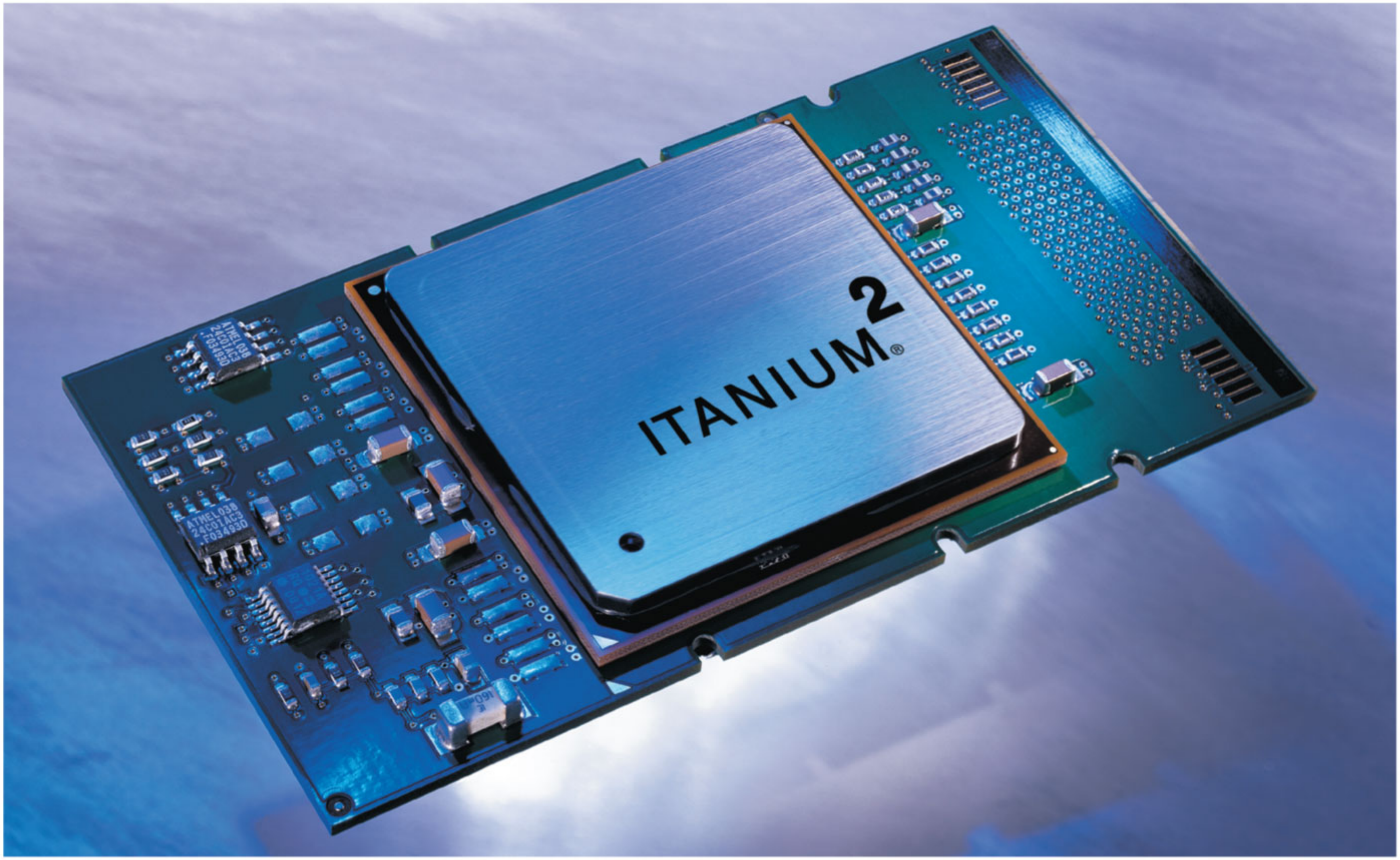
Chapter 31 Fundamentals of Circuits



Chapter Goal: To understand the fundamental physical principles that govern electric circuits.

Chapter 31 Preview

DC Circuits

Circuits—from a simple lightbulb to a supercomputer—are based on the controlled motion of charges. You will learn about the fundamental physical principles by which circuits operate.

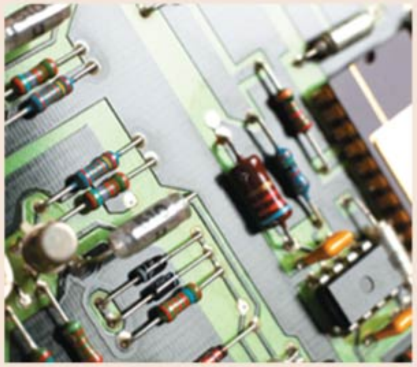
This chapter will focus on **DC circuits,** meaning *direct current*, in which potentials and currents are steady. Chapter 35 will extend these ideas to AC circuits in which the potential difference oscillates sinusoidally.

Analyzing Circuits

Circuits consist of many elements—batteries, resistors, capacitors, and more—connected together. Two basic tools will help you find the potential difference across and current through each element:

- Kirchhoff's junction law.
- Kirchhoff's loop law.

Also important will be Ohm's law, for resistors, and the properties of batteries and capacitors.



Chapter 31 Preview

Energy and Power

Circuits do things by using energy. You'll learn to calculate *power*, the rate at which the battery supplies energy to a circuit and the rate at which a resistor dissipates it.

The power delivered by these photo-voltaic cells is the product of their emf and the current they deliver. One solar panel provides about 200 W at midday on a sunny day.

Chapter 31 Preview

Circuit Diagrams

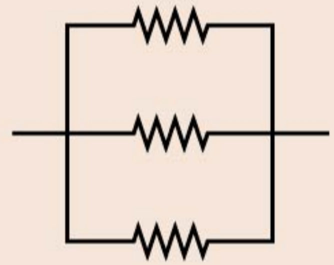
You will learn how to use symbols of circuit elements to draw a **circuit diagram.** This is a logical picture of how the circuit elements are related rather than a literal picture of how they look.

This is the circuit diagram of a simple circuit in which a resistor is connected to a battery.

Chapter 31 Preview

Combining Resistors

Resistors often occur **in series** or **in parallel.**



Resistors connected in series and in parallel

You'll learn that these combinations of resistors can be "simplified" by replacing them with one **equivalent resistor.**

Reading Question 31.5

The equivalent resistance for a group of parallel resistors is

A. Less than any resistor in the group.
B. Equal to the smallest resistance in the group.
C. Equal to the average resistance of the group.
D. Equal to the largest resistance in the group.
E. Larger than any resistor in the group.

Reading Question 31.5

The equivalent resistance for a group of parallel resistors is

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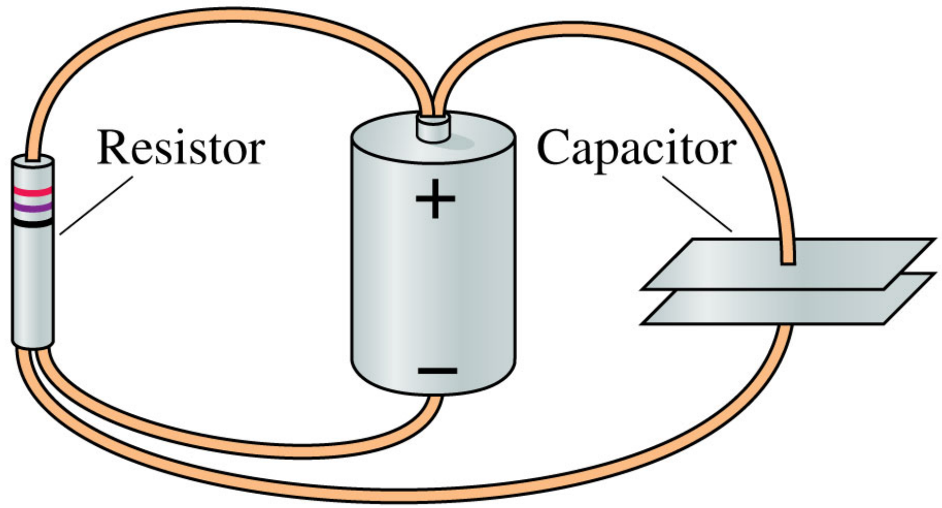
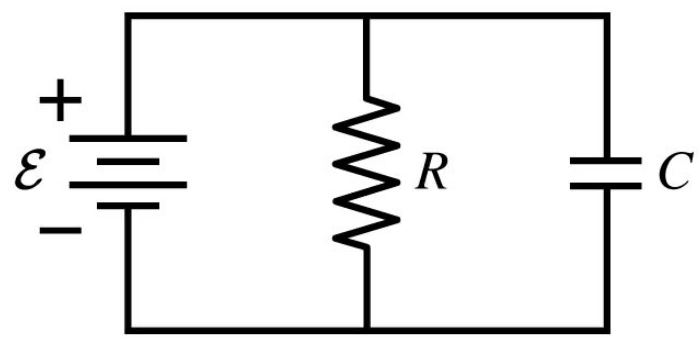
D. Equal to the largest resistance in the group.
E. Larger than any resistor in the group.

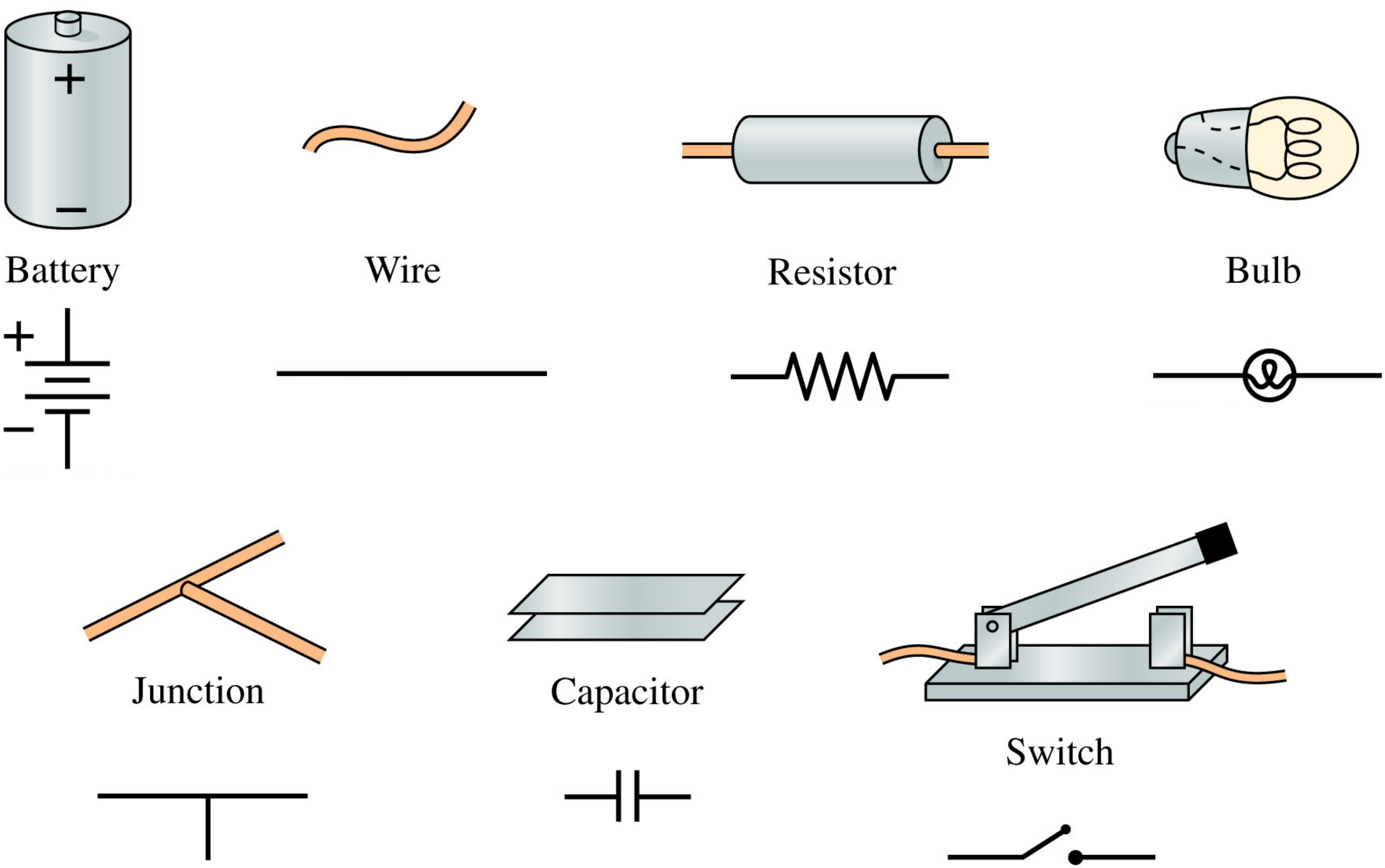
Circuit Diagrams

- The top figure shows a literal picture of a resistor and a capacitor connected by wires to a battery.
- The bottom figure is a **circuit diagram** of the same circuit.
- A circuit diagram is a *logical* picture of what is connected to what.



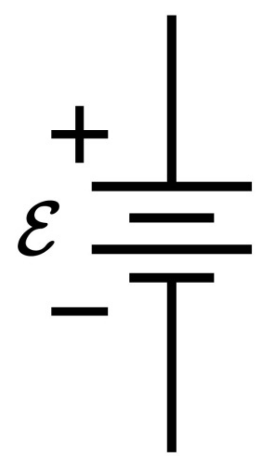


Circuit Elements



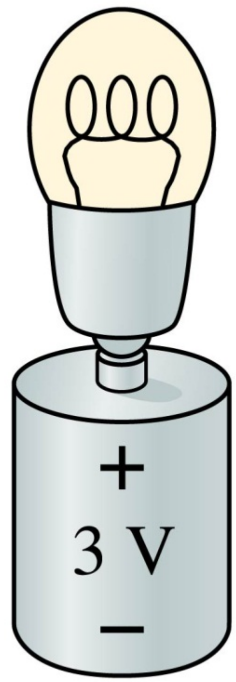
Circuit Diagrams

- A circuit diagram replaces pictures of the circuit elements with symbols.
- The longer line at one end of the battery symbol represents the positive terminal of the battery.
- The battery's emf is shown beside the battery.
- + and – symbols, even though somewhat redundant, are shown beside the terminals.



QuickCheck 31.1

Does the bulb light?



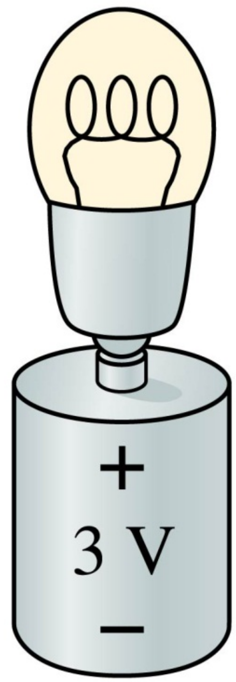
A. Yes.

B. No.

C. I’m not sure.

QuickCheck 31.1

Does the bulb light?



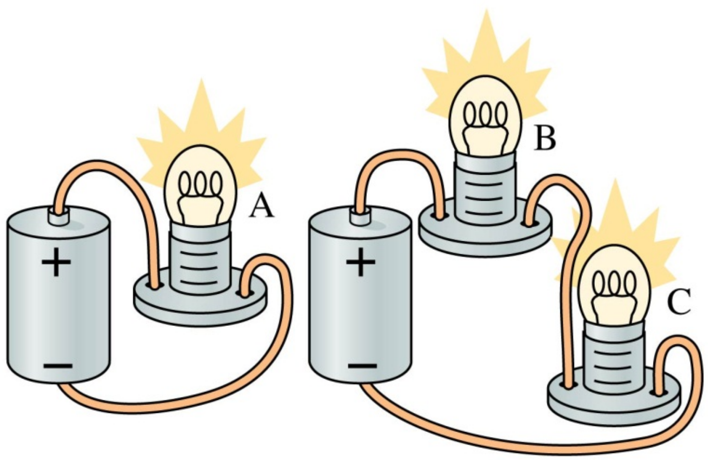
A. Yes.

B. **No.** Not a complete circuit

C. I' m not sure.

QuickCheck 31.2

The three bulbs are identical and the two batteries are identical. Compare the brightnesses of the bulbs.



A. $A > B > C$.

B. $A > C > B$.

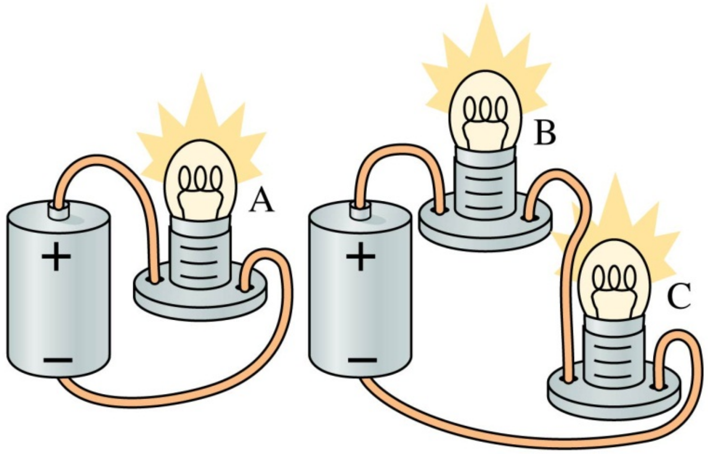
C. $A > B = C$.

D. $A < B = C$.

E. $A = B = C$.

QuickCheck 31.2

The three bulbs are identical and the two batteries are identical. Compare the brightnesses of the bulbs.



A. $A > B > C$.

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C. $A > B = C$. ✔

D. $A < B = C$.

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QuickCheck 31.3

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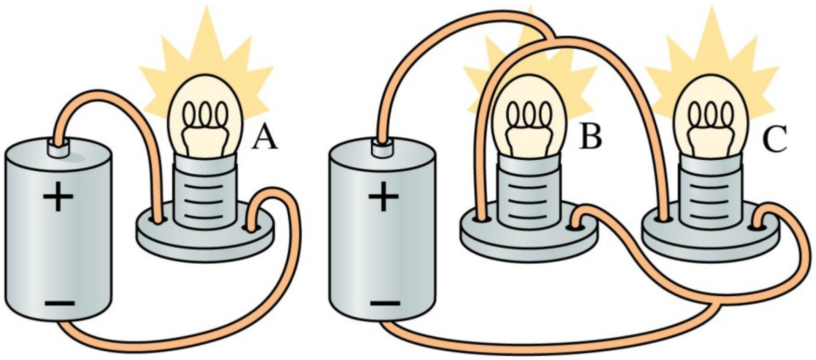

A. $A > B > C$.

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QuickCheck 31.3

The three bulbs are identical and the two batteries are identical. Compare the brightnesses of the bulbs.

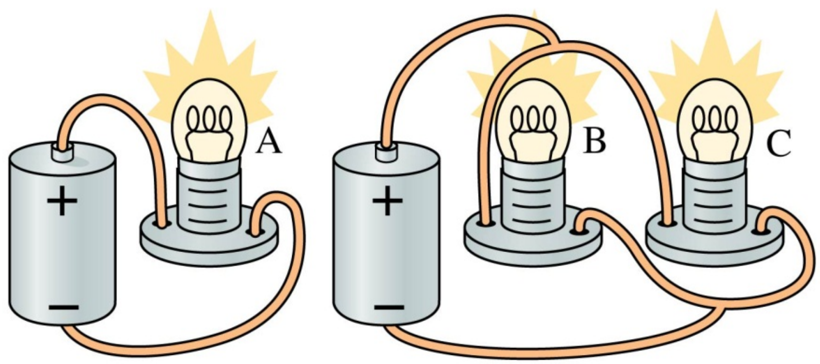
A. A > B > C.

B. A > C > B.

C. A > B = C.

D. A < B = C. ✔

E. A = B = C.

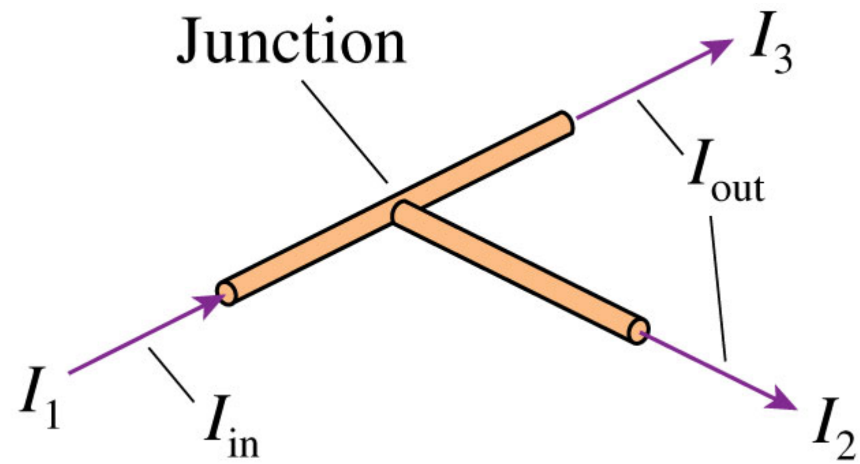


Kirchhoff's Junction Law

For a *junction*, the law of conservation of current requires that:

$$\sum I_{\text{in}} = \sum I_{\text{out}}$$

where the Σ symbol means summation. This basic conservation statement is called **Kirchhoff's junction law.**



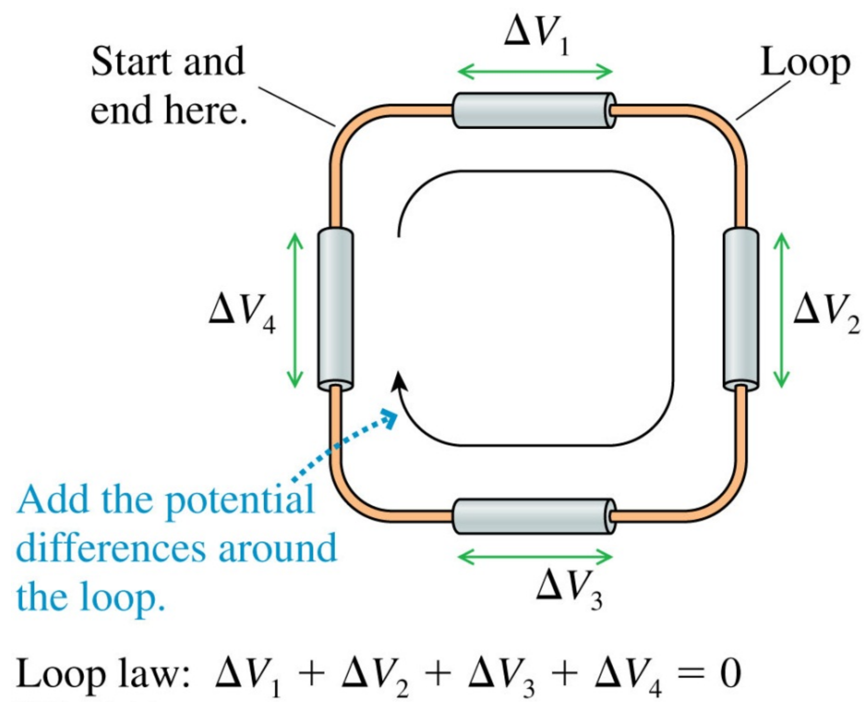
Junction law: $I_1 = I_2 + I_3$

Kirchhoff's Loop Law

- For any path that starts and ends at the same point:

$$\Delta V_{\text{loop}} = \sum (\Delta V)_i = 0$$

- The sum of all the potential differences encountered while moving around a loop or closed path is zero.
- This statement is known as **Kirchhoff's loop law.**



Tactics: Using Kirchhoff's Loop Law

TACTICS BOX 31.1 Using Kirchhoff's loop law

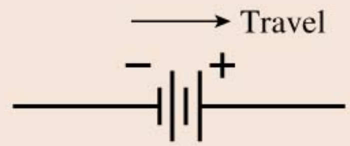
1. **Draw a circuit diagram.** Label all known and unknown quantities.
2. **Assign a direction to the current.** Draw and label a current arrow I to show your choice.
   - If you know the actual current direction, choose that direction.
   - If you don't know the actual current direction, make an arbitrary choice. All that will happen if you choose wrong is that your value for I will end up negative.

Tactics: Using Kirchhoff’ s Loop Law

TACTICS BOX 31.1 **Using Kirchhoff’s loop law**

❸ **“Travel” around the loop.** Start at any point in the circuit, then go all the way around the loop in the direction you assigned to the current in step 2. As you go through each circuit element, ΔV is interpreted to mean

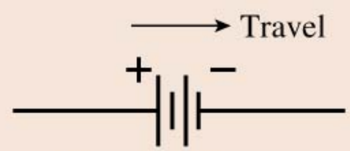
$$\Delta V = V_{\text{downstream}} - V_{\text{upstream}}$$



Potential increases

- For an ideal battery in the negative-to-positive direction:

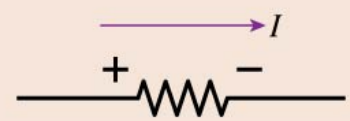
$$\Delta V_{\text{bat}} = +\mathcal{E}$$



Potential decreases

- For an ideal battery in the positive-to-negative direction:

$$\Delta V_{\text{bat}} = -\mathcal{E}$$



Potential decreases

- For a resistor: $\Delta V_{\text{res}} = -\Delta V_R = -IR$

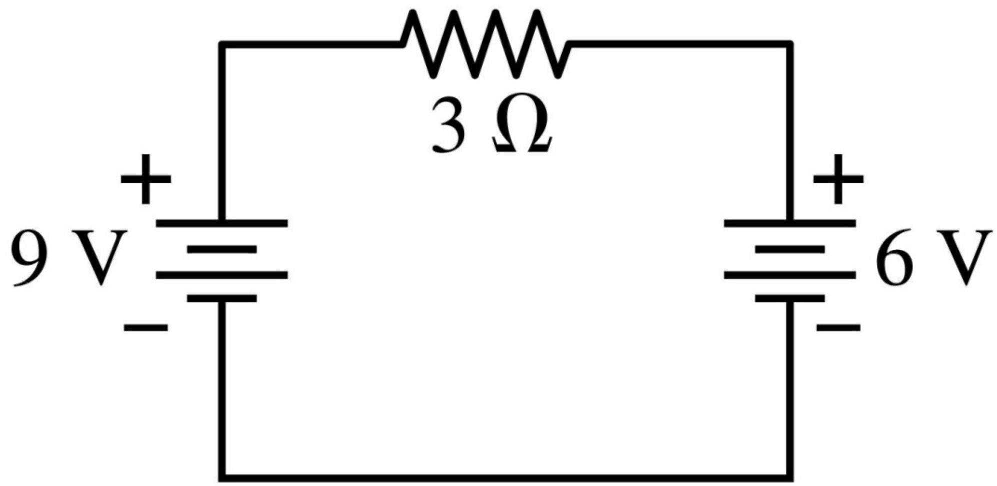
❹ **Apply the loop law:** $\sum(\Delta V)_i = 0$

Exercises 4–7

QuickCheck 31.4

The current through the 3 Ω resistor is

A. 9 A.
B. 6 A.
C. 5 A.
D. 3 A.
E. 1 A.



QuickCheck 31.4

The current through the 3 Ω resistor is

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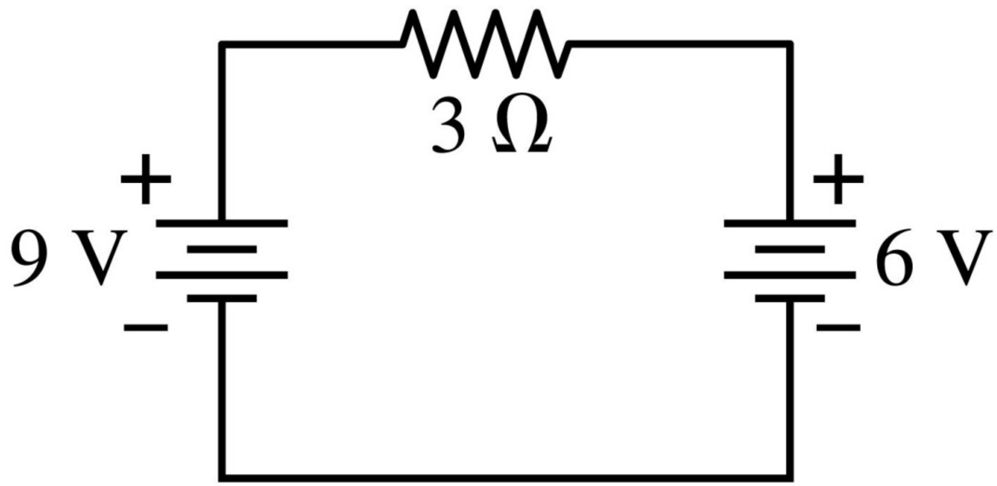
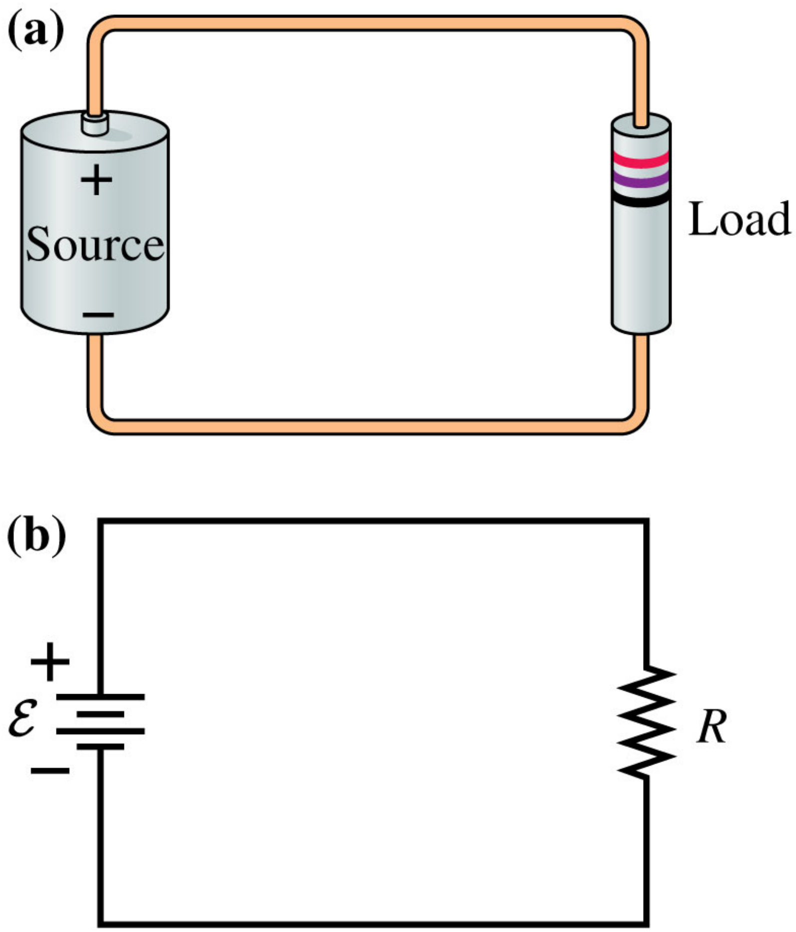
✔ **E. 1 A.**

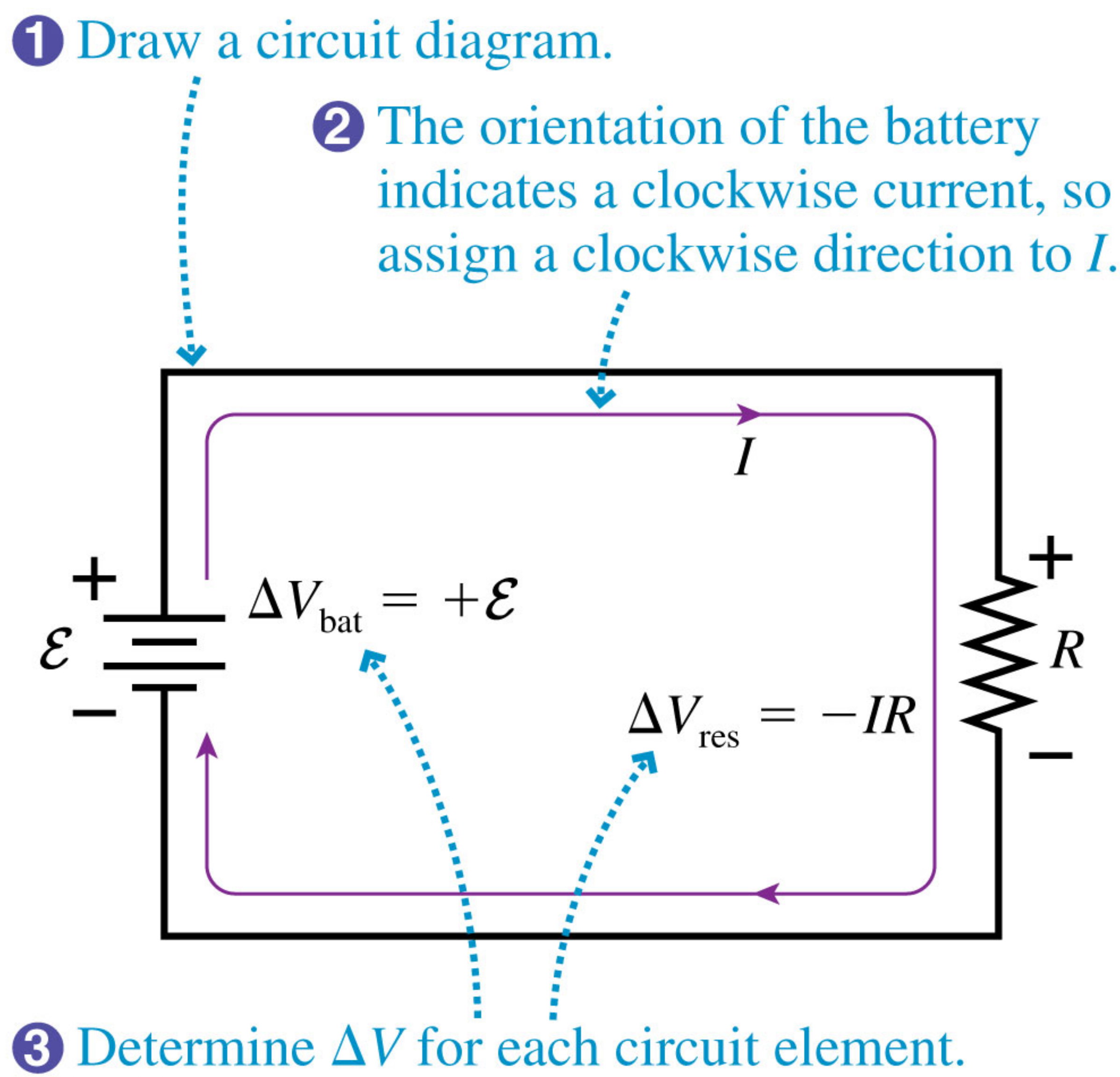


The Basic Circuit



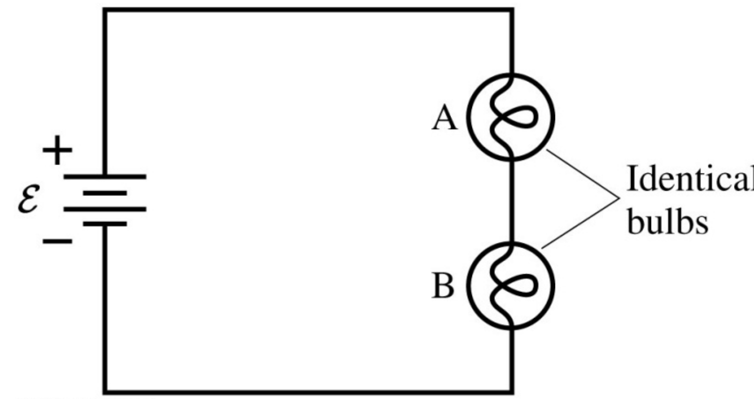
- The most basic electric circuit is a single resistor connected to the two terminals of a battery.
- Figure (a) shows a literal picture of the circuit elements and the connecting wires.
- Figure (b) is the circuit diagram.
- This is a **complete circuit**, forming a continuous path between the battery terminals.

Analyzing the Basic Circuit



Lightbulb Puzzle #1

- The figure shows two identical lightbulbs in a circuit.
- The current through both bulbs is *exactly the same!*
- It's not the current that the bulbs use up, it's *energy.*



- The battery creates a potential difference, which supplies potential energy to the charges.
- As the charges move through the lightbulbs, they lose some of their potential energy, transferring the energy to the bulbs.

QuickCheck 31.5

The potential difference across the 10 resistor is

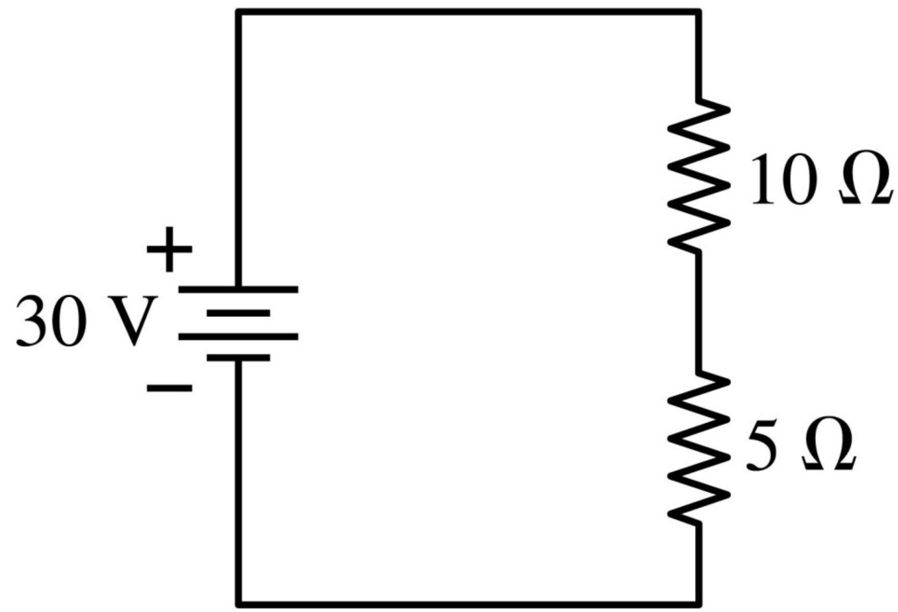
A. 30 V.

B. 20 V.

C. 15 V.

D. 10 V.

E. 5 V.



QuickCheck 31.5

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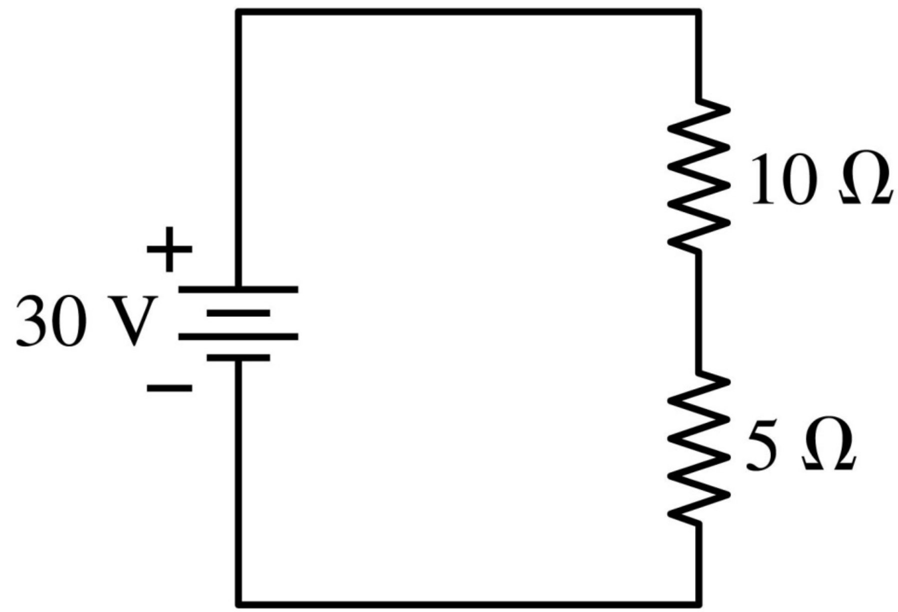
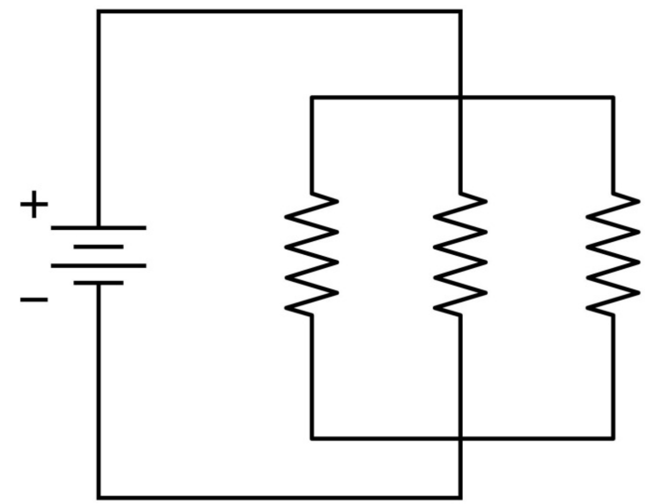


QuickCheck 31.6

What things about the resistors in this circuit are the same for all three?



A. Current I.
B. Potential difference ΔV.
C. Resistance R.
D. A and B.
E. B and C.

QuickCheck 31.6

What things about the resistors in this circuit are the same for all three?

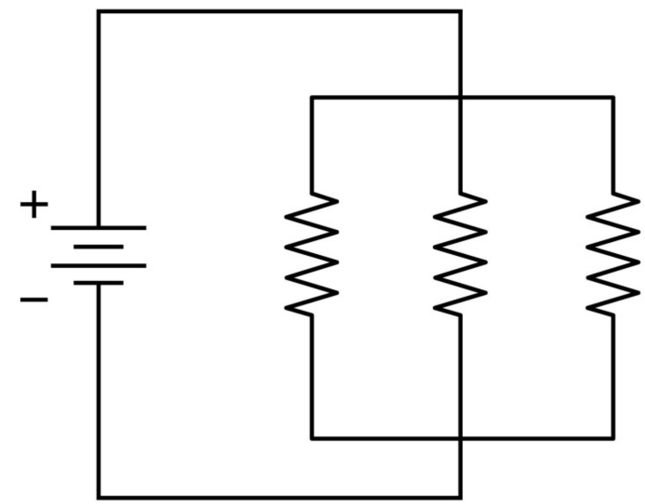
A. Current I.

B. **Potential difference ΔV.**

C. Resistance R.

D. A and B.

E. B and C.



Energy and Power

- The power supplied by a battery is:

$$P_{\text{bat}} = I\mathcal{E} \qquad \text{(power delivered by an emf)}$$

- The units of power are J/s or W.
- The power dissipated by a resistor is: $\boldsymbol{P_R = I\Delta V_R}$
- Or, in terms of the potential drop across the resistor:

$$P_{\text{R}} = I\,\Delta V_{\text{R}} = I^2R = \frac{(\Delta V_{\text{R}})^2}{R} \qquad \text{(power dissipated by a resistor)}$$

Example 31.2 Delivering Power

EXAMPLE 31.2 Delivering power

A 90 Ω load is connected to a 120 V battery. How much power is delivered by the battery?

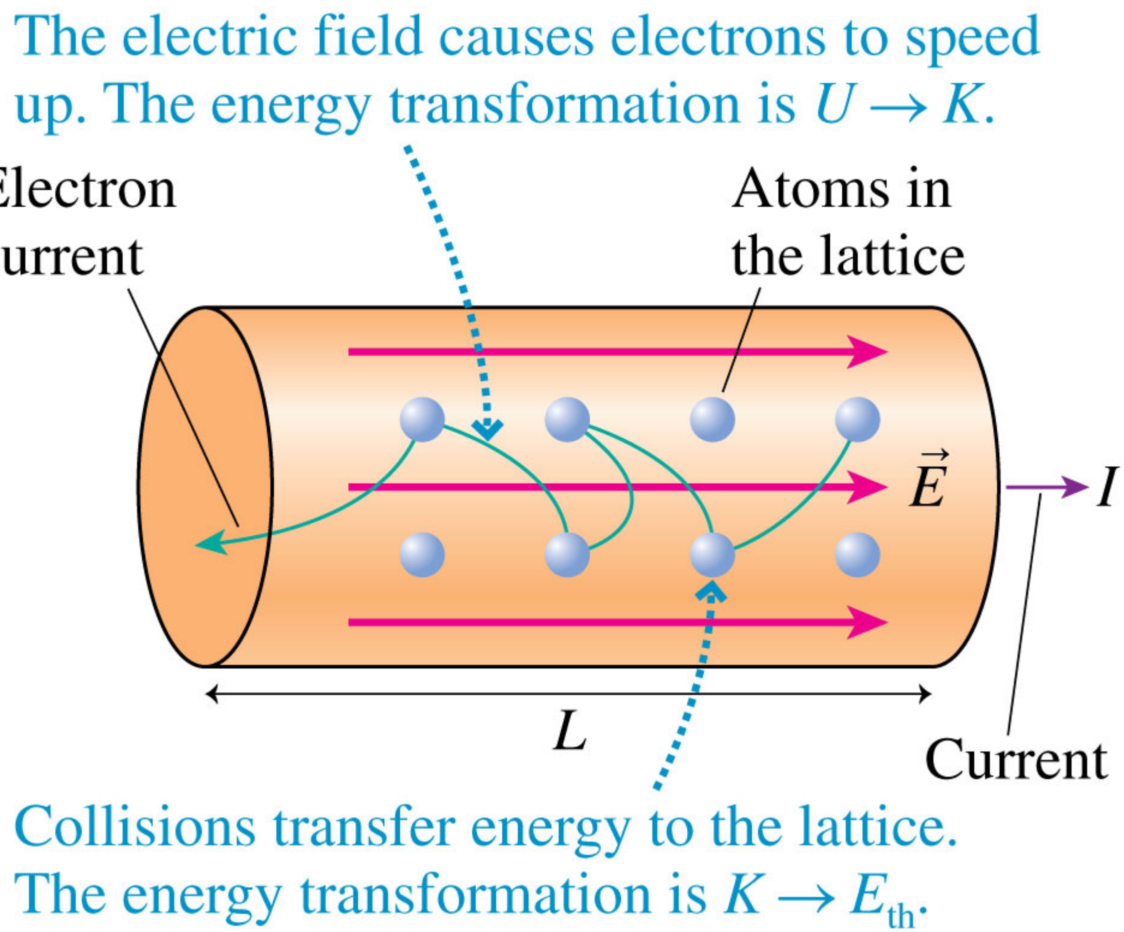
SOLVE This is our basic battery-and-resistor circuit, which we analyzed earlier. In this case

$$I = \frac{\mathcal{E}}{R} = \frac{120\ \text{V}}{90\ \Omega} = 1.33\ \text{A}$$

Thus the power delivered by the battery is

$$P_{\text{bat}} = I\mathcal{E} = (1.33\ \text{A})(120\ \text{V}) = 160\ \text{W}$$

Power Dissipation in a Resistor



A current-carrying resistor dissipates power because the electric force does work on the charges.

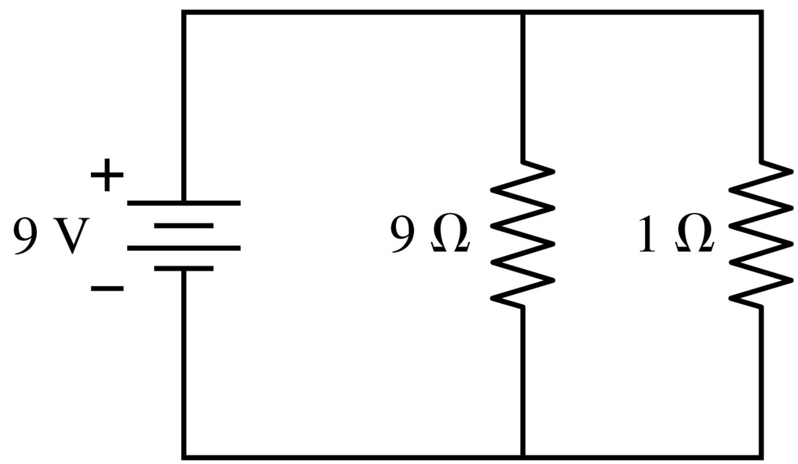
QuickCheck 31.7

Which resistor dissipates more power?

A. The $9\ \Omega$ resistor.

B. The $1\ \Omega$ resistor.

C. They dissipate the same power.



QuickCheck 31.7

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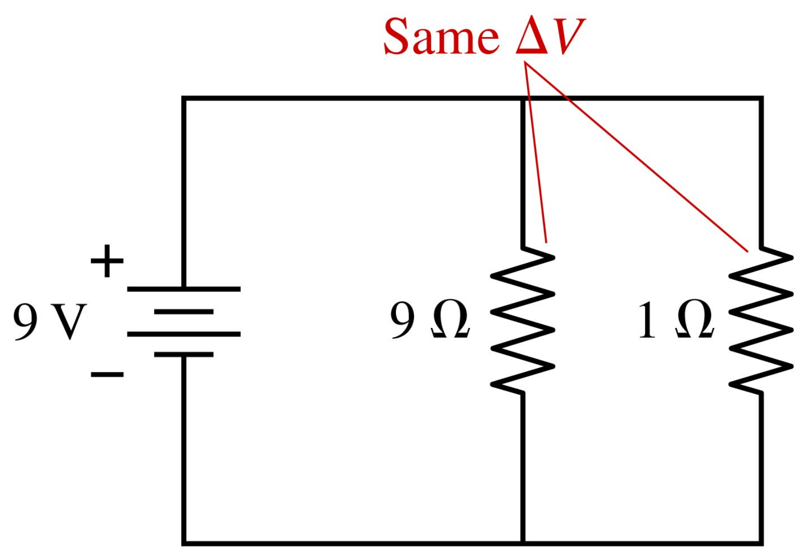


$$P = \frac{(\Delta V)^2}{R}$$

QuickCheck 31.8

Which has a larger resistance, a 60 W lightbulb or a 100 W lightbulb?

A. The 60 W bulb.
B. The 100 W bulb.
C. Their resistances are the same.
D. There's not enough information to tell.

QuickCheck 31.8

Which has a larger resistance, a 60 W lightbulb or a 100 W lightbulb?

A. The 60 W bulb.

✔ **B. The 100 W bulb.** $P = \dfrac{(\Delta V)^2}{R}$ with both used at $\Delta V = 120$ V

C. Their resistances are the same.

D. There's not enough information to tell.

Example 31.3 The Power of Light

EXAMPLE 31.3 The power of light

How much current is "drawn" by a 100 W lightbulb connected to a 120 V outlet?

MODEL Most household appliances, such as a 100 W lightbulb or a 1500 W hair dryer, have a power rating. The rating does *not* mean that these appliances *always* dissipate that much power. These appliances are intended for use at a standard household voltage of 120 V, and their rating is the power they will dissipate *if* operated with a potential difference of 120 V. Their power consumption will differ from the rating if they are operated at any other potential difference.

Example 31.3 The Power of Light

EXAMPLE 31.3 **The power of light**

SOLVE Because the lightbulb is operating as intended, it will dissipate 100 W of power. Thus

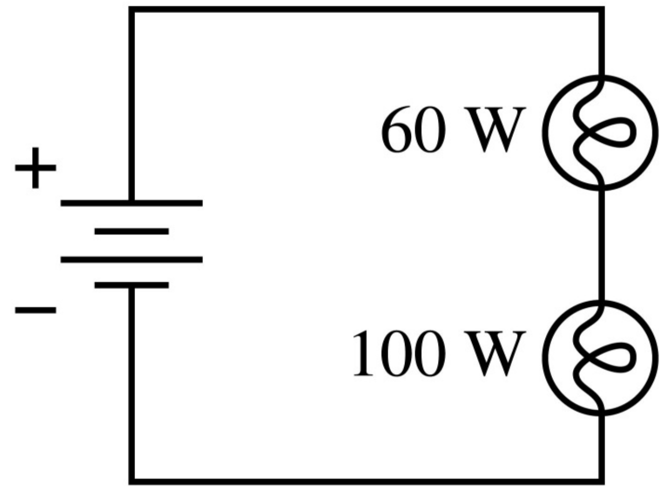
$$I = \frac{P_R}{\Delta V_R} = \frac{100\ \text{W}}{120\ \text{V}} = 0.833\ \text{A}$$

ASSESS A current of 0.833 A in this lightbulb transfers 100 J/s to the thermal energy of the filament, which, in turn, dissipates 100 J/s as heat and light to its surroundings.

QuickCheck 31.9

[Video about problem]

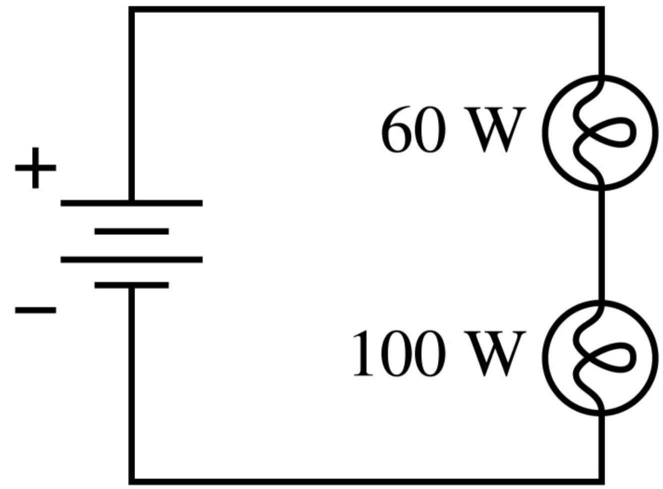
Which bulb is brighter? [Article about the problem]



A. The 60 W bulb.
B. The 100 W bulb.
C. Their brightnesses are the same.
D. There’s not enough information to tell.

QuickCheck 31.9

Which bulb is brighter?



✔ **A. The 60 W bulb.**
B. The 100 W bulb.
C. Their brightnesses are the same.
D. There's not enough information to tell.

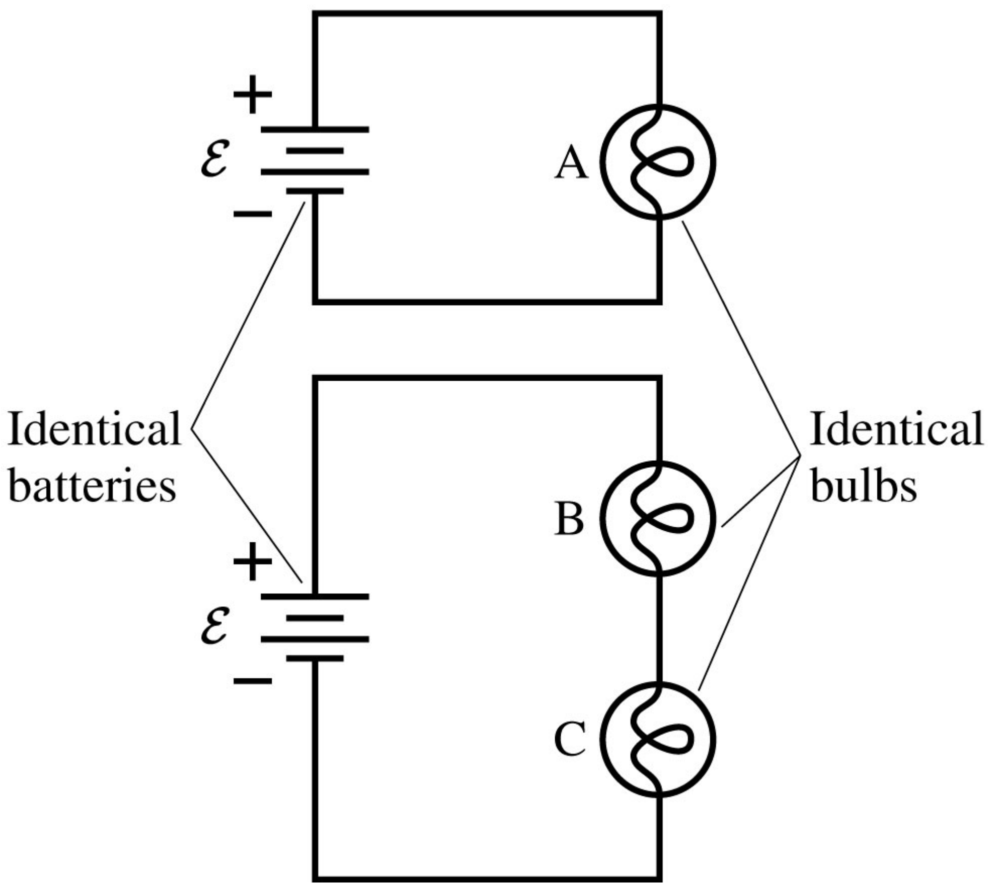
$P = I^2R$ and both have the same current.

Kilowatt Hours

- The product of watts and seconds is joules, the SI unit of energy.
- However, most electric companies prefers to use the **kilowatt hour**, to measure the energy you use each month.
- Examples:
    - A 4000 W electric water heater uses 40 kWh of energy in 10 hours.
    - A 1500 W hair dryer uses 0.25 kWh of energy in 10 minutes.
- The average cost of electricity in the United States is ≈10¢ per kWh ($0.10/kWh).

Lightbulb Puzzle #2

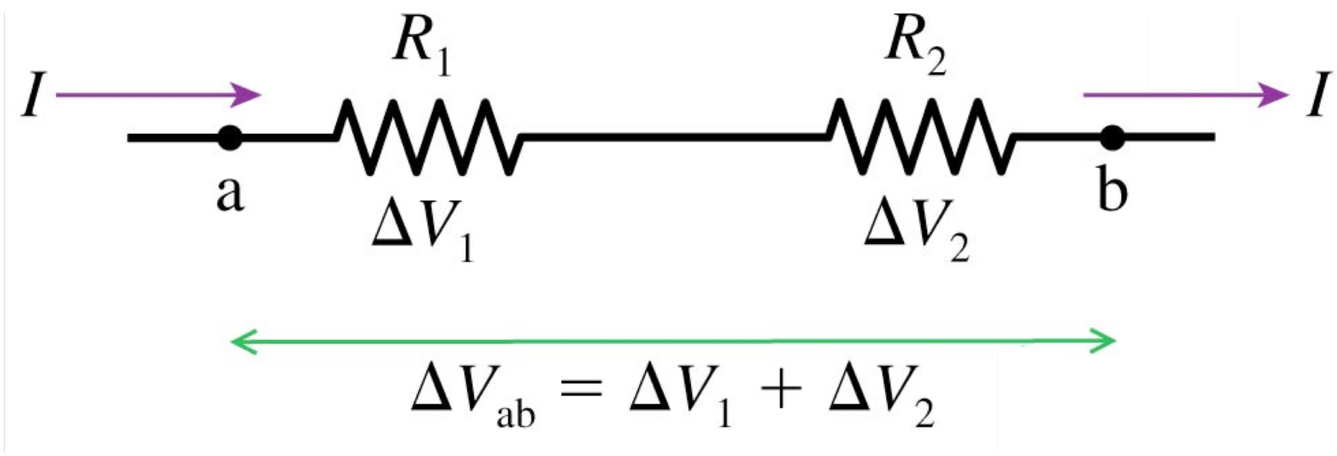
- The figure shows three identical lightbulbs in two different circuits.
- The voltage drop across A is the *same* as the total voltage drop across both B and C.
- More current will pass through Bulb A, and it will be *brighter* than either B or C.



Series Resistors

- The figure below shows two resisters connected *in series* between points a and b.
- The total potential difference between points a and b is the sum of the individual potential differences across R_1 and R_2:

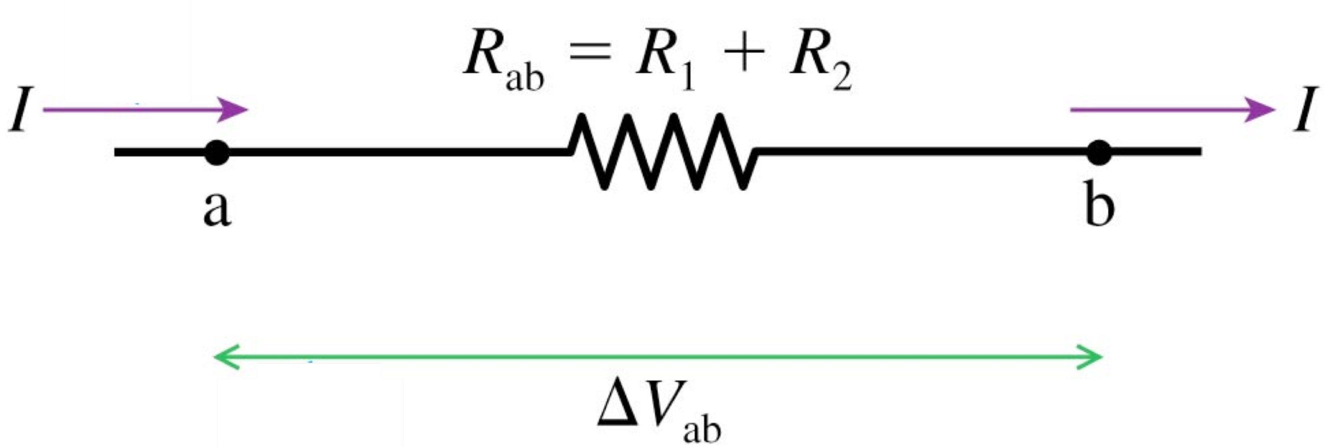
$$\Delta V_{ab} = \Delta V_1 + \Delta V_2 = IR_1 + IR_2 = I(R_1 + R_2)$$



Series Resistors

- Suppose we replace R_1 and R_2 with a single resistor with the same current I and the same potential difference ΔV_{ab}.
- Ohm's law gives resistance between points a and b:

$$R_{ab} = \frac{\Delta V_{ab}}{I} = \frac{I(R_1 + R_2)}{I} = R_1 + R_2$$



Series Resistors

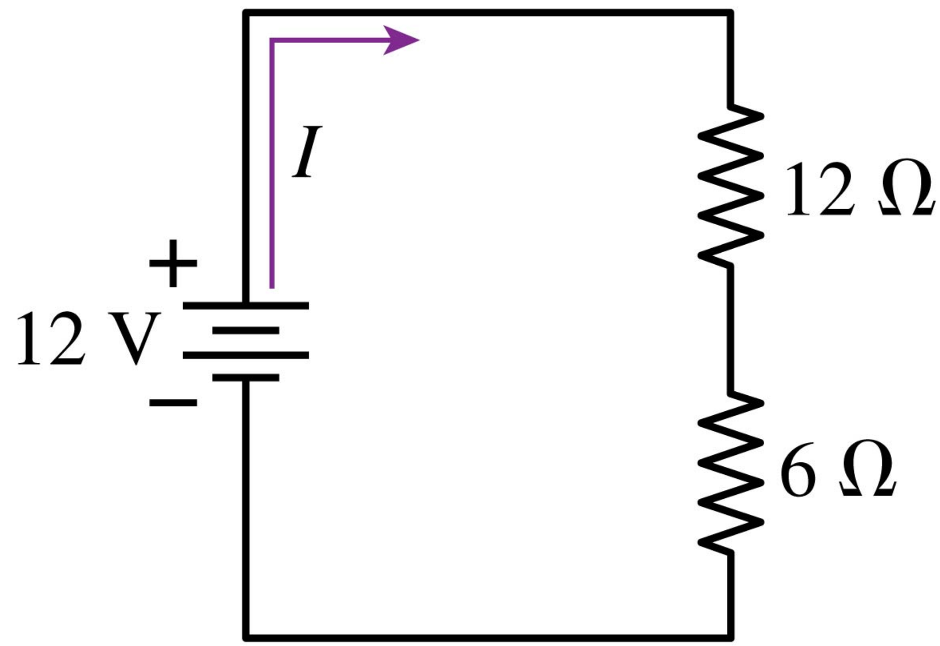
- Resistors that are aligned end to end, *with no junctions between them,* are called **series resistors** or, sometimes, resistors "in series."
- The current I is the same through all resistors placed in series.
- If we have N resistors in series, their **equivalent resistance** is:

$$R_{eq} = R_1 + R_2 + \cdots + R_N \qquad \text{(series resistors)}$$

The behavior of the circuit will be unchanged if the N series resistors are replaced by the single resistor R_{eq}.

QuickCheck 31.10

The battery current *I* is



A. 3 A.

B. 2 A.

C. 1 A.

D. 2/3 A.

E. 1/2 A.

QuickCheck 31.10

The battery current I is

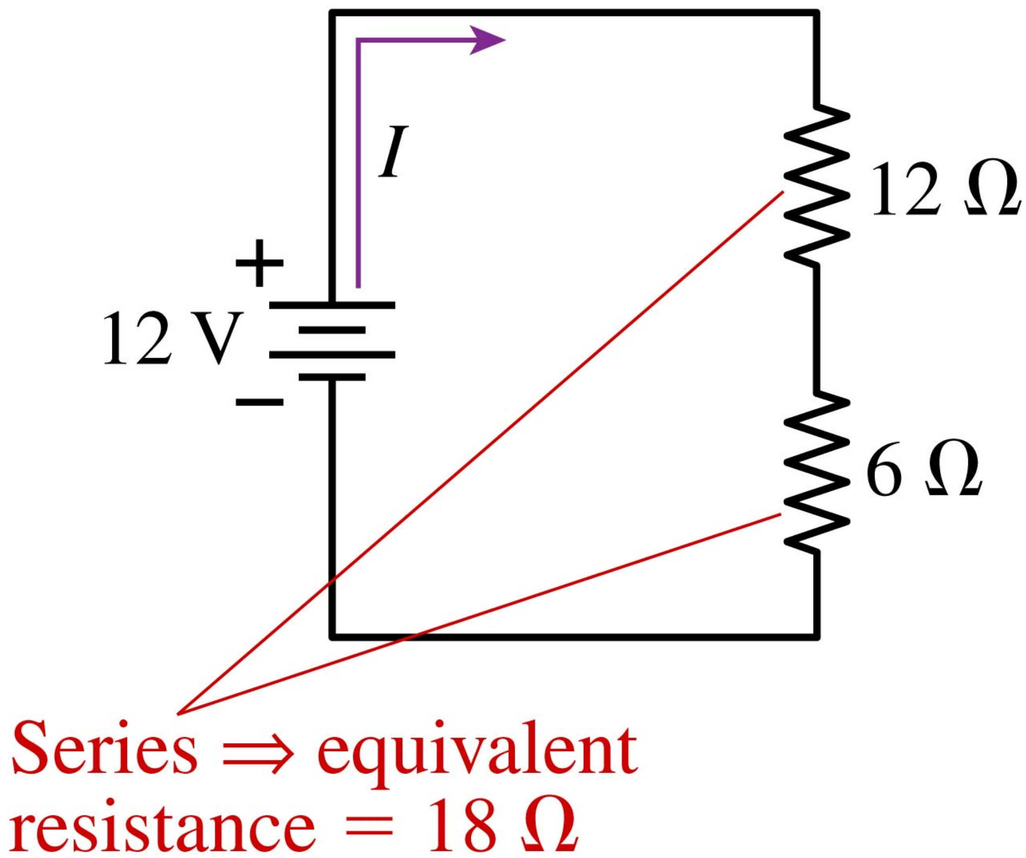
A. 3 A.

B. 2 A.

C. 1 A.

✔ **D. 2/3 A.**

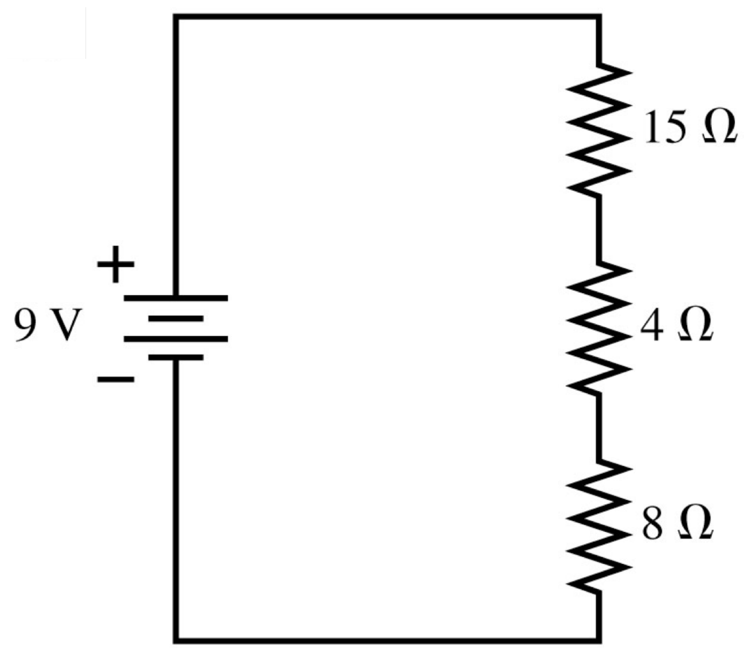
E. 1/2 A.



Example 31.5 A Series Resistor Circuit

EXAMPLE 31.5 A series resistor circuit

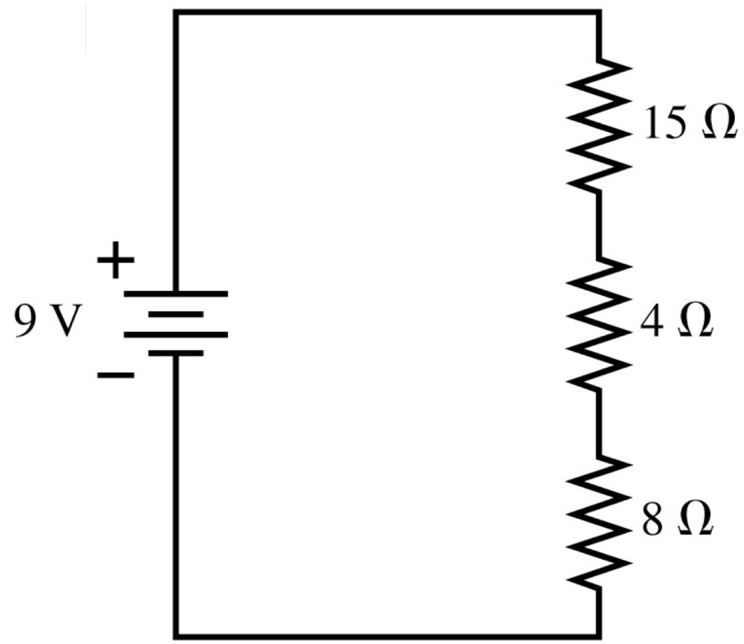
a. What is the current in the circuit below?
b. Draw a graph of potential versus position in the circuit, going cw from $V = 0$ V at the battery's negative terminal.



Example 31.5 A Series Resistor Circuit

EXAMPLE 31.5 A series resistor circuit

MODEL The three resistors are end to end, with no junctions between them, and thus are in series. Assume ideal connecting wires and an ideal battery.



Example 31.5 A Series Resistor Circuit

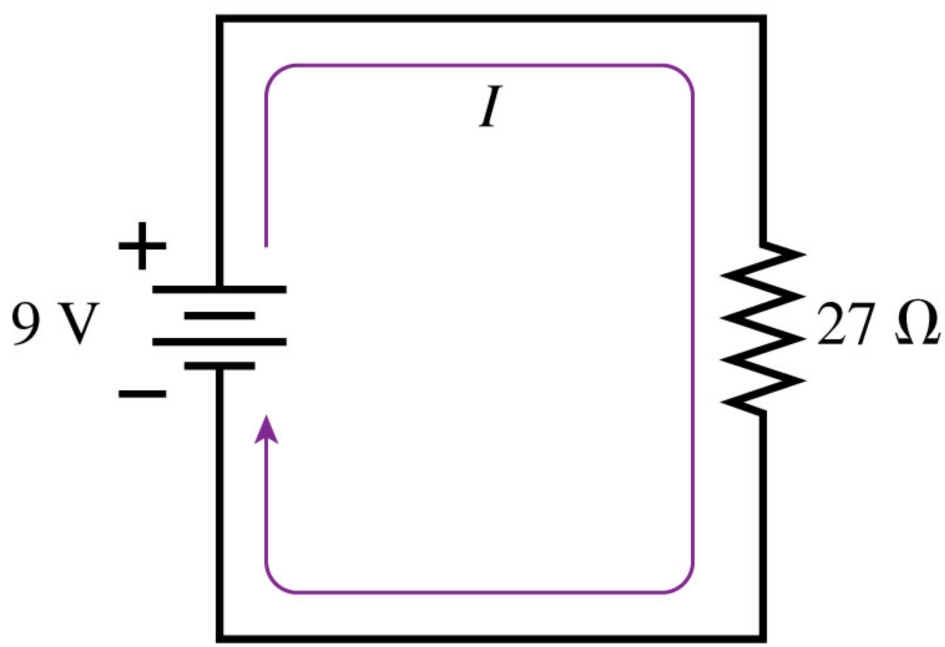
EXAMPLE 31.5 A series resistor circuit

SOLVE a. The battery "acts" the same—it provides the same current at the same potential difference—if we replace the three series resistors by their equivalent resistance

$$R_{eq} = 15\ \Omega + 4\ \Omega + 8\ \Omega = 27\ \Omega$$

This is shown as an equivalent circuit below. Now we have a circuit with a single battery and a single resistor, for which we know the current to be

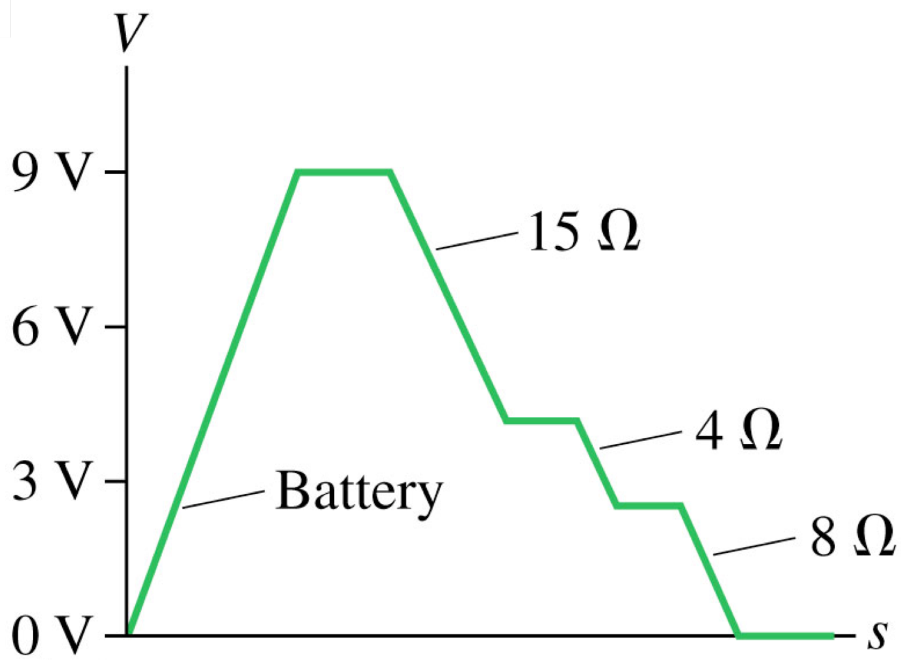
$$I = \frac{\mathcal{E}}{R_{eq}} = \frac{9\ \text{V}}{27\ \Omega} = 0.333\ \text{A}$$



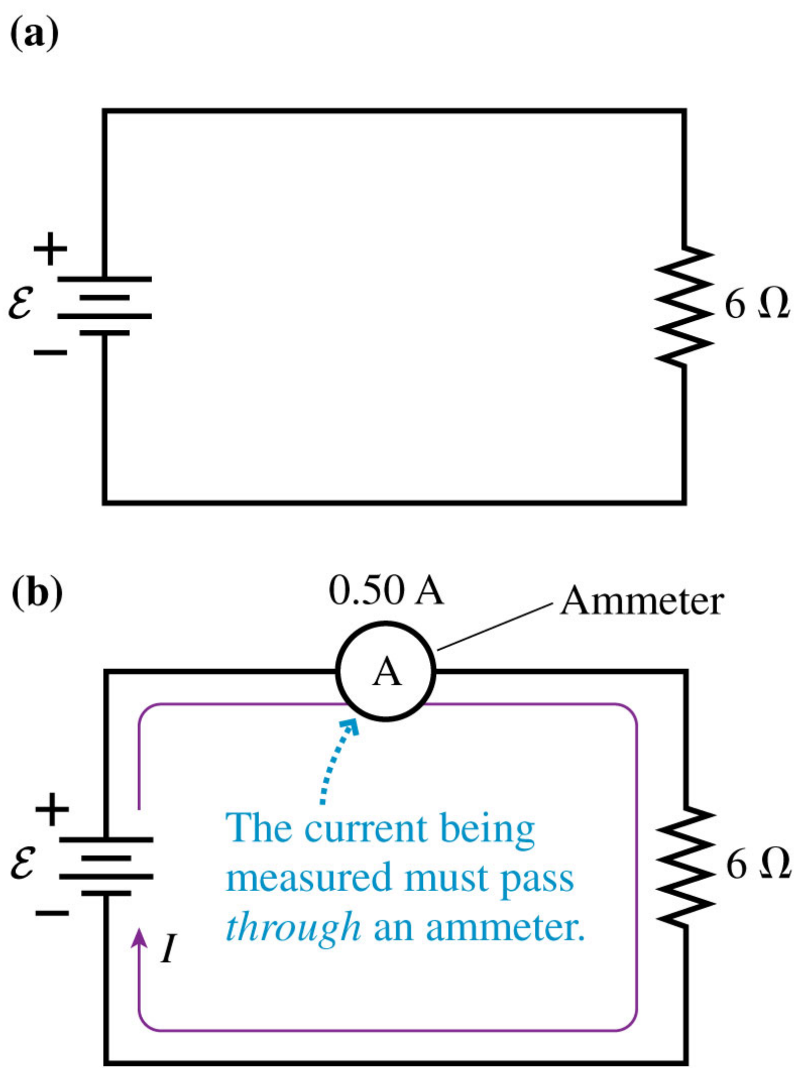
Example 31.5 A Series Resistor Circuit

EXAMPLE 31.5 A series resistor circuit

b. $I = 0.333$ A is the current in each of the three resistors in the original circuit. Thus the potential differences across the resistors are $\Delta V_{\text{res 1}} = -IR_1 = -5.0$ V, $\Delta V_{\text{res 2}} = -IR_2 = -1.3$ V, and $\Delta V_{\text{res 3}} = -IR_3 = -2.7$ V for the 15 Ω, the 4 Ω, and the 8 Ω resistors, respectively. The figure below shows that the potential increases by 9 V due to the battery's emf, then decreases by 9 V in three steps.



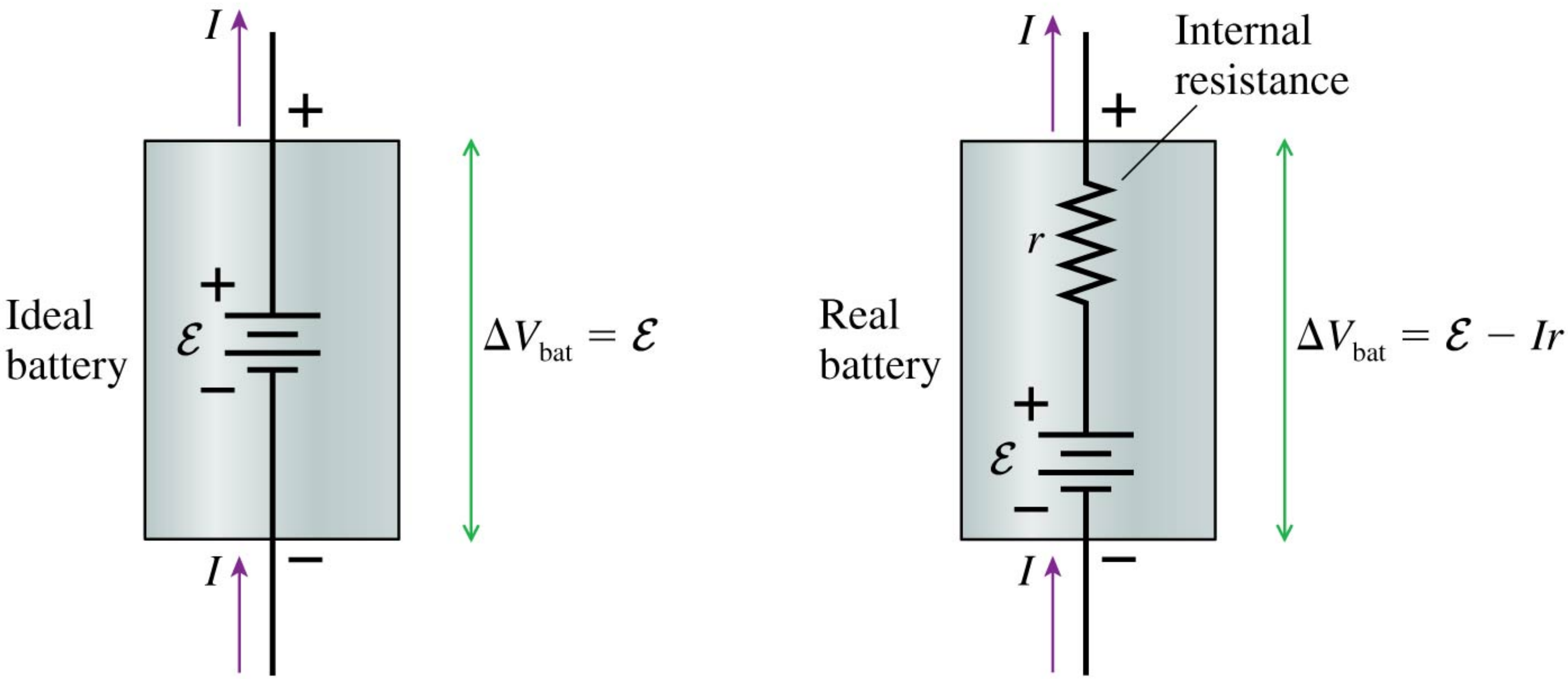
Ammeters



- Figure (a) shows a simple one-resistor circuit.
- We can measure the current by breaking the connection and inserting an ammeter *in series.*
- The resistance of the ammeter is negligible.
- The potential difference across the resistor must be $\Delta V_R = IR = 3.0$ V.
- So the battery's emf must be 3.0 V.

Real Batteries

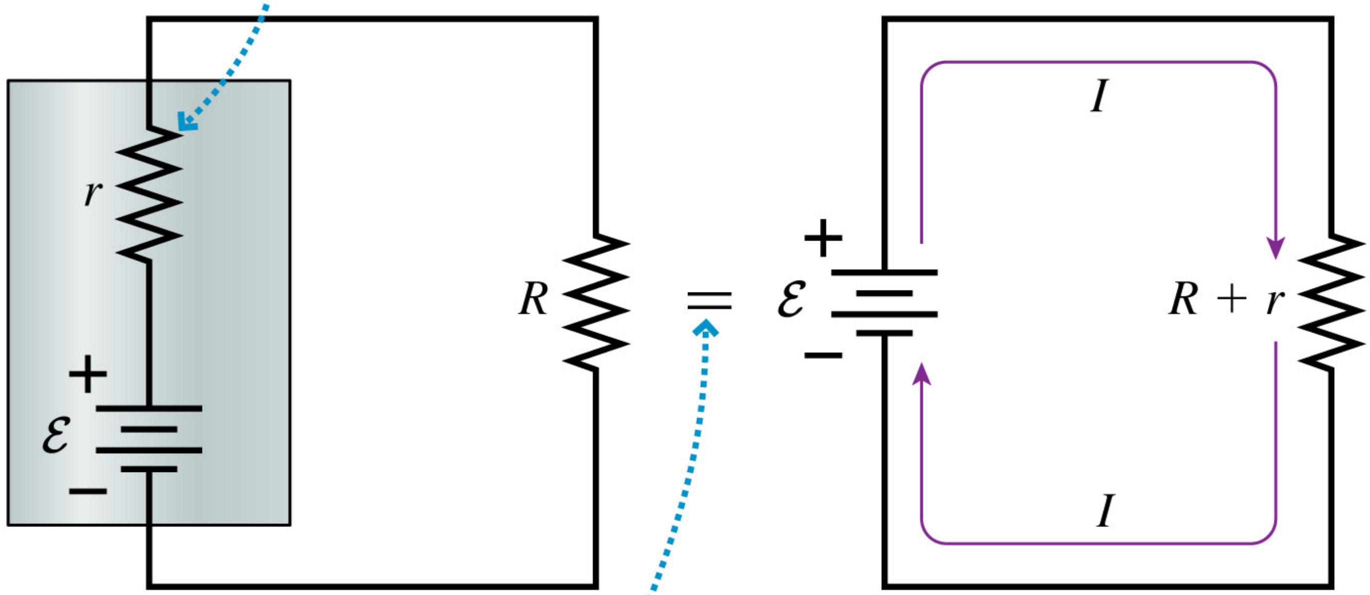
Real batteries have what is called an internal resistance, which is symbolized by r.



Real Batteries

A single resistor connected to a real battery is in series with the battery's internal resistance, giving $R_{eq} = R + r$.

Although physically separated, the internal resistance r is electrically in series with R.



This means the two circuits are equivalent.

Example 31.6 Lighting Up a Flashlight

EXAMPLE 31.6 Lighting up a flashlight

A 6 Ω flashlight bulb is powered by a 3 V battery with an internal resistance of 1 Ω. What are the power dissipation of the bulb and the terminal voltage of the battery?

MODEL Assume ideal connecting wires but not an ideal battery.

Example 31.6 Lighting Up a Flashlight

EXAMPLE 31.6 **Lighting up a flashlight**

SOLVE Equation 31.19 gives us the current:

$$I = \frac{\mathcal{E}}{R + r} = \frac{3\ \text{V}}{6\ \Omega + 1\ \Omega} = 0.43\ \text{A}$$

This is 15% less than the 0.5 A an ideal battery would supply. The potential difference across the resistor is $\Delta V_R = IR = 2.6$ V, thus the power dissipation is

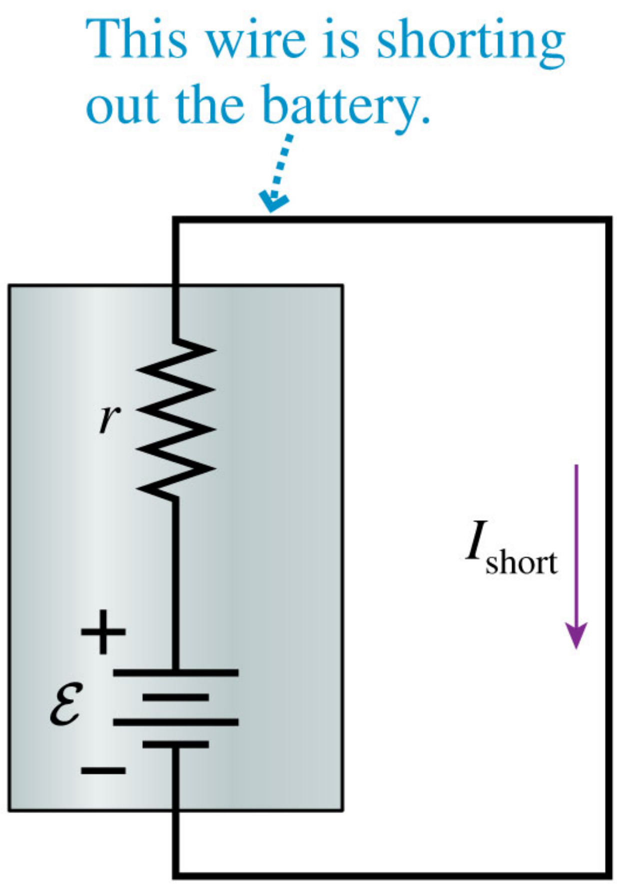
$$P_R = I\,\Delta V_R = 1.1\ \text{W}$$

The battery's terminal voltage is

$$\Delta V_{bat} = \frac{R}{R + r}\mathcal{E} = \frac{6\ \Omega}{6\ \Omega + 1\ \Omega}3\ \text{V} = 2.6\ \text{V}$$

ASSESS 1 Ω is a typical internal resistance for a flashlight battery. The internal resistance causes the battery's terminal voltage to be 0.4 V less than its emf in this circuit.

A Short Circuit



- The figure shows an ideal wire *shorting out* a battery.
- If the battery were ideal, shorting it with an ideal wire ($R = 0\ \Omega$) would cause the current to be infinite!
- In reality, the battery's internal resistance r becomes the only resistance in the circuit.
- The *short-circuit current* is:

$$I_{short} = \frac{\mathcal{E}}{r}$$

Example 31.7 A Short-Circuited Battery

EXAMPLE 31.7 **A short-circuited battery**

What is the short-circuit current of a 12 V car battery with an internal resistance of 0.020 Ω? What happens to the power supplied by the battery?

SOLVE The short-circuit current is

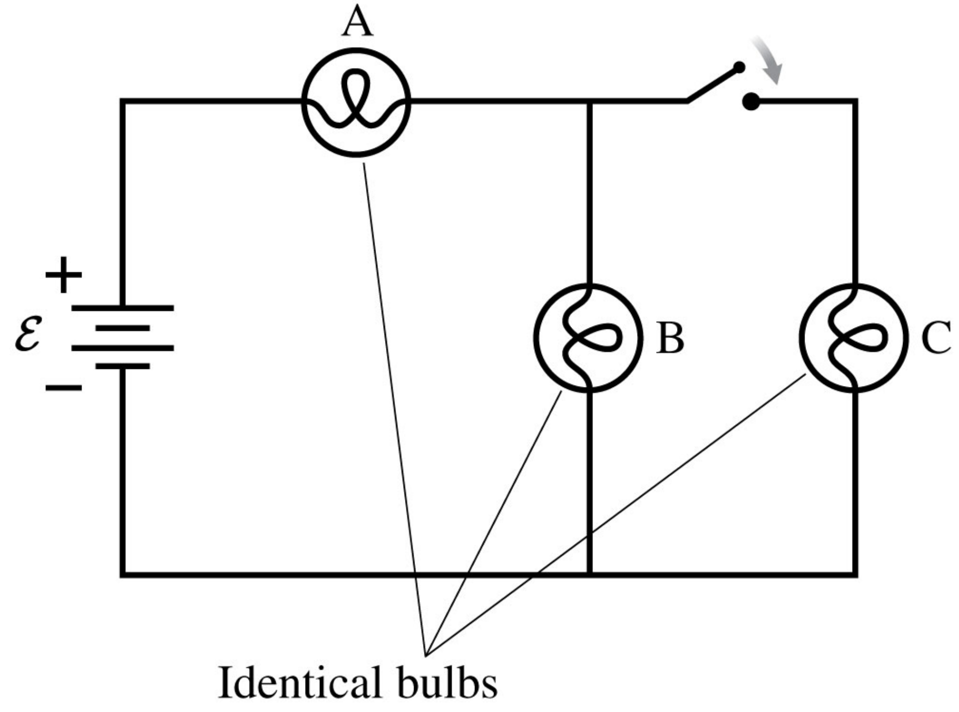
$$I_{\text{short}} = \frac{\mathcal{E}}{r} = \frac{12\ \text{V}}{0.02\ \Omega} = 600\ \text{A}$$

Power is generated by chemical reactions in the battery and dissipated by the load resistance. But with a short-circuited battery, the load resistance is *inside* the battery! The "shorted" battery has to dissipate power $P = I^2 r = 7200$ W *internally*.

ASSESS This value is realistic. Car batteries are designed to drive the starter motor, which has a very small resistance and can draw a current of a few hundred amps. That is why the battery cables are so thick. A shorted car battery can produce an *enormous* amount of current. The normal response of a shorted car battery is to explode; it simply cannot dissipate this much power. Shorting a flashlight battery can make it rather hot, but your life is not in danger. Although the voltage of a car battery is relatively small, a car battery can be dangerous and should be treated with great respect.

Lightbulb Puzzle #3

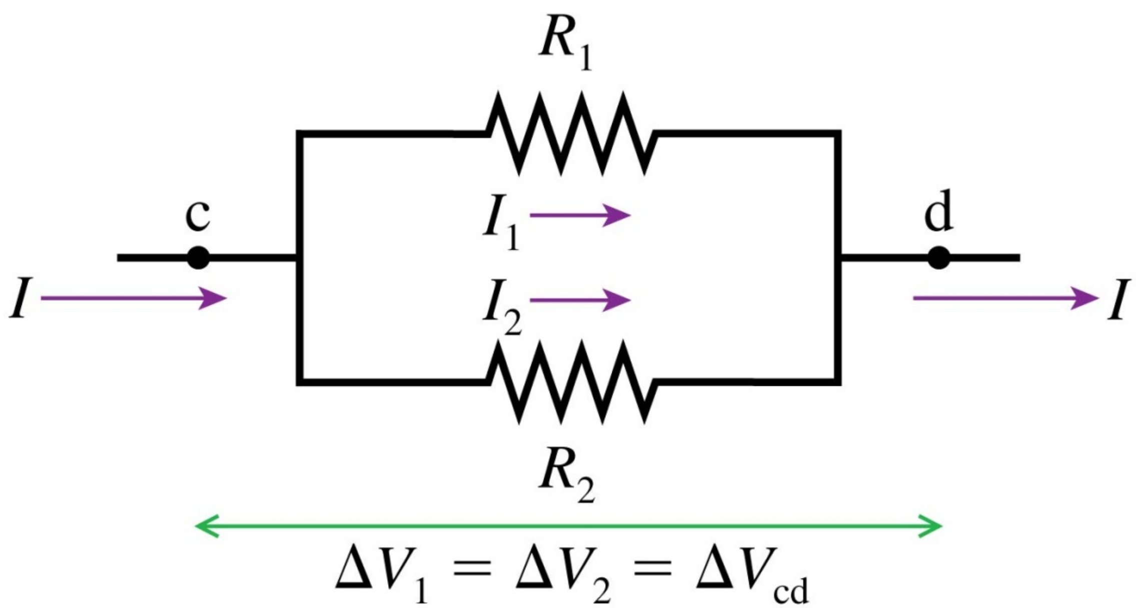
- The figure shows three identical lightbulbs in a circuit.
- When the switch is closed, an alternate pathway for the current to get from bulb A back to the battery is created.
- This *decreases* the overall resistance of the circuit, and the brightess of bulb A *increases.*



Parallel Resistors

- The figure below shows two resisters connected *in parallel* between points c and d.
- By Kirchhoff' s junction law, the input current is the sum of the current through each resistor: $I = I_1 + I_2$.

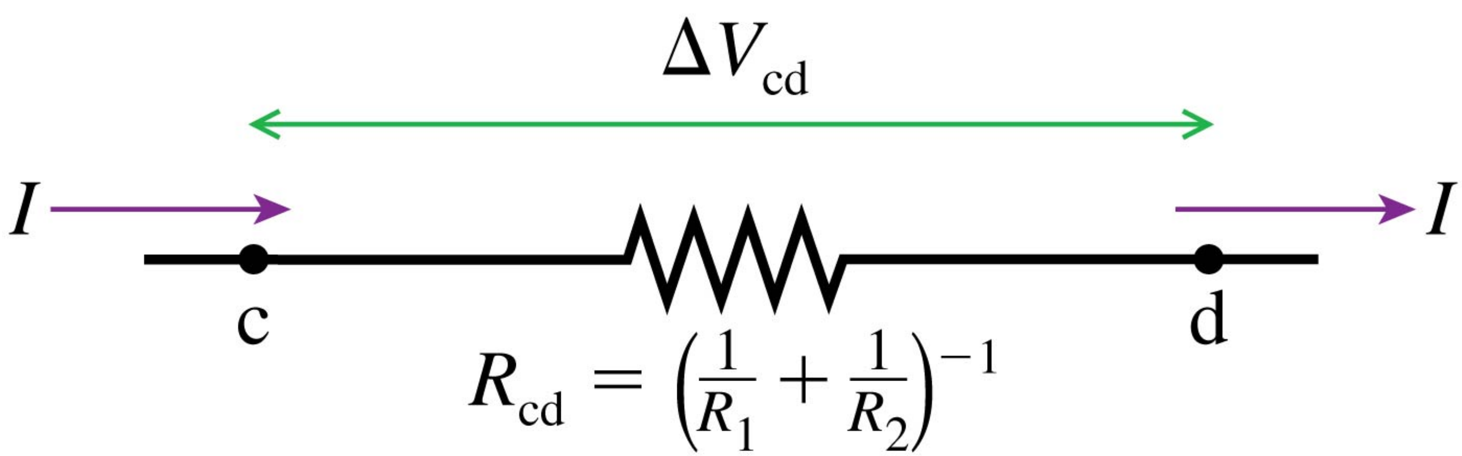
$$I = \frac{\Delta V_1}{R_1} + \frac{\Delta V_2}{R_2} = \frac{\Delta V_{cd}}{R_1} + \frac{\Delta V_{cd}}{R_2} = \Delta V_{cd}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$



Series Resistors

- Suppose we replace R_1 and R_2 with a single resistor with the same current I and the same potential difference ΔV_{cd}.
- Ohm's law gives resistance between points c and d:

$$R_{\text{cd}} = \frac{\Delta V_{\text{cd}}}{I} = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1}$$



Parallel Resistors

- Resistors connected *at both ends* are called **parallel resistors** or, sometimes, resistors "in parallel."
- The left ends of all the resistors connected in parallel are held at the same potential V_1, and the right ends are all held at the same potential V_2.
- The potential differences ΔV are the *same* across all resistors placed in parallel.
- If we have N resistors in parallel, their **equivalent resistance** is:

$$R_{eq} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_N}\right)^{-1} \quad \text{(parallel resistors)}$$

The behavior of the circuit will be unchanged if the N parallel resistors are replaced by the single resistor R_{eq}.

QuickCheck 31.11

The battery current *I* is

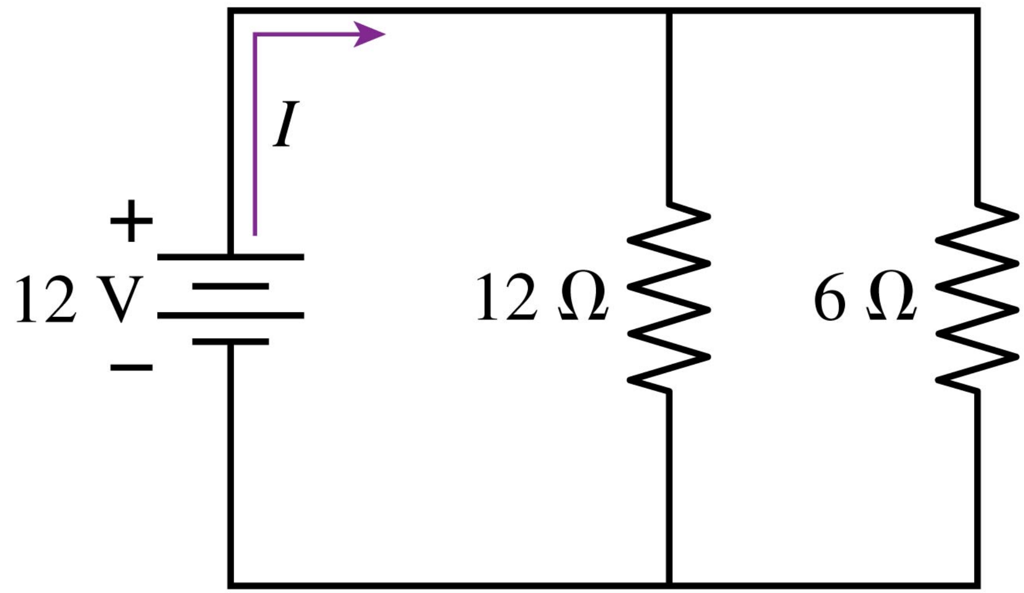
A. 3 A.

B. 2 A.

C. 1 A.

D. 2/3 A.

E. 1/2 A.



QuickCheck 31.11

The battery current I is

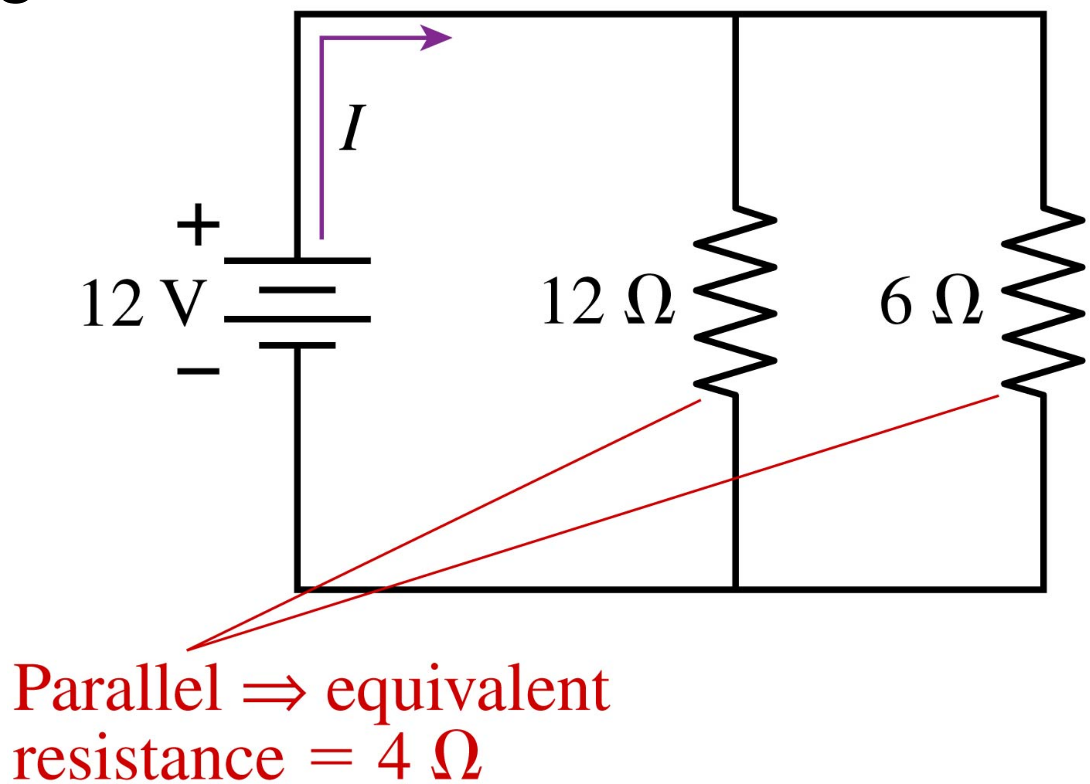
✔ **A. 3 A.**

B. 2 A.

C. 1 A.

D. 2/3 A.

E. 1/2 A.

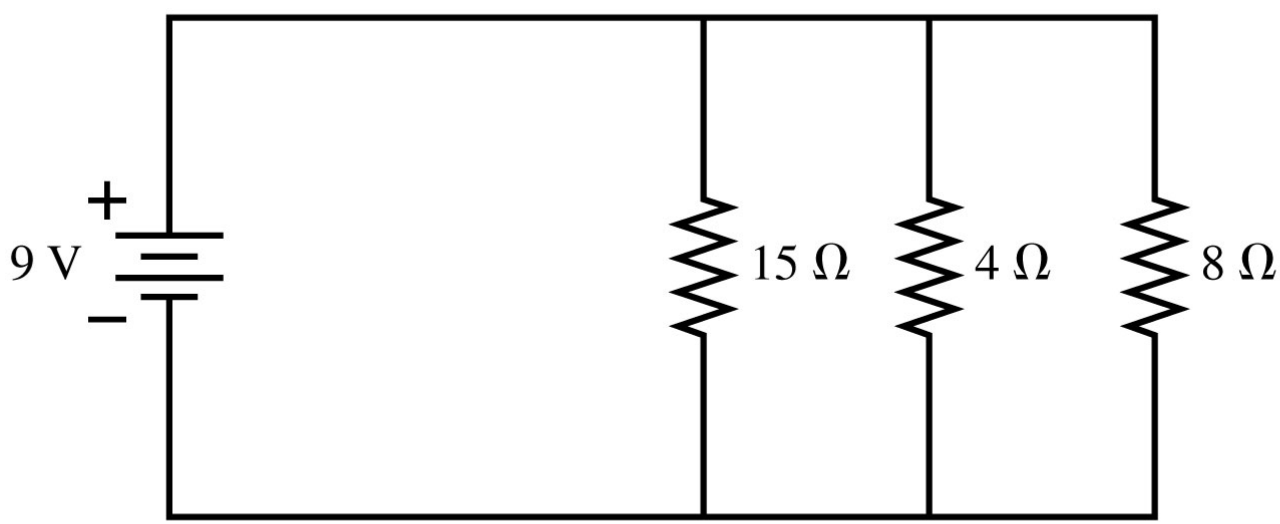


Example 31.8 A Parallel Resistor Circuit

EXAMPLE 31.8 A parallel resistor circuit

The three resistors below are connected to a 9 V battery. Find the potential difference across and the current through each resistor.

MODEL The resistors are in parallel. Assume an ideal battery and ideal connecting wires.



Example 31.8 A Parallel Resistor Circuit

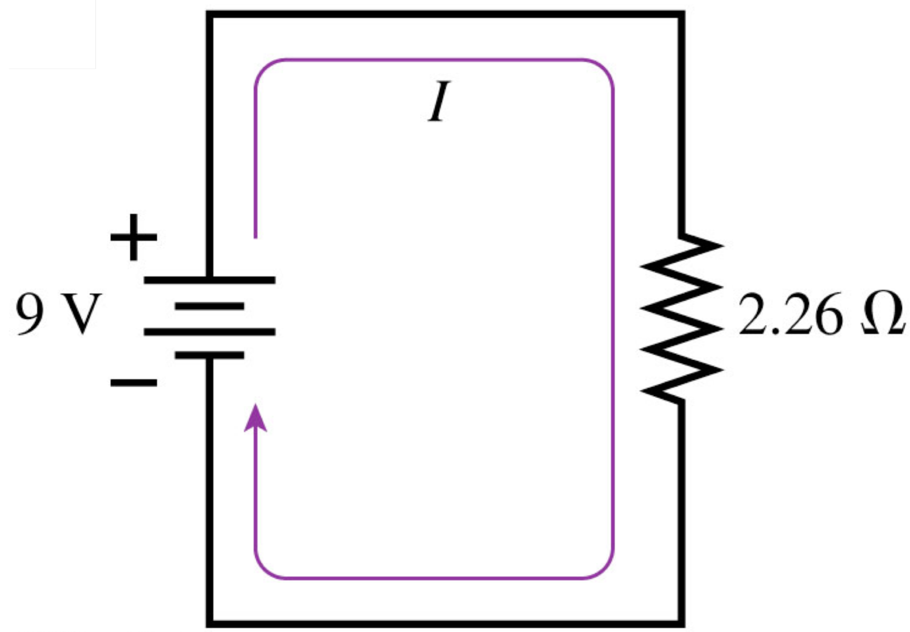
EXAMPLE 31.8 A parallel resistor circuit

SOLVE The three parallel resistors can be replaced by a single equivalent resistor

$$R_{eq} = \left(\frac{1}{15\ \Omega} + \frac{1}{4\ \Omega} + \frac{1}{8\ \Omega}\right)^{-1} = (0.4417\ \Omega^{-1})^{-1} = 2.26\ \Omega$$

The equivalent circuit is shown below from which we find the current to be

$$I = \frac{\mathcal{E}}{R_{eq}} = \frac{9\ \text{V}}{2.26\ \Omega} = 3.98\ \text{A}$$



Example 31.8 A Parallel Resistor Circuit

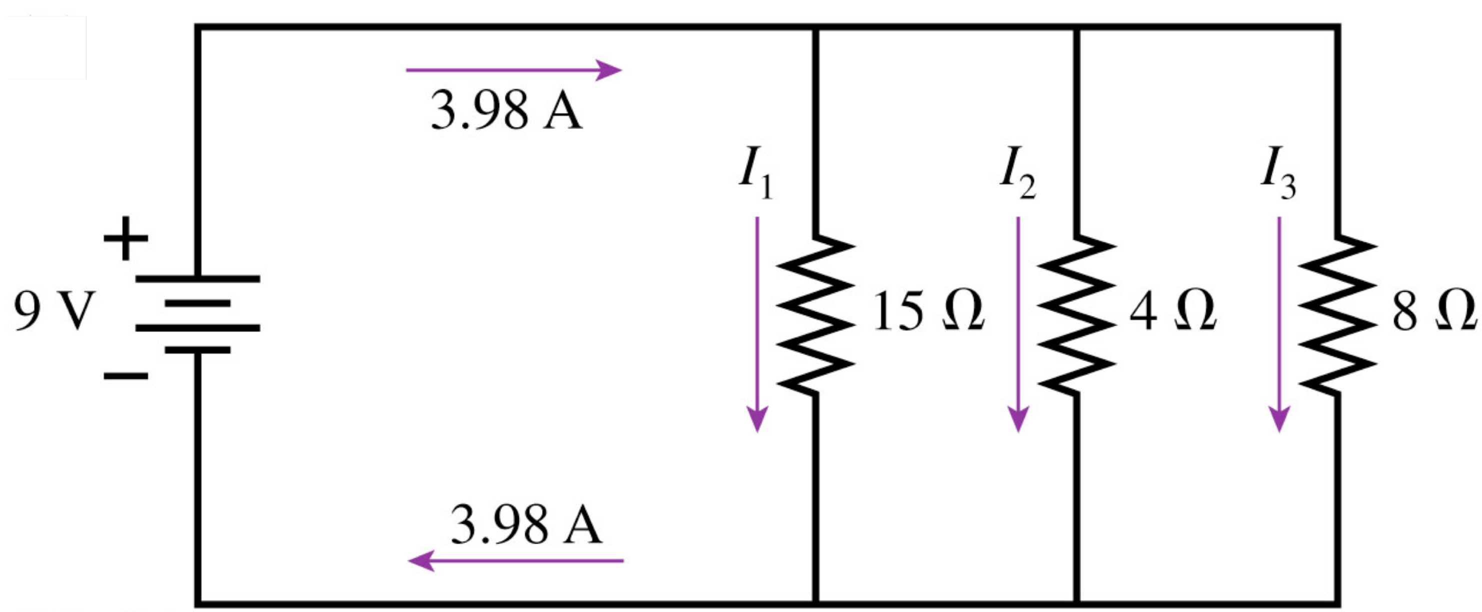
EXAMPLE 31.8 **A parallel resistor circuit**

Thus the currents are

$$I_1 = \frac{9\text{ V}}{15\ \Omega} = 0.60\text{ A} \qquad I_2 = \frac{9\text{ V}}{4\ \Omega} = 2.25\text{ A}$$

$$I_3 = \frac{9\text{ V}}{8\ \Omega} = 1.13\text{ A}$$

ASSESS The *sum* of the three currents is 3.98 A, as required by Kirchhoff's junction law.



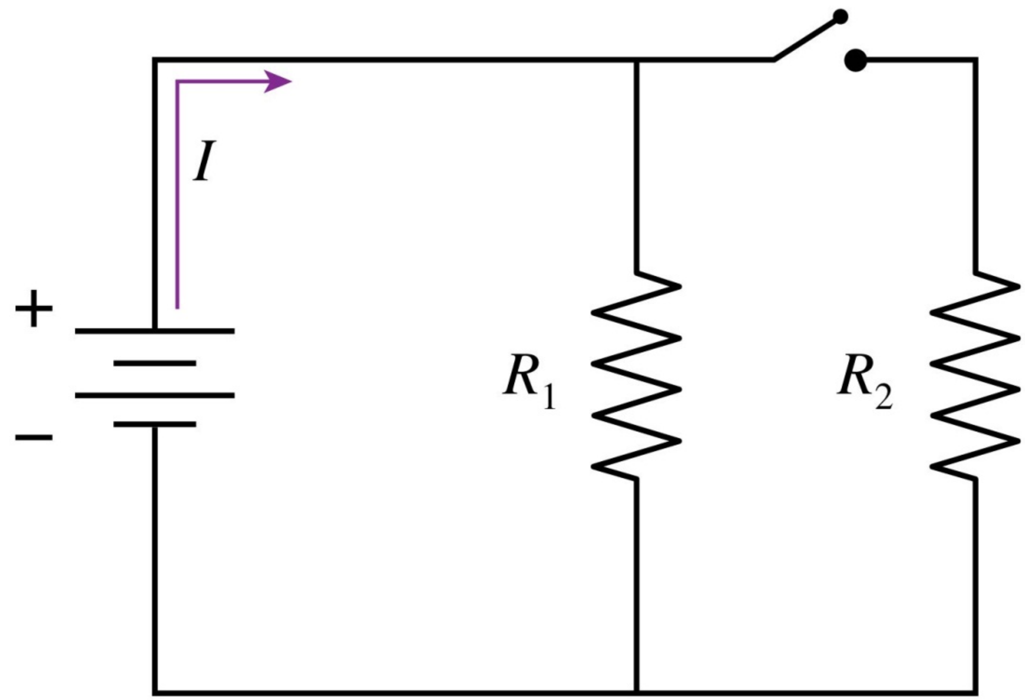
QuickCheck 31.12

When the switch closes, the battery current

A. Increases.

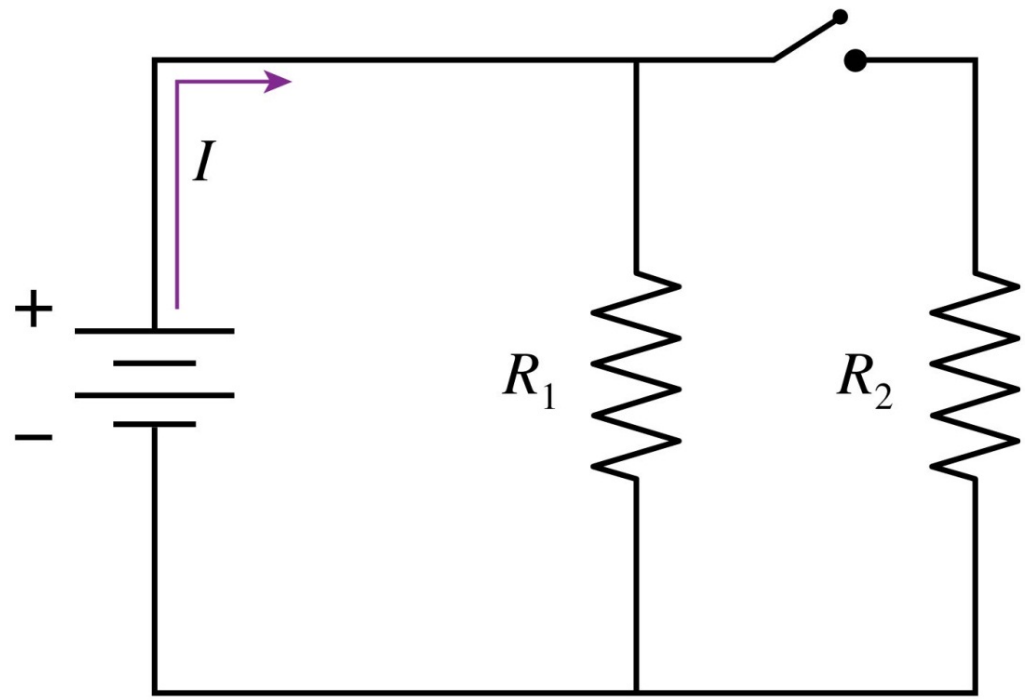
B. Stays the same.

C. Decreases.



QuickCheck 31.12

When the switch closes, the battery current



✔ **A. Increases.**

B. Stays the same.

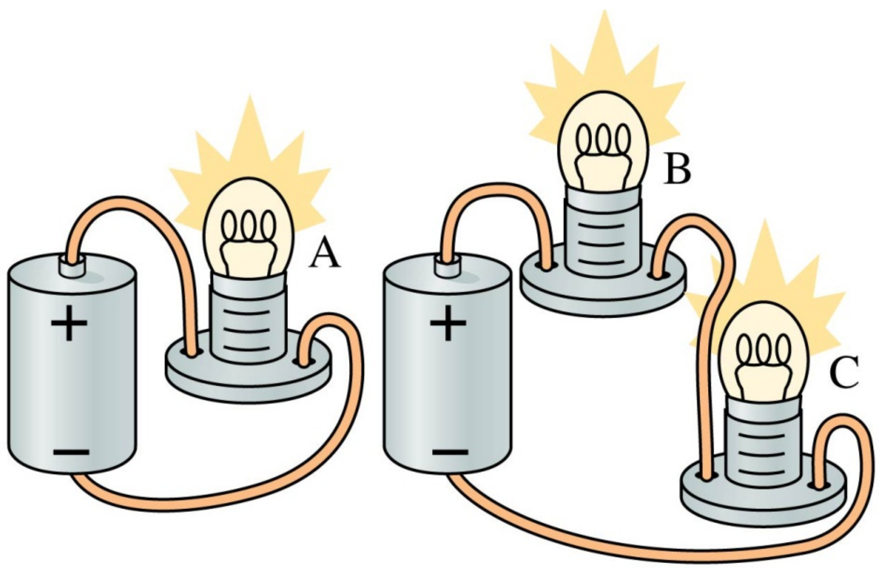
C. Decreases.

Equivalent resistance decreases.
Potential difference is unchanged.

QuickCheck 31.13

The three bulbs are identical and the two batteries are identical. Compare the brightnesses of the bulbs.

A. A > B > C.
B. A > C > B.
C. A > B = C.
D. A < B = C.
E. A = B = C.



QuickCheck 31.13

The three bulbs are identical and the two batteries are identical. Compare the brightnesses of the bulbs.

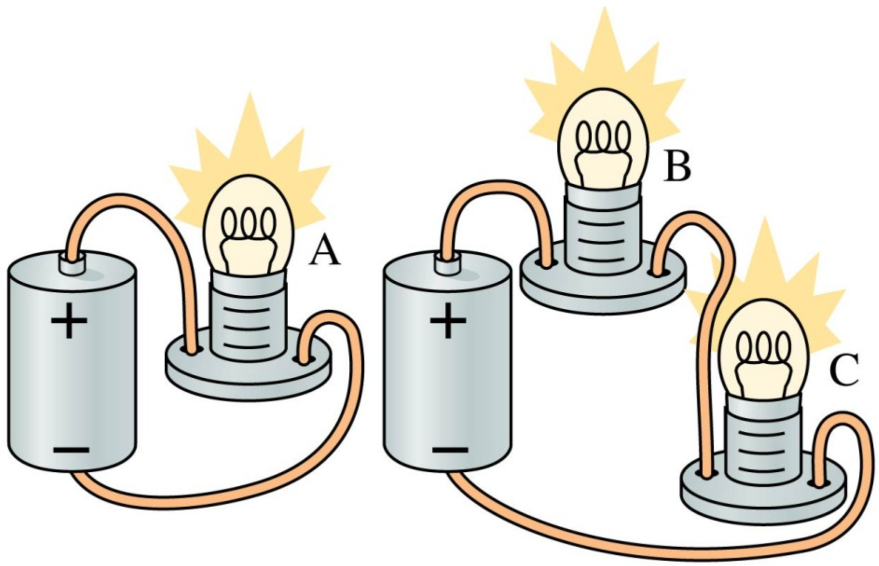
A. $A > B > C$.

B. $A > C > B$.

C. $\mathbf{A > B = C}$.

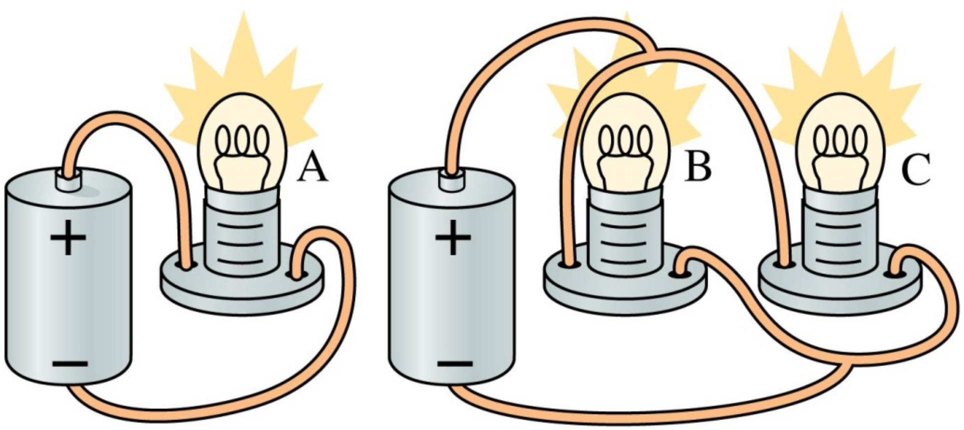
D. $A < B = C$.

E. $A = B = C$.



QuickCheck 31.14

The three bulbs are identical and the two batteries are identical. Compare the brightnesses of the bulbs.

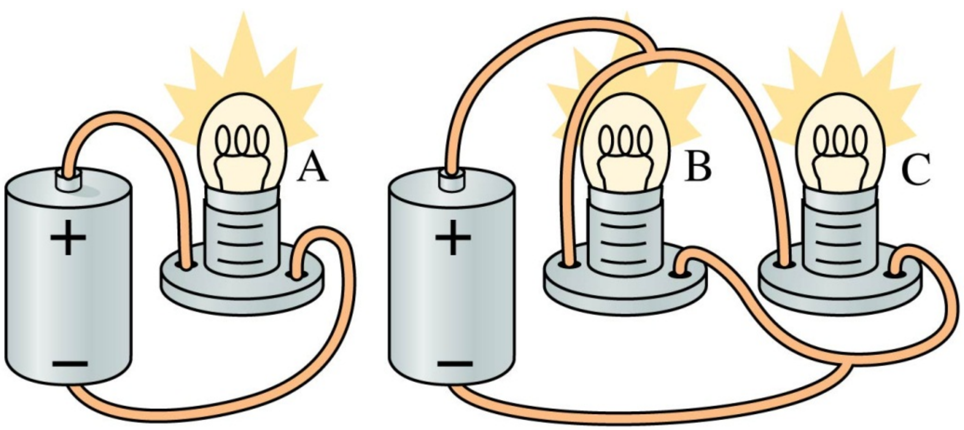


A. A > B > C.
B. A > C > B.
C. A > B = C.
D. A < B = C.
E. A = B = C.

QuickCheck 31.14

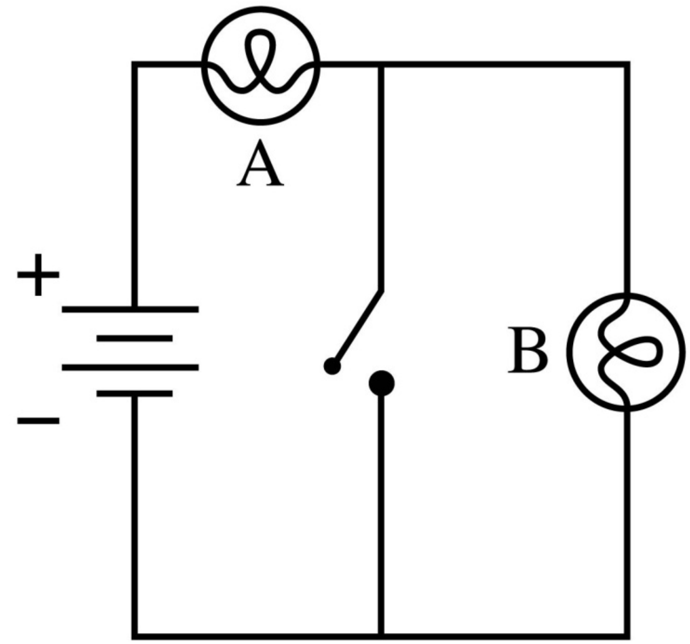
The three bulbs are identical and the two batteries are identical. Compare the brightnesses of the bulbs.

A. A > B > C.
B. A > C > B.
C. A > B = C.
D. A < B = C.
E. **A = B = C.**



QuickCheck 31.15

The lightbulbs are identical. Initially both bulbs are glowing. What happens when the switch is closed?



A. Nothing.
B. A stays the same;
   B gets dimmer.
C. A gets brighter;
   B stays the same.
D. Both get dimmer.
E. A gets brighter;
   B goes out.

QuickCheck 31.15

The lightbulbs are identical. Initially both bulbs are glowing. What happens when the switch is closed?

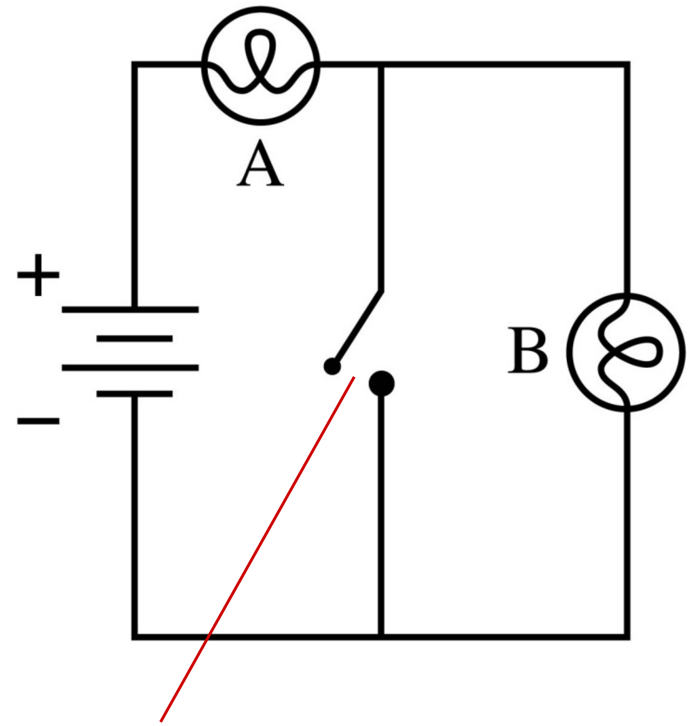
A. Nothing.

B. A stays the same;
B gets dimmer.

C. A gets brighter;
B stays the same.

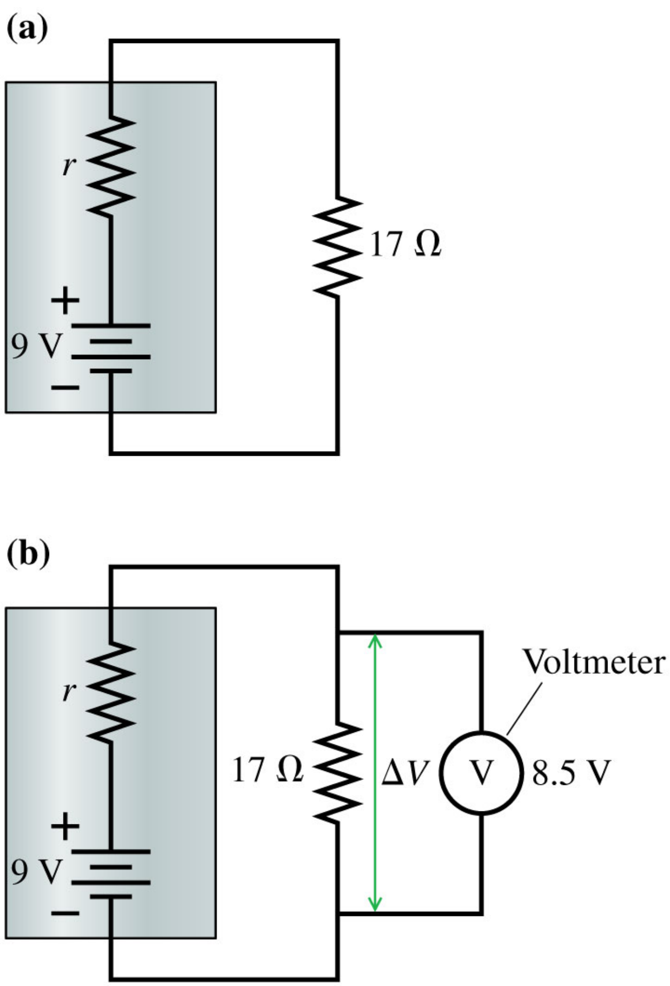
D. Both get dimmer.

✔ **E. A gets brighter;**
B goes out.



Short circuit.
Zero resistance
path.

Voltmeters



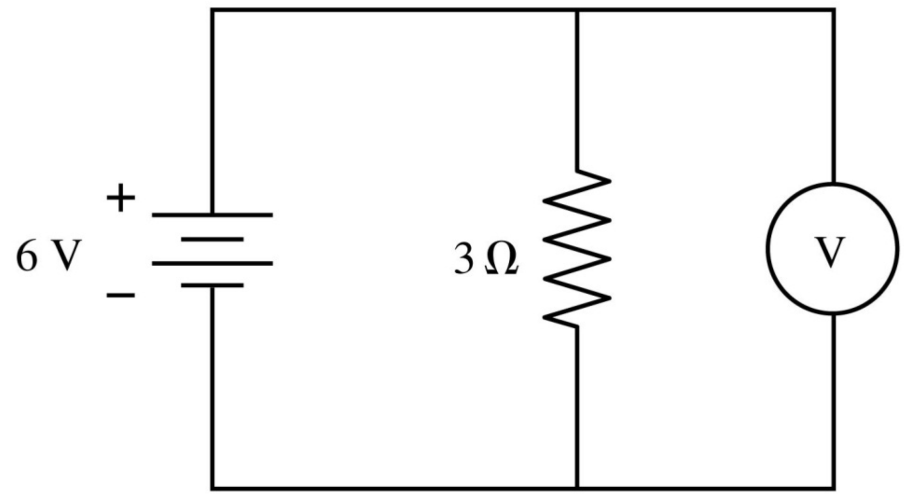
- Figure (a) shows a simple circuit with a resistor and a real battery.
- We can measure the potential difference across the resistor by connecting a voltmeter *in parallel* across the resistor.
- The resistance of the voltmeter must be very high.
- The internal resistance is:

$$r = \frac{\mathcal{E} - \Delta V_R}{\Delta V_R} R = \frac{0.5\ \text{V}}{8.5\ \text{V}} 17\ \Omega = 1.0\ \Omega$$

QuickCheck 31.16

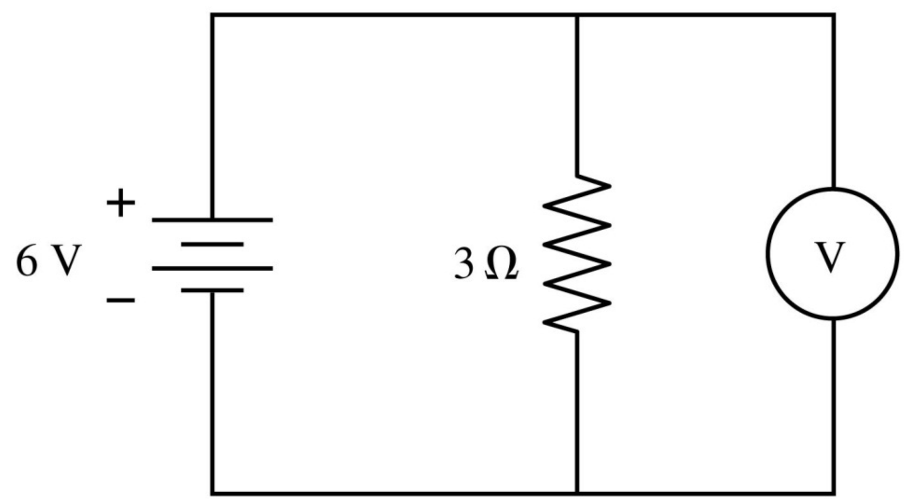
What does the voltmeter read?

A. 6 V.
B. 3 V.
C. 2 V.
D. Some other value.
E. Nothing because this will fry the meter.



QuickCheck 31.16

What does the voltmeter read?



- ✔ **A. 6 V.**
- B. 3 V.
- C. 2 V.
- D. Some other value.
- E. Nothing because this will fry the meter.

QuickCheck 31.17

What does the ammeter read?

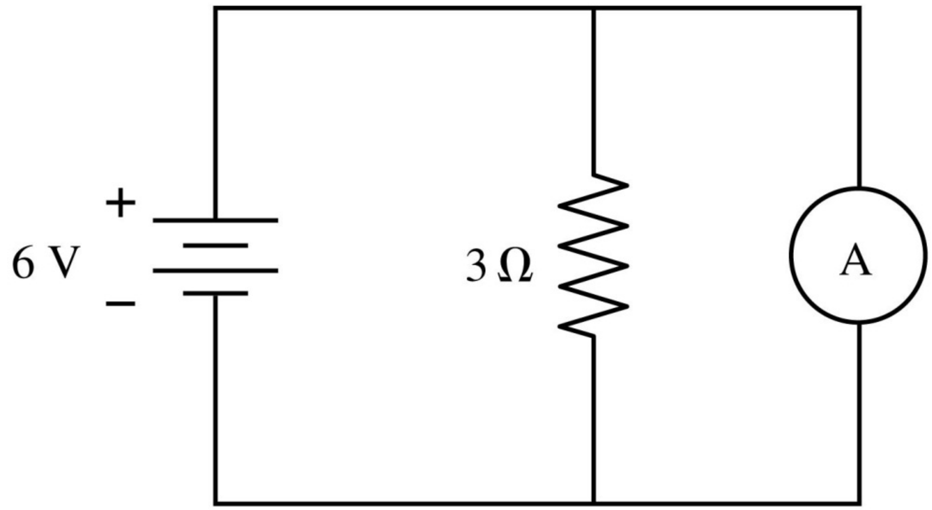
A. 6 A.

B. 3 A.

C. 2 A.

D. Some other value.

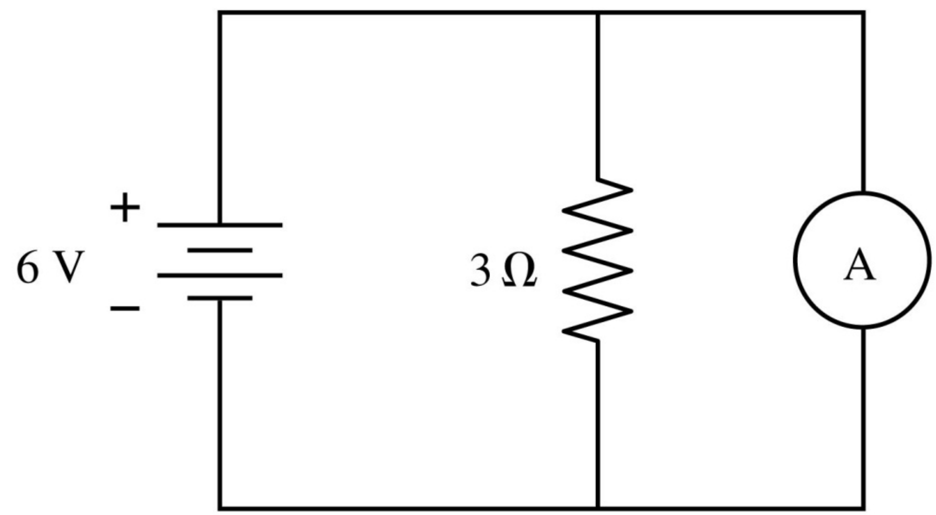
E. Nothing because this will fry the meter.



QuickCheck 31.17

What does the ammeter read?

A. 6 A.
B. 3 A.
C. 2 A.
D. Some other value.
E. **Nothing because this will fry the meter.**



Problem-Solving Strategy: Resistor Circuits

PROBLEM-SOLVING STRATEGY 31.1 **Resistor circuits**

MODEL Assume that wires are ideal and, where appropriate, that batteries are ideal.

VISUALIZE Draw a circuit diagram. Label all known and unknown quantities.

Problem-Solving Strategy: Resistor Circuits

PROBLEM-SOLVING STRATEGY 31.1 **Resistor circuits**

SOLVE Base your mathematical analysis on Kirchhoff's laws and on the rules for series and parallel resistors.

- Step by step, reduce the circuit to the smallest possible number of equivalent resistors.
- Write Kirchhoff's loop law for each independent loop in the circuit.
- Determine the current through and the potential difference across the equivalent resistors.
- Rebuild the circuit, using the facts that the current is the same through all resistors in series and the potential difference is the same for all parallel resistors.

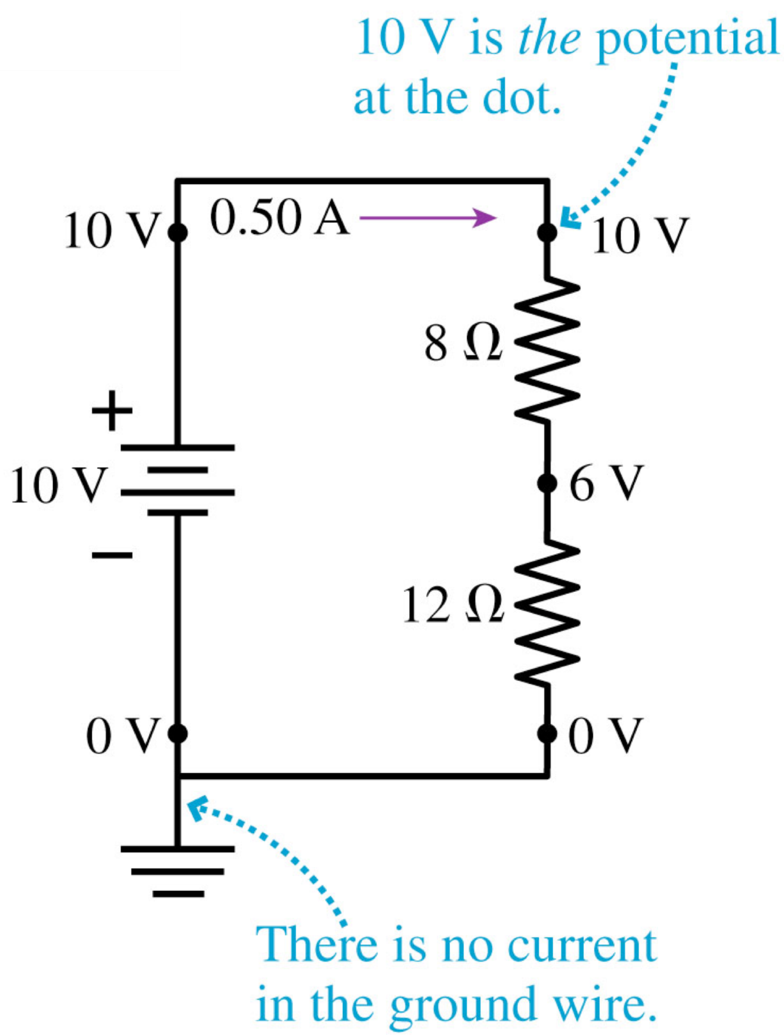
ASSESS Use two important checks as you rebuild the circuit.

- Verify that the sum of the potential differences across series resistors matches ΔV for the equivalent resistor.
- Verify that the sum of the currents through parallel resistors matches I for the equivalent resistor.

Getting Grounded

- The earth itself is a conductor.
- If we connect one point of a circuit to the earth by an ideal wire, we can agree to call potential of this point to be that of the earth: $V_{\text{earth}} = 0\text{ V}$.
- The wire connecting the circuit to the earth is not part of a complete circuit, so there is no current in this wire!
- A circuit connected to the earth in this way is said to be **grounded**, and the wire is called the *ground wire.*
- The circular prong of a three-prong plug is a connection to ground.

A Circuit That Is Grounded

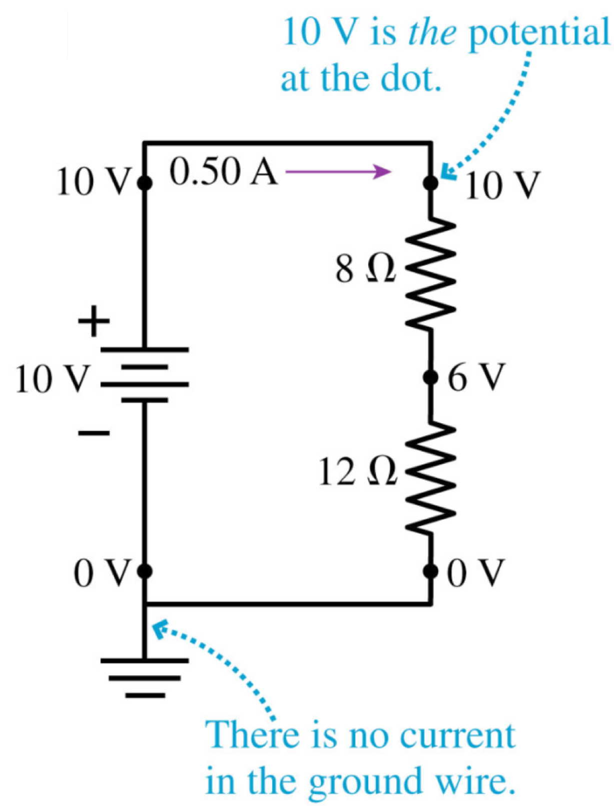


- The figure shows a circuit with a 10 V battery and two resistors in series.
- The symbol beneath the circuit is the ground symbol.
- The potential at the ground is $V = 0$.
- Grounding the circuit allows us to have *specific values* for potential at each point in the circuit, rather than just potential differences.

Example 31.12 A Grounded Circuit

EXAMPLE 31.12 A grounded circuit

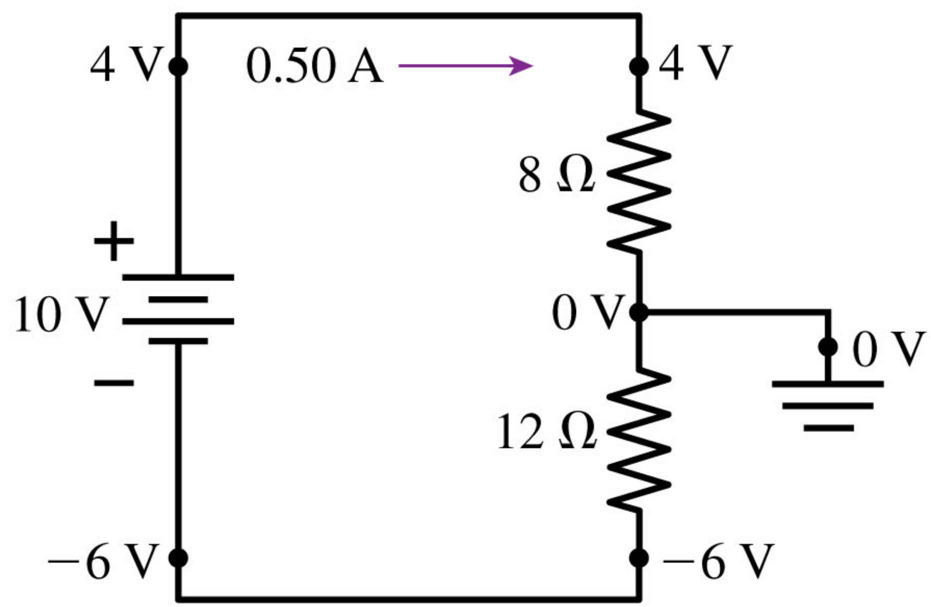
Suppose the circuit below were grounded at the junction between the two resistors instead of at the bottom. Find the potential at each corner of the circuit.



Example 31.12 A Grounded Circuit

EXAMPLE 31.12 A grounded circuit

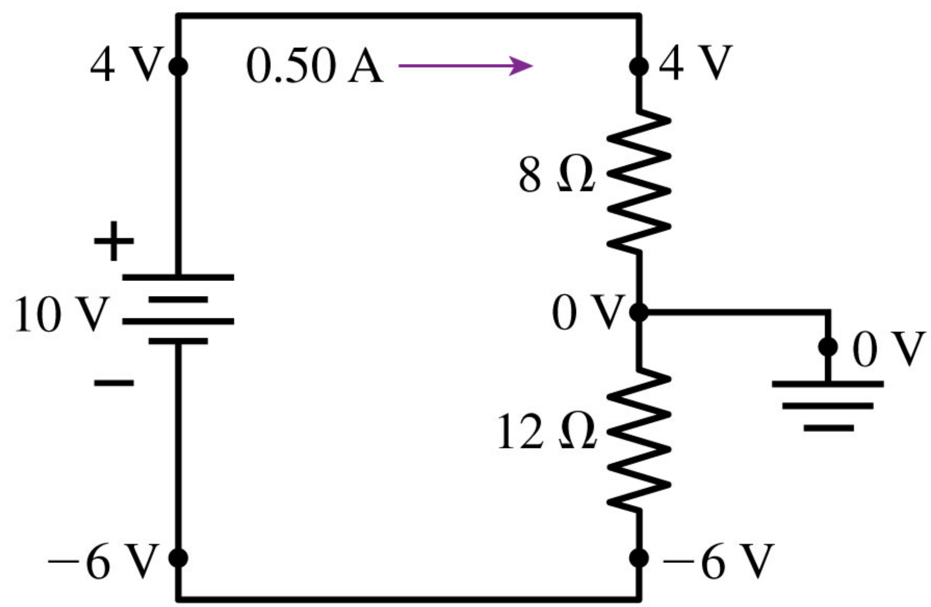
VISUALIZE The figure below shows the new circuit. (It is customary to draw the ground symbol so that its "point" is always down.)



Example 31.12 A Grounded Circuit

EXAMPLE 31.12 **A grounded circuit**

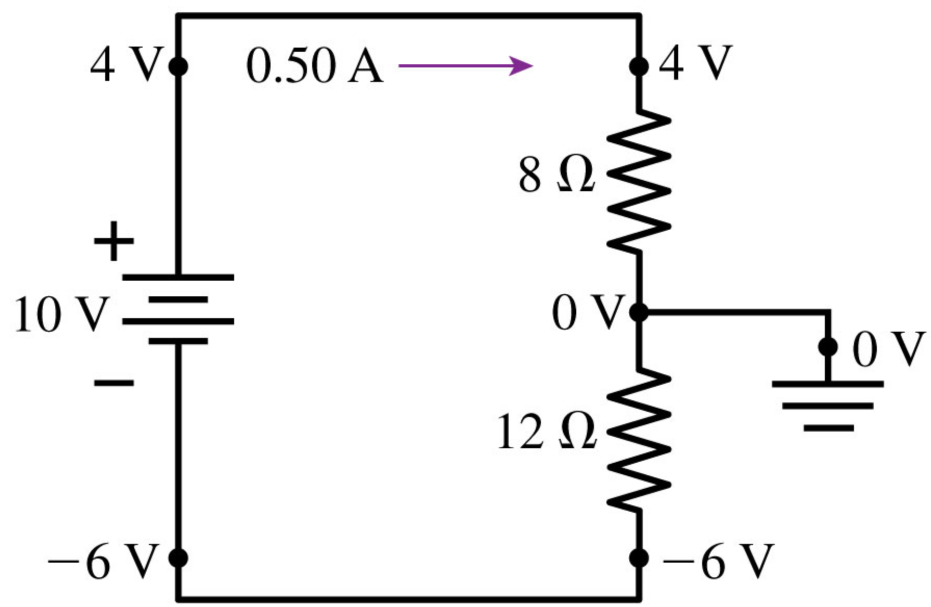
SOLVE Changing the ground point does not affect the circuit's behavior. The current is still 0.50 A, and the potential differences across the two resistors are still 4 V and 6 V. All that has happened is that we have moved the $V = 0$ V reference point. Because the earth has $V_{earth} = 0$ V, the junction itself now has a potential of 0 V. The potential decreases by 4 V as charge flows through the 8 Ω resistor. Because it *ends* at 0 V, the potential at the top of the 8 Ω resistor must be +4 V.



Example 31.12 A Grounded Circuit

EXAMPLE 31.12 A grounded circuit

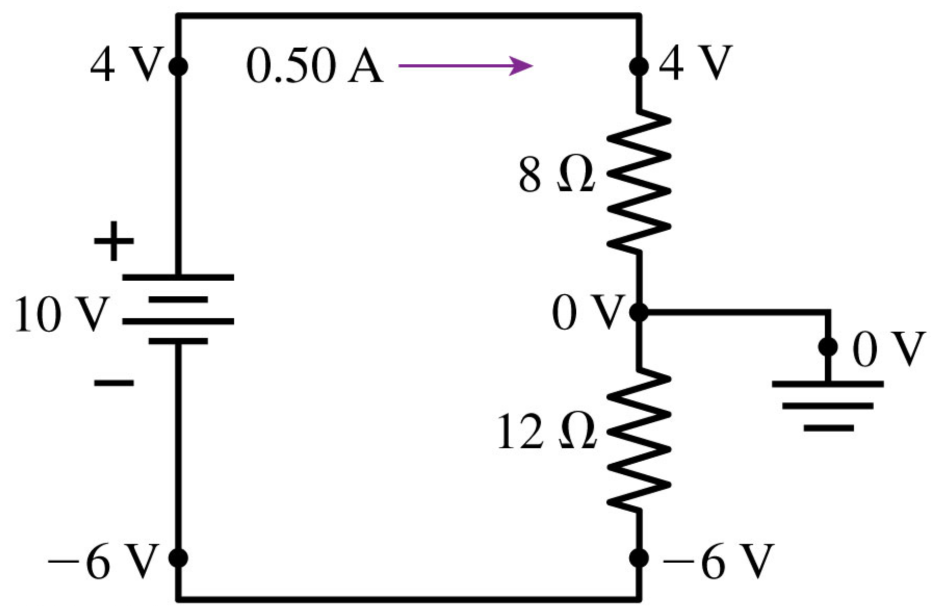
Similarly, the potential decreases by 6 V through the 12 Ω resistor. Because it *starts* at 0 V, the bottom of the 12 Ω resistor must be at −6 V. The negative battery terminal is at the same potential as the bottom of the 12 Ω resistor, because they are connected by a wire, so $V_{neg} = -6$ V. Finally, the potential increases by 10 V as the charge flows through the battery, so $V_{pos} = +4$ V, in agreement, as it should be, with the potential at the top of the 8 Ω resistor.



Example 31.12 A Grounded Circuit

EXAMPLE 31.12 A grounded circuit

ASSESS A negative voltage means only that the potential at that point is less than the potential at some other point that we chose to call $V = 0$ V. Only potential *differences* are physically meaningful, and only potential differences enter into Ohm's law: $I = \Delta V/R$. The potential difference across the 12 Ω resistor in this example is 6 V, decreasing from top to bottom, regardless of which point we choose to call $V = 0$ V.



Chapter 31 Summary Slides

General Strategy

MODEL Assume that wires and, where appropriate, batteries are ideal.

VISUALIZE Draw a circuit diagram. Label all known and unknown quantities.

SOLVE Base the solution on Kirchhoff's laws.

- Reduce the circuit to the smallest possible number of equivalent resistors.
- Write one loop equation for each independent loop.
- Find the current and the potential difference.
- Rebuild the circuit to find I and ΔV for each resistor.

ASSESS Verify that

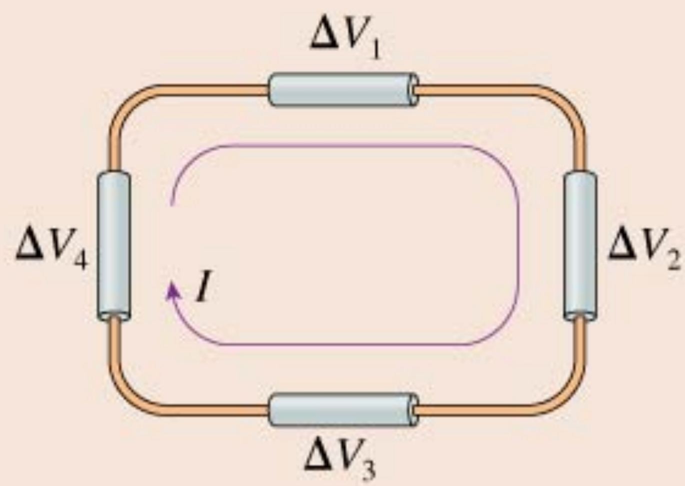
- The sum of potential differences across series resistors matches ΔV for the equivalent resistor.
- The sum of the currents through parallel resistors matches I for the equivalent resistor.

General Strategy

Kirchhoff's loop law

For a closed loop:

- Assign a direction to the current I.
- $\sum(\Delta V)_i = 0$

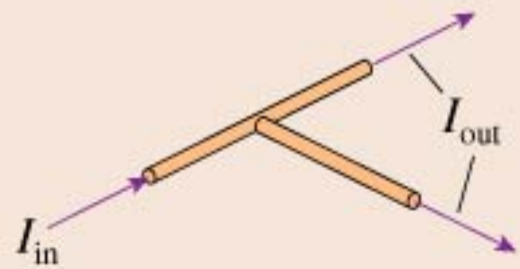


General Strategy

Kirchhoff's junction law

For a junction:

- $\sum I_{\text{in}} = \sum I_{\text{out}}$

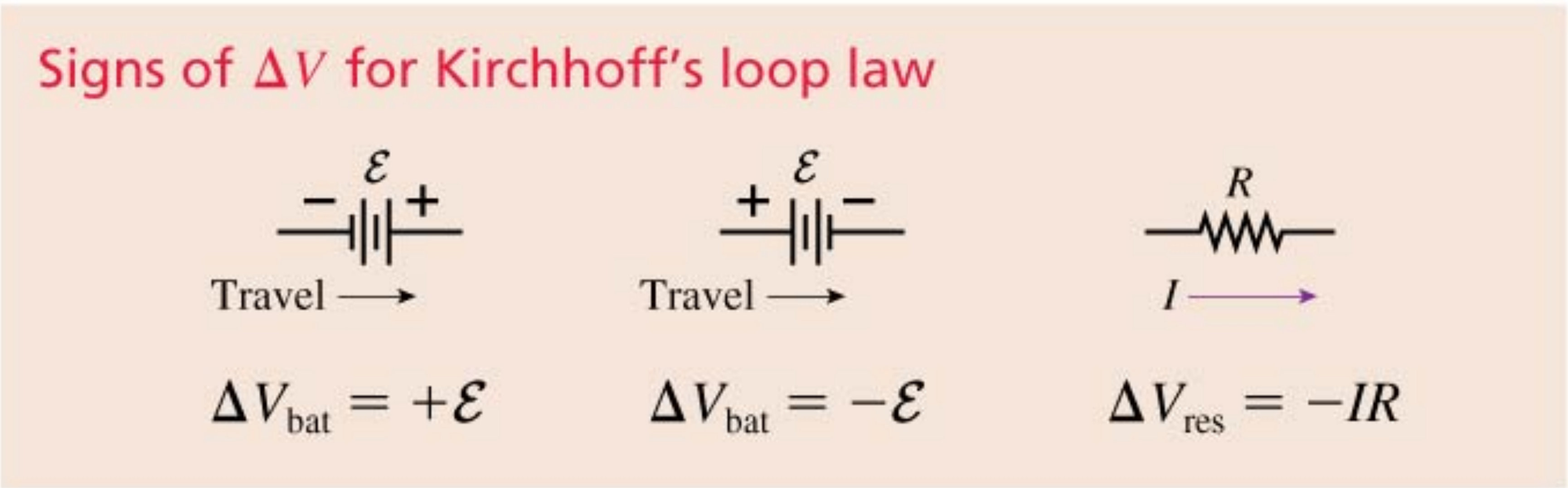


Important Concepts

Ohm's Law

A potential difference ΔV between the ends of a conductor with resistance R creates a current

$$I = \frac{\Delta V}{R}$$


Signs of ΔV for Kirchhoff's loop law
$\mathcal{E}$
− +
Travel
$\Delta V_{\text{bat}} = +\mathcal{E}$
$\mathcal{E}$
+ −
Travel
$\Delta V_{\text{bat}} = -\mathcal{E}$
R
I
$\Delta V_{\text{res}} = -IR$

Important Concepts

The energy used by a circuit is supplied by the emf $\mathcal{E}$ of the battery through the energy transformations

$$E_{\text{chem}} \rightarrow U \rightarrow K \rightarrow E_{\text{th}}$$

The battery *supplies* energy at the rate

$$P_{\text{bat}} = I\mathcal{E}$$

The resistors *dissipate* energy at the rate

$$P_{\text{R}} = I\,\Delta V_{\text{R}} = I^2 R = \frac{(\Delta V_{\text{R}})^2}{R}$$