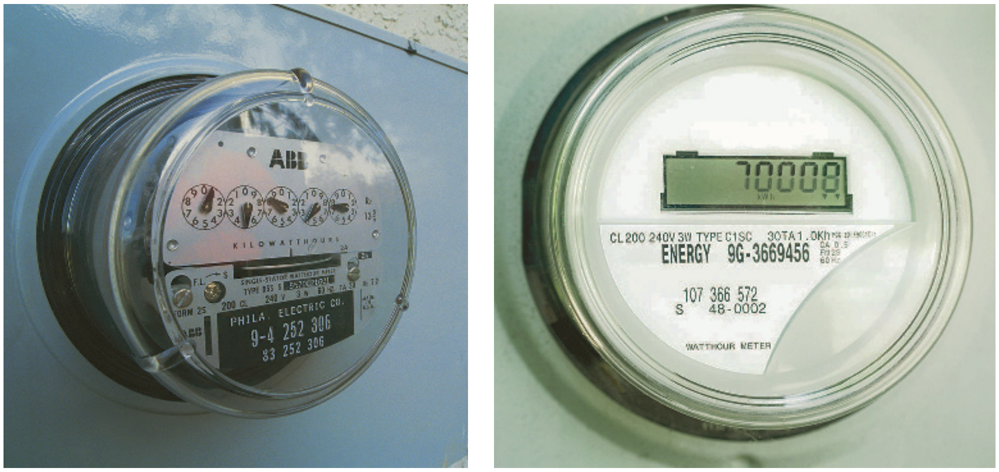


Figure 9.23

Electric meters used to measure home energy consumption (*Left*, Comstock/Punchstock; *right*, Robert Llewllyn/ Photolibrary/Getty Images).

The energy consumption is typically measured by meters, of the form shown in **Fig. 9.23**, which are a familiar sight on the outside of our homes.

9.9 Safety Considerations

Although this book is concerned primarily with the theory of circuit analysis, we recognize that, by this point in their study, most students will have begun to relate the theory to the electrical devices and systems that they encounter in the world around them. Thus, it seems advisable to depart briefly from the theoretical and spend some time discussing the very practical and important subject of safety. Electrical safety is a very broad and diverse topic that would require several volumes for a comprehensive treatment. Instead, we will limit our discussion to a few introductory concepts and illustrate them with examples.

It would be difficult to imagine that anyone in our society could have reached adolescence without having experienced some form of electrical shock. Whether that shock was from a harmless electrostatic discharge or from accidental contact with an energized electrical circuit, the response was probably the same—an immediate and involuntary muscular reaction. In either case, the cause of the reaction is current flowing through the body. The severity of the shock depends on several factors, the most important of which are the magnitude, the duration, and the pathway of the current through the body.

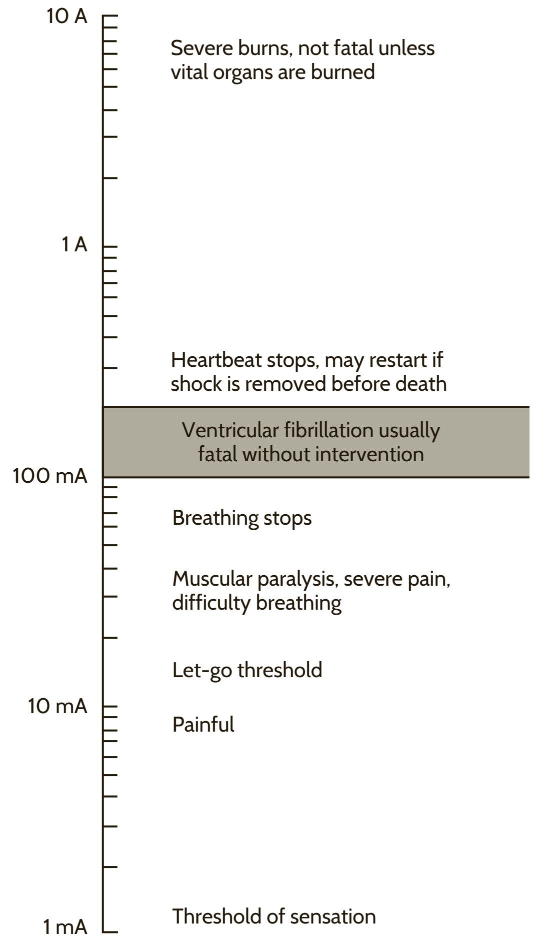
The effect of electrical shock varies widely from person to person. **Figure 9.24** shows the general reactions that occur as a result of 60-Hz ac current flow through the body from hand to hand, with the heart in the conduction pathway. Observe that there is an intermediate range of current, from about 0.1 to 0.2 A, which is most likely to be fatal. Current levels in this range are apt to produce ventricular fibrillation, a disruption of the orderly contractions of the heart muscle. Recovery of the heartbeat generally does not occur without immediate medical intervention. Current levels above that fatal range tend to cause the heart muscle to contract severely, and if the shock is removed soon enough, the heart may resume beating on its own.

The voltage required to produce a given current depends on the quality of the contact to the body and the impedance of the body between the points of contact. The electrostatic voltage such as might be produced by sliding across a car seat on a dry winter day may be on the order of 20,000 to 40,000 V, and the current surge on touching the door handle, on the order of 40 A. However, the pathway for the current flow is mainly over the body surface, and its duration is for only a few microseconds. Although that shock could be disastrous for some electronic components, it causes nothing more than mild discomfort and aggravation to a human being.

Electrical appliances found about the home typically require 120 or 240 V rms for operation. Although the voltage level is small compared with that of the electrostatic shock, the potential for harm to the individual and to property is much greater. Accidental contact is more apt to result in current flow either from hand to hand or from hand to foot—either of which will subject the heart to shock. Moreover, the relatively slowly changing (low frequency) 60-Hz current tends to penetrate more deeply into the body as opposed to remaining on the surface as a rapidly changing (high frequency) current would tend to do. In addition, the energy source has the capability of sustaining a current flow without depletion. Thus, subsequent discussion will concentrate primarily on hazards associated with the 60-Hz ac power system.

Figure 9.24

Effects of electrical shock (From C. F. Dalziel and W. R. Lee, "Lethal Electric Currents, "*IEEE Spectrum*, February 1969, pp. 44–50; and C. F. Dalziel, "Electric Shock Hazard, "*IEEE Spectrum*, February 1972, pp. 41–50).



The single-phase three-wire system introduced earlier is commonly, though not exclusively, used for electrical power distribution in residences. Two important aspects of this or any system that relate to safety were not mentioned earlier: circuit fusing and grounding.

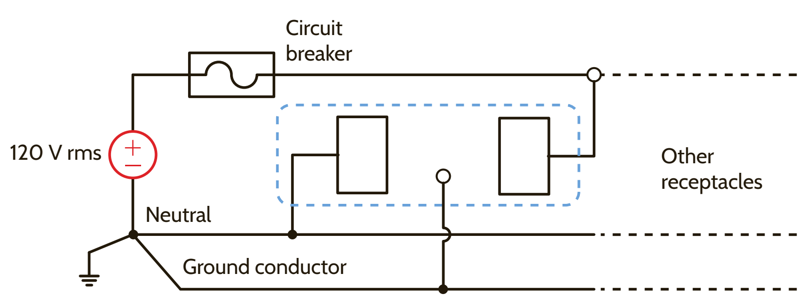
Each branch circuit, regardless of the type of load it serves, is protected from excessive current flow by circuit breakers or fuses. Receptacle circuits are generally limited to 20 amps and lighting circuits to 15 amps. Clearly, these cannot protect persons from lethal shock. The primary purpose of these current-limiting devices is to protect equipment.

The neutral conductor of the power system is connected to ground (earth) at a multitude of points throughout the system and, in particular, at the service entrance to the residence. The connection to earth may be by way of a driven ground rod or by contact to a cold water pipe of a buried metallic water system. The 120-V branch circuits radiating from the distribution panel (fuse box) generally consist of three conductors rather than only two, as was shown in Fig. 9.21. The third conductor is the ground wire, as shown in Fig. 9.25.

The ground conductor may appear to be redundant, since it plays no role in the normal operation of a load that might be connected to the receptacle. Its role is illustrated by the following example.

Figure 9.25

A household receptacle.



EXAMPLE 9.16

Joe has a workshop in his basement where he uses a variety of power tools such as drills, saws, and sanders. The basement floor is concrete, and being below ground level, it is usually damp. Damp concrete is a relatively good conductor. Unknown to Joe, the insulation on a wire in his electric drill has been nicked, and the wire is in contact with (or shorted to) the metal case of the drill, as shown in Fig. 9.26. Is Joe in any danger when using the drill?

SOLUTION

Without the ground conductor connected to the metal case of the tool, Joe would receive a severe, perhaps fatal, shock when he attempted to use the drill. The voltage between his hand and his feet would be 120 V, and the current through his body would be limited by the resistance of his body and of the concrete floor. Typically, the circuit breakers would not operate. However, if the ground conductor is present and properly connected to the drill case, the case remains at ground potential, the 120-V source becomes shorted to ground, the circuit breaker operates, and Joe lives to drill another hole.

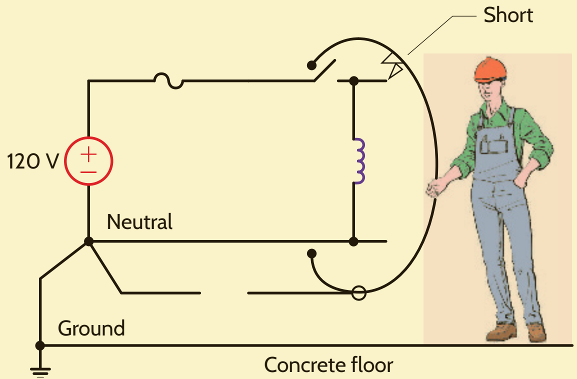


Figure 9.26
Faulty circuit, when the case of the tool is not grounded through the power cord.

It was mentioned earlier that the circuit breaker or fuse cannot provide effective protection against shock. There is, however, a special type of device called a ground-fault interrupter (GFI) that can provide protection for personnel. This device detects current flow outside the normal circuit. Consider the circuit of Fig. 9.26. In the normal safe operating condition, the current in the neutral conductor must be the same as that in the line conductor. If at any time the current in the line does not equal the current in the neutral, then a secondary path has somehow been established, creating an unsafe condition. This secondary path is called a fault. For example, the fault path in Fig. 9.26 is through Joe and the concrete floor. The GFI detects this fault and opens the circuit in response. Its principle of operation is illustrated by the following example.

EXAMPLE 9.17

Let us describe the operation of a GFI.

SOLUTION

Consider the action of the magnetic circuit in Fig. 9.27. Under normal operating conditions, i_1 and i_2 are equal, and if the coils in the neutral and line conductors are identical, as we learned in basic physics, the magnetic flux in the core will be zero. Consequently, no voltage will be induced in the sensing coil.

If a fault should occur at the load, current will flow in the ground conductor and perhaps in the earth; thus, i_1 and i_2 will no longer be equal, the magnetic flux will not be zero, and a voltage will be induced in the sensing coil. That voltage can be used to activate a circuit breaker. This is the essence of the GFI device.

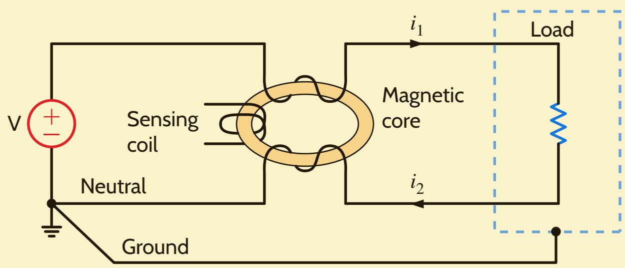


Figure 9.27
Ground-fault interrupter circuit.

Ground-fault interrupters are available in the form of circuit breakers and also as receptacles. They are now required in branch circuits that serve outlets in areas such as bathrooms, basements, garages, and outdoor sites. The devices will operate at ground-fault currents on the order of a few milliamperes. Unfortunately, the GFI is a relatively new device, and electrical code requirements are generally not retroactive. Thus, few older residences have them.

Requirements for the installation and maintenance of electrical systems are meticulously defined by various codes that have been established to provide protection of personnel and property. Installation, alteration, or repair of electrical devices and systems should be undertaken only by qualified persons. The subject matter that we study in circuit analysis does not provide that qualification.

The following examples illustrate the potential hazards that can be encountered in a variety of everyday situations. We begin by revisiting a situation described in a previous example.

EXAMPLE 9.18

Suppose that a man is working on the roof of a mobile home with a hand drill. It is early in the day, the man is barefoot, and dew covers the mobile home. The ground prong on the electrical plug of the drill has been removed. Will the man be shocked if the "hot" electrical line shorts to the case of the drill?

SOLUTION

To analyze this problem, we must construct a model that adequately represents the situation described. In his book *Medical Instrumentation* (Boston: Houghton Mifflin, 1978), John G. Webster suggests the following values for resistance of the human body: $R_{\text{skin}}(\text{dry}) = 15\ \text{k}\Omega$, $R_{\text{skin}}(\text{wet}) = 150\ \Omega$, $R_{\text{limb}}(\text{arm or leg}) = 100\ \Omega$, and $R_{\text{trunk}} = 200\ \Omega$.

The network model is shown in **Fig. 9.28**. Note that since the ground line is open-circuited, a closed path exists from the hot wire through the short, the human body, the mobile home, and the ground. For the conditions stated previously, we assume that the surface contact resistances R_{sc_1} and R_{sc_2} are 150 Ω each. The body resistance, R_{body}, consisting of arm, trunk, and leg, is 400 Ω. The mobile home resistance is assumed to be zero, and the ground resistance, R_{gnd}, from the mobile home ground to the actual source ground is assumed to be 1 Ω. Therefore, the magnitude of the current through the body from hand to foot would be

$$\begin{aligned}\mathbf{I}_{\text{body}} &= \frac{120}{R_{sc_1} + R_{\text{body}} + R_{sc_2} + R_{\text{gnd}}}\\ &= \frac{120}{701}\\ &= 171\ \text{mA}\end{aligned}$$

A current of this magnitude can easily cause heart failure.

Additional protection would be provided if the circuit breaker were a ground-fault interrupter.

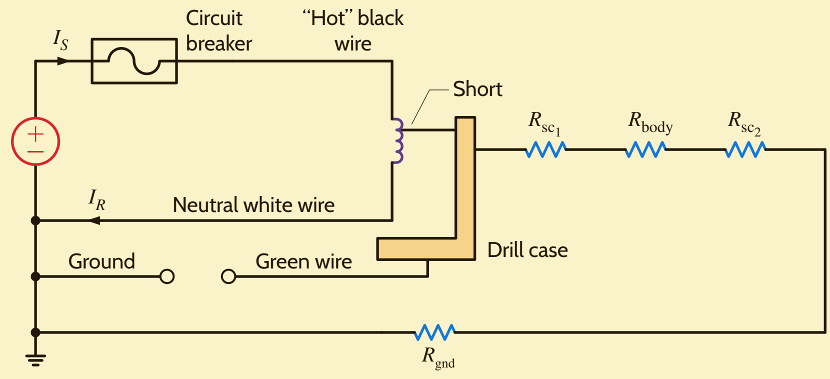


Figure 9.28 Model for Example 9.18.

EXAMPLE 9.19

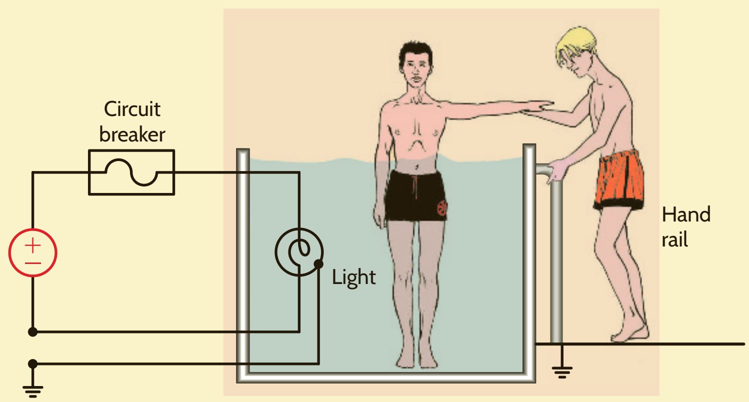
Two boys are playing basketball in their backyard. To cool off, they decide to jump into their pool. The pool has a vinyl lining, so the water is electrically insulated from the earth. Unknown to the boys, there is a ground fault in one of the pool lights. One boy jumps in and while standing in the pool with water up to his chest, reaches up to pull in the other boy, who is holding onto a grounded hand rail, as shown in Fig. 9.29a. What is the impact of this action?

SOLUTION

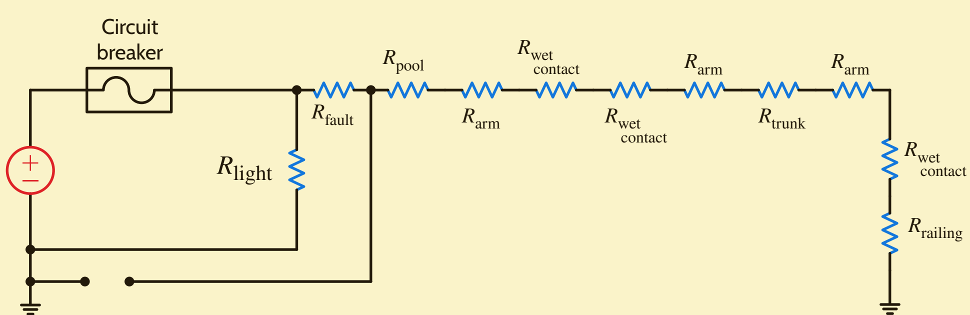
The action in Fig. 9.29a is modeled as shown in Fig. 9.29b. Note that since a ground fault has occurred, there exists a current path through the two boys. Assuming that the fault, pool, and railing resistances are approximately zero, the magnitude of the current through the two boys would be

$$\begin{aligned}\mathbf{I} &= \frac{120}{(3R_{\text{arm}}) + 3(3R_{\text{wet contact}}) + R_{\text{trunk}}}\\ &= \frac{120}{950}\\ &= 126 \text{ mA}\end{aligned}$$

This current level would cause severe shock in both boys. The boy outside the pool could experience heart failure.



(a)



(b)

Figure 9.29 Diagrams used in Example 9.19.

EXAMPLE 9.20

A patient in a medical laboratory has a muscle stimulator attached to her left forearm. Her heart rate is being monitored by an EKG machine with two differential electrodes over the heart and the ground electrode attached to her right ankle. This activity is illustrated in Fig. 9.30a. The stimulator acts as a current source that drives 150 mA through the muscle from the active electrode to the passive electrode. If the laboratory technician mistakenly decides to connect the passive electrode of the stimulator to the ground electrode of the EKG system to achieve a common ground, is there any risk?

SOLUTION When the passive electrode of the stimulator is connected to the ground electrode of the EKG system, the equivalent network in Fig. 9.30b illustrates the two paths for the stimulator current: one through half an arm and the other through half an arm and the body. Using current division, the body current is

$$\mathbf{I}_{body} = \frac{(150)(10^{-3})(50)}{50 + 50 + 200 + 100}$$
$$= 19 \text{ mA}$$

Therefore, a dangerously high level of current will flow from the stimulator through the body to the EKG ground.

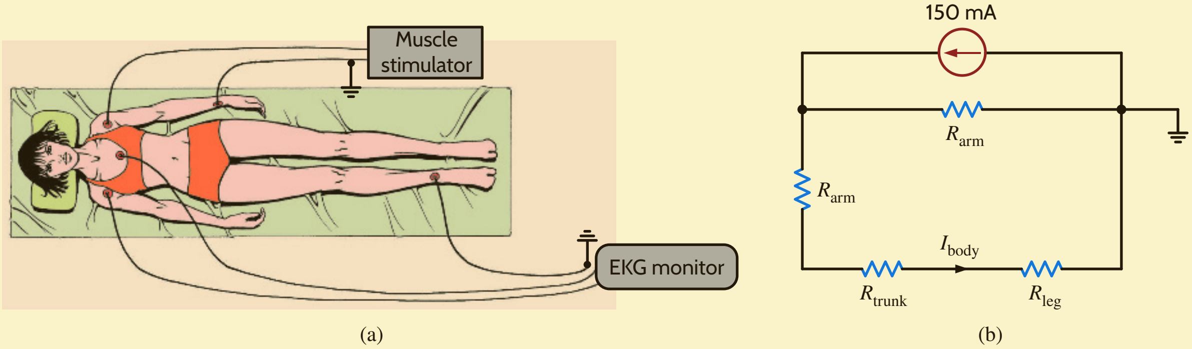


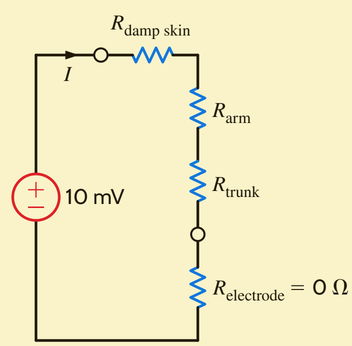
Figure 9.30
Diagrams used in Example 9.20.

EXAMPLE 9.21

A cardiac care patient with a pacing electrode has ignored the hospital rules and is listening to a cheap stereo. The stereo has an amplified 60-Hz hum that is very annoying. The patient decides to dismantle the stereo partially in an attempt to eliminate the hum. In the process, while he is holding one of the speaker wires, the other touches the pacing electrode. What are the risks in this situation?

SOLUTION Let us suppose that the patient's skin is damp and that the 60-Hz voltage across the speaker wires is only 10 mV. Then the circuit model in this case would be as shown in Fig. 9.31.

Figure 9.31
Circuit model for Example 9.21.



The current through the heart would be

$$I = \frac{(10)(10^{-3})}{150 + 100 + 200}$$
$$= 22.2\ \mu\text{A}$$

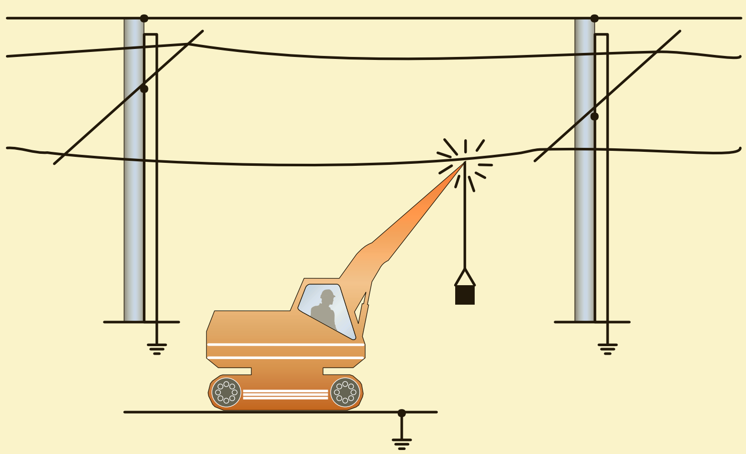
It is known that 10 μA delivered directly to the heart is potentially lethal.

EXAMPLE 9.22

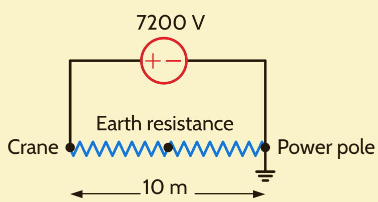
While maneuvering in a muddy area, a crane operator accidentally touched a high-voltage line with the boom of the crane, as illustrated in **Fig. 9.32a**. The line potential was 7200 V. The neutral conductor was grounded at the pole. When the crane operator realized what had happened, he jumped from the crane and ran in the direction of the pole, which was approximately 10 m away. He was electrocuted as he ran. Can we explain this very tragic accident?

SOLUTION

The conditions depicted in Fig. 9.32a can be modeled as shown in **Fig. 9.32b**. The crane was at 7200 V with respect to earth. Therefore, a gradient of 720 V/m existed along the earth between the crane and the power pole. This earth between the crane and the pole is modeled as a resistance. If the man's stride was about 1 m, the difference in potential between his feet was approximately 720 V. A man standing in the same area with his feet together was unharmed.



(a)



(b)

Figure 9.32 Illustrations used in Example 9.22.

The examples of this section have been provided in an attempt to illustrate some of the potential dangers that exist when working or playing around electric power. In the worst case, failure to prevent an electrical accident can result in death. However, even nonlethal electrical contacts can cause such things as burns or falls. Therefore, we must always be alert to ensure not only our own safety, but also that of others who work and play with us.

The following guidelines will help minimize the chances of injury:

HINT Safety guidelines.

1. Avoid working on energized electrical systems.
2. Always assume that an electrical system is energized unless you can absolutely verify that it is not.
3. Never make repairs or alterations that are not in compliance with the provisions of the prevailing code.
4. Do not work on potentially hazardous electrical systems alone.
5. If another person is "frozen" to an energized electrical circuit, deenergize the circuit, if possible. If that cannot be done, use nonconductive material such as dry wooden boards, sticks, belts, and articles of clothing to separate the body from the contact. Act quickly but take care to protect yourself.
6. When handling long metallic equipment, such as ladders, antennas, and so on, outdoors, be continuously aware of overhead power lines and avoid any possibility of contact with them.

LEARNING ASSESSMENT

E9.22 A woman is driving her car in a violent rainstorm. While she is waiting at an intersection, a power line falls on her car and makes contact. The power line voltage is 7200 V.

(a) Assuming that the resistance of the car is negligible, what is the potential current through her body if, while holding the door handle with a dry hand, she steps out onto the wet ground?

(b) If she remained in the car, what would happen?

ANSWER:

(a) $\mathbf{I}$ = 463 mA, extremely dangerous;

(b) She should be safe.

Safety when working with electric power must always be a primary consideration. Regardless of how efficient or expedient an electrical network is for a particular application, it is worthless if it is also hazardous to human life.

The safety device shown in Fig. 9.33, which is also used for troubleshooting, is a proximity-type sensor that will indicate whether a circuit is energized by simply touching the conductor on the outside of the insulation. This device is typically carried by all electricians and is helpful when working on electric circuits.

In addition to the numerous deaths that occur each year due to electrical accidents, fire damage that results from improper use of electrical wiring and distribution equipment amounts to millions of dollars per year.

To prevent loss of life and damage to property, very detailed procedures and specifications have been established for the construction and operation of electrical systems to ensure their safe operation. The *National Electrical Code* ANSI C1 (ANSI—American National Standards Institute) is the primary guide. There are other codes, however: for example, the National Electric Safety Code, ANSI C2, which deals with safety requirements for public utilities. Underwriters Laboratory (UL) tests all types of devices and systems to ensure that they are safe for use by the general public. We find the UL label on all types of electrical equipment that is used in the home, such as appliances and extension cords.

Electric energy plays a central role in our lives. It is extremely important to our general health and well-being. However, if not properly used, it can be lethal.

Figure 9.33

A modern safety or trouble-shooting device (Reproduced with Permission, Fluke Corporation).