QUESTIONS

1. Explain the difference between load resistance in a circuit and internal resistance in a battery.
2. Under what condition does the potential difference across the terminals of a battery equal its emf? Can the terminal voltage ever exceed the emf? Explain.
3. Is the direction of current through a battery always from the negative terminal to the positive terminal? Explain.
4. How would you connect resistors so that the equivalent resistance is larger than the greatest individual resistance? Give an example involving three resistors.
5. How would you connect resistors so that the equivalent resistance is smaller than the least individual resistance? Give an example involving three resistors.
6. Given three lightbulbs and a battery, sketch as many different electric circuits as you can.
7. When resistors are connected in series, which of the following would be the same for each resistor: potential difference, current, power?
8. When resistors are connected in parallel, which of the following would be the same for each resistor: potential difference, current, power?
9. What advantage might there be in using two identical resistors in parallel connected in series with another identical parallel pair, rather than just using a single resistor?
10. An incandescent lamp connected to a 120-V source with a short extension cord provides more illumination than the same lamp connected to the same source with a very long extension cord. Explain.
11. Why is it possible for a bird to sit on a high-voltage wire without being electrocuted?
12. When can the potential difference across a resistor be positive?
13. Referring to Figure Q28.13, describe what happens to the lightbulb after the switch is closed. Assume that the capacitor has a large capacitance and is initially uncharged, and assume that the light illuminates when connected directly across the battery terminals.

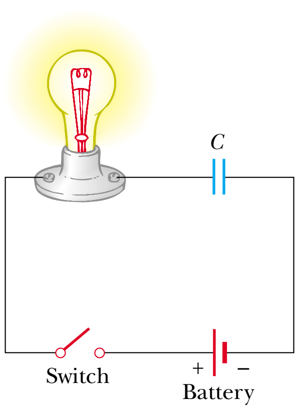

Figure Q28.13

14. What is the internal resistance of an ideal ammeter? Of an ideal voltmeter? Do real meters ever attain these ideals?
15. A "short circuit" is a path of very low resistance in a circuit in parallel with some other part of the circuit. Discuss the effect of the short circuit on the portion of the circuit it parallels. Use a lamp with a frayed cord as an example.
16. If electric power is transmitted over long distances, the resistance of the wires becomes significant. Why? Which method of transmission would result in less energy wasted—high current and low voltage or low current and high voltage? Explain your answer.
17. Are the two headlights of a car wired in series or in parallel? How can you tell?
18. Embodied in Kirchhoff's rules are two conservation laws. What are they?
19. Figure Q28.19 shows a series combination of three lightbulbs, all rated at 120 V with power ratings of 60 W, 75 W, and 200 W. Why is the 60-W lamp the brightest and the 200-W lamp the dimmest? Which bulb has the greatest resistance? How would their intensities differ if they were connected in parallel?

Henry Leap and Jim Lehman

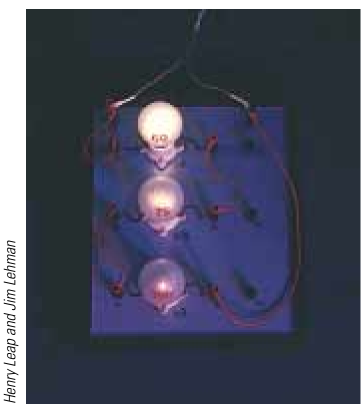

Figure Q28.19

20. A student claims that the second lightbulb in series is less bright than the first, because the first bulb uses up some of the current. How would you respond to this statement?
21. Is a circuit breaker wired in series or in parallel with the device it is protecting?
22. So that your grandmother can listen to *A Prairie Home Companion*, you take her bedside radio to the hospital where she is staying. You are required to have a maintenance worker test it for electrical safety. Finding that it develops 120 V on one of its knobs, he does not let you take it up to your grandmother's room. She complains that she has had the radio for many years and nobody has ever gotten a shock from it. You end up having to buy a new plastic radio. Is this fair? Will the old radio be safe back in her bedroom?

23. Suppose you fall from a building and on the way down grab a high-voltage wire. If the wire supports you as you hang from it, will you be electrocuted? If the wire then breaks, should you continue to hold onto an end of the wire as you fall?

24. What advantage does 120-V operation offer over 240 V? What disadvantages?

25. When electricians work with potentially live wires, they often use the backs of their hands or fingers to move wires. Why do you suppose they use this technique?

26. What procedure would you use to try to save a person who is "frozen" to a live high-voltage wire without endangering your own life?

27. If it is the current through the body that determines how serious a shock will be, why do we see warnings of *high voltage* rather than *high current* near electrical equipment?

28. Suppose you are flying a kite when it strikes a high-voltage wire. What factors determine how great a shock you receive?

29. A series circuit consists of three identical lamps connected to a battery as shown in Figure Q28.29. When the switch S is closed, what happens (a) to the intensities of lamps A and B; (b) to the intensity of lamp C; (c) to the current in the circuit; and (d) to the voltage across the three lamps? (e) Does the power delivered to the circuit increase, decrease, or remain the same?

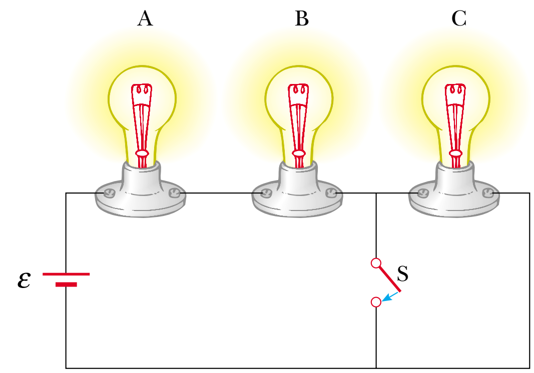

Figure Q28.29

30. If your car's headlights are on when you start the ignition, why do they dim while the car is starting?

31. A ski resort consists of a few chair lifts and several interconnected downhill runs on the side of a mountain, with a lodge at the bottom. The lifts are analogous to batteries, and the runs are analogous to resistors. Describe how two runs can be in series. Describe how three runs can be in parallel. Sketch a junction of one lift and two runs. State Kirchhoff's junction rule for ski resorts. One of the skiers happens to be carrying a skydiver's altimeter. She never takes the same set of lifts and runs twice, but keeps passing you at the fixed location where you are working. State Kirchhoff's loop rule for ski resorts.

PROBLEMS

1, 2, 3 = straightforward, intermediate, challenging ☐ = full solution available in the *Student Solutions Manual and Study Guide*

= coached solution with hints available at http://www.pse.com = computer useful in solving problem

= paired numerical and symbolic problems

Section 28.1 Electromotive Force

1. A battery has an emf of 15.0 V. The terminal voltage of the battery is 11.6 V when it is delivering 20.0 W of power to an external load resistor R. (a) What is the value of R? (b) What is the internal resistance of the battery?

2. (a) What is the current in a 5.60-Ω resistor connected to a battery that has a 0.200-Ω internal resistance if the terminal voltage of the battery is 10.0 V? (b) What is the emf of the battery?

3. Two 1.50-V batteries—with their positive terminals in the same direction—are inserted in series into the barrel of a flashlight. One battery has an internal resistance of 0.255 Ω, the other an internal resistance of 0.153 Ω. When the switch is closed, a current of 600 mA occurs in the lamp. (a) What is the lamp's resistance? (b) What fraction of the chemical energy transformed appears as internal energy in the batteries?

4. An automobile battery has an emf of 12.6 V and an internal resistance of 0.080 0 Ω. The headlights together present equivalent resistance 5.00 Ω (assumed constant). What is the potential difference across the headlight bulbs (a) when they are the only load on the battery and (b) when the starter motor is operated, taking an additional 35.0 A from the battery?

Section 28.2 Resistors in Series and Parallel

5. The current in a loop circuit that has a resistance of R_1 is 2.00 A. The current is reduced to 1.60 A when an additional resistor $R_2 = 3.00\ \Omega$ is added in series with R_1. What is the value of R_1?

6. (a) Find the equivalent resistance between points a and b in Figure P28.6. (b) A potential difference of 34.0 V is applied between points a and b. Calculate the current in each resistor.

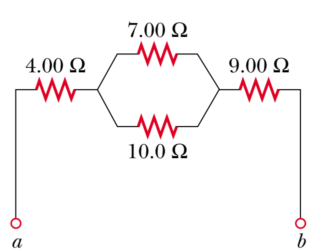

Figure P28.6

7. A lightbulb marked "75 W [at] 120 V" is screwed into a socket at one end of a long extension cord, in which each of the two conductors has resistance 0.800 Ω. The other end of the extension cord is plugged into a 120-V outlet. Draw a circuit diagram and find the actual power delivered to the bulb in this circuit.

8. Four copper wires of equal length are connected in series. Their cross-sectional areas are 1.00 cm^2, 2.00 cm^2, 3.00 cm^2, and 5.00 cm^2. A potential difference of 120 V is applied across the combination. Determine the voltage across the 2.00-cm^2 wire.

9. Consider the circuit shown in Figure P28.9. Find (a) the current in the 20.0-Ω resistor and (b) the potential difference between points *a* and *b*.

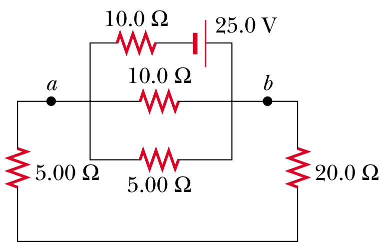

Figure P28.9

10. For the purpose of measuring the electric resistance of shoes through the body of the wearer to a metal ground plate, the American National Standards Institute (ANSI) specifies the circuit shown in Figure P28.10. The potential difference ΔV across the 1.00-MΩ resistor is measured with a high-resistance voltmeter. (a) Show that the resistance of the footwear is given by

$$R_{\text{shoes}} = 1.00\ \text{M}\Omega\left(\frac{50.0\ \text{V} - \Delta V}{\Delta V}\right)$$

(b) In a medical test, a current through the human body should not exceed 150 μA. Can the current delivered by the ANSI-specified circuit exceed 150 μA? To decide, consider a person standing barefoot on the ground plate.

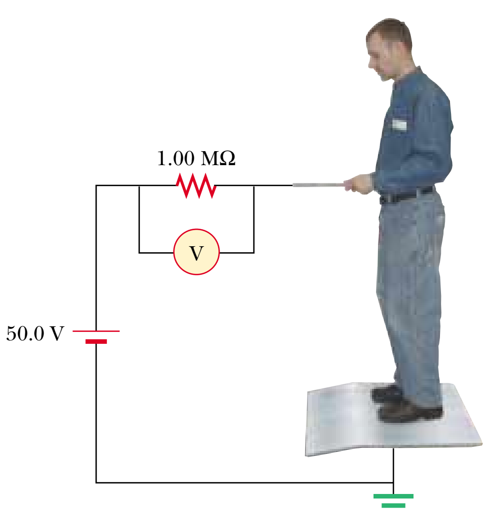

Figure P28.10

11. Three 100-Ω resistors are connected as shown in Figure P28.11. The maximum power that can safely be delivered to any one resistor is 25.0 W. (a) What is the maximum voltage that can be applied to the terminals *a* and *b*? For the voltage determined in part (a), what is the power delivered to each resistor? What is the total power delivered?

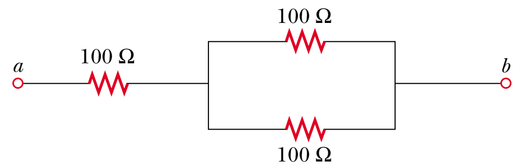

Figure P28.11

12. Using only three resistors—2.00 Ω, 3.00 Ω, and 4.00 Ω—find 17 resistance values that may be obtained by various combinations of one or more resistors. Tabulate the combinations in order of increasing resistance.

13. The current in a circuit is tripled by connecting a 500-Ω resistor in parallel with the resistance of the circuit. Determine the resistance of the circuit in the absence of the 500-Ω resistor.

14. A 6.00-V battery supplies current to the circuit shown in Figure P28.14. When the double-throw switch S is open, as shown in the figure, the current in the battery is 1.00 mA. When the switch is closed in position 1, the current in the battery is 1.20 mA. When the switch is closed in position 2, the current in the battery is 2.00 mA. Find the resistances R_1, R_2, and R_3.

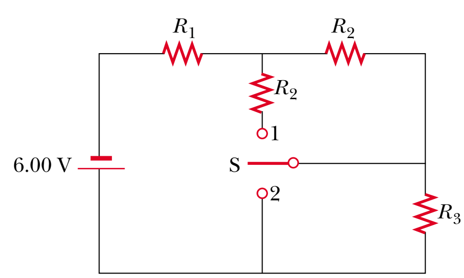

Figure P28.14

15. Calculate the power delivered to each resistor in the circuit shown in Figure P28.15.

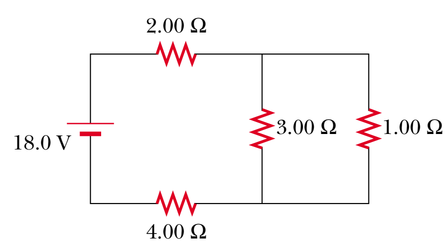

Figure P28.15

16. Two resistors connected in series have an equivalent resistance of 690 Ω. When they are connected in parallel, their equivalent resistance is 150 Ω. Find the resistance of each resistor.

17. An electric teakettle has a multiposition switch and two heating coils. When only one of the coils is switched on, the well-insulated kettle brings a full pot of water to a boil over the time interval Δt. When only the other coil is switched on, it requires a time interval of $2\Delta t$ to boil the same amount of water. Find the time interval required to boil the same amount of water if both coils are switched on (a) in a parallel connection and (b) in a series connection.

18. In Figures 28.4 and 28.6, let $R_1 = 11.0\ \Omega$, $R_2 = 22.0\ \Omega$, and let the battery have a terminal voltage of 33.0 V. (a) In the parallel circuit shown in Figure 28.6, to which resistor is more power delivered? (b) Verify that the sum of the power (I^2R) delivered to each resistor equals the power supplied by the battery ($\mathcal{P} = I\Delta V$). (c) In the series circuit, which resistor uses more power? (d) Verify that the sum of the power (I^2R) used by each resistor equals the power supplied by the battery ($\mathcal{P} = I\Delta V$). (e) Which circuit configuration uses more power?

19. Four resistors are connected to a battery as shown in Figure P28.19. The current in the battery is I, the battery emf is $\boldsymbol{\mathcal{E}}$, and the resistor values are $R_1 = R$, $R_2 = 2R$, $R_3 = 4R$, $R_4 = 3R$. (a) Rank the resistors according to the potential difference across them, from largest to smallest. Note any cases of equal potential differences. (b) Determine the potential difference across each resistor in terms of $\boldsymbol{\mathcal{E}}$. (c) Rank the resistors according to the current in them, from largest to smallest. Note any cases of equal currents. (d) Determine the current in each resistor in terms of I. (e) **What If?** If R_3 is increased, what happens to the current in each of the resistors? (f) In the limit that $R_3 \to \infty$, what are the new values of the current in each resistor in terms of I, the original current in the battery?

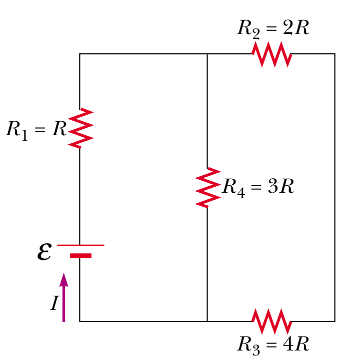

Figure P28.19

Section 28.3 Kirchhoff's Rules

> *Note:* The currents are not necessarily in the direction shown for some circuits.

20. The ammeter shown in Figure P28.20 reads 2.00 A. Find I_1, I_2, and $\boldsymbol{\mathcal{E}}$.

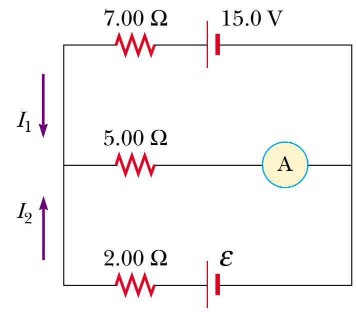

Figure P28.20

21. Determine the current in each branch of the circuit shown in Figure P28.21.

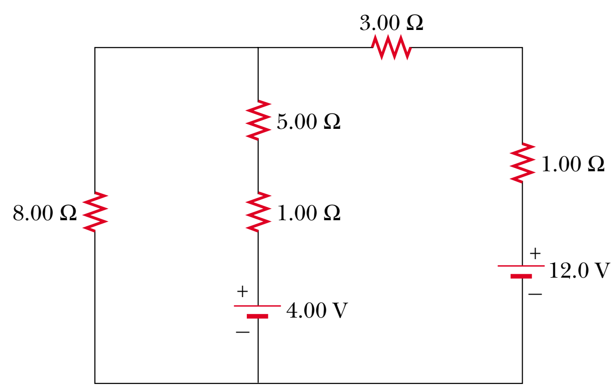

Figure P28.21 Problems 21, 22, and 23.

22. In Figure P28.21, show how to add just enough ammeters to measure every different current. Show how to add just enough voltmeters to measure the potential difference across each resistor and across each battery.

23. The circuit considered in Problem 21 and shown in Figure P28.21 is connected for 2.00 min. (a) Find the energy delivered by each battery. (b) Find the energy delivered to each resistor. (c) Identify the types of energy transformations that occur in the operation of the circuit and the total amount of energy involved in each type of transformation.

24. Using Kirchhoff's rules, (a) find the current in each resistor in Figure P28.24. (b) Find the potential difference between points c and f. Which point is at the higher potential?

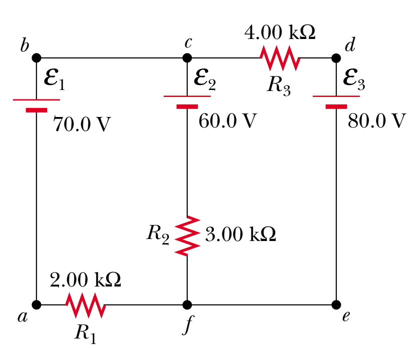

Figure P28.24

25. Taking $R = 1.00\ \text{k}\Omega$ and $\mathcal{E} = 250$ V in Figure P28.25, determine the direction and magnitude of the current in the horizontal wire between a and e.

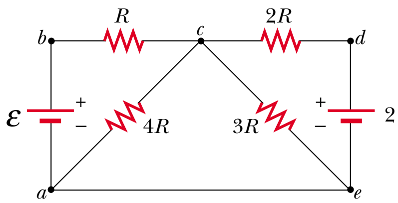

Figure P28.25

26. In the circuit of Figure P28.26, determine the current in each resistor and the voltage across the 200-Ω resistor.

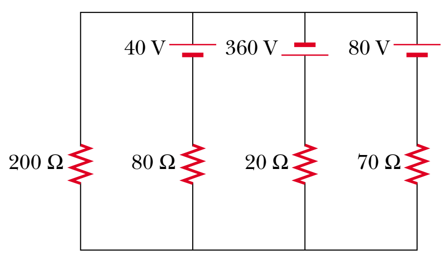

Figure P28.26

27. A dead battery is charged by connecting it to the live battery of another car with jumper cables (Fig. P28.27). Determine the current in the starter and in the dead battery.

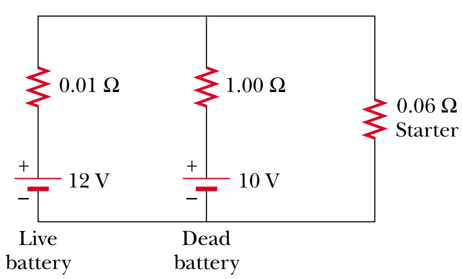

Figure P28.27

28. For the network shown in Figure P28.28, show that the resistance $R_{ab} = (27/17)\ \Omega$.

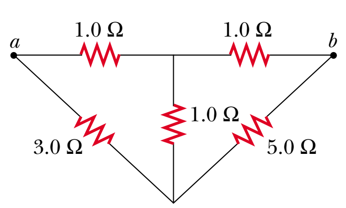

Figure P28.28

29. For the circuit shown in Figure P28.29, calculate (a) the current in the 2.00-Ω resistor and (b) the potential difference between points a and b.

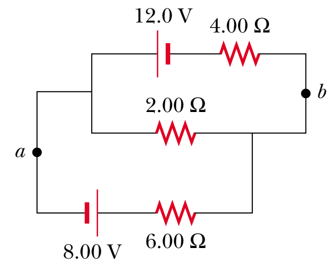

Figure P28.29

30. Calculate the power delivered to each resistor shown in Figure P28.30.

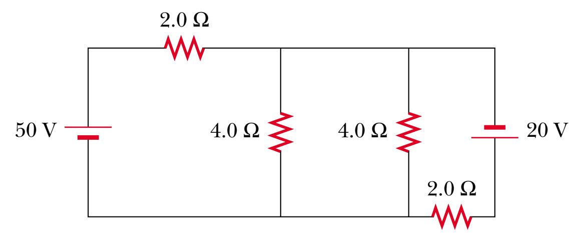

Figure P28.30

Section 28.4 *RC* Circuits

31. Consider a series *RC* circuit (see Fig. 28.19) for which $R = 1.00\ \text{M}\Omega$, $C = 5.00\ \mu\text{F}$, and $\mathcal{E} = 30.0$ V. Find (a) the time constant of the circuit and (b) the maximum charge on the capacitor after the switch is closed. (c) Find the current in the resistor 10.0 s after the switch is closed.

32. A 2.00-nF capacitor with an initial charge of 5.10 μC is discharged through a 1.30-kΩ resistor. (a) Calculate the current in the resistor 9.00 μs after the resistor is connected across the terminals of the capacitor. (b) What charge remains on the capacitor after 8.00 μs? (c) What is the maximum current in the resistor?

33. A fully charged capacitor stores energy U_0. How much energy remains when its charge has decreased to half its original value?

34. A capacitor in an *RC* circuit is charged to 60.0% of its maximum value in 0.900 s. What is the time constant of the circuit?

35. Show that the integral in Equation (1) of Example 28.14 has the value $RC/2$.

36. In the circuit of Figure P28.36, the switch S has been open for a long time. It is then suddenly closed. Determine the time constant (a) before the switch is closed and (b) after the switch is closed. (c) Let the switch be closed at $t = 0$. Determine the current in the switch as a function of time.

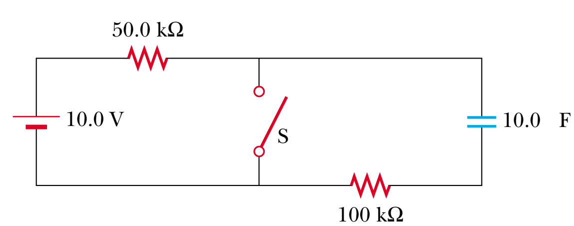

Figure P28.36

37. The circuit in Figure P28.37 has been connected for a long time. (a) What is the voltage across the capacitor? (b) If the battery is disconnected, how long does it take the capacitor to discharge to one tenth of its initial voltage?

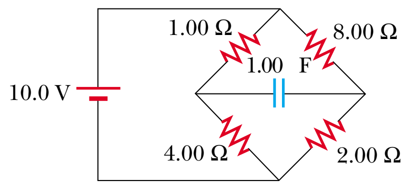

Figure P28.37

38. In places such as a hospital operating room and a factory for electronic circuit boards, electric sparks must be avoided. A person standing on a grounded floor and touching nothing else can typically have a body capacitance of 150 pF, in parallel with a foot capacitance of 80.0 pF produced by the dielectric soles of his or her shoes. The person acquires static electric charge from interactions with furniture, clothing, equipment, packaging materials, and essentially everything else. The static charge is conducted to ground through the equivalent resistance of the two shoe soles in parallel with each other. A pair of rubber-soled street shoes can present an equivalent resistance of 5 000 MΩ. A pair of shoes with special static-dissipative soles can have an equivalent resistance of 1.00 MΩ. Consider the person's body and shoes as forming an *RC* circuit with the ground. (a) How long does it take the rubber-soled shoes to reduce a 3 000-V static charge to 100 V? (b) How long does it take the static-dissipative shoes to do the same thing?

39. A 4.00-MΩ resistor and a 3.00-μF capacitor are connected in series with a 12.0-V power supply. (a) What is the time constant for the circuit? (b) Express the current in the circuit and the charge on the capacitor as functions of time.

40. Dielectric materials used in the manufacture of capacitors are characterized by conductivities that are small but not zero. Therefore, a charged capacitor slowly loses its charge by "leaking" across the dielectric. If a capacitor having capacitance C leaks charge such that the potential difference has decreased to half its initial ($t = 0$) value at a time t, what is the equivalent resistance of the dielectric?

Section 28.5 Electrical Meters

41. Assume that a galvanometer has an internal resistance of 60.0 Ω and requires a current of 0.500 mA to produce full-scale deflection. What resistance must be connected in parallel with the galvanometer if the combination is to serve as an ammeter that has a full-scale deflection for a current of 0.100 A?

42. A typical galvanometer, which requires a current of 1.50 mA for full-scale deflection and has a resistance of 75.0 Ω, may be used to measure currents of much greater values. To enable an operator to measure large currents without damage to the galvanometer, a relatively small shunt resistor is wired in parallel with the galvanometer, as suggested in Figure 28.27. Most of the current then goes through the shunt resistor. Calculate the value of the shunt resistor that allows the galvanometer to be used to measure a current of 1.00 A at full-scale deflection. (*Suggestion:* use Kirchhoff's rules.)

43. The same galvanometer described in the previous problem may be used to measure voltages. In this case a large resistor is wired in series with the galvanometer, as suggested in Figure 28.29. The effect is to limit the current in the galvanometer when large voltages are applied. Most of the potential drop occurs across the resistor placed in series. Calculate the value of the resistor that allows the galvanometer to measure an applied voltage of 25.0 V at full-scale deflection.

44. *Meter loading.* Work this problem to five-digit precision. Refer to Figure P28.44. (a) When a 180.00-Ω resistor is connected across a battery of emf 6.000 0 V and internal resistance 20.000 Ω, what is the current in the resistor? What is the potential difference across it? (b) Suppose now an ammeter of resistance 0.500 00 Ω and a voltmeter of resistance 20 000 Ω are added to the circuit as shown in Figure P28.44b. Find the reading of each. (c) **What If?** Now one terminal of one wire is moved, as shown in Figure P28.44c. Find the new meter readings.

45. Design a multirange ammeter capable of full-scale deflection for 25.0 mA, 50.0 mA, and 100 mA. Assume the meter movement is a galvanometer that has a resistance of 25.0 Ω and gives a full-scale deflection for 1.00 mA.

46. Design a multirange voltmeter capable of full-scale deflection for 20.0 V, 50.0 V, and 100 V. Assume the meter movement is a galvanometer that has a resistance of 60.0 Ω and gives a full-scale deflection for a current of 1.00 mA.

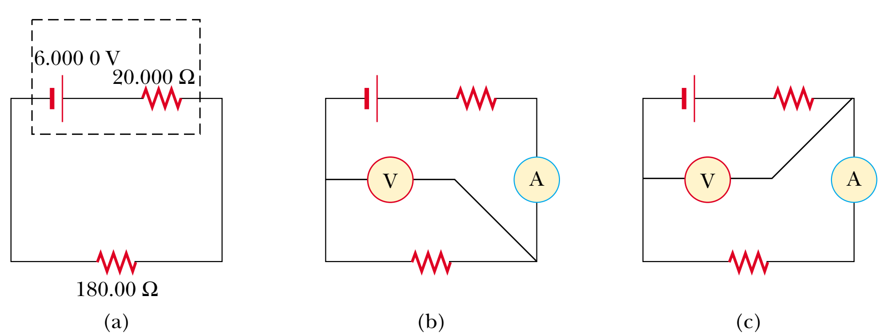

Figure P28.44

47. A particular galvanometer serves as a 2.00-V full-scale voltmeter when a 2 500-Ω resistor is connected in series with it. It serves as a 0.500-A full-scale ammeter when a 0.220-Ω resistor is connected in parallel with it. Determine the internal resistance of the galvanometer and the current required to produce full-scale deflection.

Section 28.6 Household Wiring and Electrical Safety

48. An 8.00-ft extension cord has two 18-gauge copper wires, each having a diameter of 1.024 mm. At what rate is energy delivered to the resistance in the cord when it is carrying a current of (a) 1.00 A and (b) 10.0 A?

49. An electric heater is rated at 1 500 W, a toaster at 750 W, and an electric grill at 1 000 W. The three appliances are connected to a common 120-V household circuit. (a) How much current does each draw? (b) Is a circuit with a 25.0-A circuit breaker sufficient in this situation? Explain your answer.

50. Aluminum wiring has sometimes been used instead of copper for economy. According to the National Electrical Code, the maximum allowable current for 12-gauge copper wire with rubber insulation is 20 A. What should be the maximum allowable current in a 12-gauge aluminum wire if the power per unit length delivered to the resistance in the aluminum wire is the same as that delivered in the copper wire?

51. Turn on your desk lamp. Pick up the cord, with your thumb and index finger spanning the width of the cord. (a) Compute an order-of-magnitude estimate for the current in your hand. You may assume that at a typical instant the conductor inside the lamp cord next to your thumb is at potential $\sim 10^2$ V and that the conductor next to your index finger is at ground potential (0 V). The resistance of your hand depends strongly on the thickness and the moisture content of the outer layers of your skin. Assume that the resistance of your hand between fingertip and thumb tip is $\sim 10^4$ Ω. You may model the cord as having rubber insulation. State the other quantities you measure or estimate and their values. Explain your reasoning. (b) Suppose that your body is isolated from any other charges or currents. In order-of-magnitude terms describe the potential of your thumb where it contacts the cord, and the potential of your finger where it touches the cord.

Additional Problems

52. Four 1.50-V AA batteries in series are used to power a transistor radio. If the batteries can move a charge of 240 C, how long will they last if the radio has a resistance of 200 Ω?

53. A battery has an emf of 9.20 V and an internal resistance of 1.20 Ω. (a) What resistance across the battery will extract from it a power of 12.8 W? (b) a power of 21.2 W?

54. Calculate the potential difference between points *a* and *b* in Figure P28.54 and identify which point is at the higher potential.

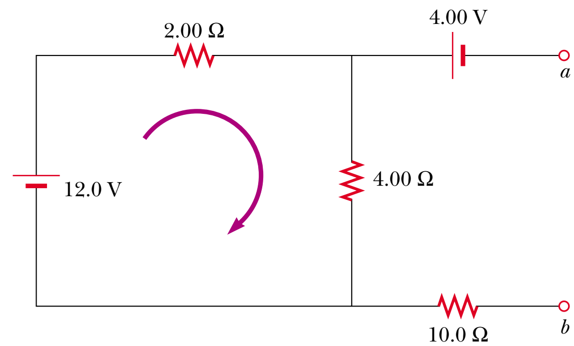

Figure P28.54

55. Assume you have a battery of emf $\mathcal{E}$ and three identical lightbulbs, each having constant resistance *R*. What is the total power delivered by the battery if the bulbs are connected (a) in series? (b) in parallel? (c) For which connection will the bulbs shine the brightest?

56. A group of students on spring break manages to reach a deserted island in their wrecked sailboat. They splash ashore with fuel, a European gasoline-powered 240-V generator, a box of North American 100-W 120-V lightbulbs, a 500-W 120-V hot pot, lamp sockets, and some insulated wire. While waiting to be rescued, they decide to use the generator to operate some lightbulbs. (a) Draw a diagram of a circuit they can use, containing the minimum number of lightbulbs with 120 V across each bulb, and no higher voltage. Find the current in the generator and its power output. (b) One student catches a fish and wants to cook it in the hot pot. Draw a diagram of a circuit containing the hot pot and the minimum number of lightbulbs with 120 V across each device, and not more. Find the current in the generator and its power output.

57. A battery has an emf $\mathcal{E}$ and internal resistance *r*. A variable load resistor *R* is connected across the terminals of the battery. (a) Determine the value of *R* such that the potential difference across the terminals is a maximum. (b) Determine the value of *R* so that the current in the circuit is a maximum. (c) Determine the value of *R* so that the power delivered to the load resistor is a maximum. Choosing the load resistance for maximum power transfer is a case of what is called *impedance matching* in general. Impedance matching is important in shifting gears on a bicycle, in connecting a loudspeaker to an audio amplifier, in connecting a battery charger to a bank of solar photoelectric cells, and in many other applications.

58. A 10.0-μF capacitor is charged by a 10.0-V battery through a resistance *R*. The capacitor reaches a potential difference of 4.00 V in a time 3.00 s after charging begins. Find *R*.

59. When two unknown resistors are connected in series with a battery, the battery delivers 225 W and carries a total current of 5.00 A. For the same total current, 50.0 W is delivered when the resistors are connected in parallel. Determine the values of the two resistors.

60. When two unknown resistors are connected in series with a battery, the battery delivers total power $\mathcal{P}_s$ and carries a total current of *I*. For the same total current, a total power

$\mathcal{P}_p$ is delivered when the resistors are connected in parallel. Determine the values of the two resistors.

61. A power supply has an open-circuit voltage of 40.0 V and an internal resistance of 2.00 Ω. It is used to charge two storage batteries connected in series, each having an emf of 6.00 V and internal resistance of 0.300 Ω. If the charging current is to be 4.00 A, (a) what additional resistance should be added in series? (b) At what rate does the internal energy increase in the supply, in the batteries, and in the added series resistance? (c) At what rate does the chemical energy increase in the batteries?

62. Two resistors R_1 and R_2 are in parallel with each other. Together they carry total current I. (a) Determine the current in each resistor. (b) Prove that this division of the total current I between the two resistors results in less power delivered to the combination than any other division. It is a general principle that *current in a direct current circuit distributes itself so that the total power delivered to the circuit is a minimum.*

63. The value of a resistor R is to be determined using the ammeter–voltmeter setup shown in Figure P28.63. The ammeter has a resistance of 0.500 Ω, and the voltmeter has a resistance of 20 000 Ω. Within what range of actual values of R will the measured values be correct to within 5.00% if the measurement is made using the circuit shown in (a) Figure P28.63a and (b) Figure P28.63b?

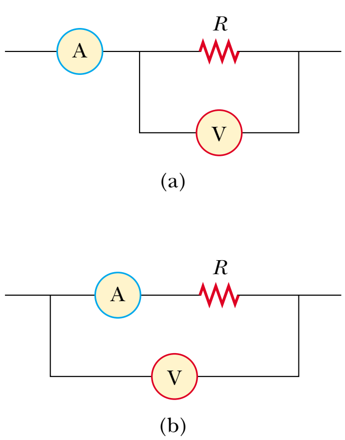

Figure P28.63

64. A battery is used to charge a capacitor through a resistor, as shown in Figure 28.19. Show that half the energy supplied by the battery appears as internal energy in the resistor and that half is stored in the capacitor.

65. The values of the components in a simple series RC circuit containing a switch (Fig. 28.19) are $C = 1.00\ \mu$F, $R = 2.00 \times 10^6$ Ω, and $\boldsymbol{\mathcal{E}} = 10.0$ V. At the instant 10.0 s after the switch is closed, calculate (a) the charge on the capacitor, (b) the current in the resistor, (c) the rate at which energy is being stored in the capacitor, and (d) the rate at which energy is being delivered by the battery.

66. The switch in Figure P28.66a closes when $\Delta V_c > 2\Delta V/3$ and opens when $\Delta V_c < \Delta V/3$. The voltmeter reads a voltage as plotted in Figure P28.66b. What is the period T of the waveform in terms of R_1, R_2, and C?

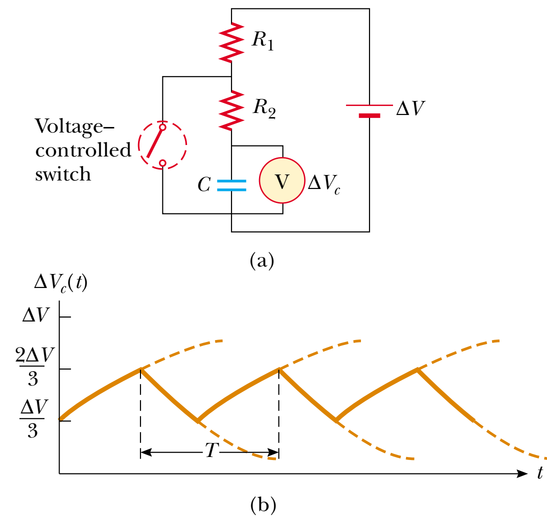

Figure P28.66

67. Three 60.0-W, 120-V lightbulbs are connected across a 120-V power source, as shown in Figure P28.67. Find (a) the total power delivered to the three bulbs and (b) the voltage across each. Assume that the resistance of each bulb is constant (even though in reality the resistance might increase markedly with current).

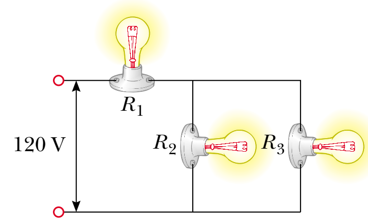

Figure P28.67

68. Switch S has been closed for a long time, and the electric circuit shown in Figure P28.68 carries a constant current. Take $C_1 = 3.00\ \mu$F, $C_2 = 6.00\ \mu$F, $R_1 = 4.00$ kΩ, and $R_2 = 7.00$ kΩ. The power delivered to R_2 is 2.40 W. (a) Find the charge on C_1. (b) Now the switch is opened. After many milliseconds, by how much has the charge on C_2 changed?

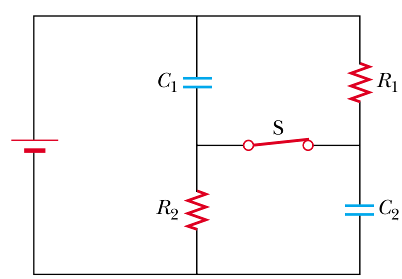

Figure P28.68

69. Four resistors are connected in parallel across a 9.20-V battery. They carry currents of 150 mA, 45.0 mA, 14.00 mA, and 4.00 mA. (a) If the resistor with the largest resistance is replaced with one having twice the resistance, what is the ratio of the new current in the battery to the original current? (b) **What If?** If instead the resistor with the smallest resistance is replaced with one having twice the resistance, what is the ratio of the new total current to the original current? (c) On a February night, energy leaves a house by several heat leaks, including the following: 1 500 W by conduction through the ceiling; 450 W by infiltration (air flow) around the windows; 140 W by conduction through the basement wall above the foundation sill; and 40.0 W by conduction through the plywood door to the attic. To produce the biggest saving in heating bills, which one of these energy transfers should be reduced first?

70. Figure P28.70 shows a circuit model for the transmission of an electrical signal, such as cable TV, to a large number of subscribers. Each subscriber connects a load resistance R_L between the transmission line and the ground. The ground is assumed to be at zero potential and able to carry any current between any ground connections with negligible resistance. The resistance of the transmission line itself between the connection points of different subscribers is modeled as the constant resistance R_T. Show that the equivalent resistance across the signal source is

$$R_{\text{eq}} = \tfrac{1}{2}\left[(4R_TR_L + R_T^2)^{1/2} + R_T\right]$$

Suggestion: Because the number of subscribers is large, the equivalent resistance would not change noticeably if the first subscriber cancelled his service. Consequently, the equivalent resistance of the section of the circuit to the right of the first load resistor is nearly equal to R_{eq}.

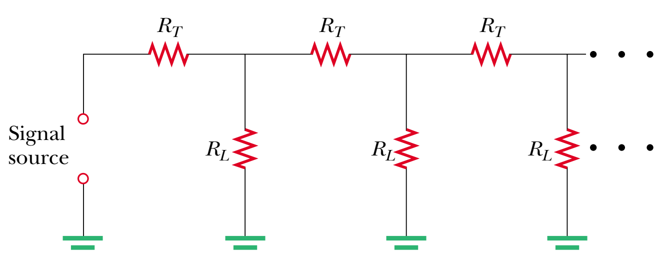

Figure P28.70

71. In Figure P28.71, suppose the switch has been closed for a time sufficiently long for the capacitor to become fully charged. Find (a) the steady-state current in each resistor and (b) the charge Q on the capacitor. (c) The switch is now opened at $t = 0$. Write an equation for the current I_{R_2} through R_2 as a function of time and (d) find the time interval required for the charge on the capacitor to fall to one-fifth its initial value.

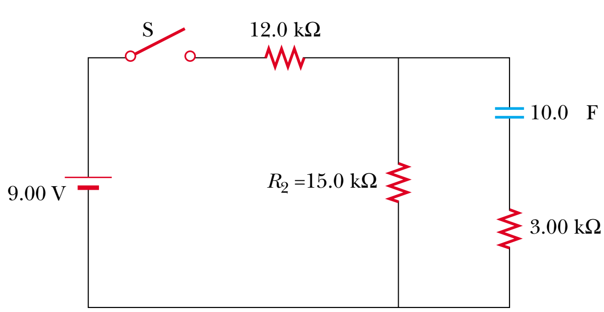

Figure P28.71

72. A regular tetrahedron is a pyramid with a triangular base. Six 10.0-Ω resistors are placed along its six edges, with junctions at its four vertices. A 12.0-V battery is connected to any two of the vertices. Find (a) the equivalent resistance of the tetrahedron between these vertices and (b) the current in the battery.

73. The circuit shown in Figure P28.73 is set up in the laboratory to measure an unknown capacitance C with the use of a voltmeter of resistance $R = 10.0$ MΩ and a battery whose emf is 6.19 V. The data given in the table are the measured voltages across the capacitor as a function of time, where $t = 0$ represents the instant at which the switch is opened. (a) Construct a graph of $\ln(\mathcal{E}/\Delta V)$ versus t, and perform a linear least-squares fit to the data. (b) From the slope of your graph, obtain a value for the time constant of the circuit and a value for the capacitance.

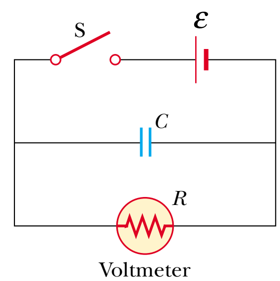

Figure P28.73

ΔV (V)	t (s)	$\ln(\mathcal{E}/\Delta V)$
6.19	0	
5.55	4.87	
4.93	11.1	
4.34	19.4	
3.72	30.8	
3.09	46.6	
2.47	67.3	
1.83	102.2	

74. The student engineer of a campus radio station wishes to verify the effectiveness of the lightning rod on the antenna mast (Fig. P28.74). The unknown resistance R_x is between points C and E. Point E is a true ground but is inaccessible for direct measurement since this stratum is several meters below the Earth's surface. Two identical rods are driven into the ground at A and B, introducing an unknown resistance R_y. The procedure is as follows. Measure resistance R_1 between points A and B, then connect A and B with a heavy conducting wire and measure resistance R_2 between

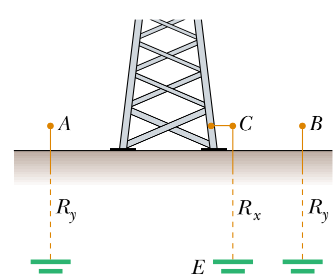

Figure P28.74

points A and C. (a) Derive an equation for R_x in terms of the observable resistances, R_1 and R_2. (b) A satisfactory ground resistance would be $R_x < 2.00\ \Omega$. Is the grounding of the station adequate if measurements give $R_1 = 13.0\ \Omega$ and $R_2 = 6.00\ \Omega$?

75. The circuit in Figure P28.75 contains two resistors, $R_1 = 2.00\ \text{k}\Omega$ and $R_2 = 3.00\ \text{k}\Omega$, and two capacitors, $C_1 = 2.00\ \mu\text{F}$ and $C_2 = 3.00\ \mu\text{F}$, connected to a battery with emf $\boldsymbol{\mathcal{E}} = 120$ V. No charge is on either capacitor before switch S is closed. Determine the charges q_1 and q_2 on capacitors C_1 and C_2, respectively, after the switch is closed. (*Suggestion:* First reconstruct the circuit so that it becomes a simple RC circuit containing a single resistor and single capacitor in series, connected to the battery, and then determine the total charge q stored in the equivalent circuit.)

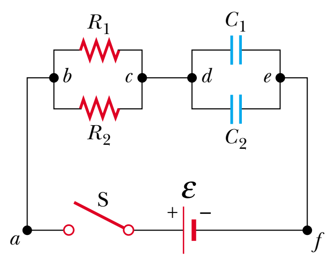

Figure P28.75

76. This problem[6] illustrates how a digital voltmeter affects the voltage across a capacitor in an RC circuit. A digital voltmeter of internal resistance r is used to measure the voltage across a capacitor after the switch in Figure P28.76 is closed. Because the meter has finite resistance, part of the current supplied by the battery passes through the meter. (a) Apply Kirchhoff's rules to this circuit, and use the fact that $i_C = dq/dt$ to show that this leads to the differential equation

$$R_{\text{eq}}\frac{dq}{dt} + \frac{q}{C} = \frac{r}{r+R}\boldsymbol{\mathcal{E}}$$

where $R_{\text{eq}} = rR/(r+R)$. (b) Show that the solution to this differential equation is

$$q = \frac{r}{r+R}C\boldsymbol{\mathcal{E}}\,(1 - e^{-t/R_{\text{eq}}C})$$

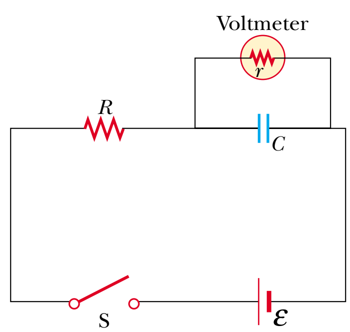

Figure P28.76

and that the voltage across the capacitor as a function of time is

$$V_C = \frac{r}{r+R}\boldsymbol{\mathcal{E}}(1 - e^{-t/R_{\text{eq}}C})$$

(c) **What If?** If the capacitor is fully charged, and the switch is then opened, how does the voltage across the capacitor behave in this case?

[6] After Joseph Priest, "Meter Resistance: Don't Forget It!" *The Physics Teacher,* January 2003, p. 40.

Answers to Quick Quizzes

28.1 (a). Power is delivered to the internal resistance of a battery, so decreasing the internal resistance will decrease this "lost" power and increase the percentage of the power delivered to the device.

28.2 (c). In a series circuit, the current is the same in all resistors in series. Current is not "used up" as charges pass through a resistor.

28.3 (a). Connecting b to c "shorts out" bulb R_2 and changes the total resistance of the circuit from $R_1 + R_2$ to just R_1. Because the resistance of the circuit has decreased (and the emf supplied by the battery does not change), the current in the circuit increases.

28.4 (b). When the switch is opened, resistors R_1 and R_2 are in series, so that the total circuit resistance is larger than when the switch was closed. As a result, the current decreases.

28.5 (b), (d). Adding another series resistor increases the total resistance of the circuit and thus reduces the current in the circuit. The potential difference across the battery terminals increases because the reduced current results in a smaller voltage decrease across the internal resistance.

28.6 (a), (e). If the second resistor were connected in parallel, the total resistance of the circuit would decrease, and the current in the battery would increase. The potential difference across the terminals would decrease because the increased current results in a greater voltage drop across the internal resistance.

28.7 (a). When the switch is closed, resistors R_1 and R_2 are in parallel, so that the total circuit resistance is smaller than when the switch was open. As a result, the current increases.

28.8 (c). A current is assigned to a given branch of a circuit. There may be multiple resistors and batteries in a given branch.

28.9 (b), (d). Just after the switch is closed, there is no charge on the capacitor, so there is no voltage across it. Charges begin to flow in the circuit to charge up the capacitor, so that all of the voltage $\Delta V = IR$ appears across the resistor. After a long time, the capacitor is fully charged and the current drops to zero. Thus, the battery voltage is now entirely across the capacitor.

28.10 (c), (i). Just after the switch is closed, there is no charge on the capacitor. Current exists in both branches of the circuit as the capacitor begins to charge, so the right half of the circuit is equivalent to two resistances R in parallel for an equivalent resistance of $\frac{1}{2}R$. After a long time, the capacitor is fully charged and the current in the right-hand branch drops to zero. Now, current exists only in a resistance R across the battery.