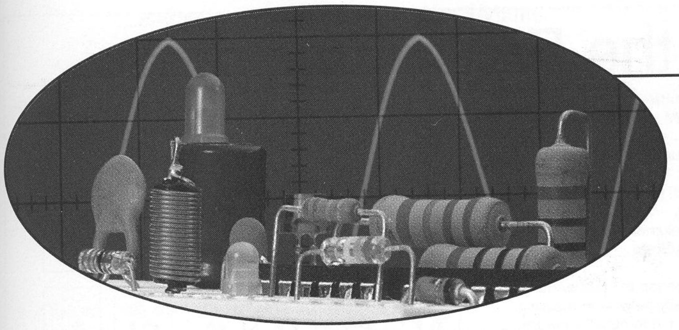


1

Science of Electricity and Electronics

Objectives

After studying this chapter, you will be able to:

- Identify the relationship between elements and compounds.
- Construct a model of an atom.
- Discuss the concepts of atomic weight and atomic number.
- State the law of charges and explain it using several examples.
- Explain what is meant by electric current, voltage, and resistance.
- Describe the two theories of current direction.
- Distinguish between conductors, insulators, and semiconductors.
- State and explain Ohm's law.

Key Words and Terms

The following words and terms will become important pieces of your electricity and electronics vocabulary. Look for them as you read this chapter.

alternating current	insulator
ampere (A)	neutron
atom	Ohm's law
conductor	ohm
coulomb	potential difference
current (I)	proton
direct current	resistance
electromotive force (emf)	semiconductor
electron	volt (V)
element	voltage (*E* or *V*)

We are fortunate to live in an age in which the opportunity exists to study the electron. New discoveries, developments, and applications in electronics occur almost daily. These open a promising vista of unlimited opportunities for the creative scientist as well as for the skilled technician. We are living in a truly electronic age.

1.1 THE NATURE OF MATTER

Everything in the universe is made up of matter. ***Matter*** can be defined as anything that occupies space or has mass. Matter can be found in the form of solids, liquids, and gases. However, these states are subject to relative temperature. Water is usually found in liquid form. Yet water can be readily changed to a solid or a vapor form by changing its temperature. Matter can also be described by color, taste, and hardness, but these are only observable characteristics. They may not truly identify a substance. To truly identify a substance, the substance must be broken down into its smallest parts. The substance must be described in terms of its *atomic structure*. Only then can it truly be defined and its behavioral characteristics identified.

A substance has been broken down to its purest form when breaking it down further will change its atomic characteristics. This form is called an ***element.*** There are over 100 elements. Most of these elements occur naturally in our universe. Some of the elements do not occur naturally, but have been created in laboratories. Some common examples of naturally occurring elements are iron, copper, gold, aluminum, carbon, and oxygen. **Figure 1-1** is a periodic table. This table lists all of the known elements and describes them in the scientific terms that make them each unique. If two or more of these elements are mixed together, a ***compound*** is created. A compound can be reduced to its individual elements. An element can be reduced to its atomic structure. If the atomic structure is reduced, that element is changed to a different element.

Molecule and the Atom

If a crystal of table salt is cut in half, the result is two smaller crystals of common salt. The composition of the salt crystal does not change; it is simply smaller. Salt is a

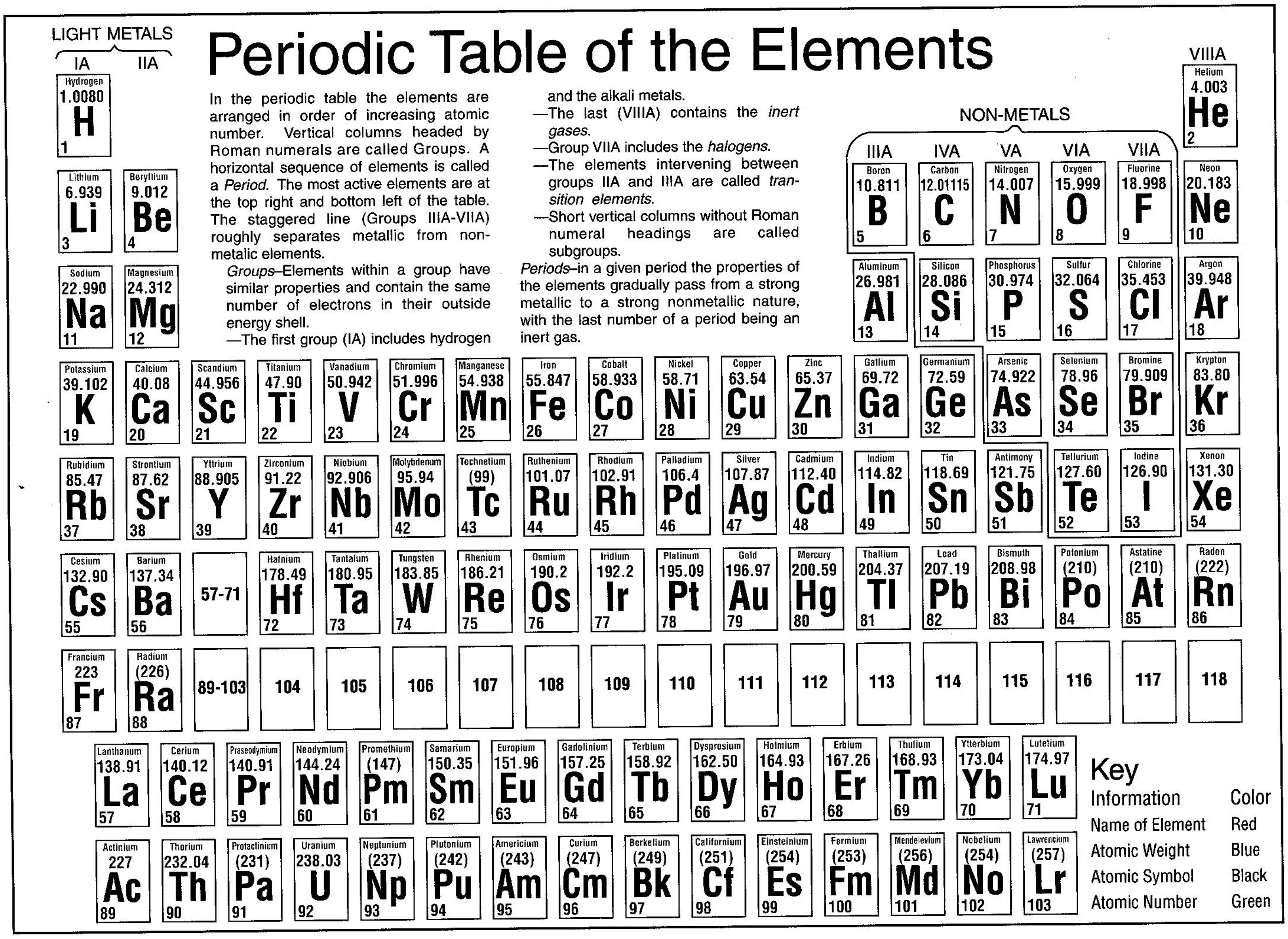


Figure 1-1. Periodic table. (U.S. Air Force)

chemical compound composed of two different elements. The elements are sodium (Na) and chlorine (Cl). Each of these elements, sodium and chlorine, are deadly poisons to the human body. But when combined, sodium and chlorine become the harmless compound known as common table salt, (NaCl). See **Figure 1-2.**

If it were possible for you to smash that crystal of salt into its smallest possible piece, you would have one molecule of salt. A ***molecule*** is the smallest part of a compound that still retains all the characteristics of that compound. If you reduce that single molecule of salt into its next smallest form, it is no longer salt. It is now broken into two different parts. These two parts are the basic elements sodium and chlorine. You have now created poisons out of the normally harmless salt. Do not worry, we have never known salt to be reduced at the dinner table.

The smallest form of an element is known as the ***atom***. The word atom is derived from the Greek word meaning indivisible. The atom is so small that it is difficult to visualize. If we attempted to fill a matchbox with atoms at a rate of ten million per second, it would take over a billion years to fill the box! The atom is the smallest form any material can assume without changing its characteristics. See **Figure 1-3** for a chart and illustrations showing the relationship of matter, compounds, elements, molecules, and atoms.

Electrons, Protons, and Neutrons

To understand the mystery of electricity, and especially the characteristics of solid state electronics, we must have a basic understanding of the structure and forces that make up the atom. Physicists have discovered that atoms are composed of many minute particles. We will be concerned with only the three basic parts of the atom.

The structure of the atom, **Figure 1-4,** is similar to our solar system. In our solar system, the planets (Earth, Venus, Mars, etc.) revolve around the Sun. The planets

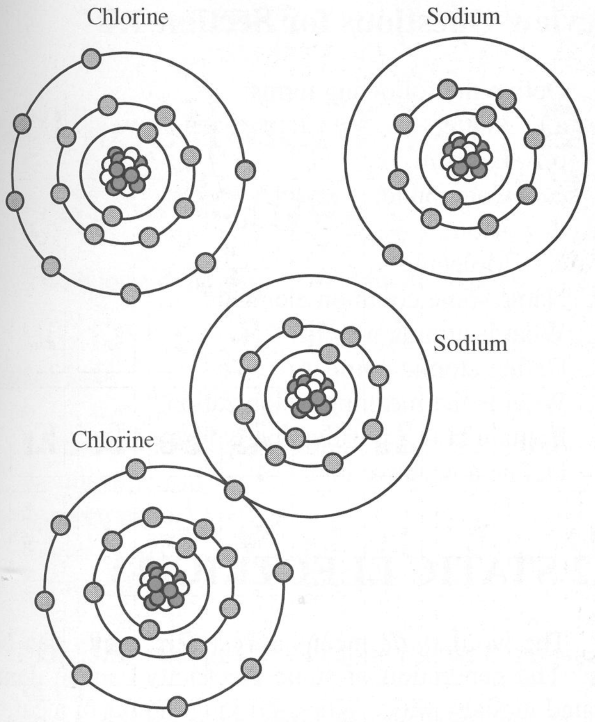


Figure 1-2. Sodium and chloride are both elements. When the atoms of these two elements combine they form a molecule of the compound commonly referred to as table salt.

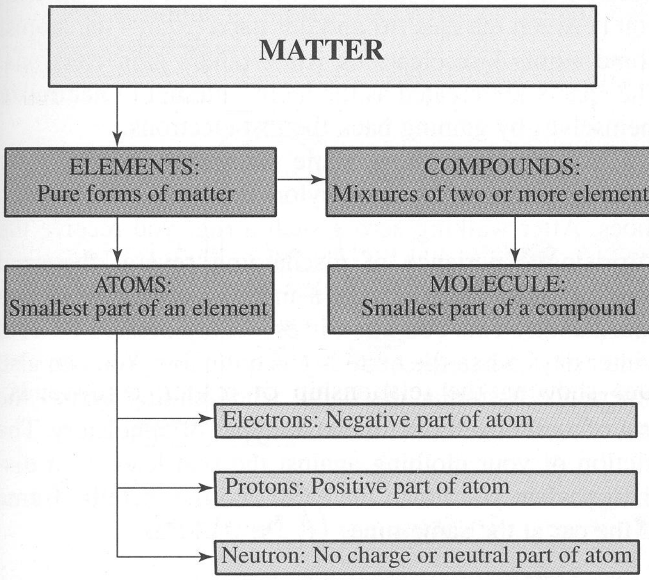


Figure 1-3. The relationship between matter, elements, compounds, atoms, and molecules.

whirl around the sun in their orbits suspended in space by the effects of centrifugal force (pushing them away from the sun) and gravitational attraction (pulling them toward the sun). In an atom, the sun's place is taken by the ***nucleus*** in the center. ***Electrons*** whirl around this nucleus.

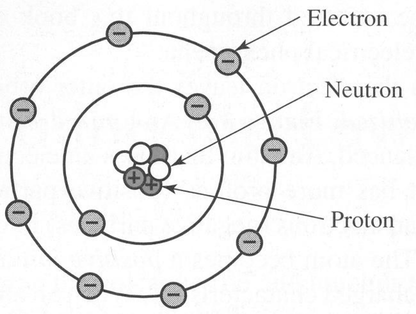


Figure 1-4. The atom consists of electrons, protons, and neutrons.

While planets are held in place with gravity, electrons are held in their orbit by their attraction to the nucleus, overcoming the centrifugal force. The electrons orbiting around the nucleus display a negative charge. The nucleus displays a positive charge because it is composed of positively charged ***protons*** and neutrally charged (neither negative or positive) ***neutrons***. The number of electrons and protons that make up a particular atom are usually equal in number. This equal number creates a canceling effect between the negative and positive charges. The atomic structure of each element can be described as having a fixed number of electrons in orbit. Examples of the atomic structure of two common elements are displayed in **Figure 1-5.**

All elements are arranged in the periodic Table of Elements according to their atomic number. The ***atomic number*** of an element refers to the number of protons or electrons that make up an atom of that element. The order of elements may also be arranged by ***atomic weight***. The atomic weight of an element refers to the approximate number of protons and neutrons in the nucleus. Referring to Figure 1-1, note that the atomic weight of hydrogen is one (scientifically 1.008), and its atomic number is one. The atomic weight of oxygen is sixteen; its atomic number is eight.

Ionization

Usually, an atom remains in its normal state unless energy is added by some exterior force such as heat, friction, or bombardment by other electrons. When energy is added to an atom, the atom becomes excited. If the exterior force is of sufficient strength, electrons in the atoms outer rings or orbits can leave their orbit. How tightly bound these outer electrons are to an atom depends on the element and the number of electrons in the outer orbit. If electrons leave the outer orbit, the atom becomes out of balance electrically. This concept is extremely important and will be repeated throughout this book and in your studies of electrical phenomena.

When the electron leaves the outer orbit, the atom becomes ***ionized,*** **Figure 1-6.** An ionized atom is electrically unbalanced. An atom that loses an electron from its outer orbit has more protons (positive particles) in the nucleus than electrons (negative particles) in orbit around the atom. The atom becomes a ***positive ion*** and displays positively charged characteristics. When an atom gains an extra electron, it becomes a ***negative ion.*** Negative ions display negatively charged characteristics. The electron that has broken out of its orbit is negatively charged. This concept of negative and positive ions is a key building block to understanding electronic theory.

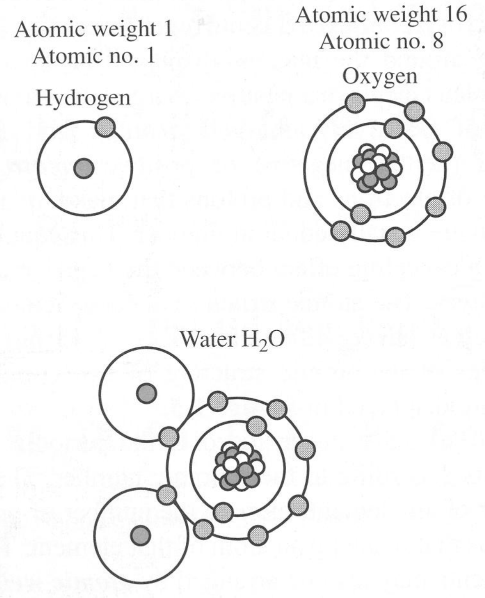


Figure 1-5. The atomic weight is the approximate number of protons and neutrons that compose the nucleus of the atom. The atomic number is the number of electrons or protons in an atom. When two hydrogen atoms combine with one oxygen atom, a single molecule of water is formed.

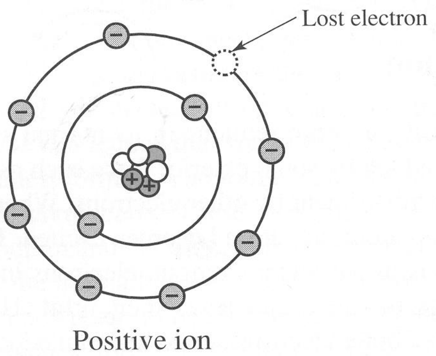


Figure 1-6. Ionization occurs when an atom gains or loses an electron. When there are more protons than electrons remaining, a positive ion is created.

Review Questions for Section 1.1

1. Define the following terms:
   a. Matter.
   b. Element.
   c. Compound.
   d. Atom.
   e. Molecule.
2. Name some common elements.
3. What is atomic weight?
4. Define atomic number.
5. What is the meaning of ionization?
6. Explain how a positive ion is formed.
7. Define a negative ion.

1.2 STATIC ELECTRICITY

The word *static* means at rest. Electricity can be at rest. The generation of static electricity can be demonstrated in many ways. When stroking the fur of a cat, you will notice that its fur is attracted to your hand as you bring your hand back over the cat. You will also hear a crackling sound. If this is done at night, you may see tiny sparks. The sound is caused by the discharge of static electricity. When we stroke the fur with our hand, the friction between the cats fur and our hand excites the atoms. Some atoms lose electrons while others gain electrons. The sparks are created as the atoms attempt to neutralize themselves by gaining back the lost electrons.

You can generate a static charge of electricity by walking across a wool or nylon rug with plastic-soled shoes. After walking across such a rug, you receive the surprising experience of discharging several thousand volts of static electricity to a metallic object such as a door handle. This condition is especially present on cold winter days when the humidity is quite low. You can also experience a similar discharge when sliding across the seat of a car covered with certain types of upholstery. The friction of your clothing against the seat leads to a discharge when you touch the earth and the metallic frame of the car at the same time.

Law of Charges

One of the fundamental laws in the study of electricity is the law of charges. The law of charges states that: *"Like charges repel each other and unlike charges attract each other."* The power of attraction can be seen when you run a comb through your hair several times. The comb will attract some of the hair towards itself because of the unbalanced electrical charge created by the friction between the hair and plastic comb.

➢ Experiment 1-1: Demonstrating the Law of Charges

These tests demonstrate the law of charges.

Materials

2–stands with suspended pith balls
1–vulcanite rod
1–piece of fur
1–glass rod
1–piece of silk

1. Negatively charge the vulcanite rod with the piece of fur.
2. Bring the rod close to one hanging pith ball.
3. Observe that the ball is first attracted to the rod because of unlike charges. When the ball touches the rod, it is immediately repelled. Continue to attempt to touch the pith ball with the vulcanite rod. Examine **Exhibit 1-1A.** Why has the pith ball acted this way?

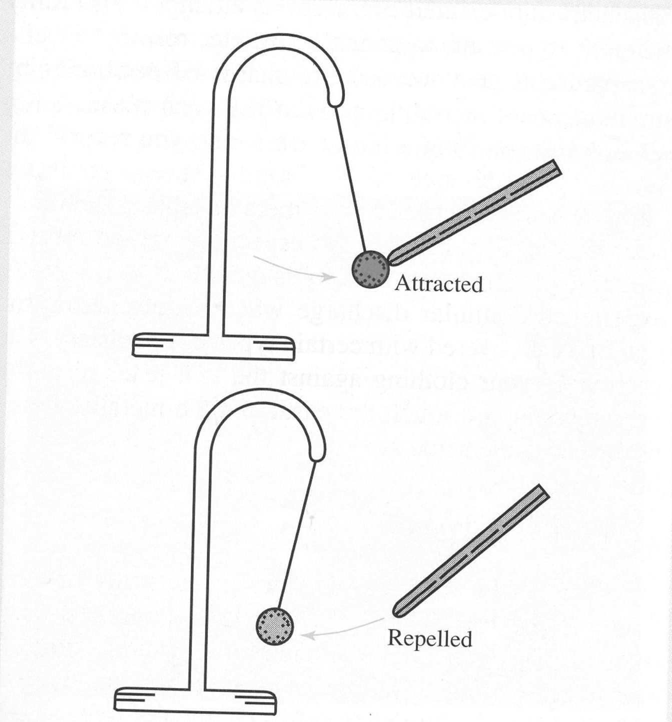


Exhibit 1-1A.

4. Recharge the vulcanite rod and touch it to the second pith ball. You now have two negatively charged pith balls.
5. Bring the two pith balls near each other. Do your observations match **Exhibit 1-1B?**

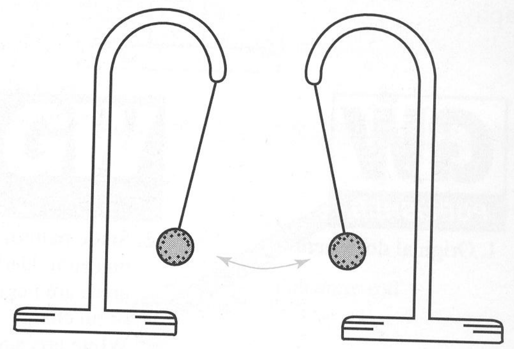


Exhibit 1-1B.

6. Charge up the glass rod by rubbing it with a piece of silk. Touch the glass rod to one of the pith balls. Leave the other negatively charged.
7. Bring the two pith balls near each other. Do your observations match **Exhibit 1-1C?**

Explain what you have just observed using the law of charges.

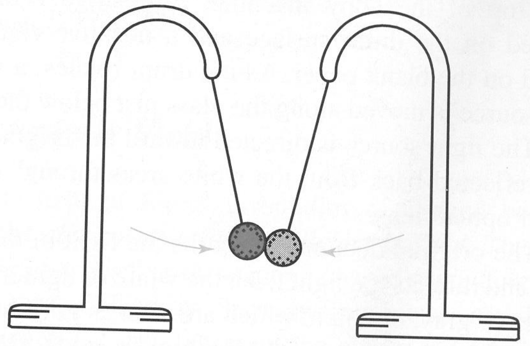
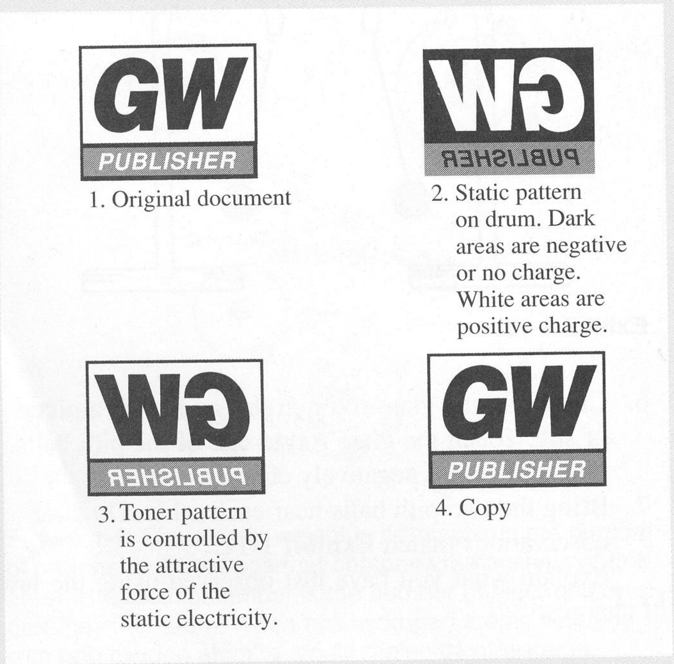


Exhibit 1-1C.

➢ Copy Machines

There are many different copying machines available today. The copying method explained here is based upon the xerography system of copying. The term *xerography* is derived from the Greek *xeros* and *graphe*, meaning *dry writing*. The xerography process uses powder toner, heat, light electrostatics, and photoelectric phenomena to produce a copy.

Recall that like charges repel and unlike charges attract. Now, let's introduce a new electrostatic principle. When a strong beam of light strikes a positively charged area or surface, the light photons will dissipate the positively charged surface areas. Photons exhibit a negatively charged characteristic. This is the underlying principle of xerography.



The original document is placed face down on the glass top of the copy machine. A positive charge is induced on the drum surface and a negative charge is placed on the blank paper. As the drum rotates, a strong light source is moved along the glass just below the original. The light source is directed toward the original and then reflected back from the white areas through a system of optical lenses.

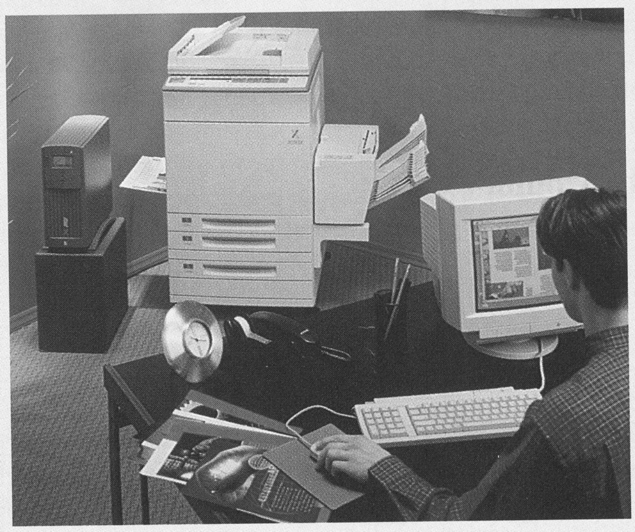
The original document absorbs the light in the dark areas and reflects the light from the white or lighter areas. Shades of gray, or colors which are seen as gray, are partially reflected. The reflected light is directed toward the positively charged drum area through the optical lenses. The positive charge on the drum surface is neutralized by the light. Photon energy is negative.

The areas not affected by the light are left with a positive charge on the surface of the drum. The toner is dispersed on the drum and is attracted to the remaining positively charged areas. The negatively charged paper passes under the drum transferring the toner to the paper. Toner is fused to the paper as it passes by a heater. The paper is ejected to the outside collection tray.

A color copier uses the same principles as described above except it makes use of color filters and four shades of toner. The four shades of toner are magenta, cyan, yellow, and black. These four colors are mixed to reproduce the different colors on the original. The light and optic systems use color filters to transfer the image to the roller and add the colored toner in stages.

Other refinements of copier systems include the use of electronics and advanced optical lens systems. The size of the copy can be enlarged or reduced by adjusting the distance between the optical lens and the image. Lightening or darkening of the copy is achieved by changing the intensity of the light beam. Electronic counters are used to indicate the number of copies needed.

Diagnostic circuits can also be used to indicate conditions such as paper jams, low toner, or an empty paper tray. Many machines can switch between applications such as copying, faxing, scanning, and printing. Advances in design also allow the user to print on different types of material including mailing labels, transparencies, and even envelopes. Some machines print simultaneously on both sides of the paper, reducing printing time and paper jams.



The digital copier/printer illustrated above is compact. The digital design enables greater machine dependability and its versatility makes it a very economical choice. (XEROX Corporation)

➢ Experiment 1-2: Examining Electrical Induction and Conduction

These two short tests examine the law of charges using electrical induction and conduction.

Materials

1–electroscope
1–vulcanite rod
1–piece of fur

1. Quickly rub the vulcanite rod with the fur. You have just placed a negative charge on the rod. Electrons have been transferred to the rod from the fur by friction.
2. Bring the charge rod close to (but do not touch) the electroscope. The leaves in the electroscope expand.
3. Move the rod away from the electroscope. The leaves drop back down.
4. Examine **Exhibit 1-2A**. Can you explain what you have just observed?
5. Recharge the vulcanite rod with the fur.
6. Touch the ball on the electroscope with the rod. Observe that the leaves in the electroscope expand.
7. Move the rod away from the electroscope. Observe that the leaves do not drop back down.
8. Examine **Exhibit 1-2B**. Can you explain why the leaves behaved differently in this test?

Discuss the concepts of induction and conduction with your instructor.

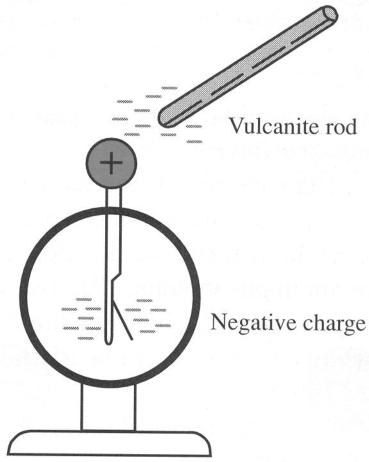


Exhibit 1-2A.

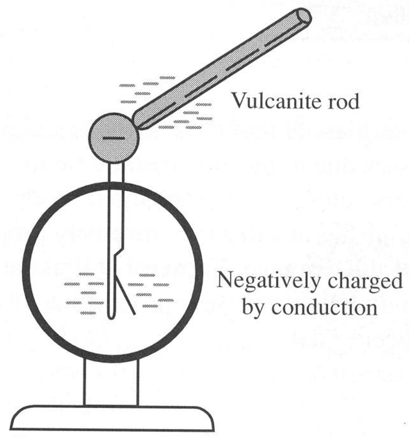


Exhibit 1-2B.

The Coulomb

The force of attraction and repulsion of charged particles was studied by the French scientist, Charles A. Coulomb. Because an atom, and electrons in particular, are so very small, a charge of just a few electrons, say a dozen, is almost impossible to measure. Consequently, Coulomb developed a practical unit for measurement of an amount of electricity. It is known as the ***coulomb.*** One coulomb represents approximately 6.24×10^{18} electrons (6,240,000,000,000,000,000). While the coulomb is used to describe the flow of electricity, it is not used to describe static charges. It is impractical to describe the very small difference in charges between two bodies using values so large.

Electrostatic Fields

The field of force surrounding a charged body is called the ***electrostatic field*** or ***dielectric field.*** The field can exhibit a positive or negative charge depending on a gain or loss of electrons. Two charged masses are shown in **Figure 1-7**. Lines represent the electrostatic fields of opposite polarity and the attractive force existing between the masses. In **Figure 1-8**, two charged masses are shown

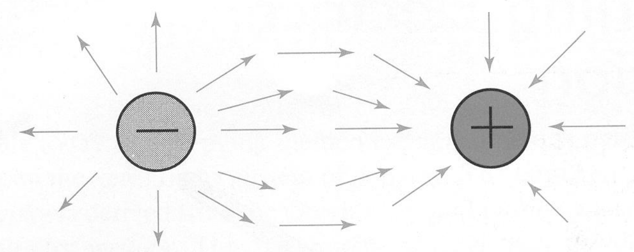


Figure 1-7. The electrostatic fields of unlike charged bodies show attractive forces.

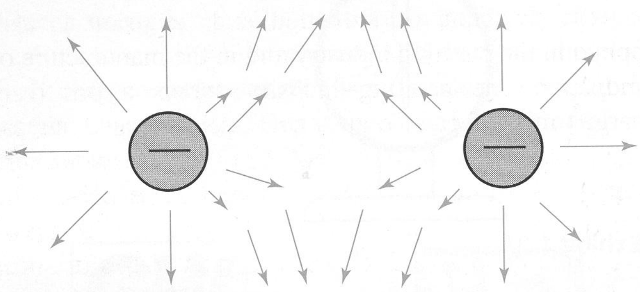


Figure 1-8. The electrostatic fields of like charged bodies repel each other.

with like polarities. A repulsive force exists between the charged masses due to the electrostatic fields. The field is strongest very close to the charged body. The field strength diminishes at a distance inversely proportional to the square of the distance. **Figure 1-9** illustrates the concept of strength being inversely proportional to the square of the distance.

When two electrostatic fields are joined together, the electrons flow from the mass with an excess of electrons to the mass that has a need of electrons. **Figure 1-10** illustrates this principle. The excess electrons flow from the body that is negatively charged to the positively charged body that has the electron deficiency. This transfer of electrons can be accomplished by touching the two bodies together or by connecting them with a material that supports the flow of electrons between the two bodies. This connecting material is known as a conductor because it "conducts" electricity.

Induction

Charges can be transferred in two ways. One way is by direct contact. When a charged body such as a glass rod touches another body such as the top of an electroscope, the electroscope takes on part of the charge of the rod. Another way of transferring a charge is ***induction.*** A charge is induced by bringing a charged object near another object. The glass rod need only be brought near the top of the electroscope to charge it. When an object is charged by induction, the object takes on the *opposite* charge as the rod. When the rod touches the object, the object takes the *same* charge as the rod. Refer back to Experiment 1-2.

Static Electricity Applications

The principles of static electricity are used in industry to reduce air pollution. One piece of equipment used

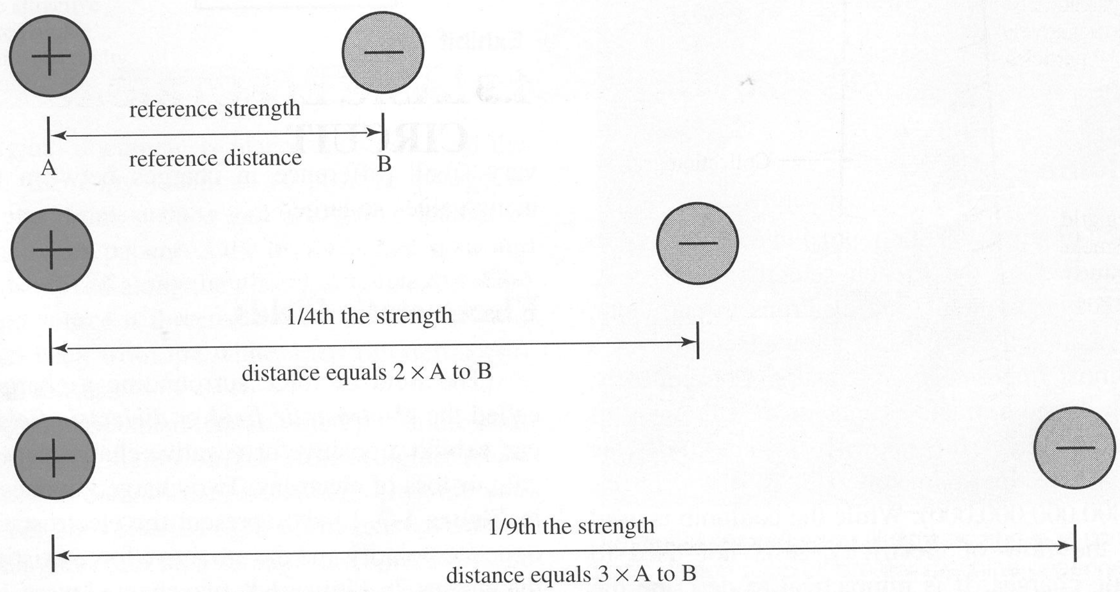


Figure 1-9. The strength of the force between two charged bodies is inversely proportional to the square of the distance.

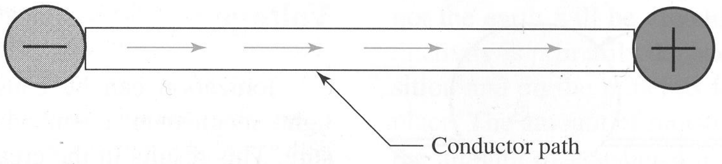


Figure 1-10. When two charged bodies are connected with a conductor, excess electrons will flow through the conductor from the mass having a surplus of electrons to the mass having a deficit of electrons.

in reducing pollution is called an ***electrostatic precipitator.*** Most precipitators are divided into two parts, a charging section and a collecting section. The charging section can be designed in many different ways. It can be an assembly of parallel rods or wires, a screen pattern, or a bank of piping. Regardless of the physical design, the electrical principle is the same in all cases.

In **Figure 1-11,** a wire mesh is installed across a chimney. The wire mesh is negatively charged by an external source, in this case a power supply. When the smoke and other air pollutants pass by the screen, they are attracted to the negatively charged screen. When the particles of smoke touch the negatively charged screen, they too become negatively charged. The particles are then repelled from the screen. As the negatively charged particles travel further up the chimney, they encounter a positively charged screen. As predicted by the law of charges, the negatively charged smoke particles are attracted to the positively charged screen. The pollutants remain there until they are removed, usually by mechanical means such as scrubbers designed specifically for this purpose.

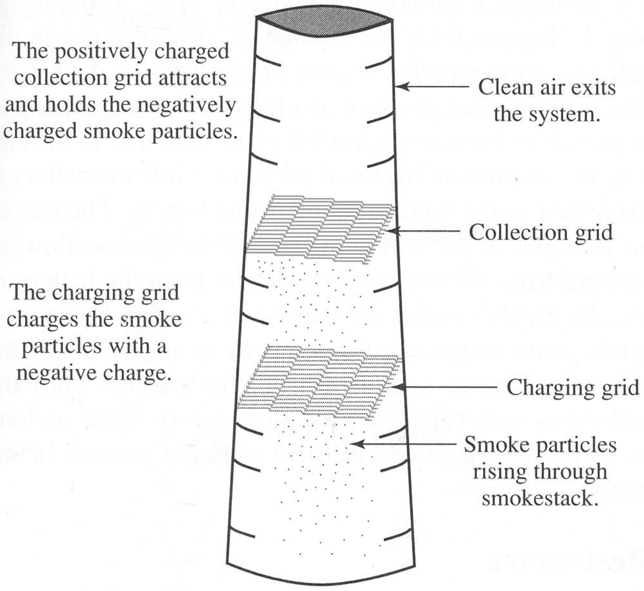


Figure 1-11. The operation of the electrostatic precipitator is based upon the laws of charges.

The application of electrostatics is also gaining popularity in residential use. Electrostatic filters are a part of the latest air-conditioning systems.

The principle of attraction and repulsion is also applied in the painting industry and in the manufacture of sandpaper. The painting industry sprays a positively charged mist of paint onto a negatively charged surface such as the panels of an automobile. This procedure reduces the amount of overspray and saves paint. The sandpaper industry charges the backing paper with a positive static charge, and the silica crystals (sand or some other abrasive) with a negative charge. The result is an even spread of granules over the entire surface of the paper.

Review Questions for Section 1.2

1. Define static electricity.
2. What is a coulomb?
3. Explain what is meant by electrostatic field.
4. Like charges __________ each other.
5. Unlike charges __________ each other.
6. What is meant by a negatively charged body?
7. Define induction.

1.3 BASIC ELECTRICAL CIRCUIT

A basic electrical circuit consists of three main parts, a source of voltage, a load, and conductors. In **Figure 1-12,** a basic circuit is illustrated. This circuit consists of a battery as the source of electrical energy, a lamp as the electrical load, and two wires as the conductors connecting the battery to the lamp. In the source of this circuit, the battery, a chemical reaction takes place that results in ionization. This ionization produces an excess of electrons (negative charge) and a depletion of electrons (positive charge).

The battery has two terminals. These terminals are connection points for the two conductors. One terminal is

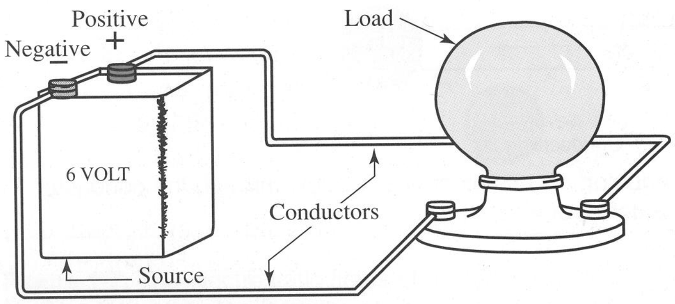


Figure 1-12. A basic electrical circuit consists of three main parts: the source, the load, and the conductors.

marked with a plus sign (+) and the other a negative sign (–). These two markings are referred to as *polarity markings*. Not all electrical devices have polarity markings. However, when polarity is a critical issue, it will be marked on the device. The proper polarity must be followed to avoid damage to equipment and/or personnel.

> **Lesson in safety:**
> There will be occasions when you become confused while working on electrical projects and with unfamiliar devices. Anytime you are uncertain about connecting any electrical device, check with your instructor. Damage from an improperly connected circuit is usually instantaneous and cannot be reversed.

A load is created when the electrical energy produced in a circuit is converted to some other form of energy such as heat, light, or magnetism. The load in the simple circuit of **Figure 1-12** is a lamp that produces light. The source and the load should match according to voltage rating. If the lamp is rated at 6 volts, then the battery should also be rated at 6 volts. If the battery is rated at a lower voltage rating, the lamp will appear dim or will not light. If the battery is rated at a much higher voltage, the lamp will be damaged by the excess electrical energy.

The conductors we are using are two copper wires covered with a plastic insulation coating. The copper wire provides a path through which the electrical energy can flow, while the plastic coating restricts the electrical energy to the copper wire. This makes the conductor pathway safe for personnel. This completes the description of the basic components of a circuit in which electrical energy is channeled by way of electrical conductors, through a device, where it is then converted to some useful form.

Voltage

Ionization can be caused by forces such as heat, light, magnetism, chemical action, or mechanical pressure. This results in the creation of an electrical voltage. What is voltage? ***Voltage*** is the force behind electron flow. In the simple circuit just described, the battery was the source of electrical energy. This battery has a rating of 6 volts. The ***volt (V)*** is the electrical unit used to express the amount of electrical pressure present, or the amount of electrical force produced by the chemical action inside the battery.

The term voltage is used to express the amount of electrical force in much the same way we use horsepower to express the amount of mechanical force for an automobile. Electrical pressure or voltage can also be expressed as ***potential, potential difference***, or as ***electromotive force (emf).*** For our purposes, these terms mean the same thing. Voltage is usually represented by the capital letter ***E*** or ***V***.

Current

Electrical ***current*** is the flow of electrons. The amount of electrons flowing past any given point in one second is rated in the electrical unit ***ampere (A)***. The ampere is expressed using the letter ***I.*** Remember that a coulomb is a quantity of electrons. The ampere describes the rate of flow of the electrons past any given point in a circuit. One ampere is equal to one coulomb of charge flowing past a point in one second.

Compare a balloon filled with air to an electrical battery. In **Figure 1-13**, the amount of air molecules in the balloon represents the amount of electrons or coulombs. The amount of air pressure inside the balloon is expressed as pounds per square inch (PSI) of air pressure. In the battery, the amount of electrical pressure inside the battery is expressed as the voltage rating of the battery. The rate of air flow out of the balloon is similar to electron flow, or current, from the battery. The current from the battery in the electrical circuit is the volume of electron flow past a given point, and is rated in amperes or amps. Just as the air will continue to escape from the balloon until the balloon is empty, the electron flow can continue as long as there is voltage or electrical pressure present in the battery.

Resistance

All electrical circuits have resistance. ***Resistance*** is the opposition to the flow of electrons. Resistance is

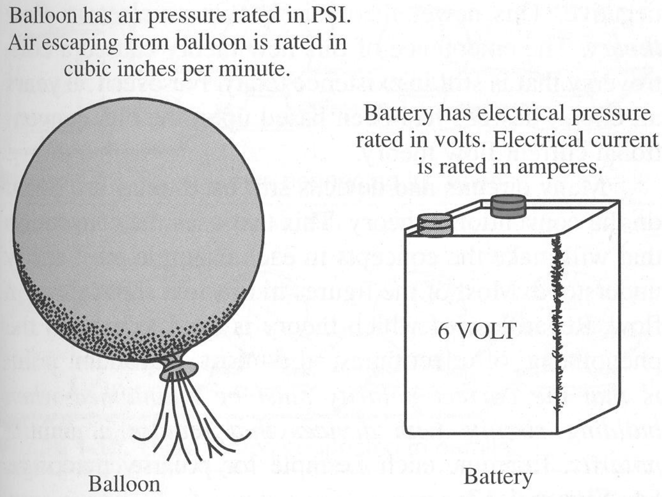


Figure 1-13. A balloon is similar to an electrical source. Air escaping from the balloon is similar to electrons flowing from a source.

measured in ***ohms***, and the electrical symbol for ohm is Ω (the Greek letter omega). The resistance values of elements and compounds differ according to the atomic structure of the material. A good ***conductor*** of electricity is anything that permits the free flow of electrons. A poor conductor of electricity is a material that will not permit the free flow of electrons. Extremely poor conductors are referred to as ***insulators***. A ***semiconductor*** is a material that limits the flow of free electrons. A semiconductor is considered neither a good conductor nor poor conductor of electricity. Semiconductor materials are at the very heart of modern electronic applications and will be explored in depth in Chapter 17. Some examples of conductors and insulators are listed in **Figure 1-14.**

Note that the earth can be a good conductor of electricity. There are many factors that determine whether or not the earth will be a good conductor. The earth's conductivity is primarily dependent upon its organic composition and on the minerals found in the soil at any given place. The amount of moisture in the soil also determines the amount of resistance in the soil. Moisture can affect the electrical conducting ability of many materials. It can even cause an insulator to become a good conductor. Take wood as an example to illustrate this point. When wood is dry, it is classified as an insulator, but when wood becomes wet or moist, it behaves more like a semiconductor.

Conductors	Insulators
copper	Bakelite®
iron	glass
steel	mica
aluminum	porcelain
silver	air
tin	dry wood
damp earth	sand
salt water	distilled water
	some plastics
	paper
	rubber
	oil

Figure 1-14. Common conductors and insulators.

It is the outer ring of an atom that determines whether an element is a good or poor conductor. If the outer ring has only one electron, that electron can be freed from its orbit rather easily by an outside force. If there are many electrons in the outer orbit, the electrons are held tighter in orbit. They are harder to free from the atom. Elements that do not readily give up an electron are insulators.

Figure 1-15 is an illustration of the copper atom. Notice how this atom has only one electron in its outer orbit. This electron can be easily freed by an outside force. Copper is an excellent conductor of electricity.

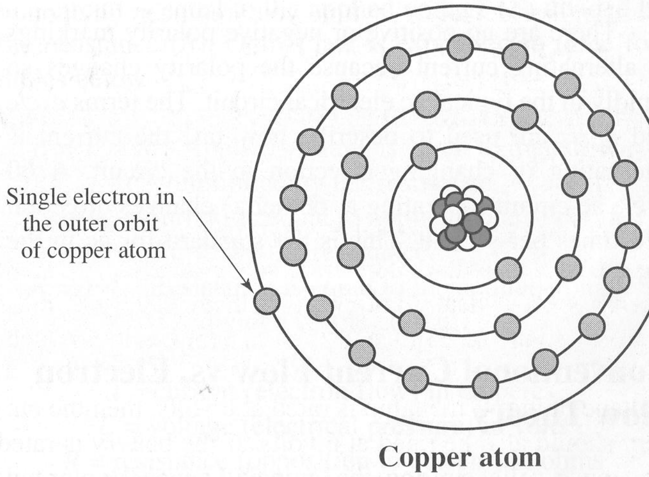


Figure 1-15. The element copper is an excellent conductor. It has only one electron in its outer orbit. This electron can be easily released from its orbit by an outside force.

Current, AC and DC

There are two types of electrical current, dc (direct current) and ac (alternating current). The difference between these currents is how they flow through an electrical circuit. ***Direct current*** flows in only one direction through an electrical circuit. An example of direct current is a standard battery. The battery has a set polarity (positive and negative terminals) and will produce an electric current in only one direction. On the other hand, ***alternating current,*** as its name implies, flows in both directions. First it flows in one direction, and then it reverses its flow to the opposite direction. See **Figure 1-16.**

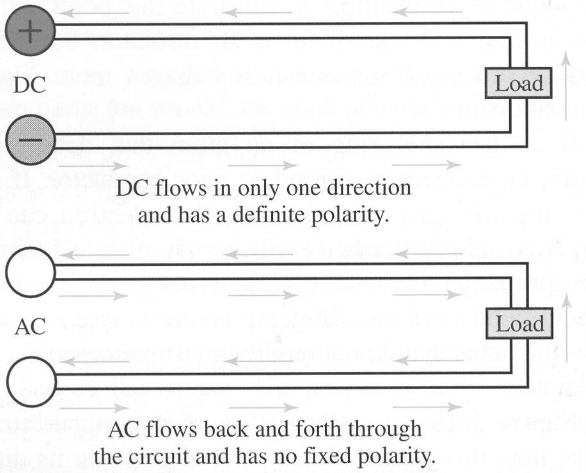


Figure 1-16. Direct current flows in one direction while alternating current repeatedly alternates direction.

There are no positive or negative polarity markings in alternating current because the polarity changes so rapidly in the typical ac electrical circuit. The terms *cycle* and *hertz* are used to describe how fast the current is alternating or changing direction in the circuit. A 60 cycle ac circuit (operating at 60 hertz) changes direction 120 times per second. This is the standard for ac in the USA.

Conventional Current Flow vs. Electron Flow Theory

Approximately 200 years ago, scientists theorized that electricity had both positive and negative polarities. At that time they arbitrarily decided that electrical current flowed from positive to negative. While it was never actually proven as fact, this theory was accepted for quite some time. This theory is known as the ***conventional current flow theory.*** As our knowledge of science progressed, and with the discovery of the atom and semiconductor electronics, it became apparent that the conventional current flow theory was incorrect. It is widely accepted that it is the electrons that actually move, and they flow from negative to positive, not from positive to negative. This newer theory is known as ***electron flow theory.*** The emergence of this new theory caused a controversy that is still in existence today. For over 150 years all circuit designs had been based upon the old, conventional current flow theory.

Many circuits and devices still used today are based on the conventional theory. This text uses the convention that will make the concepts in each example most easily understood. Most of the figures in this text show electron flow. Regardless of which theory is used to explain the phenomena of electronics, the most important point is *that the correct polarity must be maintained when building circuits with devices that require a definite polarity*. Examine each example for polarity markings. See **Figure 1-17.**

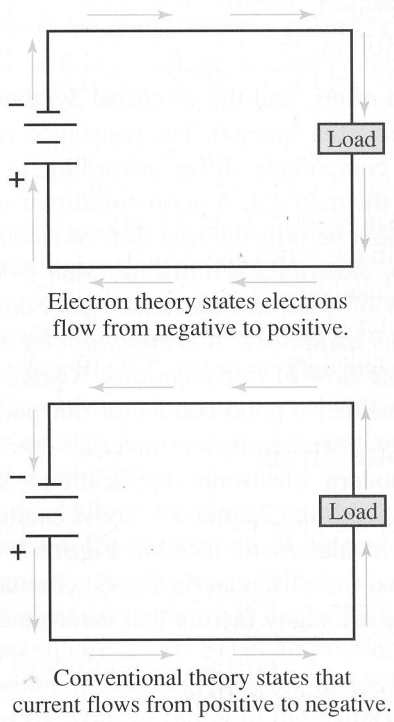


Figure 1-17. Electron flow theory and conventional current flow theory.

Series and Parallel

Series and parallel are two important concepts. They must be learned early to fully understand the next few chapters. There are two ways a component can be connected in a circuit, either series or parallel. **Figure 1-18** and **Figure 1-19** illustrate the two types of connections. The circuit in Figure 1-18 has three lamps connected to a

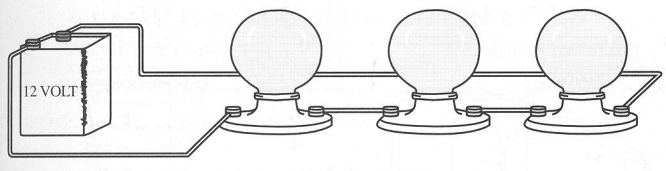


Figure 1-18. Three lamps connected in series.

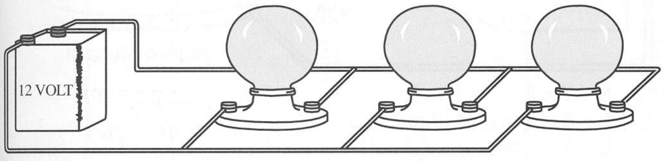


Figure 1-19. Three lamps connected in parallel.

battery. In this circuit, there is only one path over which the electrons can flow. When electrons only have one circuit path to follow, that circuit is called a *series* circuit. The lamps are said to be wired in series with respect to each other.

In Figure 1-19, there are three lamps connected in *parallel*. In this circuit, there are three different paths for the electrons to follow from battery terminal to battery terminal. Both the series and parallel circuits have advantages and disadvantages. These will be thoroughly covered in later chapters in this text. For now, be able to readily distinguish between the two types of circuits.

Review Questions for Section 1.3

1. What are the three main parts of an electrical circuit?
2. The __________ supplies the electrons that will flow through the circuit.
3. The __________ provide a path through which the electrical energy can flow.
4. The __________ is where the electrical energy is converted to another form of energy.
5. The source has __________ markings that are identified with a ___ or ___ symbol.
6. The movement of electrons is known as __________.
7. Opposition to current flow is called __________.
8. Opposition to current is measured in __________.
9. Electrical pressure is measured in __________.
10. __________ theory states that electrons flow from negative to positive.
11. __________ current flows only in one direction while __________ current constantly changes direction.
12. Connecting the correct __________ of an electrical device in an electrical circuit is more important than which theory of current flow is used.
13. A(n) __________ circuit provides only one path for electron flow.
14. A(n) __________ circuit provides more than one path for electron flow.

1.4 OHM'S LAW

Electrical circuits that are built correctly will be in perfect electrical balance. The current through the resistance is directly related to the amount of electrical pressure or voltage applied to the circuit. This balance of the three factors, voltage (E), resistance (R), and current (I), can be expressed by ***Ohm's law***. Ohm's law is named for the 19th century German scientist George Simon Ohm.

The relationship expressed by Ohm's law is the basic formula that is used more extensively than any other electrical formula you will encounter in your study of electricity and electronics. It is the basis for many other formulas and electrical relationships studied in this text. Ohm's law states that the current measured in amperes (I) in a circuit is equal to the applied voltage (E) divided by the resistance (R). Ohm's law is expressed in three formulas below.

$E = I \times R$ Applied voltage is equal to the current multiplied by the resistance.

$I = E/R$ Current is equal to applied voltage divided by the resistance.

$R = E/I$ Resistance is equal to the applied voltage divided by the current.

I = current (electron flow) in amperes
E = voltage (electrical pressure) in volts
R = resistance (opposition to current) in ohms

A memory device commonly used to assist you in learning Ohm's law is illustrated in **Figure 1-20.** To see how easy it is to use, simply cover the unknown quantity with your finger, and the remaining letters will show the solving equation. For example, when the voltage is the unknown quantity, cover E with your finger. The I and R remain. Thus $E = I \times R$. Now cover I with your finger. An E over R remains. Thus, $I = E/R$.

Let's look at an application of Ohm's law. In **Figure 1-21,** a lamp with a resistance of 4 ohms has been connected to a 12 volt source. The current is unknown. By applying Ohm's law you can determine the current to be equal to 3 amperes.

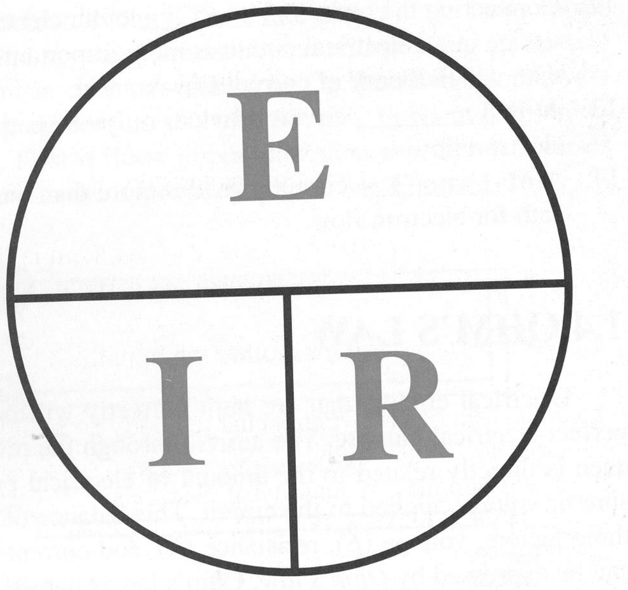
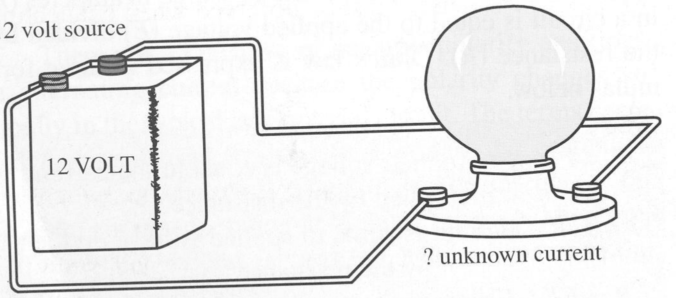


Figure 1-20. A memory device used to help solve Ohm's law problems. Cover the unknown quantity and the remaining letters show the correct equation. Example: *I* is equal to *E* divided by *R*.



$I = E / R$

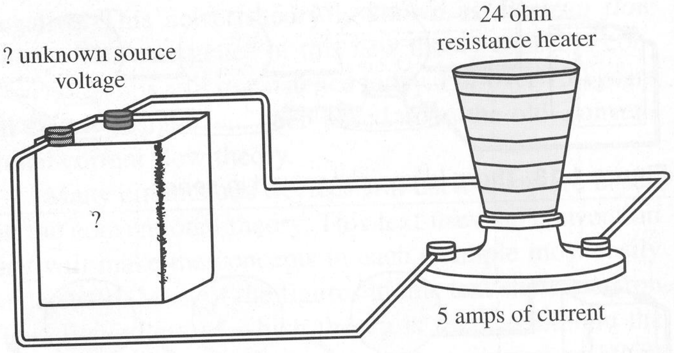
$I = 12 \text{ volts} / 4 \text{ ohms}$

$I = 3 \text{ amps}$

Figure 1-21. Current is equal to voltage divided by resistance.

In **Figure 1-22,** a 24 ohm resistance heater works most efficiently when using 5 amps of current. How much voltage is required for the heater to operate at 5 amps? By applying Ohm's law, the amount of electrical pressure needed to conduct 5 amps through a 24 ohm resistance is 120 volts.

In **Figure 1-23** a resistor is connected to a 24 volt source. A meter that measures current indicates there are 3 amperes present in the circuit. Again, by applying Ohm's law, the amount of resistance needed to limit the current value to 3 amperes is found to be 8 ohms. The application of Ohm's law may seem strange at first, but with a little practice, it will become second nature to you.

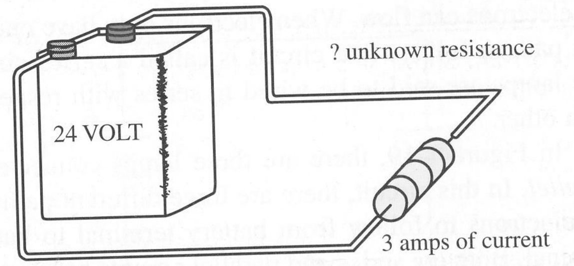


$E = I \times R$

$E = 5 \text{ amps} \times 24 \text{ ohms}$

$E = 120 \text{ volts}$

Figure 1-22. Voltage is equal to resistance multiplied by current.



$R = E / I$

$R = 24 \text{ volts} / 3 \text{ amps}$

$R = 8 \text{ ohms}$

Figure 1-23. Resistance is equal to voltage divided by current.

Electrical Prefixes

Measurements of electrical quantities vary from small amounts to large amounts. To make it easier to label electronic parts and equipment, and to make electronic calculations easier, a system of prefixes is used when expressing electrical quantities. Without this system we would need to use an excessive amount of zeros to the left and right of a decimal point. **Figure 1-24** is a listing of the most common prefixes used in the electronics industry today.

When an electrical quantity such as voltage is written, it is expressed in units such as kilovolt, megavolt, millivolt, and microvolt to avoid using an awkward numerical form. For example, the quantity 5,000,000 (five million) volts, would be written as 5 MV. If the quantity was 0.005 (five thousandths) volts, it would be

COMMON ELECTRICAL PREFIXES

Prefix	Symbol	Decimal Equivalent	Power of Ten
tera	T	1,000,000,000,000.	10^{12}
giga	G	1,000,000,000.	10^{9}
mega	M	1,000,000.	10^{6}
kilo	k	1,000.	10^{3}
basic unit		1.	
milli	m	.001	10^{-3}
micro	µ	.000 001	10^{-6}
nano	n	.000 000 001	10^{-9}
pico	p	.000 000 000 001	10^{-12}

Figure 1-24. Shown is a list of the electrical prefixes you will most often encounter.

written as 5 mV. It is important to note the use of the upper case letters and duplicate lower case letters in these units. When voltage is expressed with a capital letter M, it represents millions of volts, but when voltage is expressed using a lower case m, it represents the fractional unit of thousandths.

Review Questions for Section 1.4

1. A voltage of __________ is needed to produce a current of 2 amps through a resistance of 6 ohms.
2. When 12 volts are connected to 4 ohms, a current equal to __________ flows through the resistance.
3. A resistance of __________ produces a current equal to 8 amps when connected to 24 volts.
4. How many volts does 4 kV represent?
5. What is 8 MΩ equal to in kΩ?
6. Write 3 mV as a decimal unit of voltage.
7. One millivolt is how much larger than one microvolt?
8. How many milliamps are there in 20 amps?
9. Is 5×10^{-3} larger or smaller than 5×10^{-6}?
10. Express 6×10^{6} ohms with a prefix.

Summary

1. Matter is anything that occupies space or has mass.
2. Elements are basic or pure forms of matter.
3. Compounds are mixtures or combinations of two or more elements.
4. Atoms are the simplest forms of an element still having the unique characteristics of that element.
5. Molecules are the simplest form of a compound still having the unique characteristics of that compound.
6. The negatively charged particle of the atom is the electron and the positively charged particle is the proton.
7. Like charges repel each other while unlike charges attract each other.
8. Induction occurs when a charged body is brought close to another body.
9. The coulomb is a quantity of electrons (6,240,000,000,000,000,000, or 6.24×10^{18} electrons).
10. Current is the movement of electrons in a conductor.
11. Voltage is the force behind the electrons. It moves them along a conductor resulting in current.
12. Ohm's law can be stated three ways, $E = I \times R$, $I = E/R$, and $R = E/I$
13. There are two types of current, ac (alternating current) and dc (direct current).
14. Correct polarity must be observed when connecting electrical devices.

Test Your Knowledge

Please do not write in the text. Place your answers on a separate piece of paper.

1. An electron displays a(n) __________ charge, a proton displays a(n) __________ charge, and a neutron displays a(n) __________ charge.
2. What is the name for the electrical unit based on the number of electrons? How many electrons does it represent?
3. What are the two laws of electrostatic charges?
4. Electron movement is called __________.
   A. voltage
   B. current
   C. resistance
   D. ohm
5. The force behind electron movement is called __________.
   A. voltage
   B. current
   C. resistance
   D. ohm

6. When an atom loses an electron, it becomes __________.
   A. vaporized
   B. ionized
   C. resistance
   D. negative
7. The invisible line of force that surrounds a charged body is called the __________.
   A. electron force
   B. electrostatic field
   C. electric field
   D. None of the above.
8. What causes ionization to occur?
9. Matter is found in what three forms?
10. The smallest part of a compound is called a(n) __________.
11. The smallest part of an element is called a(n) __________.
12. What are the three basic parts of a circuit?
13. Which part of a circuit provides electrical energy?
14. Which part of a circuit converts the electrical energy to another form of energy?
15. Which part of the circuit provides a current path?
16. Write 16,000 volts with a prefix.
17. Write 0.005 volts with a prefix.
18. Write the three forms of Ohm's law.
19. How much voltage is required to force 3 amperes through a resistance of 36 ohms? (Include the formula with your answer.)
20. How much current will a 24-ohm resistor connected to a 6-volt source produce? (Include the formula with your answer.)
21. A meter indicates 5 amps in a simple circuit connected to a 12-volt source. How much resistance is present? (Include the formula with your answer.)
22. How much current will a 12 V car battery produce when connected to a lamp with a 600 ohm resistance value?
23. A 5 kΩ resistance connected to a 100-volt source will produce how much current?
24. A 6 V battery is connected to a 240 Ω lamp. What is the expected amount of amperes produced by this circuit?
25. How much voltage is needed to produce a current of 50 μA through a resistance of 1 kΩ?

8. An electromechanical load is rated at 2238 watts. What is the equivalent rating in horsepower?

4.2 OHM'S LAW AND WATT'S LAW

It is possible to combine Ohm's law and Watt's law to produce simple formulas that permit you to solve for current, voltage, resistance, or power if any two of those quantities are known. In **Figure 4-3,** these equations are listed with an explanation of how they were created from the two laws.

These formulas can be arranged in a wheel-shaped memory device for ready reference. Refer to **Figure 4-4.** To use this device, find your *unknown* quantity in the smaller center circle. This is the left half of your equation. Next, choose one of the three variable combinations in outer circle that falls in the same quarter of the chart as

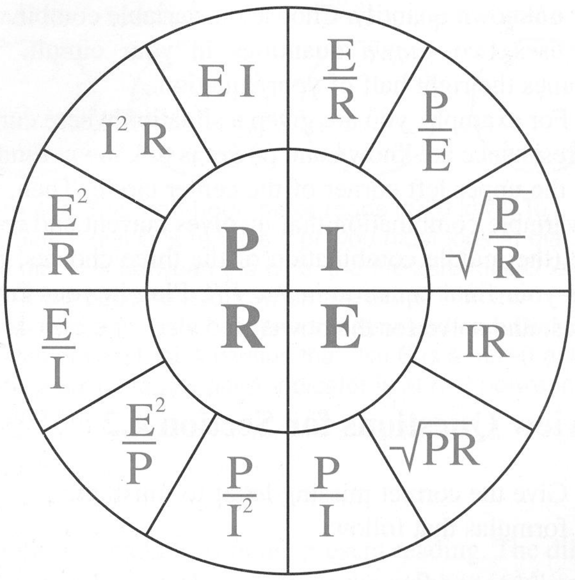
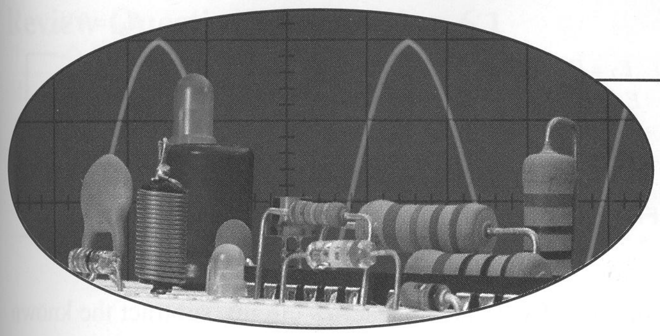


Figure 4-4. A memory device combining Ohm's law and the power formulas. It can be a great help when solving problems.

1. $E = I \times R$	Ohm's law
2. $E = \frac{P}{I}$	Watt's law
3. $E = \sqrt{PR}$	By transposing equation 12 and taking the square root.
4. $I = \frac{E}{R}$	Ohm's law
5. $I = \frac{P}{E}$	Watt's law
6. $I = \sqrt{\frac{P}{R}}$	By transposing equation 9 and taking the square root.
7. $R = \frac{E}{I}$	Ohm's law
8. $R = \frac{E^2}{P}$	By transposing equation 12.
9. $R = \frac{P}{I^2}$	By transposing equation 11.
10. $P = I \times E$	Watt's law
11. $P = I^2 \times R$	By substituting $I \times R$ from equation 1, for E.
12. $P = \frac{E^2}{R}$	By substituting $\frac{E}{R}$ from equation 4, for I.

Figure 4-3. This table states a variety of basic formulas that are needed to solve problems.



6 Series Circuits

Objectives

After studying this chapter, you will be able to:

- Determine the total resistance of a series circuit.
- Determine the voltage drops in a series circuit.
- Determine the current values of a series circuit.
- Determine the wattage values of a series circuit.
- Apply Ohm's law to solve for unknown voltage, current, and resistance in a series circuit.
- Apply series circuit theory to assist in troubleshooting a series circuit.

Key Words and Terms

The following words and terms will become important pieces of your electricity and electronics vocabulary. Look for them as you read this chapter.

Kirchhoff's voltage law   series circuit

Chapters 6, 7, and 8, cover series, parallel, and combination circuits. Series, parallel, and combination are the only three ways an electrical circuit can be constructed. The combination circuit is simply a combination of a series circuit and a parallel circuit. These three chapters, when mastered, will provide you with the basic skills to construct, analyze, and troubleshoot many electrical systems.

6.1 SERIES CIRCUIT PRINCIPLES

A ***series circuit*** has only one path for electron flow through the devices wired in the circuit. There are three formulas used to explain the laws of series circuits.

$$E_T = E_1 + E_2 + E_3 ... + E_N$$
$$R_T = R_1 + R_2 + R_3 ... + R_N$$
$$I_T = I_1 = I_2 = I_3 ... = I_N$$

Where N is the total number of voltage sources, resistances, or current sources in a circuit.

Voltage in a Series Circuit

Gustav R. Kirchhoff was a mid-nineteenth century scientist who discovered that the total voltage applied to a series circuit is equal to the total number of individual voltage drops in a series circuit.

$$E_T = E_1 + E_2 + E_3 ... + E_N$$

This is known as ***Kirchhoff's voltage law*** as applied to series circuits. The source voltage of a series circuit is equal to the total value of each individual voltage drop. **Figure 6-1** has three resistors wired in series with a voltage drop indicated at each resistor. When the three voltage drops are added together, they equal the source voltage.

$E_T = E_1 + E_2 + E_3$
$E_T = 3\text{ V} + 5\text{ V} + 4\text{ V}$
$E_T = 12\text{ V}$

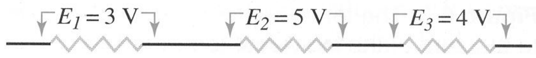


Figure 6-1. The total voltage is equal to the sum of the individual voltage drops.

Current in a Series Circuit

The current in a series circuit is equal throughout the circuit. In **Figure 6-2,** three resistors are connected in series to the source. Since there is only one path for the electron flow, the current *must* be the same value at any point in the circuit.

$$I_T = I_1 = I_2 = I_3 ... = I_N$$

The formula for series circuit current value is a mathematical way of expressing that a current value measured at any point in a series circuit is equal to the current value at any other point in that same circuit. If there are 5 mA flowing through R_1, then there must be 5 mA flowing through any resistor or conductor in that circuit.

Figure 6-2. In a series circuit, there is only one path for the current.

Resistance in a Series Circuit

Total resistance in a series circuit is equal to the total circuit resistance combined. By adding the value of the individual resistors together we find the total resistance of the circuit.

$$R_T = R_1 + R_2 + R_3 ...+ R_N$$

Figure 6-3 consists of 20 ohm, 40 ohm, and 60 ohm resistors connected in series. The total resistance value for this circuit is 120 ohms.

$R_T = R_1 + R_2 + R_3$

$R_T = 20\ \Omega + 40\ \Omega + 60\ \Omega$

$R_T = 120\ \Omega$

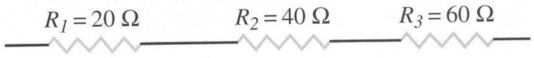


Figure 6-3. The total resistance in a series circuit is equal to the sum of the individual resistances.

Determining an Unknown Voltage

To find a single unknown voltage value, subtract the known resistance voltage drop values from the source. In **Figure 6-4,** two resistors are wired in series. The value of R_1 is 8 volts and the source is equal to 12 volts. To apply

$E_T = E_1 + E_2$

$E_{R_2} = E_T - E_1$

$E_{R_2} = 12\ V - 8\ V$

$E_{R_2} = 4\ V$

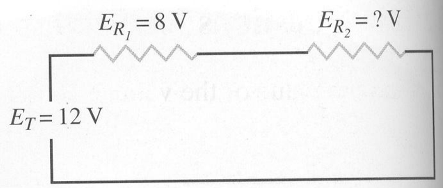


Figure 6-4. Determining an unknown voltage drop.

the law of voltages in a series circuit, subtract the known circuit voltage drops from the source.

Power in a Series Circuit

The total amount of power consumed in a series circuit is equal to the source voltage multiplied by the circuit current.

$$P_T = E_T \times I_T$$

Each device in the circuit that consumes power is part of the total load. An example of consumed power is the amount of wattage dissipated as heat by each resistor. See **Figure 6-5.** Devices that are not normally considered to consume power in a lab circuit are switches, fuses, and conductors.

$P_T = I_T \times E_T$

$P_T = I_T^2 \times R_T$

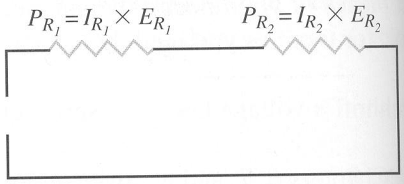


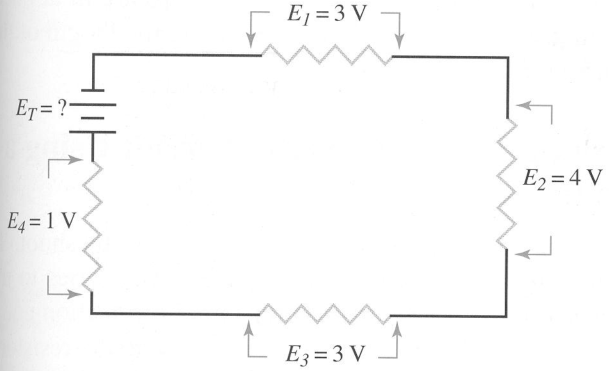
Figure 6-5. Calculating power in a series circuit.

There are several methods of determining total power rated in watts consumed by a series circuit. In the first method we multiply the source voltage times the current value of the circuit ($E_T \times I_T$). Another easy method is to multiply the current squared by the total circuit resistance ($I_T^2 \times R_T$).

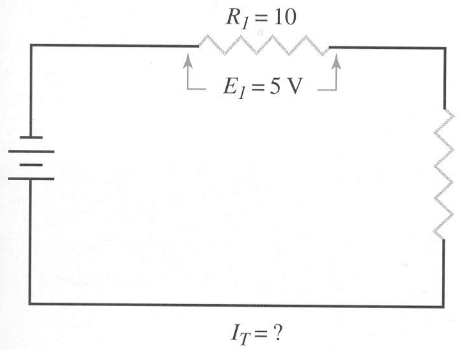
It is very important to remember that the wattage rating of a resistor is *not* the amount of energy it uses. The wattage rating of a resistor is the amount of energy, in the form of heat, the resistor can safely dissipate without being damaged. In other words, a 2.2 kΩ resistor rated at 1/4 watt does not consume 0.250 watts. The wattage (1/4 W) is the maximum amount of heat energy it can safely dissipate without damage.

Review Questions for Section 6.1

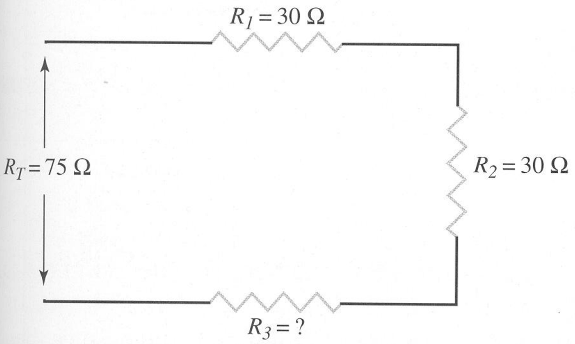
1. Find the value of the voltage source.



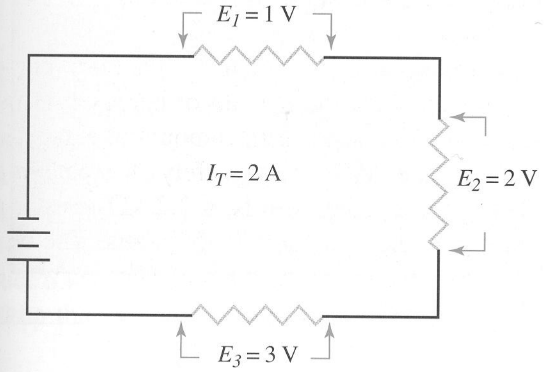
2. Find the total current.



3. Find the missing resistance.



4. Find the power in the circuit shown.



6.2 APPLICATIONS AND TROUBLESHOOTING SERIES CIRCUITS

There are numerous applications for the principles of series circuits. This section demonstrates how to apply those principles and shows you the specific example of an airfield lighting system. In addition, troubleshooting (always an important topic) series circuits are discussed.

Applying Ohm's Law to a Series Circuit

Ohm's law can be applied to any individual component of a series circuit. Look at **Figure 6-6.** The Ohm's law formulas are noted at each location. If you know any two values at an individual location, you can apply Ohm's law to find the third value.

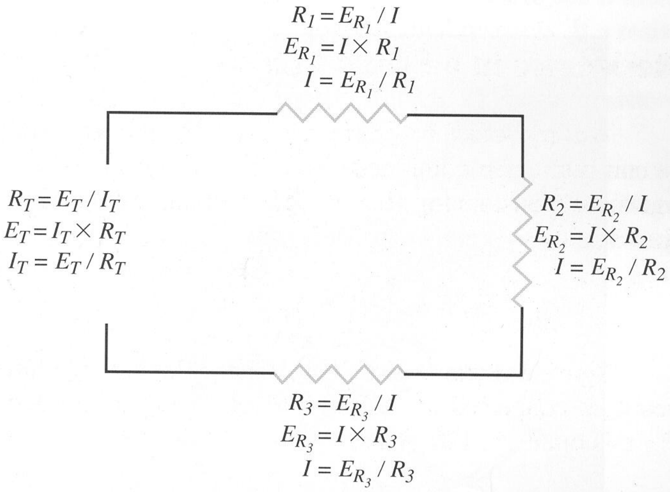


Figure 6-6. Ohm's law can be applied at each location in the circuit. Note that when the current value is found it can be applied anywhere in the circuit.

Example: If R_1 has a resistance value of 10 ohms and a voltage drop of five volts, then applying Ohm's law to the R_1 location will give you a current value of 0.5 amperes.

$$I_1 = \frac{V_1}{R_1}$$

$$I_1 = \frac{5\ \text{V}}{10\ \Omega} = 0.5\ \text{A}$$

Could you go on from this point and calculate the amount of power used by R_1?

Airfield Lighting System

An airfield lighting system has many miles of circuit cable. The system has miles of cable originating from the source of power to the runway, plus the distance around the runway itself. The only practical way to light a runway and taxiway system is to use the series circuit principles. **Figure 6-7** illustrates how large the system may be. The voltage losses caused by the resistance of the copper lines do not permit a practical application of a parallel circuit. The lighting consists of a series circuit with a transformer located at each individual light location. The circuit is connected to a voltage regulator that maintains a constant amperage applied to the circuit. Since the circuit has a constant amperage, and each transformer and lighting unit has equal resistance, each lamp will have the same voltage drop value.

At times, the number of lamps in the circuit will change due to lamp failure. When the number of lamps change, the amount of applied voltage from the regulator will change in order to maintain the constant 6.6 amperes applied to the circuit. By maintaining a constant 6.6 amperes to the circuit, each lamp will burn at the same brightness, regardless of how many lamps are lit at once, and regardless of the voltage drop along the length of the conductor. See **Figure 6-8.**

Troubleshooting a Series Circuit Using a Voltmeter

A series circuit is really easy to troubleshoot. In **Figure 6-9,** three resistors are connected in series to the power supply. A fuse is used for circuit protection and a SPST switch is used to control the current to the resistors. One of the most common circuit faults in a series circuit is an open. A voltmeter, combined with the knowledge of the laws of voltages, is a quick and easy method of analysis. There are several ways to locate a circuit fault. The following step-by-step presentation is not the only way to locate the fault.

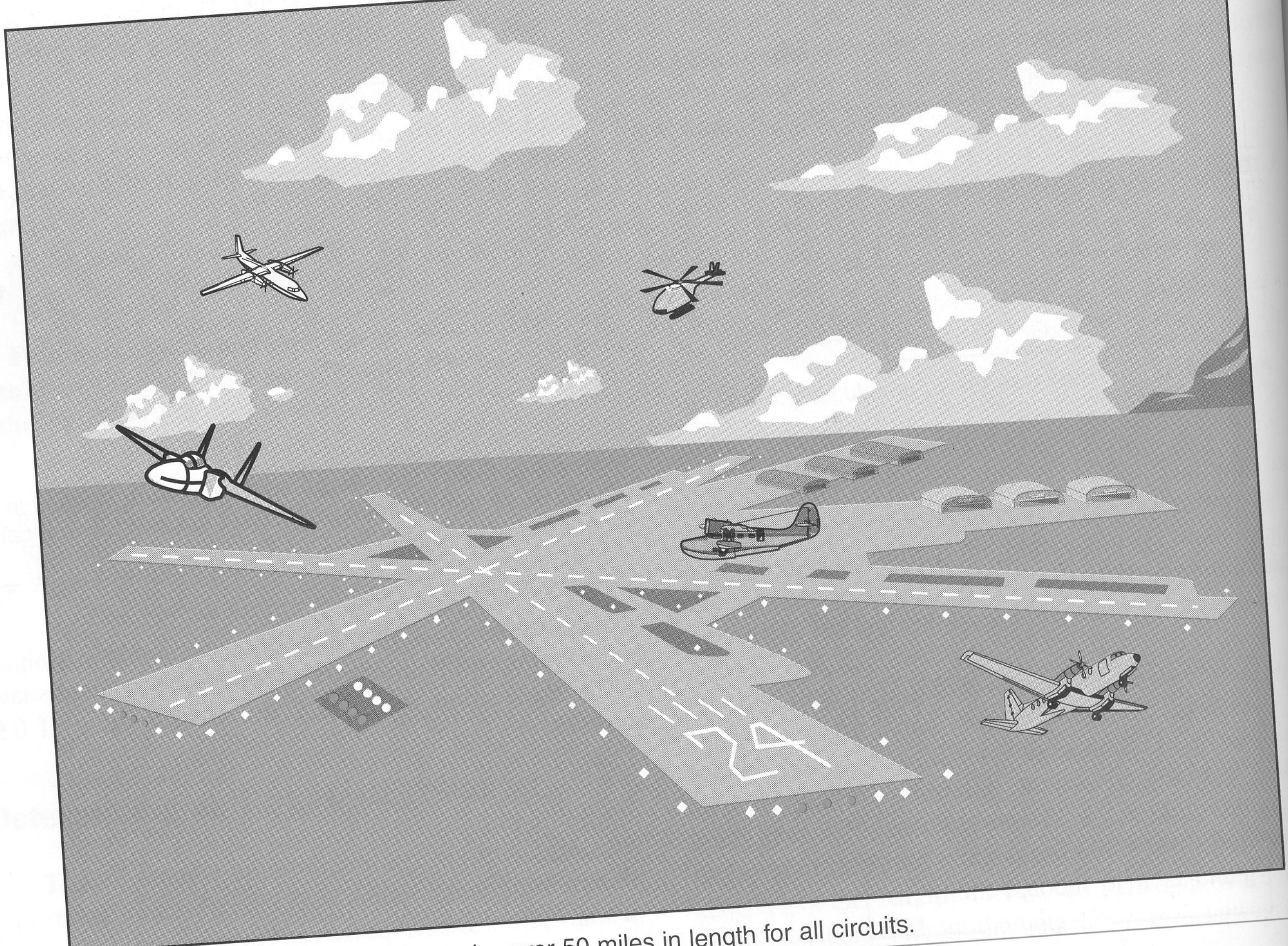


Figure 6-7. An airport lighting system can be over 50 miles in length for all circuits.

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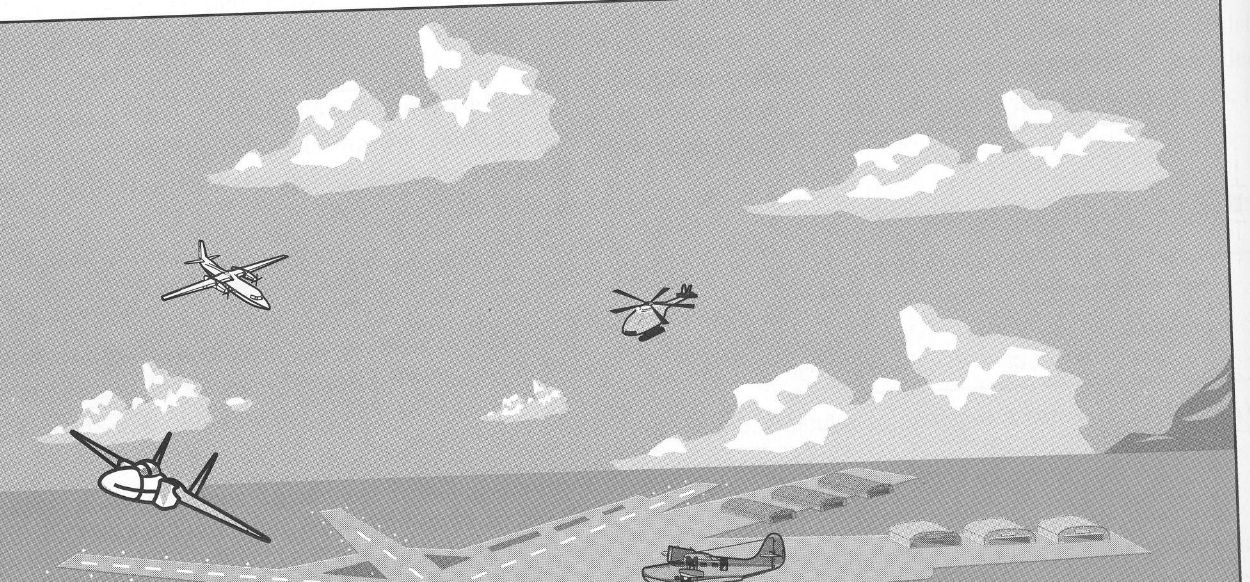


Figure 6-7. An airport lighting system can be over 50 miles in length for all circuits.

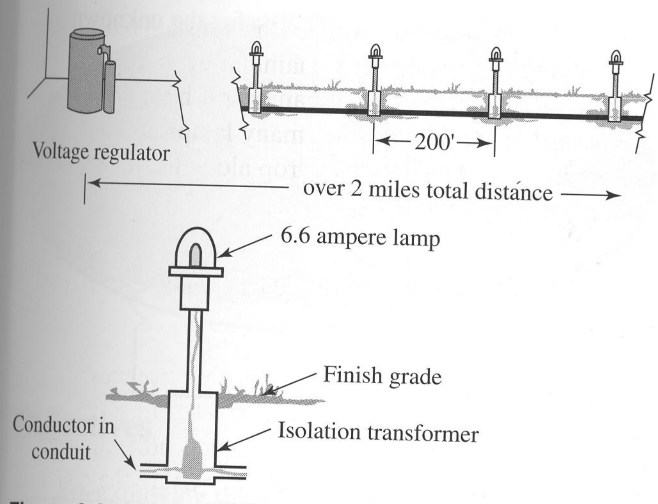


Figure 6-8. A typical airfield lighting system consists of a series of lamps connected to a voltage regulator. Each lamp will glow at equal brightness.

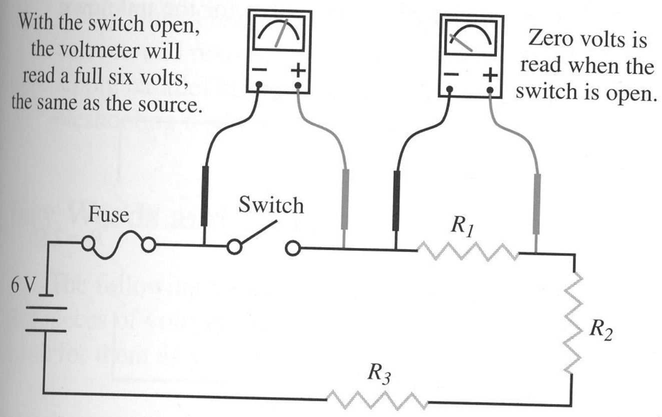


Figure 6-9. An open switch in a series circuit produces a reading on a voltmeter equal to the source voltage.

> **Lesson in safety:**
> Remember good safety is a habit that needs to be developed over a period of time. When troubleshooting even low voltage circuits, practice all safety techniques. Safety must become second nature to a technician when working on electrical circuits.

To begin the troubleshooting process, measure to determine if there is voltage at the supply. *Remember, a bad battery can still have a high voltage reading when it is not connected to a load.* When checking the battery for proper voltage, make sure the switch (S_1) is closed. If the voltage at the battery is good, move to the fuse. Take a voltage drop reading across the fuse. A good fuse will not produce a voltage drop. A blown fuse will produce a voltage drop that is equal to the source voltage. Also check

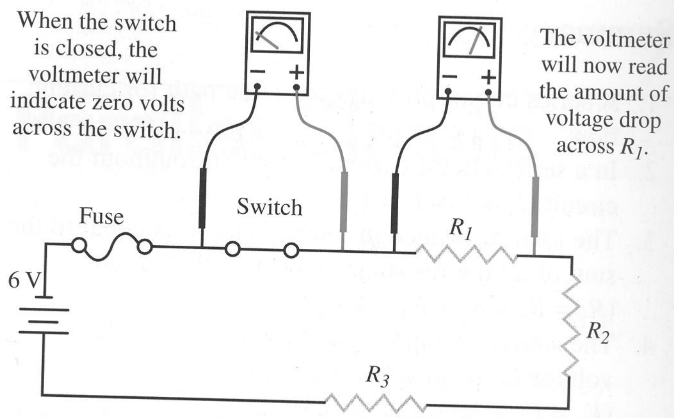


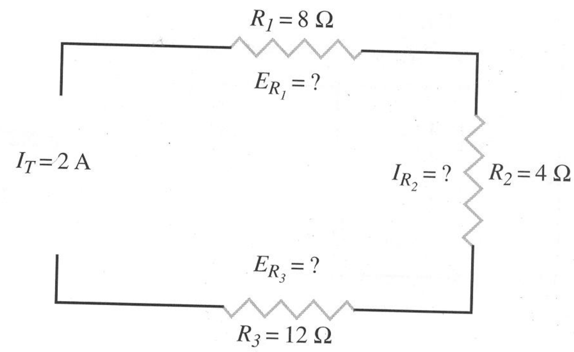
Figure 6-10. When the series circuit is complete, there will be voltage drops across each load component in the circuit.

the voltage drop across the switch. The closed switch should not produce a voltage drop, **Figure 6-10.** A single-pole single-throw (SPST) switch that produces a voltage drop when closed is defective. Next, check to see if there is a voltage drop across the individual resistors. If a resistor connected in a series circuit is open, it will have a voltage drop equal to the source voltage. The other resistors will have no voltage drop at all.

A short circuit is another possible problem. If one of the resistors is shorted, that resistor will show a voltage drop of zero. The other resistors in the circuit will drop the entire source voltage.

Review Questions for Section 6.2

1. Find the missing values of the three resistors.



2. What does a voltage regulator do for the lights in an airfield lighting system?
3. How much voltage will be found across a good fuse?
4. How much voltage will be found across a blown fuse?

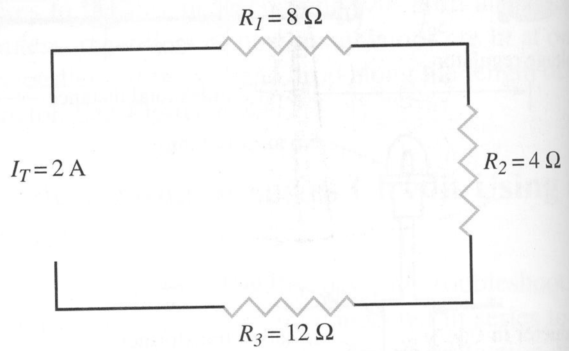
Summary

1. A series circuit provides only one path for current flow.
2. In a series circuit current is equal throughout the circuit ($I_T = I_1 = I_2 = I_3 ... = I_N$).
3. The total resistance in a series circuit is equal to the sum of all the resistance values in the circuit ($R_T = R_1 + R_2 + R_3 ... + R_N$).
4. The source voltage is equal to the sum of the voltage drops in a series circuit ($E_T = E_1 + E_2 + E_3 ... + E_N$).
5. Total power consumed in the series circuit is equal to the sum of the individual power consummation ($P_T = P_1 + P_2 + P_3 ... + P_N$).

Test Your Knowledge

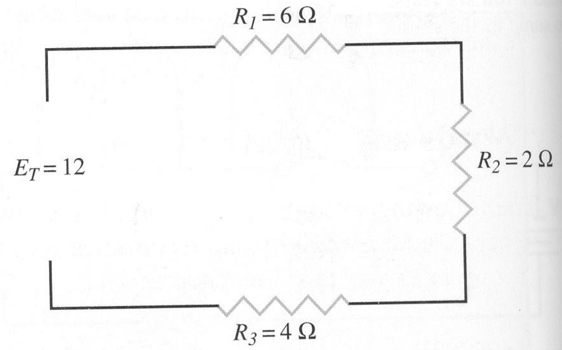
Please do not write in the text. Place your answers on a separate sheet of paper.

1. In a series circuit, the current values are __________ everywhere in that circuit.
2. In a series circuit, the source voltage is equal to the __________ of the individual voltage drops.
3. __________ is the total circuit resistance for two 25 ohm resistors connected in series.
4. When resistors of equal value are connected in series, they will develop voltage drops of __________ value.
5. Two 25 ohm resistors connected in series will require a __________ voltage source to produce a 6 volt voltage drop across one 25 ohm resistor.
6. Using the circuit below, solve for the unknown values.

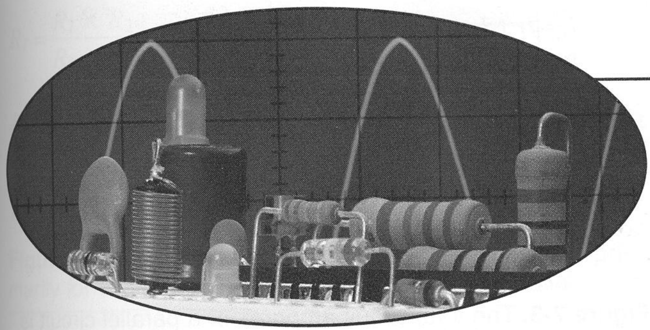


R_T = __________ E_T = __________ P_T = __________
I_{R1} = __________ E_{R1} = __________ P_{R1} = __________
I_{R2} = __________ E_{R2} = __________ P_{R2} = __________
I_{R3} = __________ E_{R3} = __________ P_{R3} = __________

7. Using the circuit below, solve for the unknown values.



I_T = __________ R_T = __________ P_T = __________
I_{R1} = __________ E_{R1} = __________ P_{R1} = __________
I_{R2} = __________ E_{R2} = __________ P_{R2} = __________
I_{R3} = __________ E_{R3} = __________ P_{R3} = __________



7 Parallel Circuits

Objectives

After studying this chapter, you will be able to:

- ➢ Determine the total resistance of a parallel circuit.
- ➢ Determine the voltage drops in a parallel circuit.
- ➢ Determine the current values of a parallel circuit.
- ➢ Determine the wattage values of a parallel circuit.
- ➢ Apply Ohm's law to solve for unknown voltage, current, and resistance in a parallel circuit.
- ➢ Apply parallel circuit theory to assist in troubleshooting a series circuit.

Key Words and Terms

The following words and terms will become important pieces of your electricity and electronics vocabulary. Look for them as you read this chapter.

branch currents
mainline current
reciprocal
Kirchhoff's current law
parallel circuit

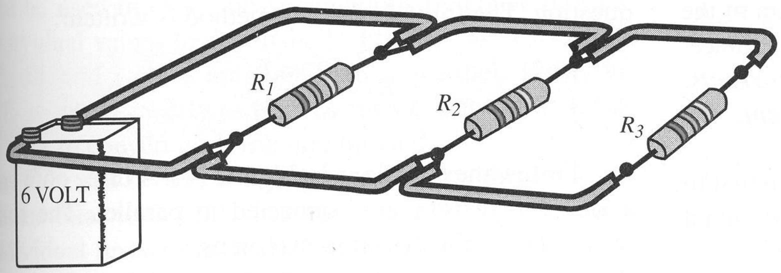
7.1 PARALLEL CIRCUITS PRINCIPLES

In simple terms, a ***parallel circuit*** provides two or more paths for electron flow through a circuit. Look at **Figure 7-1.** Take note of how each of the three resistors are connected to the source with each electron flow path being independent of the other.

When three resistors are connected in series and one resistor is removed, the entire circuit appears to be dead and the electrons cease flowing. There is no complete path for the current. If the same three resistors are connected in parallel, one of the resistors can be removed from the circuit without stopping the flow of electrons in the circuit. This unique condition of the parallel circuit is the basis of the first parallel circuit formula we will study.

Parallel Circuit Voltage

The voltage in a parallel circuit is equal to the source voltage. If two or more components are connected to the



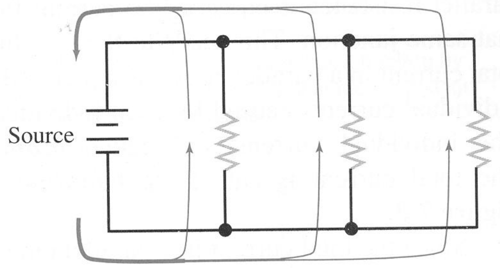


Figure 7-1. Three resistors connected in parallel.

source in parallel, the voltage drop across each component is equal to the source voltage. The formula representing the voltage condition of a parallel circuit in words is: The total voltage is equal to any individual voltage drop in the parallel circuit. The formula can be written:

$$E_T = E_1 = E_2 = E_3 ... = E_N$$

where N is the total number of voltages.

In **Figure 7-2,** there are three resistors connected in parallel. A six volt source is connected to the circuit. Each resistor has a full voltage potential applied across it. Each resistor voltage is equal to the source voltage.

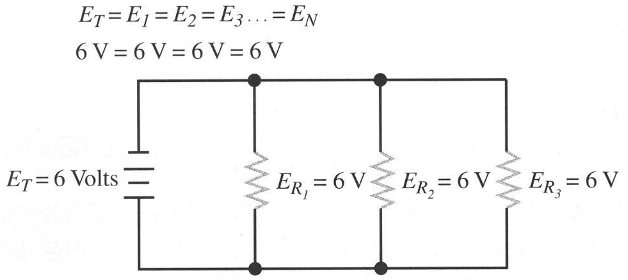


Figure 7-2. The voltage applied to each component is equal to the source voltage in a parallel circuit.

Parallel Circuit Current

Current in a parallel circuit follows some simple principles. These principles are summed up in Kirchhoff's current law. ***Kirchhoff's current law*** states that *the algebraic sum of all currents entering any point will equal the sum of all currents leaving that point.*

Simply stated, the current flowing into a junction of parallel resistance is equal to the current flowing out of that same junction. This leads to the conclusion that the total current in a parallel circuit is equal to the sum of the individual currents caused by each individual resistance. The individual currents are called ***branch currents.*** The total current is called the ***mainline current,*** see **Figure 7-3.**

Since the total current in a parallel circuit is equal to the sum of the branch currents caused by each individual resistance, a formula can be written:

$$I_T = I_1 + I_2 + I_3 ... + I_N$$

where N is the total number of currents.

Work through the circuit shown in Figure 7-3. You can see that the sum total of the three individual resistor currents equals the total source current of nine amperes.

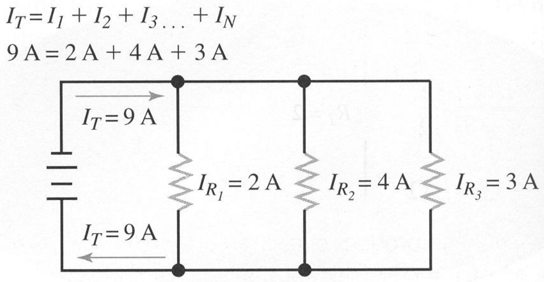


Figure 7-3. The total circuit amperes of a parallel circuit is equal to the sum total of the individual branch currents.

Parallel Circuit Resistance

When resistors are connected in a parallel circuit the *total resistance* of the parallel circuit *is always less than the smallest resistance* in the parallel group. In other words, if a six ohm and a four ohm resistor are connected in parallel, the total resistance will be less than four ohms. This principle is extremely important and should be memorized. There are several methods to determine the total resistance of a parallel circuit. These methods include:

- The product over the sum method.
- The reciprocal method.
- The equal resistances method.
- The graph method.

Product over the sum method

The product over the sum method is used as a quick way to solve for the total resistance when there are two resistances of unequal value connected in parallel. The product over the sum method derives its name from the mathematical terms used in the formula. The product is the term used for the answer to a multiplication problem, and the term sum is used for the answer to an addition question. The formula for this method is written:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

Follow the equations in **Figure 7-4.** A three ohm and a six ohm resistor are connected in parallel. The total resistance for the circuit is two ohms.

Reciprocal method

The reciprocal method can be used to find the total circuit resistance when there are three or more resistances connected in parallel. The reciprocal method gets its name because the reciprocal of the resistance values is used in finding the total resistance. A ***reciprocal*** of a

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$R_T = \frac{3\ \Omega \times 6\ \Omega}{3\ \Omega + 6\ \Omega}$$

$$R_T = \frac{18}{9}\ \Omega = 2\ \Omega$$

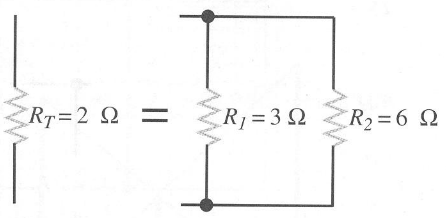


Figure 7-4. The product over the sum method is used primarily for two unequal resistors connected in parallel.

number is equal to 1 divided by that number. For example, the reciprocal of 2 is 1 ÷ 2, or 1/2. The reciprocal of 3/4 is 1 ÷ 3/4, or 4/3. The formula used for the reciprocal method is:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \cdots + \frac{1}{R_N}$$

where N is the total number of resistances.

Notice that when using the reciprocal method, each resistance value is expressed as a fraction (the resistance value's reciprocal). The number 1 is the numerator for the fraction and the value of individual resistance is the denominator.

Figure 7-5 has a four, a six, and a twelve ohm resistor connected in parallel. Since the values are expressed as fractions, a common denominator must be found. Then the values can be added together. In this problem the common denominator is twelve. The total resistance is equal to six over twelve. The six over twelve is the reciprocal of the total resistance. The fraction is inverted and twelve is then divided by six to find the total resistance value of two ohms (6/12: Reciprocal = 12/6 = 2 = R_T).

Unfortunately, most circuits do not have resistance values that lend themselves as neatly as our example to this method of solution. However, the reciprocal method can be used in these messy situations by converting the individual values to decimals. In **Figure 7-6,** resistors of 35, 18, and 7 ohms are connected in parallel. The problem is set up exactly as before, but we simply use a calculator to convert each fraction into a decimal number so that they can be added together easily. The three resistor values total to 0.2271. The combined total of the three individual resistances is the reciprocal of the total resistance value of the circuit. The total resistance is equal to one divided by 0.2271 or 4.4.

Equal resistances method

When a parallel circuit consists of two or more resistors of equal value, the total resistance is equal to the

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R_T} = \frac{1}{4\ \Omega} + \frac{1}{6\ \Omega} + \frac{1}{12\ \Omega}$$ Express each resistor as a fraction.

$$\frac{1}{R_T} = \frac{3}{12\ \Omega} + \frac{2}{12\ \Omega} + \frac{1}{12\ \Omega}$$ Convert each fraction to a common denominator.

$$\frac{1}{R_T} = \frac{6}{12\ \Omega}$$ The fractions are added together to arrive at the reciprocal of total resistance.

$$R_T = \frac{12\ \Omega}{6}$$ Invert the reciprocal and divide the new numerator by the new denominator.

$$R_T = 2\ \Omega$$

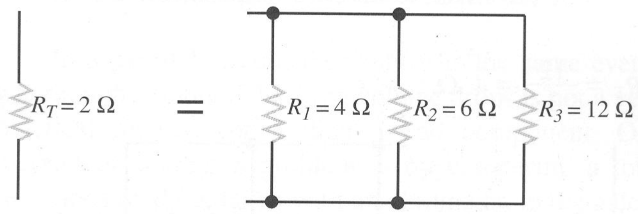


Figure 7-5. The reciprocal method is used when there are three or more unequal resistors connected in parallel.

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R_T} = \frac{1}{35\ \Omega} + \frac{1}{18\ \Omega} + \frac{1}{7\ \Omega}$$ Express each resistor as a fraction.

$$\frac{1}{R_T} = 0.0286\ \text{S} + 0.0556\ \text{S} + 0.1429\ \text{S}$$ Convert each fraction to a decimal number.

$$\frac{1}{R_T} = 0.2271\ \text{S}$$ The decimal numbers are totaled.

$$R_T = \frac{1}{0.2271\ \text{S}}$$ The one over R_T is cleared as a fraction by placing the one over the decimal equivalent of the resistance values.

$$R_T = 4.4\ \Omega$$

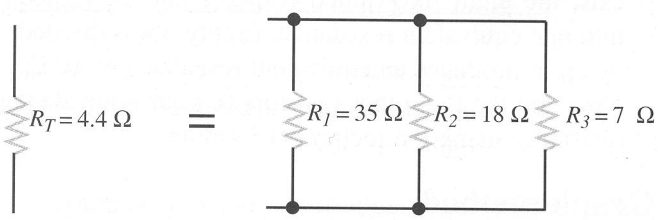


Figure 7-6. The reciprocal method can also be used with decimals rather than fractions. Notice during some intermediate steps, while working with the reciprocal of the total resistance, the values are in siemens.

value of any one resistor divided by the total number of equal resistors in the parallel circuit. The formula is written:

$$R_T = \frac{R}{N}$$

where N is the total number of resistances.

In **Figure 7-7,** three twelve ohm resistors are connected in parallel. The total resistance for the circuit in Figure 7-7 is four ohms (12 Ω ÷ 3 = 4 Ω).

$$R_T = \frac{R \text{ (the value of any one resistor in the parallel circuit)}}{N \text{ (the number of resistors in the parallel circuit)}}$$

$$R_T = \frac{12}{3} = 4\ \Omega$$

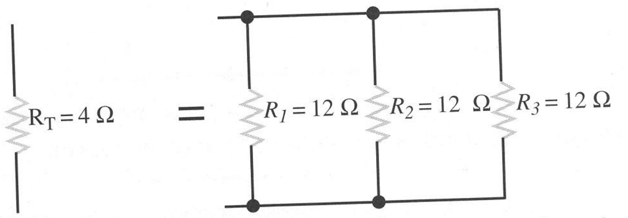
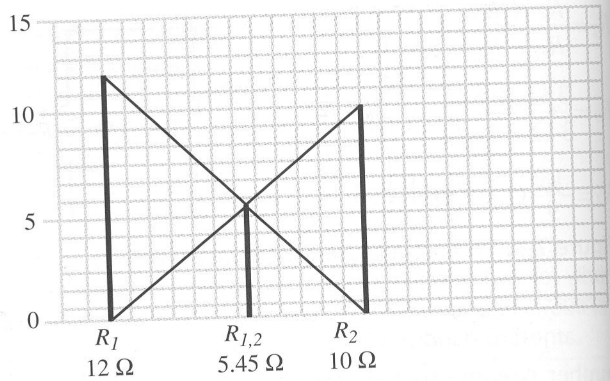


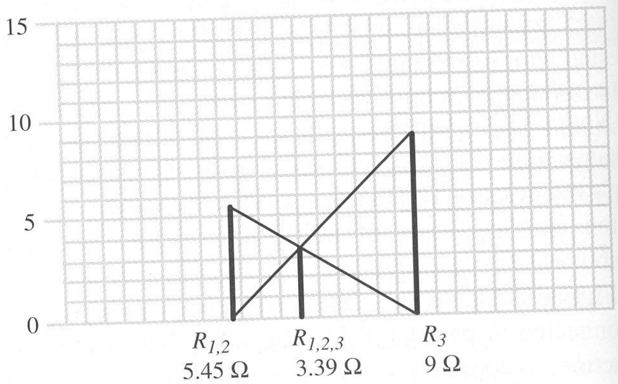
Figure 7-7. When all resistances are the same value, simply divide the value of one resistance by the number of resistances.

Note that the equal resistances method can be used in combination with other methods to simplify calculations. If a number of resistors are of an equal value, but not all of them, the equal resistances method can be used to produce an equivalent resistance from the equal value resistors.

Example: You have a circuit with 10 resistors in parallel. Eight of the resistors have a value of 80 Ω. The other resistors have values of 20 Ω and 40 Ω. How do you find the total resistance? Rather than having a total resistance equation with 10 reciprocals, the eight like-valued resistors can be turned into one equivalent resistance. Eighty ohms divided by eight produces an equivalent resistance of 10 Ω. Now add the two other resistors to your equivalent resistance using the reciprocal formula.



The total resistance of R_1 and R_2 is equal to 5.45 ohms.



The total resistance of the three resistors is 3.39 ohms.

Figure 7-8. The graph method of solving parallel circuits.

Graph method

An interesting method of estimating the value of total resistance is the graph method. The values of two resistances are expressed on a bar graph, like the one shown in **Figure 7-8.** A line is then drawn from the base of the first resistance to the top of the second resistance. A second line is then drawn from the base of the second resistance to the top of the first resistance (making a crisscross). The total resistance value of these resistances may be read where the two lines intersect. A third resistance may be added and the process repeated. This method is not considered to be very accurate, but it is a quick and easy method to check your work.

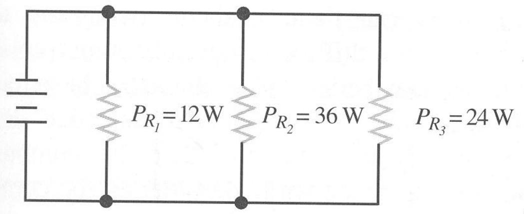
Power in a Parallel Circuit

The total power consumed in a parallel circuit is equal to the sum of all the individual powers in the circuit. The formula is written:

$$P_T = P_1 + P_2 + P_3 ... + P_N$$

where N is the total number of powers.

In **Figure 7-9,** you can see that the total power consumed (72 W) is equal to the sum total of the individual electrical power units (R_1 = 12 W, R_2 = 36 W, R_3 = 24 W) consumed at each resistance.



$P_T = P_{R_1} + P_{R_2} + P_{R_3}$

$P_T = 12\,W + 36\,W + 24\,W = 72\,W$

Figure 7-9. The total wattage in a parallel circuit is equal to the sum of the individual wattages.

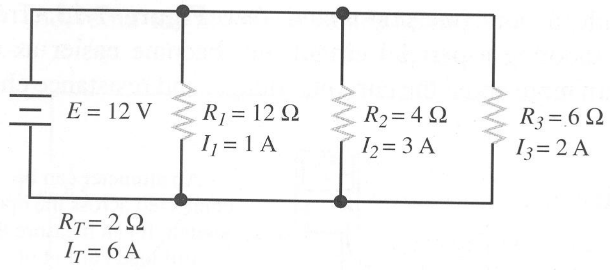


Figure 7-10. By applying Ohm's law at each location you can solve for total resistance after the total circuit current value is known.

Review Questions for Section 7.1

1. If the source voltage in a parallel circuit is equal to 10 volts, what is the voltage drop across resistor R_3? Assume R_3 is equal to 50 Ω.
2. A circuit containing three resistors in parallel has branch currents of 3 A, 5 A, and 10 A. What is the mainline current in the circuit?
3. List three formulas that can be used to find the total resistance in a parallel circuit.
4. What formula for finding the total resistance in a parallel circuit will work for any number of resistors of any value?
5. A parallel circuit has two resistors. Each consumes 6 W. Calculate the total power for the circuit.

7.2 APPLICATIONS AND TROUBLESHOOTING PARALLEL CIRCUITS

Parallel circuits are found in the home and industry alike. They allow the remaining bulbs in a string of lights to stay lit when one bulb burns out, and they allow computers to work on many parts of a problem at one time.

Applying Ohm's Law to Parallel Circuits

Ohm's law can be applied to the individual components of a parallel circuit to find unknown values such as current. The total circuit resistance in a parallel circuit is always equal to the source voltage divided by the sum total of the individual resistor currents.

An example is shown in **Figure 7-10.** You can see that the total of the individual circuit current values ($I_1 + I_2 + I_3$) equals six amperes. The source voltage of twelve volts is divided by six amperes. The total resistance is found to be two ohms.

Troubleshooting a Parallel Circuit

In a parallel circuit, the voltage is the same everywhere in the circuit. Checking voltage drops is not a very practical method for finding a bad component. One method of finding a problem is by comparing a total resistance reading, taken with an ohmmeter, to the calculated total resistance value. Looking at **Figure 7-11,** we can see that the total resistance value of the ohmmeter is 20 ohms. The calculated total resistance value is 10 ohms (20 Ω ÷ 2). Using a little deduction, you can determine that one of the resistors is open. If one of the resistors were shorted, it would cause the fuse to blow.

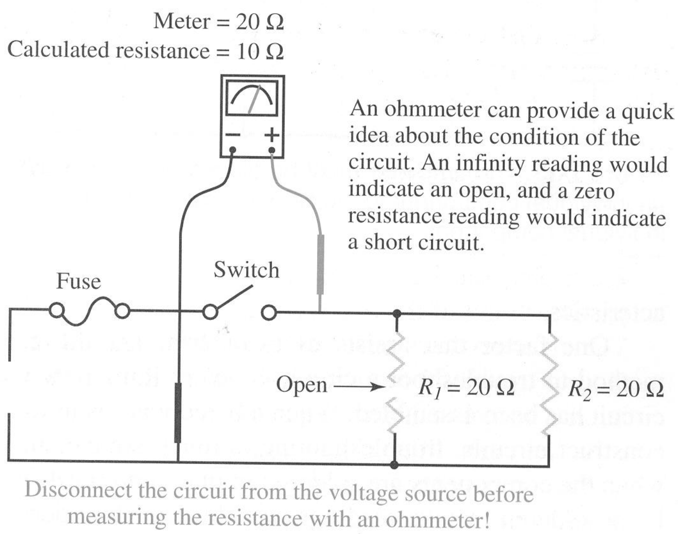


Figure 7-11. Troubleshooting a parallel circuit.

Another method of troubleshooting uses current readings taken at each resistor location. First, the total current for the circuit is calculated. Then, this value is verified with an ammeter. See **Figure 7-12.** Using the ammeter, a current reading can be taken across an open switch. This reading is then compared to the calculated total current. An open resistor would draw no current while a good resistor would. See **Figure 7-13.** Troubleshooting a parallel circuit will become easier as we learn more about the current, voltage, and resistance characteristics.

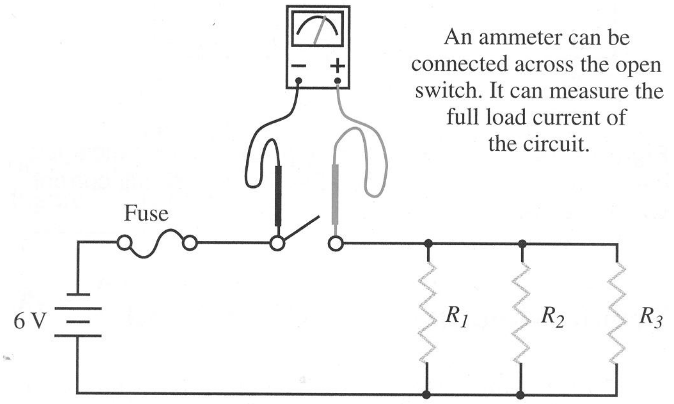


Figure 7-12. The switch location of a circuit is an ideal location to connect an ammeter to the circuit.

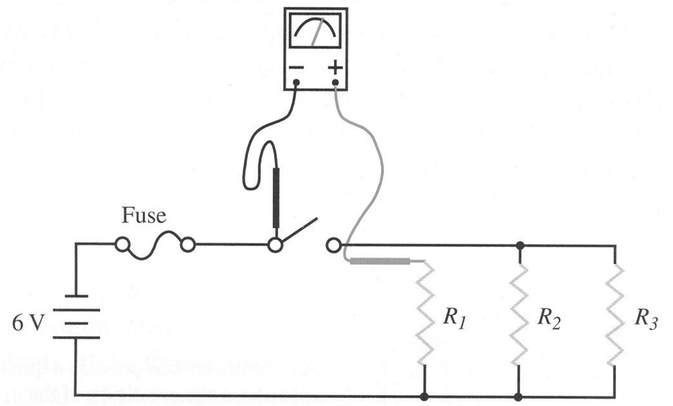


Figure 7-13. The ammeter must be placed in series with an individual component to indicate the current of only the individual component.

One factor that assists us in determining the best method to troubleshoot a circuit is determining how the circuit has been assembled. When a breadboard is used to construct circuits, troubleshooting is much simpler than when the components are soldered in place and must first be desoldered to take readings. In addition, desoldering components can damage them giving the technician an even more difficult troubleshooting problem. The technician may believe the problem has been located, and corrected, only to find another defective component. Unfortunately, the additional defective component may have been damaged while desoldering the component in order to obtain a meter reading.

Review Questions for Section 7.2

1. A parallel circuit consists of three resistors. All three resistors are 20 Ω. If the current through the third resistor is 7 amps, what is the source voltage?
2. Checking voltage drops is a __________ (practical/impractical) method of troubleshooting a parallel circuit.

Summary

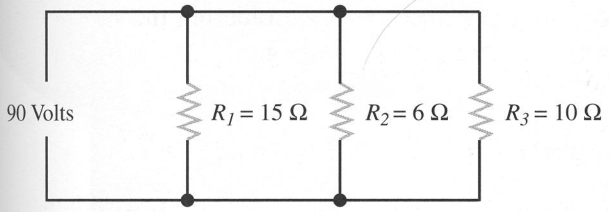
1. A parallel circuit provides more than one path for current flow.
2. In a parallel circuit, the voltage is equal throughout the circuit ($E_T = E_1 = E_2 = E_3 ... = E_N$).
3. Kirchhoff's current law states that the total current entering a junction or parallel circuit is equal to the current leaving that junction or parallel circuit.
4. The total circuit current value in a parallel circuit is equal to the sum of the individual current values ($I_T = I_1 + I_2 + I_3 ... + I_N$).
5. The total circuit resistance is always less than the smallest resistance value in the parallel circuit.
6. Total power consumed in the circuit is equal to the sum of the individual power consumptions ($P_T = P_1 + P_2 + P_3 ...+ P_N$).

Test Your Knowledge

Please do not write in the text. Place your answers on a separate sheet of paper.

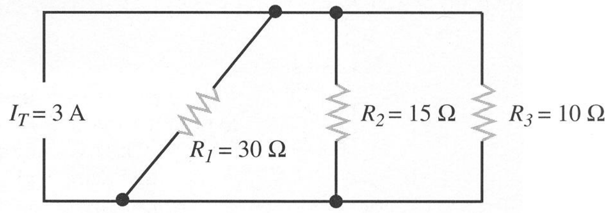
1. What is the total circuit resistance of two 10 ohm resistors connected in parallel?

2. What is the total resistance of a 12 ohm and an 8 ohm resistor connected in parallel?
3. Solve for the unknown values in the parallel circuit below.



R_T = __________ Ω
I_T = __________ A
P_T = __________ W
E_{R_1} = __________ V
E_{R_2} = __________ V
E_{R_3} = __________ V
I_{R_1} = __________ A
I_{R_2} = __________ A
I_{R_3} = __________ A

4. Solve for the unknown values below.



R_T = __________ Ω
E_T = __________ A
P_T = __________ W
I_{R_1} = __________ A
I_{R_2} = __________ A
I_{R_3} = __________ A

5. In a parallel circuit containing a 4 ohm, a 5 ohm, and a 6 ohm resistor, the current flow is:
   a. highest through the 4 ohm resistor.
   b. lowest through the 4 ohm resistor.
   c. highest through the 6 ohm resistor.
   d. the same for all three resistors.