CHAPTER 4

DC Electricity

Benjamin Franklin proved an important scientific point, which is that electricity originates inside clouds. There, it forms into lightning, which is attracted to the earth by golfers. After entering the ground, the electricity hardens into coal, which, when dug up by power companies and burned in big ovens called "generators," turns back into electricity, which is sent in the form of "volts" (also known as "watts," or "rpm" for short), through special wires with birds sitting on them to consumers' homes, where it is transformed by TV sets into commercials for beer, which passes through the consumers and back into the ground, thus completing what is known as a "circuit."—Dave Barry, humorist

One of the keys to understanding automated lighting, or any lighting, for that matter, is to follow the flow of energy from the input to the output. A fundamental law of nature is that energy can be neither created nor destroyed; it can only change forms. Electricity is one form of energy, and the job of any lighting system is to take electrical energy and efficiently convert it to light energy. In the real world, only a fraction of the energy put into a lighting system comes out as visible light. Most is lost to heat, some is lost to mechanical energy, and some is converted to invisible light waves.

The process of converting electrical energy to light can be as simple as passing a current through a filament to heat it up to the point where it gives off light (incandescence), or it can be a much more complicated process involving arc lamps or LEDs. In automated lighting, we will come across each of these scenarios, and it's imperative that we understand them all. In each case, understanding begins with the concept of direct current (DC) electricity.

Figure 4-1 An electron is an electrostatically charged particle. Electricity is the flow of electrons.

The Flow of Electrons

In simple terms, electricity is nothing more than the flow of electrons (Figure 4-1). A single electron is an extremely small particle that carries a negative electrostatic charge. Whether it's at rest or in motion, it's a charged particle. An electron is a subatomic particle that's so small that it takes millions and millions of them to produce any significant amount of electricity.

The Relative Size of Electrons

Because an electron is so small, it's sometimes difficult to grasp the simple concept of electricity. We can't see electrons flowing with the naked eye, nor can we see electrostatic attraction; therefore, it's difficult to learn by direct observation. To give you an idea of the scale we're talking about, let's suspend our belief momentarily and pretend that we can shrink down to the atomic level. Now, take a look at the period at the end of this sentence and you will find that we can fit something on the order of 6.25 trillion atoms within the circumference of it. Atoms vary in size according to their type, but a simple carbon atom is approximately 0.1 nm, or 0.0000000001 m, in diameter, and the vast majority of its empty space. If the nucleus of an atom were half a centimeter in diameter, then you would have to walk about a mile to find the orbit of the outermost electrons. The electrons orbiting the nucleus of the atom are much smaller than the nucleus—approximately one-billionth of a nanometer in diameter, perhaps even smaller; no one knows for sure. Given the dimensions we're dealing with, it's no wonder we sometimes find it difficult to grasp the concept of electricity (Figure 4-2).

The Electron Drift Theory

Still, the flow of electrons is a relatively simple concept that becomes clear when you understand what happens when you apply a voltage to a conducting material. The nucleus of an atom is made up of positively charged protons and uncharged neutrons. Since opposite charges attract, the electrostatic attraction between the positively charged protons in the nucleus and the negatively charged electrons orbiting the nucleus is the main force that holds an atom together. The residual attraction of neighboring atoms

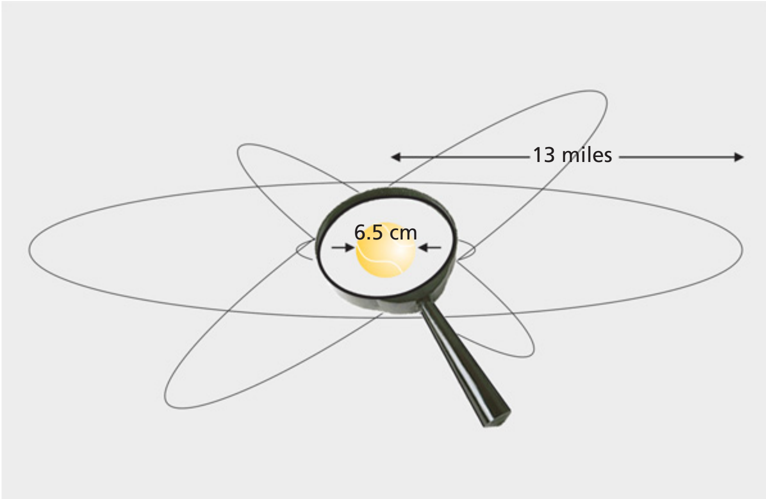

Figure 4-2 If the nucleus of an atom were the size of a tennis ball, the orbit of the outermost electron would be about 13 miles away.

binds them together to form molecules, of which the entire world is made. Under normal circumstances, the total number of electrons and protons in an atom is exactly the same, producing a net charge of zero (neither positively or negatively charged).

When voltage is applied to a conductor, the more loosely bound electrons in the outermost orbit of the atom are pulled from their orbit and follow the path of least resistance toward the higher voltage potential. When one electron is pulled away from an atom, it leaves a "hole," and that atom now carries a net positive charge in the absence of the electron. The free electron will "drift" toward the higher potential, colliding with atoms along the way. Each collision the electron encounters takes away some of its kinetic energy and converts it to heat energy. As the kinetic energy of the traveling electron is lost it slows down. The more it slows down, the more likely it is to "fall" back into the orbit of another atom that has lost its outer electrons (Figure 4-3). This is known as electron drift. Billions and billions of these interactions are going on at lightning speed, creating the massive flow of energy due to the motion of the electrons. This is what we know as electricity. More specifically, we refer to the flow of energy through the motion of the electrons as current.

Friction

In the process of the mass migration of electrons, the collisions between free electrons and the larger molecules produce friction that heats up the conducting material. For a given amount of current, the amount of friction produced is directly proportional to the resistance of the conducting material.

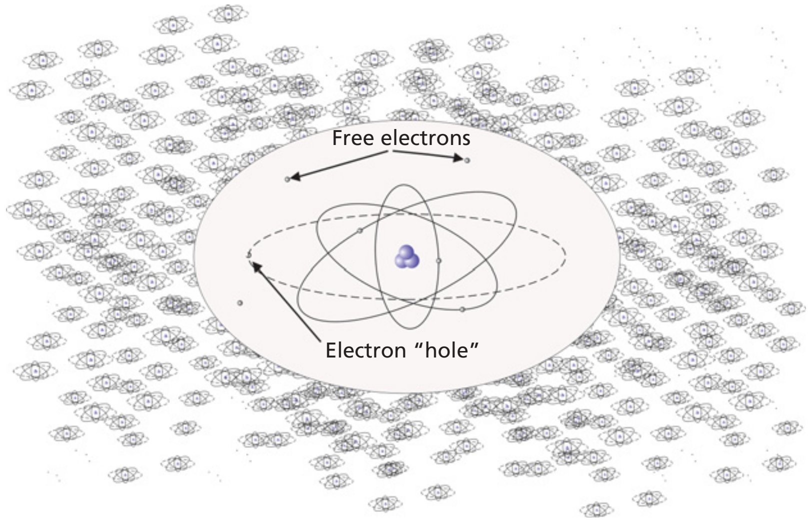

Figure 4-3 When voltage is applied to a conductor, electrons are pulled from the outermost orbit of the atoms. The free electrons move toward the higher potential, colliding with atoms along the way. As the electrons collide, they lose energy and eventually "fall" back into the orbit of an atom with a missing electron.

$$\text{Heat} \sim \text{Resistance}$$

Friction is lost energy that won't be recovered. In addition, the added thermal load in the venue due to lost heat energy contributes to the heating, ventilation, and air conditioning (HVAC) requirements for the building, which drives up the cost of operating lighting systems. As we will see later on, there's a simple way to calculate the heat load in British Thermal Units (BTUs) or in joules based on the inefficiency of a power distribution and lighting system. This should be taken into consideration in the design phase of a lighting system for permanent installation. In touring situations it's less of an issue because the building architects have most likely already taken into consideration the HVAC requirements under normal show conditions, including the building occupancy and the lighting and electrical loads.

Conductive Properties of Materials

For current to flow, there must be a conducting medium such as a wire or cable. Some materials are better conductors than others because their molecules contain atoms that more readily give up electrons. These materials are known as good

Table 4-1 Resistivity and temperature coefficient at 20°C.

Material	Resistivity (ρ) (ohm m)	Conductivity (σ) $\times 10^7$ (/ohm m)
Silver	1.59×10^{-8}	6.29
Copper	1.68×10^{-8}	5.95
Aluminum	2.65×10^{-8}	3.77
Tungsten	5.6×10^{-8}	1.79
Iron	9.71×10^{-8}	1.03
Platinum	10.6×10^{-8}	0.943
Lead	22×10^{-8}	0.45
Mercury	98×10^{-8}	0.10
Nichrome (Ni, Fe, Cr alloy)	100×10^{-8}	0.10
Constantan	49×10^{-8}	0.20
Carbon (graphite)	$3 \times 10^{-5} - 60 \times 10^{-5}$	—
Germanium	$1 \times 10^{-3} - 500 \times 10^{-3}$	—
Silicon	$0.1 - 60$	—
Glass	$1 \times 10^{9} - 10{,}000 \times 10^{9}$	—
Quartz (fused)	7.5×10^{17}	—
Hard rubber	$1 \times 10^{13} - 100 \times 10^{13}$	—

Source: Giancoli, Douglas C., *Physics*, 4th ed., Prentice Hall (1995).

conductors, and they offer little resistance to the flow of electrons. Copper, gold, silver, aluminum, and other metallic elements are good conductors and have a very low resistance value (Table 4-1). Other materials such as carbon, wood, paper, and rubber are poor conductors of electricity. They're considered insulators because they inhibit the flow of electricity. Still others, such as germanium and silicon, will conduct electricity under certain conditions and are known as semiconductors.

Current Convention

When we think of the direction of the flow of DC electricity, we tend to think in positive terms. For example, if a current flows from left to right, then we tend to think of some ethereal substance traveling from left to right. But electrons are negatively charged. Therefore, when an electron travels from left to right, the standard convention is that the current is flowing in the opposite direction

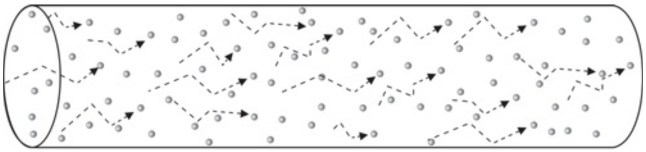

Figure 4-4 The direction of current is opposite the direction of the flow of electrons because electrons carry a negative charge.

(Figure 4-4). Only the U.S. Navy refers to the direction of current flow as the same direction as the flow of electrons.

Voltage, Current, and Resistance

In the study of DC electricity, it's important to have a firm grasp of at least three basic concepts: voltage, current, and resistance. Those three parameters are closely related in an electric circuit. You already have a basic understanding of current, which is the flow of electrons, and resistance, which is the resistance to the flow of electrons.

Voltage is sometimes referred to as potential because, like gravity, it has the potential to cause something to happen. Gravity has a potential to make something fall, thereby giving it kinetic energy; electricity has the potential to make electrons flow, thereby producing electrical energy. In both cases, there's potential energy available.

Water and Electricity—Bad Mix, Good Analogy

To better understand the concept of electricity flowing in a circuit, it's sometimes easier to consider an analogy between water and electricity. In the water–electricity analogy, water pressure is analogous to voltage; it's the force that causes water to flow. Without water pressure, water won't flow. Without voltage, current won't flow. A water pipe is analogous to a conductor. The bigger the pipe, the easier the water flows. The smaller the pipe, the less water can flow. A very small pipe, then, is analogous to a small conductor with a high resistance and a large pipe is analogous to a large pipe with low resistance.

A complete water distribution system, then, is analogous to an electric circuit (Figure 4-5). The water stored in a reservoir is like a battery that stores a

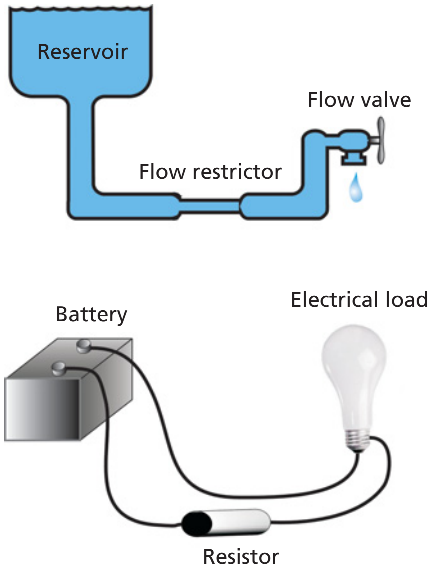

Figure 4-5 *Top*: The water pressure from the reservoir forces water through the pipe, the flow restrictor limits the amount of flow, and the flow valve turns the flow on and off. *Bottom*: The voltage supplied by the battery drives current through the wires, the resistor limits the flow of electricity, and the light bulb draws the current.

charge. The dam that holds back the water has a tremendous amount of water pressure at the bottom. That water pressure is like the voltage in the battery, ready to deliver the water or electricity on demand. The pipe that carries the water to the subdivision is like the feeder cables that carry electricity from the power generation station to the houses in the subdivision. Along the way there are switches and valves that turn the water and electricity on and off. When the tap is on, the water flows. When the light switch is on, current flows.

The DC Circuit

A simple DC circuit is shown in Figure 4-6. The battery provides the voltage that makes the current flow when the circuit is completed. The wiring provides a path for the flow of electricity, and it completes the circuit. The resistance of the load prevents the current from becoming too large and destroying the entire circuit. The load, in this case, is a light bulb, but it might just as well be a motor, a fog machine, or anything that uses electricity.