“ Basic Circuit Analysis “

This course is designed for use as a textbook for a first course in basic circuit analysis for a first year mechanical engineers and can be used as well as other engineering and technology students. Emphasis is placed on the basic laws, theorems, and problem-solving techniques which are common to most courses.

Introduction

Technology is rapidly changing the way we do things; we now have computers in our homes, electronic control systems in our cars, cellular phones that can be used just about anywhere, robots that assemble products on production lines, and so on.

A first step to understanding these technologies is electric circuit theory. Circuit theory provides you with the knowledge of basic principles that you need to understand the behavior of electric and electronic devices, circuits, and systems. In this book, we develop and explore its basic ideas.

Circuit diagrams

Electric circuits are constructed using components such as batteries, switches, resistors, capacitors, transistors, interconnecting wires, etc. To represent these circuits on paper, diagrams are used. In this book, we use three types: block diagrams, schematic diagrams, and pictorials.

Block Diagrams

Block diagrams describe a circuit or system in simplified form. The overall problem is broken into blocks, each representing a portion of the system or circuit. Blocks are labelled to indicate what they do or what they contain, then interconnected to show their relationship to each other. General signal flow is usually from left to right and top to bottom. Figure 1–5, for example, represents an audio amplifier. Although you have not covered any of its circuits yet, you should be able to follow the general idea quite easily—sound is picked up by the microphone, converted to an electrical signal, amplified by a pair of amplifiers, then output to the speaker, where it is converted back to sound. A power supply energizes the system. The advantage of a block diagram is that it gives you the overall picture and helps you understand the general nature of a problem. However, it does not provide detail.

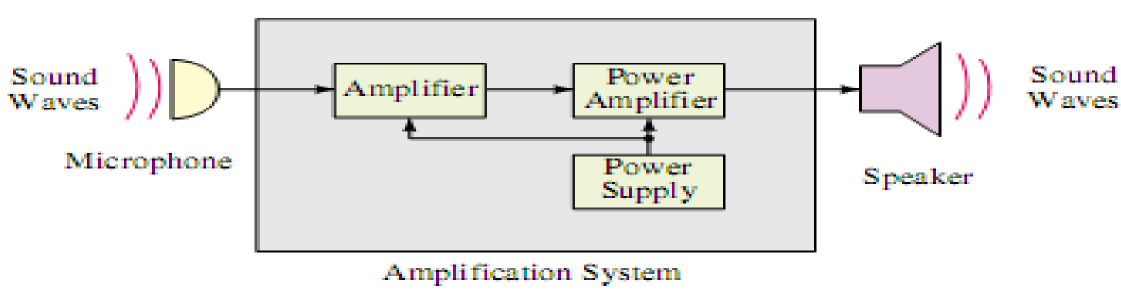


FIGURE 1–5 An example block diagram. Pictured is a simplified representation of an audio amplification system.

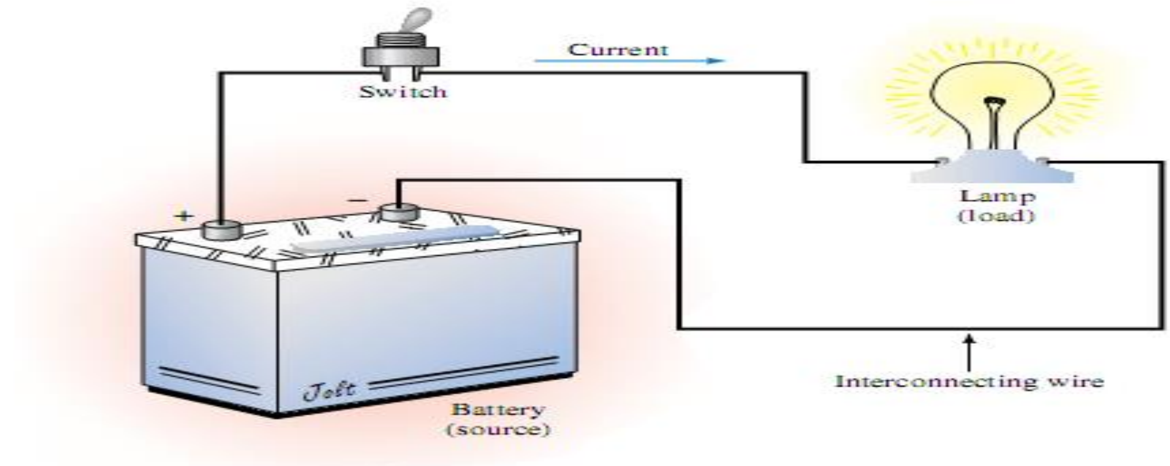


FIGURE 1–6 A pictorial diagram. The battery is referred to as a *source* while the lamp is referred to as a *load*. (The + and − on the battery are discussed in Chapter 2.)

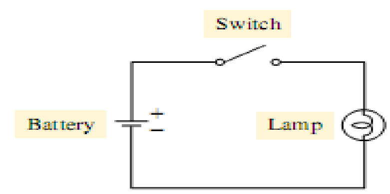
Pictorial Diagrams

Pictorial diagrams are one of the types of diagrams that provide detail. They help you visualize circuits and their operation by showing components as they actually appear. For example, the circuit of Figure 1–6 consists of a battery, a switch, and an electric lamp, all interconnected by wire. Operation is easy to visualize—when the switch is closed, the battery causes current in the circuit, which lights the lamp. The battery is referred to as the source and the lamp as the load.

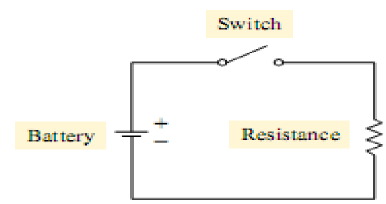
Schematic Diagrams

While pictorial diagrams help you visualize circuits, they are cumbersome to draw. **Schematic diagrams** get around this by using simplified, standard symbols to represent components; see Table 1–7. (The meaning of these symbols will be made clear as you progress through the book.) In Figure 1–7(a), for example, we have used some of these symbols to create a schematic for the circuit of Figure 1–6. Each component has been replaced by its corresponding circuit symbol.

When choosing symbols, choose those that are appropriate to the occasion. Consider the lamp of Figure 1–7(a). As we will show later, the lamp possesses a property called *resistance* that causes it to resist the passage of charge. When you wish to emphasize this property, use the resistance symbol rather than the lamp symbol, as in Figure 1–7(b).



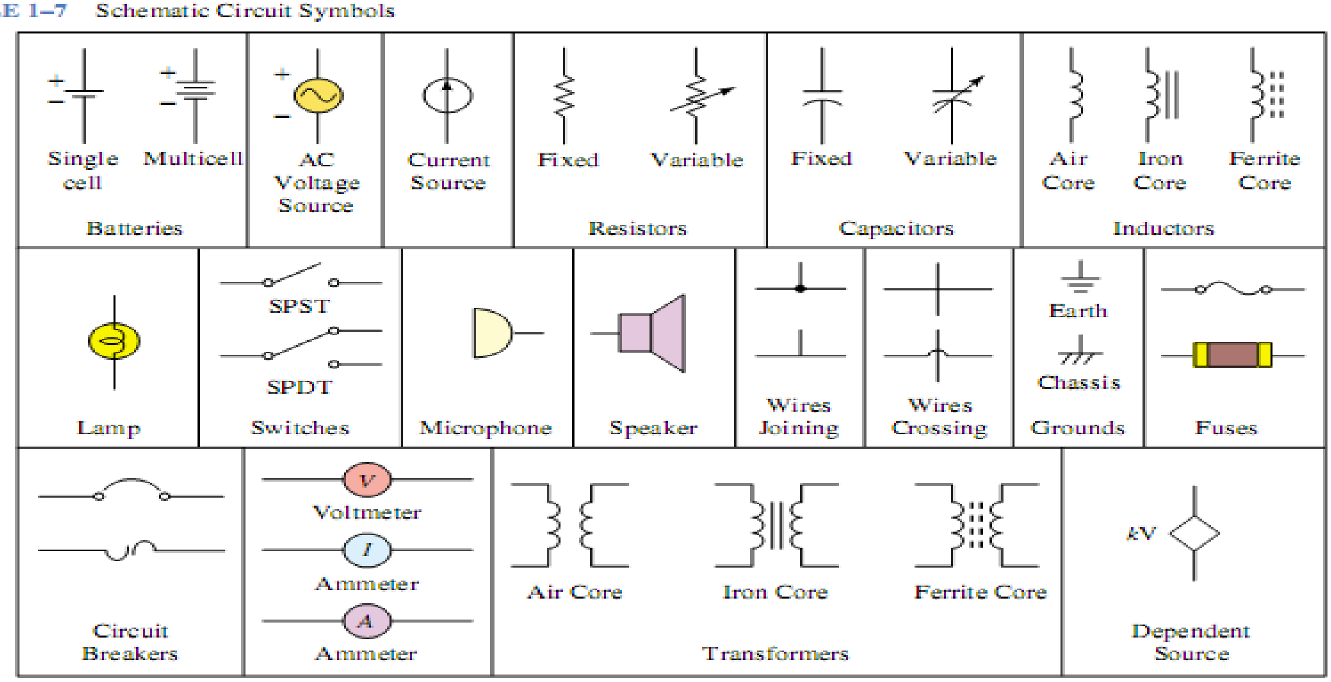
(a) Schematic using lamp symbol



(b) Schematic using resistance symbol

FIGURE 1–7 Schematic representation of Figure 1–6. The lamp has a circuit property called resistance (discussed in Chapter 3).

TABLE 1–7 Schematic Circuit Symbols



Example 1:

Consider the pictorial diagram of Figure 1—11. Using the appropriate symbols from Table 1—7, draw this in schematic form. Hint: In later chapters, there are many schematic circuits containing resistors, inductors, and capacitors. Use these as aids.

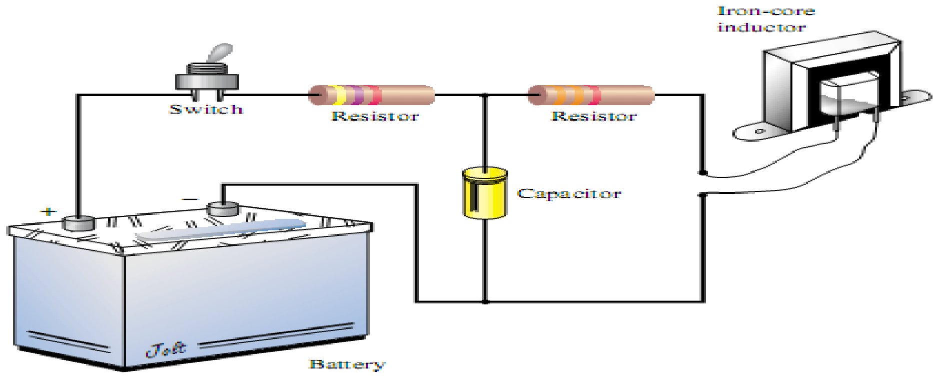


FIGURE 1—11

Voltage and Current

OBJECTIVES

After studying this chapter, you will be able to

- describe the makeup of an atom,
- explain the relationships between valence shells, free electrons, and conduction,
- describe the fundamental (coulomb) force within an atom, and the energy required to create free electrons,
- describe what ions are and how they are created,
- describe the characteristics of conductors, insulators, and semiconductors,
- describe the coulomb as a measure of charge,
- define voltage,
- describe how a battery "creates" voltage,
- explain current as a movement of charge and how voltage causes current in a conductor,

Circuit Breaker
Conductor
Coulomb
Coulomb's Law
Current
Electric Charge
Electron
Free Electrons
Fuse
Insulator
Ion
Neutron
Polarity
Potential Difference
Proton
Semiconductor
Shell
Switch
Valence
Volt

Conductors

Materials through which charges move easily are termed **conductors.** The most familiar examples are metals. Good metal conductors have large numbers of free electrons that are able to move about easily. In particular, silver, copper, gold, and aluminum are excellent conductors. Of these, copper is the most widely used. Not only is it an excellent conductor, it is inexpensive and easily formed into wire, making it suitable for a broad spectrum of applications ranging from common house wiring to sophisticated electronic equipment. Aluminum, although it is only about 60% as good a conductor as copper, is also used, mainly in applications where light weight is important, such as in overhead power transmission lines. Silver and gold are too expensive for general use. However, gold, because it oxidizes less than other materials, is used in specialized applications; for example, some critical electrical connectors use it because it makes a more reliable connection than other materials.

Insulators

Materials that do not conduct (e.g., glass, porcelain, plastic, rubber, and so on) are termed **insulators.** The covering on electric lamp cords, for example, is an insulator. It is used to prevent the wires from touching and to protect us from electric shock.

Insulators do not conduct because they have full or nearly full valence shells and thus their electrons are tightly bound. However, when high enough voltage is applied, the force is so great that electrons are literally torn from their parent atoms, causing the insulation to break down and conduction to occur. In air, you see this as an arc or flashover. In solids, charred insulation usually results.

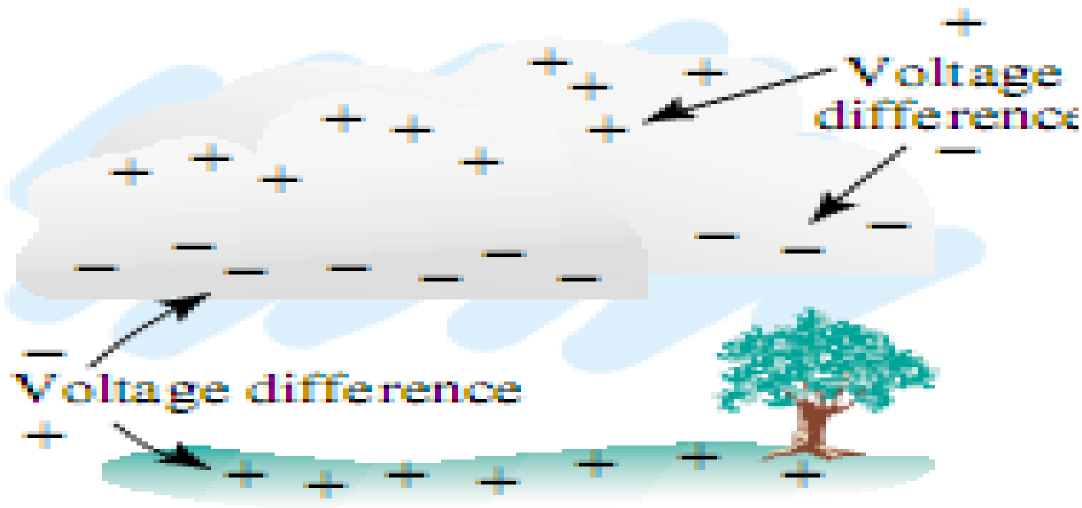
Semiconductors

Silicon and germanium (plus a few other materials) have half-filled valence shells and are thus neither good conductors nor good insulators. Known as **semiconductors,** they have unique electrical properties that make them important to the electronics industry. The most important material is silicon. It is used to make transistors, diodes, integrated circuits, and other electronic devices. Semiconductors have made possible personal computers, VCRs, portable CD players, calculators, and a host of other electronic products. You will study them in great detail in your electronics courses.

Voltage

When charges are detached from one body and transferred to another, a *potential difference* or *voltage* results between them. A familiar example is the voltage that develops when you walk across a carpet. Voltages in excess of ten thousand volts can be created in this way. (We will define the volt rigorously very shortly.) This voltage is due entirely to the separation of positive and negative charges.

Figure 2–7 illustrates another example. During electrical storms, electrons in thunderclouds are stripped from their parent atoms by the forces of turbulence and carried to the bottom of the cloud, leaving a deficiency of electrons (positive charge) at the top and an excess (negative charge) at the bottom. The force of repulsion then drives electrons away beneath the cloud, leaving the ground positively charged. Hundreds of millions of volts are created in this way. (This is what causes the air to break down and a lightning discharge to occur.)



Potential Energy

The concept of voltage is tied into the concept of potential energy. We therefore look briefly at energy.

In mechanics, potential energy is the energy that a body possesses because of its position. For example, a bag of sand hoisted by a rope over a pulley has the potential to do work when it is released. The amount of work that went into giving it this potential energy is equal to the product of force times the distance through which the bag was lifted (i.e., work equals force times distance).

In a similar fashion, work is required to move positive and negative charges apart. This gives them potential energy. To understand why, consider again the cloud of Figure 2–7. Assume the cloud is initially uncharged. Now assume a charge of Q electrons is moved from the top of the cloud to the bottom. The positive charge left at the top of the cloud exerts a force on the electrons that tries to pull them back as they are being moved away. Since the electrons are being moved against this force, work (force times distance) is required. Since the separated charges experience a force to return to the top of the cloud, they have the potential to do work if released, i.e., they possess potential energy.

Definition of Voltage: The Volt

In electrical terms, a difference in potential energy is defined as **voltage.** In general, the amount of energy required to separate charges depends on the voltage developed and the amount of charge moved. By definition, *the voltage between two points is one volt if it requires one joule of energy to move one coulomb of charge from one point to the other.* In equation form,

$$V = \frac{W}{Q} \quad \text{[volts, V]} \tag{2–2}$$

where W is energy in joules, Q is charge in coulombs, and V is the resulting voltage in volts.

Note carefully that voltage is defined between points. For the case of the battery, for example, voltage appears between its terminals. Thus, voltage does not exist at a point by itself; it is always determined with respect to some other point. (For this reason, voltage is also called **potential difference.** We often use the terms interchangeably.) Note also that, although we considered static electricity in developing the energy argument, the same conclusion results regardless of how you separate the charges; this may be by chemical means as in a battery, by mechanical means as in a generator, by photoelectric means as in a solar cell, and so on.

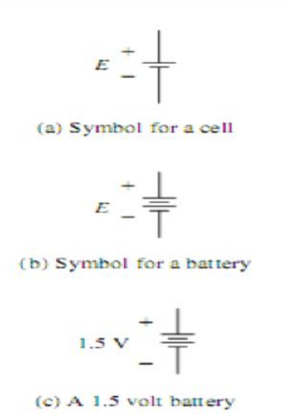
Alternate arrangements of Equation 2–2 are useful:

$$W = QV \quad \text{[joules, J]}$$

$$Q = \frac{W}{V} \quad \text{[coulombs, C]}$$

Symbol for DC Voltage Sources

Consider again Figure 2–1. The battery is the source of electrical energy that moves charges around the circuit. This movement of charges, as we will soon see, is called an electric current. Because one of the battery's terminals is always positive and the other is always negative, current is always in the same direction. Such a unidirectional current is called **dc** or **direct current,** and the battery is called a **dc source.** Symbols for dc sources are shown in Figure 2–9. The long bar denotes the positive terminal. On actual batteries, the positive terminal is usually marked POS (+) and the negative terminal NEG (−).



2.4 Current

Earlier, you learned that there are large numbers of free electrons in metals like copper. These electrons move randomly throughout the material (Figure 2–6), but their net movement in any given direction is zero.

Assume now that a battery is connected as in Figure 2–10. Since electrons are attracted by the positive pole of the battery and repelled by the negative pole, they move around the circuit, passing through the wire, the lamp, and the battery. This movement of charge is called an **electric current.** The more electrons per second that pass through the circuit, the greater is the current. Thus, current is the *rate of flow* (or *rate of movement*) of charge.

The Ampere

Since charge is measured in coulombs, its rate of flow is coulombs per second. In the SI system, one coulomb per second is defined as one **ampere** (commonly abbreviated A). From this, we get that *one ampere is the current in a circuit when one coulomb of charge passes a given point in one second* (Figure 2–10). The symbol for current is I. Expressed mathematically,

$$I = \frac{Q}{t} \quad \text{[amperes, A]} \tag{2–5}$$

where Q is the charge (in coulombs) and t is the time interval (in seconds) over which it is measured. *In Equation 2–5, it is important to note that t does not represent a discrete point in time but is the interval of time during which the transfer of charge occurs.* Alternate forms of Equation 2–5 are

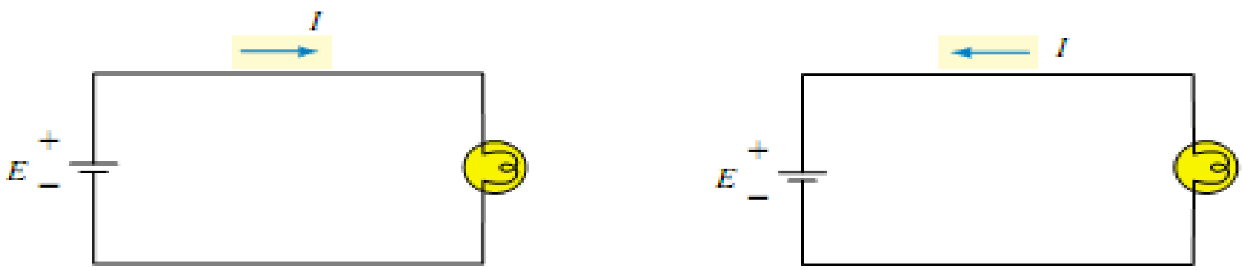
$$Q = It \quad \text{[coulombs, C]} \tag{2–6}$$

and

$$t = \frac{Q}{I} \quad \text{[seconds, s]} \tag{2–7}$$

Current Direction

In the early days of electricity, it was believed that current was a movement of positive charge and that these charges moved around the circuit from the positive terminal of the battery to the negative as depicted in Figure 2–11(a). Based on this, all the laws, formulas, and symbols of circuit theory were developed. (We now refer to this direction as the **conventional current direction.**) After the discovery of the atomic nature of matter, it was learned that what actually moves in metallic conductors are electrons and that they move through the circuit as in Figure 2–11(b). This direction is called the **electron flow direction.** However, because the conventional current direction was so well established, most users stayed with it. We do likewise. Thus, *in this book, the conventional direction for current is used.*



(a) Conventional current direction (b) Electron flow direction

Battery Capacity

Batteries run down under use. Their **capacity** is specified in **ampere-hours** (Ah). The ampere-hour rating of a battery is equal to the product of its current drain times the length of time that you can expect to draw the specified current before the battery becomes unusable. For example, a battery rated at 200 Ah can theoretically supply 20 A for 10 h, or 5 A for 40 h, etc. The relationship between capacity, life, and current drain is

$$\text{life} = \frac{\text{capacity}}{\text{current drain}} \tag{2–8}$$

The capacity of batteries is not a fixed value as suggested above but is affected by discharge rates, operating schedules, temperature, and other factors. At best, therefore, capacity is an estimate of expected life under certain conditions. Table 2–1 illustrates approximate service capacities for several sizes of carbon-zinc batteries at three values of current drain at 21°C. Under the conditions listed, the AA cell has a capacity of (3 mA)(450 h) = 1350 mAh at a drain of 3 mA, but its capacity decreases to (30 mA)(32 h) = 960 mAh at a drain of 30 mA. Figure 2–14 shows a typical variation of capacity of a Ni-Cad battery with changes in temperature.

TABLE 2–1 Capacity-Current Drain of Selected Carbon-Zinc Cells

Cell	Starting Drain (mA)	Service Life (h)
AA	3.0	450
	15.0	80
	30.0	32
C	5.0	520
	25.0	115
	50.0	53
D	10.0	525
	50.0	125
	100.0	57

Courtesy T. R. Crompton, *Battery Reference Book*, Butterworths & Co. (Publishers) Ltd, 1990.

Other Characteristics

Because batteries are not perfect, their terminal voltage drops as the amount of current drawn from them increases. (This issue is considered in Chapter 5.) In addition, battery voltage is affected by temperature and other factors that affect their chemical activity. However, these factors are not considered in this book.

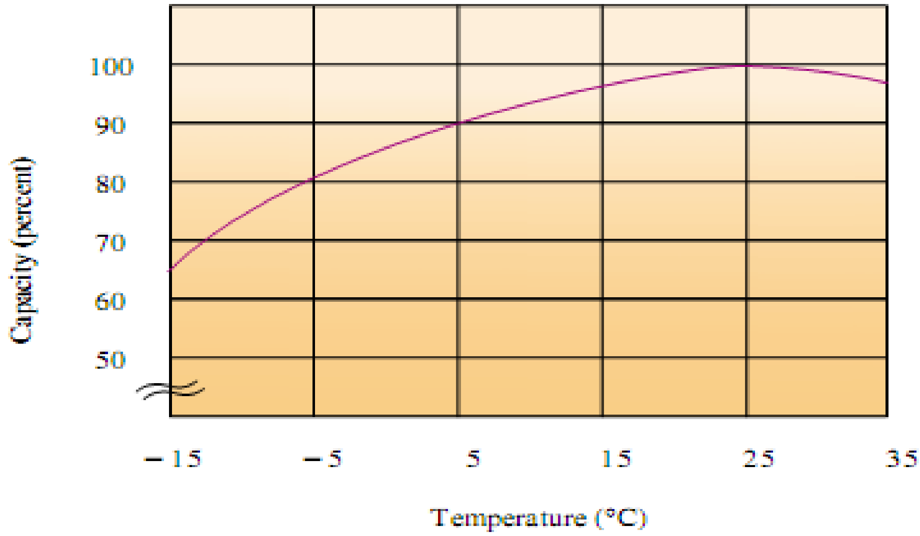


FIGURE 2–14 Typical variation of capacity versus temperature for a Ni-Cad battery.

EXAMPLE 2–4 Assume the battery of Figure 2–14 has a capacity of 240 Ah at 25°C. What is its capacity at −15°C?

Solution From the graph, capacity at −15°C is down to 65%. Thus, capacity = 0.65 × 240 = 156 Ah.

(a) Analog multimeter.

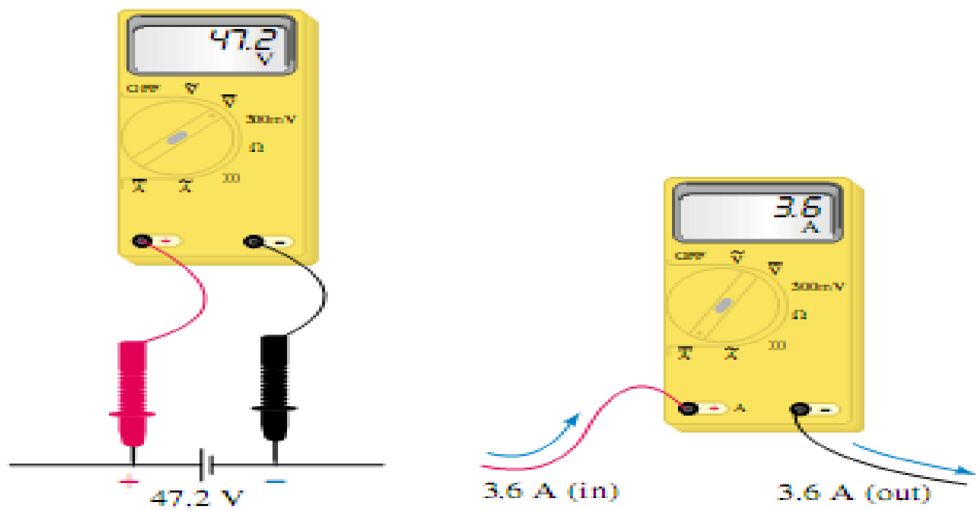
(b) Hand-held digital multimeter (DMM). (*Reproduced with permission from the John Fluke Mfg. Co., Inc.*)

Voltage Select

When set to dc voltage ($\overline{\text{V}}$), the meter measures the dc voltage between its VΩ (or +) and COM (or −) terminals. In Figure 2–21(a), for example, with its leads placed across a 47.2-volt source, the instrument indicates 47.2 V.

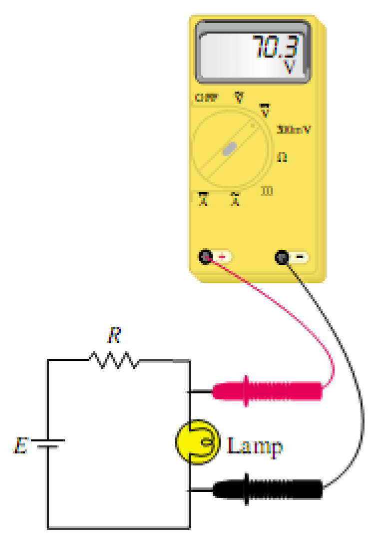
Current Select

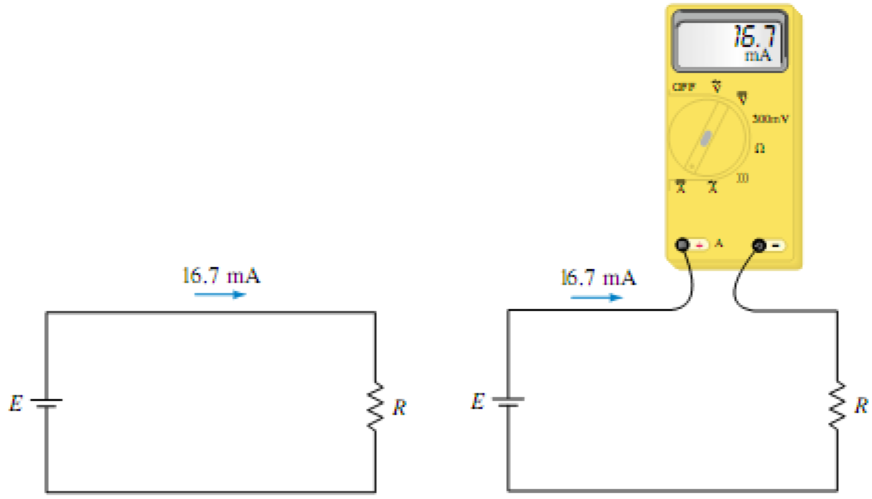
When set to dc current ($\overline{\text{A}}$), the multimeter measures the dc current passing through it, i.e., the current entering its A (or +) terminal and leaving its COM (or −) terminal. In Figure 2–21(b), the meter measures and displays a current of 3.6 A.



(a) Set selector to $\overline{\text{V}}$ to measure dc voltage

(b) Set selector to $\overline{\text{A}}$ to measure dc current





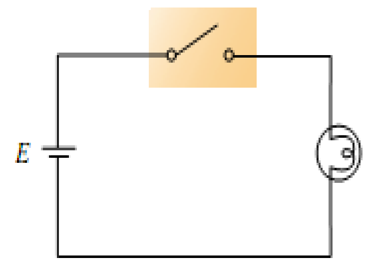
(a) Current to be measured (b) Ammeter correctly inserted

2.7 Switches, Fuses, and Circuit Breakers

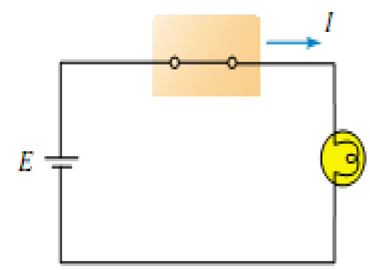
Switches

The most basic switch is a single-pole, single-throw (SPST) switch as shown in Figure 2–27. With the switch open, the current path is broken and the lamp is off; with it closed, the lamp is on. This type of switch is used, for example, for light switches in homes.

Figure 2–28(a) shows a single-pole, double-throw (SPDT) switch. Two of these switches may be used as in (b) for two-way control of a light. This type of arrangement is sometimes used for stairway lights; you can turn the light on or off from either the bottom or the top of the stairs.

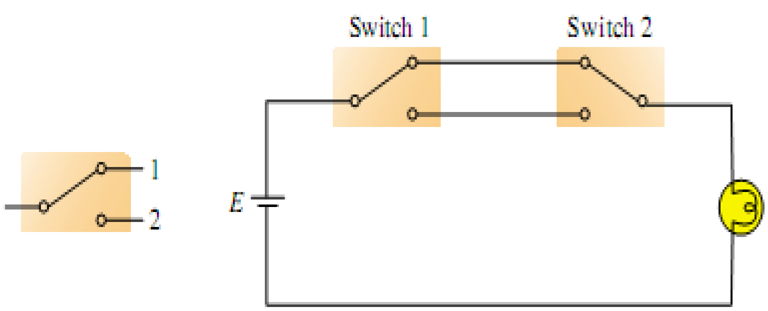


(a) Open



(b) Closed

FIGURE 2–27 Single-pole, single-throw (SPST) switch.



(a) SPDT switch (b) Two-way switch control of a light

FIGURE 2–28 Single-pole, double-throw (SPDT) switch.

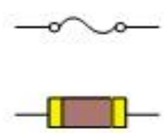
Fuses and Circuit Breakers

Fuses and circuit breakers are used to protect equipment or wiring against excessive current. For example, in your home, if you connect too many appliances to an outlet, the fuse or circuit breaker in your electrical panel "blows." This opens the circuit to protect against overloading and possible fire. Fuses and circuit breakers may also be installed in equipment such as your automobile to protect against internal faults. Figure 2–29 shows a variety of fuses and breakers.

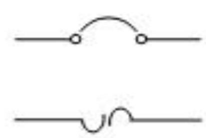
Fuses use a metallic element that melts when current exceeds a preset value. Thus, if a fuse is rated at 3 A, it will "blow" if more than 3 amps passes through it. Fuses are made as fast-blow and slow-blow types. Fast-blow fuses are very fast; typically, they blow in a fraction of a second. Slow-blow fuses, on the other hand, react more slowly so that they do not blow on small, momentary overloads.

Circuit breakers work on a different principle. When the current exceeds the rated value of a breaker, the magnetic field produced by the excessive current operates a mechanism that trips open a switch. After the fault or overload condition has been cleared, the breaker can be reset and used again. Since they are mechanical devices, their operation is slower than that of a fuse; thus, they do not "pop" on momentary overloads as, for example, when a motor is started.

(a) A variety of fuses and circuit breakers.



(b) Fuse symbols



(c) Circuit breaker symbols

2–29 Fuses and circuit breakers.

Discussion

42. The digital voltmeter of Figure 2–31 has autopolarity. For each case, determine its reading.

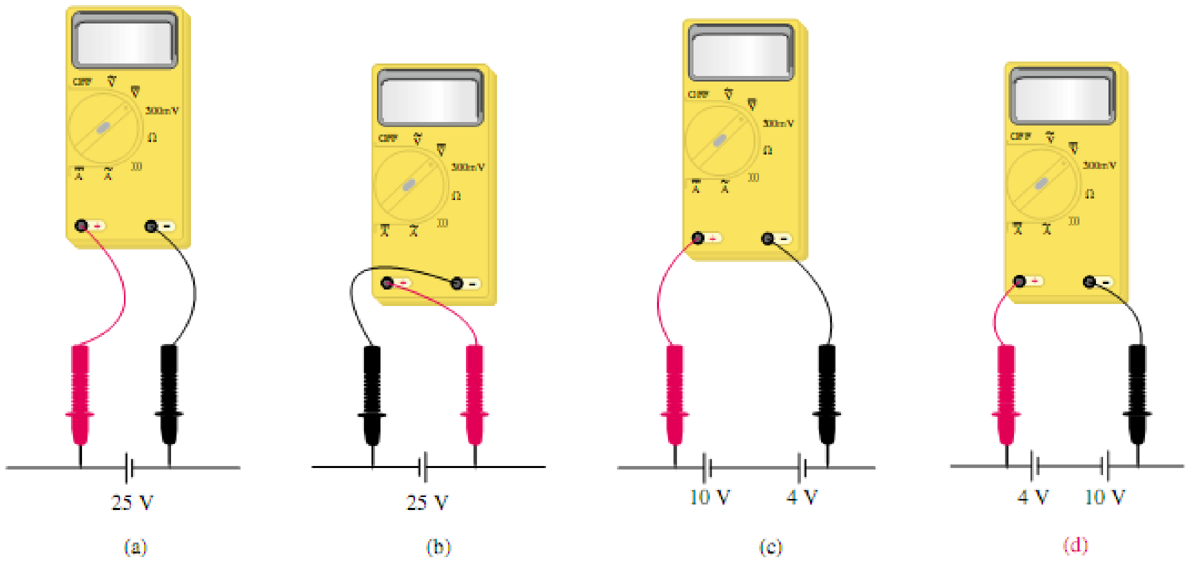


FIGURE 2–31

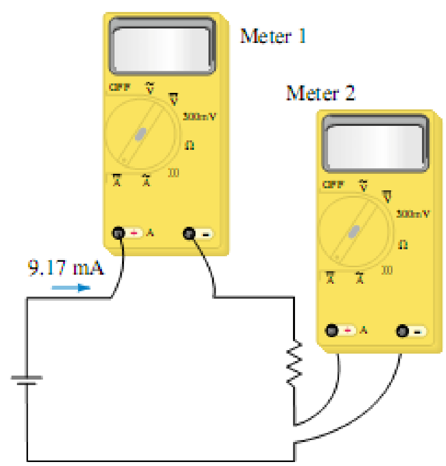


FIGURE 2–32

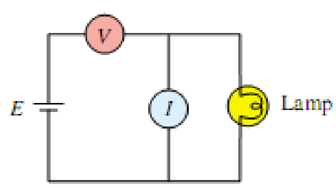


FIGURE 2–33 What is wrong here?

2.7 Switches, Fuses, and Circuit Breakers

46. It is desired to control a light using two switches as indicated in Table 2–2. Draw the required circuit.

47. Fuses have a current rating so that you can select the proper size to protect a circuit against overcurrent. They also have a voltage rating. Why? Hint: Read the section on insulators, i.e., Section 2.1.

TABLE 2–2

Switch 1	Switch 2	Lamp
Open	Open	Off
Open	Closed	On
Closed	Open	On
Closed	Closed	On