PROBLEMS

Section 18.2

•P20 Which of the following statements about a metal wire *in equilibrium* are true? List all that apply. (1) There cannot be excess charges on the surface of the wire. (2) There is no net flow of mobile electrons inside the wire. (3) There are no excess charges in the interior of the wire. (4) There may be excess charges in the interior of the wire. (5) The net electric field everywhere inside the wire is zero. (6) There may be excess charges on the surface of the wire. (7) The interior of the metal wire is neutral. (8) There may be a constant flow of mobile electrons inside the wire. (9) The electric field inside the wire may be nonzero but uniform.

•P21 Which of the following statements about a metal wire *in the steady state* are true? List all that apply. (1) There is a constant flow of mobile electrons inside the wire. (2) The net electric field everywhere inside the wire is zero. (3) There are no excess charges in the interior of the wire. (4) There cannot be excess charges on the surface of the wire. (5) There is no net flow of mobile electrons inside the wire. (6) There may be excess charges on the surface of the wire. (7) There may be excess charges in the interior of the wire. (8) There may be a nonzero, uniform electric field inside the wire. (9) The interior of the metal wire is neutral.

•P22 Electron current $i = nA\bar{v} = nAuE$: **(a)** What are the units of electron current? **(b)** What is n? What are its units? **(c)** What is A? What are its units? **(d)** What is $\bar{v}$? What are its units? **(e)** What is u? What are its units?

•P23 In the circuit shown in Figure 18.92, what are the relationships among i_A, i_B, i_C, and i_D? How much current flows through the lower battery?

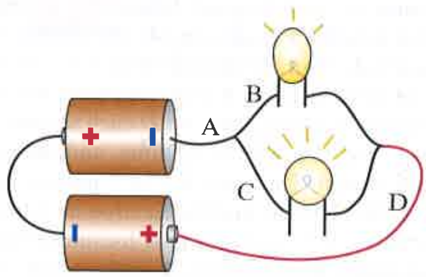

Figure 18.92

•P24 A steady-state current runs in the circuit shown in Figure 18.93. The narrow resistor and thick connecting wires are made of the same material.

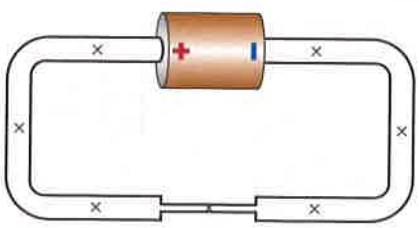

Figure 18.93

Which of the following quantities are greater in the thin resistor than in the thick wire? List all that apply: u, n, E, v, A, i, or none of these.

•P25 Consider the circuit fragment in Figure 18.94. **(a)** What is the absolute value of the outward-going conventional current I_2? **(b)** In this case, did we make the right guess about the direction of the conventional current I_2? **(c)** Suppose I_3 is 20 A; what is the absolute value of the outward-going conventional current I_2? **(d)** In this case, did we make the right guess about the direction of the conventional current I_2?

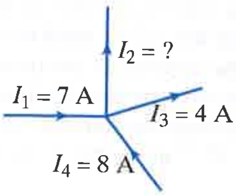

Figure 18.94

•P26 In the circuit in Figure 18.95 the narrow resistor is made of the same material as the thick connecting wires. In the steady state, which graph in Figure 18.96 correctly shows the magnitude of the electric field at locations around the circuit?

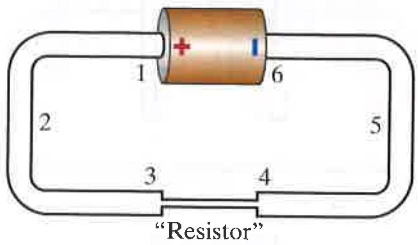

Figure 18.95

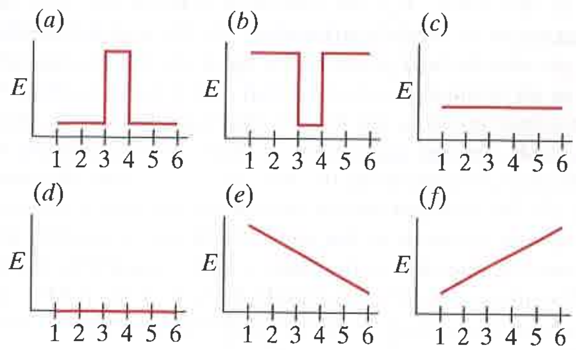

Figure 18.96

In the steady state, which graph in Figure 18.97 correctly shows the drift speed of the electrons at locations around the circuit?

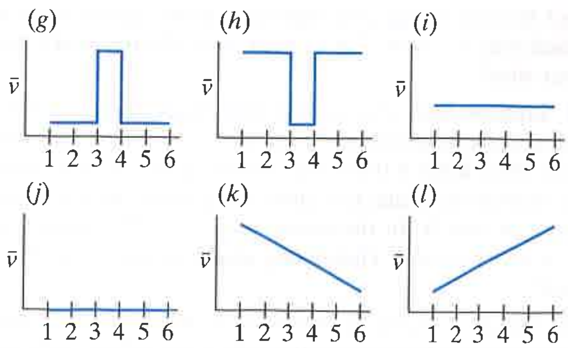

Figure 18.97

Section 18.3

•P27 The drift speed in a copper wire is 7×10^{-5} m/s for a typical electron current. Calculate the magnitude of the electric field E inside the copper wire. The mobility of mobile electrons in copper is 4.5×10^{-3} (m/s)/(N/C). (Note that though the electric field in the wire is very small, it is adequate to push a sizable electron current through the copper wire.)

•P28 Suppose that a wire leads into another, thinner wire of the same material that has only a third the cross-sectional area. In the steady state, the number of electrons per second flowing through the thick wire must be equal to the number of electrons per second flowing through the thin wire. If the drift speed $\bar{v}_1$ in the thick wire is 4×10^{-5} m/s, what is the drift speed $\bar{v}_2$ in the thinner wire?

•P29 In the circuit in Figure 18.98 a mechanical battery keeps a steady-state current running in a wire that has rather low electron mobility.

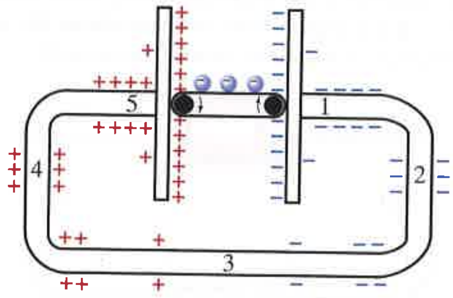

Figure 18.98

Which of the following statements about the circuit are true? List all that apply. (1) The electric field inside the wire varies in magnitude, depending on location. (2) At location 3 inside the wire the electric field points to the right. (3) The electric field is zero at all locations inside the metal wire. (4) At location 3 the electric field points to the left. (5) The magnitude of the electric field inside the wire is the same at all locations inside the wire. (6) Mobile electrons inside the wire push each other through the wire. (7) The nonzero electric field inside the wire is created by the moving electrons in the wire. (8) At every location inside the wire the direction of the electric field is parallel to the wire. (9) The nonzero electric field inside the wire is created by excess charges on the surface of the wire and in and on the mechanical battery.

•P30 Suppose that a wire leads into another, thinner wire of the same material that has only half the cross-sectional area. In the steady state, the number of electrons per second flowing through the thick wire must be equal to the number of electrons per second flowing through the thin wire. If the electric field E_1 in the thick wire is 1×10^{-2} N/C, what is the electric field E_2 in the thinner wire?

•P31 Suppose that wire A and wire B are made of different metals and are subjected to the same electric field in two *different* circuits. Wire B has 6 times the cross-sectional area, 1.3 times as many mobile electrons per cubic centimeter, and 4 times the mobility of wire A. In the steady state, 2×10^{18} electrons enter wire A every second. How many electrons enter wire B every second?

••P32 Inside a chemical battery it is not actually individual electrons that are transported from the + end to the − end. At the + end of the battery an "acceptor" molecule picks up an electron entering the battery, and at the − end a different "donor" molecule gives up an electron, which leaves the battery. Ions rather than electrons move between the two ends to transport the charge inside the battery.

When the supplies of acceptor and donor molecules are used up in a chemical battery, the battery is dead, because it can no longer accept or release electrons. The electron current in electrons per second, times the number of seconds of battery life, is equal to the number of donor (or acceptor) molecules in the battery.

A flashlight battery contains approximately half a mole of donor molecules. The electron current through a thick-filament bulb powered by two flashlight batteries in series is about 0.3 A. About how many hours will the batteries keep this bulb lit?

••P33 All of the wires in the circuit shown in Figure 18.99 are made of the same material, but one wire has a smaller radius than the other wires.

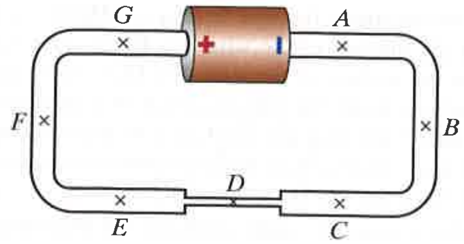

Figure 18.99

Which of the following statements are true of this circuit in the steady state? List all that apply. (1) The drift speed of electrons passing location D is greater than the drift speed of electrons passing location G. (2) The magnitude of the electric field is the same at each location labeled by a letter. (3) The electric field at location F points up. (4) The electric field at G is larger in magnitude than the electric field at C. (5) The number of electrons passing location B each second is the same as the number of electrons passing location D each second.

The radius of the thin wire is 0.22 mm, and the radius of the thick wire is 0.55 mm. There are 4×10^{28} mobile electrons per cubic meter of this material, and the electron mobility is 6×10^{-4} (m/s)/(V/m). If 6×10^{18} electrons pass location D each second, how many electrons pass location B each second? What is the magnitude of the electric field at location B?

19,5 **••P34** Figure 18.100 is a top view of a portion of a circuit containing three identical light bulbs (the rest of the circuit including the batteries is not shown). The connecting wires are made of copper.

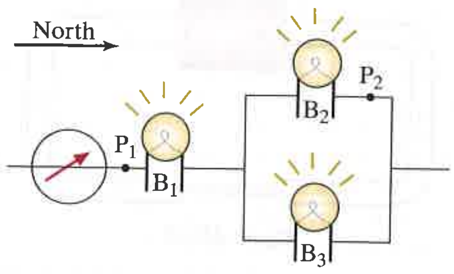

Figure 18.100

(a) The compass is placed on top of the wire, and it deflects 20° away from north as shown (the wire is underneath the compass). In what direction are the electrons moving at location P_1? How do you know? **(b)** In the steady state, 3×10^{18} electrons pass location P_1 every second. How many electrons pass location P_2 every second? Explain briefly. **(c)** Give the relative brightnesses of bulbs B_1, B_2, and B_3. Explain briefly. **(d)** There are 6.3×10^{28} mobile electrons per cubic meter in tungsten. The cross-sectional area of the tungsten filament in bulb B_1 is $0.01\,\text{mm}^2$ (which is $1 \times 10^{-8}\,\text{m}^2$). The electron mobility in hot tungsten is 1.2×10^{-4} (m/s)/(N/C). Calculate the electric field inside the tungsten filament in bulb B_1. Give both the direction and the magnitude of the electric field.

••P35 Consider the circuit containing three identical light bulbs shown in Figure 18.101. North is indicated in the diagram. Compasses are placed under the wires at locations A and B. **(a)** The magnitude of the deflection of compass A is 13° away from north. In what direction does the needle point? Draw a sketch. **(b)** What is the magnitude of the deflection of the needle of compass B? In what direction does the needle point? Draw a sketch. Explain your reasoning. **(c)** In the steady state 1.5×10^{18} electrons per second enter bulb 1. There are 6.3×10^{28} mobile electrons per cubic meter in tungsten. The cross-sectional area of the tungsten filament in bulb 1 is $1 \times 10^{-8}\,\text{m}^2$. The electron mobility in hot tungsten is 1.2×10^{-4} (m/s)/(N/C). Calculate the electric field inside the tungsten filament in bulb 3. Give both the direction and the magnitude of the electric field.

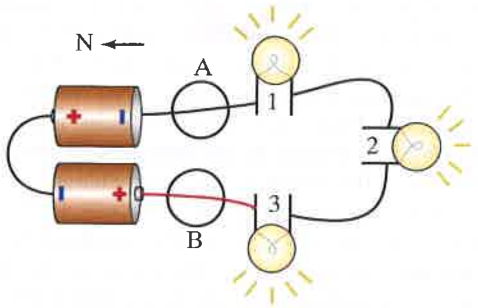

Figure 18.101

Section 18.10

Base your analyses in the following problems on the principles discussed in this chapter. If you wish to use equations derived elsewhere, you must justify them in terms of the microscopic analysis in terms of field that was introduced in this chapter.

•P36 **(a)** The emf of a particular flashlight battery is 1.7 V. If the battery is 4.5 cm long and the radius of the cylindrical battery is 1 cm, estimate roughly the amount of charge on the positive end plate of the battery. **(b)** Is this amount of charge sufficient to repel noticeably a positively charged piece of invisible tape?

•P37 A Nichrome wire 30 cm long and 0.25 mm in diameter is connected to a 1.5 V flashlight battery. What is the electric field inside the wire? Why don't you have to know how the wire is bent? How would your answer change if the wire diameter were 0.35 mm? (Note that the electric field in the wire is quite small compared to the electric field near a charged tape.)

•P38 Why does the brightness of a bulb not change noticeably when you use longer copper wires to connect it to the battery? (1) Very little energy is dissipated in the thick connecting wires. (2) The electric field in connecting wires is very small, so emf $\approx E_{\text{bulb}}L_{\text{bulb}}$. (3) Electric field in the connecting wires is zero, so emf $= E_{\text{bulb}}L_{\text{bulb}}$. (4) Current in the connecting wires is smaller than current in the bulb. (5) All the current is used up in the bulb, so the connecting wires don't matter.

•P39 A Nichrome wire 48 cm long and 0.25 mm in diameter is connected to a 1.6 V flashlight battery. What is the electric field inside the wire? Next, the wire is replaced by a different Nichrome wire with the same length, but diameter 0.20 mm. Now what is the electric field inside the wire?

•P40 In a circuit with one battery, connecting wires, and a 12 cm length of Nichrome wire, a compass deflection of 6° is observed. What compass deflection would you expect in a circuit containing two batteries in series, connecting wires, and a 36 cm length of thicker Nichrome wire (double the cross-sectional area of the thin piece)? Explain.

•P41 In Figure 18.102, suppose that $V_C - V_F = 8$ V, and $V_D - V_E = 4.5$ V.

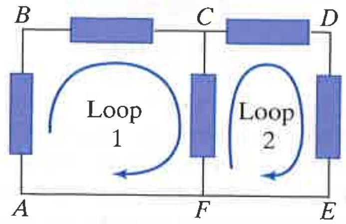

Figure 18.102

(a) What is the potential difference $V_C - V_D$? **(b)** If the element between C and D is a battery, is the + end of the battery at C or at D?

•P42 What would be the potential difference $V_C - V_B$ across the thin resistor in Figure 18.103 if the battery emf is 3.5 V? Assume that the electric field in the thick wires is very small (so that the potential differences along the thick wires are negligible). Do you have enough information to determine the current I in the circuit?

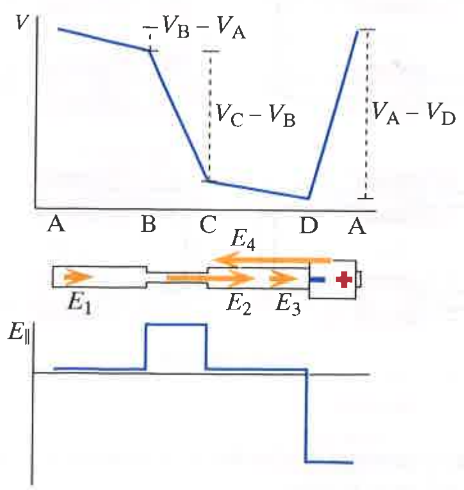

Figure 18.103

••P43 A circuit is constructed from two batteries and two wires, as shown in Figure 18.104. Each battery has an emf of 1.3 V. Each wire is 26 cm long and has a diameter of 7×10^{-4} m. The wires are made of a metal that has 7×10^{28} mobile electrons per cubic meter; the electron mobility is 5×10^{-5} (m/s)/(V/m). A steady current runs through the circuit. The locations marked by × and labeled by a letter are in the interior of the wire.

(a) Which of these statements about the electric field in the interior of the wires, at the locations marked by ×'s, are true? List all that apply. (1) The magnitude of the electric field at location G is larger than the magnitude of the electric field at location F.

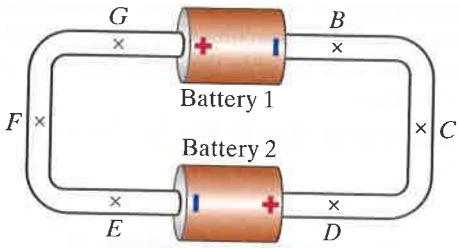

Figure 18.104

(2) At every marked location the magnitude of the electric field is the same. (3) At location B the electric field points to the left. **(b)** Write a correct energy conservation (round-trip potential difference) equation for this circuit, along a round-trip path starting at the negative end of battery 1 and traveling counterclockwise through the circuit (that is, traveling to the left through the battery, and continuing on around the circuit in the same direction). **(c)** What is the magnitude of the electric field at location B? **(d)** How many electrons per second enter the positive end of battery 2? **(e)** If the cross-sectional area of both wires were increased by a factor of 2, what would be the magnitude of the electric field at location B? **(f)** Which of the diagrams in Figure 18.105 best shows the approximate distribution of excess charge on the surface of the circuit?

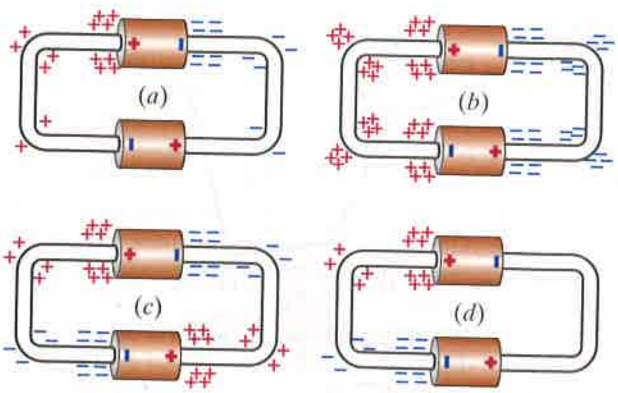

Figure 18.105

••P44 Three identical light bulbs are connected to two batteries as shown in Figure 18.106.

(a) To start the analysis of this circuit you must write energy conservation (loop) equations. Each equation must involve a round-trip path that begins and ends at the same location. Each segment of the path should go through a wire, a bulb, or a battery (not through the air). How many valid energy conservation (loop) equations is it possible to write for this circuit? **(b)** Which of the following equations are valid energy conservation (loop) equations for this circuit? E_1 refers to the electric field in bulb 1; L refers to the length of a bulb filament. Assume that the electric field in the connecting wires is small enough to neglect.

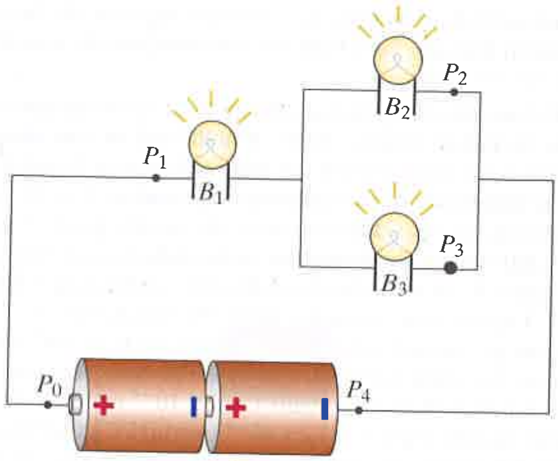

Figure 18.106

(1) $+E_2L - E_3L = 0$, (2) $E_1L - E_3L = 0$, (3) $+2\text{emf} - E_2L - E_3L = 0$, (4) $E_1L - E_2L = 0$, (5) $+2\text{emf} - E_1L - E_2L = 0$, (6) $+2\text{emf} - E_1L - E_3L = 0$, (7) $+2\text{emf} - E_1L - E_2L - E_3L = 0$. **(c)** It is also necessary to write charge conservation equations (node) equations. Each such equation must relate electron current flowing into a node to electron current flowing out of a node. Which of the following are valid charge conservation equations for this circuit? (1) $i_1 = i_3$, (2) $i_1 = i_2$, (3) $i_1 = i_2 + i_3$.

Each battery has an emf of 1.5 V. The length of the tungsten filament in each bulb is 0.008 m. The radius of the filament is 5×10^{-6} m (it is very thin!). The electron mobility of tungsten is 1.8×10^{-3} (m/s)/(V/m). Tungsten has 6×10^{28} mobile electrons per cubic meter. Since there are three unknown quantities, we need three equations relating these quantities. Use any two valid energy conservation equations and one valid charge conservation equation to solve for E_1, E_2, i_1, and i_2.

••P45 The circuit shown in Figure 18.107 consists of a single battery, whose emf is 1.8 V, and three wires made of the same material but having different cross-sectional areas. Each thick wire has cross-sectional area 1.4×10^{-6} m^2 and is 25 cm long. The thin wire has cross-sectional area 5.9×10^{-8} m^2 and is 6.1 cm long.

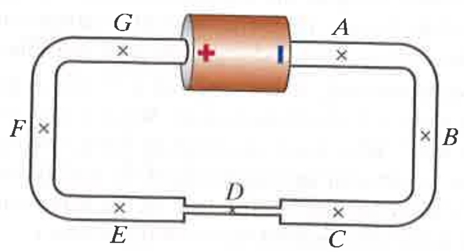

Figure 18.107

In this metal, the electron mobility is 5×10^{-4} (m/s)/(V/m), and there are 4×10^{28} mobile electrons/m^3.

(a) Which of the following statements about the circuit in the steady state are true? (1) At location B the electric field points toward the top of the page. (2) The magnitude of the electric field at locations F and C is the same. (3) The magnitude of the electric field at locations D and F is the same. (4) The electron current at location D is the same as the electron current at location F. **(b)** Write a correct energy conservation (loop) equation for this circuit, following a path that starts at the negative end of the battery and goes counterclockwise. **(c)** Write a correct charge conservation (node) equation for this circuit. **(d)** Use the appropriate equation(s), plus the equation relating electron current to electric field, to solve for the magnitudes E_D and E_F of the electric field at locations D and F. **(e)** Use the appropriate equation(s) to calculate the electron current at location D in the steady state.

••P46 In the circuit shown in Figure 18.108, two thick copper wires connect a 1.5 V battery to a Nichrome wire. Each thick connecting wire is 17 cm long and has a radius of 9 mm. Copper has 8.4×10^{28} mobile electrons per cubic meter and an electron mobility of 4.4×10^{-3} (m/s)/(V/m). The Nichrome wire is 8 cm long, and has a radius of 3 mm. Nichrome has 9×10^{28} mobile electrons per cubic meter and an electron mobility of 7×10^{-5} (m/s)/(V/m).

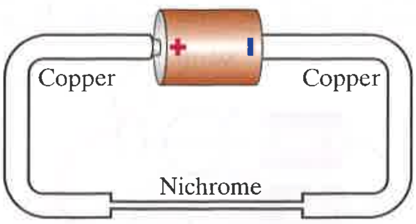

Figure 18.108

(a) What is the magnitude of the electric field in the thick copper wire? **(b)** What is the magnitude of the electric field in the thin Nichrome wire?

••P47 When a single thick-filament bulb of a particular kind and two batteries are connected in series, 3×10^{18} electrons pass through the bulb every second. When two batteries connected in series are connected to a single thin-filament bulb, with a filament made of the same material and the same length as that of the thick-filament bulb but smaller cross section, only 1.5×10^{18} electrons pass through the bulb every second.
(a) In the circuit shown in Figure 18.109, how many electrons per second flow through the thin-filament bulb? **(b)** What approximations or simplifying assumptions did you make? **(c)** Show approximately the surface charge on a diagram of the circuit.

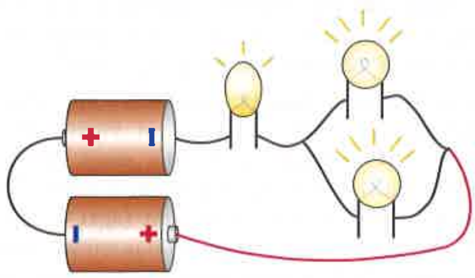

Figure 18.109

••P48 In the circuit shown in Figure 18.110, the two thick wires and the thin wire are made of Nichrome.

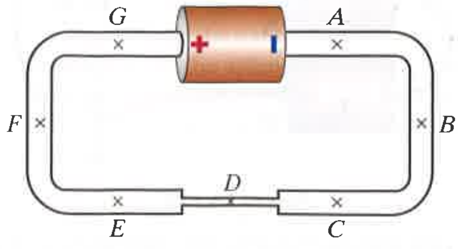

Figure 18.110

(a) Show the steady-state electric field at the locations indicated, including in the thin wire. **(b)** Carefully draw pluses and minuses on your own diagram to show the approximate surface-charge distribution in the steady state. Make your drawing show clearly the differences between regions of high surface-charge density and regions of low surface-charge density. **(c)** The emf of the battery is 1.5 V. In Nichrome there are $n = 9 \times 10^{28}$ mobile electrons per m^3, and the mobility of mobile electrons is $u = 7 \times 10^{-5}$ (m/s)/(N/C). Each thick wire has length $L_1 = 20\,\text{cm} = 0.2\,\text{m}$ and cross-sectional area $A_1 = 9 \times 10^{-8}\,\text{m}^2$. The thin wire has length $L_2 = 5\,\text{cm} = 0.05\,\text{m}$ and cross-sectional area $A_2 = 1.5 \times 10^{-8}\,\text{m}^2$. (The total length of the three wires is 45 cm.) In the steady state, calculate the number of electrons entering the thin wire every second. Do not make any approximations, and do not use Ohm's law or series-resistance equations. State briefly where each of your equations comes from.

••P49 Three identical thick-filament bulbs are in series as shown in Figure 18.111. Thick copper wires connect the bulbs. In the steady state, 3×10^{17} electrons leave the battery at location A every second.

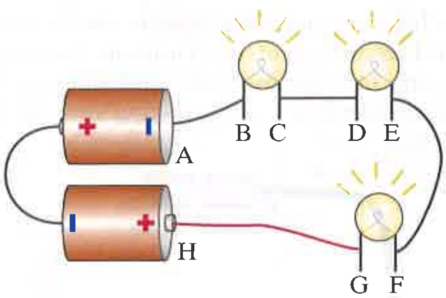

Figure 18.111

(a) How many electrons enter the second bulb at location D every second? If there is insufficient information to give a numerical answer, state how it compares with 3×10^{17}. Justify your answer carefully. **(b)** Next, the middle bulb (at DE) is replaced by a wire, as shown in Figure 18.112. Now how many electrons leave the batteries at location A every second? Explain clearly! If you have to make an approximation, state what it is. Do not use ohms or series-resistance equations in your explanation, unless you can show in detail how these concepts follow from the microscopic analysis introduced in this chapter.

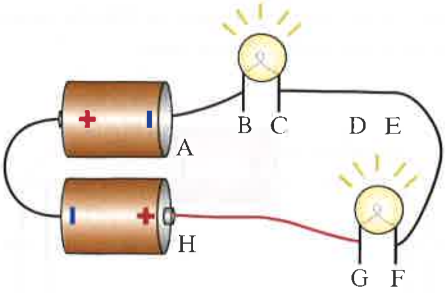

Figure 18.112

(c) Check your analysis by trying the experiment with a partner. Try to find three thick-filament bulbs that glow equally brightly when in series with each other, because bulb construction varies slightly in manufacturing. Remember to arrange the circuit so that the largest compass deflection is no more than 15°. Report the deflections that you observe. Does the experiment agree with your prediction? (If not, can you explain the discrepancy? Be specific. For example, if the current is larger than predicted, explain why it is larger than predicted.) **(d)** Finally, the last bulb (at FG) is replaced by a bulb identical in every way except that its filament has twice as large a cross-sectional area, as shown in Figure 18.113. Now how many electrons leave the batteries at location A every second? Explain clearly! If you have to make an approximation, state what it is.

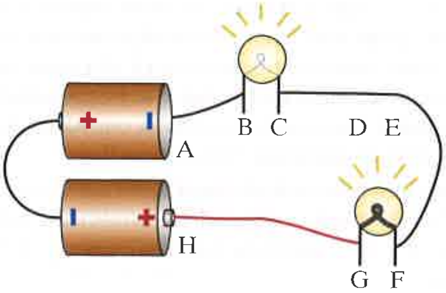

Figure 18.113

••P50 The following questions refer to the circuit shown in Figure 18.114, consisting of two flashlight batteries and two Nichrome wires of different lengths and different thicknesses as shown (corresponding roughly to your own thick and thin Nichrome wires).

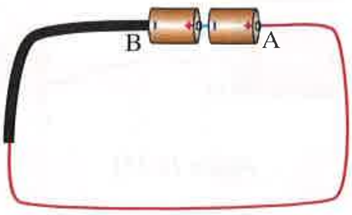

Figure 18.114

The thin wire is 50 cm long, and its diameter is 0.25 mm. The thick wire is 15 cm long, and its diameter is 0.35 mm. **(a)** The emf of each flashlight battery is 1.5 V. Determine the steady-state electric field inside each Nichrome wire. Remember that in the steady state you must satisfy both the current node rule and energy conservation. These two principles give you two equations for the two unknown fields. **(b)** The electron mobility in room-temperature Nichrome is about 7×10^{-5} (m/s)/(N/C). Show that it takes an electron 36 min to drift through the two Nichrome wires from location B to location A. **(c)** On the other hand, about how long did it take to establish the steady state when the circuit was first assembled? Give a very approximate numerical answer, not a precise one. **(d)** There are about 9×10^{28} mobile electrons per cubic meter in Nichrome. How many electrons cross the junction between the two wires every second?

•P51 A Nichrome wire 75 cm long and 0.25 mm in diameter is connected to a 1.7 V flashlight battery. **(a)** What is the electric field inside the wire? **(b)** Next, the Nichrome wire is replaced by a wire of the same length and diameter, and same mobile electron density but with electron mobility 4 times as large as that of Nichrome. Now what is the electric field inside the wire? **(c)** The electron current in the first circuit (Nichrome) is i_1. The electron current in the second circuit (wire with higher mobility) is i_2. Which of the following statements is true? (1) $i_2 = i_1$, (2) $i_2 < i_1$, (3) $i_2 > i_1$, (4) Not enough information is given to compare the two currents.

••P52 Two circuits are assembled using 1.5 V batteries, thick copper connecting wires, and thin-filament bulbs (Figure 18.115). Bulbs A, B, and C are identical thin-filament bulbs. Compasses are placed under the wires at the indicated locations. **(a)** On sketches of the circuits, draw the directions the compass needles will point, and indicate the approximate magnitude of the compass deflections in degrees. Note that the deflection is given at one location. If you do not have enough information to give a number, then indicate whether it will be greater than, less than, or equal to 5°. (Assume that the compasses are adequately far away from the steel-jacketed batteries.) **(b)** Briefly explain your reasoning about the magnitudes of the compass deflections. **(c)** On the same sketches of the circuits, show very approximately the distribution of surface charge. **(d)** The tungsten filament in each of the bulbs is 4 mm long with a radius of 6×10^{-6} m. Calculate the electric field inside each of the three bulbs, E_A, E_B, and E_C.

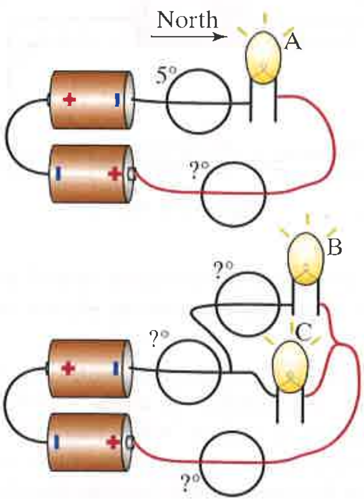

Figure 18.115

••P53 A circuit is assembled that contains a thin-filament bulb and a thick-filament bulb as shown in Figure 18.116, with four compasses placed underneath the wires (we're looking down on the circuit). When the thin-filament bulb is unscrewed from its socket, the compass on the left (next to the battery) deflects 15°. When the thin-filament bulb is screwed back in and the thick-filament bulb is unscrewed, the compass on the left deflects 4°.

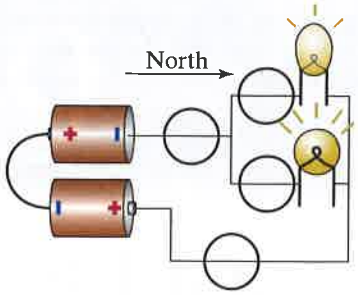

Figure 18.116

With both bulbs screwed into their sockets, draw the orientations of the needle on each compass, and write the compass deflection in degrees beside the compass. Explain briefly.

•••P54 A solid metal sphere of radius R carries a uniform charge of $+Q$. Another solid metal sphere of radius r carries a uniform charge $-q$. The amount of charge is not enough to cause breakdown in air. The two spheres are very far apart (distance $\gg R$ and distance $\gg r$). At $t = 0$ a very thin wire of length L is connected to the two spheres (Figure 18.117). The mobility u of mobile electrons in this wire is very small, and the wire conducts electrons so poorly that it takes about an hour for the system to reach equilibrium. In a short time Δt (a few seconds) how many electrons leave the sphere of radius r? There are n mobile electrons per cubic meter in the wire, and the wire has a constant cross-sectional area A. Explain your work and any approximations you need to make.

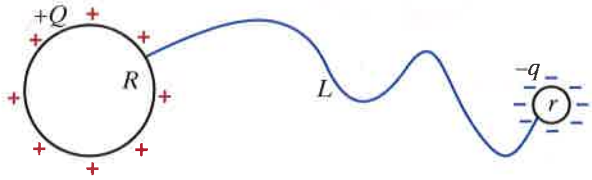

Figure 18.117

ANSWERS TO CHECKPOINTS

1 $I_1 + I_4 = I_2 + I_3$; $I_2 = 3$ A; $I_2 = -2$ A, where the minus sign means that the current is entering the node rather than leaving. It is not true that current must be the same in every part of a circuit, only that the current entering a node must equal the current leaving a node; here $i_1 = i_2 + i_3$.

2 $\bar{v}_2 = 8 \times 10^{-5}$ m/s; $E_2 = 1.8 \times 10^{-2}$ N/C

3 See Figure 18.118.

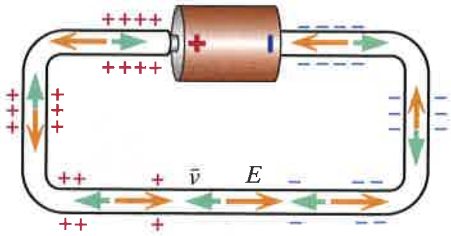

Figure 18.118

4 See Figure 18.119.

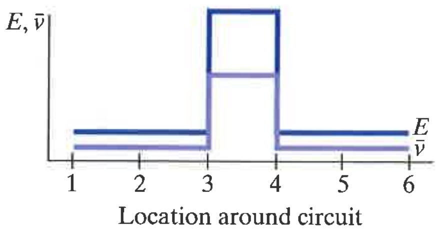

Figure 18.119

5 See Figure 18.120.

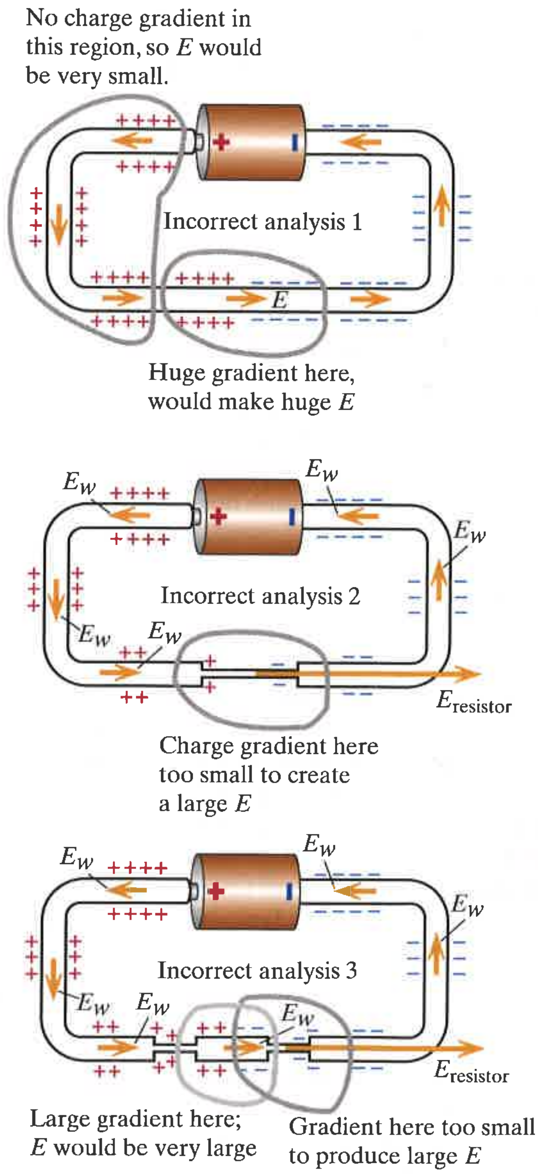

Figure 18.120