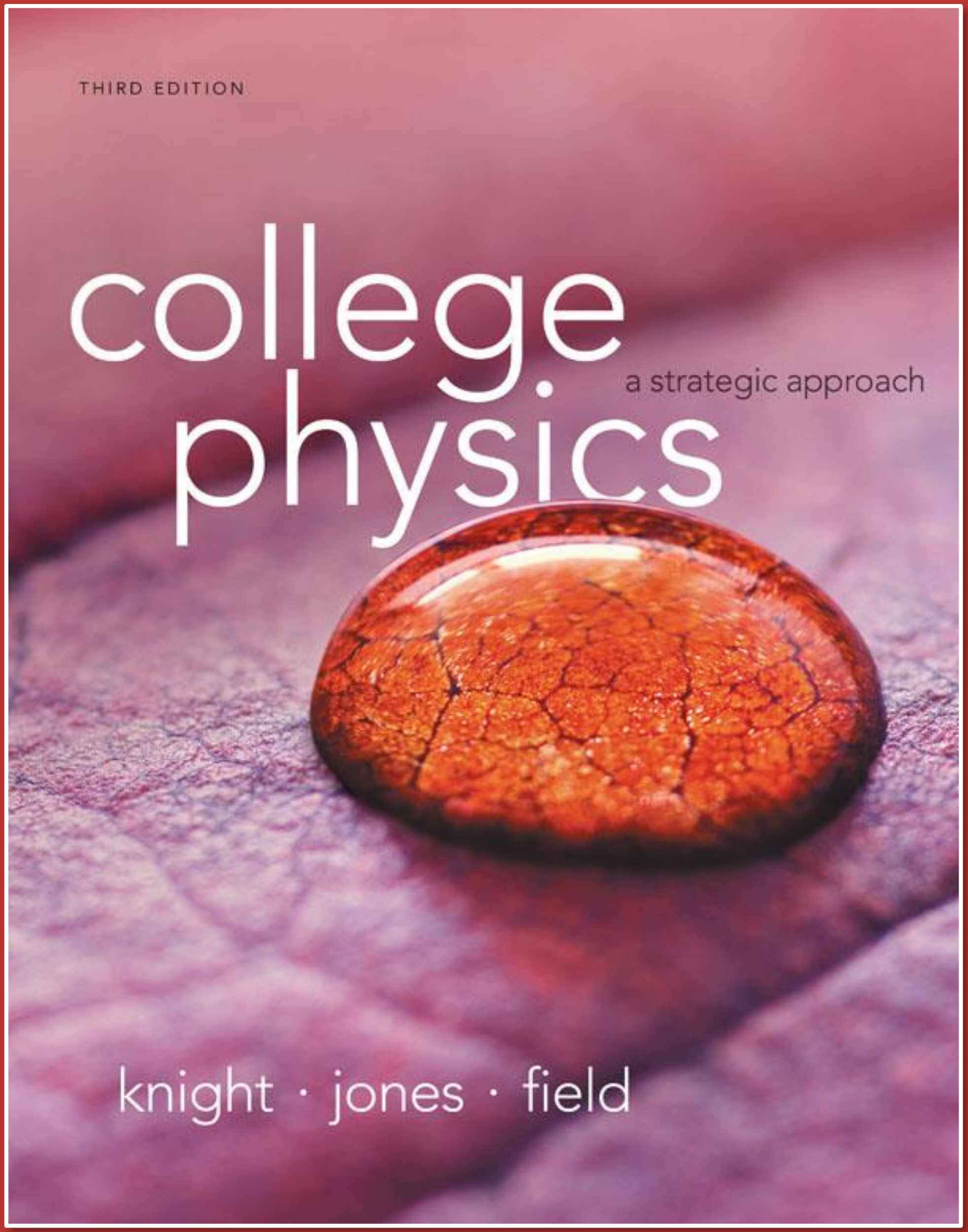


Lecture Presentation

Chapter 22

Current and Resistance

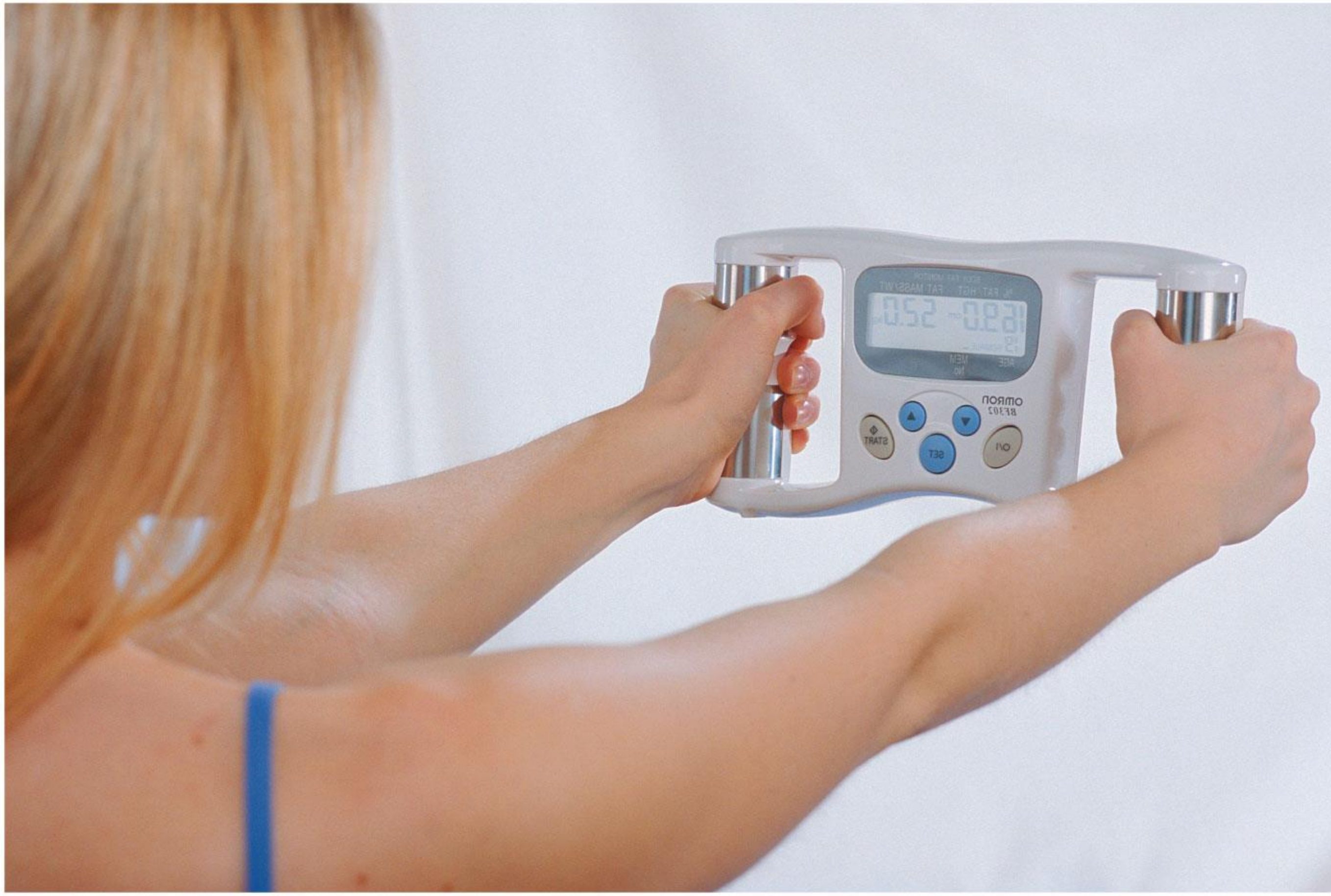
Suggested Videos for Chapter 22

- **Prelecture Videos**
  - *Current and Resistance: Part 1*
  - *Current and Resistance: Part 2*
  - *Current and Resistance: Part 3*
- **Class Videos**
  - *Determining Resistance*
  - *Basic Circuits*
  - *Practical Electrical Applications*
- **Video Tutor Solutions**
  - *Current and Resistance*
- **Video Tutor Demos**
  - *Resistance in Copper and Nichrome*

Suggested Simulations for Chapter 22

- **PhETs**
  - *Battery Voltage*
  - *Signal Circuit*
  - *Resistance in a Wire*
  - *Circuit Construction Kit (DC)*
  - *Battery-Resistor Circuit*
  - *Ohm's Law*

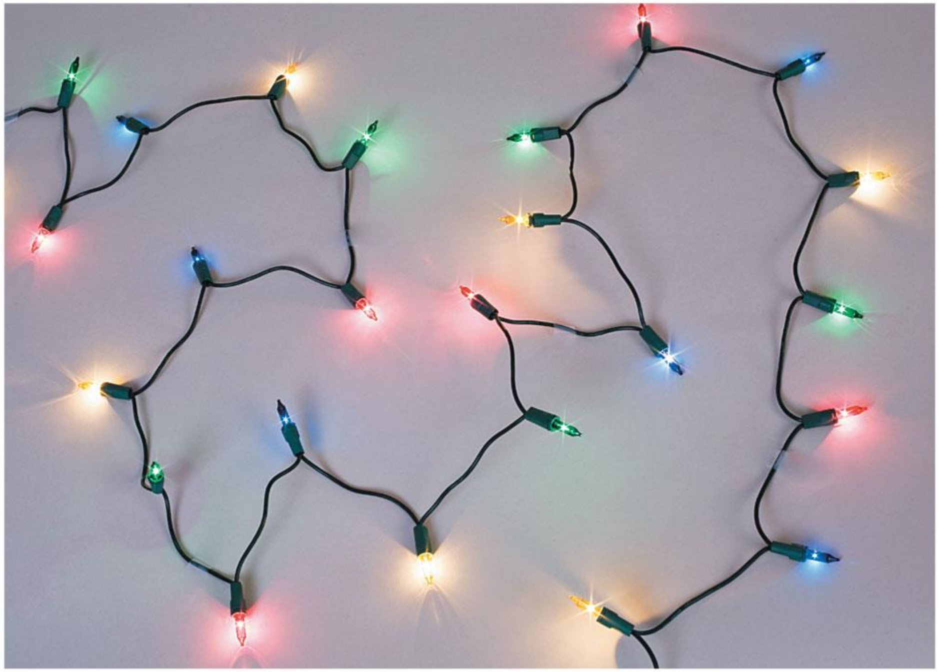
Chapter 22 Current and Resistance



Chapter Goal: To learn how and why charge moves through a conductor as what we call a current.

Chapter 22 Preview
Looking Ahead: Current

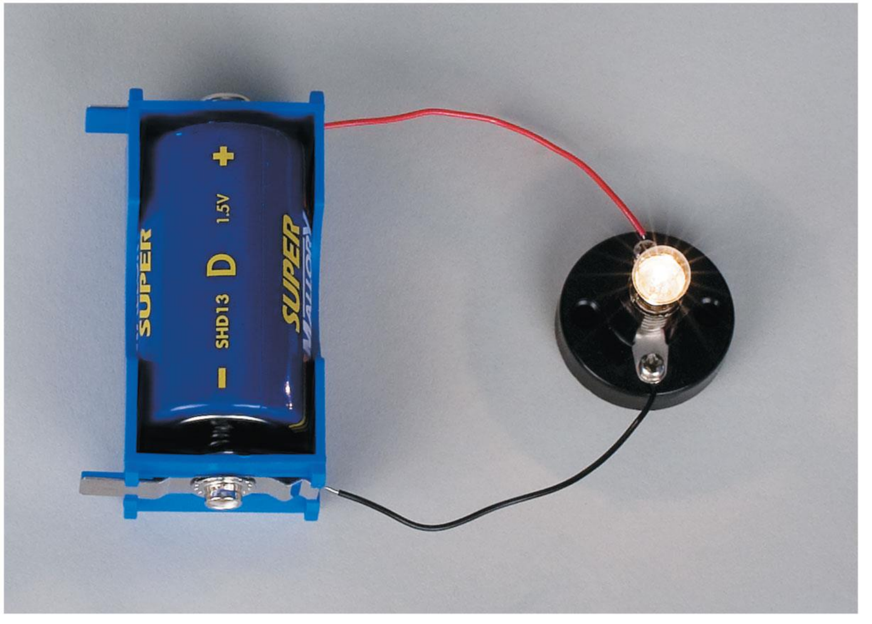
- The motion of charge through a conductor, like the wires connecting these lights, is called a **current**.



- You'll learn why **conservation of current** ensures that each bulb is equally bright.

Chapter 22 Preview
Looking Ahead: Resistance and Ohm's Law

- **Ohm's Law** relates the current in this bulb to the battery's voltage and the bulb's **resistance** to the flow of charge.



- You'll learn how to relate the resistance of a wire to its size and composition.

Chapter 22 Preview
Looking Ahead: Electric Power

- A hair dryer converts electric energy to thermal energy, leading to a blast of hot air.

- You'll learn the relationship of electric power to current, resistance, and voltage.

Chapter 22 Preview
Looking Ahead

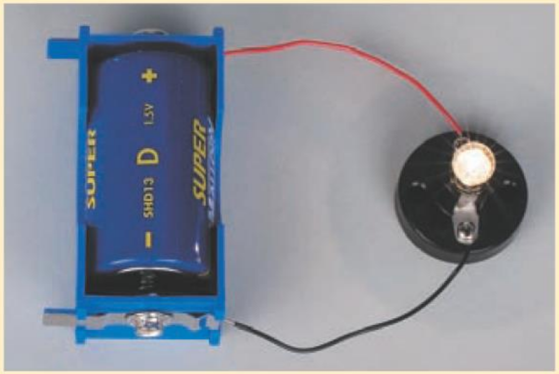
Current

The motion of charge through a conductor, like the wires connecting these lights, is called a **current.**

You'll learn why **conservation of current** ensures that each bulb is equally bright.

Resistance and Ohm's Law

Ohm's law relates the current in this bulb to the battery's voltage and the bulb's **resistance** to the flow of charge.



You'll learn how to relate the resistance of a wire to its size and composition.

Electric Power

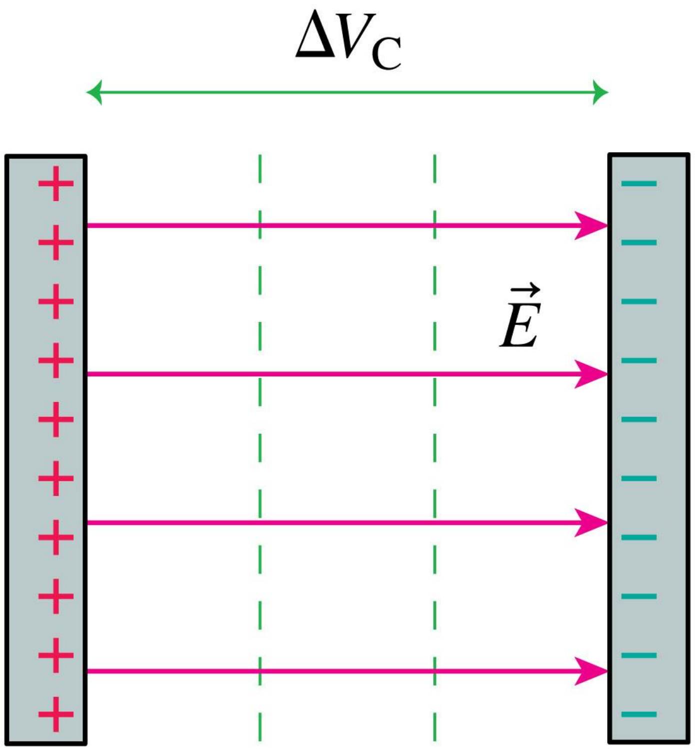
A hair dryer converts electric energy to thermal energy, leading to a blast of hot air.

You'll learn the relationship of electric power to current, resistance, and voltage.

Text: p. 702

Chapter 22 Preview
Looking Back: Electric Potential and Electric Field

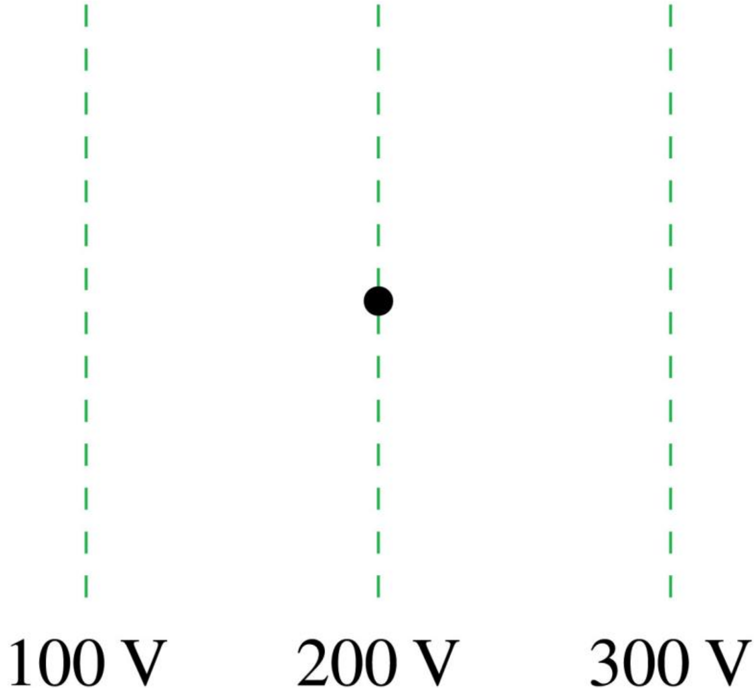
- In Section 21.5, you learned the connection between the electric potential and the electric field. In this chapter, you'll use this connection to understand why charges move in conductors.
- The electric field always points "downhill," from higher to lower potential, as in this parallel-plate capacitor.



Chapter 22 Preview
Stop to Think

An electron is released from rest at the dot. Afterward, the electron

A. Starts moving to the right.
B. Starts moving to the left.
C. Remains at rest.



Reading Question 22.1

The charge carriers in metals are

A. Electrons.
B. Positrons.
C. Protons.
D. A mix of protons and electrons.

Reading Question 22.1

The charge carriers in metals are

✔ A. Electrons.

B. Positrons.

C. Protons.

D. A mix of protons and electrons.

Reading Question 22.2

A battery is connected to a resistor. Increasing the resistance of the resistor will

A. Increase the current in the circuit.
B. Decrease the current in the circuit.
C. Not affect the current in the circuit.

Reading Question 22.2

A battery is connected to a resistor. Increasing the resistance of the resistor will

A. Increase the current in the circuit.
✔ B. Decrease the current in the circuit.
C. Not affect the current in the circuit.

Reading Question 22.3

A battery is connected to a resistor. As charge flows, the chemical energy of the battery is dissipated as

A. Current.
B. Voltage.
C. Charge.
D. Thermal energy.

Reading Question 22.3

A battery is connected to a resistor. As charge flows, the chemical energy of the battery is dissipated as

A. Current.
B. Voltage.
C. Charge.
✔ D. Thermal energy.

Reading Question 22.4

The equation is called

A. Ampère's law.
B. Faraday's law.
C. Ohm's law.
D. Weber's law.

Reading Question 22.4

The equation is called

A. Ampère's law.
B. Faraday's law.
✔ C. Ohm's law.
D. Weber's law.

Reading Question 22.5

The power dissipated in a resistor can be written as

A. $I\Delta V_R$
B. $(\Delta V_R)^2 / R$
C. I^2R
D. All of the above.
E. None of the above.

Reading Question 22.5

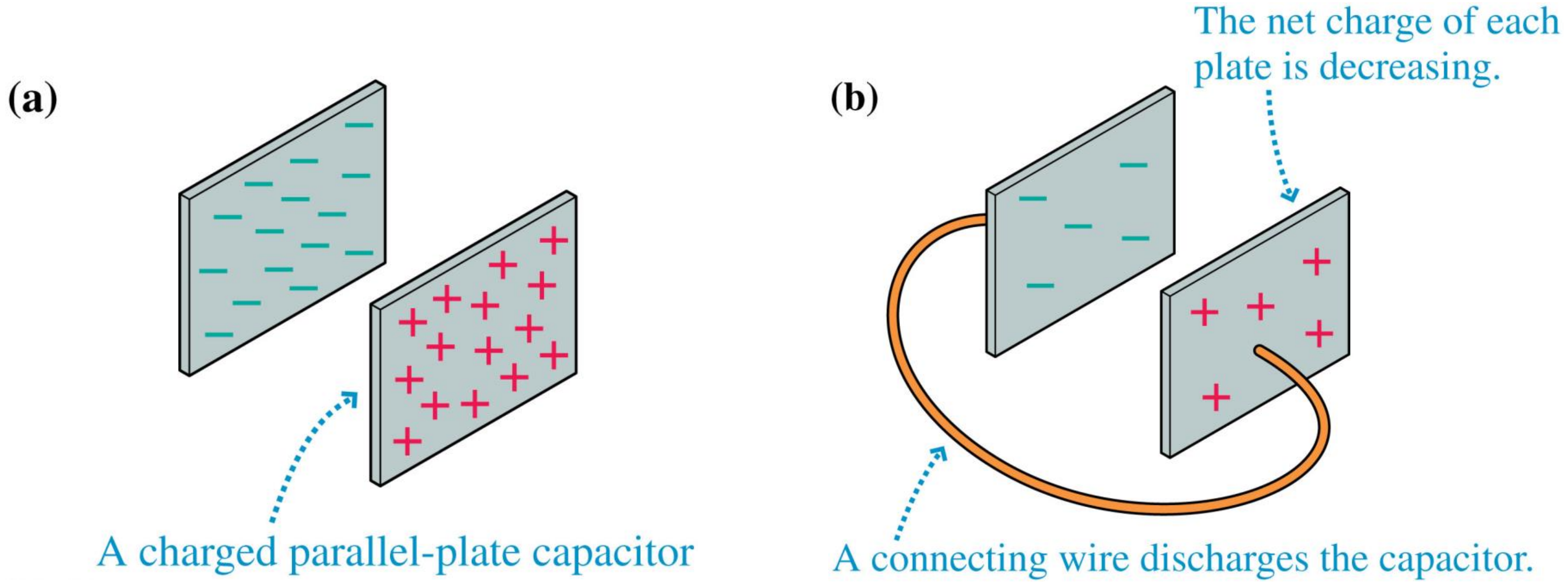
The power dissipated in a resistor can be written as

A. $I\Delta V_R$
B. $(\Delta V_R)^2 / R$
C. I^2R
✔ D. All of the above.
E. None of the above.

Section 22.1 A Model of Current

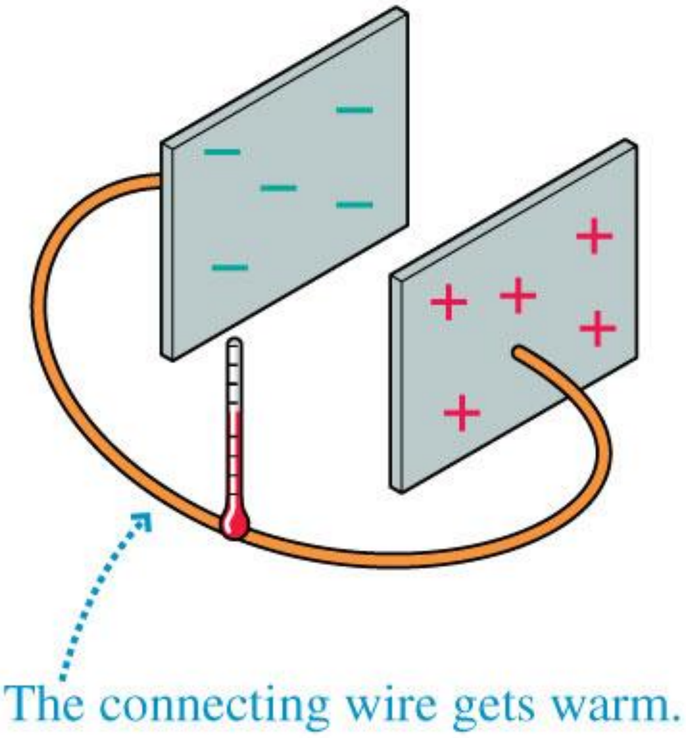
A Model of a Current

- If we connect the two capacitor plates of a parallel-plate capacitor with a metal wire, the plates become neutral. The capacitor has been *discharged*.



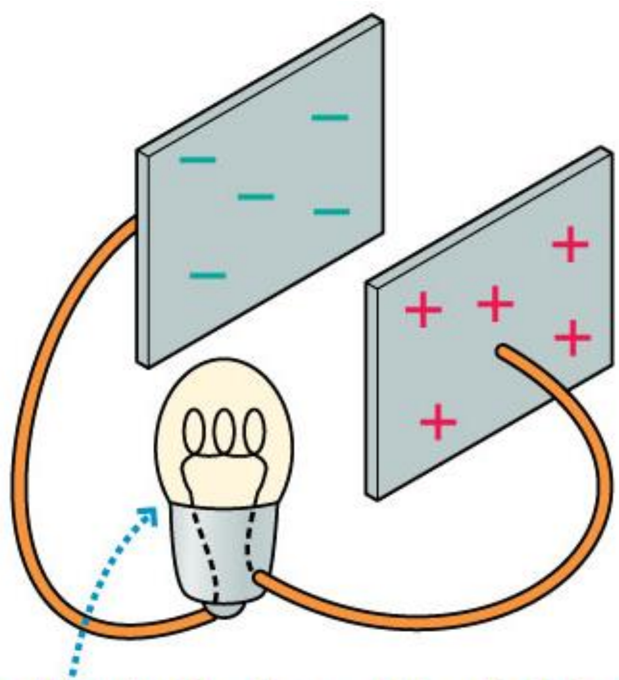
A Model of a Current

- The motion of charges through a material is called a *current*.
- If we observe a capacitor discharge, we see other effects. As the capacitor discharges, the connecting wire gets warmer.



A Model of a Current

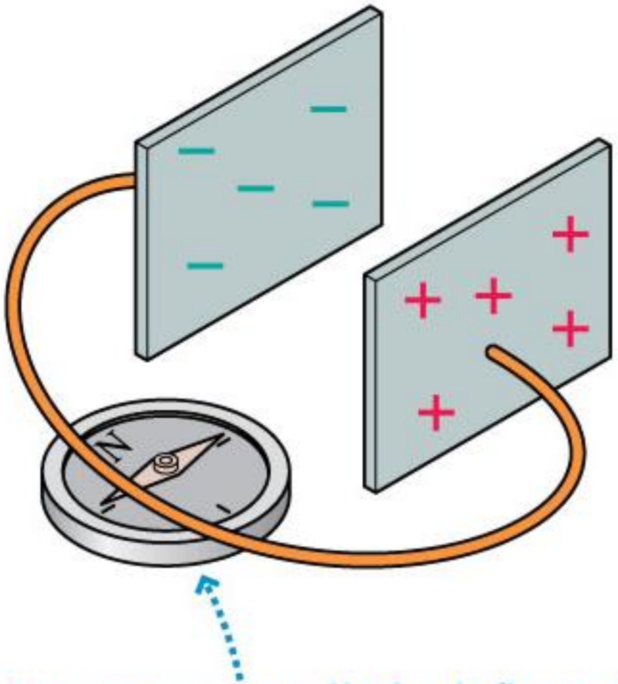
- As the capacitor discharges, if the wire is very thin in places like the filament of a lightbulb, the wire gets hot enough to glow.
- **More current means a brighter bulb.**



A lightbulb glows. The lightbulb filament is part of the connecting wire.

A Model of a Current

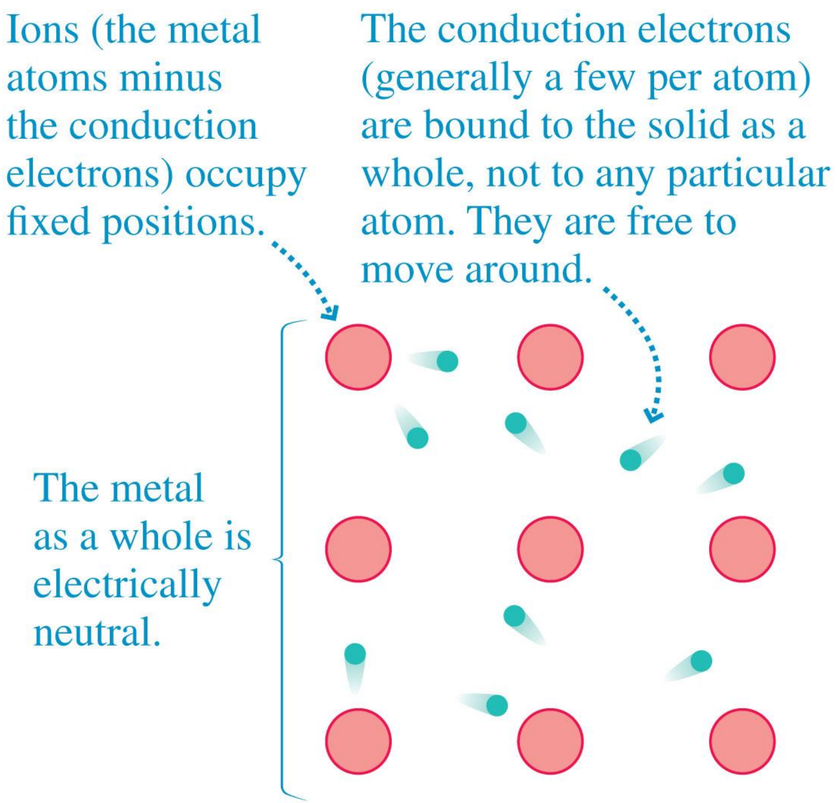
- As the capacitor discharges, the current-carrying wire deflects a compass needle.



A compass needle is deflected.

Charge Carriers

- The charges that move in a current are called *charge carriers*.
- In a metal, the charge carriers are electrons.
- It is the motion of the *conduction electrons*, which are free to move around, that forms a current in the metal.



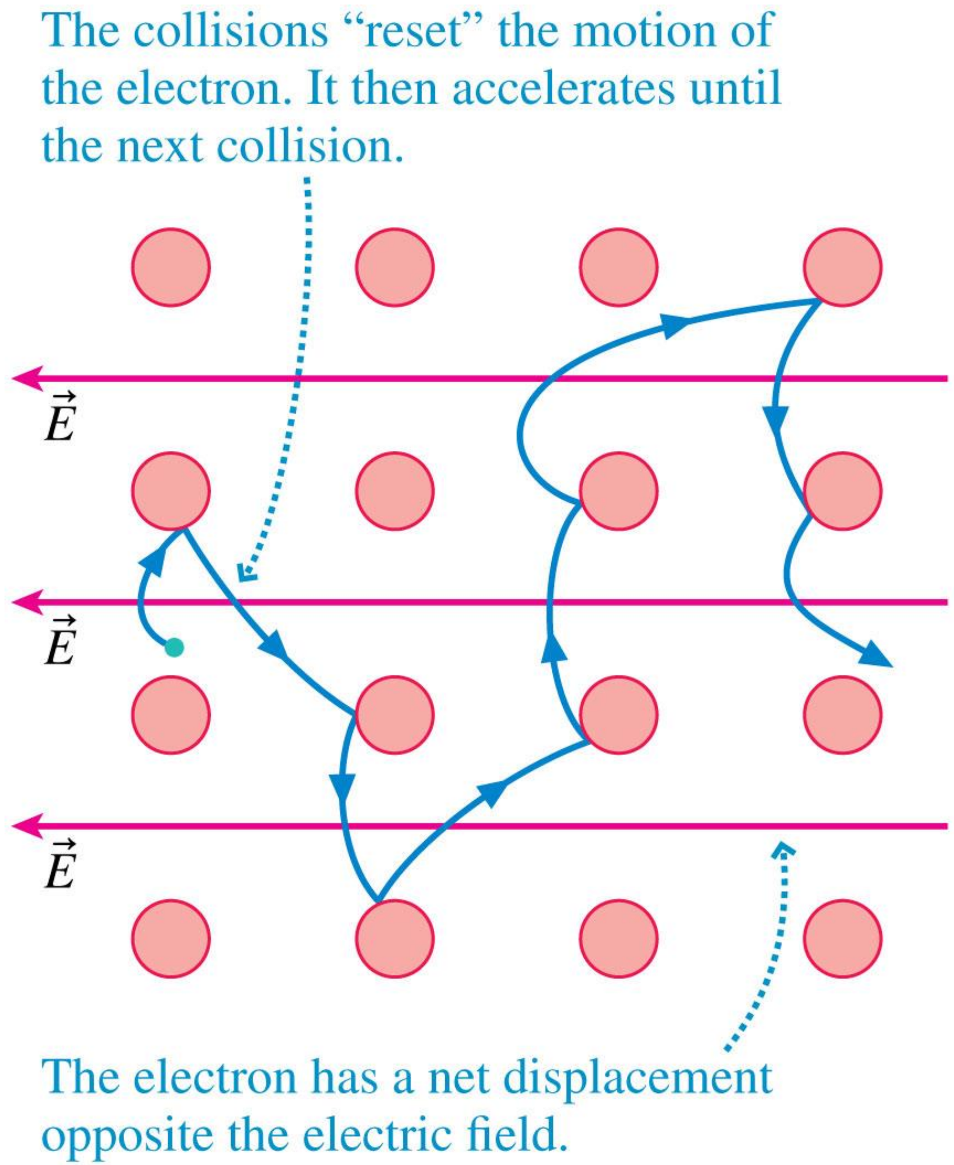
Charge Carriers

- An *insulator* does not have free charges and cannot carry a current.
- Other materials may have different charge carriers. Both positive and negative ions carry charge in ionic solutions such as seawater, blood, and intercellular fluids.

Creating a Current

- When we apply an electric field to a metal, the field exerts a force on the electrons and they begin to accelerate.
- Collisions between the electrons and the atoms of the metal slow them down, transforming the electron's kinetic energy into thermal energy, making the metal warmer.
- The motion of the electrons will cease *unless you continue pushing* by maintaining an electric field.
- In a constant field, an electron's average motion will be opposite the field. The motion is the electron's *drift velocity*.

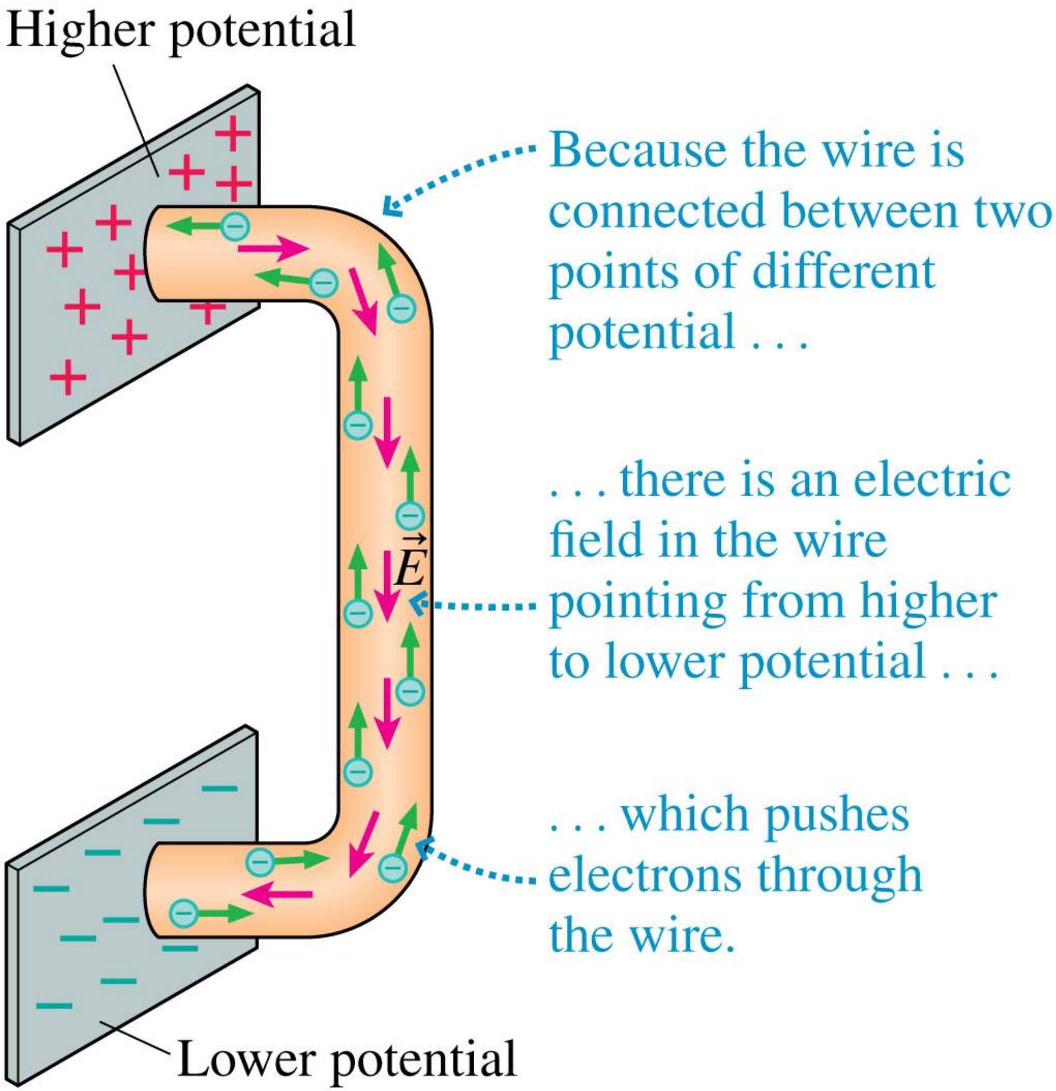
Creating a Current



Creating a Current

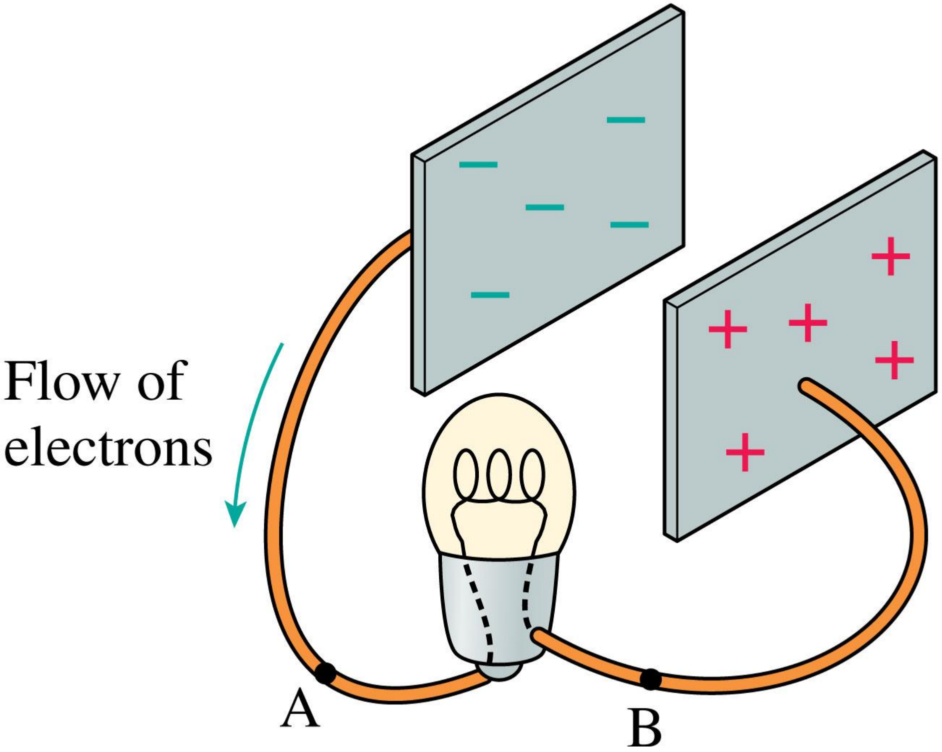
- In a parallel-plate capacitor, the initial separation of charges creates a potential difference between the plates.
- Connecting a wire between the plates establishes an electric field in the wire, which causes electrons to flow from the negative plate (which has an excess of electrons) toward the positive plate.
- **The potential difference creates the electric field that drives the current in the wire.**
- Eventually the plates will be completely discharged, meaning no more potential difference, no more field, and no more current.

Creating a Current



Creating a Current

- The current at point B is *exactly equal* to the current at point A.
- **The current leaving a lightbulb is exactly the same as the current entering the lightbulb.**

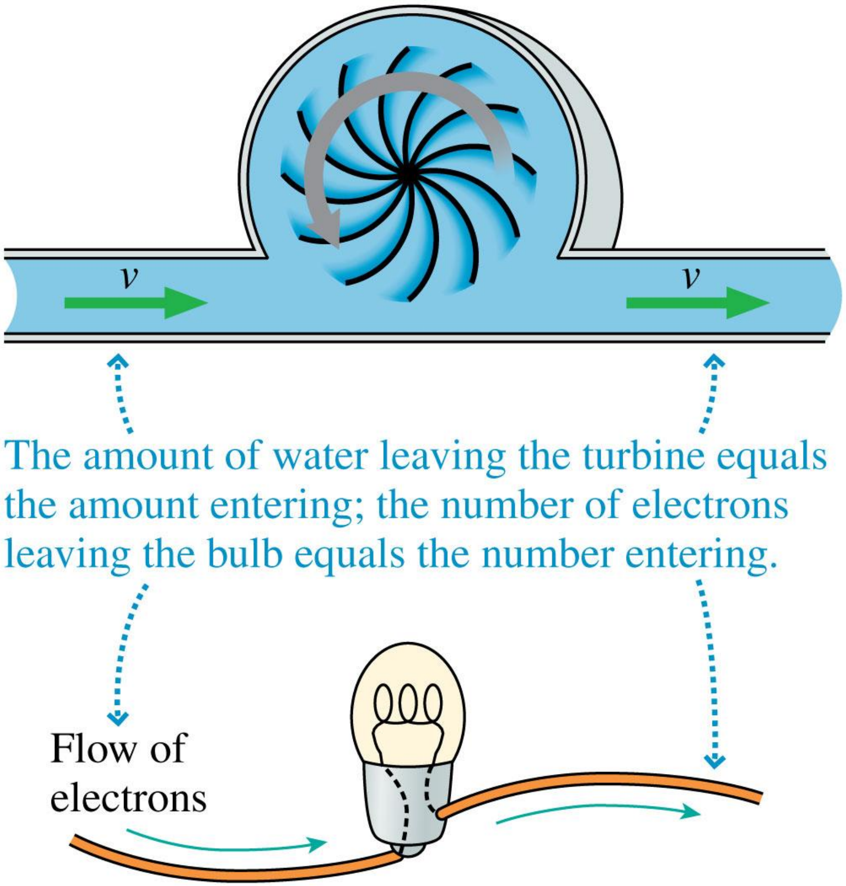


Creating a Current

- The lightbulb cannot destroy electrons without violating the law of conservation of mass and the law of conservation of charge. Thus, the *number* of electrons is not changed by the lightbulb.
- The lightbulb cannot store electrons, or it would become increasingly negative until its repulsive force would stop the flow of new electrons and the bulb would go out.
- Every electron entering the lightbulb is matched by an electron leaving the lightbulb, and thus the currents on either side of a lightbulb are equal.

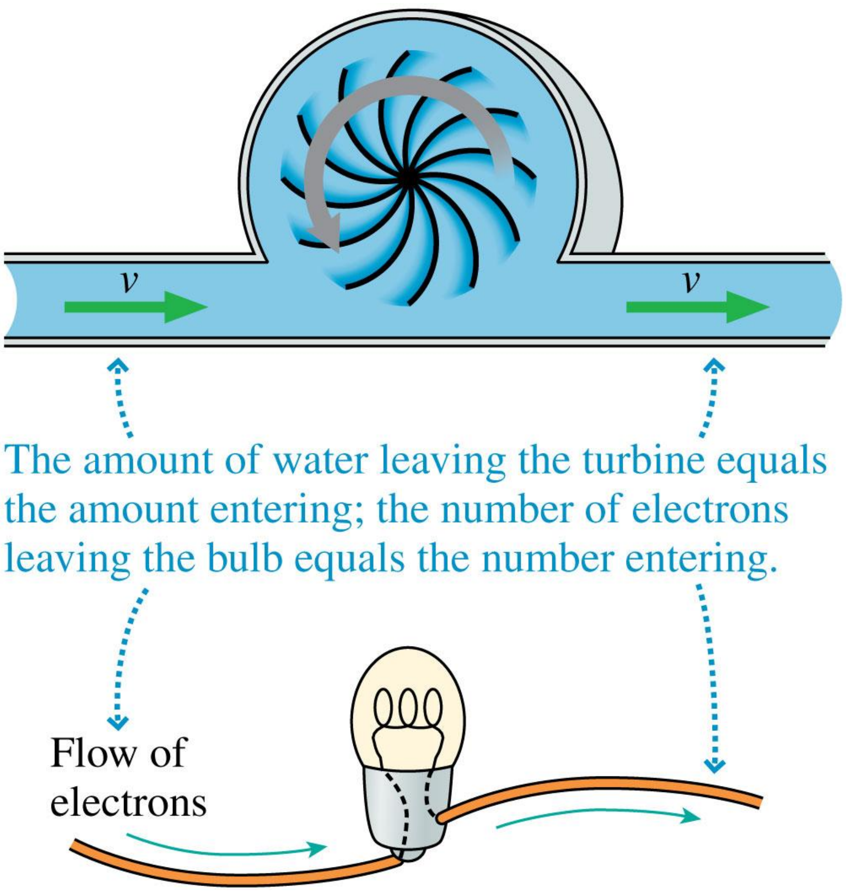
Creating a Current

- Like with an electric current and a lightbulb, water flows through a turbine, making it turn.
- The amount of water leaving the turbine equals the amount of water entering the turbine.



Creating a Current

- The water, like an electric current, is doing work, so there is an energy change.
- In a lightbulb, the energy is dissipated by atomic-level friction as the electrons move through the wire, making the wire hotter until it glows.



Creating a Current

Law of conservation of current The current is the same at all points in a current-carrying wire.

QuickCheck 22.1

A wire carries a current. If both the wire diameter and the electron drift speed are doubled, the electron current increases by a factor of

A. 2
B. 4
C. 6
D. 8
E. Some other value

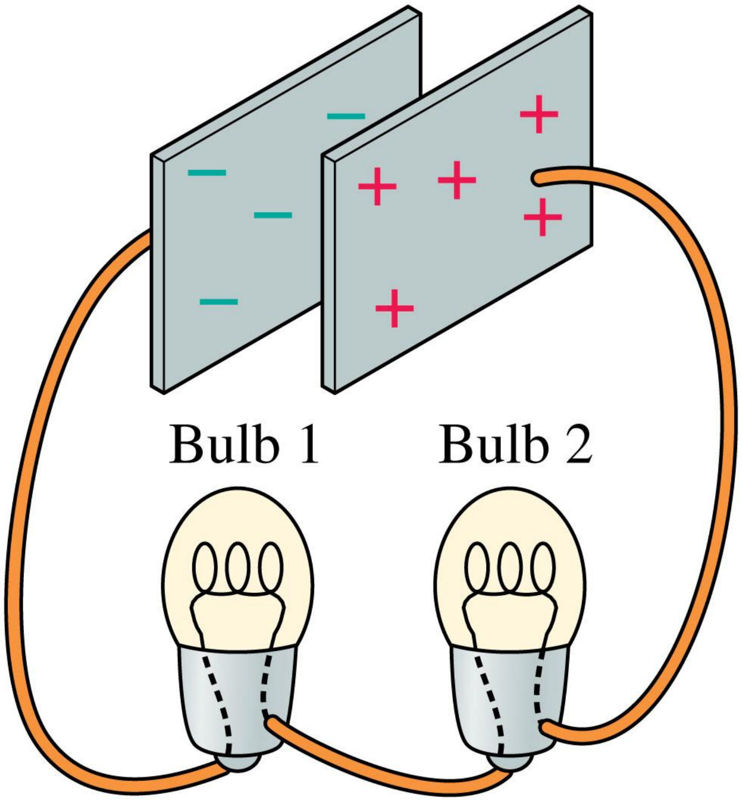
QuickCheck 22.1

A wire carries a current. If both the wire diameter and the electron drift speed are doubled, the electron current increases by a factor of

A. 2
B. 4
C. 6
✔ D. 8 $i_e \propto A v_d$
E. Some other value

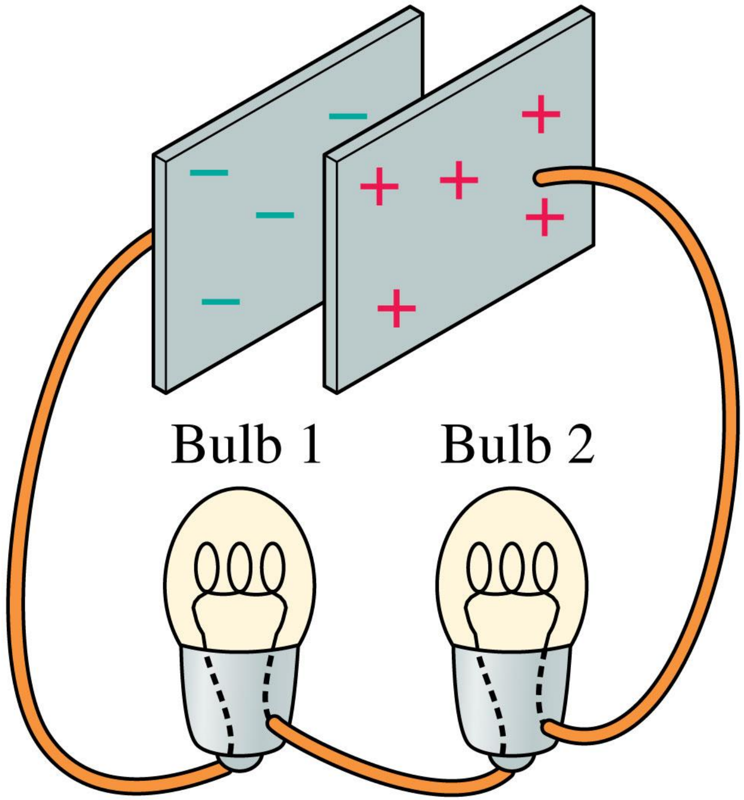
Conceptual Example 22.1 Which bulb is brighter?

The discharge of a capacitor lights two identical bulbs, as shown in FIGURE 22.8. Compare the brightness of the two bulbs.



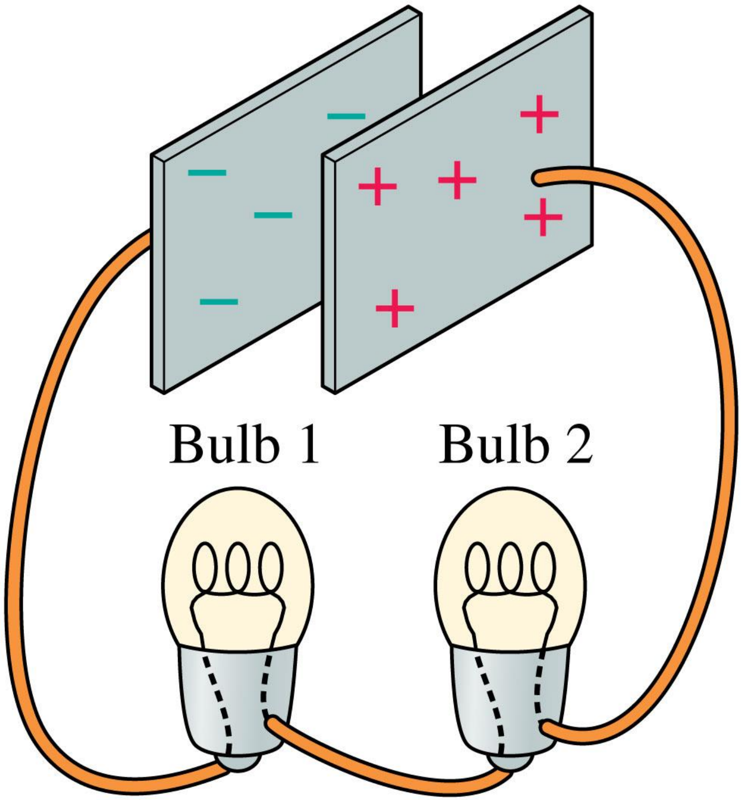
Conceptual Example 22.1 Which bulb is brighter? (cont.)

REASON Current is conserved, so any current that goes through bulb 1 must go through bulb 2 as well—the currents in the two bulbs are equal.



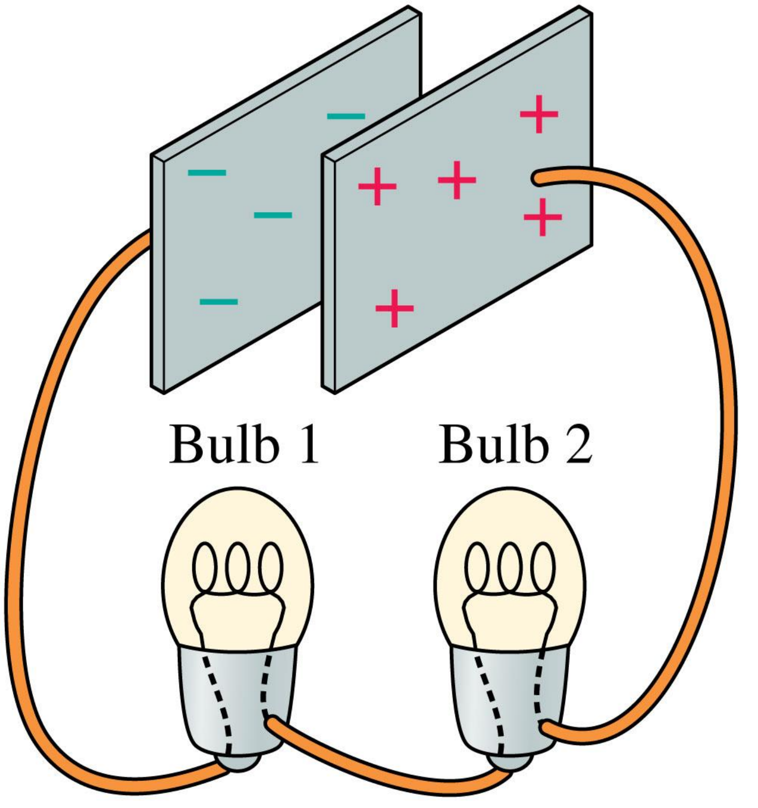
Conceptual Example 22.1 Which bulb is brighter? (cont.)

We've noted that the brightness of a bulb is proportional to the current it carries. Identical bulbs carrying equal currents must have the same brightness.



Conceptual Example 22.1 Which bulb is brighter? (cont.)

ASSESS This result makes sense in terms of what we've seen about the conservation of current. No charge is "used up" by either bulb.



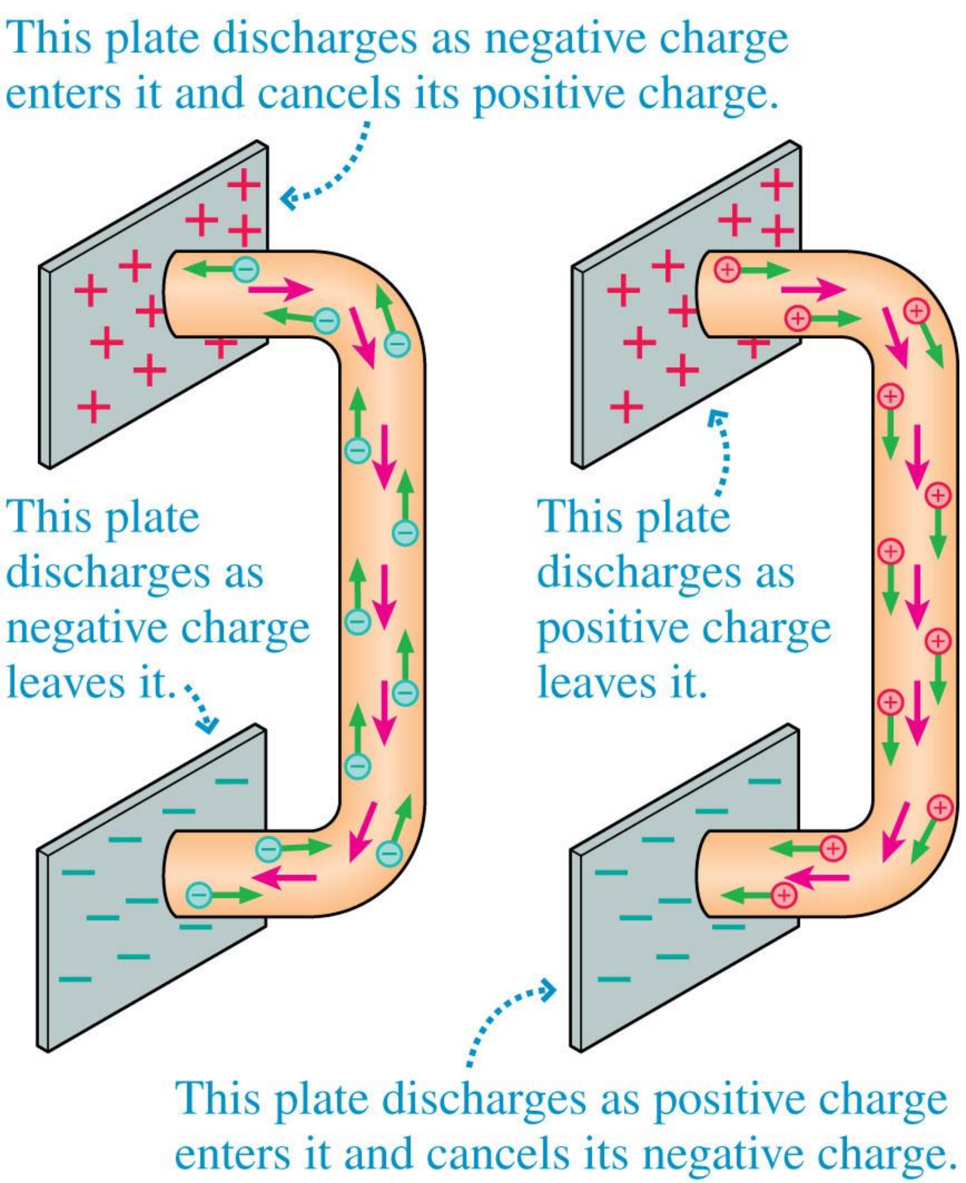
Section 22.2 Defining and Describing Current

Defining and Describing Current

- A capacitor discharges in the same way whether we consider negative charges moving opposite the field, or positive charges moving in the same direction as the field.

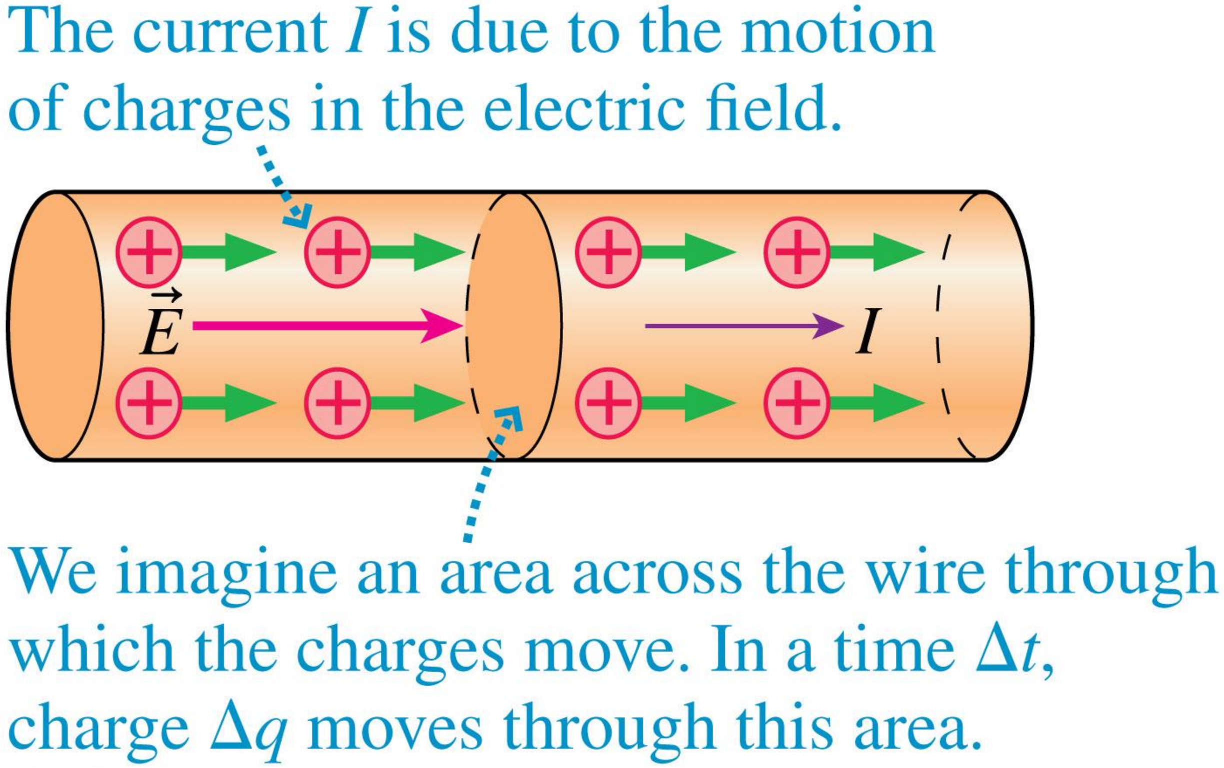
Defining and Describing Current

- We adopt the convention that the **current is the flow of positive charge**.



Definition of Current

- Currents are charges in motion, so we define current as the *rate*, in coulombs per second, at which charge moves through a wire.

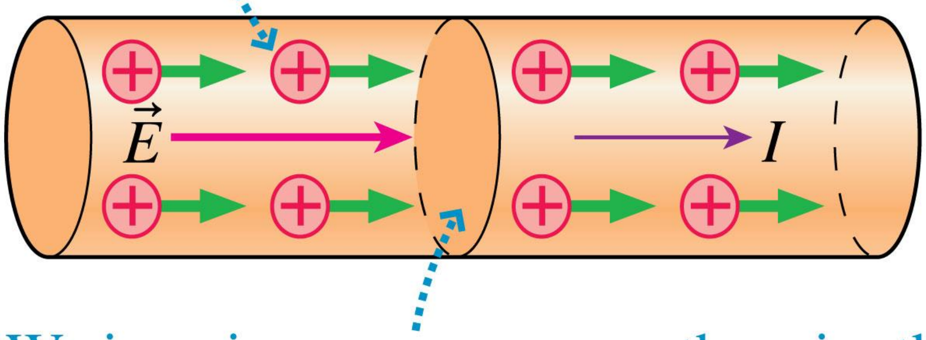


Definition of Current

- We measure the amount of charge Δq that passes through a cross section of the wire in time interval Δt:

$$I = \frac{\Delta q}{\Delta t}$$

Definition of current



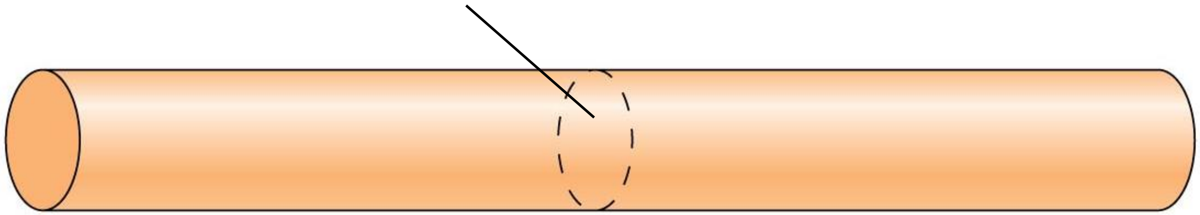
Definition of Current

- The current direction in a wire is from higher potential to lower potential, or in the direction of the electric field.
- Current is measured in coulombs/second, which we define as an **ampere** A.
- 1 ampere = 1 A = 1 coulomb/second = 1 C/s
- Household currents are typically ~ 1 A or 1 *amp*
- For a *steady current*, the total amount of charge delivered by a current I during time interval Δt is

$$q = I\,\Delta t$$

QuickCheck 22.2

Every minute, 120 C of charge flow through this cross section of the wire.

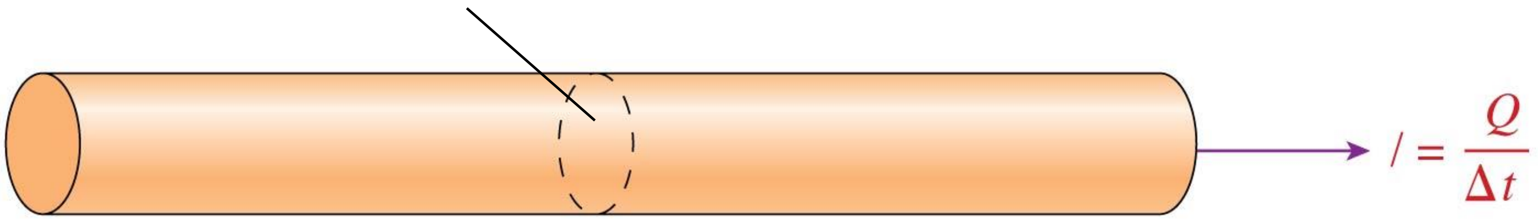


The wire's current is

A. 240 A
B. 120 A
C. 60 A
D. 2 A
E. Some other value

QuickCheck 22.2

Every minute, 120 C of charge flow through this cross section of the wire.



The wire's current is

A. 240 A

B. 120 A

C. 60 A

✔ D. 2 A

E. Some other value

Example 22.2 Charge flow in a lightbulb

A 100 W lightbulb carries a current of 0.83 A. How much charge flows through the bulb in 1 minute?

SOLVE According to Equation 22.2, the total charge passing through the bulb in 1 min = 60 s is

$$q = I\,\Delta t = (0.83\text{ A})(60\text{ s}) = 50\text{ C}$$

Example 22.2 Charge flow in a lightbulb (cont.)

ASSESS The current corresponds to a flow of a bit less than 1 C per second, so our calculation seems reasonable, but the result is still somewhat surprising. That's a lot of charge! The enormous charge that flows through the bulb is a good check on the concept of conservation of current. If even a minuscule fraction of the charge stayed in the bulb, the bulb would become highly charged.

Example 22.2 Charge flow in a lightbulb (cont.)

For comparison, a Van de Graaff generator develops a potential of several hundred thousand volts due to an excess charge of just a few μC, a ten-millionth of the charge that flows through the bulb in 1 minute. Lightbulbs do not develop a noticeable charge, so the current into and out of the bulb must be exactly the same.

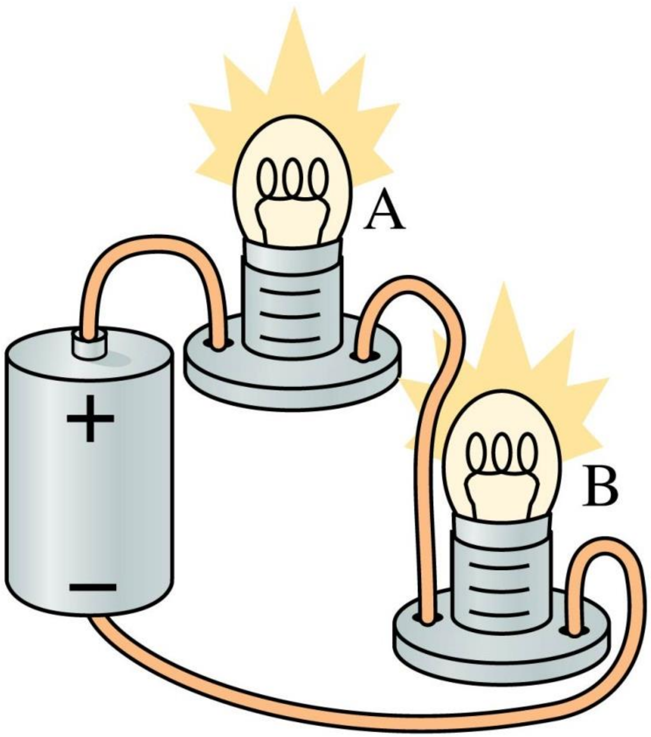
Example Problem

The discharge of the electric eel can transfer a charge of 2.0 mC in a time of 2.0 ms. What current, in A, does this correspond to?

QuickCheck 22.3

A and B are identical lightbulbs connected to a battery as shown. Which is brighter?

A. Bulb A
B. Bulb B
C. The bulbs are equally bright.

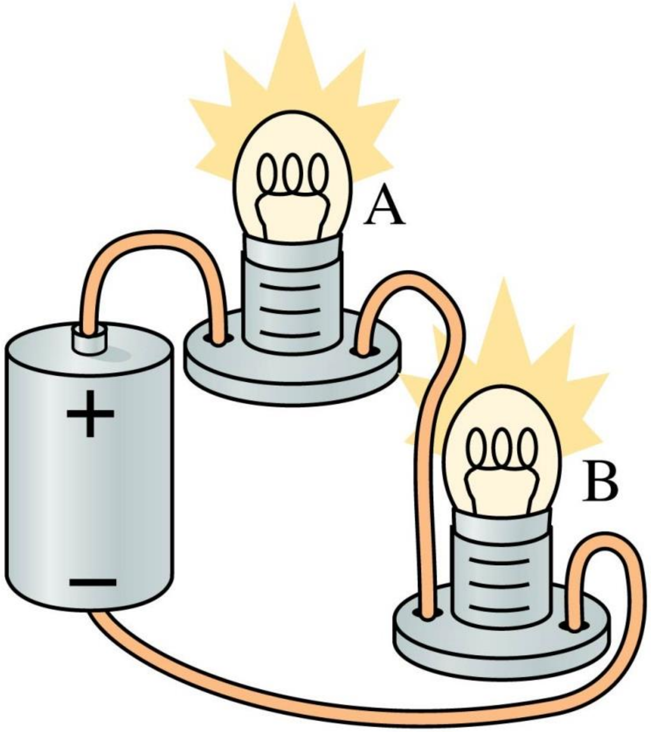


QuickCheck 22.3

A and B are identical lightbulbs connected to a battery as shown. Which is brighter?

A. Bulb A
B. Bulb B
✔ C. The bulbs are equally bright.

Conservation of current

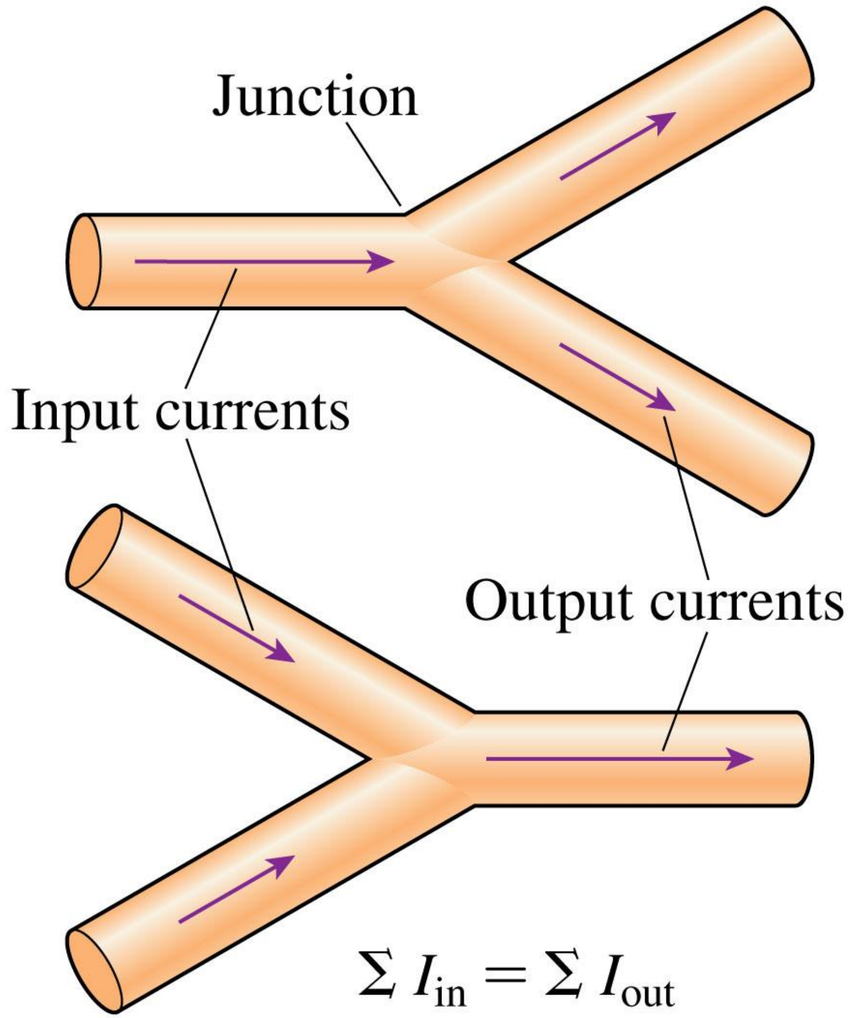


Conservation of Current at a Junction

- A **junction** is a point where a wire branches.
- For a *junction*, the law of conservation requires

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

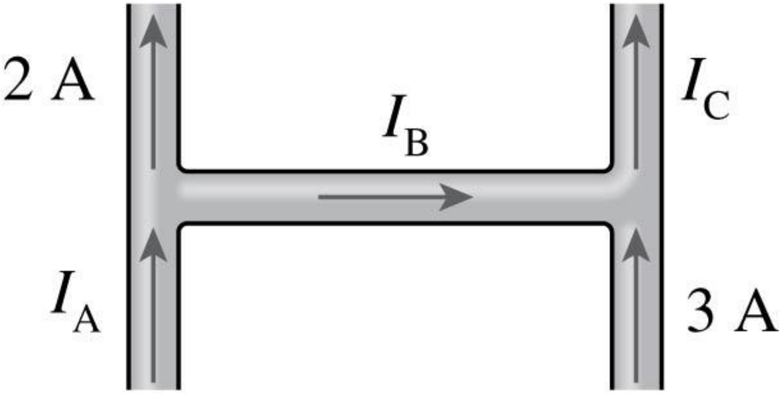
- The basic conservation statement, that the sum of the currents into a junction equals the sum of the currents leaving, is called **Kirchhoff's junction law.**



QuickCheck 22.4

The wires shown next carry currents as noted. Rate the currents I_A, I_B, and I_C.

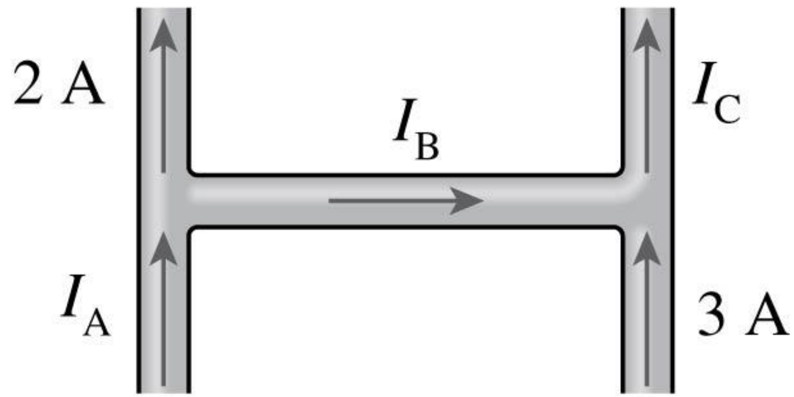
A. $I_A > I_B > I_C$
B. $I_B > I_A > I_C$
C. $I_C > I_A > I_B$
D. $I_A > I_C > I_B$
E. $I_C > I_B > I_A$



QuickCheck 22.4

The wires shown next carry currents as noted. Rate the currents I_A, I_B, and I_C.

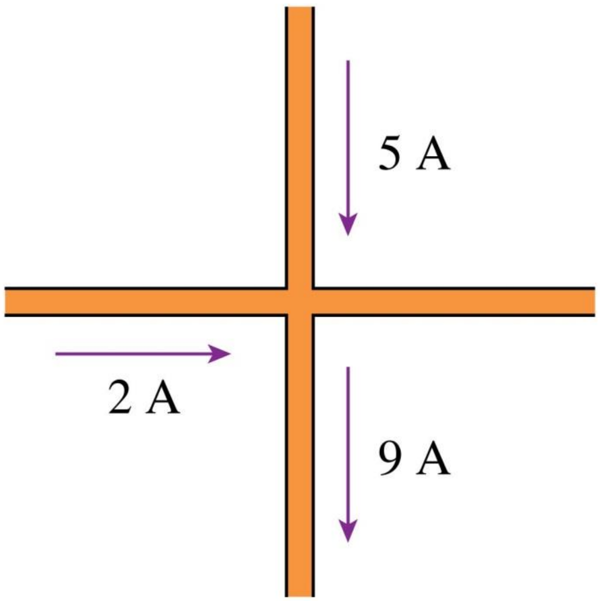
A. $I_A > I_B > I_C$
B. $I_B > I_A > I_C$
✔ C. $I_C > I_A > I_B$
D. $I_A > I_C > I_B$
E. $I_C > I_B > I_A$



QuickCheck 22.5

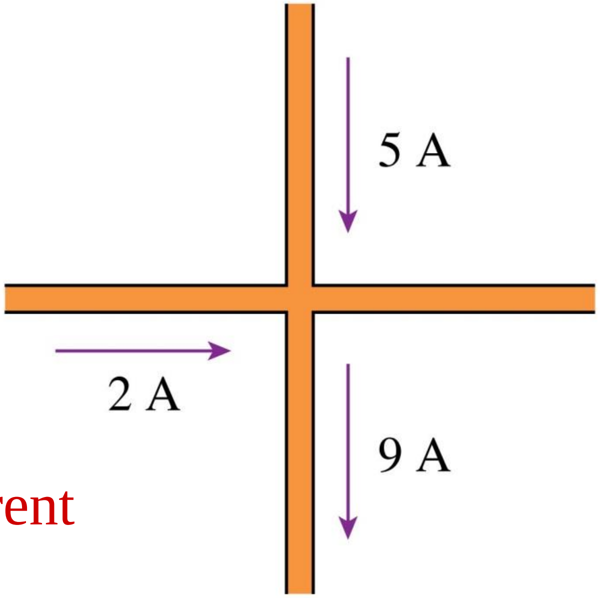
The current in the fourth wire is

A. 16 A to the right.
B. 4 A to the left.
C. 2 A to the right.
D. 2 A to the left.
E. Not enough information to tell



QuickCheck 22.5

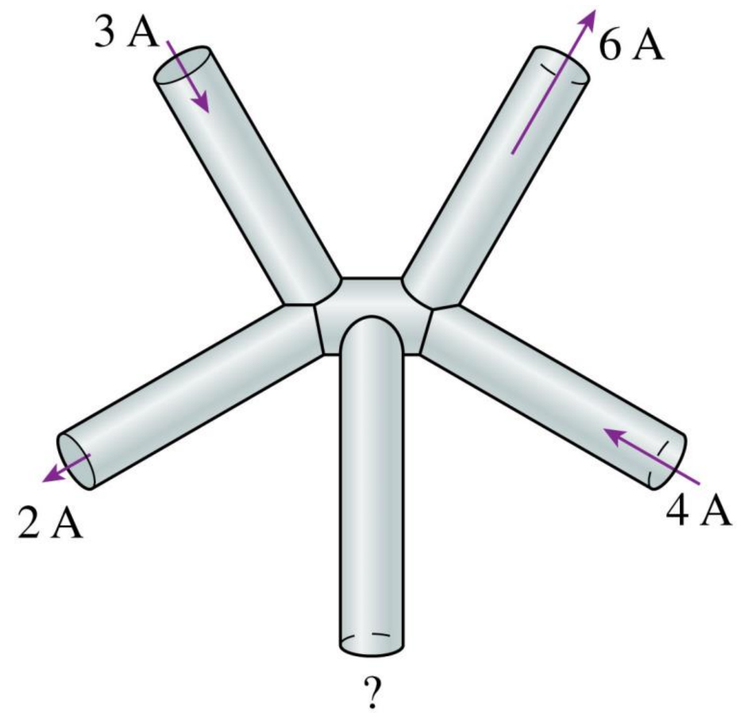
The current in the fourth wire is



A. 16 A to the right.
B. 4 A to the left.
C. 2 A to the right.
✔ D. 2 A to the left. Conservation of current
E. Not enough information to tell

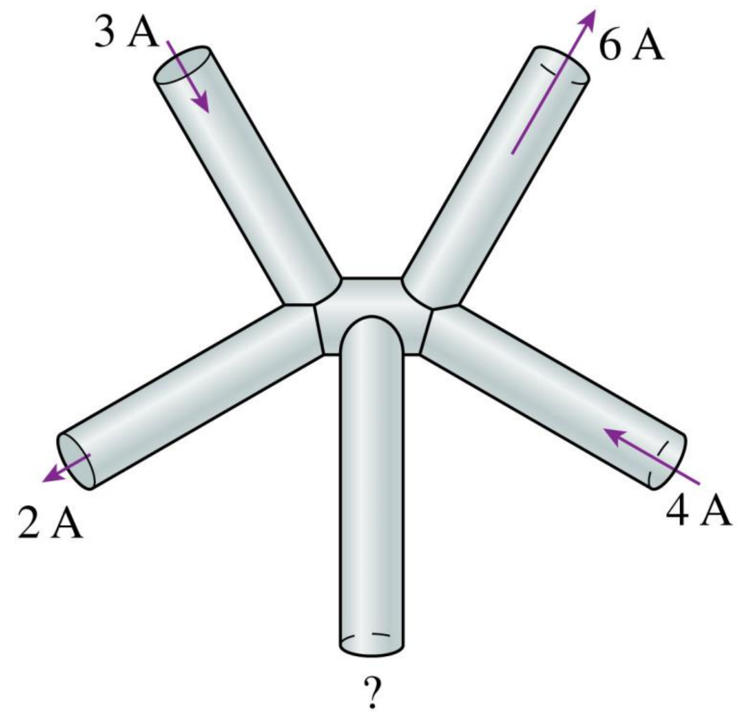
Example 22.3 Currents in a junction

Four wires have currents as noted in FIGURE 22.12. What are the direction and the magnitude of the current in the fifth wire?



Example 22.3 Currents in a junction (cont.)

PREPARE This is a conservation of current problem. We compute the sum of the currents coming into the junction and the sum of the currents going out of the junction, and then compare these two sums. The unknown current is whatever is required to make the currents into and out of the junction "balance."



Example 22.3 Currents in a junction (cont.)

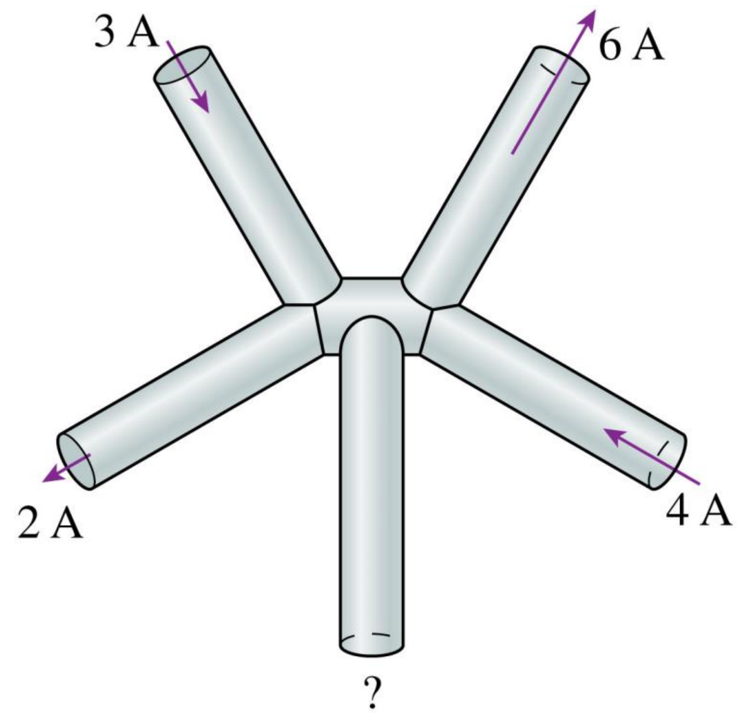
SOLVE Two of the wires have currents into the junction:

$$\Sigma I_{\text{in}} = 3\text{ A} + 4\text{ A} = 7\text{ A}$$

Two of the wires have currents out of the junction:

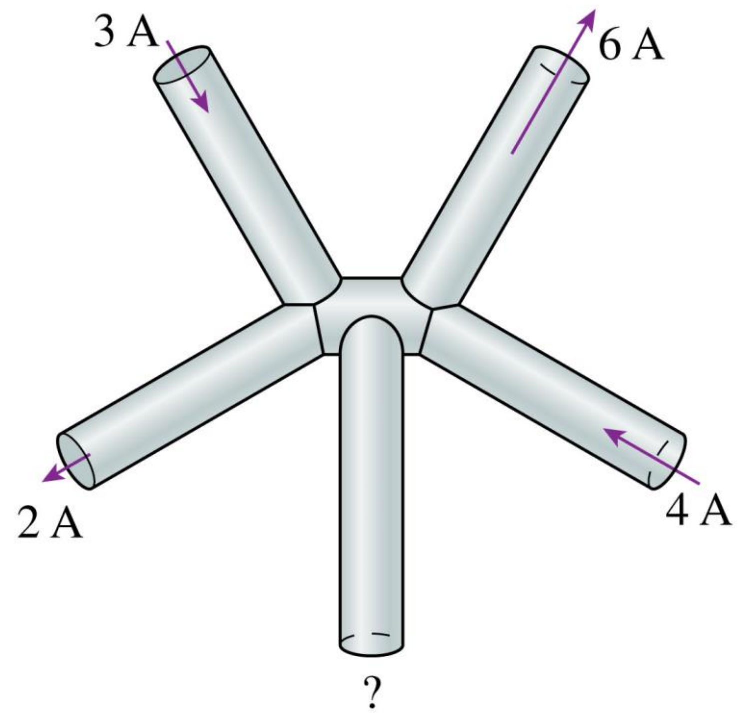
$$\Sigma I_{\text{out}} = 6\text{ A} + 2\text{ A} = 8\text{ A}$$

To conserve current, the fifth wire must carry a current of 1 A into the junction.



Example 22.3 Currents in a junction (cont.)

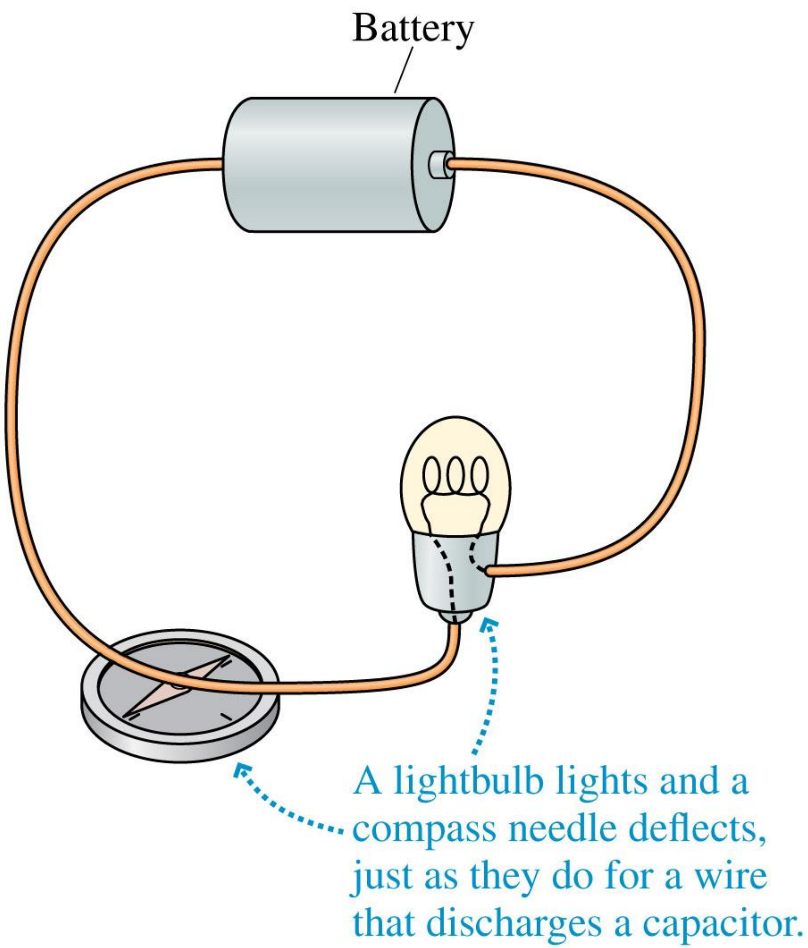
ASSESS If the unknown current is 1 A into the junction, a total of 8 A flows in—exactly what is needed to balance the current going out.



Section 22.3 Batteries and emf

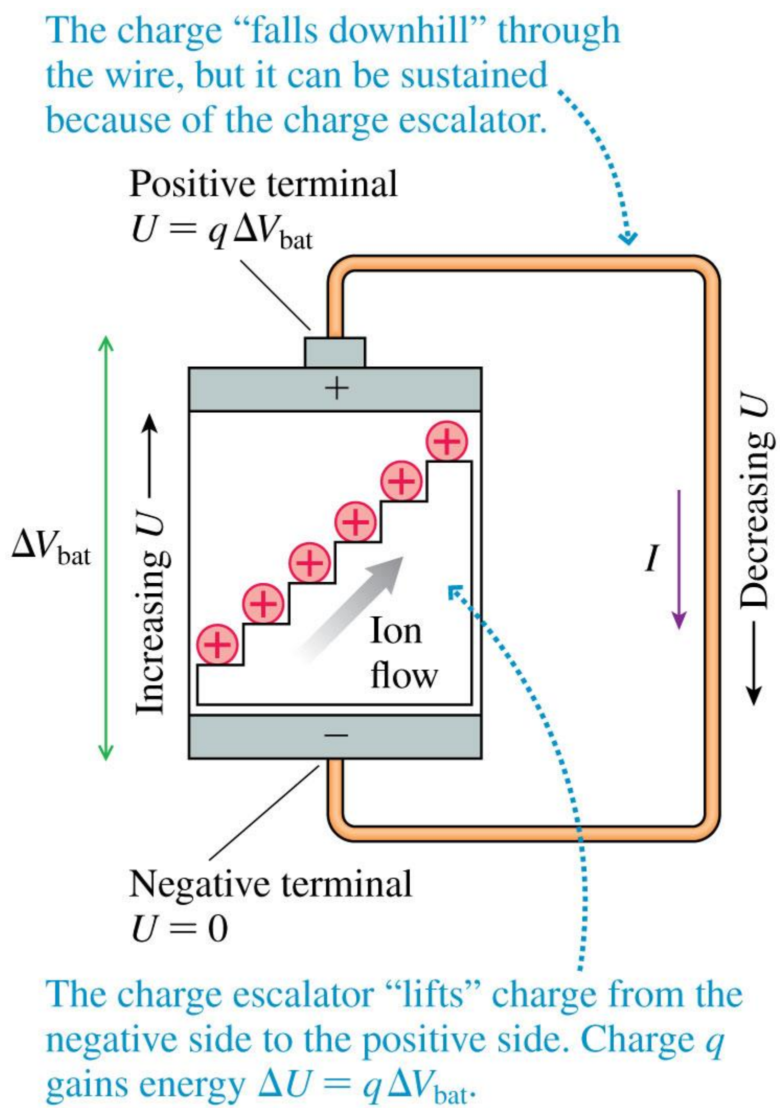
Batteries and emf

- A capacitor quickly runs out of excess charge, but a wire connecting the battery terminals can keep the charges in motion.



Batteries and emf

- The inner workings of a battery act like a *charge escalator* between the two terminals.
- Charges are removed from the negative terminal and "lifted" to the positive terminal.



Batteries and emf

- The charge escalator in a battery sustains the current in a wire by providing a continuously renewed supply of charges at the positive terminal.
- Once a charge reaches the positive terminal, it can flow downhill through the wire until it reaches the negative terminal again.
- The flow of charge in a continuous loop is called a **complete circuit.**

Batteries and emf

- The charge escalator in a battery is powered by chemical reactions. Chemicals called *electrolytes* are sandwiched between two electrodes of different material. The chemicals react and move the positive ions to one electrode, the negative ions to the other.
- A dead battery is one in which the supply of chemicals has been exhausted.

Batteries and emf

- By separating charge, a charge escalator establishes the potential difference between the terminals of a battery.
- The potential difference established by a device, such as a battery, that can actively separate charge is called **emf.**
- The symbol for emf is $\mathcal{E}$ and its units are volts.
- A capacitor *stores* separated charges, but has no means to do the separation. A charged capacitor has a potential difference but not an emf.

Batteries and emf

- The *rating* of a battery, such as 1.5 V, is the battery's emf. It is determined by the chemicals in the battery.
- A battery with no current in it has a potential difference equal to its emf. With a current, the battery's potential difference is slightly less than its emf. We'll overlook this small difference and assume $\Delta V_{\text{bat}} = \mathcal{E}$.

QuickCheck 22.6

A battery is connected to a wire, and creates a current in the wire. Which of the following changes would increase the current?

A. Increasing the length of the wire
B. Keeping the wire the same length, but making it thicker
C. Using a battery with a lower emf
D. Making the wire into a coil, but keeping its dimensions the same
E. Changing the wire material from copper to nichrome

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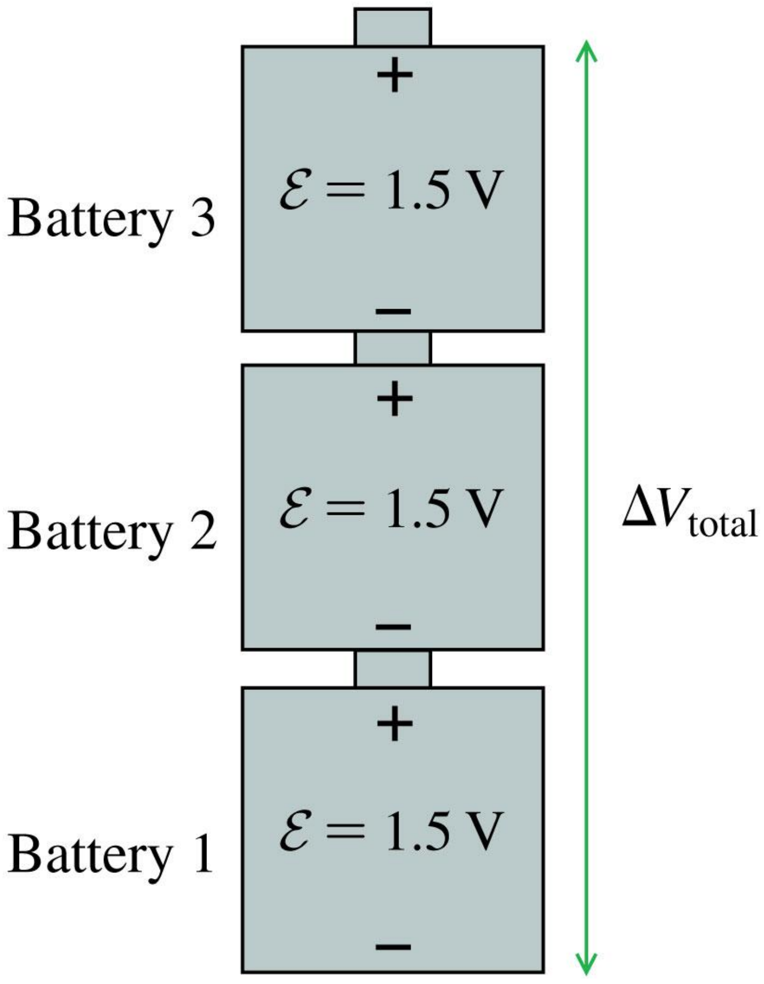
E. Changing the wire material from copper to nichrome

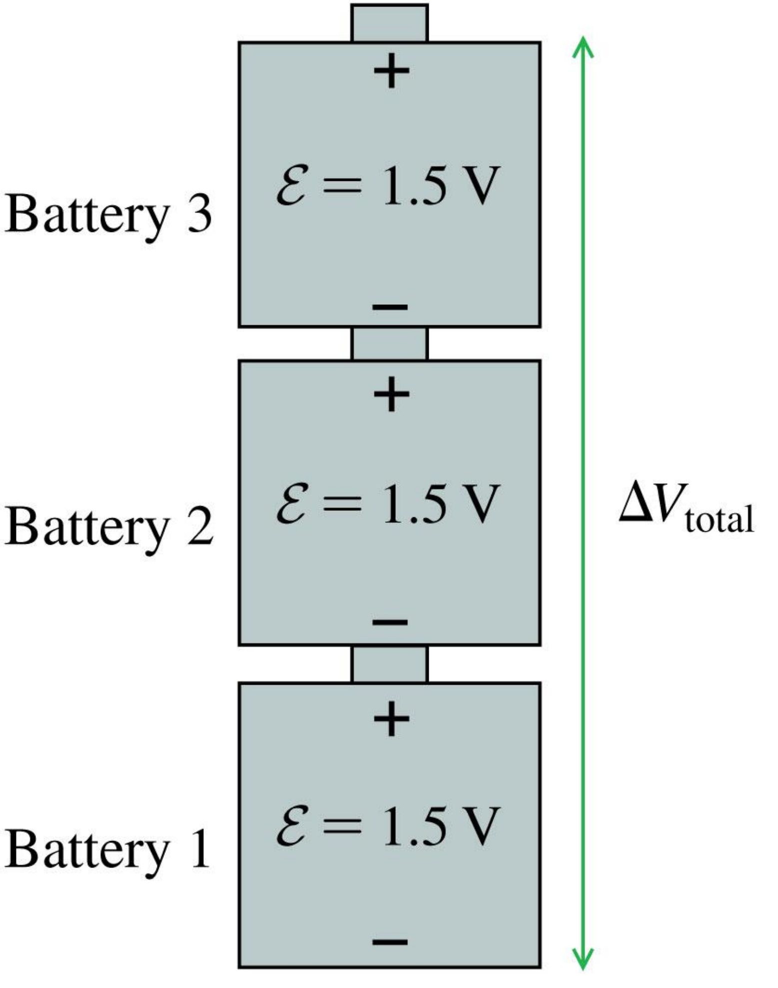
Conceptual Example 22.4 Potential difference for batteries in a series

Three batteries are connected one after the other as shown in FIGURE 22.15; we say they are connected in *series*. What's the total potential difference?



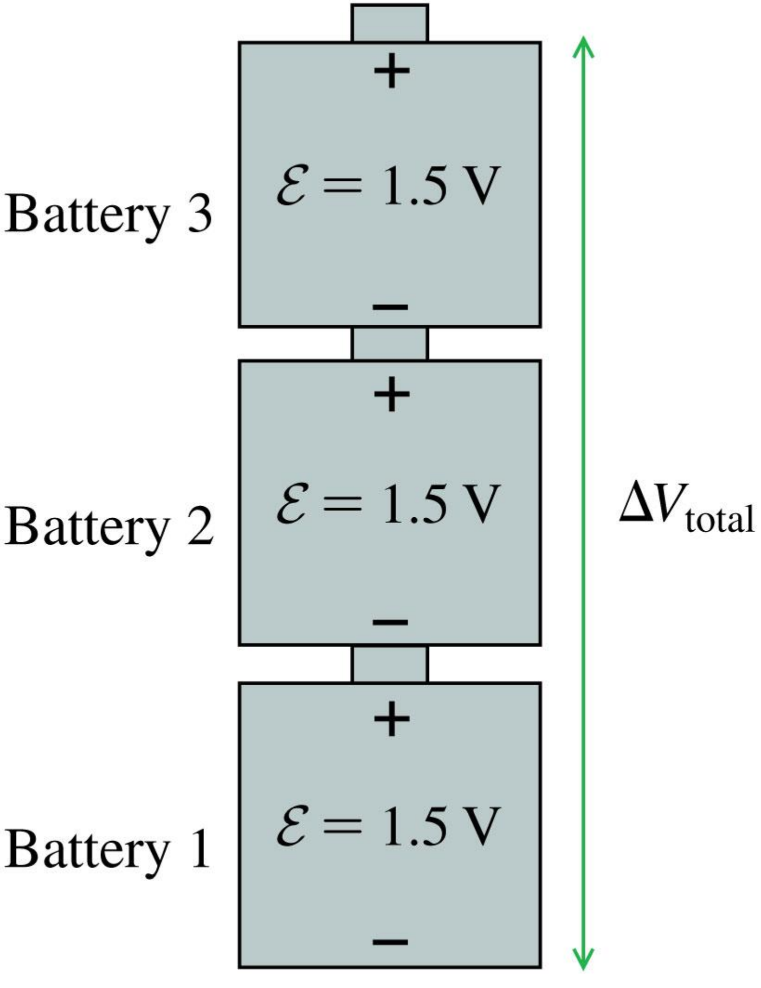
Conceptual Example 22.4 Potential difference for batteries in a series (cont.)

REASON We can think of this as three charge escalators, one after the other. Each one lifts charges to a higher potential. Because each battery raises the potential by 1.5 V, the total potential difference of the three batteries in series is 4.5 V.

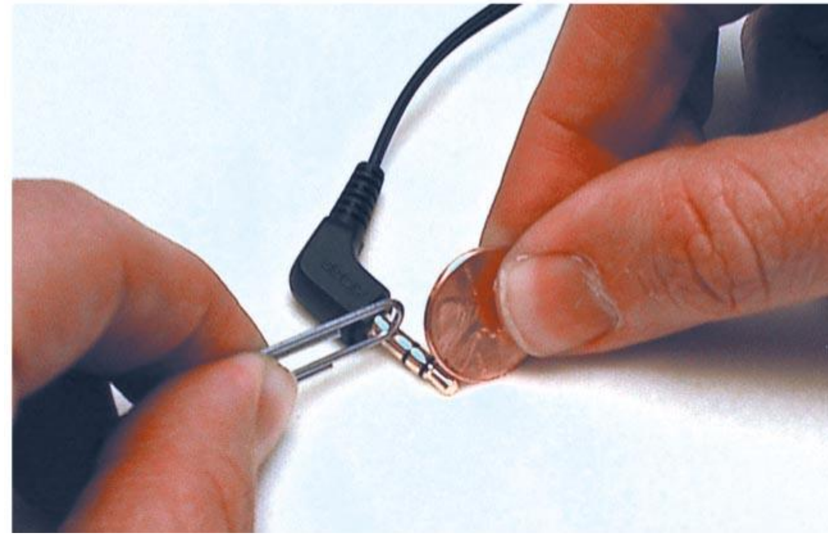


Conceptual Example 22.4 Potential difference for batteries in a series (cont.)

ASSESS Common AA and AAA batteries are 1.5 V batteries. Many consumer electronics, such as digital cameras, use two or four of these batteries. Wires inside the device connect the batteries in series to produce a total 3.0 V or 6.0 V potential difference.



Try It Yourself: Listen to Your Potential



Put on a set of earphones from a portable music player and place the plug on the table. Moisten your fingertips and hold a penny in one hand and a paper clip in the other. This makes a very weak battery; the penny and the clip are the electrodes and your moist skin the electrolyte. Touch the paper clip to the innermost contact on the headphone plug and the penny to the outermost. You will hear a *very* soft click as the potential difference causes a small current in the headphones.

Section 22.4 Connecting Potential and Current

Connecting Potential and Current

- **A battery is a source of potential difference.** The current that flows through a wire connecting the battery terminals is a *consequence* of the potential difference.
- Because the ends of the wire are connected to the terminals of the battery, the potential difference between the two ends is equal to the potential difference between the battery terminals:

$$\Delta V_{\text{wire}} = \Delta V_{\text{bat}}$$

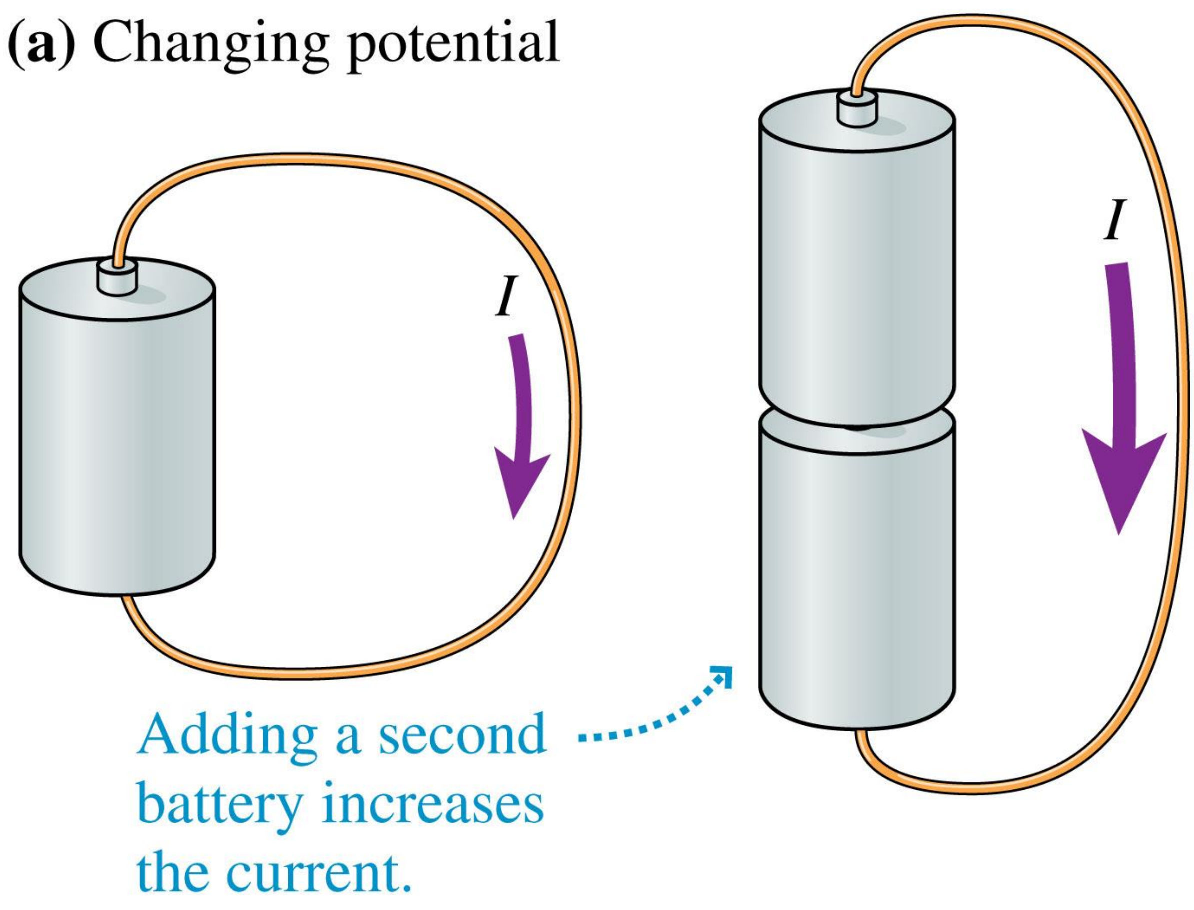
- The potential difference causes a current in the direction of decreasing potential.

Resistance

- Two factors determine the current: the potential difference and the properties of the wire.
- The current is proportional the the potential difference.

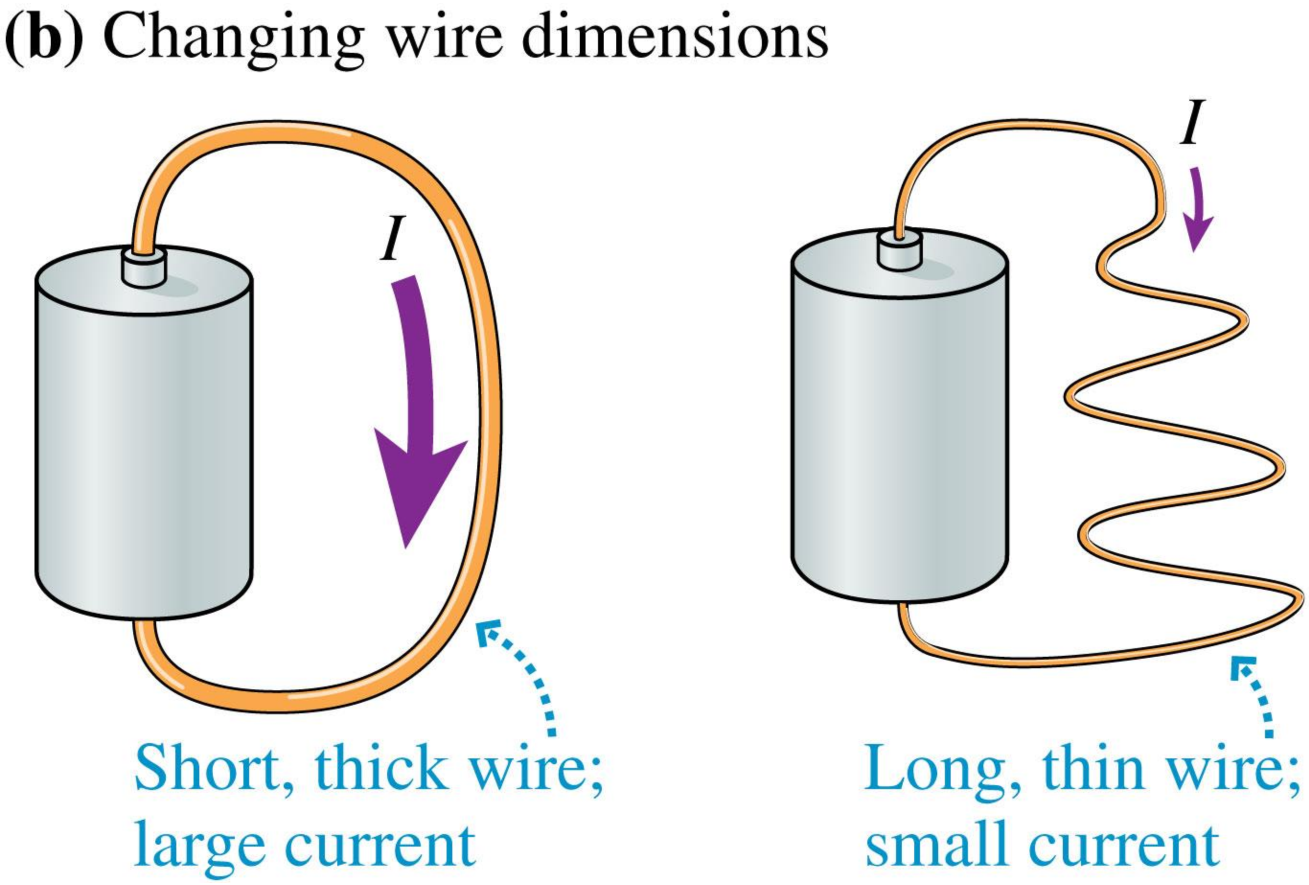
Resistance

- Adding a second battery increases the potential difference, which increases the electric field and therefore the current.



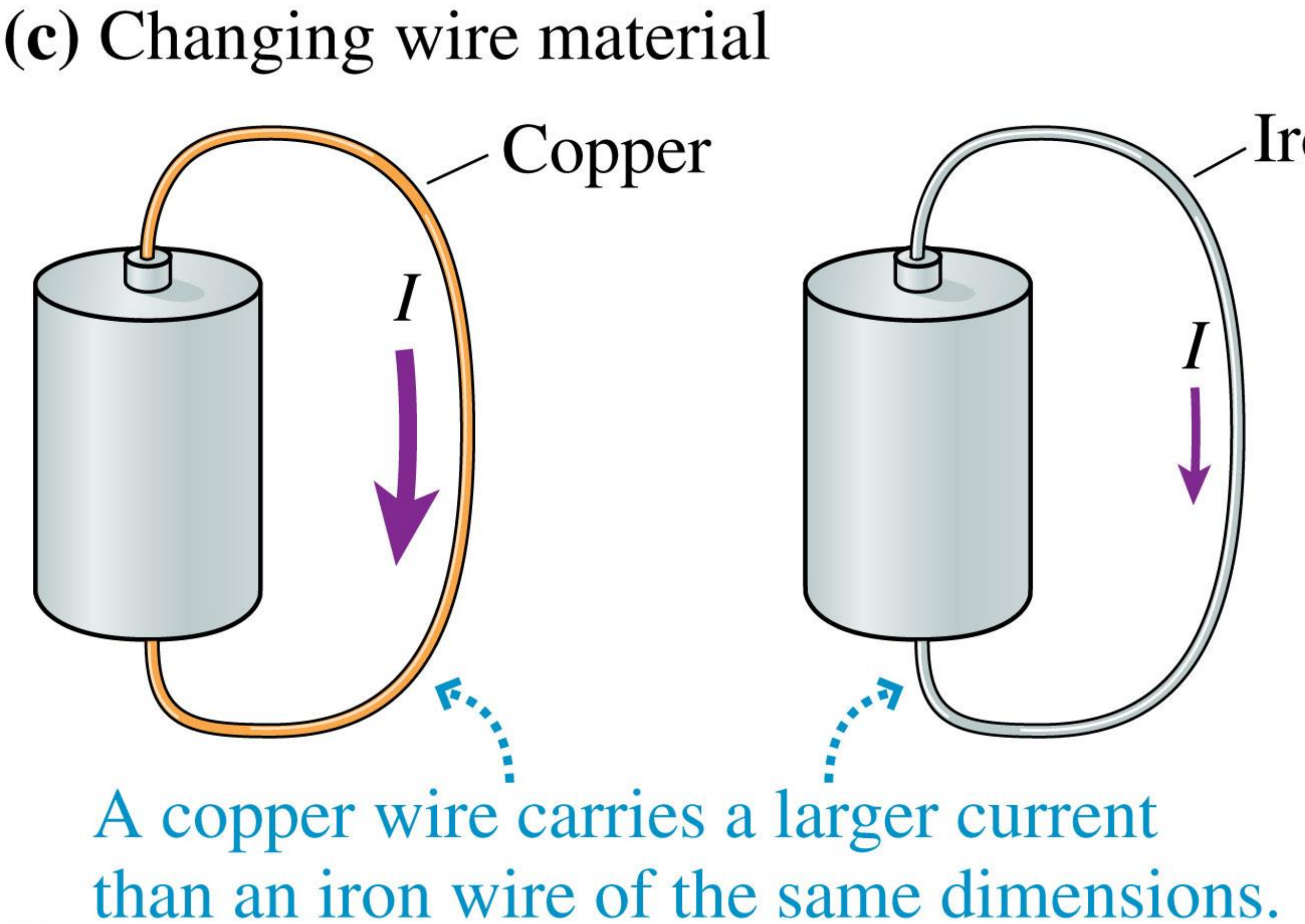
Resistance

- Increasing the length of the wire connecting a battery decreases the current, while increasing the thickness of the wire increases the current.



Resistance

- Wires of different material will carry different currents—some materials are better conductors than others.



Resistance

- **Resistance** *R* is a measure of how hard it is to push charges through a wire. A large resistance implies that it is hard to move charges through the wire.
- The current depends on the resistance of the wire and the potential difference between the ends of the wire:

$$I = \frac{\Delta V_{\text{wire}}}{R}$$

Resistance

- The wire's resistance is

$$R = \frac{\Delta V_{\text{wire}}}{I}$$

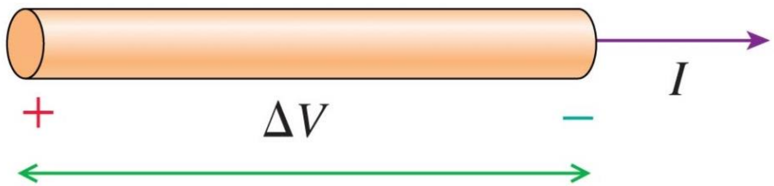
- The SI unit of resistance is the **ohm**, defined as

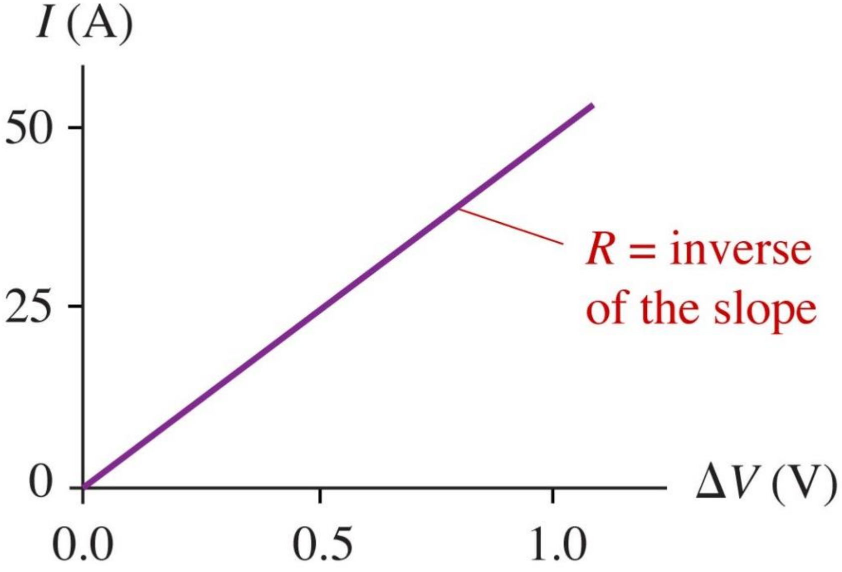
$$1 \text{ ohm} = 1\ \Omega = 1 \text{ V/A}$$

QuickCheck 22.7

The current through a wire is measured as the potential difference ΔV is varied. What is the wire's resistance?

A. 0.01 Ω
B. 0.02 Ω
C. 50 Ω
D. 100 Ω
E. Some other value





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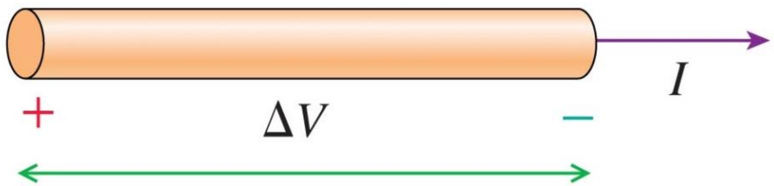
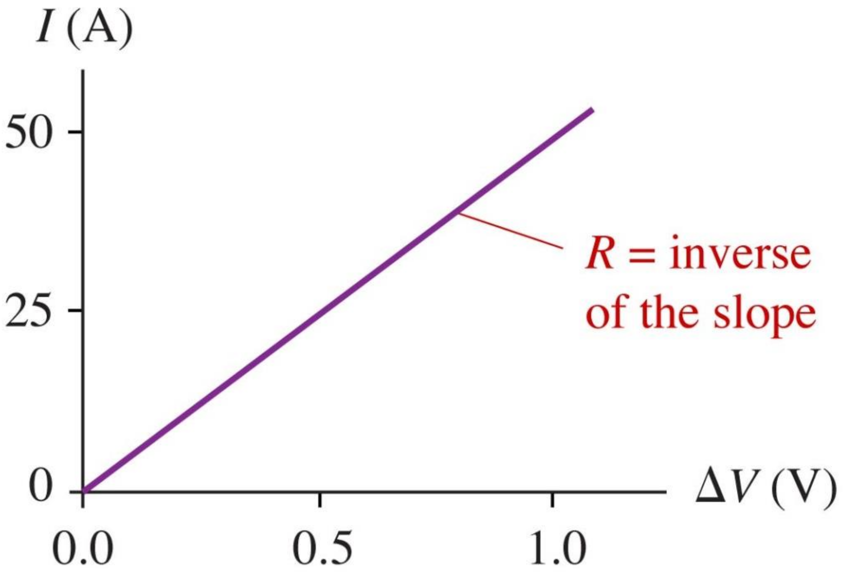




Example 22.5 Resistance of a lightbulb

The glowing element in an incandescent lightbulb is the *filament*, a long, thin piece of tungsten wire that is heated by the electric current through it. When connected to the 120 V of an electric outlet, a 60 W bulb carries a current of 0.50 A. What is the resistance of the filament in the lamp?

Example 22.5 Resistance of a lightbulb (cont.)

SOLVE We can use Equation 22.6 to compute the resistance:

$$R = \frac{\Delta V_{\text{wire}}}{I} = \frac{120\ \text{V}}{0.50\ \text{A}} = 240\ \Omega$$

ASSESS As we will see below, the resistance of the filament varies with temperature. This value holds for the lightbulb only when the bulb is glowing and the filament is hot.

Resistivity

- **Resistivity** ρ characterizes the electrical properties of materials.
- Materials that are good conductors have low resistivity. Materials that are poor conductors (and thus good insulators) have high resistivity.
- The resistivity of a metal decreases with increasing temperature.

Resistivity

TABLE 22.1 Resistivities of materials

Material	Resistivity ($\Omega \cdot m$)
Copper	1.7×10^{-8}
Aluminum	2.7×10^{-8}
Tungsten (20°C)	5.6×10^{-8}
Tungsten (1500°C)	5.0×10^{-7}
Iron	9.7×10^{-8}
Nichrome	1.5×10^{-6}
Seawater	0.22
Blood (average)	1.6
Muscle	13
Fat	25
Pure water	2.4×10^{5}
Cell membrane	3.6×10^{7}

Resistivity

- A wire made of a material of resistivity ρ, with length L, and cross section area A has resistance

$$R = \frac{\rho L}{A}$$

Resistance of a wire in terms of resistivity and dimensions

- Resistance is a property of a *specific* wire, since it depends on the conductor's length, diameter, and material.

Example Problem

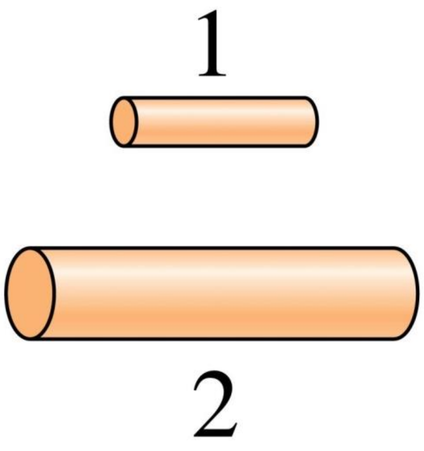
The filament of a 100 W bulb carries a current of 0.83 A at the normal operating voltage of 120 V.

A. What is the resistance of the filament?
B. If the filament is made of tungsten wire of diameter 0.035 mm, how long is the filament?

QuickCheck 22.8

Wire 2 is twice the length and twice the diameter of wire 1. What is the ratio R_2/R_1 of their resistances?

A. 1/4
B. 1/2
C. 1
D. 2
E. 4



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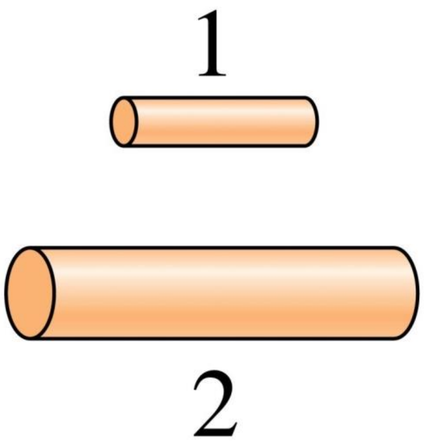


Example 22.6 The length of a lightbulb filament

We calculated in Example 22.5 that a 60 W lightbulb has a resistance of 240 Ω. At the operating temperature of the tungsten filament, the resistivity is approximately $5.0 \times 10^{-7}\ \Omega \cdot \text{m}$. If the wire used to make the filament is 0.040 mm in diameter (a typical value), how long must the filament be?

Example 22.6 The length of a lightbulb filament (cont.)

PREPARE The resistance of a wire depends on its length, its cross-section area, and the material of which it is made.

SOLVE The cross-section area of the wire is $A = \pi r^2 = \pi(2.0 \times 10^{-5}\text{ m})^2 = 1.26 \times 10^{-9}\text{ m}^2$. Rearranging Equation 22.7 shows us that the filament must be of length

$$L = \frac{AR}{\rho} = \frac{(1.26 \times 10^{-9}\text{ m}^2)(240\ \Omega)}{5.0 \times 10^{-7}\ \Omega \cdot \text{m}} = 0.60\text{ m}$$

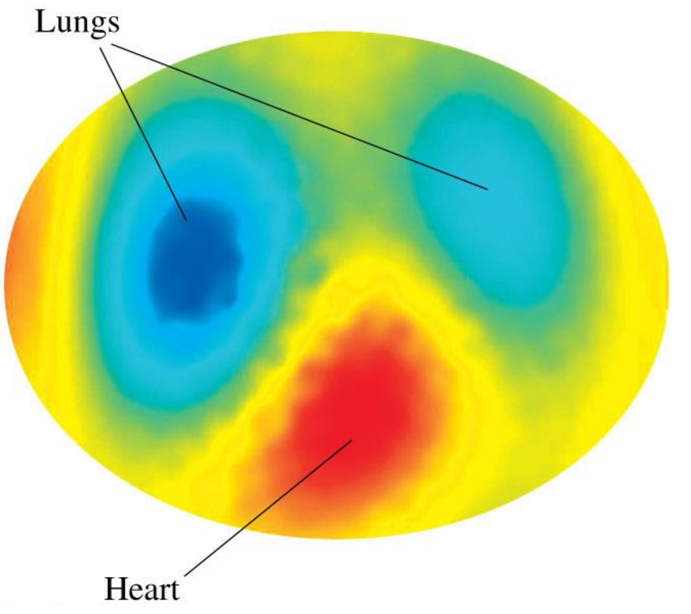
Example 22.6 The length of a lightbulb filament (cont.)

ASSESS This is quite long—nearly 2 feet. This result may seem surprising, but some reflection shows that it makes sense. The resistivity of tungsten is low, so the filament must be quite thin and long.

Electrical Measurements of Physical Properties

- Different tissues in the body have different resistivities. Fat has a higher resistivity than muscle, and so a higher resistance in the body indicates a higher proportion of fat.
- *Electrical impedance tomography* passes a small current through a patient's torso to measure the resistance of intervening tissue.

Electrical Measurements of Physical Properties



- An image of a patient's torso generated from the resistance between many pairs of electrodes shows decreasing resistance in red, and increasing resistance in blue.
- Blood is a better conductor than tissues of the heart and lungs, so the motion of blood decreased the patient's resistance of the heart and increased that of the lungs.
- In a patient with circulatory problems, any deviation from normal blood flow would lead to abnormal patterns of resistance in this image.

Section 22.5 Ohm's Law and Resistor Circuits

Ohm's Law and Resistor Circuits

- **Ohm's Law** describes the relationship between the potential difference across a conductor and the current passing through it:

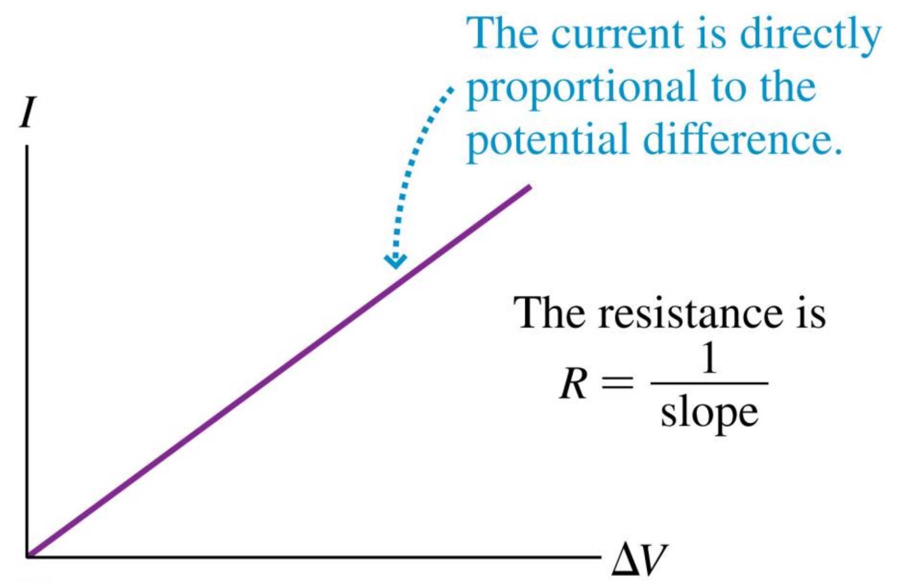
$$I = \frac{\Delta V}{R}$$

Ohm's law for a conductor of resistance R

- Ohm's law is not a law of nature; it is limited to those materials whose resistance R remains constant during use.
- Materials to which Ohm's law applies are called **ohmic.**

Ohm's Law and Resistor Circuits

- The current through an ohmic material is directly proportional to the potential difference.



- Other material and devices are **nonohmic**, meaning the current through the device is *not* directly proportional to the potential difference.
- Nonohomic devices include batteries and capacitors.

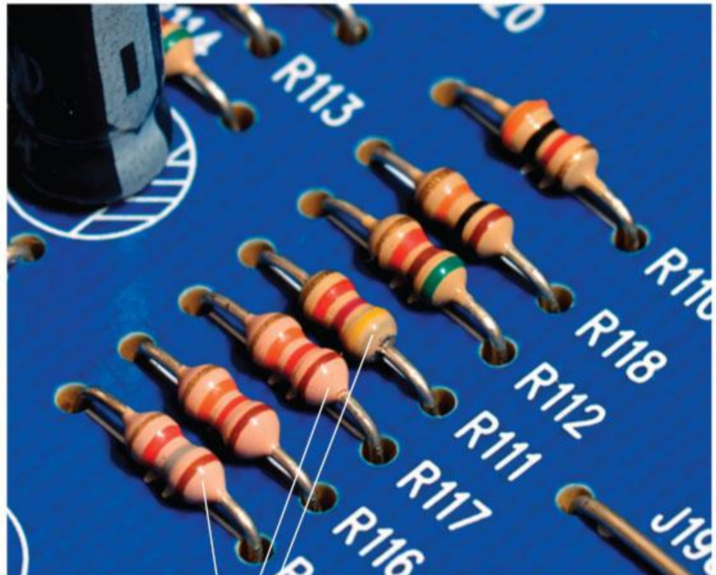
Resistors

- **Resistors** are circuit elements that are designed to have certain resistance for practical reasons.

Resistors: Heating Elements

As charges move through a resistive wire, their electric energy is transformed into thermal energy, heating the wire. Wires in a toaster, a stove burner, or the rear window defroster of a car are practical examples of this electric heating.

Resistors: Circuit Elements



Resistors

Inside many electronic devices is a circuit board with many small cylinders. These cylinders are resistors that help control currents and voltages in the circuit. The colored bands on the resistors indicate their resistance values.

Resistors: Sensor Elements

A resistor whose resistance changes in response to changing circumstances can be used as sensor. The resistance of this night-light sensor changes when daylight strikes it. A circuit detects this change and turns off the light during the day.

Example Problem

An electric blanket has a wire that runs through the interior. A current causes energy to be dissipated in the wire, warming the blanket. A new, low-voltage electric blanket is rated to be used at 18 V. It dissipates a power of 82 W. What is the resistance of the wire that runs through the blanket?

Example Problem

Many web sites describe how to add wires to your clothing to keep you warm while riding your motorcycle. The wires are added to the clothing; a current from the 12 V battery of the motorcycle passes through the wires, warming them. One recipe for a vest calls for 10 m of 0.25-mm-diameter copper wire. How much power will this vest provide to warm the wearer?

Conceptual Example 22.9 The changing current in a toaster

When you press the lever on a toaster, a switch connects the heating wires to 120 V. The wires are initially cool, but the current in the wires raises the temperature until they are hot enough to glow. As the wire heats up, how does the current in the toaster change?

Conceptual Example 22.9 The changing current in a toaster (cont.)

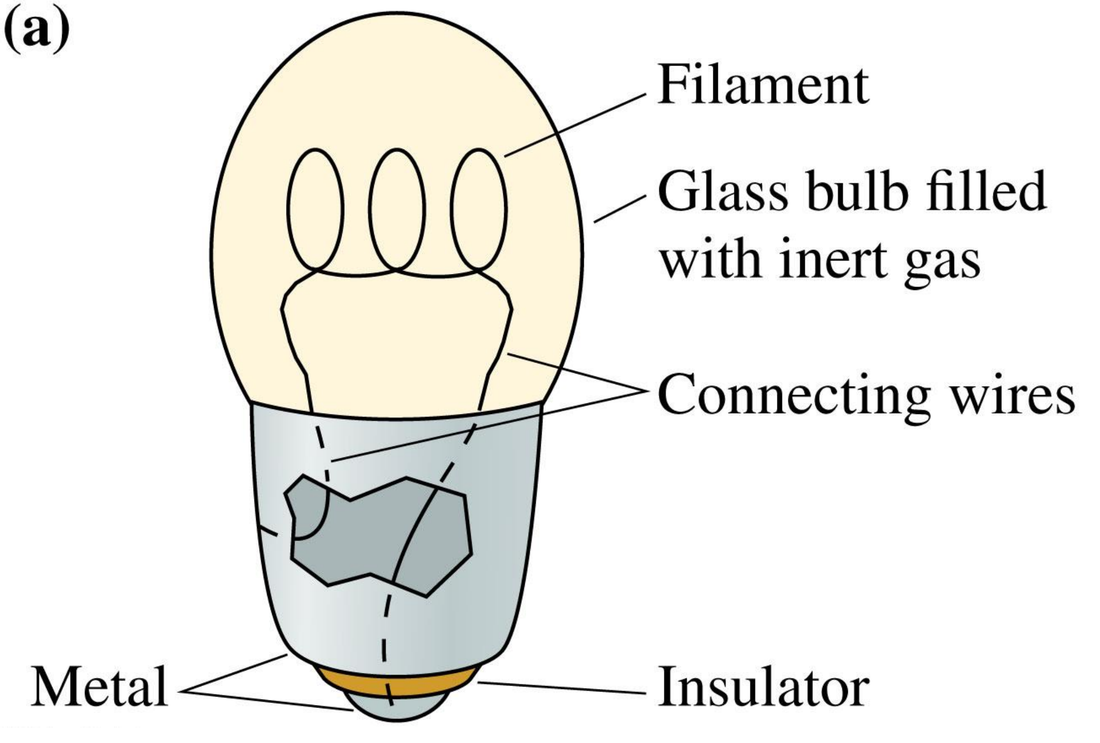
REASON As the wire heats up, its resistivity increases, as noted above, so the resistance of the wires increases. Because the potential difference stays the same, an increasing resistance causes the current to decrease. The current through a toaster is largest when the toaster is first turned on.

Conceptual Example 22.9 The changing current in a toaster (cont.)

ASSESS This result makes sense. As the wire's temperature increases, the current decreases. This makes the system stable. If, instead, the current increased as the temperature increased, higher temperature could lead to more current, leading to even higher temperatures, and the toaster could overheat.

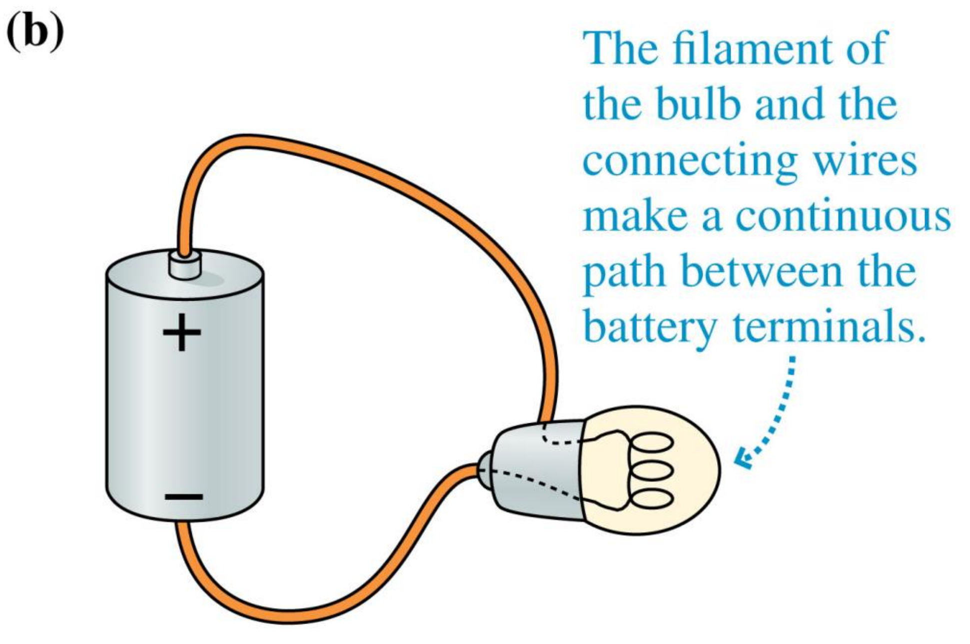
Analyzing a Simple Circuit

- In a lightbulb, connections to the filament in the bulb are made at the tip and along side the metal cylinder.
- It is useful to think of a lightbulb as a resistor that happens to give off light when a current is present.



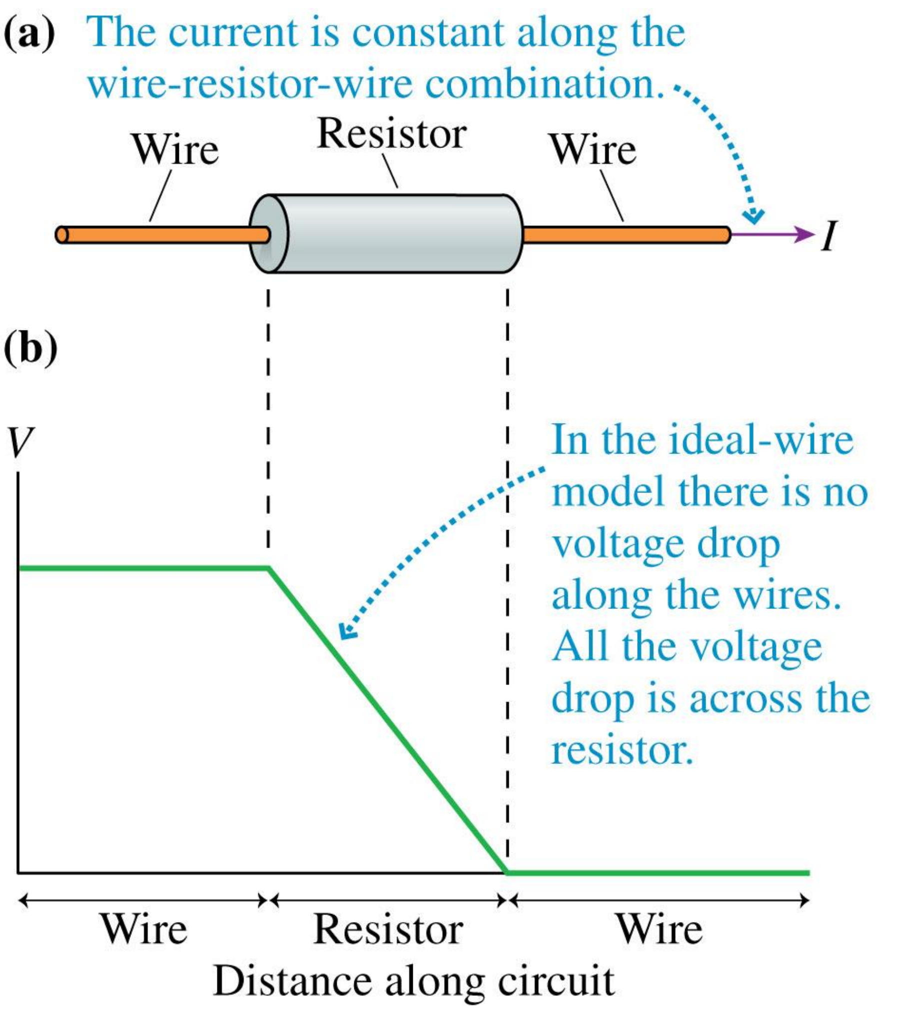
Analyzing a Simple Circuit

- In a circuit using a battery, a lightbulb, and wires (a flashlight), the lightbulb has a resistance of ~3 Ω. The wires typically have a much lower resistance.
- We use an **ideal wire** where its resistance is 0. The potential difference in the wire is 0, *even if there is current in it*.



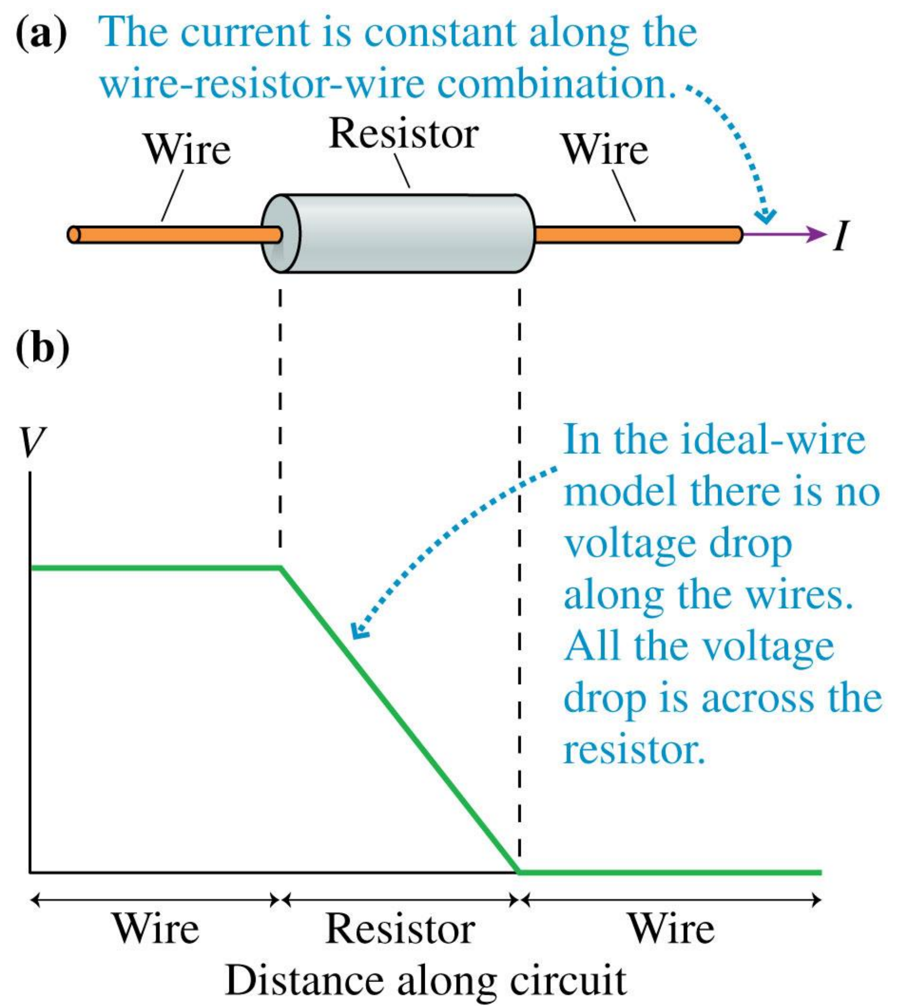
Analyzing a Simple Circuit

- For the ideal-wire model, two wires are connected to a resistor. Current flows through all three, but the current only requires a potential difference across the resistor.



Analyzing a Simple Circuit

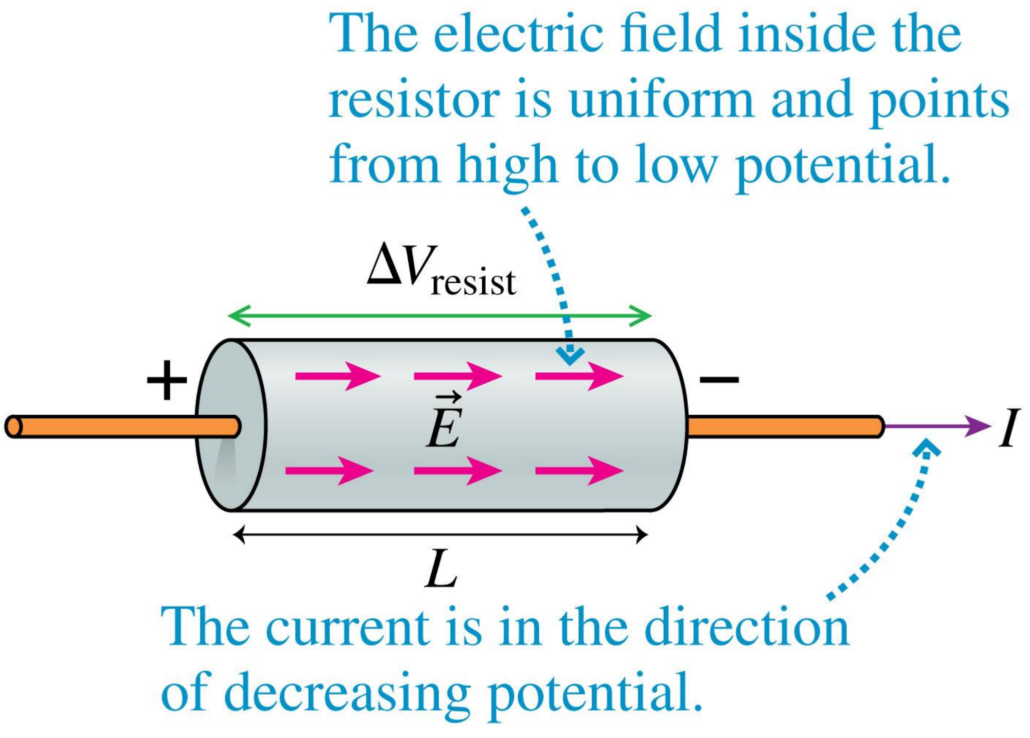
- Current moves in the direction of decreasing potential, so there is a *voltage drop* when the current passes through the resistor left to right.



Analyzing a Simple Circuit

- The electric field in a resistor carrying a current in a circuit is uniform. The strength of the electric field is

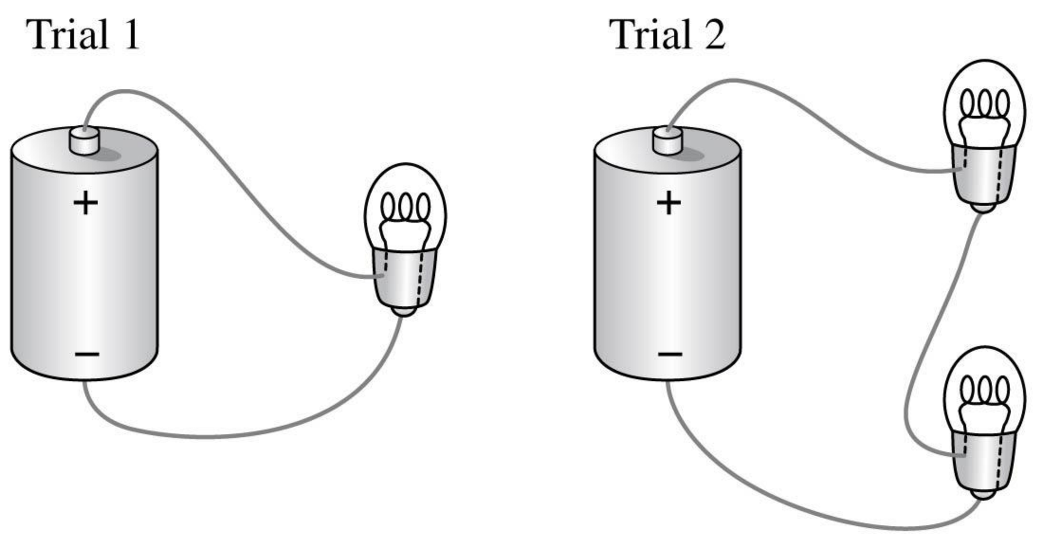
$$E = \frac{\Delta V}{L}$$



QuickCheck 22.9

In Trial 1, a battery is connected to a single lightbulb, and the brightness noted. Now, in Trial 2, a second, identical, lightbulb is added. How does the brightness of these two bulbs compare to the brightness of the single bulb in Trial 1?

A. The brightness is greater.
B. The brightness is the same.
C. The brightness is less.



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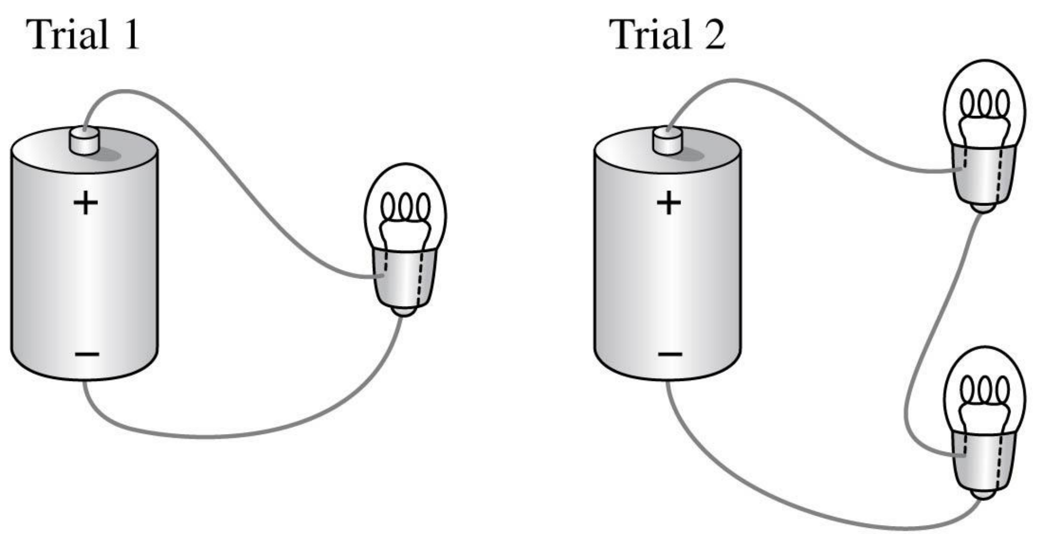
A. The brightness is greater.
B. The brightness is the same.
✔ C. The brightness is less.



Example 22.11 Using a thermistor

A thermistor is a device whose resistance varies with temperature in a well-defined way. A certain thermistor has a resistance of 2.8 kΩ at 20°C and 0.39 kΩ at 70°C. This thermistor is used in a water bath in a lab to monitor the temperature. The thermistor is connected in a circuit with a 1.5 V battery, and the current measured. What is the change in current in the circuit as the temperature rises from 20°C to 70°C?

Example 22.11 Using a thermistor (cont.)

SOLVE We can use Ohm's law to find the current in each case:

$$I(20°\text{C}) = \frac{\Delta V}{R} = \frac{1.5\ \text{V}}{2.8 \times 10^3\ \Omega} = 0.54\ \text{mA}$$

$$I(70°\text{C}) = \frac{\Delta V}{R} = \frac{1.5\ \text{V}}{0.39 \times 10^3\ \Omega} = 3.8\ \text{mA}$$

The change in current is thus 3.3 mA.

Example 22.11 Using a thermistor (cont.)

ASSESS A modest change in temperature leads to a large change in current, which is reasonable—this is a device intended to provide a sensitive indication of a temperature change.

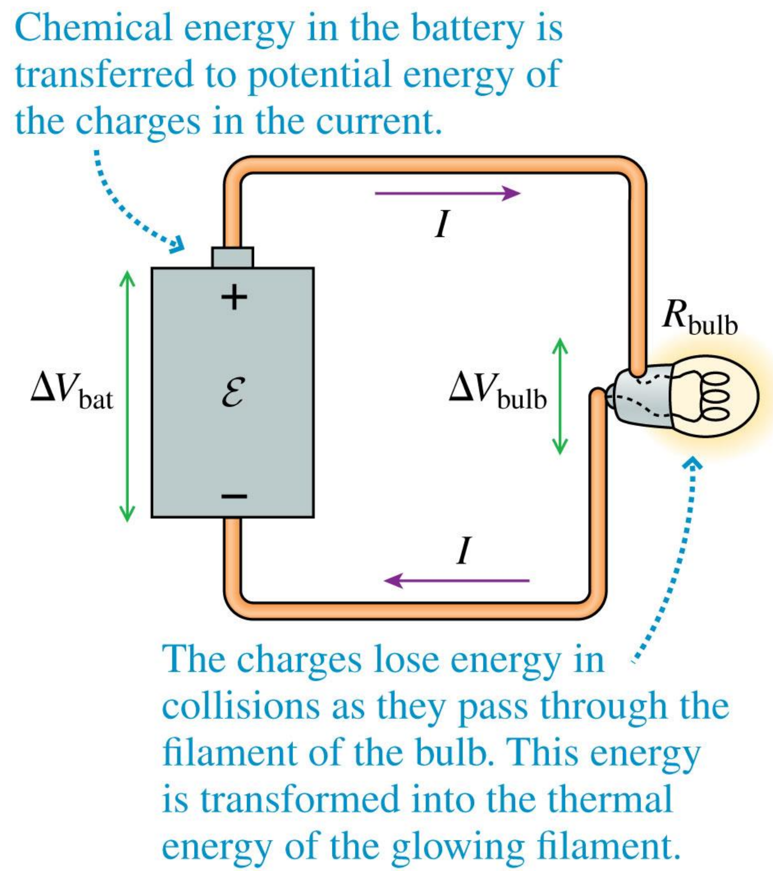
Section 22.6 Energy and Power

Energy and Power

- A battery not only supplies a potential difference but also supplies energy.

Energy and Power

- The charge escalator transfers the chemical energy E_{chem} to the electric potential energy U of the charges.
- That energy is then dissipated as the charges move through the lightbulb, keeping the filament warm and glowing.



Energy and Power

- A charge q gains potential energy $\Delta U = q\Delta V$ as it moves through a potential difference ΔV.
- The potential difference of a battery is $\Delta V_{bat} = \mathcal{E}$, so the battery supplies $\Delta U = q\mathcal{E}$ to charge q as it lifts the charge up the charge escalator from the negative to the positive terminal.

Energy and Power

- The *rate* at which energy is transferred from the battery to the moving charges is

$$P_{\text{bat}} = \text{rate of energy transfer} = \frac{\Delta U}{\Delta t} = \frac{\Delta q}{\Delta t}\mathcal{E}$$

- $\Delta q/\Delta t$, the rate at which charge moves through the battery, is the current I.

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

Power delivered by a source of emf

- Power has units of J/s or W.

Example 22.12 Power delivered by a car battery

A car battery has $\mathcal{E} = 12$ V. When the car's starter motor is running, the battery current is 320 A. What power does the battery supply?

SOLVE The power is the product of the emf of the battery and the current:

$$P_{\text{bat}} = I\mathcal{E} = (320\text{ A})(12\text{ V}) = 3.8\text{ kW}$$

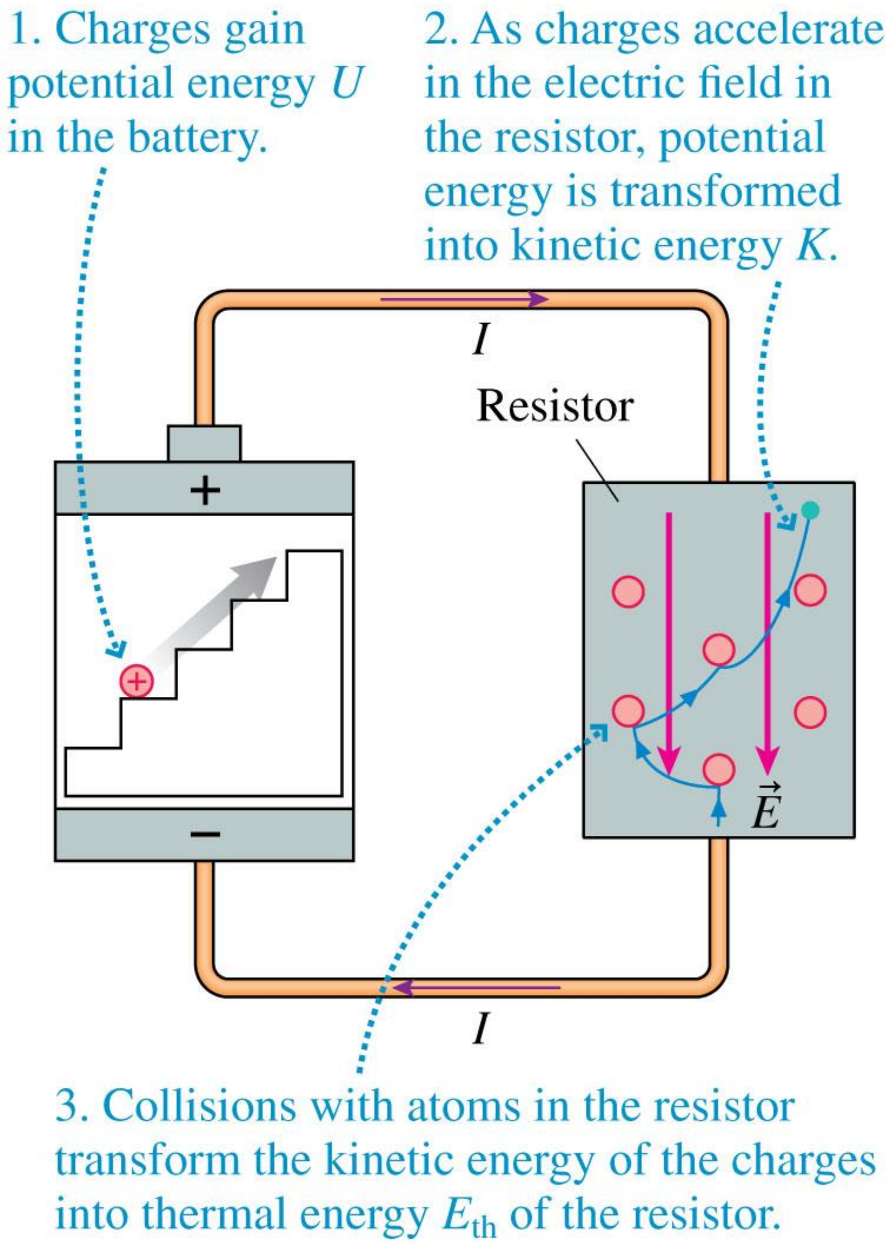
ASSESS This is a lot of power (about 5 hp), but this amount makes sense because turning over a car's engine is hard work. Car batteries are designed to reliably provide such intense bursts of power for starting the engine.

Energy and Power

- In a circuit consisting of a battery and a single resistor, the entire sequence of energy transformations is

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

Energy and Power



Energy and Power

- The net result of a circuit consisting of a battery and a single resistor is that **the battery's chemical energy is transferred to the thermal energy of the resistor,** raising its temperature.
- The rate at which the energy is transferred from the current to the resistor is

$$P_R = \frac{\Delta U}{\Delta t} = \frac{\Delta q}{\Delta t}\Delta V_R = I\,\Delta V_R$$

Energy and Power

- In a single-resistor circuit, the current is the same in the battery and the resistor, so

$$P_{\text{R}} = P_{\text{bat}}$$

- The power dissipated in the resistor is exactly equal to the power supplied by the battery.
- The *rate* at which the battery supplies energy is exactly equal to the *rate* at which the resistor dissipates energy.

QuickCheck 22.10

A resistor is connected to a 3.0 V battery; the power dissipated in the resistor is 1.0 W. The battery is traded for a 6.0 V battery. The power dissipated by the resistor is now

A. 1.0 W
B. 2.0 W
C. 3.0 W
D. 4.0 W

QuickCheck 22.10

A resistor is connected to a 3.0 V battery; the power dissipated in the resistor is 1.0 W. The battery is traded for a 6.0 V battery. The power dissipated by the resistor is now

A. 1.0 W
B. 2.0 W
C. 3.0 W
✔ D. 4.0 W

Example 22.13 Finding the current in a lightbulb

How much current is “drawn” by a 75 W lightbulb connected to a 120 V outlet?

PREPARE We can model the lightbulb as a resistor.

Example 22.13 Finding the current in a lightbulb (cont.)

SOLVE Because the lightbulb is operating as intended, it will dissipate 75 W of power. We can rearrange Equation 22.11 to find

$$I = \frac{P_R}{\Delta V_R} = \frac{75\ \text{W}}{120\ \text{V}} = 0.63\ \text{A}$$

ASSESS We've said that we expect currents on the order of 1 A for lightbulbs and other household items, so our result seems reasonable.

Energy and Power

- A resistor obeys Ohm's law: $I = \Delta V_R / R$. Thus

$$P_R = I\,\Delta V_R = I^2 R = \frac{(\Delta V_R)^2}{R}$$

Power dissipated by resistance R with current I and potential difference ΔV_R

- Power varies as the square of both the current and the potential difference.

Example Problem

An electric kettle has a coiled wire inside that dissipates power when it carries a current, warming the water in the kettle. A kettle designed for use in England carries 13 A when connected to a 230 V outlet.

A. What is the resistance of the wire?
B. What power is dissipated when the kettle is running?
C. The kettle can hold 1.7 l of water. Assume that all power goes to heating the water. How long will it take for the kettle to heat the water from 20°C to 100°C?

Example Problem

The kettle in the previous example is now redesigned to work at the lower voltage of outlets in the United States. Now, the kettle carries 13 A when connected to 120 V.

D. What is the new resistance of the wire?
E. How long will it take for the redesigned kettle to heat 1.7 l of water from 20°C to 100°C?

QuickCheck 22.11

Several light bulbs, different rated voltages, powers. Which one has highest resistance?

Bulb	Voltage across Bulb	Power Dissipated by Bulb
A	10 V	1 W
B	8 V	1 W
C	12 V	2 W
D	6 V	2 W
E	3 V	3 W

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✔ A	10 V	1 W
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QuickCheck 22.12

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 22.12

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

A. The 60 W bulb

✔ B. The 100 W bulb

$P = \frac{(\Delta V)^2}{R}$ with both used at $\Delta V = 120$ V

C. Their resistances are the same.

D. There's not enough information to tell.

Example 22.14 Finding the power of a dim bulb

How much power is dissipated by a 60 W (120 V) lightbulb when operated, using a dimmer switch, at 100 V?

Example 22.14 Finding the power of a dim bulb (cont.)

PREPARE The 60 W rating is for operation at 120 V. We will assume that the resistance doesn't change if the bulb is run at a lower power—not quite right, but a reasonable approximation for this case in which the voltage is only slightly different from the rated value. We can compute the resistance for this case and then compute the power with the dimmer switch.

Example 22.14 Finding the power of a dim bulb (cont.)

SOLVE The lightbulb dissipates 60 W at $\Delta V_R = 120$ V. Thus the filament's resistance is

$$R = \frac{(\Delta V_R)^2}{P_R} = \frac{(120\text{ V})^2}{60\text{ W}} = 240\ \Omega$$

The power dissipation when operated at $\Delta V_R = 100$ V is

$$P_R = \frac{(\Delta V_R)^2}{R} = \frac{(100\text{ V})^2}{240\ \Omega} = 42\text{ W}$$

Example 22.14 Finding the power of a dim bulb (cont.)

ASSESS Reducing the voltage by 17% leads to a 30% reduction of the power. This makes sense; the power is proportional to the square of the voltage, so we expect a proportionally larger change in power.

Summary: General Principles

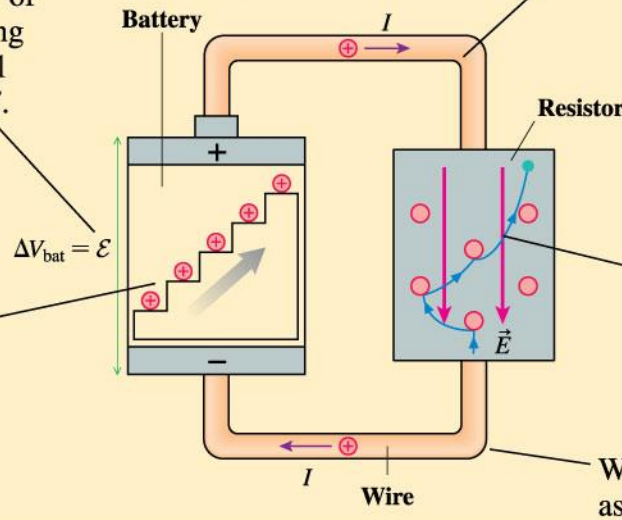
Batteries, Resistors, and Current

The **current** is defined to be the motion of positive charges

$$I = \frac{\Delta q}{\Delta t}$$

The battery transforms its chemical energy into electric potential energy of the charges passing through it, raising their electric potential. The potential difference of the battery is its **emf** $\mathcal{E}$.

Conservation of current dictates that the current is the same at all points in the circuit.



The battery creates an electric field in the circuit that causes charges to move. Positive charges move in the direction of the electric field, which is the direction of decreasing potential.

A **battery** is a source of potential difference. Chemical processes in the battery separate charges. We use a **charge escalator** model to show the lifting of charges to higher potential.

The actual charge carriers are electrons. Their random collisions with atoms impede the flow of charge and are the source of **resistance.** The collisions increase the thermal energy of the **resistor.**

We use the **ideal-wire model** in which we assume that there is no resistance in the wires.

Text: p. 720

Summary: Important Concepts

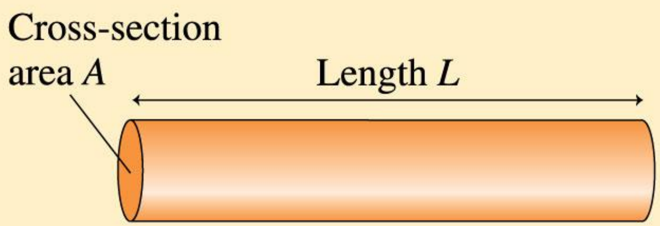
Resistance, resistivity, and Ohm's law

The **resistivity** ρ is a property of a material, a measure of how good a conductor the material is.

- Good conductors have low resistivity.
- Poor conductors have high resistivity.

The **resistance** is a property of a particular wire or conductor. The resistance of a wire depends on its resistivity and dimensions.

$$R = \frac{\rho L}{A}$$



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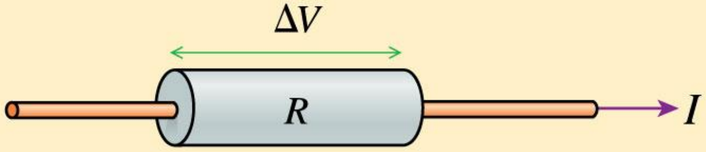

Text: p. 720

Summary: Important Concepts

Energy and power

The energy used by a circuit is supplied by the emf of the battery through a series of energy transformations:

$$E_{\text{chem}} \rightarrow U_{\text{elec}} \rightarrow K \rightarrow E_{\text{th}}$$

- E_{chem}: Chemical energy in the battery
- U_{elec}: Potential energy of separated charges
- K: Kinetic energy of moving charges
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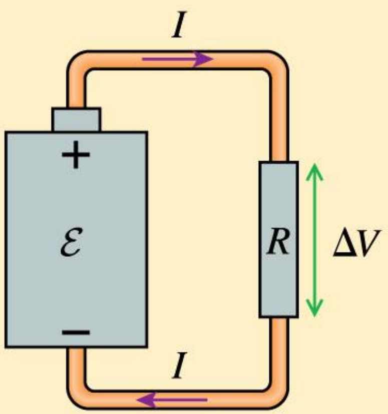


The battery *supplies* power at the rate

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

The resistor *dissipates* power at the rate

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

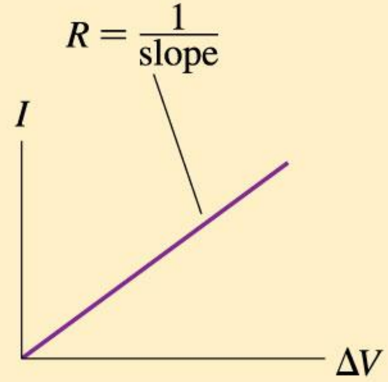
Text: p. 720

Summary: Applications

Conducting materials

When a potential difference is applied to a wire, if the relationship between potential difference and current is linear, the material is **ohmic.**

The resistance is



Resistors are made of ohmic materials and have a well-defined value of resistance:

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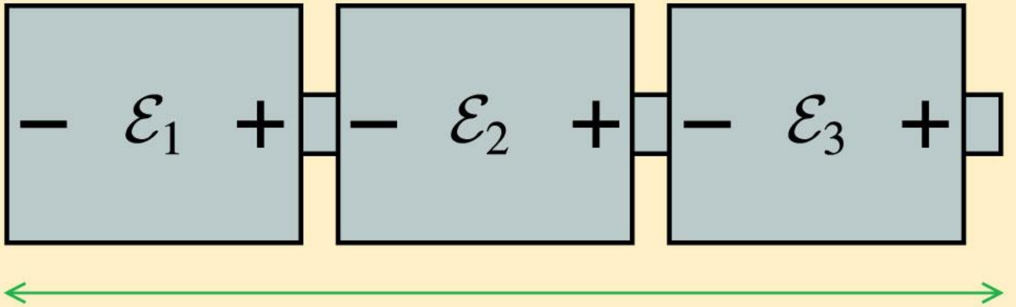
Text: p. 720

Summary: Applications

Batteries in series

Batteries connected one after the other are in *series*. The total potential difference is the sum of the potential differences of each battery.



$$\Delta V_{\text{total}} = \mathcal{E}_1 + \mathcal{E}_2 + \mathcal{E}_3$$

Text: p. 720

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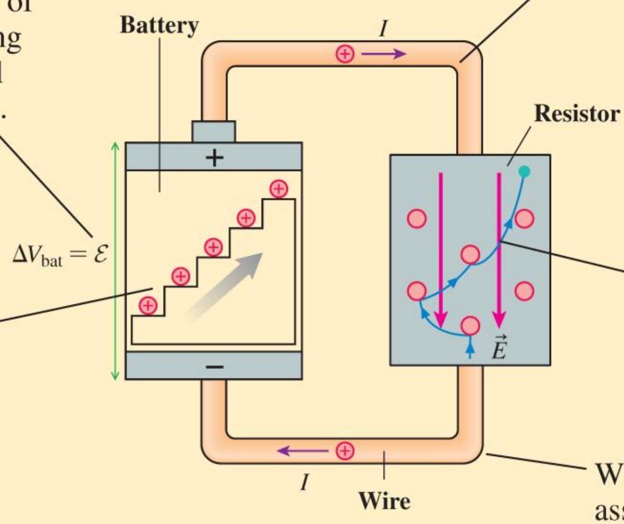

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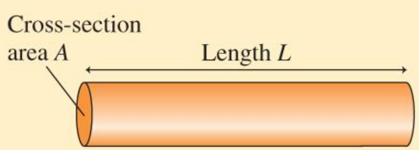

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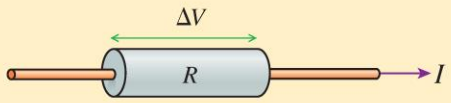

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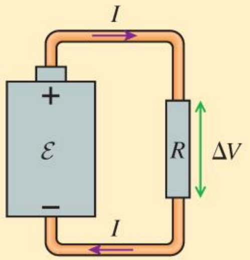

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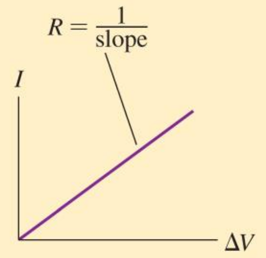

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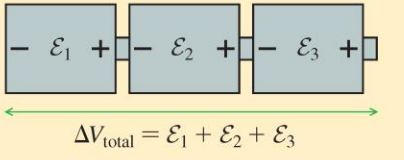

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