. This variation is sometimes undesirable. In such cases, a dc source must be used instead.

10-19 An indirectly-heated cathode consists of two separate elements, a *heater* and a *cathode*. The heater is similar to the filament of the directly-heated cathode, but it is not designed to emit electrons.

10-20 The heater is located inside the cathode, as shown at the right in Figure 10.2. The cathode is a hollow metal sleeve that fits over the heater. The heater receives electricity through pins in the base of the tube, just as the filament does. The heater raises the temperature of the cathode to the operating temperature.

10-21 An indirectly-heated cathode does not reach emission temperature as quickly as a directly heated cathode. However, it also does not vary in temperature when the heater is supplied by an ac source. Therefore, ac power can be used in vacuum tubes with indirectly-heated cathodes.

Vacuum-Tube Diode

10-22 An electron tube that contains nothing but a cathode and an anode is called a **diode**. The prefix *di*- means the tube has only *two* electrodes. The heater of an indirectly-heated cathode is not counted as an electrode, because it serves no function in the electronic operation of the tube.

10-23 A diode can conduct current continuously when the anode is positive and the cathode is negative. But it does not conduct when the potential difference is reversed.

10-24 This one-way conducting property of a diode is very useful when changing ac electricity to dc electricity. The device that makes such a change is called a **rectifier**. It requires one or more diodes to prevent electrons from flowing backward when the alternating potential difference changes direction.

Vacuum-Tube Triode

10-25 A vacuum tube with three electrodes is called a **triode**. The prefix *tri-* means *three*. The third electrode is called the *control grid*. The control grid is a wire-mesh structure that fits between the cathode and the anode. It is placed closer to the cathode than to the anode. The shape of the grid affects how the tube works.

10-26 Electrons must pass through the control grid in order to go from the cathode to the anode. If the grid is negative with respect to the cathode, the grid will repel some of the electrons and reduce the number that get through to the anode.

10-27 The number of electrons reaching the anode is reduced according to the potential difference between the cathode and the grid. If the potential difference is made high enough to repel all the electrons leaving the cathode, then the current through the tube will be zero.

10-28 Any steady dc potential difference between the control grid and cathode is called grid bias. The potential difference required to reduce the plate current to zero is called cutoff bias.

10-29 The action of the grid in the triode is shown by the diagrams in Figure 10.3.

- The diagram at the far left shows the triode with cutoff bias applied to the grid. The grid repels all the electrons back toward the cathode. No electrons get to the anode.
- When the grid has a lower bias applied to it, as shown in the center diagram in Figure 10.3, some electrons get through and others are repelled. The electrons that get through the grid continue to the anode, producing a small plate current.
- When the grid has a small bias, or zero bias, more electrons get through the grid. The plate current is then greater.

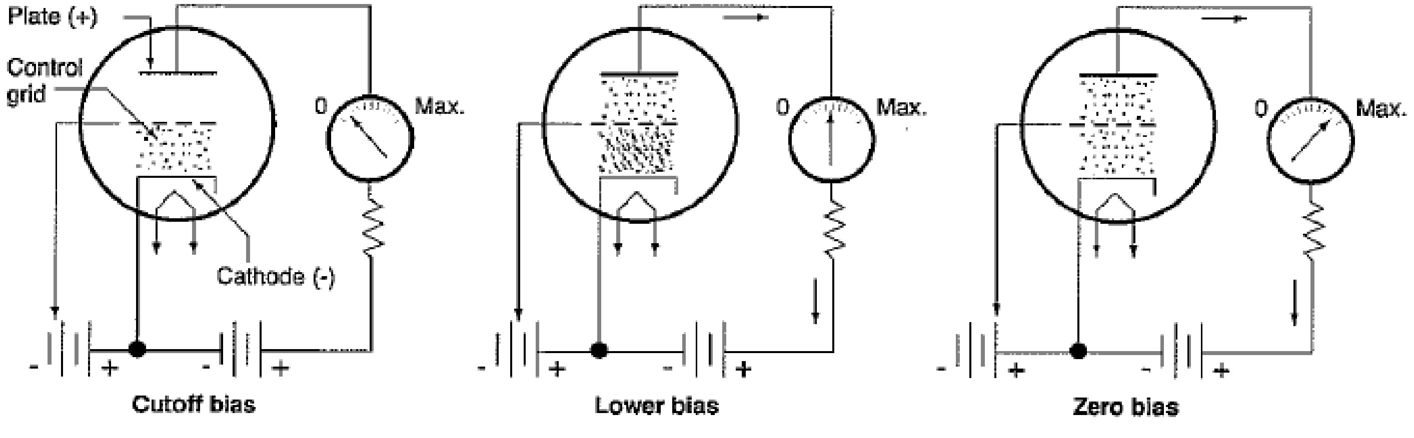


Figure 10.3: Operation of a Triode

10-30 If you vary the potential difference between the control grid and the cathode, the plate current will increase and decrease in response. The changes in plate current will match the variations in the potential difference between the cathode and the control grid.

How a Triode Amplifies

10-31 The control grid in a triode works much like a control valve in a piping system. It controls the rate at which electrons reach the anode. If the grid bias is constant, electrons will flow at a steady rate from the cathode to the anode. By adding an ac signal between the grid and the cathode, you can vary the plate current.

10-32 The signal to the cathode may be very small, and the response in the plate current can be much larger. The output into a load resistor is an exact reproduction of the ac signal on the grid, but amplified. The ac potential difference across the load can be as much as 100 times greater than the input potential difference applied to the grid.

A Vacuum-Tube Circuit

10-33 Vacuum tubes used as amplifiers had many industrial applications. For example, the photoelectric circuit, shown in Figure 10.4, was used for controlling lighting. When light shined on the cathode of a photoelectric cell, labeled V_1 in the diagram, the light-sensitive material emitted electrons. These electrons were attracted by the positively-charged anode, producing a small current.

10-34 The plate current from the photoelectric cell was too small to operate a relay and turn the lighting on or off. Therefore, the current had to be amplified. Before transistors were available, a triode was used to amplify the plate current. The triode is labeled V_2 in Figure 10.4.

10-35 In the circuit, the triode was biased at cutoff. Therefore, no plate current flowed. The cathode of the phototube was connected to the grid of the triode.

10-36 When light fell on the phototube, electrons emitted by the cathode were attracted to the anode of the phototube, leaving a deficiency. Electrons were then drawn from the control grid of the triode to replace the emitted electrons, making the grid of the triode less negative. The lower bias on the grid permitted enough current to flow in the triode to operate the relay. The resistor R_2 was adjusted so the relay operated only when the correct amount of light was shining on the photocell.

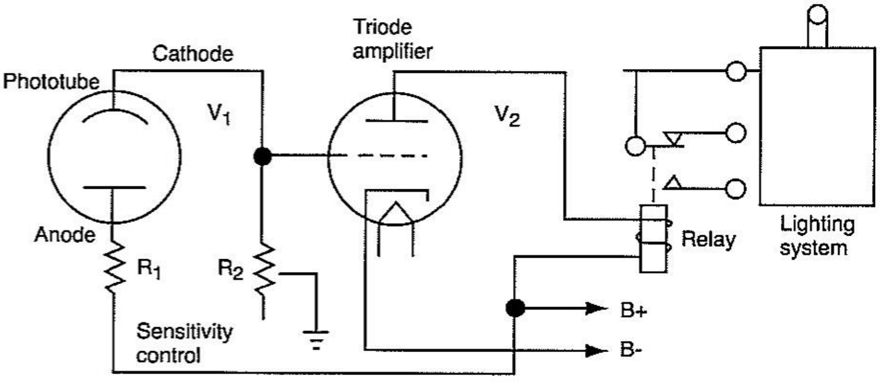


Figure 10.4: Photoelectric Control Unit

A Vacuum-Tube Circuit (continued

10-37 This circuit operated yard lights and parking-lot lights. The photocell usually faced north when controlling outside lighting, so that sunlight never fell directly on the cell. The sensitivity control was adjusted so that the lights were turned on at a certain light level in the evening, and off again at a similar light level in the morning.

10-38 Photocells are still used for this purpose today, and the control circuit is basically the same. However, the circuits use transistors or integrated circuits instead of vacuum tubes.

Semiconductors

10-39 A semiconductor is neither a *conductor* nor an *insulator*, but somewhere between the two. A **semiconductor** is a material with more resistance than a conductor, but with much less resistance than an insulator. Silicon is the chemical element most widely used as a semiconductor material, but the element germanium is also used.

10-40 Few free electrons exist in pure germanium or silicon. In their pure form, these materials are not very good for transistors. However, when a small amount of the proper impurity is mixed with the germanium or silicon, the resistance decreases to the proper level.

10-41 The materials added as impurities can be classified into two groups, depending on the effect they have on the germanium or silicon. One type of impurity produces a material that has a greater number of free electrons. The other type produces a material which lacks certain electrons, leaving "holes" in their place.

10-42 The elements arsenic and antimony are examples of impurities that produce materials with an increased number of free electrons. Figure 10.5 shows the internal structure of a semiconductor material made of silicon with arsenic as an impurity. Notice that the presence of the arsenic atom produces a free electron in the material.

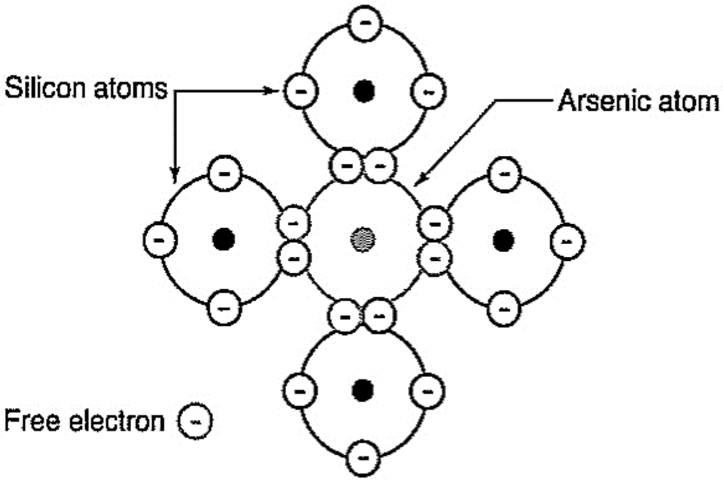


Figure 10.5: *N-Type* Semiconductor Material

Semiconductors (continued)

10-43 The resulting semiconductor material is called an *n-type* material, because when the free electrons move they carry *negative* charges around in the material. An *n-type* semiconductor is also called a *donor*, because it can "donate" electrons to another material.

10-44 If a potential difference is applied across an n-type semiconductor, the free electrons move away from the negative terminal and toward the positive terminal. That is, the semiconductor conducts charge in the same way an ordinary conductor does by means of moving electrons that carry negative charges.

10-45 The elements aluminum and gallium are examples of impurities that produce materials with "holes" where electrons are missing. Figure 10.6 shows the internal structure of a semiconductor made of silicon with aluminum as an impurity. Notice that there is an electron missing in the structure. The spot where the electron is missing is called a *hole*.

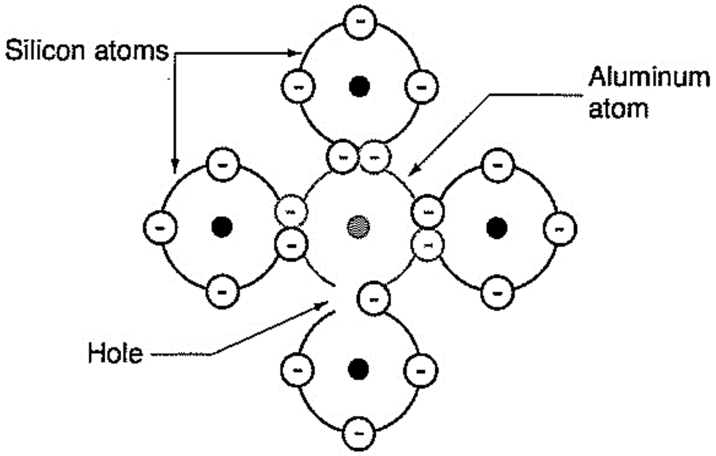


Figure 10.6: *P-Type* Semiconductor Material

10-46 The holes in this semiconductor material can move around. Each hole is the absence of an electron. Therefore, it can be thought of as carrying a *positive* charge. As a result, the semiconductor material is called a *p-type* material. A *p-type* material is also called an *acceptor*, because it can "accept" electrons into the holes.

10-47 If a potential difference is applied across a *p-type* semiconductor, the holes move away from the positive terminal and toward the negative terminal. That is, the semiconductor conducts charge in the opposite way from an *n-type* semiconductor by means of moving holes that carry positive charges.

Semiconductors (continued)

10-48 The movement of holes in a *p-type* semiconductor is shown in Figure 10.7. A hole is actually not a physical object, but an empty spot caused by the absence of an electron. The hole "moves" because an electron moves from another spot to fill the hole.

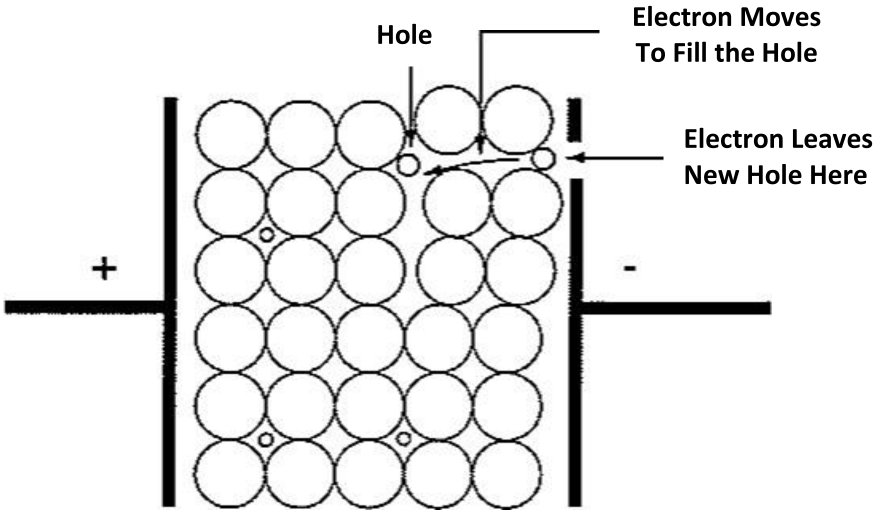


Figure 10.7: N-Type Semiconductor Material

10-49 When the electron moves, it leaves a hole in the place it left. In this way, the hole appears to have moved from one place to another, in a direction opposite from the electrons.

Semiconductor Junctions

10-50 *P-type* semiconductor material conducts because it has a deficiency of electrons, and the conduction is called *hole conduction*. *N-type* material has an excess of electrons, and conduction occurs by means of *electron flow*.

10-51 When a piece of *p-type* material is joined to a piece of *n-type* material, as shown at the left in Figure 10.8, the junction is called a *p-n junction*. This junction can either conduct electricity or not, depending on how the battery is connected.

- If you connect a battery as shown in the center diagram in Figure 10.8 with the *positive* terminal connected to the *p-type* material, a current will flow across the junction and through the external circuit.
- If you reverse the battery connections, so that the *negative* terminal is connected to the *p-type* material, no current will flow. This arrangement is shown at the right in Figure 10.8.

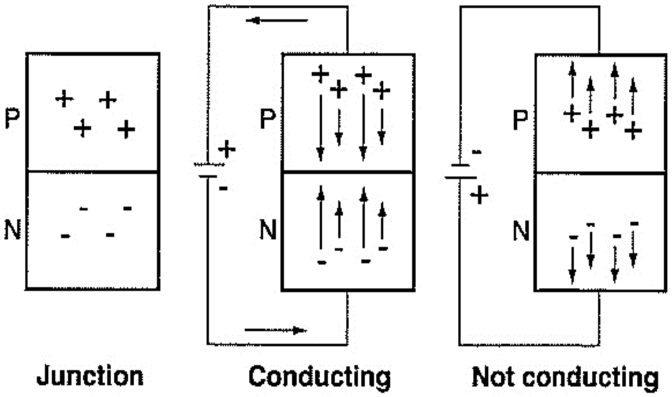


Figure 10.8: Junction Diode

10-52 The electrons are indicated by the *negative* signs in Figure 10.8. When the battery is connected as shown in the center diagram, the electrons are attracted across the junction from the *n-type* material into the *p-type* material. Then they move toward the positive terminal of the battery.

10-53 The holes are indicated by the *positive* signs in Figure 10.8. They are attracted in the opposite direction across the junction by the negative terminal of the battery. With the electrons moving one way across the junction and the holes moving the other way, current flows.

10-54 When the battery is connected in the opposite way, as shown at the right in Figure 10.8, the electrons in the *n-type* material are attracted *away* from the junction, toward the positive terminal of the battery. At the same time, the holes in the *p-type* material are also attracted *away* from the junction, toward the negative terminal of the battery. The material at the junction region then has no current carriers.

10-55 A junction of *p-type* and *n-type* materials works like a vacuum-tube diode. That is, it conducts in one direction but not in the other. The junction is even called a "diode."

Semiconductor Junctions (continued)

10-56 The semiconductor diode does not work quite as well as a vacuum-tube diode, because it allows a small current to flow in the "wrong" direction. It does so because the *n-type* material contains a few holes in addition to its free electrons, and the *p-type* material contains a few free electrons in addition to its holes.

Kinds of Semiconductor Diodes

10-57 A diode is a "two-element unidirectional conductor." That is, it has an anode and a cathode, and it allows current to flow in one direction only. A **junction diode** is made by joining a piece of *p-type* material (the anode) to a piece of *n-type* material (the cathode).

10-58 If the positive terminal of a battery is connected to the anode, and the negative terminal is connected to the cathode, current flows through the diode. The diode is then said to be **forward biased**. If the battery connections are reversed, the diode is said to be **reverse biased**.

10-59 Another type of diode is the **point-contact diode**. It is made of a very small piece of *n-type* germanium. A phosphor-bronze wire, called a *catwhisker*, is pressed into the germanium. A large current is then passed through the catwhisker into the germanium. This action forms a *p-type* region around the catwhisker, as shown in Figure 10.9.

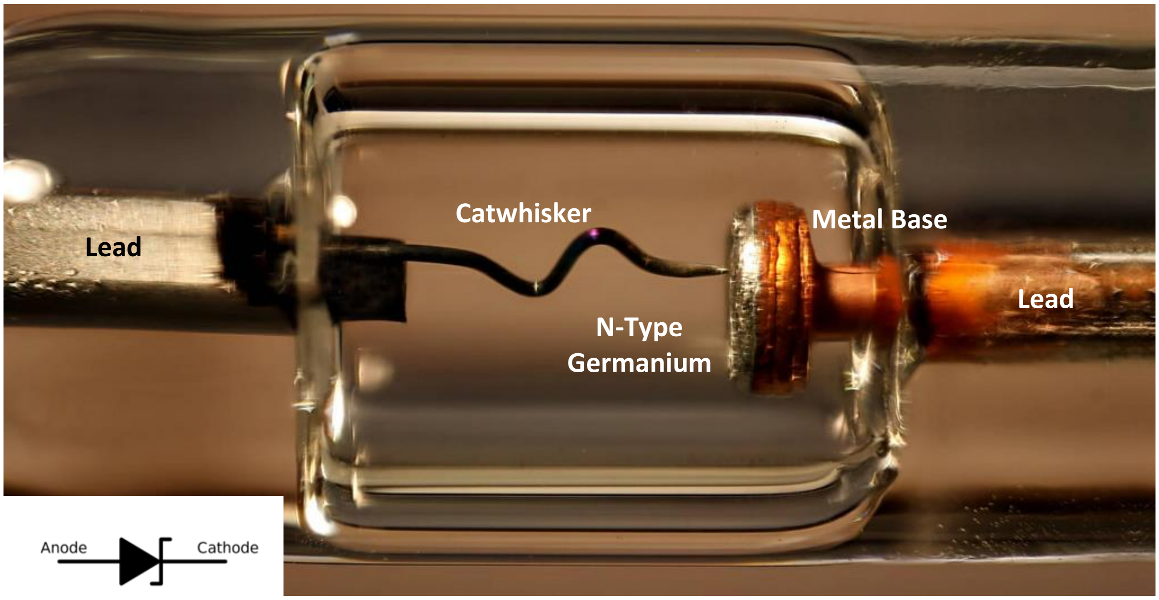
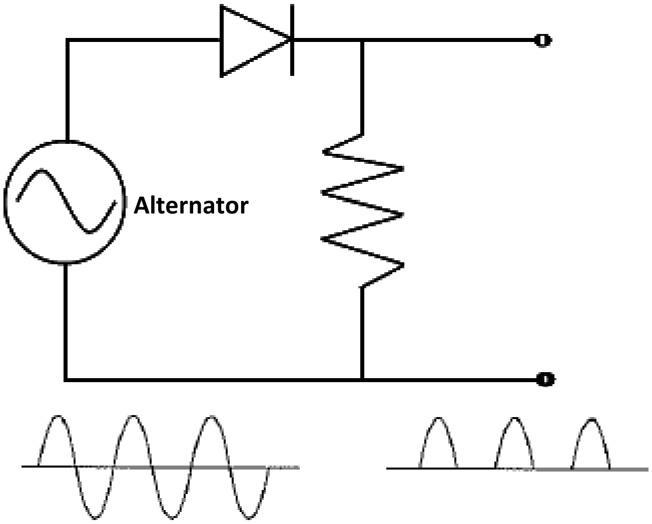


Figure 10.9: Point-Contact Diode

Kinds of Semiconductor Diodes (continued)

10-60 One use of a semiconductor diode is shown in Figure 10.10. The alternator supplies an alternating potential difference, shown by the graph at the left. The diode is connected so that it can conduct *electrons* toward the left and *positive charge* (holes) toward the right. On the diode symbol, the arrow points in the direction *positive* charge can flow.



Output of Alternator **Output of Rectifier**

Figure 10.10: Half-Wave Rectifier

10-61 With the diode connected as shown in Figure 10.10, the potential difference across the resistor varies as shown by the graph at the right. When the diode conducts, current flows through the resistor and the potential difference increases and decreases. When the diode does not conduct, no current flows through the resistor and the potential difference across it remains zero.

10-62 The graph at the right in Figure 10.10 shows that the potential difference across the resistor looks like the upper half of the graph at the left. The lower half of the graph appears to be missing. The output is *rectified*. That is, the current and the potential difference are restricted to one direction only but it is not steady. This kind of circuit is called a *half-wave rectifier*.

Kinds of Semiconductor Diodes (continued)

10-63 The manufacturers of diodes supply operating specifications for each diode. Reading the specifications will help you choose the right kind of diode for a specific use. The specifications include the following kinds of information.

- **Peak inverse voltage** (**PIV**) is the maximum potential difference that can be applied across the diode in the reverse direction without destroying it.
- **Average rectified forward current** is the current the diode can conduct on the average.
- **Peak rectified current** is the maximum current a semiconductor diode can conduct for part of an ac cycle.
- **Surge current** is the maximum current the diode can conduct for one second.
- **Forward voltage** is the forward bias, usually at a definite forward current.
- **Reverse current** is the current at maximum reverse bias.

Transistors

10-64 The invention of the transistor revolutionized the electronics industry. Transistors are much smaller than vacuum tubes, and they are less expensive to manufacture. They are also more rugged than vacuum tubes, and they last longer. Transistors do not need a hot cathode to produce electrons, so they operate on far less power and they require no warmup period.

10-65 A **transistor** consists of two junction diodes joined back-to-back. An example is shown in Figure 10.11. When forward bias is applied to the junction on the left, electrons move from the *n-type* material to the *p-type* material. Holes move in the opposite direction.

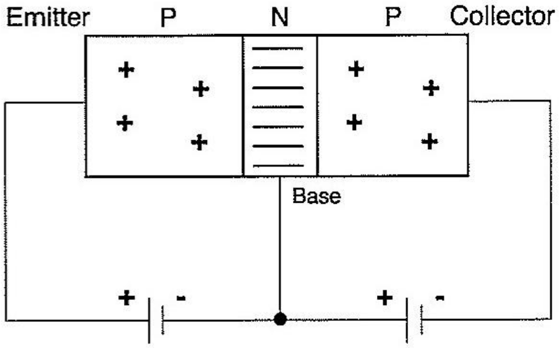


Figure 10.11: Transistor

10-66 Many of the holes moving into the *n-type* material combine with the electrons and are neutralized. But many others travel through the *n-type* material and enter the p-type material at the right.

10-67 When the junction at the right is *reverse* biased, as shown in Figure 10.11, you would expect very little current to flow. But the additional holes made available from the left-hand junction travel toward the right, providing a significant current.

Transistors

10-68 The result is a strong current through the transistor. The current consists of positive holes moving from the *p-type* material at the left to the *p-type* material at the right. The current through the conductor attached to the *n-type* material in the middle is much smaller than the current through the body of the transistor.

10-69 The three sections of the transistor have names based on their function in the device.

- **Base**: The center section of the transistor
- **Emitter**: The part of the transistor that, with the base, makes up the forward-biased junction
- **Collector**: The part of the transistor that, with the base, makes up the reverse-biased junction

10-70 The current in the emitter determines how rapidly holes enter the collector. These holes, in turn, determine the current in the collector. Therefore, the emitter current controls the collector current.

10-71 The current through the base-emitter junction is very small compared to the current through the transistor as a whole. Yet this small current controls the large current. The transistor is said to *amplify* the base-emitter current.

10-72 The current in the emitter and collector are almost equal. However, the resistance of the collector is much higher than the resistance of the emitter, because the base-collector junction is reverse biased. Therefore, the potential difference across the base collector junction is much higher than across the base-emitter junction. Thus, the transistor amplifies the potential difference as well as the current.

10-73 Electric power is the product of potential difference and current ($P = E \times I$). The transistor amplifies both of these values. Therefore, it amplifies the power. A small amount of power into the base-emitter junction is amplified to a much greater power in the base-collector junction.

Kinds of Transistors

10-74 The *junction transistor*, like the one shown in Figure 10.11, can be made in two ways. In one, the base is *n-type* material, and in the other the base is *p-type* material. The first kind is called a *pnp* transistor, and the second is an *npn* transistor.

10-75 The *point-contact transistor*, shown in Figure 10.12 on the next page, has two catwhiskers placed very close together on the surface of a germanium wafer. It is principally of historical interest, because it has been replaced in use by the junction transistor.

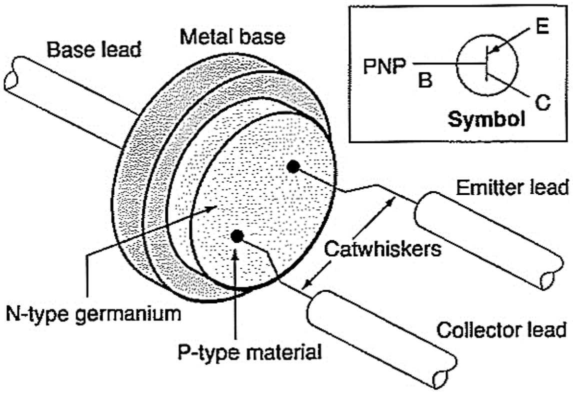


Figure 10.12: Point-Contact Transistor

10-76 The point-contact transistor was difficult to manufacture. The two contact points had to be very close together in order to provide good operating characteristics. In addition, the point-contact transistors had lower power-handling capacities than junction transistors.

10-77 Note the symbols for the kinds of transistors shown in Figure 10.13 on the next page. In the symbol for the *pnp* transistor, the arrowhead on the emitter points toward the base. In the symbol for the *npn* transistor, the arrowhead points away from the base.

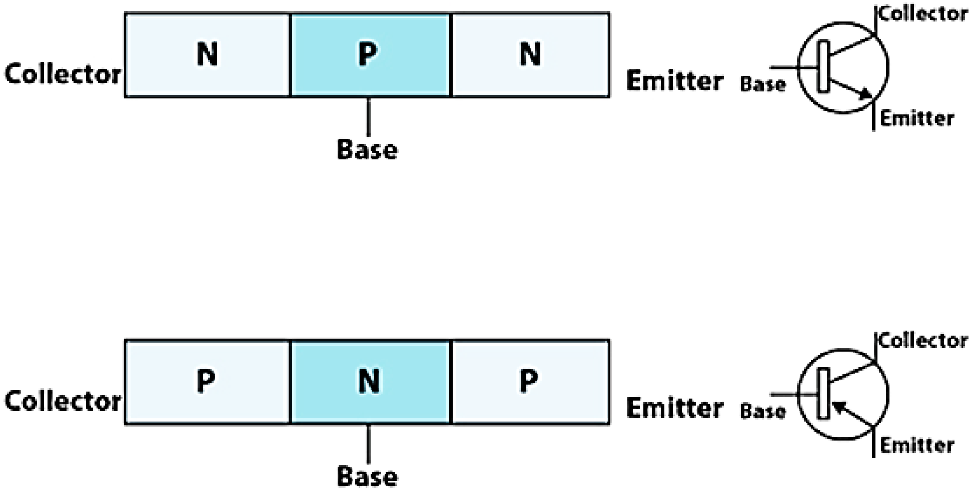


Figure 10.13: ***PNP*** **and** ***NPN*** **Transistors**

Kinds of Transistors (continued)

10-78 Transistors work well on low potential differences. They are widely used in battery-operated devices. Examples include portable radios and calculators. A typical single-battery circuit is shown in Figure 10.14.

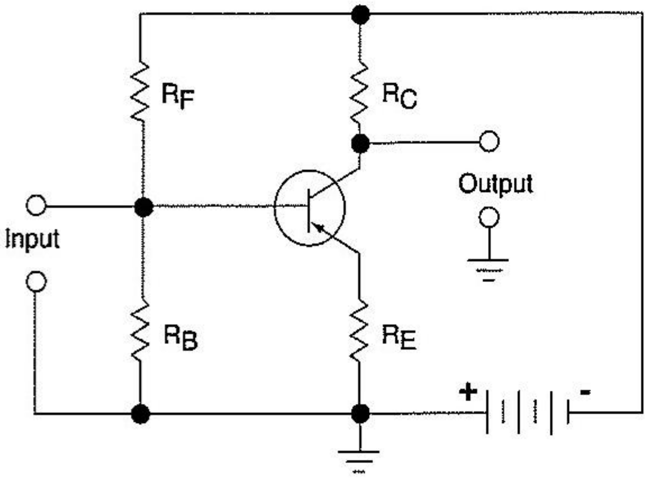


Figure 10.14: Typical Transistor Circuit

10-79 The resistor R_E in the emitter circuit improves stability. The dc current in this resistor applies bias to the base of the transistor, making it negative with respect to the emitter. Therefore, a separate battery is not needed to provide the base bias.

Microprocessors

10-80 The general trend in designing electronic circuits has always been to reduce the size of any given circuit. You can see this trend if you compare antique devices to modern ones.

- A portable tube-type radio made in the 1940s required a sturdy carrying handle and a strong arm to move it. The battery made up much of the weight, and the battery life was measured in hours of playing time. A modem transistor radio slips into your shirt pocket, and the battery lasts for months.
- The first electronic calculator filled a large room. It had thousands of vacuum tubes that consumed many kilowatts of electric power. The tubes gave off so much heat that the calculator needed its own ventilating system. Today a calculator fits in the palm of your hand and runs on a small battery.

10-81 The reason for reducing the size of electronic equipment involves more than saving weight and power. In calculators and in control equipment, it is also important to save the *time* it takes for an electric signal to go from one component to another. The signal takes less time to travel the length of a *short* conductor than to travel the length of a *long* conductor. Therefore, the device can perform more steps in a given time.

Microprocessors (continued)

10-82 After the invention of transistors, the next logical step was to manufacture whole circuits with transistors and other components in place, connected, and ready to work. These devices are called **integrated circuits** (abbreviated IC).

10-83 Integrated circuits are mass produced by photochemical methods on a base of silicon. The final product is called a "chip." A single chip can include many thousands of transistors and other components all connected together in a complex circuit. You can hold it on your fingertip. You need a microscope to see the individual parts.

10-84 A **microprocessor** is an integrated circuit used as a miniature computer. It can take information in, perform complex calculations, and send the resulting information out to control a process or display information to an operator.

10-85 Some microprocessors are used in controlling complex operations in the plant. Others control only simple devices, including motors, valves, and other equipment. A **microprocessor system** is a group of chips and related components.

10-86 Memory is an important part of a microprocessor system. Two kinds of memory systems are in common use.

- **Random-access memory** (abbreviated RAM) is used for storing information temporarily.

  The microprocessor can recall information from any location in the RAM at any time. When the information is no longer needed, that location can be used to store other information.

- **Read-only memory** (abbreviated ROM) is used for storing instructions for the microprocessor. The microprocessor uses the information in ROM in a prearranged sequence, rather than randomly.

10-87 Figure 10.15 is a simple diagram of a microprocessor system. It includes the microprocessor chip, a RAM chip, a ROM chip, and an input-output device that controls the flow of information to and from the machine. Figure 10.16 is a photograph of a microprocessor chip, greatly enlarged.

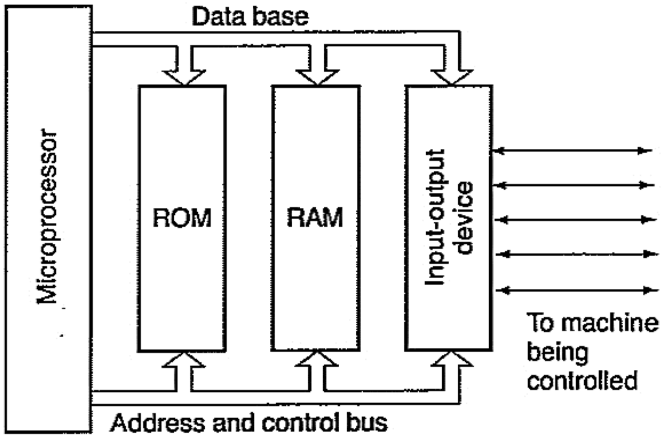


Figure 10.15: Microprocessor System

Microprocessors (continued)

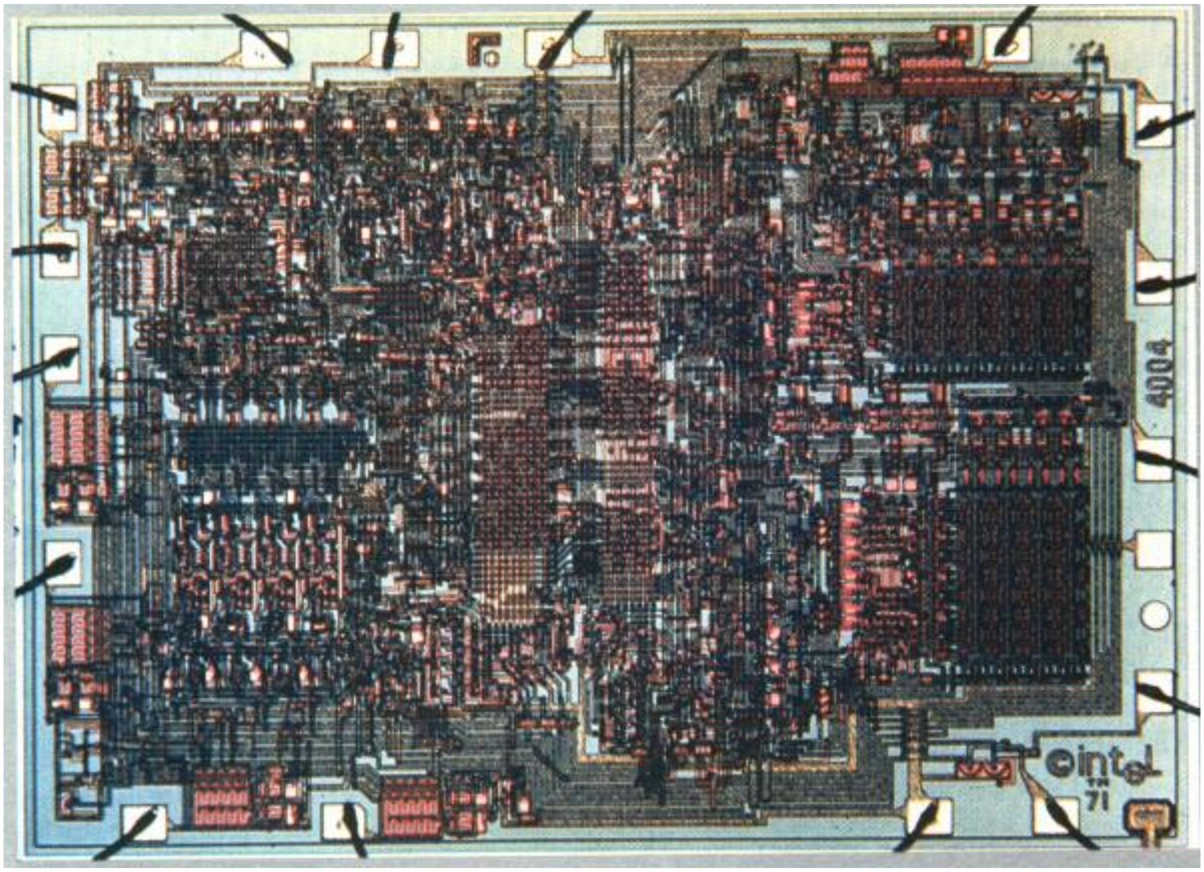


Figure 10.16: Microprocessor Chip

Chapter 10 Exercise

Circle the appropriate letter next to the correct answer.

1. Which of the following is NOT part of a vacuum tube?

   a. Anode
   b. Cathode
   c. Diode
   d. Filament

2. The third element in a triode is called the _________________.

   a. Control grid
   b. Rectifier
   c. Grid bias
   d. Insulator

3. Most photoelectric control circuits made today do NOT use __________________.

   a. Integrated circuits
   b. Transistors
   c. Electrons
   d. Vacuum tubes

4. A material with more resistance than a conductor but less than an insulator, is called a(n) __________________.

   a. Chemical element
   b. Semiconductor
   c. Donor
   d. *n-type* material

5. In n-type material, conduction occurs by means of __________________.

   a. Hole movement
   b. Amplification
   c. Electron movement
   d. Cutoff bias

Chapter 10 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. If the positive terminal of a battery is connected to the anode, and the negative terminal is connected to the cathode, will the diode conduct?

   a. Yes
   b. No
   c. Maybe
   d. Impossible to tell

7. The maximum current a diode can conduct for one second is called the _________________.

   a. Peak rectified current
   b. Average rectified current
   c. Forward voltage
   d. Surge current

8. The center of a transistor is called the _________________.

   a. Base
   b. Collector
   c. Diode
   d. Emitter

9. The reason for reducing the size of electronic equipment do NOT include saving ________________.

   a. Power
   b. Time
   c. Weight
   d. Steps

10. An integrated circuit used as a miniature computer is called a(n) ________________.

    a. Microprocessor
    b. Transistor
    c. Collector
    d. Random-access memory

Summary

Vacuum tubes, transistors, and integrated circuits are the three basic types of electronic devices. Although vacuum tubes are seldom used today, they paved the way for modern electronic technology and are important for that reason.

The parts of the vacuum tube are the filament, anode, and cathode. The cathodes are either directly heated or indirectly heated. A vacuum tube that contains only a cathode and an anode is called a diode. A vacuum tube with three electrodes is called a triode.

A transistor is made up of two junction diodes joined back-to-back. The forward-biased junction is called the emitter. The reverse-biased junction is called the collector. The center section of the transistor is called the base.

Whole circuits with transistors and other components in place, connected, and ready to work are called integrated circuits. An integrated circuit is also called a chip. A group of chips and related components is called a microprocessor system.

APPENDIX

Answers to Chapter Exercises

Chapter One

1. d. Electromagnetism (Paragraph 1-3)
2. b. Current electricity (paragraph 1-10)
3. d. Matter (Paragraph 1-16)
4. b. Atoms (Paragraph 1-17)
5. a. Nucleus (1-22)
6. c. Neutral (Paragraph 1-26)
7. a. Electrical (Paragraph 1-44)
8. b. Repel each other (Paragraph 1-44)
9. d. Current (Paragraph 1-50)
10. b. Battery (Paragraph 1-59)

Chapter Two

1. b. Leather soles (Paragraph 1-13)
2. a. Two objects (Paragraph 2-18)
3. d. At least AWG No. 8 (Paragraph 2-20)
4. c. Ions (Paragraph 2-26)
5. d. Ground it and purge it (Paragraph 2-43)
6. d. Humidity (Paragraphs 2-51, 2-52)
7. c. Frequently (Paragraph 2-62)
8. c. Metal or carbon brush (Paragraph 2-68)
9. c. Either positive or negative (Paragraph 2-81)
10. a. Electrostatic amplifier (Paragraph 2-84)

Answers to Chapter Exercises

Chapter Three

1. d. Cell (Paragraph 3-10)
2. a. Anode (Paragraph 3-11)
3. c. 6.0 Volts (Paragraph 3-16)
4. c. Sulfuric acid (Paragraph 3-23)
5. d. Series (Paragraph 3-27)
6. d. Overheat and melt down (Paragraph 3-35)
7. c. Electricity and magnetism (Paragraph 3-36)
8. a. Degrees (Paragraph 3-44)
9. d. Photoelectric devices (Paragraphs 3-46, 3-47, 3-49, 3-51)
10. b. Quartz (Paragraph 3-56)

Chapter Four

1. c. Both poles (Paragraph 4-5)
2. b. Repel each other (Paragraph 4-11)
3. b. Mass (Paragraph 4-19)
4. d. Magnetic properties (Paragraph 4-26)
5. a. Speed and strength of the charge (Paragraph 4-33)
6. b. The negative charges move (Paragraph 4-36)
7. d. Electromagnet (Paragraph 4-50)
8. a. Odd-shaped pieces (Paragraph 4-56)
9. c. is an electromagnet (Paragraph 4-59)
10. a. Magnetic pulley (Paragraph 4-60)

Answers to Chapter Exercises

Chapter Five

1. a. Conductors (Paragraph 5-2)
2. a. Ampere (Paragraph 5-18)
3. c. Resistance (Paragraph 5-24)
4. d. Potential difference (Paragraph 5-25)
5. c. Potential difference (Paragraph 5-30)
6. d. Ohms (Paragraph 5-3)
7. b. 30 Volts (Paragraph 5-48)
8. b. Digital meter (Paragraph 5-50)
9. a. Shunt (Paragraph 5-56)
10. b. Series resistor (Paragraph 5-60)

Chapter Six

1. a. Fixed resistor (Paragraph 6-18)
2. c. 20 Percent (Paragraph 6-24)
3. d. Potentiometer (Paragraph 6-43)
4. c. Dielectric (Paragraph 6-46)
5. c. Conductive surfaces (Paragraph 6-56)
6. d. Ganged capacitor (Paragraph 6-63)
7. b. Parallel (Paragraph 6-68)
8. a. Induction (Paragraph 6-73)
9. c. Inductor (Paragraph 6-86)
10. d. Transducer (Paragraph 6-89)

Answers to Chapter Exercises

Chapter Seven

1. c. Porcelain (Paragraphs 7-2, 7-3)
2. b. Copper (Paragraph s7-2, 7-3)
3. c. Circular mil (Paragraph 7-20)
4. a. Breakdown voltage (Paragraph 7-34)
5. d. Varnished-cambric (Paragraph 7-43)
6. c. The kind of conductors being installed (Paragraph 7-45)
7. b. To allow electrons to flow easily (Paragraph 7-48)
8. a. Sealtight™ conduit (Paragraph 7-61)
9. c. 40 (Paragraph 7-65)
10. c. To make good electrical contact (Paragraph 7-72)

Chapter Eight

1. b. Direct current (Paragraph 8-1)
2. c. Electromagnetic fields (Paragraph 8-2)
3. a. Ampere (Paragraph 8-11)
4. d. Watt (Paragraph 8-21)
5. d. Series circuit (Paragraph 8-27)
6. b. Voltage drop (Paragraph 8-30)
7. a. Resistance (Paragraph 8-49)
8. d. Simpler parts (Paragraph 8-53)
9. c. More than half the current (Paragraph 8-63)
10. b. Avoid electrical shock (Paragraph 8-73)

Answers to Chapter Exercises

Chapter Nine

1. a. Alternating current (Paragraph 9-1)
2. c. 60 Hz (Paragraph 9-2)
3. d. Transformer (Paragraph 9-8)
4. b. Effective value (Paragraph 9-18)
5. d. 360 (Paragraph 9-23)
6. c. Resistors (Paragraph 9-29)
7. a. Delays the charge (Paragraph 9-33)
8. d. Potential difference on the coil (Paragraph 9-38)
9. d. Impedance (Paragraph 9-50)
10. a. Phase angle (Paragraph 9-53)

Chapter Ten

1. c. Diode (Paragraph 10-3)
2. a. Control grid (Paragraph 10-25)
3. d. Vacuum tubes (Paragraph 10-38)
4. b. Semiconductor (Paragraph 10-39)
5. c. Electron movement (Paragraph 10-50)
6. a. Yes (Paragraph 10-58)
7. d. Surge current (Paragraph 10-63)
8. a. Base (Paragraph 10-69)
9. d. Steps (Paragraph 10-81)
10. a. Microprocessor (Paragraph 10-84)