2 Electricity

This chapter introduces the physical phenomenon of electricity. First it examines the overall structure of the atom, the most fundamental basis for studying electricity. Next, it examines the basics of electricity – charge, current, and voltage. The two types of current electricity, direct current and alternating current, are introduced, along with differences between conductors and insulators.

Next, this chapter introduces the topic of resistance, and its relation to voltage and current. The color codes for resistors are presented, and circuits using resistors in series and in parallel are examined. Potentiometers, resisters whose values can be varied, and photoresistors, resistors whose values vary based on the amount of light they receive, are introduced. Laboratory Experiments 1 and 2 correspond to the material covered in this chapter.

2.1 Electricity, Charge, and Current

2.1.1 Atomic Structure

To understand current, it is necessary to first understand the basic structure of the atom. An atom is composed of three basic types of particles. The nucleus, or center of the atom, contains some number of *protons* and *neutrons*. The protons are positively charged particles, and the number of protons in an atom determines the type of atom. For example, all hydrogen atoms have exactly one proton, and all atoms with 13 protons are aluminum. Most atoms (except for most hydrogen atoms) have one or more neutrons in their nuclei as well. Neutrons have no charge, and the number of neutrons in an atom may vary. Atoms with the same number of protons but different numbers of neutrons are called *isotopes*.

Outside of the nucleus, negatively charged particles called *electrons* orbit the nucleus. Electrons are much smaller and lighter than protons. The attraction between the positively charged protons in the nucleus and the negatively charged electrons normally keeps the electrons in orbit around the nucleus. The number of electrons is the same as the number of protons, and the positive and negative charges cancel out; the atom has no net charge. A typical atom is shown schematically in Figure 2.1.

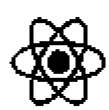

Figure 2.1: Basic atomic structure. Negative electrons orbit the positive nucleus at the center.

Sometimes an electron can escape from the orbit of its atom and be captured by another atom. The original atom now has one less electron and the atom has a net positive charge. The atom that captures the electron has one more electron than it has protons, resulting in a net negative charge. These are called *ions*, a general term that applies to all atoms with non-zero net charge, either positive or negative.

This last phenomenon, electrons moving between atoms, is the basis for electricity. Electricity is created by the flow of electrons. We'll examine this in the following subsections.

2.1.2 Charge

In the previous section we mentioned that electrons have a negative charge, but how much is this charge? To quantify charge, scientists have defined a *Coulomb* as the amount of charge contained by 6,250,000,000,000,000,000 (6.25×10^{18}) electrons. Although this sounds like a lot of electrons, keep in mind that one mole of hydrogen atoms, 6.022×10^{23} atoms, weighs only one gram, and the vast majority of that gram comes from the protons!

Charge is typically denoted as *Q*. Coulombs is abbreviated *C*; for example, a charge of 12 Coulombs is denoted as $Q = 12C$..

2.1.3 Current

Electric current is the flow of charged particles in a specific direction. In liquids and gases, these charged particles can be electrons or ions. In solids, such as the wire used in electrical circuits, electrons are the charged particles that cause electric current. Since the charge of a single electron is very small indeed ($q_e = 1.6 \times 10^{-19}$ C), any practical current involves flow of many electrons.

Current is typically denoted as *I* (for intensity). Current is the amount of charge flowing per unit time. This can be denoted by the equation:

$$I = \frac{Q}{t}$$

The same amount of charge flowing over a longer period of time would produce a smaller current, just as having a street where 20 cars pass through an intersection in one minute would be considered to have greater traffic than having the same 20 cars pass through the same intersection in an hour. The basic unit of current is the *Ampere*, or *Amp*, denoted as *A*. One Ampere is defined as the flow of one Coulomb of charge per second.

The following point is really important. *Although the electrons in a metal wire flow from the negative terminal to the positive terminal, the current flows from the positive terminal to the negative terminal*. The electrons carry a negative charge, and the current is defined by convention as the flow of positive charge. This is sort of like subtracting 1 and -1. 1 - (-1) is the same as 1 + (+1). The negative charge of the electrons flowing in one direction gives the same current as the positive charge flowing in the opposite direction. The convention of the current flow from positive to negative terminal was established before electrons were discovered and later people did not bother to change it.

2.1.4 Direct Current and Alternating Current

Two types of electric current are used in everyday life. *Direct current*, or *DC*, always flows in the same direction. This is the type of current created by batteries. The other type of current is *alternating current*, or *AC*. This is the current used to power household appliances and lights. This type of current periodically changes direction, once every 1/120 seconds in the United States (or once every 1/100 seconds in Europe).

2.1.5 Voltage

Voltage, also called the *electromotive force* or *potential difference*, is the force that causes current to flow. It can be helpful to visualize voltage as a difference in potential energy caused by differences in charges. Consider a simple battery; it has positive and negative terminals. Chemicals inside the battery cause positive charges to congregate near the positive terminal and negative charges to collect near the negative terminal. If we connected a wire from one terminal to the other, electrons would flow from the negative terminal to the positive terminal, creating a current in the wire. Eventually the charges on each side of the battery will become more neutral, and the battery will die out.

Voltage is defined as energy per unit charge. The basic unit of voltage is the *Volt*, abbreviated as *V*. One volt is equal to one joule per Coulomb. The more volts a battery has, the more joules of energy it supplies per coulomb.

2.1.6 Power

The flow of charges requires energy, and the energy per unit time, or power *P*, is proportional to both current and voltage

$$P = I \times V$$

Power is measured in watts. One watt is one joule per second, which is equal to one ampere times one volt.

2.1.7 Conductors and Insulators

Some materials allow electrons to flow more freely than others. *Conductors* are materials that give up electrons easily, offering little opposition (resistance) to current flow. Copper is a very good conductor; that is why house wiring is usually made of copper.

Other materials, called *insulators*, do not yield electrons easily. They offer high resistance to current flow. They are not perfect; some electrons do flow in insulators. However, the amount is so small that, for all practical purposes, virtually no current flows. Insulators are useful for wrapping wires, causing all current to flow from one end of the wire to the other and not allowing current to escape from within the wire. This is why an extension cord that is plugged into a wall outlet can be handled safely, as long as there is no break in the insulation!

2.2 Resistors and Ohm's Law

Resistors are fundamental components in electric circuit design. As their name implies, they resist the flow of current in a circuit. The next several sections examine resistors, their color codes, and circuits that use resistors in series, in parallel, or in both configurations. Potentiometers and photoresistors, resistors whose values can be varied, are also described.

To examine the relationship between the voltage, current, and resistance in a circuit, we will start with the simple circuit shown in Figure 2.2.

Figure 2.2: A simple 1-resistor circuit

The circle on the left hand side of the figure is a power source. It has a voltage of 1.5V, the voltage level of a standard battery. The positive terminal of the battery (+) is connected via a wire, represented by straight lines, to one end of a resistor, which is denoted by the zigzag lines. The other end of the resistor is connected to the negative terminal of the battery (-) with wires, completing the circuit.

The value of the resistor is based on how well it resists the flow of electrons. A higher resistance allows fewer electrons to flow through the resistor in a given time, reducing the current. The basic unit of measure of resistance is the *Ohm*, denoted by Ω, the Greek letter Omega. One Ohm is defined as the value of the resistance that lets the current of 1 A to flow under a voltage of 1 V (one volt per ampere). The resistor in this circuit has a value of 100 Ω.

Ohm's Law defines the relationship between voltage, current, and resistance. It was developed by German physicist Georg Ohm, for whom both Ohm's Law and the unit of measure for resistance were named. It states that the voltage (*V*) in a circuit is equal to the product of the current (*I*) and the resistance (*R*), or

$$V = I \times R$$

Manipulating this equation, we can express the current or resistance as a function of the other terms in the equation as follows.

$$I = \frac{V}{R} \quad \text{and} \quad R = \frac{V}{I}$$

A current flowing through a resistance generates power (in form of heat).

$$P = I \times V = \frac{V}{R} \times V = \frac{V^2}{R} = I^2 R$$

Now let's look back at the circuit in Figure 2.3. With a voltage of 1.5V and a resistance of 100 Ω, we can calculate its current as

$$I = \frac{V}{R} = \frac{1.5V}{100\Omega} = 0.015A = 15mA$$

The symbol *mA* stands for mili Amperes, or one-thousandths of an Ampere.

2.4 Series Resistors

A typical circuit will have more than one resistor. Resistors in a circuit may be configured in series, in parallel, or in a combination of the two. This section examines resistors connected in series; parallel resistance is examined in the next section.

Resistors that are connected end-to-end are said to be connected in series. Figure 2.3 shows a circuit with two resistors connected in series. One hallmark of series resistance is that the same current that flows through one resistor must flow through the other resistor as well. There is only one path for the current to flow in this circuit.

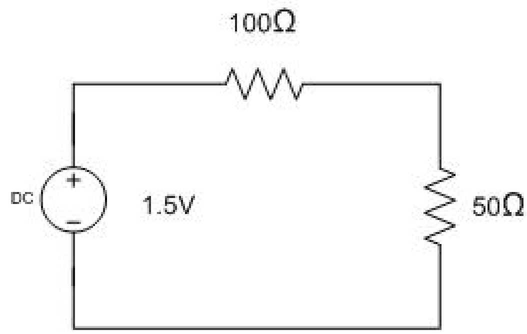

Figure 2.3: Circuit with two resistors in series

When two resistors are connected in series, their overall resistance is the sum of their individual resistances. For the circuit in Figure 2.3, the two series resistors have values of 100 Ω and 50 Ω; their overall resistance is 100 Ω + 50 Ω = 150 Ω. Using Ohm's Law, we can calculate the current in the circuit using this combined resistance.

$$I = \frac{V}{R} = \frac{1.5V}{150\Omega} = 0.01A = 10mA$$

2.5 Parallel Resistors

Resistors are not always connected in series; they can also be connected in parallel. Figure 2.4 shows a circuit with two resistors connected in parallel. Notice that both ends of the two resistors are connected together.

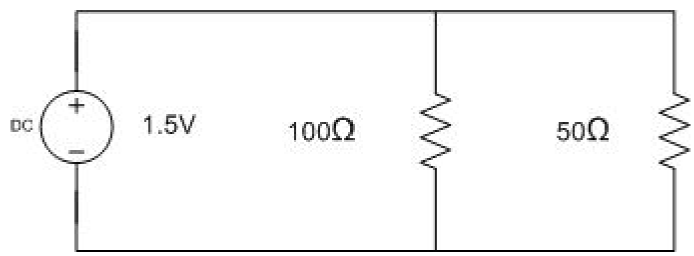

Figure 2.4: Circuit with two resistors in parallel

Although it might not seem to make sense, the overall resistance of two resistors connected in parallel is *less* than the resistance of either resistor! The basic reason this is true has to do with the current flow; adding another resistor in parallel increases the amount of current flowing in the circuit. From Ohm's Law, I = V/R; as current (I) increases and the voltage (V) remains the same, the overall resistance (R) must decrease.

Let's look at the circuit in Figure 2.4. Each resistor is connected directly to the positive and negative terminals of the battery, so each has a voltage of 1.5V. The 100 Ω resistor has a current of 1.5V/100 Ω = 15 mA, and the 50 Ω resistor has a current of 1.5V/50 Ω = 30 mA. Together the circuit has a current of 15mA + 30 mA = 45 mA. For the overall circuit, using Ohm's Law, we find R = 1.5V/45mA = 33.3 Ω.

A standard formula, called the *reciprocal formula*, is used to calculate the net resistance of two or more resistors in parallel. The reciprocal of the overall resistance is equal to the sum of the reciprocals of the individual resistors, or

$$\frac{1}{R_{OVERALL}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$$

This formula can be simplified for circuits with only two resistors. The formula becomes

$$R_{OVERALL} = \frac{R_1 R_2}{R_1 + R_2}$$

2.6 Series-Parallel Resistors

As their name implies, series-parallel circuits have resistors in series and in parallel. Figure 2.5 shows two series-parallel circuits.

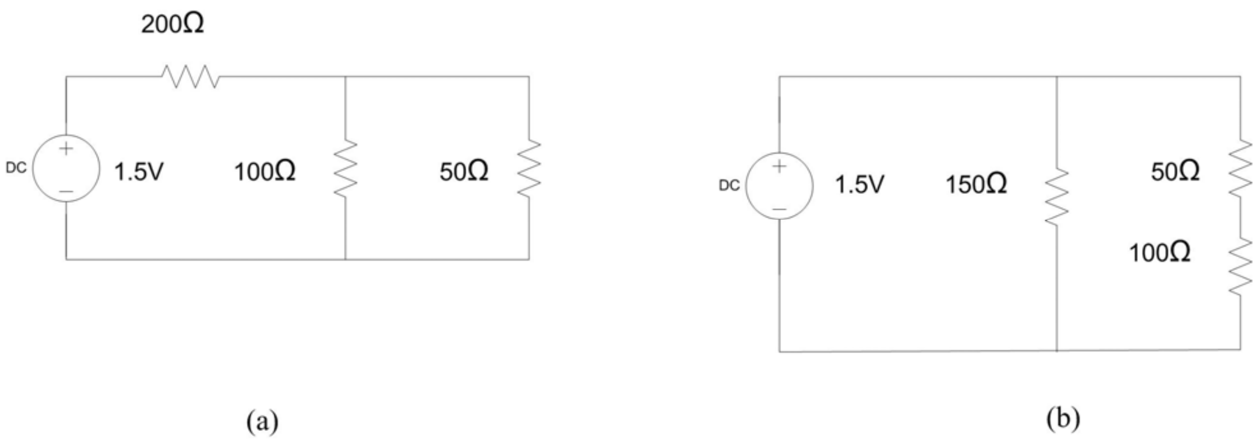

Figure 2.5: Two series-parallel circuits

We can analyze series-parallel circuits by breaking them into their individual series and parallel components. For the circuit in Figure 2.5(a), the 50 Ω and 100 Ω resistors are in parallel; their net resistance, calculated using the reciprocal formula, is 33.3 Ω. That equivalent resistance is in series with the 200 Ω resistor, producing a net resistance of 233.3 Ω in the circuit. This yields a current of 6.4mA.

For the circuit in Figure 2.5(b), we first combine the 50 Ω and 100 Ω series resistors, which results in a net resistance of 150 Ω. Combining this in parallel with the 150 Ω resistor yields a net resistance of 75 Ω, and a current of 20mA.

2.7 Potentiometers and Photoresistors

For some circuits, it would be preferable to allow a user to change the value of the resistance without having to re-wire the circuit. This is the role of the *potentiometer*. It is a variable resistor whose value can be changed, typically by turning a shaft or sliding a lever.

There are several applications for potentiometers. Dimmer switches used to vary the intensity of lights are typically potentiometers, or their close relatives *rheostats*. Volume control knobs on older radios and televisions are also potentiometers.

A photoresistor also changes its value, but the user does not directly change the value of the resistance. Instead, the resistance varies depending on the amount of light sensed by the photoresistor. The photoresistor has greater resistance in dim light and darkness. If the light is bright, the resistance decreases. The photoresistor can be used as a light sensor.

2.8 Kirchoff's Laws

Kirchoff's Laws are useful tools for analyzing circuits. There are two distinct laws, Kirchoff's Current Law (KCL) and Kirchoff's Voltage Law (KVL). This section examines both laws and how they can be used to analyze resistor circuits.

2.8.1 Kirchoff's Current Law

Kirchoff's Current Law can be summarized as follows.

Current entering a node = Current leaving a node

A node is a point in the circuit to which at least two elements, for example resistors, are connected. Intuitively this low makes sense if you consider that current flow is generated by electrons. The electrons flowing into a point in a circuit must come out somewhere; just like water flowing into a pipe must flow out of its other end or out of the pipe branches, if there are any.

To illustrate this point, consider the series resistor circuit shown in Figure 2.6. This is the same as the circuit of Figure 2.3, and we had previously calculated the current in this circuit to be 10 mA. For this circuit, this is the current in to and out of point A, as well as the current in to and out of point B.

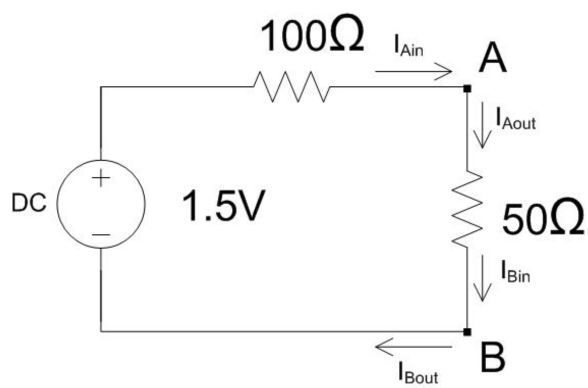

Figure 2.6: Applying Kirchoff's Current Law to a series resistor circuit

Although the KCL is valid for series resistor circuits, it isn't all that useful as an analysis tool. It is much more helpful for analyzing current flow in parallel resistors. For example, consider the circuit shown in Figure 2.7. This is the same circuit as shown in Figure 2.4, and we had calculated its overall current as 45 mA.

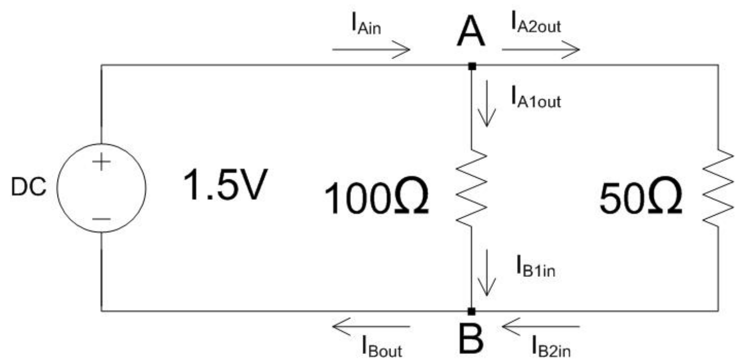

Figure 2.7: Applying Kirchoff's Current Law to a parallel resistor circuit

According to Kirchoff's Current Law, the current entering node A is equal to the current leaving the node, or

$$I_{Ain} = I_{A1out} + I_{A2out}$$

In Section 2.5 we calculated I_{A1out} = 15 mA and I_{A2out} = 30 mA, so

$$\begin{aligned} I_{Ain} &= 45 \text{ mA} = I_{A1out} + I_{A2out} \\ &= 15 \text{ mA} + 30 \text{ mA} = 45 \text{ mA} \end{aligned}$$

Similarly for node B,

$$\begin{aligned} I_{Bin} &= 45 \text{ mA} = I_{B1out} + I_{B2out} \\ &= 15 \text{ mA} + 30 \text{ mA} = 45 \text{ mA} \end{aligned}$$

An important question remains: How do we know how much current flows through each of the parallel resistors? In this example, why did the current split up as 15 mA and 30 mA instead of, say, 40 mA and 5 mA?

Clearly the current values are not selected randomly. In this case there is a straightforward explanation. *When two resistors are connected in parallel, they both have the same voltage drop*. For the circuit of Figure 2.8, the voltage drop across each resistor is 1.5V. Applying Ohm's Law gives us the following current values.

$$I_{A1out} = 1.5\text{V}/100\Omega = 15 \text{ mA}$$
$$I_{B1out} = 1.5\text{V}/50\Omega = 30 \text{ mA}$$

If two resistors are connected in parallel and one resistor has four times the resistance of the other, the larger resistor will have 1/4 the current flow of the other resistor.

2.8.2 Kirchoff's Voltage Law

The second of Kirchoff's Laws, Kirchoff's Voltage Law, is as follows.

The sum of all voltages in a loop is equal to zero

Before examining this law in detail, we first must define a loop. A loop is essentially a closed path within a circuit, consisting of part or all of the circuit. For example, Figure 2.8 shows a series resistor circuit and its one and only loop.

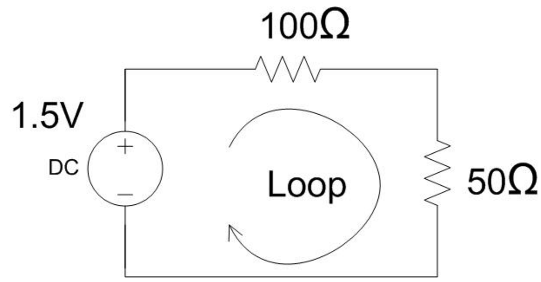

Figure 2.8: A series resistor circuit and its only loop

There are three voltages in this loop: the voltage from the 1.5V power supply and the voltages dropped across each of the two resistors. By convention, we show voltage values as positive or negative based on the direction of the current flow. Since current flows in the same direction as the loop for this circuit, the voltage across each resistor is positive. Since the loop passes from the negative to positive terminal of the power source, its value is negative. The voltage in this loop can be expressed as

$$+V_{100\Omega} + V_{50\Omega} - 1.5V = 0$$

By Ohm's Law, the voltage drop across each resistor is equal to its current multiplied by its resistance, $V = I \times R$. We had previously calculated the current flow through each resistor as 10 mA, so $V_{100\Omega} = 10\text{ mA} \times 100\Omega = 1.0V$ and $V_{50\Omega} = 10\text{ mA} \times 50\Omega = 0.5V$, or

$$V_{100\Omega} + V_{50\Omega} - 1.5V = 1.0V + 0.5V - 1.5V = 0$$

Circuits with resistors in parallel have more than one loop. As shown in Figure 2.9, a circuit with two parallel resistors actually has three loops. The sum of the voltages in each of the three loops must equal zero.

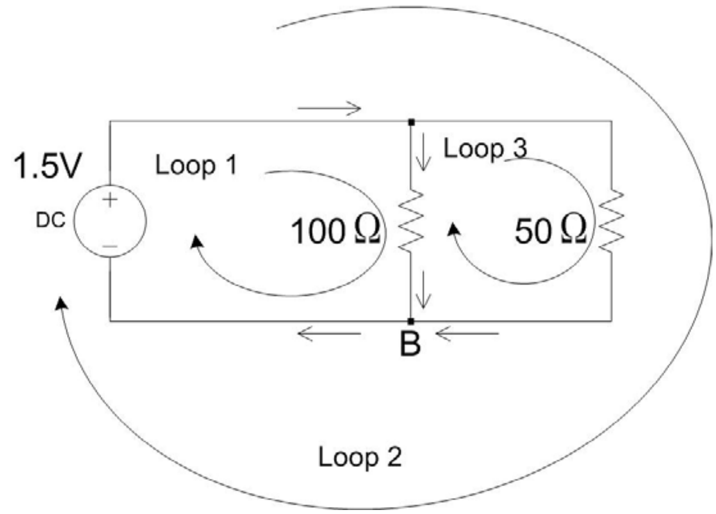

Figure 2.9: A parallel resistor circuit and its three loops

First let's look at Loop 1. It consists of the 1.5V power supply and the 100Ω resistor. We had previously calculated the current for this resistor as 15 mA, so its voltage, calculated using Ohm's Law, is 15 mA × 100Ω = 1.5V. The voltages in this loop are

$$(15\text{ mA} \times 100\Omega) - 1.5\text{V} = 1.5\text{V} - 1.5\text{V} = 0$$

The second loop consists of the 1.5V power supply and the 50Ω resistor. Since this resistor has a current of 30 mA, the voltage equation for this loop is

$$(30\text{ mA} \times 50\Omega) - 1.5\text{V} = 1.5\text{V} - 1.5\text{V} = 0$$

The third loop, consisting of the two resistors, might appear to fail under Kirchoff's Voltage Law since all voltage drops across resistors so far have been positive. If this is true for this loop, we would be adding two positive values and could not obtain a zero result. However, this is not the case here. Note the direction of the arrow for this loop. For Loop 1, the flow of the loop for the 100Ω resistor goes in the opposite direction of the current flow. For this loop, the voltage across this resistor is treated as a negative value, and the loop equation becomes

$$-(15\text{ mA} \times 100\Omega) + (30\text{ mA} \times 50\Omega) = -1.5\text{V} + 1.5\text{V} = 0$$