drop of 6.00 V is experienced as the charge emerges from the negative terminal of $\mathscr{E}_3$. The charge is back where it started and, as we can see from figure 20.27, the total change in potential in traversing the closed loop is zero. It is not necessary to draw these potential diagrams for every Kirchhoff's rules problem. The student should, however, draw at least one potential diagram to help in the understanding of Kirchhoff's second rule.

The Language of Physics

Electric current
Electric current is defined as the amount of electric charge that flows through a cross section of a wire per unit time (p. 564).

Ampere
The SI unit of current that is equal to a flow of one coulomb of charge per second (p. 564).

Conventional current
A flow of positive charges in a circuit from a position of high potential to one of low potential (p. 565).

Electron current
The actual current in a circuit; it is a flow of electrons from a position of low potential to one of high potential (p. 565).

Direct current
An electric current in which the electric charges flow in only one direction in a circuit (p. 565).

Ammeter
A device that measures the amount of current in a circuit. It is constructed by placing a low-resistance shunt in parallel with a galvanometer (p. 565).

Voltmeter
A device that measures the potential difference between any two points in an electric circuit. It is constructed by placing a high resistance in series with a galvanometer (p. 565).

Ohm's law
For metallic conductors, the current in a circuit is directly proportional to the applied potential difference and inversely proportional to the resistance in the circuit (p. 566).

Joule heat
The energy that is lost as a charge "falls" through a resistor shows up as heat in the resistor (p. 572).

Series circuit
A circuit in which each element of the circuit is connected to an adjacent element of the circuit such that the same amount of charge flows through each and every circuit element. For a resistive circuit, the current is the same through each resistor (p. 574).

Equivalent resistance
A single resistor, whose value is equal to the combined resistance of the individual resistors in the circuit. For resistors in series, the equivalent resistance is equal to the sum of the individual resistances. For resistors in parallel, the reciprocal of the equivalent resistance is equal to the sum of the reciprocals of the individual resistances (p. 575).

Parallel circuit
A circuit in which the circuit elements are connected in such a way that the potential difference across all the elements of the circuit is the same. For a resistive circuit, the potential difference across the resistors is equal (p. 576).

Law of conservation of electric charge
Electric charge can neither be created nor destroyed (p. 576).

Electromotive force (emf)
A potential difference that is supplied by a battery. If the internal resistance of the battery is relatively small, then the emf is equal to the terminal voltage of the battery (p. 581).

Galvanometer
A device that indicates that there is a current in a circuit. By appropriate construction, a galvanometer can be made into an ammeter or a voltmeter (p. 584).

Wheatstone bridge
An electric circuit that is used to measure the value of an unknown resistor very accurately (p. 589).

Kirchhoff's first rule
The sum of the currents in a circuit entering a junction is equal to the sum of the currents leaving the junction (p. 591).

Kirchhoff's second rule
The change in potential around a closed loop of a circuit is equal to zero. This can also be stated in the form, the sum of the potential rises and potential drops around any closed loop of a circuit is equal to zero (p. 591).

Summary of Important Equations

Current
$$I = \frac{q}{t} \quad (20.1)$$

Ohm's law
$$I = \frac{V}{R} \quad (20.3)$$

Resistance of a wire
$$R = \rho\frac{l}{A} \quad (20.7)$$

Work done within a battery
$$W = qV \quad (20.13)$$

Power
$$P = IV \quad (20.15)$$

Power dissipated in a resistor
$$P = I^2R \quad (20.18)$$

Resistors in series
$$V = V_1 + V_2 + V_3 \quad (20.22)$$
$$I = I_1 = I_2 = I_3$$
$$R = R_1 + R_2 + R_3 \quad (20.26)$$
$$P = P_1 + P_2 + P_3$$

Resistors in parallel
$$V = V_1 = V_2 = V_3 \quad (20.27)$$
$$I = I_1 + I_2 + I_3 \quad (20.28)$$
$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \quad (20.35)$$
$$P = P_1 + P_2 + P_3$$

Terminal voltage of a battery
$$V = \mathscr{E} - Ir \quad (20.37)$$

Batteries in series
$$\mathscr{E} = \mathscr{E}_1 + \mathscr{E}_2 + \mathscr{E}_3 + \cdots + \mathscr{E}_n \quad (20.38)$$

Identical batteries in parallel
$$\mathscr{E} = \mathscr{E}_1 = \mathscr{E}_2 = \mathscr{E}_3 \quad (20.39)$$
$$I = I_1 + I_2 + I_3 \quad (20.40)$$

Resistance for an ammeter shunt
$$R_s = \left(\frac{I_g}{I - I_g}\right)R_g \quad (20.45)$$

Series resistor for a voltmeter
$$R = \frac{V}{I_g} - R_g \quad (20.49)$$

Wheatstone bridge
$$R_2 = \frac{R_4}{R_3}R_1 \quad (20.59)$$

Kirchhoff's first rule
$$\Sigma I_{\text{entering junction}} = \Sigma I_{\text{leaving junction}} \quad (20.60)$$

Kirchhoff's second rule
$$\Delta V_{\text{closed loop}} = 0 \quad (20.62)$$

Questions for Chapter 20

1. Can the flow of electric charge in a circuit be compared to the flow of a fluid in a pipe? Point out where it is a good analogy and where it is a bad analogy.
2. Can a resistor be used as a thermometer?
†3. If a metal consists of positive ions surrounded by a sea of electrons, how does the metal stay together?
4. If the drift velocity of an electron in a wire is so small that it takes almost 30 s for it to move about 1 cm, why is no delay observed on an ammeter when a battery is connected to a circuit?
5. Describe the flow of the positive charges of a conventional current with the flow of electrons in an electron current in a circuit. What are the advantages and disadvantages of using conventional current?
6. Why would you not want to hook up the simple circuit shown in figure 20.3? Estimate the value of the resistance of the wire. Using the concept of Ohm's law, would a very large current exist? Would this be called "shorting" the battery?
7. Compare a positive charge falling through a potential difference with a mass falling in a gravitational field. Why is this a pretty good analogy? Try to make a similar analogy with the motion of an electron in a circuit.
†8. A black box is a device that is contained in a closed box, so that you cannot see inside the box to see what the device is. There is an input wire to the box and an output wire from the box. All you can do is to infer characteristics about the device from the information obtained from the input and output connections. A range of different potentials is applied to this black box, and the current coming out of the box is measured. A plot of the potential versus the current is a curve rather than a straight line. What are some of the characteristics of this black box?
9. A copper block is 35 cm long, 2 cm thick, and 2 cm wide. Does the block have the same resistance from end to end as it does from side to side? Does it depend in any way on the size of the connection to the block?
†10. In the 1970s when copper became very expensive, some new homes were built with aluminum wires rather than copper wires. If the aluminum wire is connected to a copper outlet, and the coefficient of linear expansion for aluminum and copper are different, what hazard could this produce?
11. At very low temperatures some materials become superconductors, that is, their electrical resistance becomes essentially zero. What are the advantages and disadvantages of superconductors?
12. How would you hook up three resistors in a circuit to get (a) the maximum current and (b) the minimum current?

Problems for Chapter 20

20.1 Electric Current

1. How many electrons are associated with a current of 5.00 A?
2. A wire carries a current of 7.50 A for a period of 30.0 min. How much charge flows through a cross section of the wire? How many electrons does this represent?
3. Suppose that the region between two oppositely charged parallel plates is occupied by both singly charged positive ions and by electrons. If 5×10^6 electrons flow from the negative plate to the positive plate in 4.00 s, while 6×10^6 ions flow from the positive plate to the negative plate in the same time, find the value of the net current flowing from the positive plate to the negative plate.

20.2 Ohm's Law

4. A 500-Ω resistor is connected to a 12.0-V battery. Find the current through the resistor.
5. What value of resistance is necessary to get a current of 2.50 A when it is connected to a 120-V source?
6. If a current of 8.75 mA passes through a resistor of 550 Ω, find the voltage drop across the resistor.

20.3 Resistivity

7. Find the resistance of a 100-m spool of #22 B&S gauge copper wire (diameter 6.44×10^{-4} m).
8. The connecting wires in an electrical experiment are 1.00 m long and are made of copper. Their diameter is 6.44×10^{-4} m. What is the resistance of the connecting wires? Is it reasonable to neglect their effect in analyzing a circuit?
9. Does doubling both the length and the diameter of a wire have any effect on its resistance?
10. What length of #22 B&S gauge copper wire is needed to make a resistance of 500 Ω?
11. Find the resistance of an aluminum bar 1.00 m long, 2.00 cm wide, and 1.00 cm high from (a) end to end and (b) from the 1.00-cm side to the other 1.00-cm side.
12. A wire 2.00 m long and 1.00 mm in diameter has resistance of 0.500 Ω. A second wire 4.00 m long and 2.00 mm in diameter has twice the resistivity of the first wire. Find the resistance of the second wire.

20.4 The Variation of Resistance with Temperature

13. If the resistance of a resistor is 20.00 Ω at 20.00 °C, find its resistance at 200.00 °C. The temperature coefficient of resistance α for copper is $3.93 \times 10^{-3}/°C$.
14. If the resistance of a copper wire is 500 Ω at 20 °C, find its resistance at 100 °C.
15. A copper wire has a resistance of 20.00 Ω at room temperature. The wire is placed in an oven and the resistance is then measured as 30.0 Ω. Find the temperature of the oven.
16. The resistance of a copper wire changes from 200 Ω to 210 Ω. What was the change in temperature of the wire?
17. A copper resistor has a resistance of 500 Ω at a temperature of 20.0 °C. What is the resistance if the temperature doubles?

20.5 Conservation of Energy and the Electric Circuit—Power Expended in a Circuit

18. An electric toaster is rated at 1200 W. If it is connected to a 120-V line, what current does it draw? What is the resistance of the toaster? How much energy is used if the toaster is "on" for 1.00 min?
19. A stereo amplifier is rated at 60.0 W. If it is connected to a 120-V line, how much current does it draw? If the stereo is "on" for 5 hr, how much energy is used?
20. A 60.0-W light bulb is connected to a 120-V outlet. What is the current through the bulb? How many electrons flow through the bulb per second?
21. A power line carries 1000 A and has a resistance of 20.0 Ω. How much energy is lost per second in terms of Joule heat?
22. How much power is consumed in starting a car if 200 A is drawn from a 12.0-V battery?

20.6 Resistors in Series

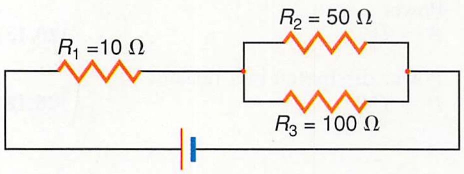
23. Find the equivalent resistance of three resistors of 100, 200, and 300 Ω when connected in series.
24. Find the equivalent resistance of four resistors of 250, 400, 186, and 375 Ω when connected in series.

20.7 Resistors in Parallel

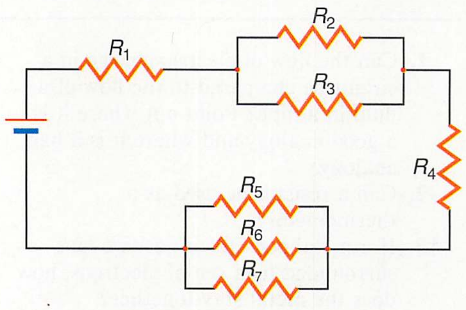
25. Find the equivalent resistance of three resistors of 100, 200, and 300 Ω when connected in parallel.
26. Find the equivalent resistance of four resistors of 250, 400, 186, and 375 Ω when connected in parallel.

20.8 Combinations of Resistors in Series and Parallel

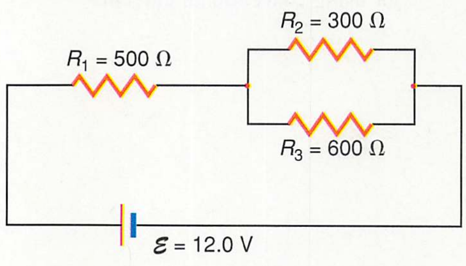
27. Find the equivalent resistance of the circuit in the diagram.



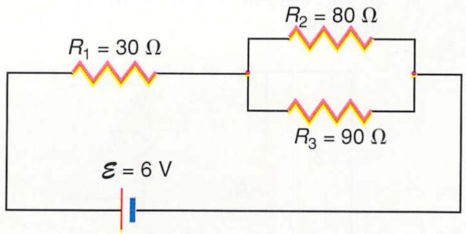
28. Find the equivalent resistance of the circuit in the diagram if $R_1 = 30.0\ \Omega$, $R_2 = 40.0\ \Omega$, $R_3 = 50.0\ \Omega$, $R_4 = 70.0\ \Omega$, $R_5 = 300\ \Omega$, $R_6 = 200\ \Omega$, and $R_7 = 100\ \Omega$.



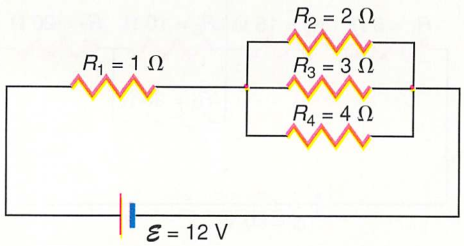
†29. In the diagram find (a) the equivalent resistance of the circuit, (b) the current flowing from the battery, (c) the voltage drop across R_1, (d) the voltage drop across R_2 and R_3, (e) the current through each resistor, (f) the power supplied to the circuit, and (g) the power dissipated in each resistor. The emf of the battery is 12.0 V.



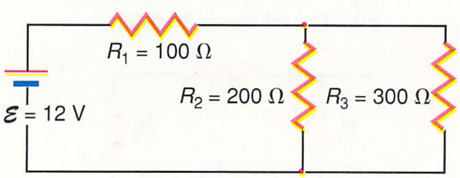
30. Find the current through each resistor in the diagram.



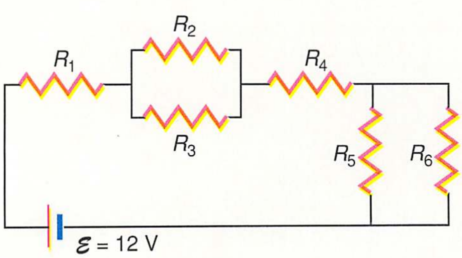
†31. In the diagram, find (a) the equivalent resistance of the resistors in parallel, (b) the equivalent resistance of the circuit, (c) the current from the battery, (d) the voltage drop across R_1, (e) the voltage drop across R_2, R_3, and R_4, (f) the current through each resistor, and (g) the power dissipated in each resistor.



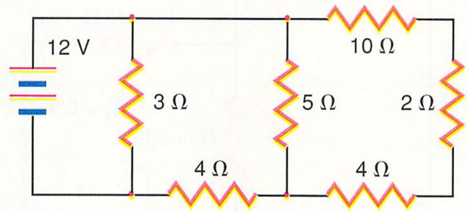
32. Find the voltage drop across R_3 in the diagram.



33. Find (a) the equivalent resistance of the circuit shown in the diagram if $R_1 = 50.0\ \Omega$, $R_2 = 80.0\ \Omega$, $R_3 = 150\ \Omega$, $R_4 = 30.0\ \Omega$, $R_5 = 200\ \Omega$, and $R_6 = 300\ \Omega$ and (b) the current through each resistor.



†34. In the diagram find (a) the equivalent resistance, (b) the current from the battery, (c) the current through each resistor, (d) the voltage drop across each resistor, (e) the power supplied to the circuit, and (f) the power dissipated in each resistor.



20.9 The Electromotive Force and the Internal Resistance of a Battery

35. A 6.00-V battery is connected to a 100-Ω resistor. A voltmeter placed across the resistor measures 5.60 V. Find the internal resistance of the battery.

36. A 12-V battery has an internal resistance of 5.5 Ω. Find the voltage applied to a circuit of 50 Ω.

37. Six 1.50-V batteries are connected in series, with the positive terminal of one battery connected to the negative terminal of the next. What is the emf of the combination? If the internal resistance of each battery is 2.00 Ω, find the terminal voltage when there is a current of 200 mA in the circuit.

38. Six 1.50-V batteries are connected in series to a resistance of 50.0 Ω. Find the current in the circuit (a) neglecting the internal resistance of the battery and (b) taking the 2.00 Ω resistance of each battery into account.

39. Three 12-V batteries are connected in series to a 35-Ω resistor. If the internal resistance of each battery is 10 Ω, 20 Ω, and 30 Ω, respectively, find the voltage drop across the 35-Ω resistor.

40. When a battery is connected to an external resistance of 10.0 Ω, the current through the external resistance is 0.100 A. When the same battery is connected to an external resistance of 5 Ω, the current is 0.150 A. Find the emf of the battery and the internal resistance of the battery.

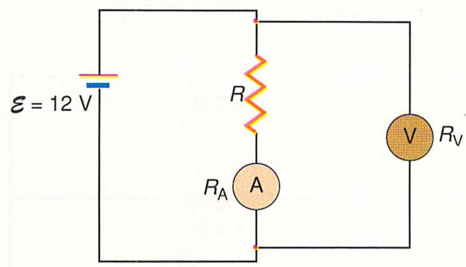
20.10 Making an Ammeter and Voltmeter from a Galvanometer

41. A galvanometer has an internal resistance of 3.00 Ω and gives full-scale deflection for a current of 10.0 mA. What shunt resistance is necessary to convert this to an ammeter that can read a maximum current of 5.00 A?

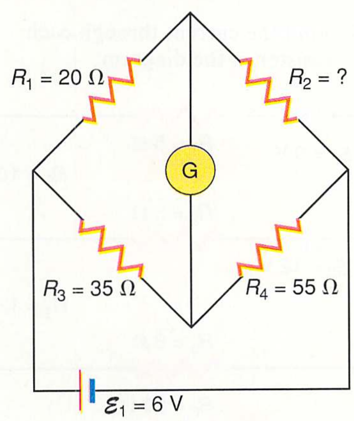
42. A galvanometer has an internal resistance of 3.00 Ω and gives full-scale deflection for a current of 10.0 mA. What series resistor is necessary to convert this to a voltmeter that can read a maximum voltage of 150 V?

20.11 The Wheatstone Bridge

43. The voltmeter reads 12.0 V and the ammeter reads a current of 5.45×10^{-2} A in the circuit shown. The ammeter has a resistance of 20.0 Ω and the voltmeter has a resistance of 5000 Ω. Taking the resistance of the ammeter and voltmeter into account, find the value of the resistor R.



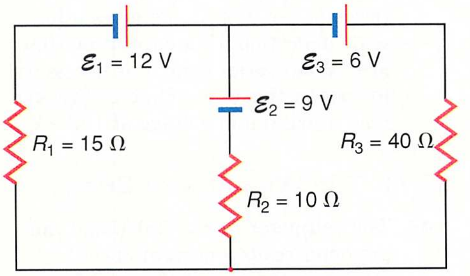
44. Find the value of R_2 in the diagram if the bridge is balanced.



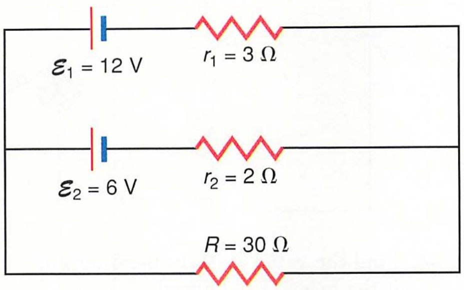
45. Find the equivalent resistance of the Wheatstone bridge in problem 44 when the bridge is balanced. Find the current through each resistor.

20.12 Kirchhoff's Rules

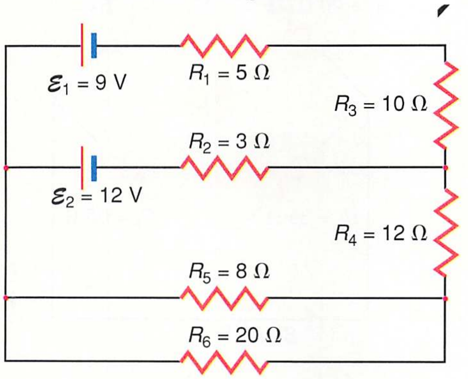
†46. In the accompanying diagram (a) find the current through each resistor and (b) plot the potential as you traverse each loop.



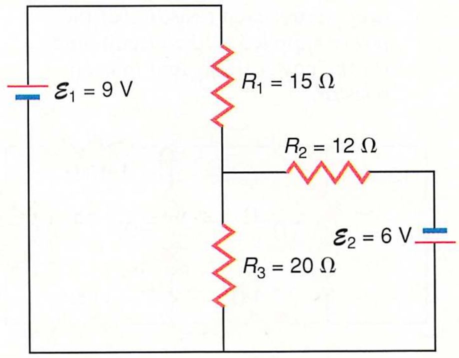
†47. Two batteries, with emf's and internal resistances shown, are connected in parallel. Using Kirchhoff's rules, find the current through R and the voltage drop across R.



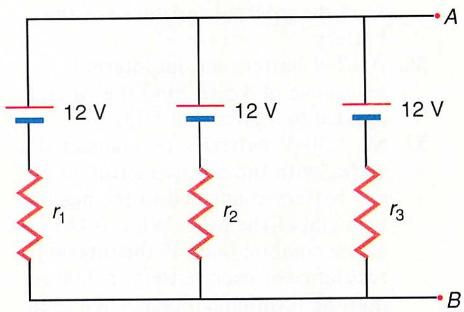
†48. Find the current through each resistor in the diagram.



†49. Using Kirchhoff's rules, find the current through each resistor in the diagram.

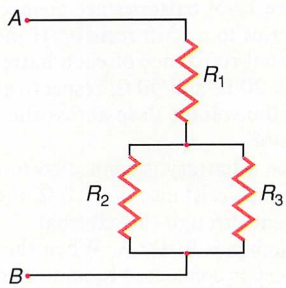


50. Three 12.0-V batteries with different internal resistances are connected in parallel as shown in the diagram. If $r_1 = 10.0\ \Omega$, $r_2 = 20.0\ \Omega$, and $r_3 = 30.0\ \Omega$, find the voltage drop across AB.

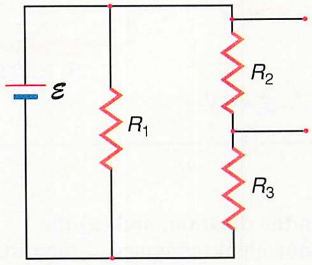


Additional Problems

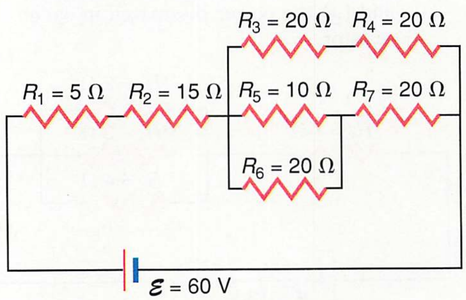
†51. Find the potential difference across AB in the accompanying diagram if $R_1 = 10.0\ \Omega$, $R_2 = 20.0\ \Omega$, $R_3 = 30.0\ \Omega$, and the current through R_3 is 0.300 A.



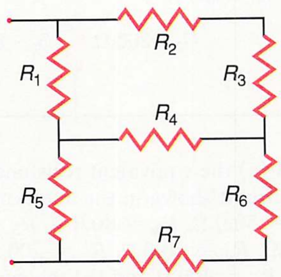
52. Find the voltage drop across R_2 if $R_1 = 20.0\ \Omega$, $R_2 = 30.0\ \Omega$, $R_3 = 50.0\ \Omega$, and the emf is 6.00 V in the diagram.



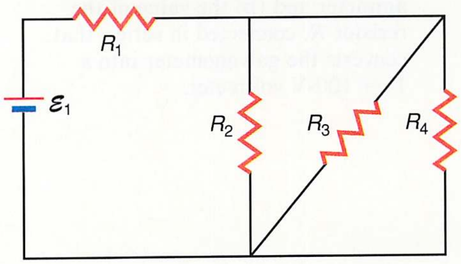
53. Find the current through each of the seven resistors, and the potential drop across each resistor in the circuit in the diagram.



†54. Find the equivalent resistance of the circuit shown in the diagram if $R_1 = 10.0\ \Omega$, $R_2 = 20.0\ \Omega$, $R_3 = 30.0\ \Omega$, $R_4 = 40.0\ \Omega$, $R_5 = 50.0\ \Omega$, $R_6 = 60.0\ \Omega$, and $R_7 = 70.0\ \Omega$.



†55. If $R_1 = 10.0\ \Omega$, $R_2 = 20.0\ \Omega$, $R_3 = 30.0\ \Omega$, and $R_4 = 40.0\ \Omega$ in the circuit shown, find (a) the equivalent resistance of the circuit and, if $\mathscr{E}_1 = 12.0$ V, (b) the current through each resistor.



56. (a) What is the resistance of 100 resistors of 10.0 Ω each if they are all in series? (b) What is the resistance of 100 resistors of 10.0 Ω each if they are all in parallel?

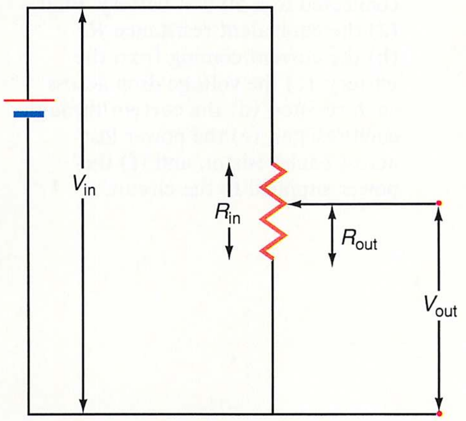
†57. A 200-W immersion heater is placed in a beaker of water containing 0.500 liters at room temperature. How long will it take for the water to boil?

†58. An electrically insulated coil of wire is immersed in 100.0 g of water in a calorimeter cup at room temperature. The wire is connected to a 120-V source and a current of 2.00 A is observed in the wire. Find the temperature of the water after 60.0 s.

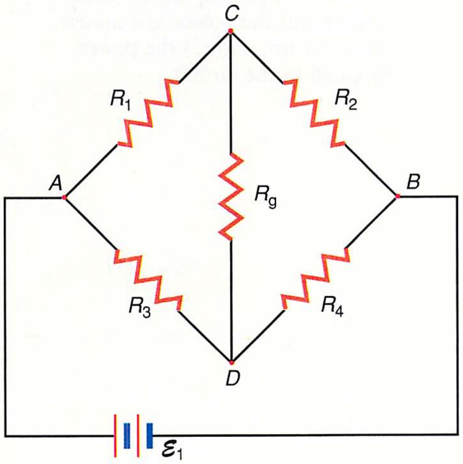
†59. A voltage divider is shown in the diagram. The resistor R is a variable slide wire resistor. Show that by sliding the arrow contact in the figure along the slide wire any fraction of the original applied voltage can be obtained. In particular show that the voltage out of the divider is given by

$$V_{out} = \frac{l_{out}}{l_{in}} V_{in}$$

where l_{in} is the original length of the wire resistor and l_{out} is the shorter length of the wire resistor that the output connector is attached to.



†60. The Wheatstone bridge shown in the diagram is *not* balanced. Using Kirchhoff's rules find the current through each resistor if $R_1 = 10.0\ \Omega$, $R_2 = 20.0\ \Omega$, $R_3 = 30.0\ \Omega$, $R_4 = 40.0\ \Omega$, $R_g = 50.0\ \Omega$, and $\mathscr{E}_1 = 6.00$ V. Find the equivalent resistance of the circuit.



†61. In problem 60, find the potential differences across points (a) *AC*, (b) *AD*, (c) *CD*, (d) *CB*, and (e) *DB*.

Interactive Tutorials

62. Resistors in series. Three resistors, $R_1 = 25.0\ \Omega$, $R_2 = 45.5\ \Omega$, and $R_3 = 83.5\ \Omega$, are connected in series to a 50.0-V battery. Find (a) the equivalent resistance R, (b) the current coming from the battery, (c) the current through each resistor, (d) the voltage drop across each resistor, (e) the power lost across each resistor, and (f) the power supplied to the circuit.

63. Resistors in parallel. Three resistors, $R_1 = 25.0\ \Omega$, $R_2 = 45.5\ \Omega$, and $R_3 = 83.5\ \Omega$, are connected in parallel to a 50.0-V battery. Find (a) the equivalent resistance R, (b) the current coming from the battery, (c) the voltage drop across each resistor, (d) the current through each resistor, (e) the power lost across each resistor, and (f) the power supplied to the circuit.

64. Combination of resistors in series and parallel. Resistor $R_1 = 25.0\ \Omega$, is in series with the parallel resistors $R_2 = 45.5\ \Omega$ and $R_3 = 83.5\ \Omega$, as in figure 20.14(a). The resistors are connected to a 50.0-V battery. Find (a) the equivalent resistance R, (b) the current coming from the battery, (c) the voltage drop across each resistor, (d) the current through each resistor, (e) the power lost across each resistor, and (f) the power supplied to the circuit.

65. A galvanometer has an internal resistance of $R_g = 3.00\ \Omega$ and gives full-scale deflection for a current of $I_g = 10.0$ mA. Calculate (a) the value of the shunt resistor R_s, connected in parallel, that converts the galvanometer into a $I = 5.00$-A ammeter and (b) the value of the resistor R, connected in series, that converts the galvanometer into a $V = 100$-V voltmeter.