THOMAS K. EISMIN

AIRCRAFT ELECTRICITY & ELECTRONICS

7TH EDITION

INCLUDES STUDY GUIDE

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Aircraft
Electricity and Electronics

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Aircraft
Electricity and Electronics

Seventh Edition

Thomas K. Eismin

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Contents

Preface

Modern aircraft and aerospace vehicles are today more reliant on electrical and electronic systems than ever before. The "more electric airplane" is a design concept that enhances the use of electric power to replace traditional hydraulic, pneumatic, and other systems found on traditional planes. Aircraft such as the Boeing B-787 and Airbus A-380 embraced this concept in order to improve aircraft efficiencies and increase performance. The introduction of satellite communications and wireless systems have made passenger entertainment and connectivity commonplace on modern aircraft. The more electric airplane design concept has also found its way into light business jets and single-engine trainer/personal aircraft. Today, there are more electrical and electronic systems found on aircraft than ever before; for this reason all design, engineering, and technical personnel employed in the aerospace industry must have a solid understanding of the material discussed in this text.

The integration of digital electronics and microprocessor technologies has allowed aircraft manufacturers to improve performance and safety while at the same time save weight compared to conventional systems. Electronic circuits are found in virtually every system of a modern aircraft. Large transport category aircraft are now fly-by-wire and utilize a variety of computers for navigation, flight management, and systems operation. Today, an aircraft technician must possess a thorough understanding of both basic electrical theory and advanced electronic systems. *Aircraft Electricity and Electronics* provides the reader with practical knowledge that can be used by students, engineers, and technicians alike.

In this seventh edition, several new technologies are introduced. As with modern aircraft, digital concepts are now integrated throughout the text. Digital data transfer systems, such as ARINC 664, AFDX, ARINC 429, and RS-232, are all presented in detail along with other data bus systems and concepts. Modern fly-by-wire aircraft are presented along with fiber-optic technologies and airborne satellite connectivity to the World Wide Web. Even battery technologies have changed dramatically; lithium-ion batteries are now covered in Chap. 3. New flightdeck instrumentation systems, such as electronic flight bags, synthetic vision systems, and heads-up displays, are also included in this edition.

The seventh edition has improved some of the basic information necessary to build a proper foundation for understanding aircraft electrical systems. The current Federal Aviation Regulations concerning the certification of Airframe and Powerplant (A&P) Mechanics remain a vital component of this text. The text also presents information well beyond these basic requirements, thus providing the student with a thorough understanding of the theory, design, and maintenance of current aircraft electrical and electronic systems.

The book is written with the assumption that the reader possesses no prior knowledge of electricity and electronics, yet it can also be used by experienced personnel to gain a better understanding of advanced systems. In Chaps. 1 through 5, basic electrical theory and concepts are discussed. These chapters include the fundamentals necessary for a strong understanding of the FAA's regulations as they pertain to aircraft electrical systems. Chapters 6 through 12 contain vital information on the design and maintenance of specific systems. This section begins with the basics of test equipment and electrical troubleshooting theory and eventually presents an in-depth look at digital and microprocessor circuits as they apply to aircraft, computerized power systems, and the test equipment used for systems troubleshooting and repair. Chapters 13 through 17 introduce the reader to the advanced electronics found on modern aircraft. Integrated communication and navigation systems, autoflight and autoland systems, flat panel display systems, and fly-by-wire components are all presented to the reader in an easy-to-understand, practical fashion.

The seventh edition of *Aircraft Electricity and Electronics* is the type of book you may acquire as a student and keep as a reference throughout your career.

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Fundamentals of Electricity 1

INTRODUCTION

Through the use of modern computer systems, electronic sensors, and high-speed data, electronic circuits are used to control virtually every system found on modern aircraft. **Electronics** is a special application of electricity wherein precise manipulation of electrons is employed. Today's aircraft use computers, electronics, and electrical circuits more than ever before. It is safe to say that all state-of-the-art aircraft and aerospace vehicles rely heavily on the use of electricity/electronics.

Electrical systems serve two basic functions on modern aircraft: (1) to power systems, such as lights and motors and (2) to collect and analyze information, such as in computer and data collection systems. The term *electricity* is used when referring to power circuits, while the term *electronics* typically refers to transistorized and computer systems. Today's technicians and engineers must possess a thorough understanding of all facets of electronics. This knowledge would be used during design, inspection, installation, and repair of the aircraft and aerospace vehicles.

THE ELECTRON THEORY

The atomic structure of matter dictates the means for the production and transmission of electrical power. All matter contains microscopic particles made of electrons and protons. The forces that bind these particles together to create matter are the same forces that create electrical current flow and produce electrical power. Every aircraft generator, alternator, and battery, virtually all electrical components, react according to the **electron theory**. The electron theory describes specifically the internal molecular forces of matter as they pertain to electrical power. The electron theory is therefore a vital foundation upon which to build an understanding of electricity and electronics.

Molecules and Atoms

Matter is defined as anything that occupies space; hence, everything that we can see and feel constitutes matter. Matter is composed of molecules, which, in turn, are composed of atoms. If a quantity of a common substance, such as water, is divided in half, and the half is then divided, and the resulting quarter divided, and so on, a point will be reached where any further division will change the nature of the water and turn it into something else. The smallest particle into which any compound can be divided and still retain its identity is called a **molecule**.

If a molecule of a substance is divided, it will be found to consist of particles called **atoms**. An atom is the smallest possible particle of an element. An **element** is a single substance that cannot be separated into different substances.

At the time this text was written, there were 118 known elements. Although some elements are radioactive and very unstable, there are 80 stable elements which are known as common elements. There are 94 elements which occur naturally on earth. Examples of common elements are iron, copper, lead, gold, zinc, oxygen, hydrogen, and so on. Any pure element consists of one type of atom and will have properties of only that one element. For example, a copper element will consist of one or more atoms; each atom will have the specific properties of copper.

A compound is a chemical combination of two or more different elements, and the smallest possible particle of a compound is a molecule. For example, a molecule of water (H_2O) consists of two atoms of hydrogen and one atom of oxygen. A diagram representing a water molecule is shown in Fig. 1-1.

Electrons, Protons, and Neutrons

An atom consists of extremely small particles of energy known as electrons, protons, and neutrons. All matter consists of two or more of these basic components. The simplest atom is that of hydrogen, which has one electron and one proton, as represented in the diagram of Fig. 1-2*a*. The structure of an oxygen atom is indicated in Fig. 1-2*b*. This atom has eight protons, eight neutrons, and eight electrons. The protons and neutrons form the **nucleus** of the atom; electrons revolve around the nucleus in orbits varying in shape from elliptical to circular and may be compared to the planets as they move around the sun. A **positive** charge is carried by each proton, no charge is carried by the neutrons, and **negative** charge is carried by each electron. The charges carried by the electron and the proton are equal in magnitude but opposite in nature. An atom that has an equal number of protons and electrons is

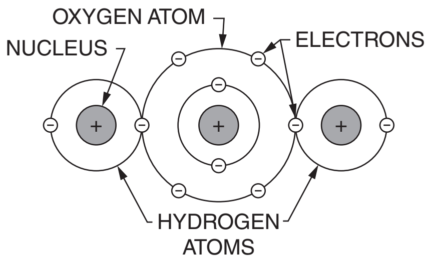

FIGURE 1-1 A water molecule.

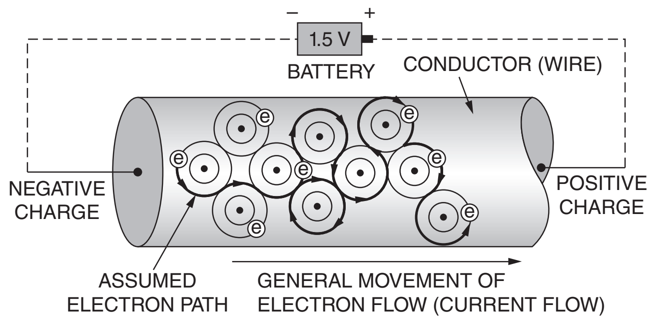

FIGURE 1-3 Electrical pressure (voltage) creates electron movement through a conductor.

electrically neutral; that is, the charge carried by the electrons is balanced by the charge carried by the protons.

It has been explained that an atom carries two opposite charges: protons in the nucleus have a positive charge, and electrons have a negative charge. When the charge of the nucleus is equal to the combined charges of the electrons, the atom is neutral; but if the atom has a shortage of electrons, it will be **positively charged.** Conversely, if the atom has an excess of electrons, it will be **negatively charged.** A positively charged atom is called a **positive ion,** and a negatively charged atom is called a **negative ion.** Charged molecules are also called ions. It should be noted that protons remain within the nucleus; only electrons are added or removed from an atom, thus creating a positive or negative ion. This movement of electrons is the basis for all electrical power.

Atomic Structure and Free Electrons

The path of an electron around the nucleus of an atom describes an imaginary sphere or shell. Hydrogen and helium atoms have only one shell, but the more complex atoms have numerous shells. Figure 1-2 illustrates this concept. When an atom has more than two electrons, it must have more than one shell, since the first shell will accommodate only two electrons. This is shown in Fig. 1-2*b*. The number of shells in an atom depends on the total number of electrons surrounding the nucleus.

The atomic structure of a substance determines how well the substance can conduct an electric current. Certain elements, chiefly metals, are known as **conductors** because an electric current will flow through them easily. The atoms of these elements give up electrons or receive electrons in the outer orbits with little difficulty. The electrons that move from one atom to another are called **free electrons.** The movement of free electrons from one atom to another is indicated by the diagram in Fig. 1-3, and it will be noted that they pass from the outer shell of one atom to the outer shell of the next. The only electrons shown in the diagram are those in the outer orbits.

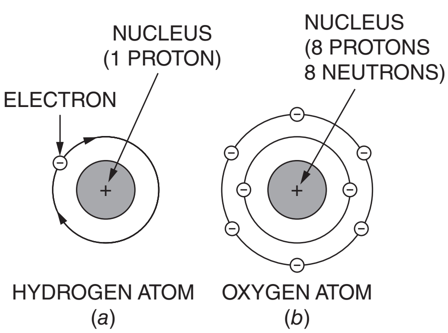

FIGURE 1-2 Structure of atoms.

The movement of free electrons does not always constitute electric current flow. There are often several free electrons randomly drifting through the atoms of any conductor. It is only when these free electrons move in the same direction that electric current exists. A power supply, such as a battery, typically creates a potential difference from one end of a conductor to another (Fig. 1-3). A strong negative charge on one end of a conductor and a positive charge on the other is the means to create a useful electron flow, commonly called “current flow.”

An element is a conductor, nonconductor (insulator), or semiconductor depending on the number of electrons in the valence orbit of the material’s atoms. The **valence orbit** of any atom is the outermost orbit (shell) of that atom. The electrons in this valence orbit are known as **valence electrons.** All atoms desire to have their valence orbit completely full of electrons, and the fewer valence electrons in an atom, the easier it will accept extra electrons. Therefore, atoms with fewer than half of their valence electrons tend to easily accept (carry) the moving electrons of an electric current flow. Such materials are called **conductors.** Materials that have more than half of their valence electrons are called **insulators.** Insulators will not easily accept extra electrons. Materials with exactly half of their valence electrons are **semiconductors.** Semiconductors have very high resistance to current flow in their pure state; however, when exact numbers of electrons are added or removed, the material offers very low resistance to electric current flow.

Semiconductors can act like a conductor or an insulator, depending on what external charge is placed on the material. Semiconductors are the basic materials used to produce diodes, transistors, and integrated circuits.

Three of the best conductors are silver, gold, and copper; their valence orbits are nearly empty, containing only one electron each. Silver is the best conductor of all metals, although copper and gold are used more often in electrical circuits. Gold has excellent corrosion-resistant properties and copper is the least expensive of the three. Two of the best insulators

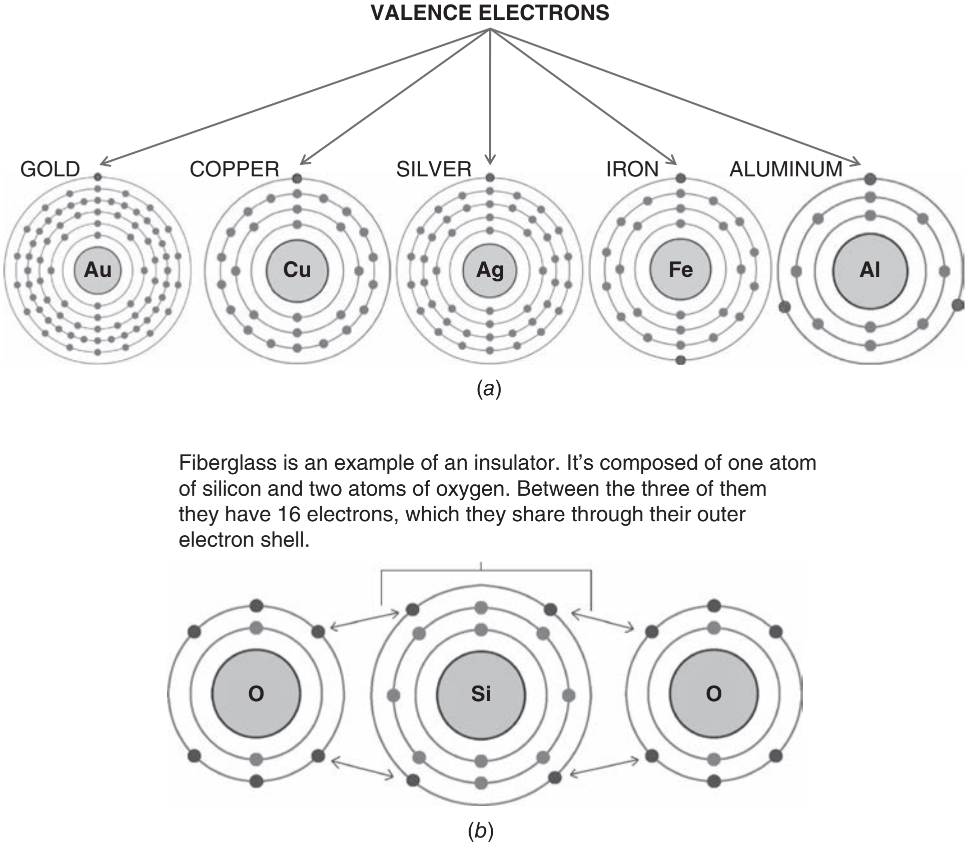

FIGURE 1-4 The number of electrons in the outer orbit of an atom determines if a material is a conductor or an insulator: (*a*) common conductors have fewer than four electrons, (*b*) insulators have more than four electrons.

are neon and helium; their atoms contain full valence orbits. We commonly substitute other "less perfect" materials for conductors and insulators to reduce costs and increase workability. Common conductors are copper and aluminum; common insulators are air, plastic, fiberglass, and rubber (Fig. 1-4). The two most common semiconductors are germanium and silicon; both of these materials have exactly four electrons in their valence orbits (Fig. 1-5). Atoms with four valence electrons are semiconductors; atoms with fewer than four valence electrons are conductors; those with more than four valence electrons are insulators.

Simply being a conductor does not create electron movement. There must be an external force in addition to the molecular forces present inside the conductor's atoms. On the aircraft the external forces are usually supplied by the battery, generator, or alternator.

When two electrons are near each other and are not acted upon by a positive charge, they repel each other with a relatively tremendous force. It is said that if two electrons could be magnified to the size of peas and were placed 100 ft apart, they would repel each other with tons of force. It is this force that causes electrons to move through a conductor. Remember, the attraction force of the protons in their nucleus to the electrons in their orbits creates stability in an atom whenever a neutral charge is present. If an extra electron enters the atom's outer orbit, the atom becomes very unstable. It is this unstable repelling force between the orbiting electrons that causes the movement of any extra electron through the conductor. When an extra electron enters the outer orbit of an atom, the repelling force immediately causes another electron to move out of the orbit of that atom and into the orbit of another. If the material is a conductor, the electrons move easily from one atom to another.

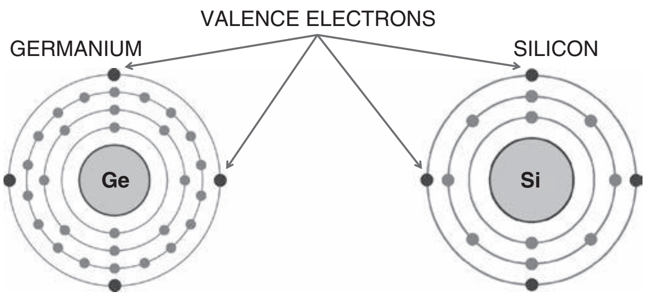

FIGURE 1-5 Semiconductors have exactly four electrons in the atom's outer orbit.

Conventional Current Flow and Electron Flow

There are two common ways to describe "the flow of electricity": (1) *conventional current flow* and (2) *electron flow*. **Conventional current flow** states that current in an electrical circuit moves from the positive connection of a power source (battery) through the circuit to the negative connection of the battery as shown in Fig. 1-6*a*. **Electron flow** is the movement of electrons through a circuit from the negative connection of a battery into the positive connection of that same battery (see Fig. 1-6*b*).

So why is there so much confusion? The answer is due to the timeline of history. The *conventional current flow* theory (also called *current flow*) was first established in the seventeenth century and made well known by Benjamin Franklin. As science advanced, it was discovered that actually electrons moved from negative to positive, known as *electron flow*. By the time the true direction of electron flow was discovered, the nomenclature of *positive* and *negative* and the direction of flow had already been so well established in the scientific community that no effort was made to change it. Today, although scientists agree on the direction of electron flow, both theories are used when describing electricity.

One of the latest theories that define the nature of electricity states that electrons flow in one direction and *holes* flow in the opposite direction. A **hole** is the space created by the absence of an electron. As electrons move from negative to positive, holes move from positive to negative. This concept is often used when studying the internal current flow of semiconductors; however, for general applications of current flow, holes need not be considered.

It is important not to let this concept of current flow direction confuse your understanding of electricity. Simply be consistent in your approach and remember while reading this text or any FAA material, *current flows from negative to positive*.

In most practical applications it is **not** important to know which direction current flows (negative to positive or positive to negative). If the battery and the load are connected correctly, there will be a current flow and the circuit should operate, see Fig. 1-6. However, if the battery becomes disconnected from the load, the circuit will not operate. So in most cases, the technician is concerned whether current flows in the circuit or not. The direction current flows in is not important.

Polarity

The specific location of the positive and negative connections of a given circuit or component is called **polarity**. For example, when replacing a battery in a simple calculator one must insert the battery in the correct direction. The positive side of the battery must be placed on the positive connection, and the negative side of the battery must be placed on the negative connection. This ensures the battery will be installed with the correct polarity. The calculator is said to be polarity sensitive and will only operate with the battery installed correctly. For most aircraft electrical installations observing the correct polarity is very important. This is because most electrical components contain semiconductor devices, such as transistors, diodes, and integrated circuits, which are all polarity sensitive.

Some electrical devices tolerate electron flow in either direction with no difference in operation (these devices are

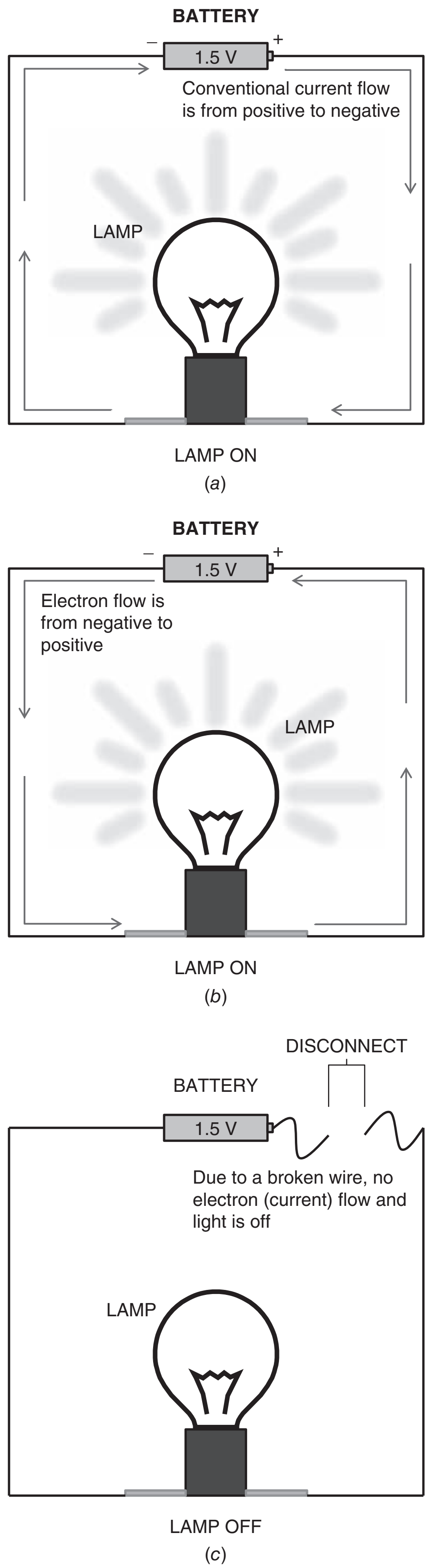

FIGURE 1-6 A complete circuit illuminates the light: (*a*) conventional current flow—from positive to negative, (*b*) electron flow—from negative to positive, (*c*) circuit disconnected—no electron/current flow.

not polarity sensitive). Incandescent lamps (the type utilizing a thin metal filament that glows white-hot with sufficient current), for example, produce light with equal efficiency regardless of current direction. Conductors and switches operate irrespective of current direction as well. The technical term for this irrelevance of flow is *nonpolarization*. We could say, then, that incandescent lamps, switches, and wires are *nonpolarized* components. Conversely, any component that will not function if the positive and negative connections are reversed is a *polarized* device.

STATIC ELECTRICITY

Electrostatics

The study of the behavior of static electricity is called **electrostatics.** The word **static** means stationary or at rest, and electric charges that are at rest are called **static electricity.**

A material with atoms containing equal numbers of electrons and protons is electrically neutral. If the number of electrons in that material should increase or decrease, the material is left with a static charge. An excess of electrons creates a negatively charged body; a deficiency of electrons creates a positively charged body. This excess or deficiency of electrons can be caused by the friction between two dissimilar substances or by contact between a neutral body and a charged body. If friction produces the static charge, the nature of that charge is determined by the types of substances. The following list of substances is called the **electric series,** and the list is so arranged that each substance is positive in relation to any one that follows it when the two are in contact.

1. Fur
2. Flannel
3. Ivory
4. Crystals
5. Glass
6. Cotton
7. Silk
8. Leather
9. The body
10. Wood
11. Metals
12. Sealing wax
13. Resins
14. Gutta percha
15. Guncotton

If, for example, a glass rod is rubbed with fur, the rod becomes negatively charged, but if it is rubbed with silk, it becomes positively charged.

When a nonconductor is charged by rubbing it with a dissimilar material, the charge remains at the points where the friction occurs because the electrons cannot move through the nonconductor material. When a conductor is charged, it can discharge easily since electrons travel freely through conductors.

An electric charge may be produced in a conductor by induction if the conductor is properly insulated. During flight metal aircraft are insulated from ground and may accumulate a static charge. This charge forms on the aluminum skin of the aircraft and will try to distribute evenly throughout the aircraft. The charge may even create a spark when moving from one component to the next. In some cases, this movement of the static charge can be a hazard to safety and is therefore kept to a minimum.

The force that is created between two charged bodies is called the **electrostatic force.** This force can be either attractive or repulsive, depending on the object's charge. Like charges repel each other. Unlike charges attract each other. The electrostatic force is similar to those forces that exist inside of an atom between electrons and protons. However, the electrostatic force is considered to be on a much larger scale, dealing with entire objects, not minute atomic particles. The amount of static charge contained within a body will determine the strength of the electrostatic field. Weak charges produce weak electrostatic fields and vice versa. Precisely, the strength of an electrostatic field between two bodies is directly proportional to the strength of the charge on those two bodies. Figure 1-7*a* demonstrates this concept. The strength of the electrostatic force is also affected by the distance between the two charged bodies. If the distance between the two charged substances increases, the electrostatic force decreases; conversely, if the distance decreases, the force increases. Precisely, the electrostatic force between two charged bodies is inversely proportional to the square of the distance between those two bodies. That is, as the distance becomes twice as large between the bodies, the electrostatic force is one-fourth as great. This concept is demonstrated in Fig. 1-7*b*.

Static electrical discharge will eventually occur to all charged bodies. Any unbalance of charge strives for equilibrium. Usually contact is made with another object to neutralize the static charge. If a charged body contacts a neutral body, both objects will then share the original charge. An example of this discharge occurs when a person gets shocked while touching a common doorknob. If the person has generated a static charge (typically occurs while walking on carpet in dry air conditions), the discharge occurs as the individual makes contact with the metal knob. If the neutral body is large enough, such as the earth, virtually all the charge will become neutralized, or absorbed, by the large body.

Static discharge has become a major problem for modern microelectronics. The miniaturization of modern computerized systems has caused them to become extremely delicate. The discharge of static electricity can easily damage these components. Sensitive electronics are known as electrostatic-discharge sensitive (ESDS) components. Anyone who designs, installs, or maintains aircraft electronics must follow proper procedures to prevent damage due to static discharge. ESDS prevention techniques will be discussed later in this text.

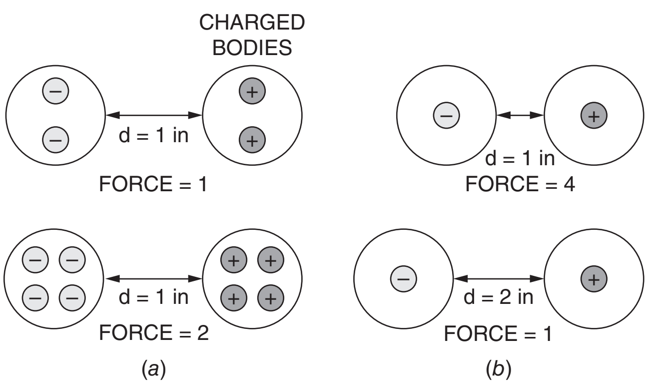

FIGURE 1-7 The strength of an electrostatic force. (*a*) Twice the static charge equals twice the static force. (*b*) Twice the distance equals one-fourth the static force.

UNITS OF ELECTRICITY

Current

An electric **current** is defined as a flow of electrons through a conductor. If the terminals of a battery are connected to the ends of a wire, the negative terminal forces electrons into the wire and the positive terminal takes electrons from the wire; hence as long as the battery is connected, there is a continuous flow of electrons (current) through the wire until the battery becomes discharged.

Because each electron has mass and inertia, electron flow is capable of doing work such as turning motors, lighting lamps, and warming heaters. Just as moving water can turn a primitive paddle wheel to grind wheat, moving electrons can do the same. Even at the speed of light, a single electron could not do much work; however, if enough electrons are set into motion, vast amounts of work can be done using electricity.

It is often hard to understand that moving electrons can do useful work; remember, electrons may be small, but they do have mass, and any moving mass can perform work.

It is said that an electric current travels at the speed of light, approximately 186,000 miles per second (mps) [299,000 km/s]. Actually, it would be more correct to say that the effect, or force, of electricity travels at this speed. Individual electrons move at a comparatively slow rate from atom to atom in a conductor, but the influence of a charge is "felt" through the entire circuit instantaneously. A simple illustration will explain this phenomenon. If we completely fill a tube with tennis balls, as shown in Fig. 1-8, and then push an additional ball into one end of the tube, one ball will fall out the other end. This is similar to the effect of electrons as they are forced into a conductor. When electrical pressure is applied to one end of the conductor, it is immediately effective at the other end. It must be remembered, however, that under most conditions, electrons must have a complete conducting path before they will enter or leave the conductor.

When it is necessary to measure the flow of a liquid through a pipe, the rate of flow is often measured in **gallons per minute.** The gallon is a definite quantity of liquid and may be called a unit of quantity. The unit of quantity for electricity is the **coulomb** (C), named for Charles A. Coulomb (1736–1806), a French physicist who conducted many experiments with electric charges. One coulomb is the amount of electricity that, when passed through a standard silver nitrate solution, will cause 0.001118 gram (g) of silver to be deposited upon one electrode. (An electrode is a terminal, or pole, of an electric circuit.) A coulomb is also defined as 6.28×10^{18} electrons, that is, 6.28 billion billion electrons As mentioned earlier, electrons are really, really small.

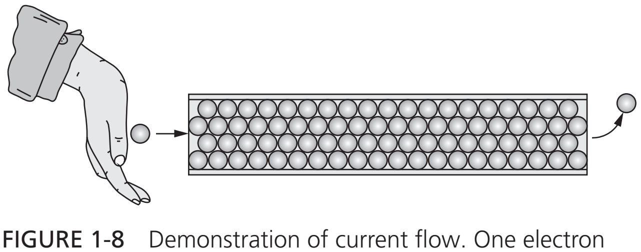

FIGURE 1-8 Demonstration of current flow. One electron into the conductor instantaneously means one electron out of the conductor.

For practical situations, electric current is measured in a unit called the *ampere.* **One ampere is the rate of flow of 1 coulomb per second.** The ampere was named in honor of the French scientist André M. Ampère (1775–1836).

The term **current** is symbolized by the letter **I.** Current is the measure of flow or movement of electrons. Current is measured in amperes, which is often abbreviated **amps.**

Voltage and Electromotive Force

Just as water flows in a pipe when there is a difference of pressure at the ends of the pipe, an electric current flows in a conductor because of a difference in electrical pressure at the ends of the conductor. If two tanks containing water at different levels are connected by a pipe with a valve, as shown in Fig. 1-9*a*, water flows from the tank with the higher level to the other tank when the valve is open. The difference in water pressure is due to the higher water level in one tank.

It may be stated that in an electric circuit, a large number of electrons at one point will cause a current to flow to another point where there is a small number of electrons if the two points are connected by a conductor (see Fig. 1-9*b*).

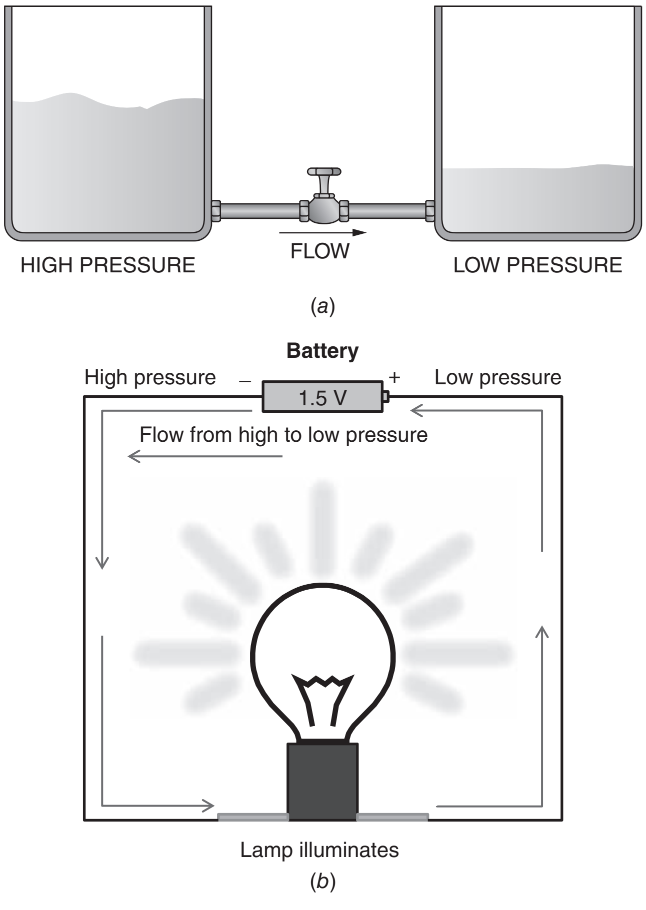

FIGURE 1-9 Pressure (force) creates movement (*a*) water flows from high to low pressure; (*b*) electrons flow from high to low pressure.

In other words, when the electron level is higher at one point than at another point, there is a difference of potential pressure between the points. When the points are connected by a conductor, electrons flow from the point of high potential to the point of low potential. There are numerous simple analogies that may be used to illustrate potential difference. For example, when an automobile tire is inflated, a difference of potential (pressure) exists between the inside of the tire and the outside. When the valve is opened, the air rushes out. In this case the air inside the tire represents an excess of electrons, a high potential. Remember we have to call this the negative electrical connection because electron flow is from negative to positive. The air outside the tire represents a deficiency of electrons, a low potential, or a positive charge.

The force that causes electrons to flow through a conductor is called **electromotive force,** abbreviated *EMF*. EMF can be thought of as the electron-moving force. The practical unit for the measurement of EMF or potential differences is the **volt** (V). The word *volt* is derived from the name of the famous electrical experimenter, Alessandro Volta (1745–1827), of Italy, who made many contributions to the knowledge of electricity.

One volt is the EMF required to cause current to flow at the rate of 1 ampere through a resistance of 1 ohm. The term *ohm* is defined later in this chapter. Electromotive force, voltage, and potential difference may be considered the same for all practical purposes. When there is a potential difference, or difference of electrical pressure, between two points, it simply means that a force exists that tends to move electrons from one point to the other. If the points are connected by a conductor, electrons will flow as long as the potential difference exists. In practical terms, a charged battery will supply current to a circuit as long as the battery remains charged. Whenever the battery is charged, there is a voltage (electromotive force) ready to "push" electrons through a circuit.

With reference to Fig. 1-10, it can be seen that the voltage of the battery creates an electron flow, just as pressure inside a balloon creates air flow. In all circuits, voltage (electrical pressure) causes electrons to flow through a conductor. This is no mystery. Any object, including electrons, will tend to move when pressure is applied in a certain direction.

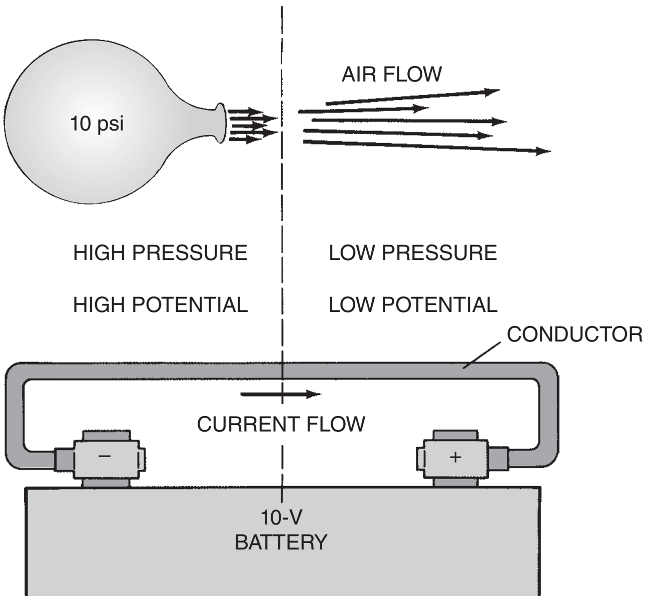

FIGURE 1-10 Comparison of voltage to air pressure.

The term **voltage,** which is measured in volts, is typically substituted for EMF. Voltage is symbolized by the letter **E,** and volts is symbolized by the letter **V.** Although this is not scientifically accurate, in some cases voltage and volts are both symbolized by the letter *V*.

Resistance

Resistance is that property of a material which tends to restrict the flow of an electric current. Some value of resistance is found in all circuits. Resistance may be termed *electrical friction* because it affects the movement of electrons in a manner similar to the effect of friction on mechanical objects. For example, if the interior of a water pipe is very rough because of rust or some other material, a smaller stream of water will flow through the pipe at a given pressure than would flow if the interior of the pipe were clean and smooth. The rough pipe offers greater resistance, or friction, than the smooth pipe.

The unit used in electricity to measure resistance is the **ohm**. The ohm is named for the German physicist Georg S. Ohm (1789–1854), who discovered the relationship between electrical quantities known as **Ohm's law**. Resistance is opposition to current flow and is symbolized by the letter **R**. Resistance is measured in ohms, which is symbolized by the Greek letter omega, Ω.

Earlier it was explained that materials with a small number of valence electrons, fewer than four, are conductors. Conductors have a relatively low resistance because they accept extra electrons (current flow) easily. If a voltage is applied to a conductor, an electric current will flow, assuming a complete circuit is present. As seen in Fig. 1-11*a*, if a heavy wooden crate is pushed on a highly polished floor, the crate will slide easily because the floor offers low resistance, or low opposition, to movement. If the same crate is placed on a rough concrete floor and pushed again with the same force, little or no movement will take place because of the high resistance offered by the rough floor. Now compare the crate in Fig. 1-11*a* with the circuit in Fig. 1-11*b*. A circuit of low resistance with an applied 5 V will easily move electrons. The same 5 V applied to a circuit of high resistance—an open switch, for example—is capable of moving no electrons. It should be noted that the resistance of an open switch is so great that no current will flow. An open switch is considered infinite resistance.

Insulators are materials that have more than four valence electrons. Insulators will not accept the extra electrons of current flow easily and therefore are considered to have relatively high resistance. If a moderate voltage is applied to an insulator, no electric current will flow. There are no perfect insulators, but many substances have such high resistance that for practical purposes they may be said to prevent the flow of current. Substances having good insulating qualities are dry air, glass, mica, porcelain, rubber, plastic, and fiber compositions. The resistance of these substances varies

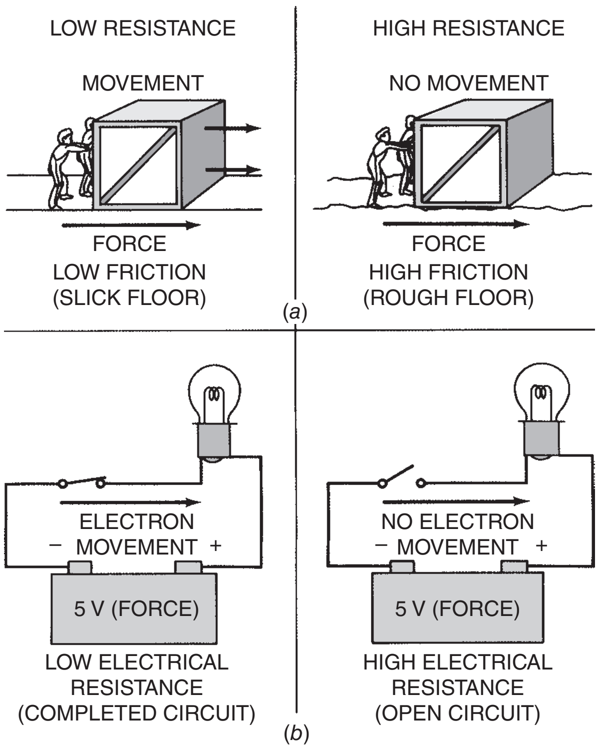

FIGURE 1-11 Comparison of resistance to friction.

to some extent, but they may all be said to block the flow of current effectively. In most cases these insulators are said to have an infinite resistance.

According to the electron theory, the atoms of an insulator do not give up electrons easily. When a voltage is applied to such a substance, the outer electron orbits are distorted, but as soon as the voltage is removed, the electrons return to their normal positions. If, however, the voltage applied is so strong that it strains the atomic structure beyond its elastic limit, the atoms lose electrons and the material becomes a conductor. When this occurs, the material is said to be ruptured. An example of this phenomenon is when a common lightning bolt travels through air during a rain storm. The lightning produces such high voltage that current is forced through the air, which is an insulator under most situations.

Elements of an Electric Circuit

There are a variety of electrical circuits found on modern aircraft. Some operate on alternating current (AC), some on direct current (DC). Aircraft have heavy-duty circuits, such as engine starter motors, and delicate circuits, such as digital communication signals. Regardless of their design and application, all electrical circuits have four common elements: the *power producer*, the *power user*, the *distribution device(s)*, and the *control device(s)*. The **power producer** is the source of electrical power, which produces the voltage and current needed to operate the system. Most systems have only one power producer; however, multiple power producers can be used. In a typical aircraft there is both a battery and alternator that can supply electrical power. The **power user** of a circuit is the device that performs the task (work) for which the circuit is designed. In most cases, it is obvious what component is the power user, such as a navigation light or flap motor. Some power users are less obvious, such as a vibration sensor used to monitor turbine engines. A **distribution device** is designed to carry the moving electrons between the power producer and the power user. The most common form of a distribution device is the wire which connects the various components of a circuit. Other items such as electrical terminals or connector plugs can also be considered a distribution device. A **control device** is that part of the circuit used to regulate or "control" how and when the circuit operates. An electrical switch is probably the most common and simple type of control device. However, there are many complex devices used to control various circuits found on aircraft, like a flight management computer used to control a motorized rudder actuator. It should be noted that some circuits may not contain a control device. In this case, the circuit is always on like a common house clock.

Figure 1-12 shows the relationships of the four common elements; please refer to this figure during the following discussions. The three electrical circuits in this figure have been greatly simplified to help with this discussion; keep in mind, you can apply these concepts to every circuit on the aircraft.

Notice the three diagrams of Fig. 1-12 all show the following:

1) The power supply is located on the left side of the diagram.
2) There must always be two wires to carry the electrical current between the power producer and power user. At least two wires are needed because the electrons must always travel in a complete path from one connection of the power supply and return to the other connection.
3) Each circuit contains all four basic elements: (1) power producer, (2) power user, (3) distribution, and (4) control.

The circuit in Fig. 1-12*a* contains a common 1.5-V AA battery as the power producer. Both the fuse and the switch are control devices. The fuse is used to protect the circuit in the event of an overload, and the switch is used to turn on/off the circuit. The wiring of the circuit, the terminal, and two connector plugs are distribution devices. The light bulb is the power user.

In Fig. 1-12*b*, a 24V aircraft battery is the power producer; this is a common power source for most aircraft. The switch and circuit breaker are control devices. A circuit breaker is a control device, similar to a fuse, which is used to protect the circuit in the event of an overload. The flight control computer (FCC) is a power user and also a control device. Like all computers, it uses power to perform various calculations and then performs some type of function. In this circuit, the FCC is used to manage the operation of the three motors which position the aircraft control surfaces during flight. So ultimately the FCC is a control device, but it also uses some power. There are four connectors on the FCC; these are used so the computer can easily be removed from the aircraft if needed. Most electrical devices have

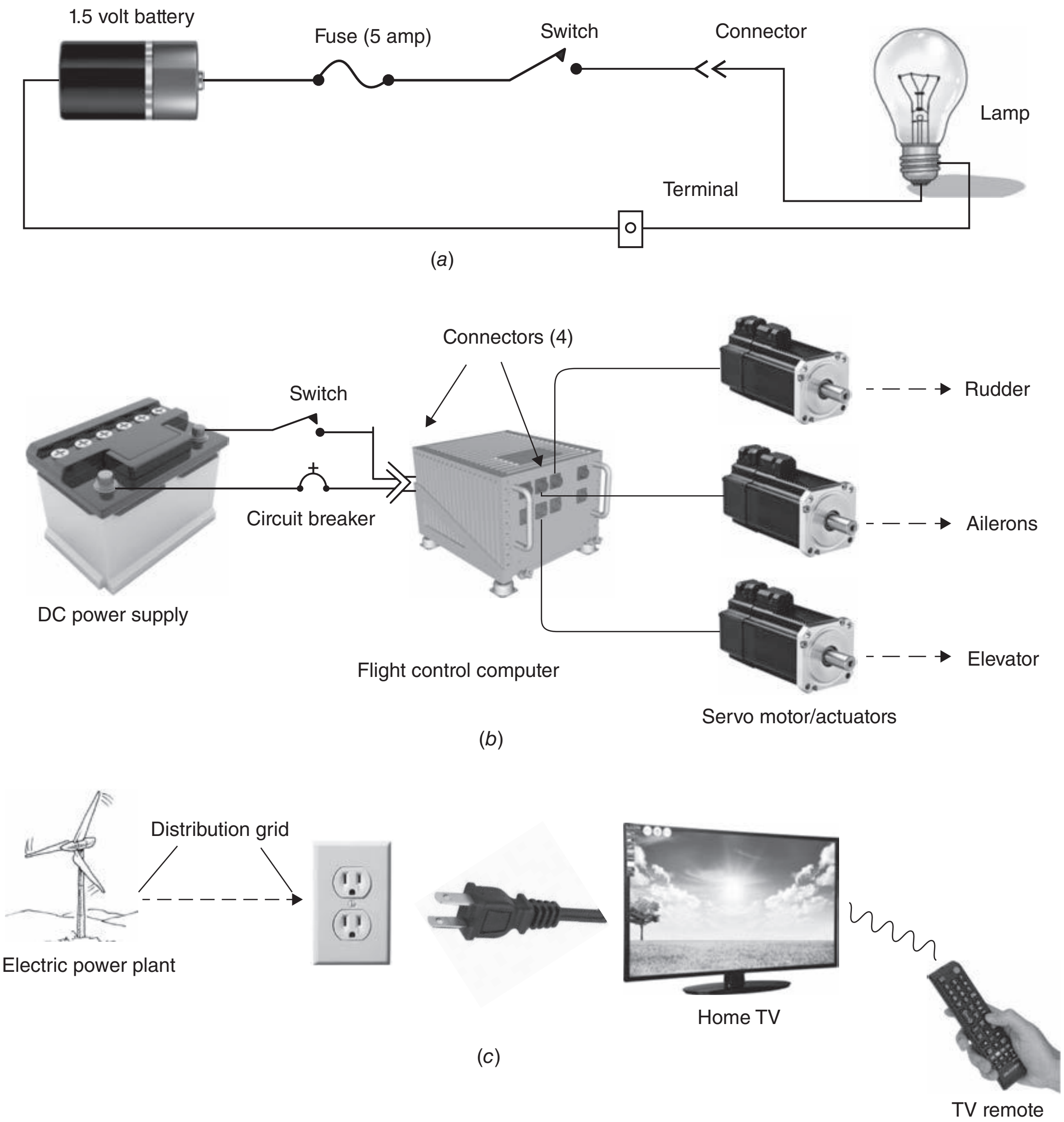

FIGURE 1-12 The four common elements of a simple circuit: (*a*) power producer—battery, power user—light bulb, distribution devices—wire connector and terminal, control devices—fuse and switch; (*b*) power producer—aircraft battery, power user—FCC and motors, control devices—switch, circuit breaker and FCC, distribution devices—wire and connectors; (*c*) power producer—electric power plant and the battery in the remote, power user—the television and the handheld remote, control devices—the handheld remote, distribution devices—distribution grid, household plug/socket and wire.

some means of disconnection from the circuit. These four connectors, like the wire of the circuit, are distribution devices.

The bottom circuit (Fig. 1-12*c*) shows a typical household circuit used to power a television. The power producer in this case is the electric power plant located miles from the home. For simplicity, most people consider the electrical receptacle and plug in the home to be the power producer (it is actually a distribution device). The wire to the TV is also a distribution device. The television is the power user, and the handheld remote is the control device. In this case the TV remote is a separate electrical circuit. The remote connects wirelessly to the TV. Inside the TV there is a circuit that turns on/off the electrical power to the screen. The TV is controlled by an internal circuit that receives a control signal from the external remote control. You could also say the remote is both a control device and a power user since it has a battery.

Obviously these three circuits are greatly simplified, and it can be seen that many electrical items can actually contain two or more of the four basic circuit elements. A common aircraft systems computer is always a power user. It most likely is a control device, and within the computer there may be wires or printed circuit boards that are distribution devices. Remember to function properly, every electric circuit must have four basic elements: (1) a power producer, (2) a power user, (3) a control device, and (4) some form of distribution device. As you read through this text keep these basic circuit elements in mind, and it will help you gain a thorough understanding of all electrical systems.

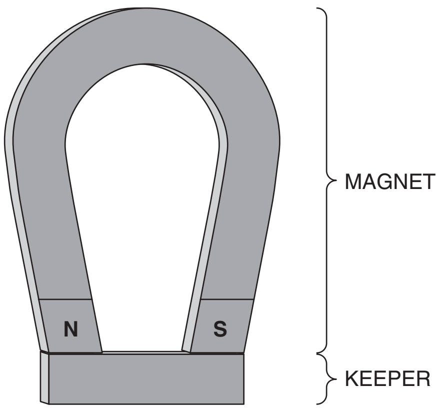

FIGURE 1-13 A permanent magnet.

THEORY OF MAGNETISM

The Magnet

Almost everyone has witnessed the effects of magnetism, and many have owned simple permanent magnets such as that illustrated in Fig. 1-13. However, few people realize the importance of magnetism and its relationship to electricity. In the scientific community it is commonly thought that electricity would not exist without magnetism. A **magnet** may be defined as an object that attracts ferrous metals such as iron or steel. It produces a magnetic field external to itself that reacts with magnetic substances.

A magnetic field is assumed to consist of invisible lines of force that leave the **north** pole of a magnet and enter the **south** pole. The direction of this force is assumed only in order to establish rules and references for operation. Whether there is any actual movement of force from the north pole to the south pole of a magnet is not known, but it is known that the force acts in a definite direction. This is indicated by the fact that a north pole will repel another north pole but will be attracted by a south pole. **Like poles repel; unlike poles attract.** A **permanent magnet** is one that maintains an almost constant magnetic field without the application of any magnetizing force. Most permanent magnets show practically no loss of magnetic strength over a period of several years.

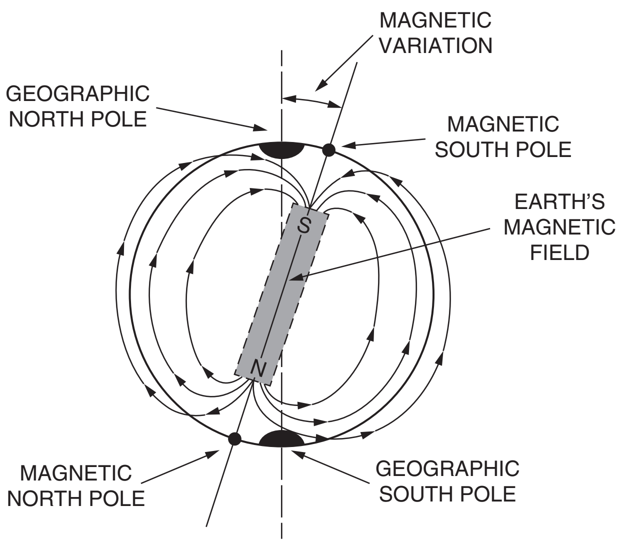

FIGURE 1-14 The earth's magnetic field.

A **natural magnet** is one found in nature; it is called a **lodestone,** or *leading stone.* The natural magnet received this name because it was used by early navigators to determine direction. The lodestone is composed of an oxide of iron called magnetite.

All magnets have certain properties; for example, if a magnet is freely suspended, one end always points in a northerly direction. For this reason, one end of the magnet is called the *north-seeking* and the other the *south-seeking* end. These terms have been shortened to *north* and *south,* respectively. The reason that a freely suspended magnet assumes a north-south position is that the earth is a large magnet and the earth's magnetic field exists over the entire surface. The suspended magnet's lines of force interact with the earth's magnetic field and align the magnet accordingly. According to definition, the magnetic pole near the earth's geographic north pole is actually the earth's south magnetic pole. However, to eliminate confusion, the direction in which a magnet's north pole points is called the earth's north pole. In reality it is magnetic south.

The magnetic poles of the earth are not located at the geographic poles. The magnetic pole in the Northern Hemisphere is located east of geographic north. The magnetic south pole is located west of geographic south, as illustrated in Fig. 1-14. The difference between the geographic and magnetic poles is called **magnetic variation.** In general, this principle of magnetic variation does not affect electrical phenomena; however, it becomes very important when navigating aircraft using a magnetic compass.

The true nature of magnetism is not clearly understood, although its effects are well known. One theory that seems to provide a logical explanation of magnetism assumes that atoms or molecules of magnetic substances are in reality small magnets. It is reasoned that electrons moving around the nucleus of an atom create minute magnetic fields. In magnetic substances such as iron, it is assumed that most of the electrons are moving in one general direction around the nuclei; hence, these electrons produce a noticeable magnetic field in each atom, and each atom or molecule becomes a tiny magnet. When the substance is not magnetized, the molecules lie in all positions in the material, as shown in Fig. 1-15*a*, and their fields tend to cancel one another. When the substance is placed in a magnetic field, the molecules align themselves with the field, and the fields of the molecules add to the strength of the magnetizing field. A diagram of a magnetized substance is shown in Fig. 1-15*b*.

When a piece of soft iron is placed in a magnetic field, almost all the molecules in the iron align themselves with the field, but as soon as the magnetizing field is removed, most of the molecules return to their random positions, and the substance is no longer magnetized. Because some of the molecules tend to remain in the aligned position, every magnetic substance retains a slight amount of magnetism after having been magnetized. This retained magnetism is called **residual magnetism.**

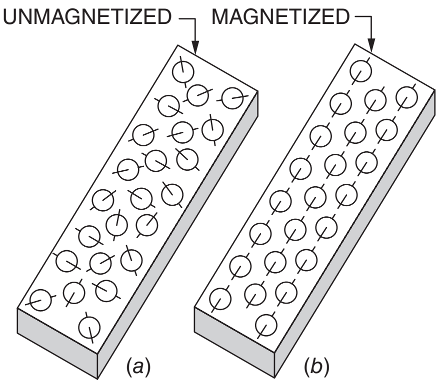

FIGURE 1-15 Theory of magnetism.

Certain substances, such as hardened steel, are more difficult to magnetize than soft iron because of the internal friction among the molecules. If such a substance is placed in a very strong magnetic field, the molecules become aligned with the field. When the substance is removed from the magnetic field, it will retain its magnetism; hence, it is called a **permanent magnet**. Hard steel and certain metallic alloys—such as Alnico, an alloy containing nickel, aluminum, and cobalt—have the ability to retain magnetism. Permanent magnets retain their magnetism for the same reason that they are difficult to magnetize; that is, the molecules do not shift their positions easily. When the molecules are aligned, all the north poles of the molecules point in the same direction and produce the north pole of the magnet. In like manner, the south poles of the molecules produce the south pole of the magnet.

Many substances have no appreciable magnetic properties. The atoms of these substances apparently have their electron orbits in positions such that their fields cancel one another. Among these substances are copper, silver, gold, and lead.

The ability of a material to become magnetized is called **permeability.** A material with high permeability is easy to magnetize or demagnetize. A material with low permeability is hard to magnetize or demagnetize. Materials with high permeability, such as soft iron, are most useful as temporary magnets. Materials with low permeability, such as Alnico, are best suited for permanent magnets.

The most newly discovered magnetic materials are known as *rare earth elements.* These rare earth elements (or rare earth metals) are a set of 17 chemical elements which occur naturally on earth. Despite their name, most rare earth elements are relatively plentiful in the earth's crust. However, these elements are typically widely dispersed and not often found in concentrated and economically usable forms. Whenever a rare earth element is formed into a magnet, it is often called a *rare earth magnet*. In general, most rare earth metals can be made into very strong magnets and have become popular in many modern electrical components due to their relative strength. For example, many compact, yet powerful, motors use rare earth magnets to help create a rotational force.

Properties of Magnetism

The field of force existing between the poles of a magnet is called a **magnetic field.** The pattern of this field may be seen by placing a stiff paper over a magnet and sprinkling iron filings on the paper. As shown in Fig. 1-16, the iron filings will line up with the lines of magnetic force. It will be noted that the lines directly between the poles are straight, but the lines farther from the direct path are curved. This curving is due to the repulsion of lines traveling in the same direction. If iron filings are sprinkled on a paper placed over two north poles, the field will have the pattern shown in Fig. 1-17. Here the lines of force from the two poles come out and curve away from one another. This pattern explains why two north poles repel each other; the flux lines create a repulsion force. Of course, two south poles will also repel for the same reason.

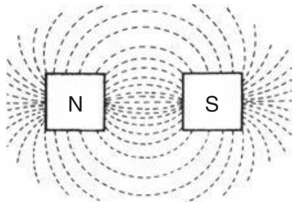

FIGURE 1-16 A magnetic field.

Magnetic force, which is also called **magnetic flux,** is said to travel from north to south in invisible lines. By assuming a direction, we provide a reference by which calculations can be made and magnetic effects determined. Since iron filings in a magnetic field arrange themselves in lines, it is logical to say that magnetic force exists in lines. The field created by magnetic flux lines is sometimes called the **magnetic circuit.**

The external field of a magnet is distorted when any magnetic substance is placed in that field because it is easier for the lines of force to travel through the magnetic substance than through the air (see Fig. 1-18). The opposition of a

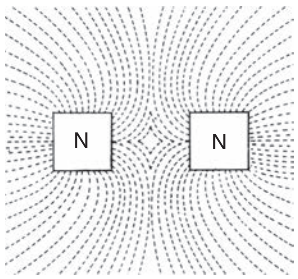

FIGURE 1-17 Magnetic field between two like magnetic poles.

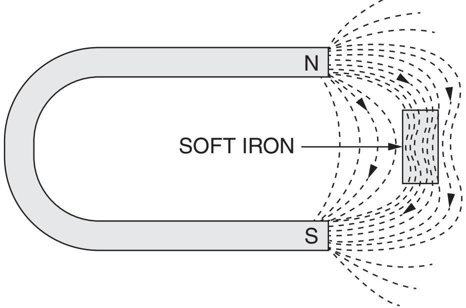

FIGURE 1-18 Field distorted by a magnetic substance.

material to magnetic flux is called **reluctance** and compares to resistance in an electric circuit. The symbol for reluctance is R and the unit is **rel.** As with electric current, the material that will completely resist magnetic flux lines is unknown. However, some materials will accept flux lines more easily than others.

In review, the properties of magnets are as follows: (1) The pole that tends to point toward the earth's geographic north is called the magnet's north pole. The opposite end is called the south pole. (2) Like magnetic poles repel each other, and unlike poles attract each other. (3) A magnetic field surrounds each magnet and contains magnetic flux lines. These flux lines are directly responsible for the magnetic properties of the material. (4) The strength of any magnet is directly proportional to the density of the flux field. That is, a stronger magnet will have a relatively high concentration of flux lines. (5) Magnetic fields are strongest near the poles of the magnet. This is due to the concentration of flux lines at each pole. (6) By definition, magnetic flux lines flow from the north to the south pole of any magnet. This property becomes important when studying certain relationships of magnetism. (7) Flux lines never intersect. This is because flux lines repel each other with relatively tremendous force. (8) Magnetic flux lines always take the path of least resistance, such as when they distort in order to travel through a piece of soft iron as opposed to traveling through air.

MAGNETIC DEVICES

Electromagnets

Electromagnets, in various forms, are very useful items and have become commonplace on modern aircraft. **Electromagnets,** as the name implies, are produced by using an electric current to create a magnetic field. Around every conductor carrying electric current a magnetic field exists. Figure 1-19(*a*) shows a compass used to detect the magnetic field adjacent to a conductor that carries current. This magnetic field is created due to the movement of electrons through the conductor. Typically this magnetic field is so small it is unnoticed. However, if the current is very strong or the conductor is formed into a coil, the magnetic field strength increases. Most electromagnets are constructed of a wire coil with hundreds of turns to create the desired magnetic field strength.

In Fig. 1-19*b*, the shaded circle represents a cross-section of a conductor with current flowing in toward the paper. The current is flowing from negative to positive. When the current flows as indicated, the magnetic field is in a counterclockwise direction. This is easily determined by the use of the left-hand rule. When a wire is grasped in the left hand with the thumb pointing from negative to positive, the magnetic field around the conductor is in the direction that the fingers are pointing.

If a current-carrying wire is bent into a loop or coil, the coil assumes the properties of a magnet; that is, one side of the loop will be a north pole, and the other side will be a

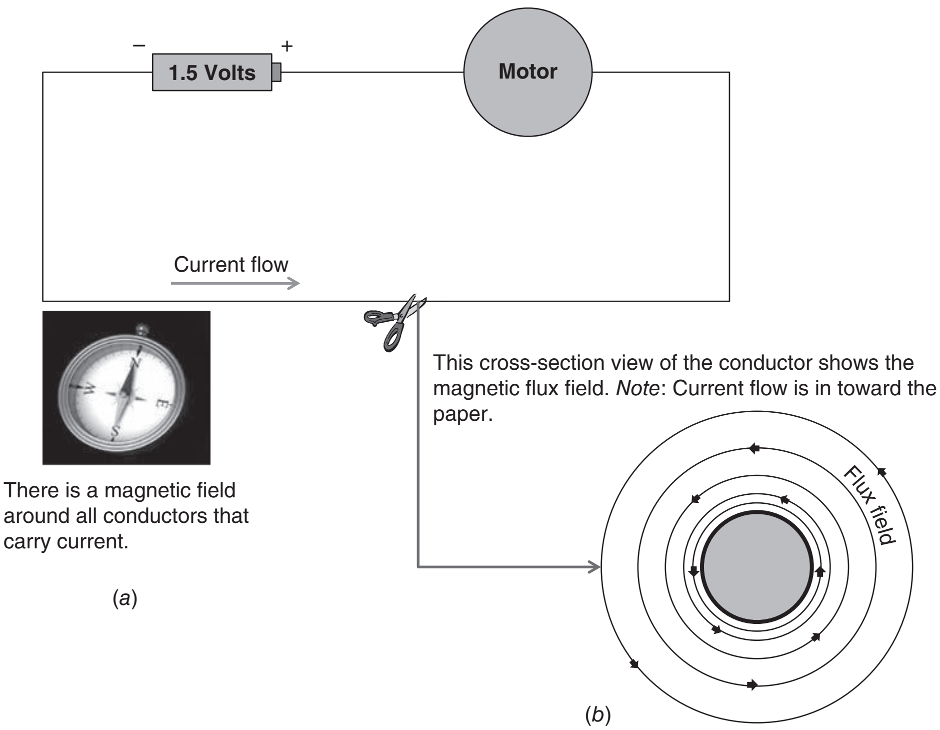

FIGURE 1-19 Electron (current) flow creates a magnetic field: (*a*) the magnetic field can be measured adjacent to a wire carrying current; (*b*) the magnetic flux field around a conductor.

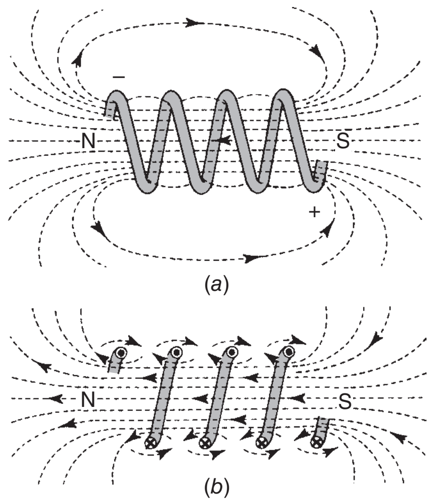

FIGURE 1-20 The magnetic field of a coil.

south pole. Remember electromagnets are made of a wire coil, not a single wire. When a wire is made into a coil and connected to a source of power, it creates a dense magnetic field, as shown in Fig. 1-20*a*. Figure 1-20*b* shows a cross-section of the same coil. Note that the lines of force produced by one turn of the coil combine with the lines of force from the other turns and thread through the coil, thus giving the coil a magnetic polarity. The polarity of the coil is easily determined by the use of the **left-hand rule for coils:** *When a coil is grasped in the left hand with the fingers pointing in the direction of current flow, that is, from negative to positive, the thumb will point toward the north pole of the coil.*

Most electromagnets wrap the wire coil around a soft iron core material. The core provides structure around which the copper wire is wrapped. And the core helps to direct the magnetic flux fields into a given area. Of course, the wire in the coil must be insulated so that there can be no short-circuit between the turns of the coil. The insulation for this type of wire is typically a thin coating of varnish or polyurethane. A typical electromagnet is made by winding many turns of insulated wire on a soft-iron core that has been wrapped with an insulating material. The turns of wire are placed as close together as possible to help prevent magnetic lines of force from passing between the turns. Figure 1-21 is a cross-sectional drawing of an electromagnet.

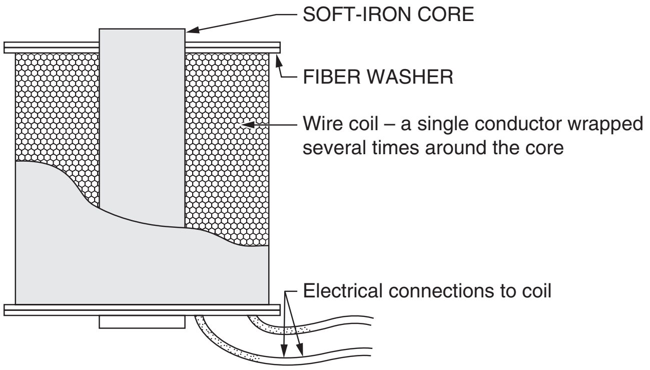

FIGURE 1-21 An electromagnet.

The strength of an electromagnet is directly proportional to (1) the strength of current flowing through the electromagnetic coil and (2) the number of turns of wire in the electromagnetic coil. That is, as either the current through the coil or the number of wire wraps around the coil increases, the electromagnet's strength also increases. Also, use of a core material of high permeability will increase an electromagnet's strength. The same electromagnet using a core of low permeability would have a decreased magnetic strength. Other factors also affect an electromagnet's strength, although they are negligible for most general-purpose applications.

The force exerted upon a magnetic material by an electromagnet is inversely proportional to the square of the distance between the pole of the magnet and the material. For example, if a magnet exerts a pull of 1 lb [0.4536 kg] upon an iron bar when the bar is $\frac{1}{2}$ in. [1.27 cm] from the magnet, then the pull will only be $\frac{1}{4}$ lb [0.1134 kg] when the bar is 1 in. [2.54 cm] from the magnet. For this reason, the design of equipment using electromagnetics requires accurate distance calculations and precise component placement.

Solenoids

Any coil of wire carrying current will have the properties of a magnet. These electromagnets are frequently used to actuate various types of mechanisms, such as a switch or mechanical latch. To explain; if an iron bar is placed inside the coil of a wire it will be affected by any magnetic field within that coil. Once current starts to flow within the coil, a magnetic field will pull the iron bar toward the center of the coil. This concept can be used to produce an electromagnet with a moving iron (steel) core which produces a powerful mechanical force. By means of a suitable attaching linkage, the movable core may be used to perform many mechanical functions, such as an electrically operated door lock. An electromagnet with a movable core is called a **solenoid.** If the core of the electromagnet cannot move inside the coil, the device is typically called a relay, as discussed later.

A solenoid typically uses a split core; one part of the core is a nonmagnetic outer sleeve fixed permanently inside the coils. The other portion of the core is allowed to slide inside this fixed outer sleeve, as demonstrated in Fig. 1-22. The spring

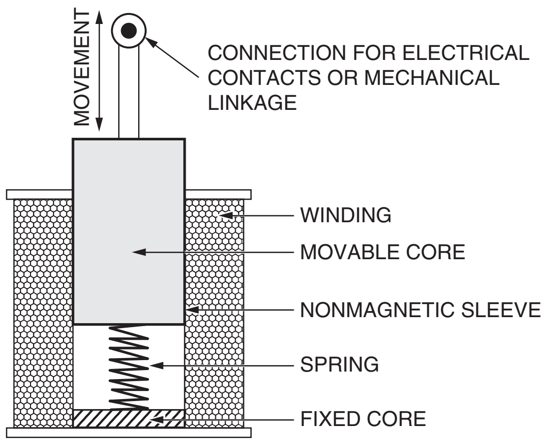

FIGURE 1-22 A solenoid.

typically holds the movable core partially extended from one end of the electromagnetic coil. When the coil is energized, the electromagnet's force pulls the movable core into the hollow sleeve opposing the spring force. This in turn moves a connecting rod and the mechanical linkage.

Solenoids are commonly used to operate electrical contacts, pneumatic and hydraulic valves, circuit breakers, and other types of mechanical devices. The chief advantage of solenoids is that they can be placed almost anywhere in an airplane and can be controlled remotely by small switches or electronic control units. Although the use of solenoids is limited to operations where only a small amount of movement is required, they have a much greater range of movement, quicker response, and greater strength than fixed-core electromagnets.

Most solenoids found on aircraft are used to operate electrical contacts. As seen in Fig. 1-23, a low-amperage circuit is used to activate the solenoid electromagnet. When the electromagnet is energized (by closing switch #1), the core material and the electrical contacts move due to the magnetic field within the coil. In this circuit, the electrical contacts are used to close a second circuit, which turns on a motor. A solenoid can be used to turn on/off a circuit whenever the coil is energized. In most cases the solenoid contains two independent circuits: (1) the controlling circuit and (2) the controlled circuit.

Relays

Electromagnets that contain a fixed core and a pivoting mechanical linkage are called **relays.** Relays are usually used for low-current switching applications. Figure 1-24 illustrates a typical switching relay. Note the electromagnet core on a relay is stationary, unlike a **solenoid.**

The part of the relay attracted by the electromagnet is called the **armature.** There are several types of armatures in electrical work, but in every case it will be found that an armature consists, in part, of a bar or core of material that may be acted upon by a magnetic field. In a relay, the armature is attracted to the electromagnet, and the movement of the armature either closes or opens the contact points. In some cases, the electromagnet operates several sets of contact points simultaneously.

There is much confusion surrounding the terminology of relays and solenoids because of their similarities. Relays are often called solenoids and vice versa. For the purpose of this text, and as generally accepted in the aircraft industry, a *solenoid* is an electromagnet with a movable core material, and a *relay* is an electromagnet with a fixed core. These definitions hold true whether the electromagnet is used for electrical switching or other mechanical functions. Figure 1-25 shows the photos of both a relay and a solenoid. Note the differences: (1) the solenoid has a movable core, while the relay core is stationary; (2) the solenoid is used to control high-current circuits, and the relay is used to control low-current circuits. Due to the movable core, a solenoid is much stronger than a relay. This is why solenoids, not relays, are typically used for operation of mechanical systems, such as a mechanical latch. Solenoids are also used to control high-current circuits, such as starter motors. To help eliminate confusion, many aircraft manufacturers have substituted the term *contactor* or *breaker* for electrical switching solenoids or relays.

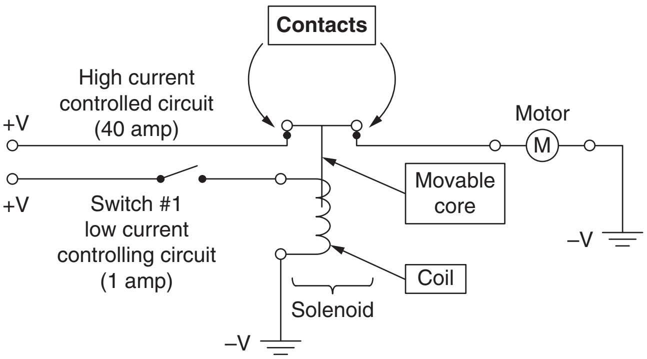

FIGURE 1-23 A solenoid has two independent circuits: a low current "controlling" circuit and a high current "controlled" circuit.

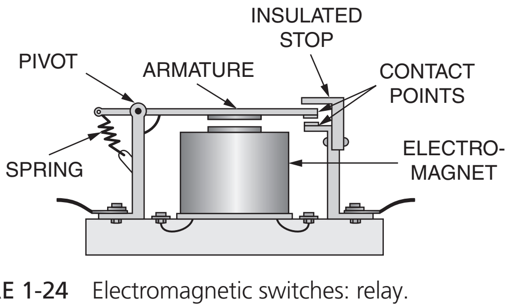

FIGURE 1-24 Electromagnetic switches: relay.

METHODS OF PRODUCING VOLTAGE

As discussed earlier, *voltage* is the force, or pressure, that creates electron movement. Voltage must be present in all circuits in order to produce current flow, but what creates voltage? Voltage is created by limited means, and only two methods produce nearly 100 percent of all electric power consumed by aircraft: chemical action and electromagnetic induction. The following paragraphs will introduce these concepts of voltage production.

Friction is a method of producing voltage by simply rubbing two dissimilar materials together. This usually produces **static electricity,** which is not typically a useful form of power. In fact, most static electricity found on the aircraft becomes a nuisance to both communication and navigation systems as well as advanced electronic devices.

Pressure is another means of producing voltage. **Piezoelectricity** means electricity created by applying pressure to certain types of crystals. Since only small amounts of power are produced using piezoelectricity, applications are limited. Some microphones used for radio communications employ the piezoelectric effect to convert sound waves into electric power. Most piezoelectric

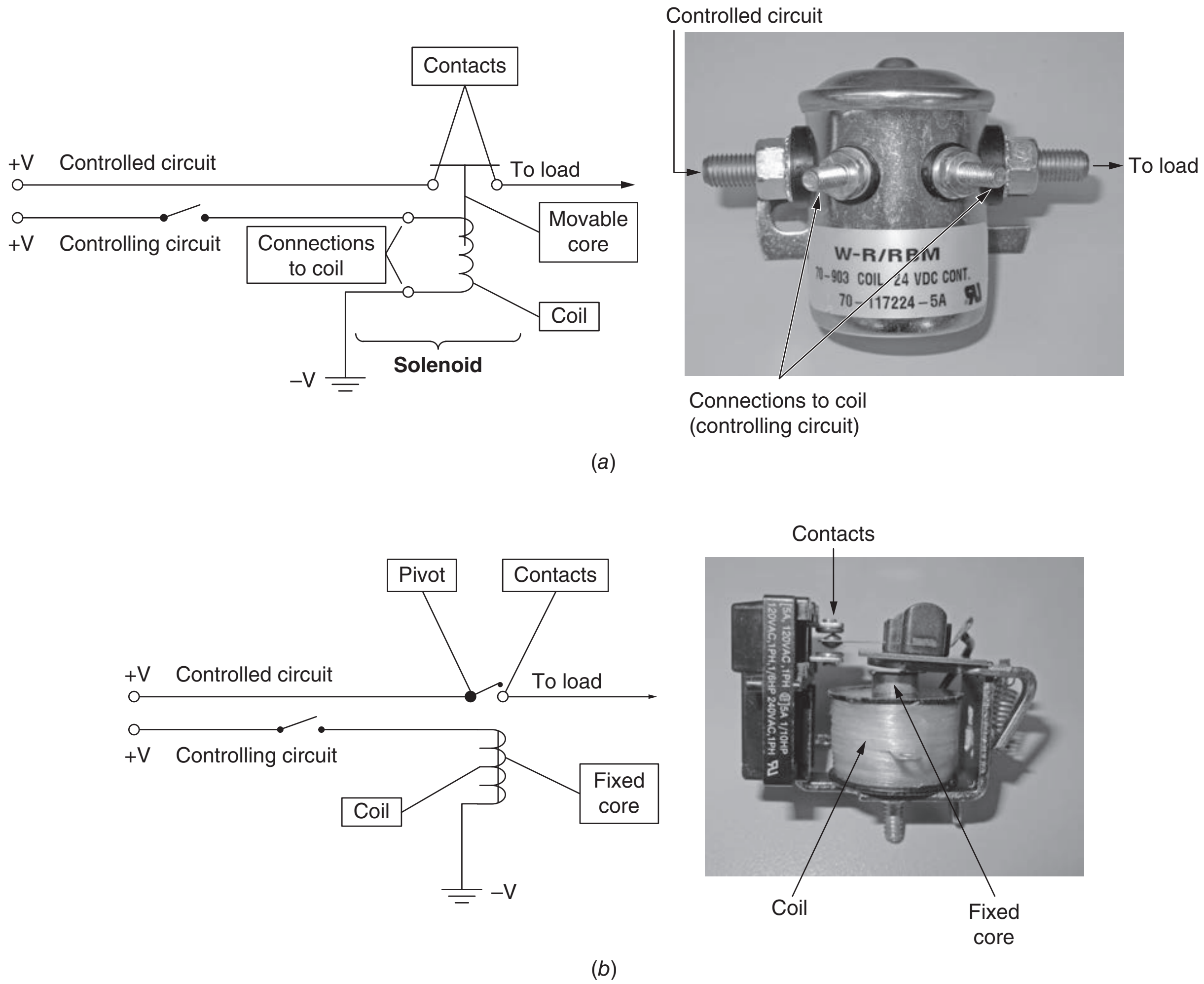

FIGURE 1-25 Comparison of a solenoid and relay: (*a*) a solenoid photo and diagram; (*b*) a relay photo and diagram.

devices use crystalline materials like quartz to produce voltage. When a force is applied to certain crystals, their molecular structure distorts and electrons may be emitted into a conductor. Piezoelectric crystals are also used in some navigation equipment and various systems sensors. These will be discussed later in this text.

Light is a source of energy that also can be converted into electricity. The **photoelectric effect** produces a voltage when light is emitted onto certain substances. Zinc is a typical photosensitive material. If exposed to ultraviolet rays, under the correct conditions, zinc will produce a voltage. Although photoelectric devices are limited in modern aircraft, spacecraft and satellites rely heavily on photo cells (solar cells) and the sun for a source of electric power. Some aircraft use light sensors on modern flight deck display systems. These sensors operate using the photoelectric effect. As more light reaches the sensor, more voltage is produced; see Fig. 1-26.

Heat can also be used to produce voltage. Electricity produced by subjecting two dissimilar metals to above normal

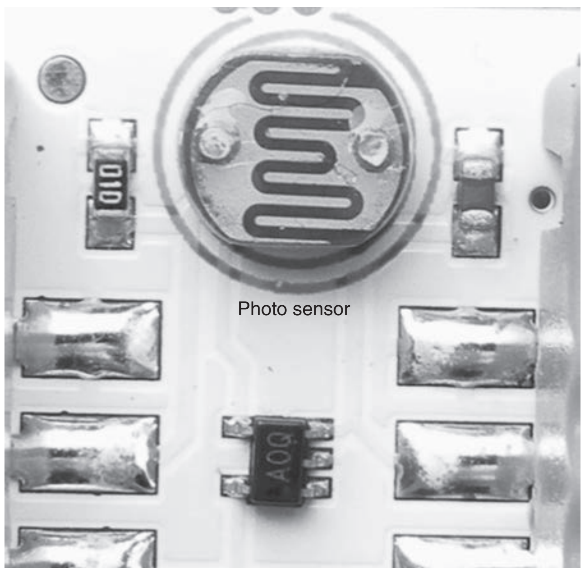

FIGURE 1-26 A typical photo sensor mounted on a circuit board.

temperatures is called the **thermoelectric effect.** For example, copper and zinc held firmly together will produce voltage when subjected to heat. This combination of two dissimilar metals is called a **thermocouple.** Thermocouples may be used in electronic temperature sensors found on aircraft. These include exhaust gas and cylinder head temperature sensors, electronic equipment temperature monitors, and some fire detectors.

Chemical action is the process used by all batteries to produce electricity for aircraft systems. When two or more of the correct chemicals come in contact, their structures are altered and a voltage is produced. Most aircraft contain at least one battery used for engine starting and emergency procedures. Modern large aircraft contain several batteries used to power a variety of equipment. Batteries will be discussed in Chapter 3.

Magnetism is used to produce the majority of all electric power. **Electromagnetic induction** is the process where voltage is produced by moving a conductor through a magnetic field.

ELECTROMAGNETIC INDUCTION

Basic Principles

The process of electromagnetic induction is used to produce the majority of all electrical power used on all aircraft. In fact, it would be safe to say the process of electromagnetic induction produces the majority of all electrical power used by humans worldwide.

The transfer of electric energy without direct electrical connections is called **induction.** When electric energy is transferred by means of a magnetic field, it is called **electromagnetic induction.** This type of induction is universally employed in the generation of electric power. Almost all electrical power is produced through electromagnetic induction using a device known as a generator or an alternator. Generators and alternators have many similarities and will be discussed in detail later in this text. Electromagnetic induction is also the principle that makes possible the operation of electric transformers and the transmission of radio signals.

Electromagnetic induction occurs whenever there is a relative movement between a conductor and a magnetic field. To produce power, the conductor moves across the magnetic lines of force (not parallel to them). The relative movement may be caused by a stationary conductor and a moving field or by a moving conductor with a stationary field.

The two general classifications of electromagnetic induction are **generator action** and **transformer action.** Both actions are the same electrically, but the methods of operation are different. Transformer action applies to AC (not DC) power circuits and will be discussed in a later chapter of this text.

Generator Action

The basic principle of generator action is shown in Fig. l-27. As the conductor is moved through the field, a voltage is induced into the wire. The same action takes place if the conductor is stationary and the magnetic field is moved. The direction of the induced voltage depends on the direction of the field and may be determined by using the **left-hand rule for generators:** *Extend the thumb, forefinger, and middle finger of the left hand so that they are at right angles to one another, as shown in Fig. 1-28. Turn the hand so that the index finger points in the direction of the magnetic field and the thumb points in the direction of conductor movement. Then the middle finger will be pointing in the direction of the induced voltage*.

Figure 1-29 illustrates another kind of generator action. Here a bar magnet is pushed into a coil of wire. A sensitive meter connected to the coil shows that a current flows in a certain direction as the magnet moves into the coil. As soon as the magnet stops moving, the current flow stops. When the magnet is pulled out of the coil, the meter shows that the current is flowing in the opposite direction. The current

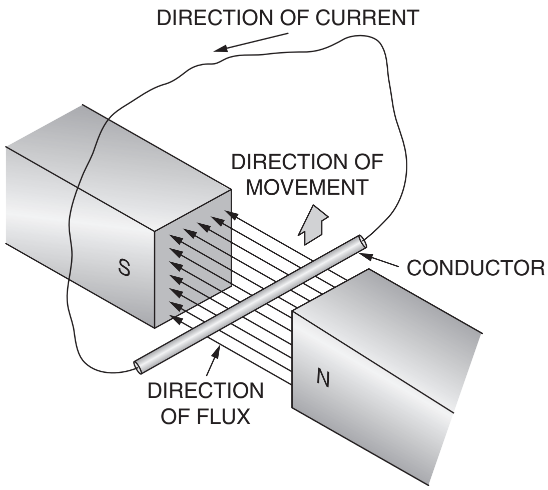

FIGURE 1-27 Generator action.

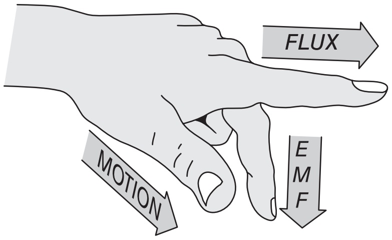

FIGURE 1-28 Left-hand rule for generators.

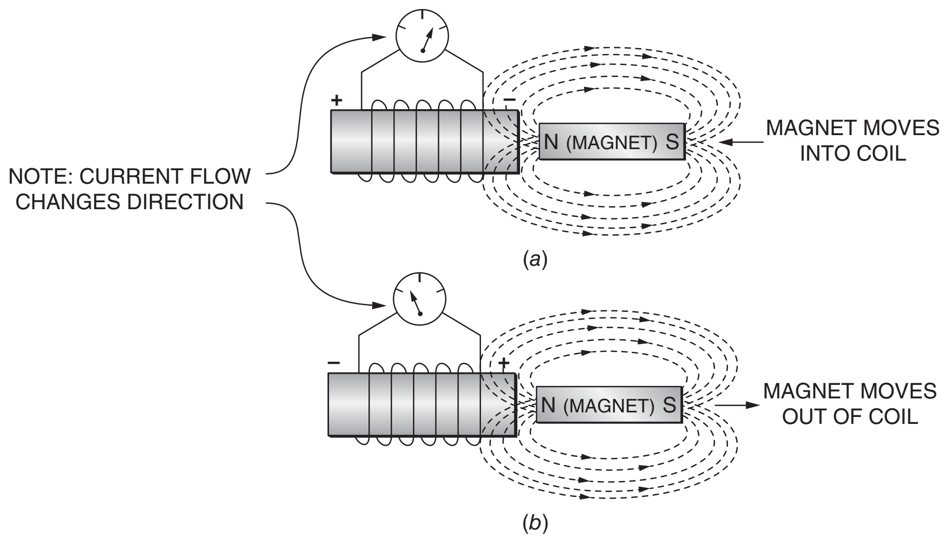

FIGURE 1-29 Induced current by a moving magnetic field: (*a*) magnet moves into coil—note meter polarity; (*b*) magnet moves out of coil—note meter polarity.

induced in the coil is caused by the field of the magnet as it cuts across the turns of wire in the coil.

Generally speaking, to produce a voltage through electromagnetic induction, there must be a magnetic field, a conductor, and relative motion between the two. The magnetic field can be produced by a permanent magnet or an electromagnet. Typically, electromagnets are used because of their advantages of increased magnetic strength. The conductor used is usually wrapped in the form of a coil, which produces a greater induced voltage. The motion can be created by moving either the magnet or the conductor. Typically, this is done by rotating a coil inside a magnetic field or by rotating a magnetic field inside a wire coil.

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2 Applications of Ohm's Law

INTRODUCTION

We have already studied the three fundamental elements of electricity: voltage, current, and resistance. **Ohm's law**, first presented by the German physicist Georg Simon Ohm (1787–1854), describes the relationships between these three elements. These relationships are the foundation upon which all electrical concepts are based. The mathematical relationships presented in Ohm's law explain the link between voltage, current, and resistance for virtually all direct-current (DC) electrical circuits. As you progress through this text, it should become clear how important Ohm's law is in the design and repair of aircraft electrical systems. For example, understanding Ohm's law is necessary to determine the correct size and length of wire to be used in a circuit, the proper sizes of fuses and circuit breakers, and many other details of a circuit and its components. It is the purpose of this chapter to introduce the concepts of Ohm's law and present their mathematical relationships.

OHM'S LAW

Definitions

In mathematical problems, EMF (voltage) is expressed in volts, and the symbol used is E. R is the symbol for resistance, which is measured in ohms. The symbol for current is I, which is measured in amps. The letter symbols E, R, and I have an exact relationship in electricity given by Ohm's law. This law may be stated as follows: **The current in an electric circuit is directly proportional to the EMF (voltage) and inversely proportional to the resistance**. Ohm's law is further expressed by the statement: **1 V causes 1 A to flow through a resistance of 1 ohm**. The equation for Ohm's law is

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

which indicates that the current in a given circuit is equal to the voltage divided by the resistance.

OHM'S LAW
$\text{CURRENT} = \dfrac{\text{VOLTAGE}}{\text{RESISTANCE}}$ $I = \dfrac{E}{R}$ (OR) $\text{AMPERES} = \dfrac{\text{VOLTS}}{\text{OHMS}}$
$\text{RESISTANCE} = \dfrac{\text{VOLTAGE}}{\text{CURRENT}}$ $R = \dfrac{E}{I}$ (OR) $\text{OHMS} = \dfrac{\text{VOLTS}}{\text{AMPERES}}$
VOLTAGE = CURRENT × RESISTANCE $E = IR$ (OR) VOLTS = AMPERES × OHMS

FIGURE 2-1 Equation for Ohm's law.

Ohm's law can be expressed in three different equations as shown in Fig. 2-1. The different forms for the Ohm's law equation are derived by either multiplication or division, as shown.

$$R(I) = R\left(\frac{E}{R}\right) \qquad \text{becomes} \qquad RI = \frac{RE}{R}$$

Then

$$RI = E \qquad \text{or} \qquad E = IR$$

In a similar manner, if both sides of the equation $E = IR$ are divided by I, we arrive at the form

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

These equations make it simple to determine any one of the three values if the other two are known. Ohm's law may be used to find any unknown voltage, current, or resistance in a given circuit.

From the study of Ohm's law, it has been shown that the current flowing in a circuit is directly proportional to the voltage and inversely proportional to the resistance of that circuit. If the voltage applied to a given circuit is doubled,

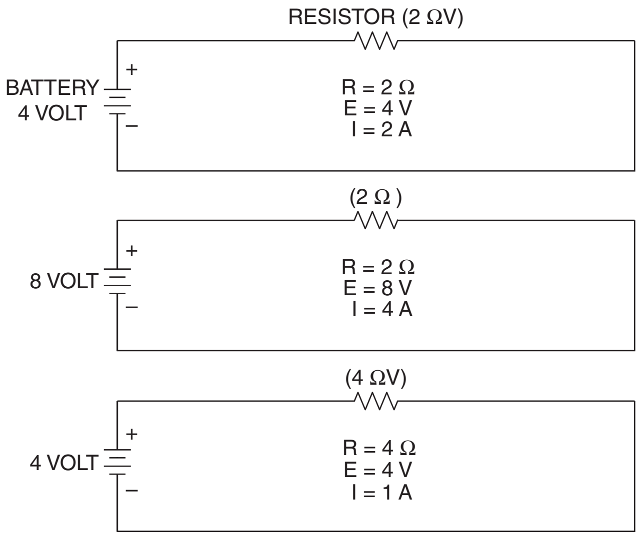

FIGURE 2-2 Effects of current and voltage.

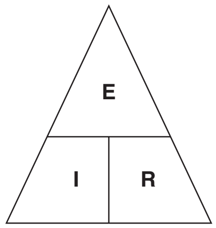

FIGURE 2-3 Diagram for Ohm's law.

the current will double. If the resistance is doubled and the voltage remains constant, the current will be reduced by one-half (see Fig. 2-2). This circuit shows the symbols for a battery and a resistor. Electrical symbols are commonly used to explain electrical circuits and will be used throughout this text. The appendix of this text contains definitions of common electrical symbols.

The equations of Ohm's law are easily remembered by using the simple diagram shown in Fig. 2-3. By covering the symbol of the unknown quantity in the diagram with the hand or a piece of paper, the known quantities are found to be in their correct mathematical arrangement. If it is desired to find the voltage in a circuit when the resistance and the amperage are known, cover the *E* in the diagram. This leaves *I* and *R* adjacent to each other; they are therefore to be multiplied according to the equation $E = IR$. In another example, if it is desired to find the total resistance of a circuit in which the voltage is 10 and the amperage is 5, cover the letter *R* in the diagram. This leaves the letter *E* over the letter *I*; then

$$R = \frac{E}{I} = \frac{10}{5} \qquad \text{or} \qquad R = 2\ \Omega$$

One of the simplest descriptions of the Ohm's law relationships is the water analogy. Water *pressure* and *flow*, along with the *restrictions* of a water valve, respond similar to the relationships of *voltage*, *current,* and *resistance* in an electric circuit. As illustrated in Fig. 2-4, an increase in voltage (electrical pressure) creates a proportional increase in current (electrical flow), just as an increase in water pressure creates an increase in water flow. Figure 2-5 shows the relationship between resistance and current. As the resistance of a circuit increases, the current decreases, assuming that the voltage remains constant. Water responds similarly. As the water valve is closed (increasing resistance), the water flow decreases.

The water analogy of Ohm's law is a simple comparison. Use the analogy to gain a better understanding of the relationships between voltage, current, and resistance.

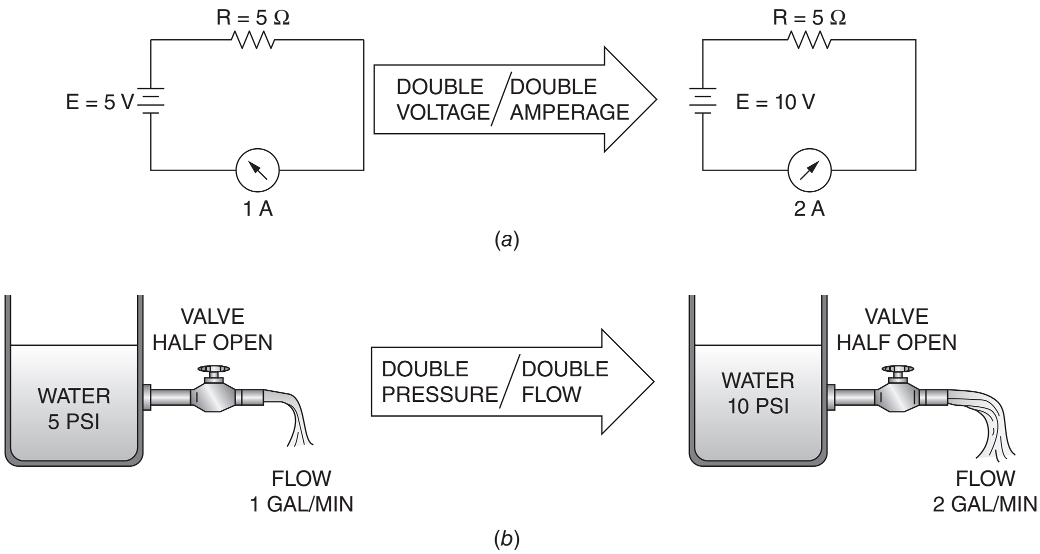

FIGURE 2-4 Water analogy of changing voltage.

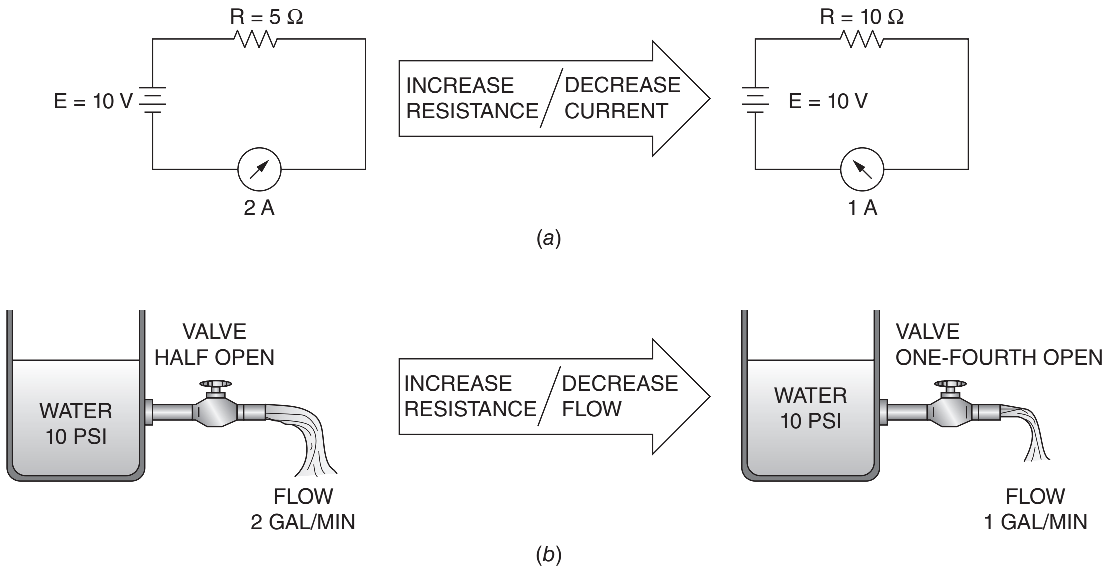

FIGURE 2-5 Water analogy of changing resistance.

Electric Power and Work

Power means the rate of doing work. One horsepower (hp) [746 watts (W)] is required to raise 550 pounds (lb) [249.5 kilograms (kg)] a distance of 1 ft [30.48 cm] in 1 s. When 1 lb [0.4536 kg] is moved through a distance of 1 ft, 1 foot-pound (ft · lb) [13.82 cm · kg] of work has been performed; hence, 1 hp is the power required to do 550 ft · lb [7601 cm · kg] of work per second. The unit of power in electricity is the **watt (W),** which is equal to 0.00 134 hp. Conversely, 1 hp is equal to 746 W. In electrical terms, 1 watt of power is expelled when 1 V of electrical pressure moves 1 A of current through a circuit. That is, 1 V at 1 A produces 1 W of power. The formula for electric power is

$$P = EI \qquad \text{or} \qquad \text{Power} = \text{voltage} \times \text{amperage}$$

The power equation can be combined with the Ohm's law equations to allow more flexibility when determining power in a circuit. The following are the three most common varieties of the power equations:

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

The derivatives of the basic power equations are found as follows:

If

$$P = EI \qquad \text{and} \qquad E = IR$$

then, substituting for *E,*

$$P = (IR)I \qquad \text{or} \qquad P = I^2R$$

Of course, these equations can be arranged to solve for *E, I*, or *R:*

$$E^2 = PR \qquad I^2 = \frac{P}{R} \qquad \text{and} \qquad R = \frac{P}{I^2}$$

When power is lost in an electric circuit in the form of heat, it is often called the *IR loss* because the heat produced is a function of a circuit's current and resistance. The equation $P = I^2R$ best represents the heat energy loss of any DC circuit, where *P* equals the lost power, measured in **watts.**

Power in an electric circuit is always additive. That is, total power equals the sum of the powers consumed by each individual unit. The power consumed by any individual load can be found using the equation

$$P = I^2R \qquad \text{or} \qquad P = IE$$

While determining power of any portion of a circuit, be sure to apply the *I, E,* or *R* (current, voltage, or resistance) that applies to the load being calculated.

Since we know the relationship between power and electrical units, it is simple to calculate the approximate amperage to operate a given motor when the efficiency and operating voltage of the motor are known. For example, if it is desired to install a 3-hp (2238 watts) motor in a 24-V system and the efficiency of the motor is 75 percent, we proceed as follows:

$$\text{Since 1 hp} = 746\text{ W \& I} = \text{P/E}\left[current = \left(\frac{Power}{voltage}\right)\right]$$

$$\text{Power of the motor} = 3\text{ hp} \times 746\text{ W/hp} = 2238\text{ W}$$

$$I\ (\text{current}) = \frac{2238\text{ W}}{24\text{ V}} = 93.25\text{ A} = 93.25\text{ A}$$

Since the motor is only 75 percent efficient, we must divide 93.25 A by 0.75 to find that approximately 124.33 A is required to operate the 3-hp motor. Thus, in a motor that is 75 percent efficient, 2984 W of input power is required to produce 2238 W (3 hp) of power at the output.

Another unit used in connection with electrical work is the joule (**J**), named for James Prescott Joule (1818–1889), an English physicist. **The joule is a unit of work**, **or energy**, **and represents the work done by 1 W in 1 second**. This is equal to approximately 0.7376 ft · lb. To apply this principle, let us assume that we wish to determine how much work in joules is done when a weight of 1 ton is raised 50 ft. First we multiply 2000 lb by 50 ft and find that 100,000 ft · lb of work is done. Then, when we divide 100,000 ft-lb by 0.7376 ft-lb/joule, we determine that approximately 135,575 J of work, or energy, was used to raise the weight.

It is wise for the technician to understand and have a good concept of the joule because this is the unit designated by the metric system for the measurement of work or energy. Other units convertible to joules are the British thermal unit (BTU), calorie (cal), foot-pound, and watt-hour (Wh). All these units represent a specific amount of work.

TYPES OF CIRCUITS

In order to have current flow through a conductor, a difference of potential (pressure) must be maintained between the ends of that conductor. In an electric circuit this difference of potential is normally produced by a battery, generator, or alternator. To simplify discussions, this text will show the battery as the typical source of electrical pressure, voltage.

Figure 2-6 shows the components of a simple circuit with a battery as the source of power. One end of the circuit is connected to the positive terminal of the battery and the other to the negative terminal. A switch is incorporated in the circuit to control the electric power to the load unit, which may be an electric lamp, motor, radio, or any other electric device that uses power. When the switch in the circuit is closed, current from the battery flows through the wire, the switch, the load, and then back to the battery. Remember that the direction of current flow is from the negative terminal to the positive terminal of the battery. The circuit will operate only when there is a continuous path through which the current may flow from one terminal of the battery to the other. When the switch is opened (turned off), the path for the current is broken, and the operation of the circuit stops.

It should be noted the circuit in Fig. 2-6 contains the four basic circuit elements: (1) the power producer (battery), (2) the power user (load), (3) a control device (switch), and (4) the distribution device (the wire). There are two general methods for connecting units in an electric system. These are

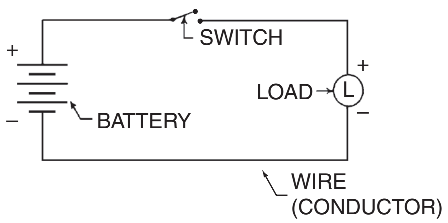

FIGURE 2-6 A simple DC circuit.

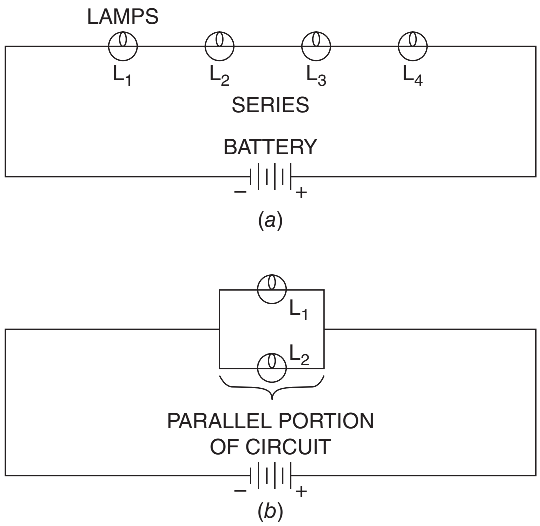

FIGURE 2-7 Two basic methods of connecting units in an electric circuit: (*a*) series—if one lamp opens, all lamps stop illuminating; (*b*) parallel—if one lamp opens, the other is unaffected.

illustrated in Fig. 2-7. The first diagram shows four lamps connected in series. A **series circuit** contains only one electron path. In a series circuit or series portion of a circuit, all the current must pass through each unit of that circuit. Therefore, if one unit of a series circuit should burn out, or opens, the entire circuit will no longer function. For example, in Fig. 2-7*a*, if lamp 1 should open, the other lamps of that circuit will also stop illuminating.

Characteristics of a series circuit are as follows:

- The current that flows through one portion of the circuit flows through all portions of the circuit.
- If one portion of a series circuit is disconnected (opens), current flow will stop in the entire circuit.

In a **parallel circuit** there are two or more paths for the current to flow. In every parallel circuit, or parallel portion of a circuit, the total current flow will divide and only part of the current will travel through each path. If the path through one of the units is broken, the other units will continue to function. The units of an aircraft electric system are usually connected in parallel; hence, the failure of one unit will not impair the operation of the remainder of the units in the system. A simple parallel circuit is illustrated in the diagram of Fig. 2-7*b*.

Characteristics of a parallel circuit are as follows:

- The total current of the circuit will divide and travel independently through each leg (current path) of the circuit.
- If one portion (load) of the circuit should fail (open), the remaining portion of the circuit will continue to operate.

The automobile analogy of current flow is shown in Fig. 2-8. Imagine that automobiles are electrons traveling between two cities, say Chicago and Detroit. The cars traveling represent current flow in an electric circuit; the road(s) represent the

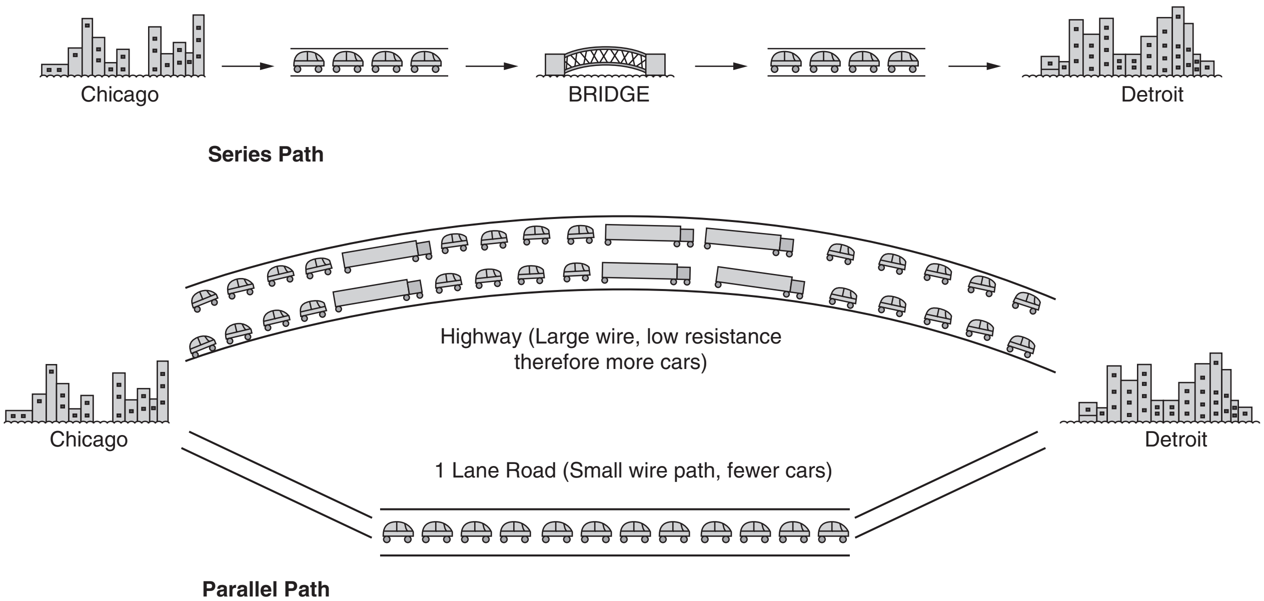

FIGURE 2-8 Characteristics of a series path and a parallel path.

current path (wires). If there were only one road from Chicago to Detroit, it would represent a **series circuit.** In this case all the automobiles would travel on only one road. In the series circuit, if a bridge should collapse, all traffic would stop and the road would no longer work; in the same way, when there is a break in a wire, all current stops and the circuit no longer works.

Now imagine there are two roads between Chicago and Detroit (Fig. 2-8). This represents a **parallel circuit.** All the cars leave Chicago, then divide, and a portion of the cars take each road. Most of the cars will take the highway because it offers lower opposition (resistance) to travel. A smaller portion of the drivers will take the scenic road or a smaller one-lane road, and all cars eventually reach Detroit. In this parallel example, it is easy to see that if a bridge is out on the one-lane road, the other road will still be operational; similarly, if one light opens on the aircraft instrument panel, the other light will still function.

A circuit that contains electrical units in both parallel and series is called a **series-parallel circuit** (see Fig. 2-9). Most complex electrical systems, such as communication radios, flight computers, and navigational equipment, consist of several combinations of series-parallel circuits. Ohm's law can be used to determine the electrical values in any common circuit, even though it may contain a number of different load units.

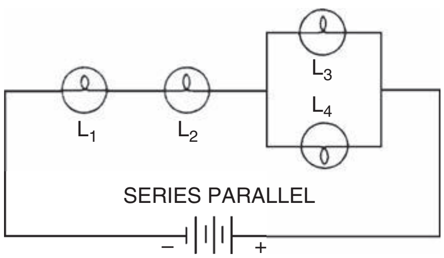

FIGURE 2-9 A series-parallel circuit diagram.

In order to mathematically solve such a circuit, it is necessary to know whether the units are connected in series, in parallel, or in a combination of the two methods. When the type of circuit is determined, the proper formula may be applied.

Voltage Drop

When a current flows through a resistance, a voltage or pressure drop is created. This loss of voltage, known as a **voltage drop** (V_x), is equal to the product of current and resistance. An individual voltage drop is expressed as $V_x = IR$, where V_x is measured in volts, I in amps, and R in ohms. *Note:* The subscript (*x*) is used here to represent a number that applies to a specific voltage drop, such as voltage drop #1 (V_1) or voltage drop #2 (V_2). In a series circuit, the sum of the individual voltage drops is equal to the applied voltage. This may be expressed as

$$E_t = V_1 + V_2 + V_3$$

for a circuit containing three resistors.

Figure 2-10 shows this concept using the water analogy. Notice that with either the water or electrical circuit, the total pressure rise is equal to the total pressure drop; that is, the electrical pressure increase created by the battery is equal to the total pressure drop across both lamps and the resistor. This can be expressed mathematically as

$$E_t = V_{L_1} + V_{L_2} + V_R$$

SOLVING SERIES CIRCUITS

As explained previously, a series circuit consists of only one current path. When two or more units are connected in series, the entire quantity of moving electrons (current) must

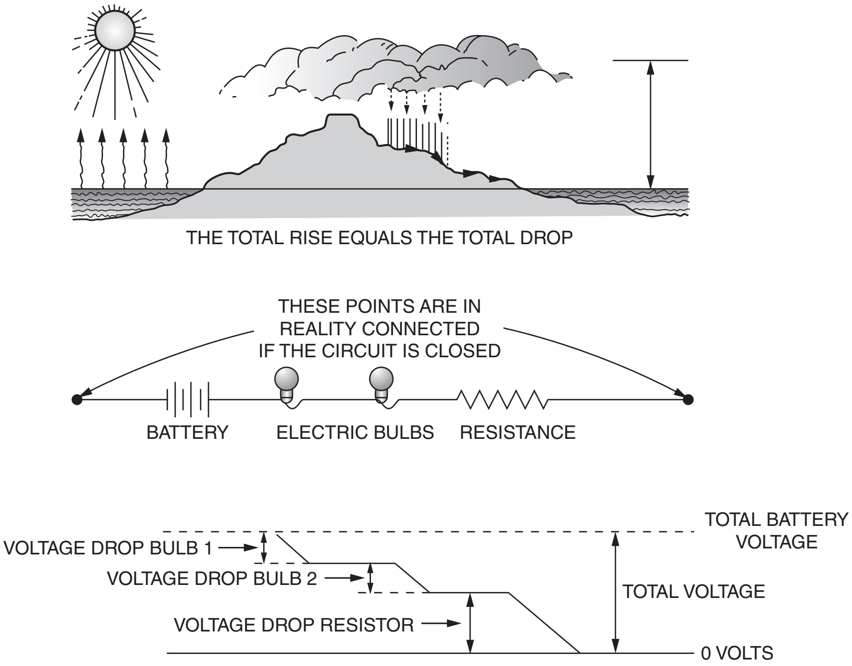

FIGURE 2-10 Water analogy of voltage drops.

pass through each unit to complete the circuit. Therefore, each unit of a series circuit receives the same current flow, even though their individual voltage drops may vary.

Two or more units do not have to be adjacent to each other in a circuit to be in series. In the circuit of Fig. 2-11, it can be seen that the current flow through each unit in the circuit must be the same, regardless of the direction of current flow. If we replace the load resistor R_2 with an electronic unit of the same resistance as shown in Fig. 2-12, the current flow in each resistor will still be the same. In this case, we regard the electronics unit as a single unit rather than concern ourselves with the separate components within that unit. Thus we see that there is only one path for current flow in a series circuit; however, an individual load unit may consist of more than one component within itself. Note that the electronics unit in Fig. 2-12 is shown with several resistances connected in a network within the box. In the series circuit under consideration, we are only concerned with the total resistance of the electronics unit. Keep in mind this type of circuit is somewhat unrealistic and is used here for explanation purposes.

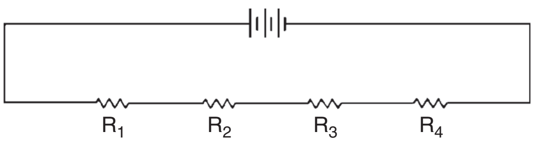

FIGURE 2-11 A series circuit with four separate loads.

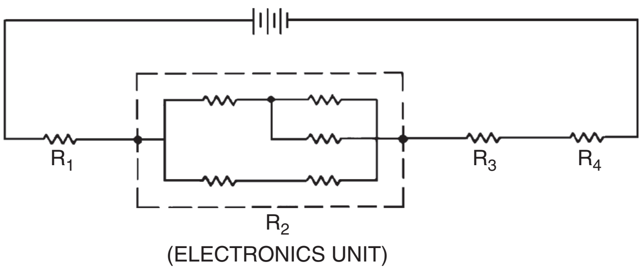

FIGURE 2–12 A series circuit containing a series-parallel load.

The load units adjacent to each other in a circuit are connected in series if there are no electrical junctions (dividing points) between the two units. This is illustrated in Fig. 2-13. In circuit *a,* R_1 and R_2 are connected in series because there is no electrical junction between them to take a part of the current, and all the current flowing through R_1 must also pass through R_2. In circuit *b,* R_1 and R_2 are not connected in series because the current that flows through R_1 is divided between R_2 and R_4. Note, however, that R_2 and R_3 are in series and the same current must pass through both.

Examine the circuit of Fig. 2-14 in which R_1, R_2, and R_3 are connected in series, not only to each other but also to the power source. The electrons flow from the negative connection of the battery through the circuit to the positive connection of the battery. The same flow exists in every part of the circuit, because there is only one path for current flow. Thus, the current is the same in all parts of the circuit.

$$I_t = I_1 = I_2 = I_3$$

That is, the total current is equal to the current through R_1, R_2, or R_3.

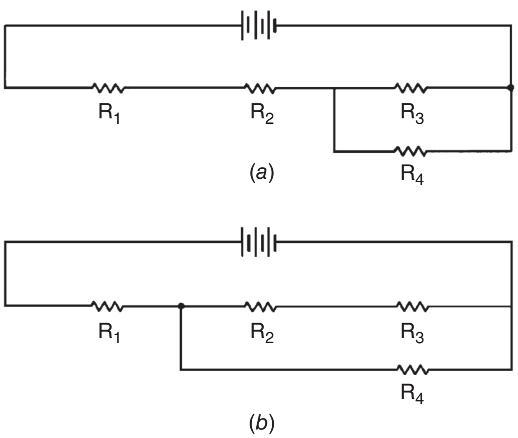

FIGURE 2-13 A circuit diagram showing load units connected in both series and parallel.

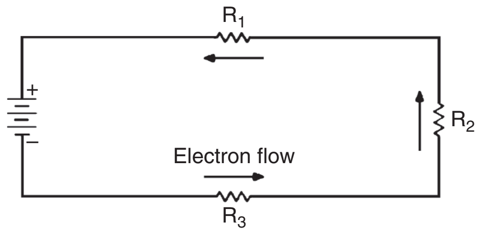

FIGURE 2-14 Current flow in a series circuit. Each load receives equal current.

Resistance and Voltage in a Series Circuit

In a series circuit, the total resistance is equal to the sum of all the resistances in the circuit; hence,

$$R_t = R_1 + R_2 + R_3 + \cdots$$

In practical terms, a resistance can be any load connected to a power supply (voltage). For example, a resistor may be placed in a series with a light bulb in order to dim the light. In this case the voltage drop of the resistor added to the voltage drop of the lamp will equal the total applied voltage.

The voltage (potential difference) measured between any two points in a series circuit depends on the resistance between the points and the current flowing in the circuit. Figure 2-15 shows a circuit with three resistances connected in series. The difference in potential supplied by the battery between the ends of the circuit is 24 V.

As previously explained in the discussion of Ohm's law, the voltage between any two points in a circuit can be determined by the equation

$$E = IR$$

That is, the voltage is equal to the current multiplied by the resistance. In the circuit of Fig. 2-15, we have given a value of 1 Ω to R_1, 3 Ω to R_2, and 8 Ω to R_3. According to our previous discussion, the total resistance of the circuit is expressed by

$$R_t = R_1 + R_2 + R_3$$

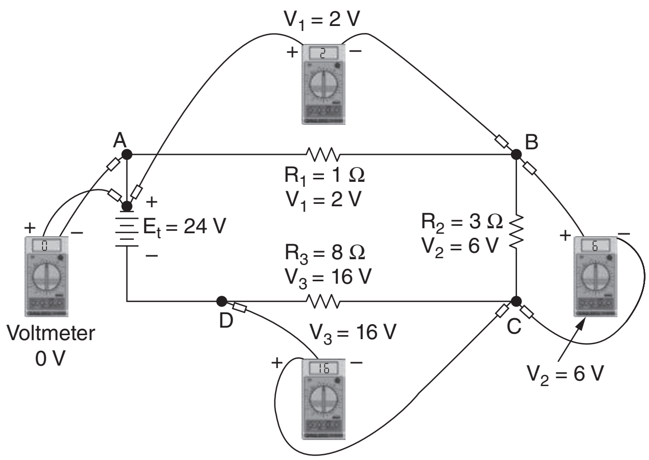

FIGURE 2-15 The summation of voltage drops.

or

$$R_t = 1 + 3 + 8$$
$$= 12\ \Omega$$

Since the total voltage E_t for the circuit is given as 24 V, we can determine the current in the circuit by Ohm's law, using the form

$$I_t = \frac{E_t}{R_t}$$

Then

$$I_t = \frac{24\ V}{12\ \Omega}$$
$$= 2\ \text{A}$$

Since we know that the current in the circuit is 2 A, it is easy to determine the voltage across each load resistor. Since R_1 = 1 Ω, we can substitute this value in Ohm's law to find the voltage difference across R_1.

$$V_1 = I_1R_1$$
$$= 2 \times 1$$
$$= 2\ \text{V}$$

In like manner,

$$V_2 = I_2R_2$$
$$= 2 \times 3$$
$$= 6\ \text{V}$$

and

$$V_3 = I_3R_3$$
$$= 2 \times 8$$
$$= 16\ \text{V}$$

When we add the voltages in the circuit, we find

$$E_t = V_1 + V_2 + V_3$$
$$V_t = 2 + 6 + 16$$
$$= 24 \text{ V}$$

We have determined by Ohm's law that the sum of the voltages (voltage drops) across units in a series circuit is equal to the voltage applied by the power source, in this case R_1(2 V) + R_2(6 V) + R_3(16 V) = the battery voltage (24 V).

In a practical experiment, we can connect a **voltmeter** (voltage-measuring instrument) from the positive terminal of the battery in a circuit such as that shown in Fig. 2-15 to point *A,* and the reading will be zero. This is because there is no appreciable resistance between these points and hence no voltage drop. When we connect the voltmeter between the positive terminal of the battery and point *B,* the instrument will give a reading of 2 V (the voltage drop of R_1). By similar use of the voltmeter, we measure between points *B* and *C* and obtain a reading of 6 V (the voltage drop of R_2), and between points *C* and *D* for a reading of 16 V (the voltage drop of R_3). In a circuit such as that shown, we can assume that the resistance of the wires connecting the resistors is negligible. If the wires were quite long or extremely small diameter, it would be necessary to consider their resistances in analyzing the circuit.

As we have shown, in a series circuit, the voltage drop across each resistor (or any electrical load unit) is directly proportional to the value of the resistor. Since the current through each unit of the circuit is the same, it is obvious that it will take a higher electrical pressure (voltage) to push the current through a higher resistance, and it will require a lower pressure to push the same current through a lower resistance.

The voltage across a load resistor is a measure of the work required to move a unit charge (given quantity of current) through the resistor. Electric energy is consumed as current flows through a resistor, and the electric energy is converted to heat energy. (In a lamp the electrical energy would be converted to light; in a motor it would be converted to rotary motion.) As long as the power source produces electric energy as rapidly as it is consumed, the voltage across a given resistor will remain constant.

Most load units in a typical aircraft are not simple resistors. For example, a practical load could be a lamp, motor, radio, flight control computer, or other such system. In each case, the concepts of Ohm's law apply to that unit just as they apply to a simple resistor. Students who have mastered Ohm's law can apply their knowledge to solve any series circuit or series portion of a circuit. The following examples are shown to illustrate the techniques for solution:

Example A: Refer to Fig. 2-16 during the following explanation:

$$E_t = 12 \text{ V}$$
$$I_1 = 3 \text{ A}$$
$$R_2 = 2\ \Omega$$
$$R_3 = 1\ \Omega$$

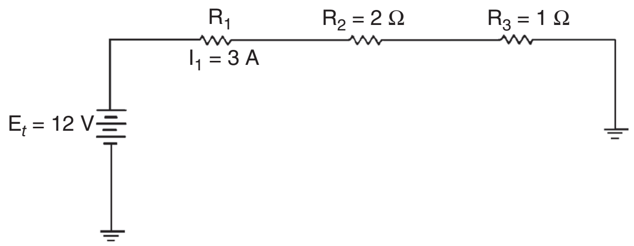

FIGURE 2-16 Series circuit for Example A.

To solve for the unknown values of the circuit, proceed as follows:

Since I_1 is given as 3 A, it follows that I_t, I_2, and I_3 are also equal to 3 A, because current is constant in a series circuit.

Then the total resistance of the circuit can be determined.

$$R_t = \frac{E_t}{I_t}$$
$$= \frac{12}{3}$$
$$= 4\ \Omega$$

To determine the resistance R_1

$R_t = R_1 + R_2 + R_3$ (R_2 and R_3 are given; R_t was previously calculated.)

Or

$$R_1 = R_t - R_2 - R_3$$
$$R_1 = 4 - 2 - 1$$
$$R_1 = 1 \text{ ohms}$$

To determine the voltage drops over each resistance, use the following:

$$V_1 = I_1 \times 2$$
$$V_1 = 3 \times 1$$
$$V_1 = 3 \text{ V}$$

$V_2 = I_2 \times R_2$ (*Note:* Current is consistent in a series circuit; in this case, 3 A.)

$$V_2 = 3 \times 2$$
$$V_2 = 6 \text{ V}$$

$$V_3 = I_3 \times R_3$$
$$V_3 = 3 \times 1$$
$$V_3 = 3 \text{ V}$$

$$V_2 = 2 \times 3 = 6 \text{ V}$$
$$V_3 = 1 \times 3 = 3 \text{ V}$$

The solved problem may then be expressed as follows:

$E_t = 12$ V	$I_t = 3$ A	$R_t = 4\ \Omega$
$V_1 = 3$ V	$I_1 = 3$ A	$R_1 = 1\ \Omega$
$V_2 = 6$ V	$I_2 = 3$ A	$R_2 = 2\ \Omega$
$V_3 = 3$ V	$I_3 = 3$ A	$R_3 = 1\ \Omega$

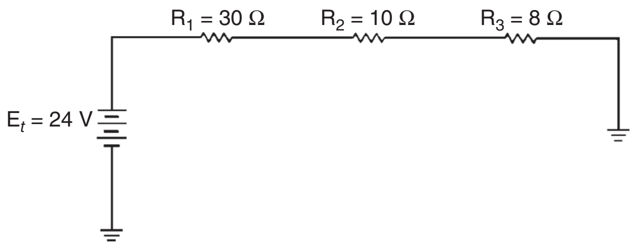

FIGURE 2-17 Series circuit for Example B.

Example B: Refer to Fig. 2-17 during the following explanation:

$$E_t = 24\ \text{V}$$
$$R_1 = 30\ \Omega$$
$$R_2 = 10\ \Omega$$
$$R_3 = 8\ \Omega$$

Then

$$R_t = R_1 + R_2 + R_3$$
$$R_t = 30 + 10 + 8$$
$$= 48\ \Omega$$

$$I_t = \frac{E_t}{R_t}$$
$$= \frac{24}{48}$$
$$= 0.5\ \text{A}$$

V_1, V_2 and V_3 are determined by multiplying each resistance value by 0.5 A, the current value of the circuit. The solved circuit is shown in Fig. 2-18.

Example C: Refer to Fig. 2-19 during the following discussion. This circuit presents the case where current and resistance are known, and it is required to find the individual and total voltages. The known circuit values are as follows:

$$I_t = 3\ \text{A}$$
$$R_1 = 9\ \Omega$$
$$R_2 = 3\ \Omega$$
$$R_3 = 4\ \Omega$$

From the values given, we can easily determine that the total resistance is 16 Ω ($R_1 + R_2 + R_3 = R_t$). The voltages can then be determined by Ohm's law:

$$E = IR$$
$$E_t = I_t \times R_t$$
$$= 3 \times 16$$
$$= 48\ \text{V}$$

The values of the solved circuit are then as shown:

$$\begin{array}{lll} E_t = 48\ \text{V} & I_t = 3\ \text{A} & R_t = 16\ \Omega \\ V_1 = 27\ \text{V} & I_1 = 3\ \text{A} & R_1 = 9\ \Omega \\ V_2 = 9\ \text{V} & I_2 = 3\ \text{A} & R_2 = 3\ \Omega \\ V_3 = 12\ \text{V} & I_3 = 3\ \text{A} & R_3 = 4\ \Omega \end{array}$$

Example D: Certain values for the circuit shown are indicated in Fig. 2-20. It is left up to the student to work out the solution. Follow the steps as previously described to find all unknown values.

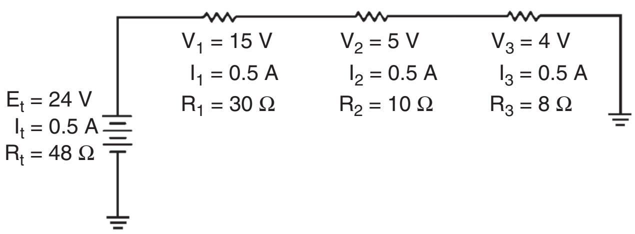

FIGURE 2-18 Simplified circuit for Example B.

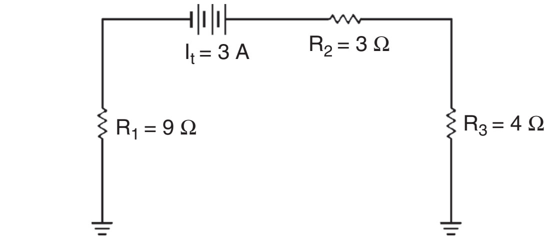

FIGURE 2-19 Series circuit for Example C.

SOLVING PARALLEL CIRCUITS

A parallel circuit always contains two or more electric current paths. When two or more units are connected in parallel, each unit will receive a portion of the circuit's total current. That is, the circuit's total current divides at one or more points, and a portion travels through each resistance of the circuit (see Fig. 2-21).

Typically, when we analyze a circuit of this type, we assume that the resistance of a wire is negligible and the power source has no internal resistance. A parallel circuit always contains more than one path for current to flow; therefore, the current can "choose" which load unit to

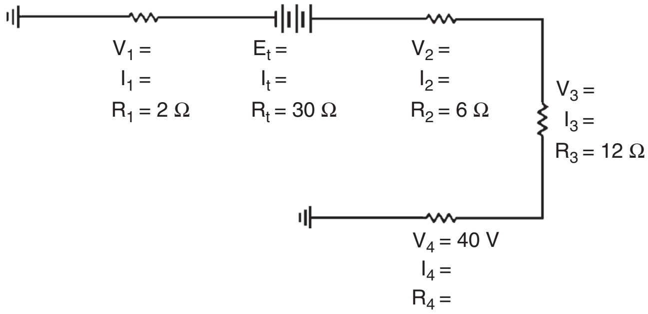

FIGURE 2-20 Series circuit for Example D.

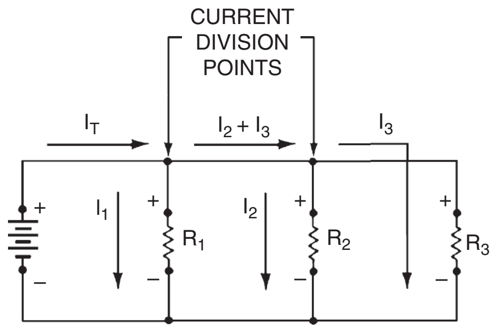

FIGURE 2-21 Current flow through a parallel circuit.

travel through. Current always tries to take the path of least resistance and will divide proportionally through a parallel circuit. In a parallel circuit, each load unit will receive a portion of the total current flow. The unit with the highest resistance will receive the least current flow. The unit with the lowest resistance will receive the highest current flow. Equal resistors receive equal current flows.

Think of current flow (electron movement) through a wire as cars traveling down a road. All the electrons desire to travel from the negative connection of the battery to the positive connection of the battery. Just as cars traveling may choose a different route from Chicago to Detroit, in a parallel circuit, some electrons will take one path and others will take another path. Due to the nature of physics (and Ohm's law) more electrons will always take the path of lower resistance and fewer electrons will always take the path of higher resistance. So in a parallel circuit, any path of higher resistance naturally receives less current, and low-resistance circuits will receive greater current.

Typically, loads such as lamps, radios, or motors are arranged in parallel with respect to each other. This is done to allow a different current path through each unit; therefore, the resistance of each unit will determine the current flow through that unit. An example is a flap motor using 30 A, a navigation light using 2 A, and the landing light, with the switch turned off, using 0 A. This type of current flexibility is a necessity for almost every electrical system.

It will be noted in Fig. 2-22 that three of the resistances, R_1, R_2, and R_3, have common terminals with one another, even though there are other resistances connected between their common terminals and the power source. It will further be noted that R_4 and R_5 are connected in parallel because they have positive terminals connected together and negative terminals connected together. The resistance R_6 is in series, not with any other single resistance, but with the parallel groups.

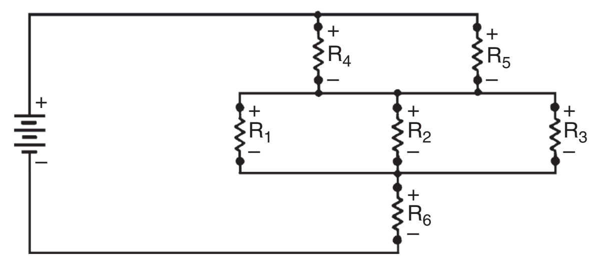

FIGURE 2-22 Parallel grouping of resistors.

The circuit shown in Fig. 2-22 would be called a series-parallel circuit, and will be discussed shortly. The voltage across any resistance in a parallel group is equal to the voltage across any other resistance in the group. Note in Fig. 2-23 that the voltage of the source is 12 V. Since the terminals of the power source are connected directly to the terminals of the resistances, the difference in potential across each resistance is the same as that of the battery. By testing with a voltmeter, it would be found that the potential difference across each resistance in the circuit would be 12 V. The formula for voltage in a parallel circuit is

$$E_t = V_1 = V_2 = V_3 = V_4 \cdots$$

This formula states that the same voltage will be applied to each unit of a parallel circuit. The ability to apply an equal voltage to all power users is another important reason that the entire aircraft electrical system (not necessarily individual electrical components) is wired in parallel. As described earlier, the current in a parallel circuit divides proportionately among each resistance (load unit).

In the circuit of Fig. 2-24, the current through R_1 is given as 4 A, the current through R_2 is 2 A, and the current through R_3 is 6 A. To supply this current flow through the three resistances, the power source must supply 4 + 2 + 6, or a total of 12 A to the circuit. It must be remembered that the power source does not actually manufacture electrons, but it does apply the pressure to move them. All the electrons that leave the battery to flow through the circuit must return to the battery. The power source for a circuit can be compared to a pump that moves water through a pipe. Eventually water must return to the pump so it can be "pushed" through the pipe in a continuous loop. The pump does not create the water; it creates the pressure to move the water.

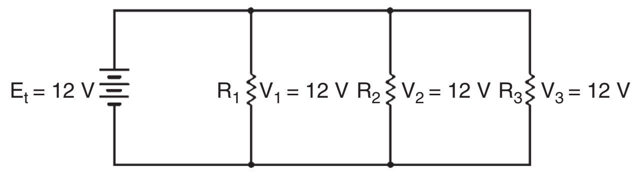

FIGURE 2-23 Voltages in a parallel circuit.

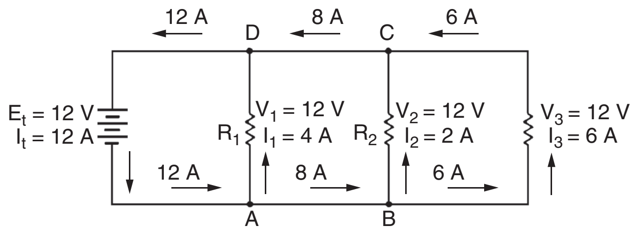

FIGURE 2-24 Current flow in a parallel circuit.

An examination of the circuit in Fig. 2-24 reveals that a flow of 12 A comes from the negative terminal of the battery, and at point *A* the flow divides to supply 4 A for R_1 and 8 A for the other two resistors. At point *B* the 8 A divides to provide 2 A for R_2 and 6 A for R_3. On the positive side of the circuit, 6 A joins 2 A at point *C*, and the resulting 8 A joins 4 A at point *D* before returning to the battery. The formula for current in a parallel circuit is then seen to be

$$I_t = I_1 + I_2 + I_3 + \cdots$$

Since the current flow and voltage are given for each resistor in Fig. 2-24, it is easy to determine the value of each resistance by means of Ohm's law; that is,

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

Then

$$R_1 = \frac{E_1}{I_1} = \frac{12}{4} = 3\,\Omega$$

$$R_2 = \frac{E_2}{I_2} = \frac{12}{2} = 6\,\Omega$$

$$R_3 = \frac{E_3}{I_3} = \frac{12}{6} = 2\,\Omega$$

$$R_t = \frac{E_t}{I_t} = \frac{12}{12} = 1\,\Omega$$

Remember when solving for R_1 to be sure to use the voltage drop for resistor 1 and current through resistor 1 (V_1 and I_1). However, E_t can be substituted for V_1 because voltage is constant in a parallel circuit.

The formula for the total resistance in a parallel circuit can be derived by use of Ohm's law and the formulas for total voltage and total current.
For parallel circuits, Ohm's law states:

$$R_t = \frac{1}{1/R_1 + 1/R_2 + 1/R_3}$$

This equation can be used to find the resistance total for all parallel circuits and is expressed verbally as follows: *The total resistance in a parallel circuit is equal to the reciprocal of the sum of the reciprocals of the resistances.*

The **reciprocal** of a number is the quantity 1 divided by that number. For example, the reciprocal of 3 is $\frac{1}{3}$.

If the formula for total resistance in a parallel circuit is applied to the circuit problem of Fig. 2-24, we find

$$R_t = \frac{1}{1/R_1 + 1/R_2 + 1/R_3}$$

$$R_t = \frac{1}{1/3 + 1/6 + 1/2}$$

$$= \frac{1}{0.33 + 0.167 + 0.5}$$

$$= \frac{1}{1}$$

$$= 1\,\Omega$$

If some or all of the resistances in a parallel circuit are of the same value, the resistance value of one can be divided by the number of equal-value resistances to obtain the total resistance value. For example, if a circuit has four 12-Ω resistors connected in parallel, the value 12 can be divided by the number 4 to obtain the total resistance value of 3 Ω for the four resistances.

When only two resistances are connected in parallel, we can use a formula derived from the general formula for R_t. Use this equation to find total resistance of only two resistance.

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

From the foregoing formula, we find that when two resistors are connected in parallel, the total resistance is equal to the product of the two resistance values divided by their sum. If a 5-Ω resistance is connected in parallel with a 6-Ω resistance, we apply the formula thus:

$$R_t = \frac{5 \times 6}{5 + 6}$$

$$= \frac{30}{11}$$

$$R_t = 2.73\,\Omega$$

Another fact of parallel resistor groups is that the total resistance of the group is always less than the smallest resistance of that group. For example, if $R_1 = 3\,\Omega$, $R_2 = 6\,\Omega$, and $R_3 = 2\,\Omega$, then R_t will be less than 2 Ω. As previously stated,

$$R_t = \frac{1}{1/R_1 + 1/R_2 + 1/R_3}$$

or

$$R_t = \frac{1}{1/3 + 1/6 + 1/2}$$

$$= \frac{1}{0.33 + 0.167 + 0.5}$$

$$= \frac{1}{1}$$

$$= 1\,\Omega$$

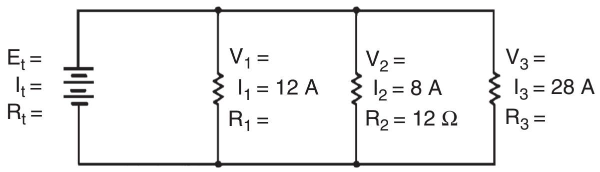

FIGURE 2-25 Diagram of a parallel circuit.

The R_t of 1 Ω is indeed less than 2 Ω(R_3), the smallest resistance of the group.

The rules to determine voltage, current, and resistance for parallel circuits have numerous applications. For example, a parallel circuit having some resistance values unknown, but at least one current value given with a known resistance value, can be solved through the use of Ohm's law and the formula for total resistance. See Fig. 2-25.

An examination of this circuit reveals that I_2 = 8 A and R_2 = 12 Ω. With these values it is apparent that the voltage across R_2 is equal to 96 V. That is,

$$\begin{aligned} V_2 &= I_2 \times R_2 \\ &= 8 \times 12 \\ &= 96\text{ V} \end{aligned}$$

Since the same voltage exists across all the load resistors in a parallel circuit, we know that E_t, V_1, and V_3 are all equal to 96 V. We can then proceed to find that $R_1 = \frac{96}{12}$ or 8 Ω and $R_3 = \frac{96}{28}$ or 3.43 Ω. Since total current is equal to the sum of the current values, I_t = 12 + 8 + 28 or 48 A. The total resistance is then $\frac{96}{48}$ = 2 Ω, since $R_t = E_t/I_t$.

In any circuit where a number of load units are connected in parallel or in series, it is usually possible to simplify the circuit in steps. A sample parallel circuit and its simplified equivalent are illustrated in Fig. 2-26.

The first step used to solve this parallel problem is to combine all individual resistors using the formula

$$R_t = \frac{1}{1/R_1 + 1/R_2 + 1/R_3 + 1/R_4}$$

or

$$R_t = \frac{1}{1/5 + 1/5 + 1/10 + 1/18}$$

or

$$R_t = 1.8\ \Omega$$

The second step is to solve for I_t.

$$\begin{aligned} I_t &= \frac{E_t}{R_t} \\ &= \frac{9\ V}{1.8\ \Omega} \\ &= 5\text{ A} \end{aligned}$$

The third step is to find the individual current flows through each resistor. Since voltage is constant in a parallel circuit. E_t can be substituted for each individual voltage drop.

$$I_1 = \frac{E_1}{R_1} \qquad I_1 = \frac{9\ V}{5\ \Omega} \qquad I_1 = 1.8\text{ A}$$

$$I_2 = \frac{E_2}{R_2} \qquad I_2 = \frac{9\ V}{5\ \Omega} \qquad I_2 = 1.8\text{ A}$$

$$I_3 = \frac{E_3}{R_3} \qquad I_3 = \frac{9\ V}{10\ \Omega} \qquad I_3 = 0.9\text{ A}$$

$$I_4 = \frac{E_4}{R_4} \qquad I_4 = \frac{9\ V}{18\ \Omega} \qquad I_4 = 0.5\text{ A}$$

The fourth step should be to check the calculations. In a parallel circuit, current is additive to find total current. Therefore, if the sum of the individual current flows equals the total current, the calculations were done correctly. The check would be as follows:

$$\begin{aligned} I_t &= I_1 + I_2 + I_3 + I_4 \\ &= 1.8 + 1.8 + 0.9 + 0.5 \\ &= 5.0\text{ A} \end{aligned}$$

Since 5 A is the calculated total current flow, one can assume that the calculations are correct.

Another quick check can be done by comparing the calculated total resistance with the smallest resistance value of the parallel group. As stated earlier, the total resistance of a parallel group must always be less than the lowest-value resistor. If this is not true for your calculations, it must be assumed that a mistake was made.

SERIES-PARALLEL CIRCUITS

As the name implies, a series-parallel circuit is one in which some load units are connected in series and some are connected in parallel. Such a circuit is shown in Fig. 2-27. In this circuit it

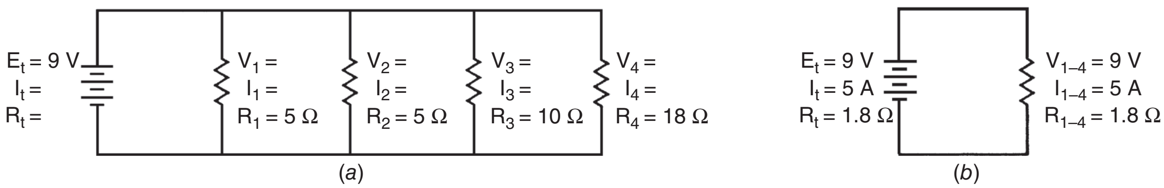

FIGURE 2-26 A parallel circuit and its simplified equivalent: (*a*) complete circuit showing all resistors, 1–4; (*b*) the simplified circuit showing effective resistor 1–4.

is quickly apparent that the resistances R_1 and R_2 are connected in series and the resistances R_3 and R_4 are connected in parallel. When the two parallel resistances are combined according to the parallel formula, one resistance, $R_{3,4}$, is found, and this value is in series with R_1 and R_2 as shown in Fig. 2-28. The total resistance R_t is then equal to the sum of R_1, R_2, and $R_{3,4}$.

If certain values are assigned to some of the load units in the circuit of Fig. 2-26, we can solve for the unknown values and arrive at a complete solution for the circuit. For the purposes of this problem, the following are known:

$$E_t = 24 \text{ V}$$
$$R_1 = 0.25\ \Omega$$
$$R_2 = 2\ \Omega$$
$$R_3 = 3\ \Omega$$
$$R_4 = 1\ \Omega$$

To solve for the unknown values, the following steps must be taken.

The first step is to combine all parallel resistors, such as in Fig. 2-28. To combine the parallel resistors R_3, and R_4, use the formula

$$R_{3,4} = \frac{1}{1/R_3 + 1/R_4}$$
$$= \frac{1}{1/3 + 1/1}$$
$$= 0.75\ \Omega$$

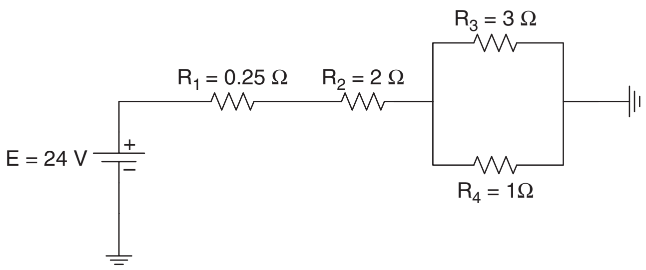

FIGURE 2-27 A simple series-parallel circuit.

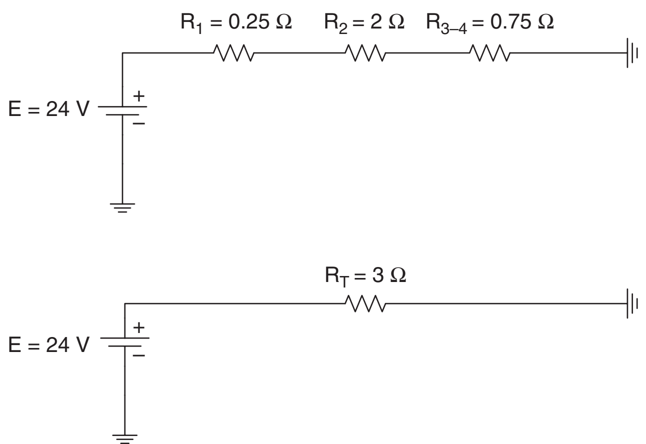

FIGURE 2-28 A series equivalent of the series-parallel circuit of Fig. 2–26.

Second, combine all series resistors using the formula

$$R_t = R_1 + R_2 + R_{3,4}$$
$$= 0.25 + 2 + 0.75$$
$$= 3\ \Omega$$

In this case, the resistance total was found by using only two steps. More complex circuits may require that these steps be performed in opposite order and/or several times to determine the value of R_t.

Third, compute total current using the formula

$$I_t = \frac{E_t}{R_t}$$
$$= \frac{24}{3}$$
$$= 8 \text{ A}$$

Fourth, compute the voltage drop across the series resistors. The formula $V_x = IR$ will be used twice in this case, once for R_1 and once for R_2 *Note:* Because I_1 and I_2 have not yet been calculated. I_t must be substituted for their values. This is possible because both R_1 and R_2 are in series.

$$V_1 = I_1 R_1$$
$$= 8 \times 0.25$$
$$= 2 \text{ V}$$
$$V_2 = I_2 R_2$$
$$= 8 \times 2$$
$$= 16 \text{ V}$$

Fifth, calculate the voltage drop across the parallel resistors using the formula $V_x = IR$. This can only be done for the entire group of parallel resistors ($R_{3,4}$) because the current flow through the individual resistors is yet unknown. *Note:* I_t was substituted for the unknown value $I_{3,4}$ because the effective resistor $R_{3,4}$ is in series (see Fig. 2-28).

$$V_{3,4} = I_{3,4} R_{3,4}$$
$$= 8 \times 0.75$$
$$= 6 \text{ V}$$

Since voltage is constant in parallel, the voltage drop across $R_{3,4}$ is equal to the voltage drop across R_3 and R_4 individually.

$$V_3 = 6 \text{ V} \qquad \text{and} \qquad V_4 = 6 \text{ V}$$

Sixth, calculate current flow through the parallel resistors using $I = V/R$.

$$I_3 = \frac{V_3}{R_3} = \frac{6}{3} = 2\ \text{A}$$

$$I_4 = \frac{V_4}{R_4} = \frac{6}{1} = 6\ \text{A}$$

The entire circuit has now been analyzed using the basic elements of Ohm's law. The completed solution is shown in Fig. 2-29 and listed here.

$E_t = 24$ V	$I_t = 8$ A	$R_t = 3\ \Omega$
$V_1 = 2$ V	$I_1 = 8$ A	$R_1 = 0.25\ \Omega$
$V_2 = 16$ V	$I_2 = 8$ A	$R_2 = 2\ \Omega$
$V_3 = 6$ V	$I_3 = 2$ A	$R_3 = 3\ \Omega$
$V_4 = 6$ V	$I_4 = 6$ A	$R_4 = 1\ \Omega$

It should be considered that the previous series-parallel circuit was relatively simple and therefore easy to solve. In many cases where several groups of series and parallel resistances are combined, the calculations shown earlier must be repeated and/or performed in different order.

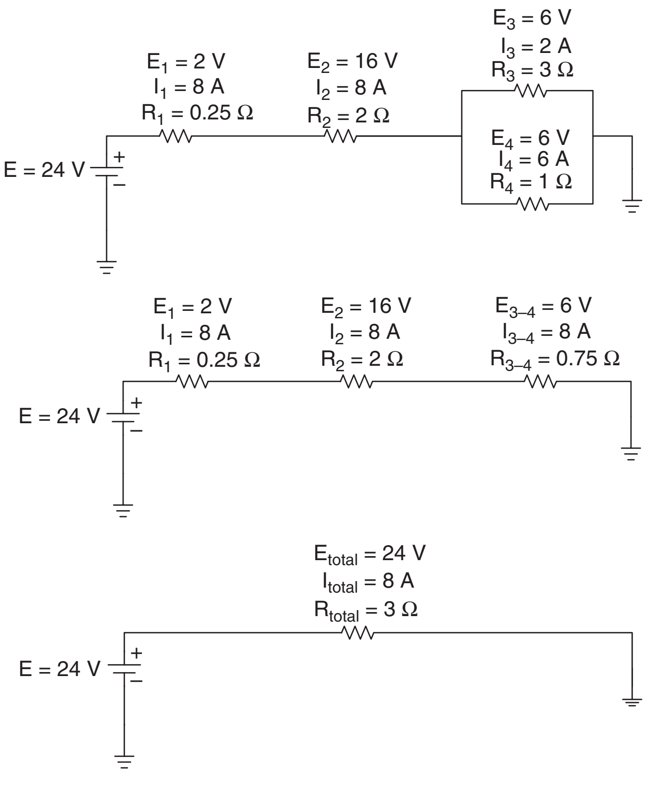

FIGURE 2-29 Solution to series-parallel circuit.

The solution of a series-parallel circuit such as that shown in Fig. 2-30 is not difficult provided that the load-unit (resistance) values are kept in their correct relationships. To determine all the values for the circuit shown, we must start with R_8, R_9, and R_{10} (Fig. 2-30*b*). Since these resistances are connected in series with each other, their total value is 2 + 4 + 6 = 12 Ω. We shall call this total $R_{8–10}$; that is, $R_{8–10} = 12\ \Omega$. The circuit can then be drawn as in Fig. 2-31, which is the equivalent of the original circuit.

In the circuit of Fig. 2-31 it can be seen that R_7 and $R_{8–10}$ are connected in parallel. The formula for two parallel resistances can be used to determine the resistance of the combination. We shall call this combination $R_{7–10}$. Then

$$R_{7-10} = \frac{R_7 \times R_{8-10}}{R_7 + R_{8-10}} = \frac{12\times 12}{12+12} = \frac{144}{24} = 6\ \Omega$$

Now an equivalent circuit can be drawn as in Fig. 2-32 to further simplify the solution. In this circuit we combine the two series resistances, $R_{7–10}$ and R_6, to obtain a value of 10 Ω for $R_{6–10}$. The equivalent circuit is then drawn as in Fig. 2-33.

Since the new equivalent circuit shows that R_5 and $R_{6–10}$ are connected in parallel and that each has a value of 10 Ω, we know that the combined value is 5 Ω. We designate this new value as $R_{5–10}$ and draw the circuit as in Fig. 2-34. $R_{5–10}$ is connected in series with R_4; hence, the total of the two resistances is 8 Ω. This is designated as $R_{4–10}$ for the equivalent circuit of Fig. 2-35. In this circuit we solve the parallel combination of R_3 and $R_{4–10}$ to obtain the value of 2.67 Ω for $R_{3–10}$. The final equivalent circuit is shown in Fig. 2-36 with R_1 $R_{3–10}$, and R_2 connected in series. These resistance values are added to find the total resistance for the circuit.

$$R_t = 1.33 + 2.67 + 2 = 6\ \Omega$$

With the total resistance known and E_t given as 48 V, it is apparent that $I_t = 8$ A ($I_t = E_t/R_t$). The values for the entire circuit can be computed using Ohm's law and proceeding in a reverse sequence from that used in determining total resistance.

First, since I_t = 8 A, I_1, $I_{3\text{-}10}$, and I_2, must each be 8 A because the resistances are shown to be connected in series in Fig. 2-34. By Ohm's law ($E = IR$) we find that $V_1 = 10.64$ V, $V_{3–10} = 21.36$ V, and $V_2 = 16$ V. Referring to Fig. 2-35, it can be seen that 21.35 V exists across R_3 and $R_{4–10}$. This makes it possible to determine that $I_3 = 5.33$ A and $I_{4–10} = 2.67$ A. In Fig. 2-34 we note that I_4 and $I_{5–10}$ must both be 2.67 A because the two resistances are connected in series. Then $V_4 =$

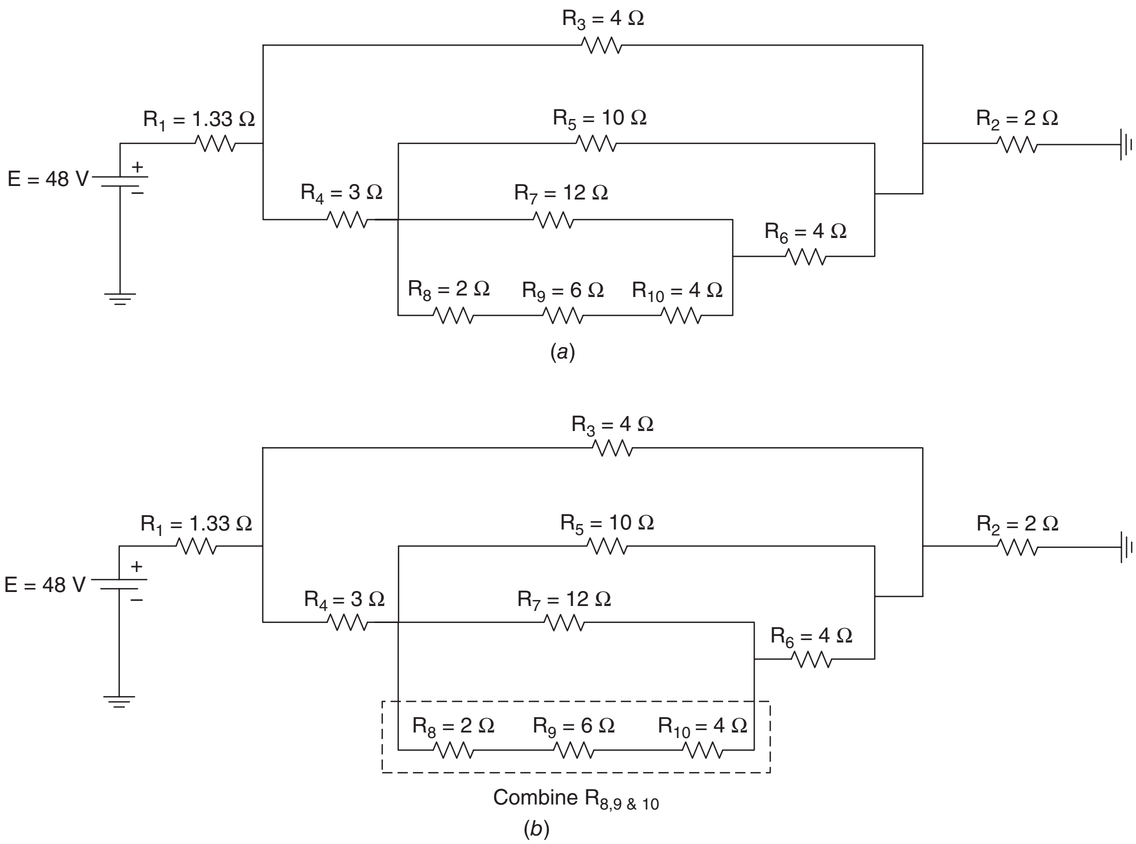

FIGURE 2-30 Series-parallel circuit: (*a*) original circuit; (*b*) first step combining series resistors.

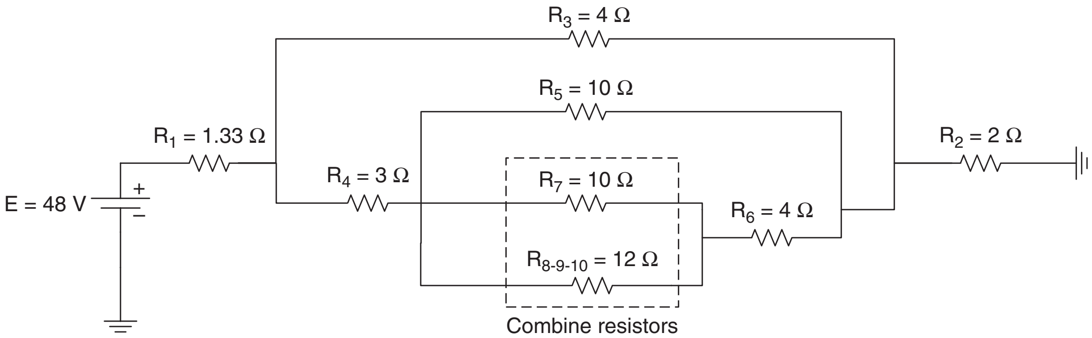

FIGURE 2-31 First simplification step.

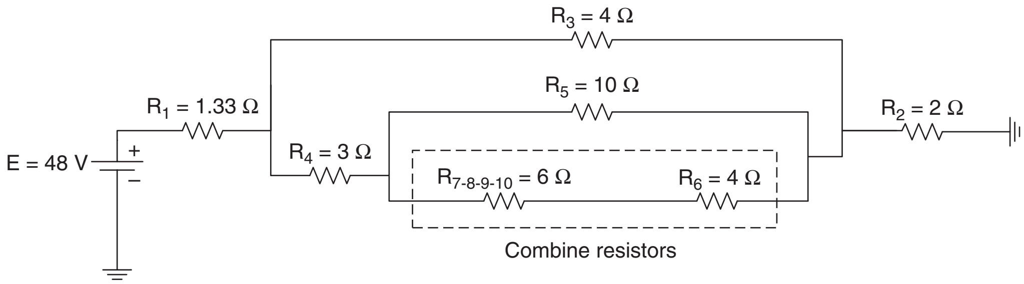

FIGURE 2-32 Second simplification step.

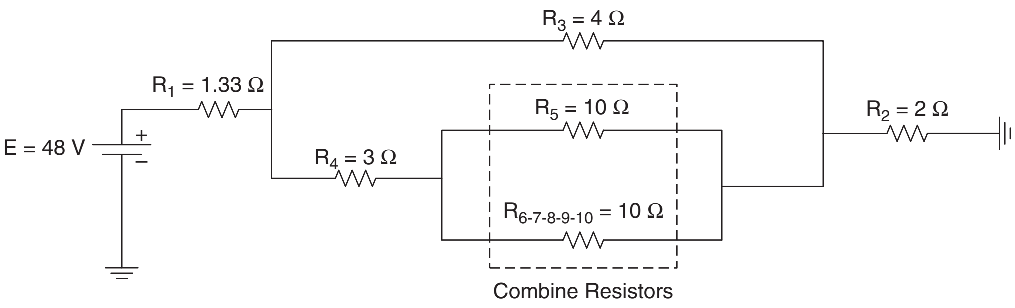

FIGURE 2-33 Third simplification step.

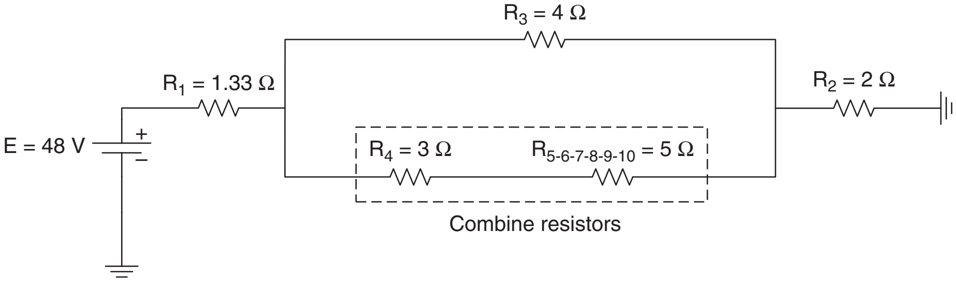

FIGURE 2-34 Fourth simplification step.

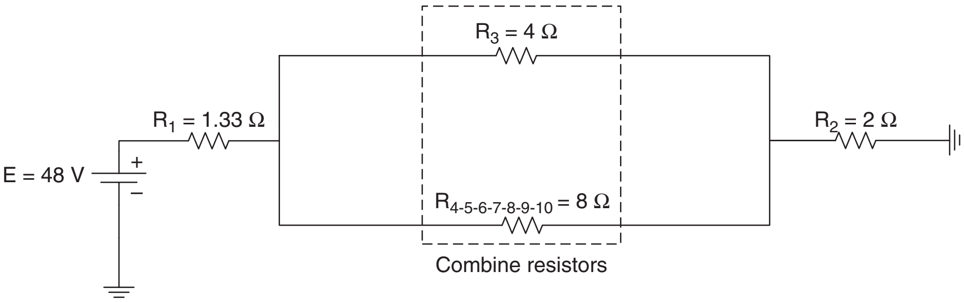

FIGURE 2-35 Fifth simplification step.

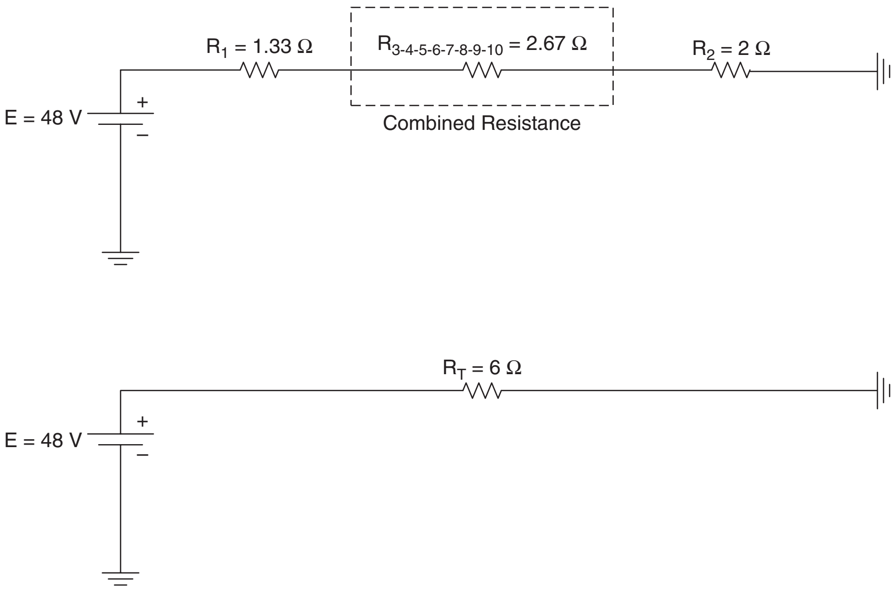

FIGURE 2-36 Final simplified version of Fig. 2–30.

8 V and V_{5-10} = 13.35 V. Since V_{5-10} is the voltage across R_5 and R_{6-10} in the circuit of Fig. 2-33, it is easily found that I_5 = 1.33 A and I_{6-10} = 1.33 A. In the circuit of Fig. 2-32 it is apparent that 1.33 A must flow through both R_{7-10} and R_6 because they are connected in series and we have already noted that I_{6-10} = 1.33 A. Then V_{7-10} = 8 V and V_5 = 13.35 V.

Since V_{7-10} = 8 V, we can apply this voltage to the circuits as shown in Figs. 2-30 and 2-31 and note that both V_7 and V_{8-10} are 8 V. Then I_7 = 0.67 A and I_{8-10} = 0.67 A. Since R_8, R_9, and R_{10} are connected in series and the same current, 0.67 A, flows through each, V_8 = 1.33 V, V_9 = 4 V, and V_{10} = 2.67 V.

The completely solved circuit is shown in Fig. 2-37. A check of all the values given will reveal that they comply with the requirements of Ohm's law. *Note:* Some minor error may exist due to rounding of the numbers during calculation.

KIRCHHOFF'S LAWS

The circuits in this chapter are all solvable by means of Ohm's law as demonstrated. There are, however, many circuits that are more complex, which cannot be solved by Ohm's law alone. For these circuits, Kirchhoff's laws may provide the necessary techniques and procedures.

Kirchhoff's laws were discovered by Gustav Robert Kirchhoff, a German physicist of the nineteenth century. The two laws may be stated as follows:

Law No. 1. *In a series circuit, the algebraic sum of the voltage drops in that circuit must be equal to the source voltage.* Kirchhoff's law of voltage drops may also be applied to any portion of a circuit that is connected in series.

Law No. 2. *In a parallel circuit, the algebraic sum of the currents entering a point is equal to the algebraic sum of the currents leaving that point.* Kirchhoff's parallel law of current flows may also be applied to any portion of a circuit that is connected in parallel.

Kirchhoff's law for series voltage drops can be expressed algebraically as follows:

$$E_t - V_1 - V_2 - V_3 = 0$$

or

$$E_t = V_1 + V_2 + V_3$$

Figure 2-38 shows a circuit to illustrate the principle of Kirchhoff's second law. In this circuit, it can be noted that I_t the current flowing to point *A*, is equal to $I_1 + I_2 + I_3$, the current flowing away from point *A*. Kirchhoff's law of parallel current flows can be expressed by the following equations:

$$I_t - I_1 - I_2 - I_3 = 0$$

or

$$I_t = I_1 + I_2 + I_3$$

Both of Kirchhoff's laws become very useful tools in finding solutions to complex electric circuits. In general, when you are solving series-parallel circuits and you are forced to solve an equation with more than one unknown, remember the following: (1) In series circuits or series portions of a circuit, the sum of the voltage drops is equal to the voltage applied across the entire group of series resistors. (2) The current flow through a series circuit is constant and equal to the total current flow through the entire series portion of the circuit.

In parallel circuits or parallel portions of a circuit: (1) The voltage applied to each resistance is constant and equal to the voltage applied to the entire parallel portion of the circuit. (2) The sum of the current flows through each parallel resistance is equal to the total current entering that parallel portion of the circuit. With these four basic principles and the correct substitution procedures, there should be no circuit too difficult to solve.

SOLUTION OF A RESISTANCE BRIDGE CIRCUIT

When resistances are connected in a bridge circuit as shown in Fig. 2-39*a,* it will be noted that two Δ (delta) circuits are formed. These circuits share the resistance R_5. Because of this, it is not possible to solve the circuit by the methods we have explained previously. However, the circuit can be solved by converting one of the Δ circuits to an equivalent Y circuit.

Figure 2-39*b* represents an equivalent circuit where the Δ circuit *ABD* of Fig. 2-39*a* has been converted to the equivalent Y circuit *ABD* in Fig. 2-39*b*. This conversion is accomplished with formulas as follows:

$$R_a = \frac{R_1 \times R_5}{R_1 + R_4 + R_5}$$

$$R_b = \frac{R_1 \times R_4}{R_1 + R_4 + R_5}$$

$$R_c = \frac{R_4 \times R_5}{R_1 + R_4 + R_5}$$

The circuit of Fig. 2-39*b* is a simple series-parallel type and can be solved as we have explained previously.

For an example of how the circuit of Fig. 2-39 can be solved, we shall first assign resistance values to the resistors in Fig. 2-39*a*: R_1 = 2 Ω, R_2 = 8 Ω, R_3 = 4 Ω, R_4 = 4 Ω, and R_5 = 10 Ω. Then

$$R_a = \frac{2 \times 10}{2+4+10} = \frac{20}{16} = 1.25\,\Omega$$

$$R_b = \frac{2 \times 4}{2+4+10} = \frac{8}{16} = 0.5\,\Omega$$

$$R_c = \frac{4 \times 10}{2+4+10} = \frac{40}{16} = 2.5\,\Omega$$

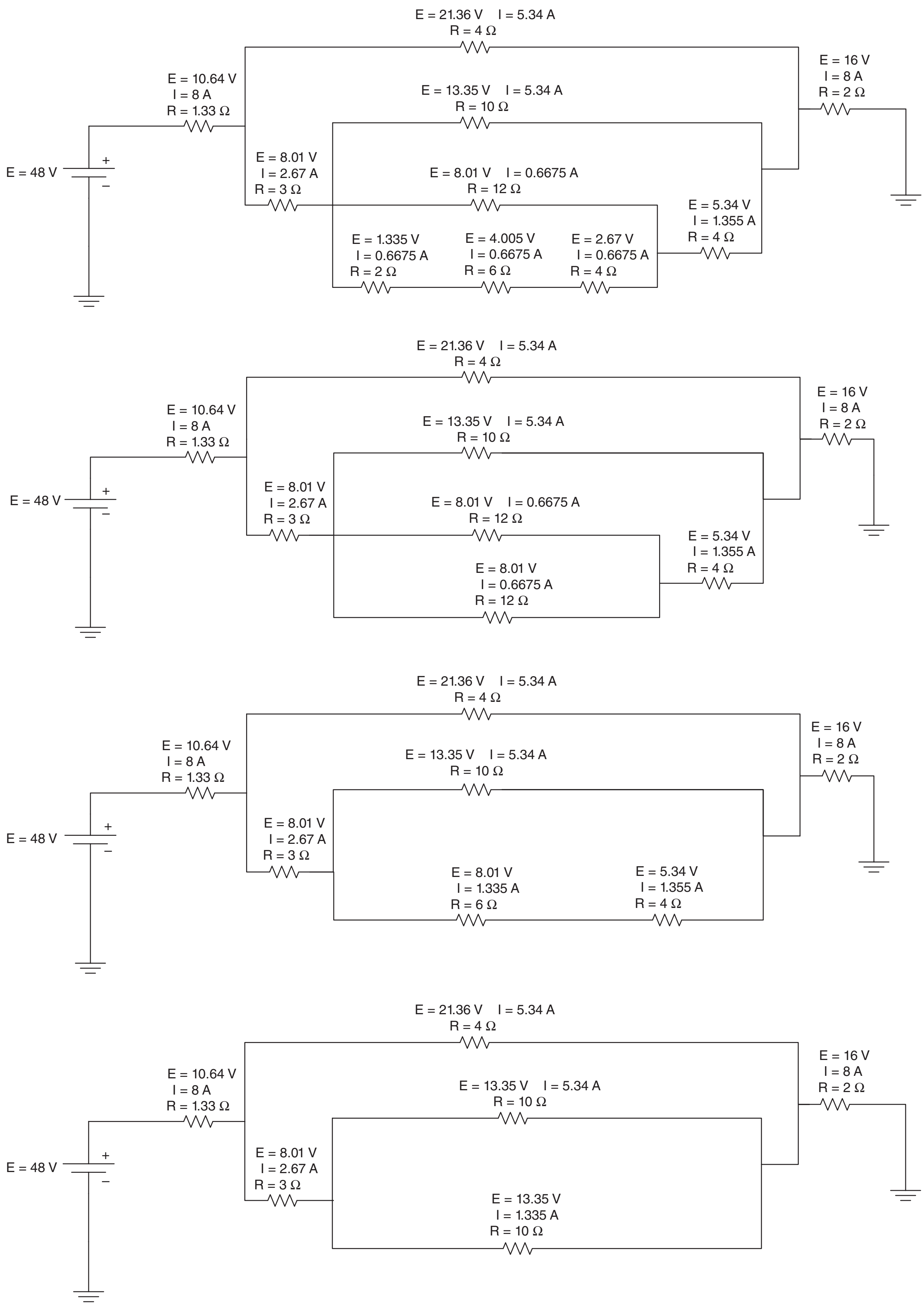

FIGURE 2-37 The completely solved version of Fig. 2-28.

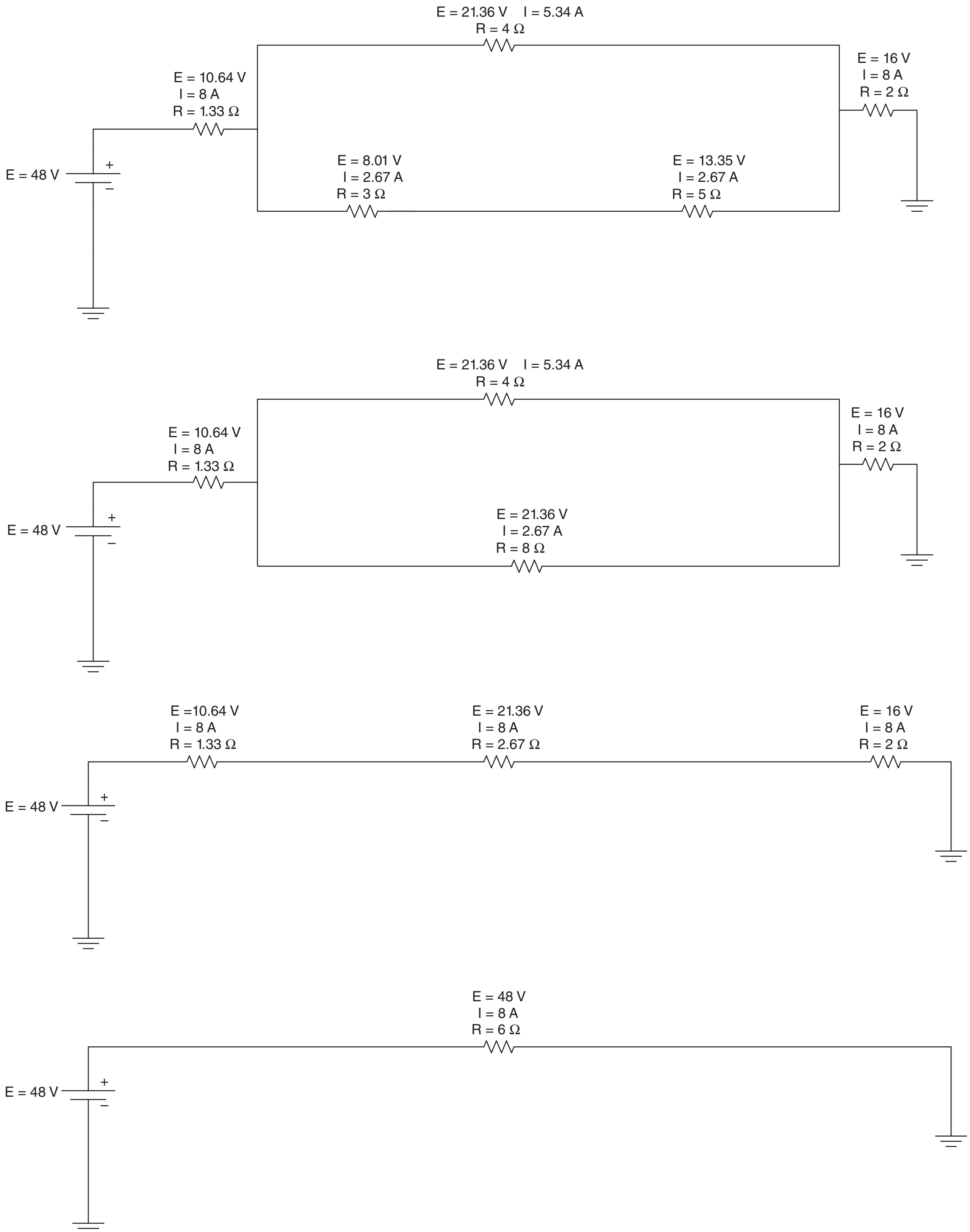

FIGURE 2-37 (*Continued*)

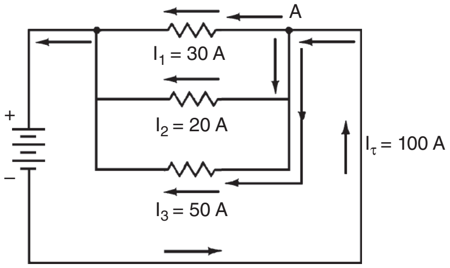

FIGURE 2-38 Diagram to illustrate Kirchhoff's second law. The current to a point is equal to the current from that point.

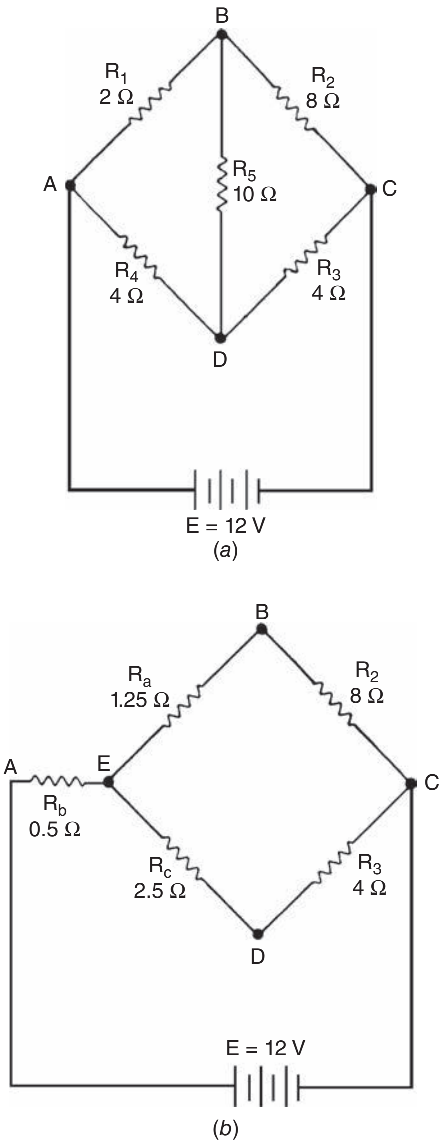

FIGURE 2-39 Circuit to illustrate the conversion of a delta circuit to an equivalent Y circuit and the solution of a resistance bridge circuit.

In the circuit of Fig. 2-39*b*, R_a and R_2 are in series and R_c is connected in series with R_3. Since series circuit values are added to determine the value of the total, we add the series resistances in this case. Then $R_a + R_2 = 1.25 + 8 = 9.25\ \Omega$ and $R_c + R_3 = 2.5 + 4 = 6.5\ \Omega$. The combination of $R_a + R_2$ is in parallel with the combination of $R_c + R_3$; hence, we use the parallel formula for two resistances to determine the equivalent value.

$$R_t = \frac{6.5 \times 9.25}{6.5 + 9.25} = \frac{60.125}{15.75} = 3.82\ \Omega$$

Since the parallel circuit is in series with R_b, we add the total of the parallel resistances (3.82 Ω) to R_B (0.5 Ω) to obtain the combined equivalent resistance for the circuit; that is,

$$0.5 + 3.82 = 4.32\ \Omega$$

Since 12 V is applied to the bridge circuit, the current through the circuit is 12/4.32 = 2.78 A.

PRACTICAL APPLICATIONS OF OHM'S LAW

For an aircraft engineer or technician, there are countless uses for the material contained in this chapter. Some examples of these applications are stated in the following problems. It should be noted that due to the brevity of these examples, they may not fully illustrate the complexity of a given situation that might be encountered on actual aircraft.

Problem No. 1. During an annual inspection it was noticed that the bus bar (the main electrical distribution connection) had been replaced by the previous aircraft owner. One way for the technician to verify the airworthiness of this bus bar is to determine its actual load-carrying capability and compare it with the aircraft's actual total load. It was determined from the specifications of the bus bar that the maximum amperage allowable to enter this part was 60 amps. Is the bus bar within its amperage limit?

Solution. By applying Kirchhoff's law for parallel circuits, it was determined that the current flowing from the bus bar was also the current flowing through the bus bar. The maximum allowable current through the bus is 60 amps; therefore, the total aircraft load could not exceed this value. Since all aircraft circuits are connected in parallel to the bus, the total current was determined using

$$I_t = I_1 + I_2 + I_3 + I_4 + I_5 + I_6 + I_7$$

If the loads on the aircraft are as follows, it is a simple process to determine if the bus bar is electrically overloaded.

Navigation lights	10 A
Navigation radio	4 A
Communication radio	3 A
Pitot heat	12 A
Flap motor	8 A
Hydraulic pump motor	16 A
Fuel pump motor	6 A

Simply sum the individual current flows to find the total current flow.

$$I_t = 10\text{ A} + 4\text{ A} + 3\text{ A} + 12\text{ A} + 8\text{ A} + 16\text{ A} + 6\text{ A}$$
$$= 59\text{ A}$$

Since the aircraft's total load is only 59 amps and the bus bar can handle 60 amps, the bus installation can be considered within its current limit.

Problem No. 2. What size generator must be placed on the aircraft used in Problem 1? The approved generators for that particular airplane are rated at 30, 60, and 90 A.

Solution. Once again, since we know that the current to a point is equal to the current from that point, we can determine that the 59 A "pulled" from the aircraft's bus bar must be "pushed" into the bus bar by the generator. Therefore, the 60-A generator would be required as a minimum. However, the 59 A calculated earlier does not include the current needed to charge the battery after starting the aircraft engine. *(Note:* On this aircraft, the battery current does not feed through the bus; it is received directly from the generator.) Since battery charging current can often exceed 20 A for short periods, the 90-A generator should be installed.

Problem No. 3. While a new electric fuel pump is installed on an antique aircraft, the fuel flow adjustment must be made by changing the voltage to the pump motor. This change in voltage changes the rpm of the pump motor, hence, changing the fuel flow through the pump. To accomplish this voltage change, the aircraft system contains an adjustable resistor in series with the fuel pump motor. If the aircraft manual calls for 8 V to be applied to the pump motor and the aircraft system voltage is 14 V, at what resistance must the variable resistor be set?

Solution. Since voltage drops are additive in a series circuit, the voltage drop of the resistor plus the voltage drop of the fuel pump must equal 14 V (system voltage); or, 14 V – 8 V = resistor voltage drop. The voltage drop of the resistor is therefore 6 V. The equation $R = E/I$ can be used to determine the resistor's value. According to the data plate of the fuel pump, the motor draws 2 A at 8 V. Since the motor and resistor are in series, 2 A must also flow through the variable resistor. Using

$$R_r = \frac{V_r}{I_r}$$

where R_r = resistance of the resistor in ohms
V_r = the voltage drop over the resistor (6 V)
I_r = the current flow through the resistor (2 A)

$$R_r = \frac{6\,V}{2\text{ A}}$$
$$= 3\,\Omega$$

The variable resistor should be set for 3 Ω in order to produce the correct fuel flow.

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