

**Problem 25.58** A resistor with resistance  $R$  is connected to a battery that has emf  $12.0\text{ V}$  and internal resistance  $r = 0.40\ \Omega$ . For what two values of  $R$  will the power in the resistor be  $80.0\text{ W}$ ?

**Solution.** The power  $P$  delivered to a resistor is

$$P = I^2 R, \quad (25.18)$$

where  $I$  is the current through the resistor and  $R$  its resistance. We can find the current from

$$V_{ab} = \mathcal{E} - Ir, \quad (25.17)$$

where  $V_{ab}$  is the voltage difference across the resistor,  $\mathcal{E}$  is the emf of the battery, and  $r$  its internal resistance. We also know that

$$V_{ab} = IR. \quad (25.11)$$

Substituting (25.11) into (25.17), we get

$$IR = \mathcal{E} - Ir \implies \mathcal{E} = I(R + r) \implies I = \frac{\mathcal{E}}{R + r}.$$

Now we can substitute this result into (25.18) and solve for  $R$ :

$$\begin{aligned} P &= \frac{\mathcal{E}^2}{(R + r)^2} R \implies \mathcal{E}^2 R = P(R^2 + 2Rr + r^2) \implies 0 = PR^2 + (2Pr - \mathcal{E}^2)R + Pr^2 \\ &\implies R = \frac{\mathcal{E}^2 - 2Pr \pm \sqrt{(2Pr - \mathcal{E}^2)^2 - 4P^2 r^2}}{2P} \end{aligned}$$

Plugging in our numerical values for  $r$ ,  $P$ , and  $\mathcal{E}$ , and recalling that  $1\text{ W} = 1\text{ V}^2\ \Omega^{-1}$ , we get

$$\begin{aligned} R &= \frac{(12.0\text{ V})^2 - 2(80.0\text{ W})(0.40\ \Omega) \pm \sqrt{[2(80.0\text{ W})(0.40\ \Omega) - (12.0\text{ V})^2]^2 - 4(80.0\text{ W})^2(0.40\ \Omega)^2}}{2(80.0\text{ W})} \\ &= \frac{80.0\text{ V}^2 - \pm \sqrt{(80\text{ V}^2)^2 - (64\text{ V}^2)}}{160\text{ V}^2\ \Omega^{-1}} = \frac{80.0\text{ V}^2 \pm \sqrt{2306\text{ V}^4}}{160\text{ V}^2\ \Omega^{-1}} = \frac{80.0 \pm 48.0}{160}\ \Omega = (0.50 \pm 0.30)\ \Omega. \end{aligned}$$

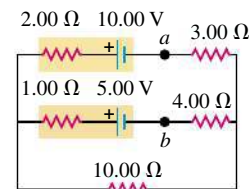
So the two possible resistances are

$$R = 0.80\ \Omega,$$

$$R = 0.20\ \Omega.$$

**Exercise 26.26** In the circuit shown in **Fig. E26.26**, find

- the current in each branch, and
- the potential difference  $V_{ab}$  of point  $a$  relative to point  $b$ .



**Figure E26.26**

**Solution.** For this problem we need to use Kirchhoff's rules:

$$\sum I = 0 \quad (\text{junction rule}), \quad (26.5)$$

$$\sum V = 0 \quad (\text{loop rule}). \quad (26.6)$$

- Let  $I_1$  be the current through the top branch,  $I_2$  the current through the middle branch, and  $I_3$  the current through the bottom branch. Let's choose all three currents to be flowing to the left. Then applying the junction rule to the junction on the left gives us

$$0 = I_1 + I_2 + I_3.$$

Now we will apply the loop rule to the top and the bottom loops, and move through each counterclockwise, starting at the battery. For the top loop,

$$0 = 10\text{ V} - (2\ \Omega)I_1 + (1\ \Omega)I_2 - 5\text{ V} + (4\ \Omega)I_2 - (3\ \Omega)I_1 \implies 5\text{ V} = (5\ \Omega)I_1 - (5\ \Omega)I_2 \implies 1\text{ A} = I_1 - I_2,$$

where in going to the final equation we have simply divided by  $5\ \Omega$ , since  $1\text{ V} = 1\ \Omega\text{ A}$ . For the bottom loop,

$$0 = 5\text{ V} - (1\ \Omega)I_2 + (10\ \Omega)I_3 - (4\ \Omega)I_2 \implies 5\text{ V} = (5\ \Omega)I_2 - (10\ \Omega)I_3 \implies 1\text{ A} = I_2 - 2I_3.$$

Now we have three equations in three unknowns, which you can solve using your favorite method. I prefer Gaussian elimination. The matrix equation is

$$\begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -2 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix},$$

which can be solved as follows:

$$\left[ \begin{array}{ccc|c} 1 & 1 & 1 & 0 \\ 1 & -1 & 0 & 1 \\ 0 & 1 & -2 & 1 \end{array} \right] \sim \left[ \begin{array}{ccc|c} 1 & -1 & 0 & 1 \\ 0 & 1 & -2 & 1 \\ 1 & 1 & 1 & 0 \end{array} \right] \sim \left[ \begin{array}{ccc|c} 1 & 0 & -2 & 2 \\ 0 & 1 & -2 & 1 \\ 0 & 2 & 1 & -1 \end{array} \right] \sim \left[ \begin{array}{ccc|c} 1 & 0 & -2 & 2 \\ 0 & 1 & -2 & 1 \\ 0 & 0 & 5 & -3 \end{array} \right] \sim \left[ \begin{array}{ccc|c} 1 & 0 & 0 & 4/5 \\ 0 & 1 & 0 & -1/5 \\ 0 & 0 & 1 & -3/5 \end{array} \right].$$

A minus sign tells us the current is in the direction opposite of what we guessed. So we have

Top branch: 0.800 A (to the left),  
 Middle branch: 0.200 A (to the right),  
 Bottom branch: 0.600 A (to the right).

- We can find the potential difference between points  $a$  and  $b$  by moving counterclockwise through the top loop, similar to applying the loop rule in (a). But now we start at  $b$  and end on  $a$ :

$$V_{ab} = (4\ \Omega)I_2 - (3\ \Omega)I_1 = (4.00\ \Omega)(-0.200\text{ A}) - (3.00\ \Omega)(0.800\text{ A}) = \mathbf{32.0\text{ V}}.$$

**Exercise 26.29** In the circuit shown in **Fig. E26.29** the batteries have negligible internal resistance and the meters are both idealized. With the switch  $S$  open, the voltmeter reads 15.0 V.

- Find the emf  $\mathcal{E}$  of the battery.
- What will the ammeter read when the switch is closed?

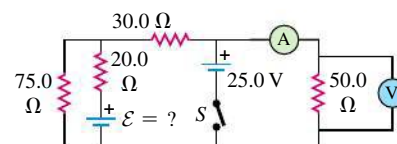
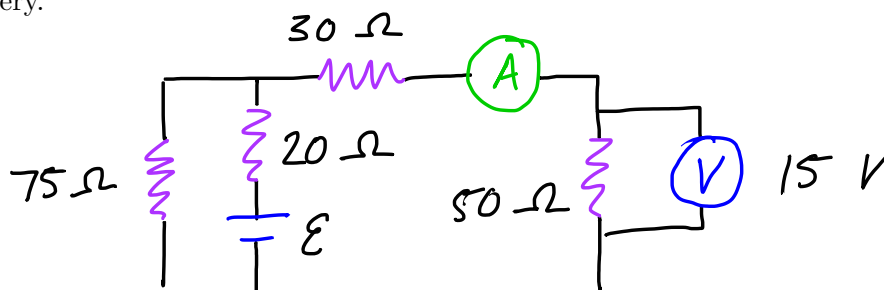


Figure E26.29

**Solution.**

- We need to simplify the circuit to the point that we know the current through the battery and the single equivalent resistance connected to it. When the switch is open, we can ignore the branch of the circuit with the 25 V battery.

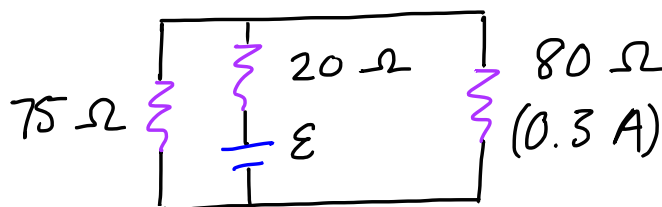


Let's begin with what we are given, which is the voltmeter reading. Since the voltmeter is connected in parallel to the  $50\ \Omega$  resistor, we know that the potential across this resistor is 15 V. So we can use Ohm's law to find the current through this resistor:

$$V = IR \implies I_{50\ \Omega} = \frac{15\ \text{V}}{50\ \Omega} = \frac{3}{10}\ \text{A} = 0.300\ \text{A}.$$

This is the current through any components connected in series with the  $50\ \Omega$  resistor, so it is also the current through their equivalent resistance. The  $30\ \Omega$  resistor is in series with the  $50\ \Omega$  resistor, and their equivalent resistance is

$$R_{\text{eq1}} = 50\ \Omega + 30\ \Omega = 80.0\ \Omega.$$



The potential difference across  $R_{\text{eq1}}$  can be found by using Ohm's law once more:

$$V_{80\ \Omega} = I_{50\ \Omega} R_{\text{eq1}} = (0.300\ \text{A})(80.0\ \Omega) = 24.0\ \text{V}.$$

This is also the potential difference across any components connected in parallel to  $R_{\text{eq1}}$ . The  $75\ \Omega$  resistor is connected in parallel, so we can find the current through it using Ohm's law:

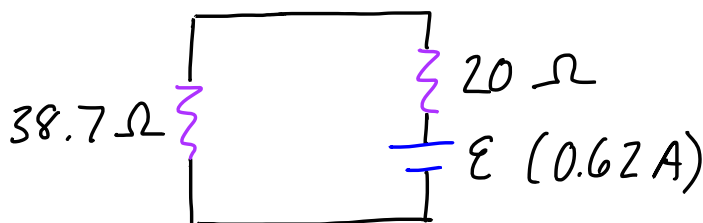
$$I_{75\ \Omega} = \frac{V_{80\ \Omega}}{75\ \Omega} = \frac{24.0\ \text{V}}{75.0\ \Omega} = 0.320\ \text{A}.$$

Applying Kirchhoff's junction rule to the top junction in the diagram just above, we can find the current through the branch of the circuit with the unknown emf  $\mathcal{E}$ :

$$0 = I_{\mathcal{E}} - I_{75\ \Omega} - I_{80\ \Omega} \implies I_{\mathcal{E}} = 0.320\ \text{A} + 0.300\ \text{A} = 0.620\ \text{A}.$$

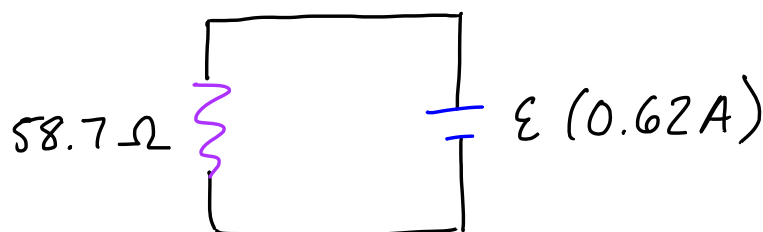
Now that we know the current through the battery, we can simplify the circuit to just one equivalent resistance. First adding the  $75\,\Omega$  and  $80\,\Omega$  resistors in parallel, we find

$$\frac{1}{R_{\text{eq}_2}} = \frac{1}{75\,\Omega} + \frac{1}{R_{\text{eq}_1}} = \frac{1}{75\,\Omega} + \frac{1}{80\,\Omega} = \frac{31}{1200}\,\Omega^{-1} \implies R_{\text{eq}_2} = \frac{1200}{31}\,\Omega = 38.7\,\Omega.$$



Adding this in series with the  $20\,\Omega$  resistor, we find

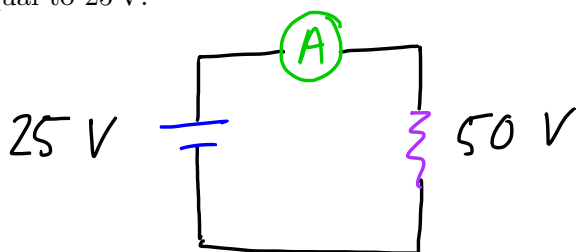
$$R_{\text{tot}} = R_{\text{eq}_2} + 20\,\Omega = 38.7\,\Omega + 20\,\Omega = 58.7\,\Omega.$$



Finally, we know that the potential across  $R_{\text{tot}}$  is the same as across the battery. So Ohm's law tells us

$$\mathcal{E} = I_{\mathcal{E}} R_{\text{tot}} = (0.620\,\text{A})(58.7\,\Omega) = 36.4\,\text{V}.$$

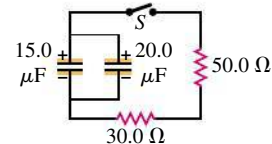
- (b) When the switch is closed, the  $50\,\Omega$  resistor is connected in parallel to the  $25\,\text{V}$  battery, so the potential across the  $50\,\Omega$  resistor is equal to  $25\,\text{V}$ .



We can apply Ohm's law once more to find the current through the  $50\,\Omega$  resistor, which is the same as the current through the ammeter connected in series:

$$I_A = \frac{25.0\,\text{V}}{50.0\,\Omega} = 0.500\,\text{A}.$$

**Exercise 26.41** In the circuit shown in **Fig. E26.41** both capacitors are initially charged to 45.0 V.



**Figure E26.41**

- (a) How long after closing the switch  $S$  will the potential across each capacitor be reduced to 10.0 V, and  
 (b) what will be the current at that time?

**Solution.** This problem is about discharging capacitors. The charge  $q$  on a capacitor at time  $t$  after closing an  $RC$  circuit is given by

$$q = Q_0 e^{-t/RC}, \quad (26.16)$$

where  $Q_0$  is the initial charge on the capacitor,  $C$  is its capacitance, and  $R$  is the resistance of the resistor connected to it in series.

- (a) The definition of capacitance is

$$C = \frac{Q}{V},$$

where  $Q$  is the charge on the capacitor and  $V$  is the potential across it.  $C$  is a property of a given capacitor and does not change with time. So we can use  $Q = CV$  and the fact that  $C$  is constant to write (26.16) in terms of  $C$  and  $V$ :

$$v = V_0 e^{-t/RC}, \quad (*)$$

where  $v$  is the potential across the capacitor at time  $t$ .

The capacitors in this problem are connected in parallel, so their equivalent capacitance is simply the sum of their individual capacitances:

$$C_{\text{eq}} = 15.0 \mu\text{F} + 20.0 \mu\text{F} = 35.0 \mu\text{F}.$$

The resistors are connected in series, so their equivalent resistance is also just the sum:

$$R_{\text{eq}} = 30.0 \Omega + 50.0 \Omega = 80.0 \Omega.$$

We can plug these values and our intended value of  $v = 10.0 \text{ V}$  into  $(*)$  to solve for the time  $t$ :

$$\begin{aligned} 10.0 \text{ V} &= (45.0 \text{ V}) \exp\left(-\frac{t}{(80.0 \Omega)(35.0 \mu\text{F})}\right) \Rightarrow \frac{2}{9} = \exp\left(-\frac{t}{2800 \mu\text{s}}\right) \Rightarrow -1.50 = -\frac{t}{2800 \mu\text{s}} \\ \Rightarrow t &= 4210 \mu\text{s} = 4.21 \text{ ms}, \end{aligned}$$

where we have used the fact that  $1 \text{ s} = 10^6 \mu\text{s}$ .

- (b) The current  $i$  through a capacitor at a given time  $t$  after the circuit is closed is given by

$$i = \frac{Q_0}{RC} e^{-t/RC}. \quad (26.13)$$

From (a), we know that  $Q_0/C = V_0$ , so we can write this as

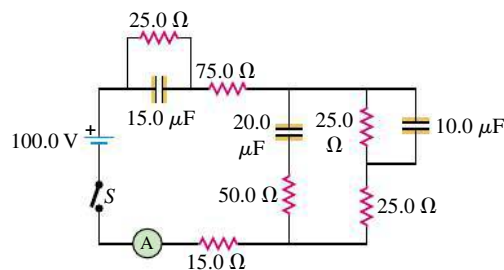
$$i = \frac{V_0}{R} e^{-t/RC}.$$

Plugging in our  $V_0$ ,  $R_{\text{eq}}$ ,  $C_{\text{eq}}$ , and  $t$  that we found in (a), we have

$$i = \frac{45.0 \text{ V}}{80.0 \Omega} \exp\left(-\frac{4210 \mu\text{s}}{2800 \mu\text{s}}\right) = \frac{9}{16} e^{-1.50} \text{ A} = \frac{9}{16} \frac{2}{9} \text{ A} = \frac{1}{8} \text{ A} = 0.125 \text{ A}.$$

**Exercise 26.47** In the circuit shown in **Fig. E26.47** the capacitors are initially uncharged, the battery has no internal resistance, and the ammeter is idealized. Find the ammeter reading

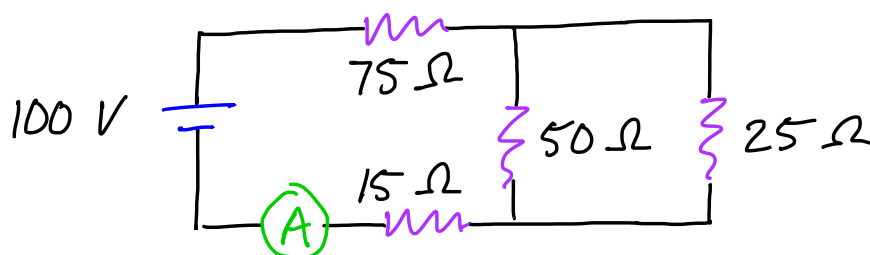
- (a) just after the switch  $S$  is closed, and
- (b) after  $S$  has been closed for a very long time.



**Figure E26.47**

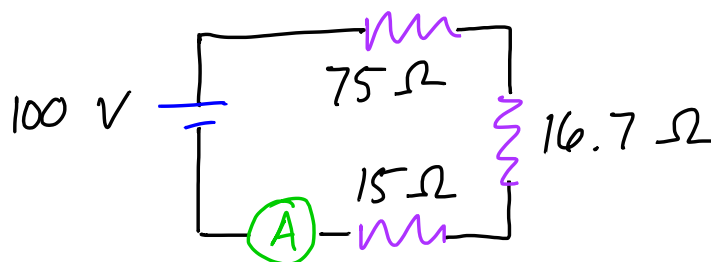
**Solution.**

- (a) Just after the switch is closed, there is no charge on any of the capacitors. This means they act like a short in the circuit, so we can ignore any resistor that is in parallel with a capacitor.



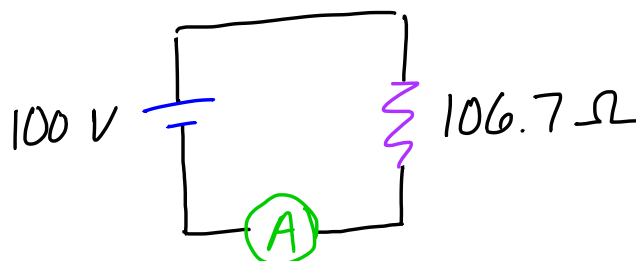
The  $50\ \Omega$  and  $25\ \Omega$  resistors are in parallel, and have the equivalent resistance  $R_{\text{eq}}$  given by

$$\frac{1}{R_{\text{eq}}} = \frac{1}{50\ \Omega} + \frac{1}{25\ \Omega} = \frac{3}{50}\ \Omega^{-1} \implies R_{\text{eq}} = \frac{50}{3}\ \Omega = 16.7\ \Omega.$$



The three resistances in series now give us the total resistance,

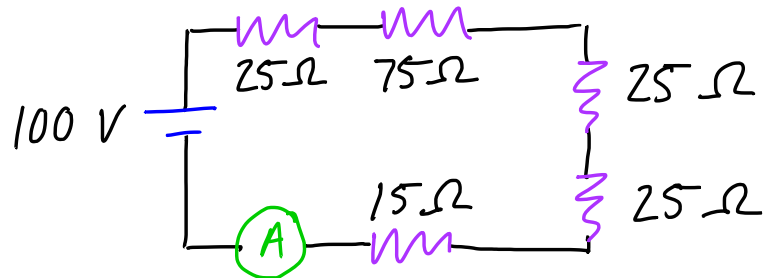
$$R_{\text{tot}} = 75.0\ \Omega + 16.7\ \Omega + 15.0\ \Omega = 106.7\ \Omega.$$



We can use Ohm's law to find the current through the equivalent resistance, which is the same as the ammeter reading:

$$\mathcal{E} = IR_{\text{tot}} \implies I = \frac{\mathcal{E}}{R_{\text{tot}}} = \frac{100.0\ \text{V}}{106.7\ \Omega} = 0.937\ \text{A}.$$

- (b) After  $S$  has been closed for a very long time, the capacitors are completely charged and current cannot flow through them. Therefore every capacitor acts like a break in the circuit, and we can adjust our diagram accordingly.

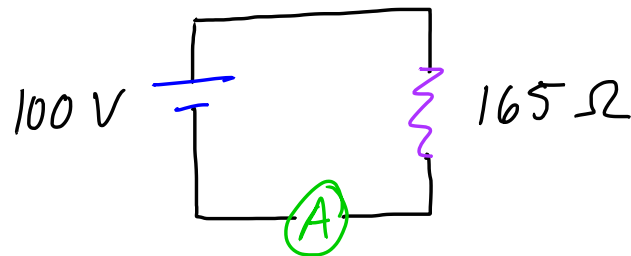


This gives us five resistors in series, which have the equivalent total resistance

$$R_{\text{tot}} = 25.0 \, \Omega + 75.0 \, \Omega + 25.0 \, \Omega + 25.0 \, \Omega + 15.0 \, \Omega = 165.0 \, \Omega.$$

Once again, we use Ohm's law to find the ammeter reading:

$$I = \frac{\mathcal{E}}{R_{\text{tot}}} = \frac{100.0 \, \text{V}}{165.0 \, \Omega} = 0.606 \, \text{A}.$$



**Problem 26.53** A capacitor with capacitance  $C$  is connected in series to a resistor of resistance  $R$  and a battery with emf  $\mathcal{E}$ . The circuit is completed at time  $t = 0$ .

- (a) In terms of  $\mathcal{E}$ ,  $R$ , and  $C$ , how much energy is stored in the capacitor when it is fully charged?
- (b) The power output of the battery is  $P_{\mathcal{E}} = \mathcal{E}i$ , with  $i$  given by Eq. (26.13). The electrical energy supplied in an infinitesimal time  $dt$  is  $P_{\mathcal{E}} dt$ . Integrate from  $t = 0$  to  $t \rightarrow \infty$  to find the total energy supplied by the battery.
- (c) The rate of consumption of electrical energy in the resistor is  $P_R = i^2 R$ . In an infinitesimal time interval  $dt$ , the amount of electrical energy consumed by the resistor is  $P_R dt$ . Integrate from  $t = 0$  to  $t \rightarrow \infty$  to find the total energy consumed by the resistor.
- (d) What fraction of the total energy supplied by the battery is stored in the capacitor? What fraction is consumed in the resistor?

**Solution.**

- (a) In general, the potential energy  $U$  stored in a capacitor is given by

$$U = \frac{1}{2}CV^2, \quad (24.9)$$

where  $C$  is the capacitor's capacitance and  $V$  the potential difference between its plates. When the capacitor is fully charged, the potential difference between its plates is the emf  $\mathcal{E}$ . So we have

$$U_C = \frac{1}{2}C\mathcal{E}^2.$$

- (b) In terms of the given quantities  $\mathcal{E}$ ,  $R$ , and  $C$ , the instantaneous current  $i$  is given by

$$i = \frac{\mathcal{E}}{R}e^{-t/RC}. \quad (26.13)$$

Plugging this in and integrating, the total energy supplied by the battery is

$$U_{\mathcal{E}} = \int_0^{\infty} P_{\mathcal{E}} dt = \int_0^{\infty} \mathcal{E}i dt = \int_0^{\infty} \mathcal{E} \frac{\mathcal{E}}{R} e^{-t/RC} dt = \frac{\mathcal{E}^2}{R} \left[ -RCe^{-t/RC} \right]_0^{\infty} = \frac{\mathcal{E}^2}{R} RC = C\mathcal{E}^2.$$

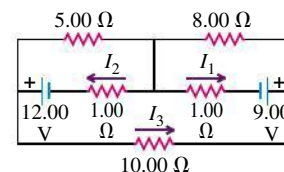
- (c) We just need to plug (26.13) in again and integrate to find the total energy consumed by the resistor:

$$\begin{aligned} U_R &= \int_0^{\infty} P_R dt = \int_0^{\infty} i^2 R dt = \int_0^{\infty} \left( \frac{\mathcal{E}}{R} e^{-t/RC} \right)^2 R dt = \frac{\mathcal{E}^2}{R} \int_0^{\infty} e^{-2t/RC} dt = \frac{\mathcal{E}^2}{R} \left[ -\frac{RCe^{-2t/RC}}{2} \right]_0^{\infty} \\ &= \frac{\mathcal{E}^2}{R} \frac{RC}{2} = \frac{1}{2}C\mathcal{E}^2. \end{aligned}$$

- (d) From (a) and (b),  $U_C/U_{\mathcal{E}} = 1/2$ , so half of the total energy supplied by the battery is stored in the capacitor. From (b) and (c),  $U_R/U_{\mathcal{E}} = 1/2$ , so the other half of the total energy is consumed by the resistor.

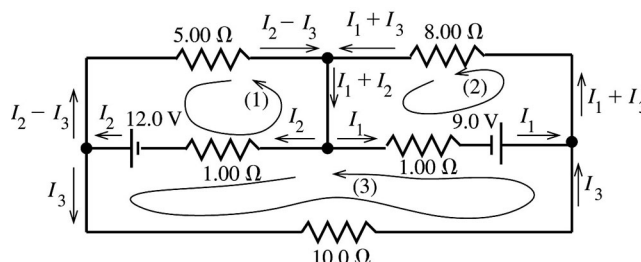


**Problem 26.59** Calculate the currents  $I_1$ ,  $I_2$ , and  $I_3$  indicated in the circuit diagram shown in **Fig. P26.59**.



**Figure P26.59**

**Solution.** This is another problem we can solve using Kirchhoff's rules.



The circuit has three loops, so we will need to use the loop rule three times. But first we need to use the junction rule to find the current through the  $5\ \Omega$  and  $8\ \Omega$  resistors. At the junction on the left, we have

$$0 = I_2 - I_3 + I_{5\Omega} \implies I_{5\Omega} = I_3 - I_2,$$

meaning it is pointing away from the junction (as shown in the diagram) if  $I_2 > I_3$ . At the junction on the right, we have

$$0 = I_1 + I_3 + I_{8\Omega} \implies I_{8\Omega} = -I_1 - I_3,$$

meaning it is pointing away from the junction as shown.

Now we can apply the loop rule, moving counterclockwise from each battery. For loop (1), we have

$$0 = -12\text{ V} + (1\ \Omega)I_2 + (5\ \Omega)(I_2 - I_3) \implies 12\text{ A} = 6I_2 - 5I_3.$$

For loop (2),

$$0 = 9\text{ V} - (8\ \Omega)(I_1 - I_3) + (1\ \Omega)I_1 \implies 9\text{ A} = 9I_1 + 8I_3.$$

For loop (3), let's start at the 12 V battery:

$$0 = 12\text{ V} - (10\ \Omega)I_3 - 9\text{ V} + (1\ \Omega)I_1 - (1\ \Omega)I_2 \implies 3\text{ A} = -I_1 + I_2 + 10I_3.$$

The matrix equation is

$$\begin{bmatrix} 0 & 6 & -5 \\ 9 & 0 & 8 \\ -1 & 1 & 10 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} 12 \\ 9 \\ 3 \end{bmatrix},$$

which can be solved using Gaussian elimination as follows:

$$\left[ \begin{array}{ccc|c} 0 & 6 & -5 & 12 \\ 9 & 0 & 8 & 9 \\ -1 & 1 & 10 & 3 \end{array} \right] \sim \left[ \begin{array}{ccc|c} 1 & 0 & 8/9 & 1 \\ 0 & 1 & -5/6 & 2 \\ -1 & 1 & 10 & 3 \end{array} \right] \sim \left[ \begin{array}{ccc|c} 1 & 0 & 8/9 & 1 \\ 0 & 1 & -5/6 & 2 \\ 0 & 1 & 98/9 & 4 \end{array} \right] \sim \left[ \begin{array}{ccc|c} 1 & 0 & 8/9 & 1 \\ 0 & 1 & -5/6 & 2 \\ 0 & 0 & 211/18 & 2 \end{array} \right] \sim \left[ \begin{array}{ccc|c} 1 & 0 & 0 & 179/211 \\ 0 & 1 & 0 & 452/211 \\ 0 & 0 & 1 & 36/211 \end{array} \right].$$

So we have

$$I_1 = 0.848\text{ A (to the right)}, \quad I_2 = 2.14\text{ A (to the left)}, \quad I_3 = 0.171\text{ A (to the right)}.$$