Chapter 18

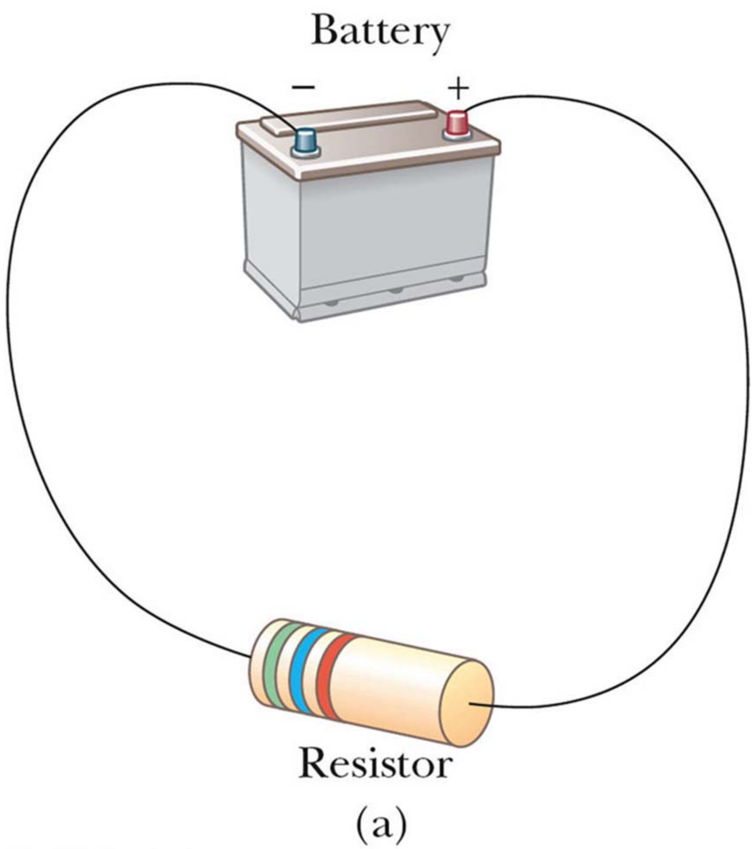
Direct Current Circuits

Sources of emf

- The source that maintains the current in a closed circuit is called a source of *emf*
  - Any devices that increase the potential energy of charges circulating in circuits are sources of emf
  - Examples include batteries and generators
- SI units are Volts
  - The emf is the work done per unit charge

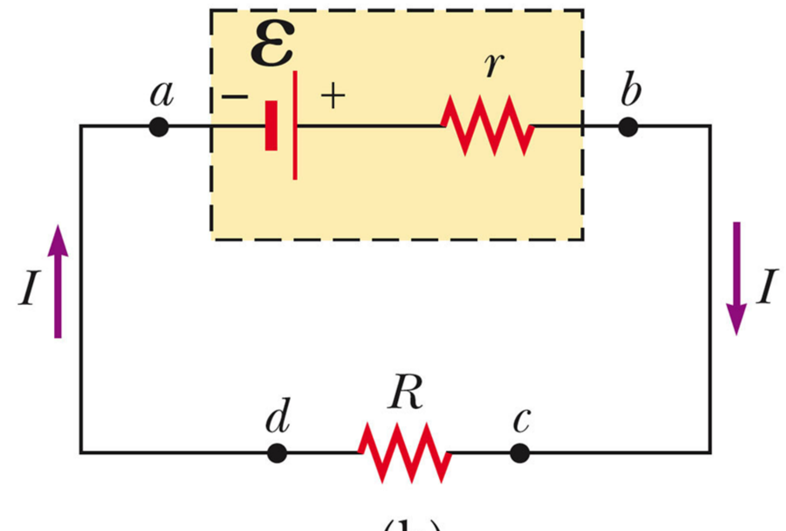
emf and Internal Resistance

- A real battery has some internal resistance
- Therefore, the terminal voltage is not equal to the emf



More About Internal Resistance

- The schematic shows the internal resistance, r
- The terminal voltage is $\Delta V = V_b - V_a$
- $\Delta V = \varepsilon - Ir$
- For the entire circuit, $\varepsilon = IR + Ir$



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Internal Resistance and emf, cont

- ε is equal to the terminal voltage when the current is zero
  - Also called the *open-circuit voltage*
- R is called the *load resistance*
- The current depends on both the resistance external to the battery and the internal resistance

Internal Resistance and emf, final

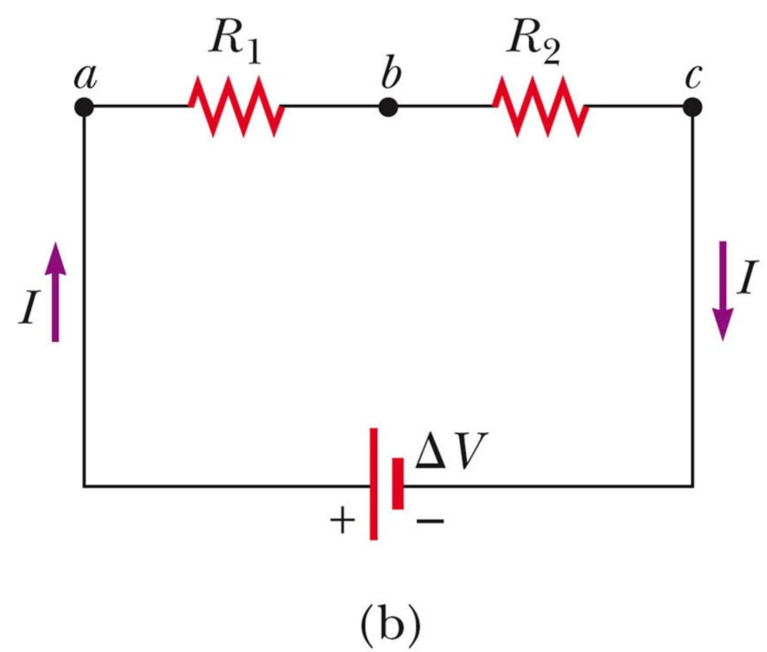
- When R >> r, r can be ignored
  - Generally assumed in problems
- Power relationship
  - $I \varepsilon = I^2 R + I^2 r$
    - When R >> r, most of the power delivered by the battery is transferred to the load resistor

Resistors in Series

- When two or more resistors are connected end-to-end, they are said to be in *series*
- The current is the same in all resistors because any charge that flows through one resistor flows through the other
- The sum of the potential differences across the resistors is equal to the total potential difference across the combination

Resistors in Series, cont

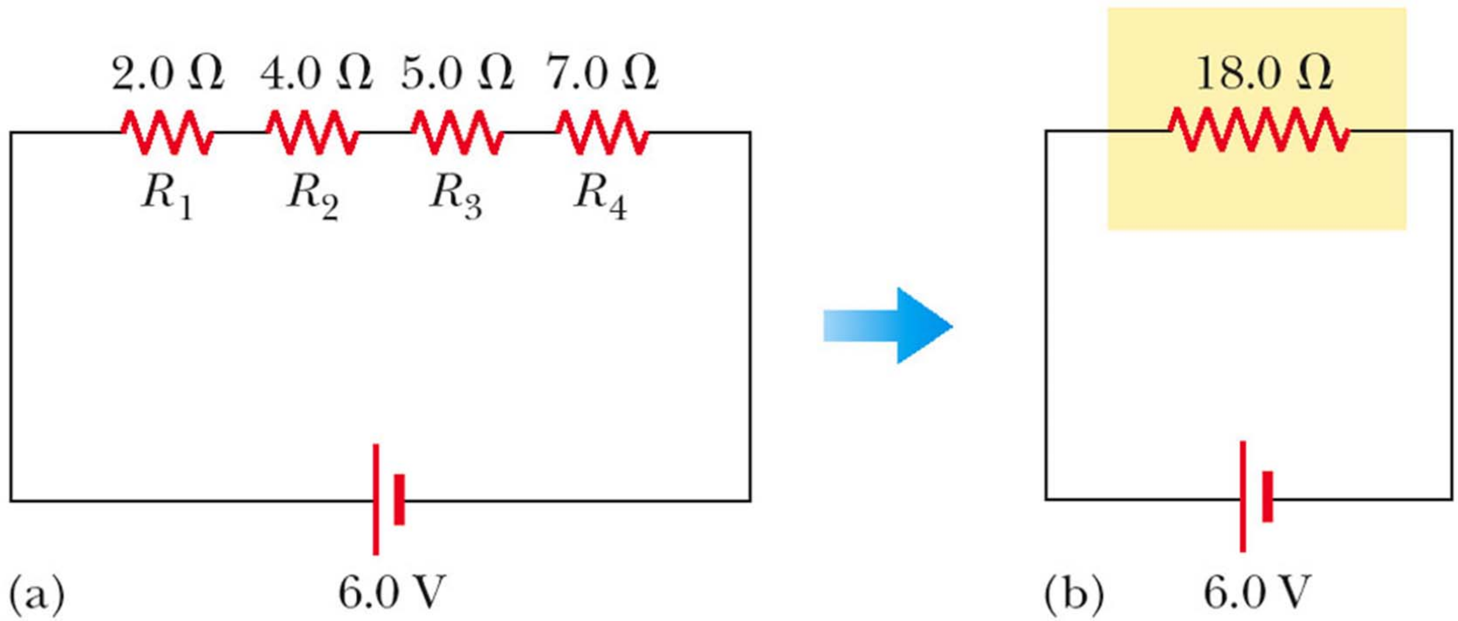
- Potentials add
  - $\Delta V = IR_1 + IR_2 = I\,(R_1+R_2)$
  - Consequence of Conservation of Energy
- The equivalent resistance has the effect on the circuit as the original combination of resistors



Equivalent Resistance – Series

- $R_{eq} = R_1 + R_2 + R_3 + \ldots$
- The equivalent resistance of a series combination of resistors is the algebraic sum of the individual resistances and is always greater than any of the individual resistors

Equivalent Resistance – Series: An Example

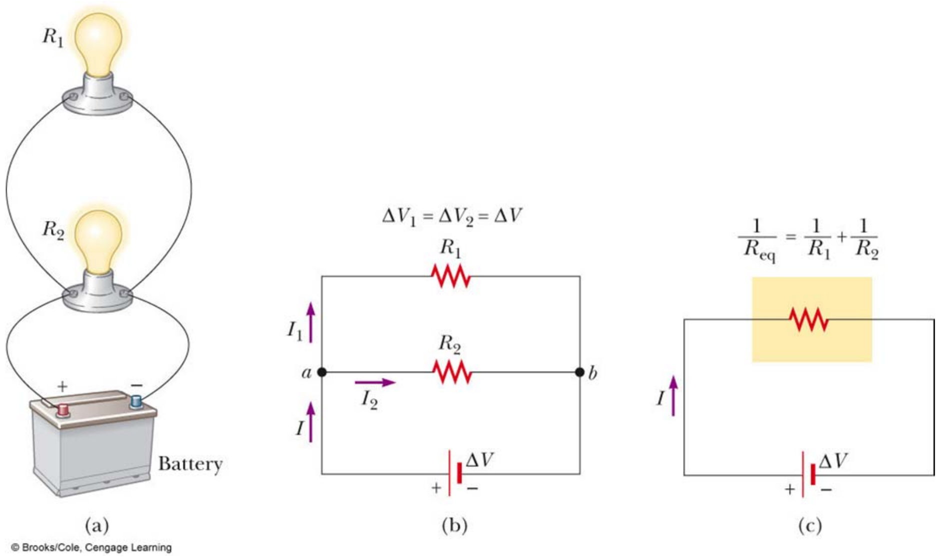


- Four resistors are replaced with their equivalent resistance

Resistors in Parallel

- The potential difference across each resistor is the same because each is connected directly across the battery terminals
- The current, I, that enters a point must be equal to the total current leaving that point
  - $I = I_1 + I_2$
  - The currents are generally not the same
  - Consequence of Conservation of Charge

Equivalent Resistance – Parallel, Example



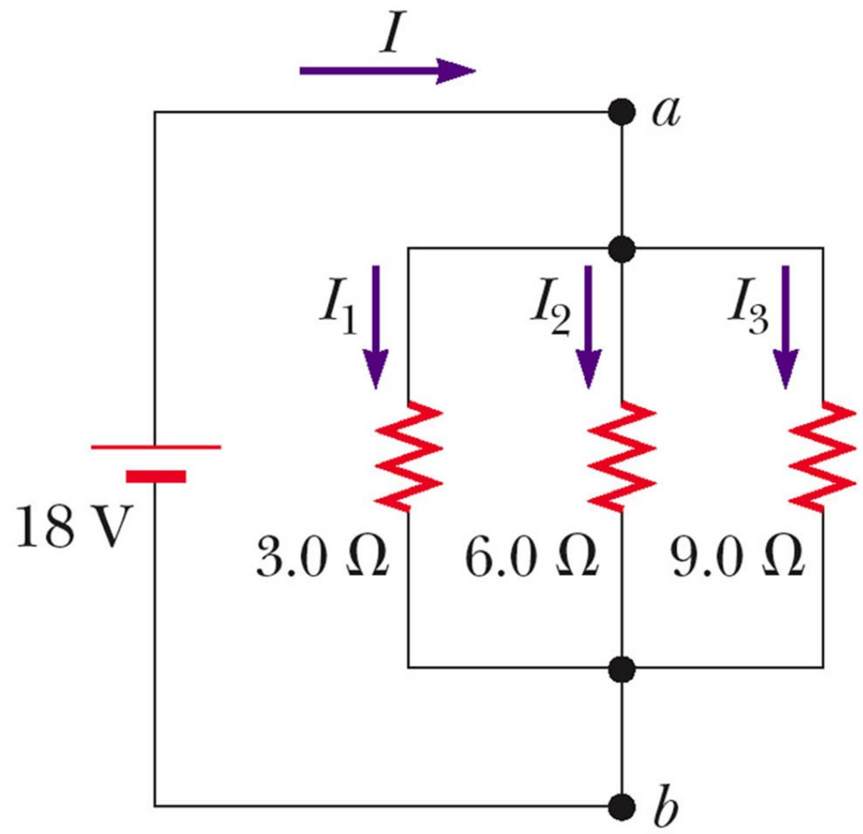
- Equivalent resistance replaces the two original resistances
- *Household circuits* are wired so the electrical devices are connected in parallel
  - Circuit breakers may be used in series with other circuit elements for safety purposes

Equivalent Resistance – Parallel

- Equivalent Resistance

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

- The inverse of the equivalent resistance of two or more resistors connected in parallel is the algebraic sum of the inverses of the individual resistance
  - The equivalent is always less than the smallest resistor in the group



Problem-Solving Strategy, 1

- Combine all resistors in series
  - They carry the same current
  - The potential differences across them are not the same
  - The resistors add directly to give the equivalent resistance of the series combination: $R_{eq} = R_1 + R_2 + \ldots$
  - Draw the simplified circuit diagram

Problem-Solving Strategy, 2

- Combine all resistors in parallel
  - The potential differences across them are the same
  - The currents through them are not the same
  - The equivalent resistance of a parallel combination is found through reciprocal addition:
    $$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$$
  - Draw the simplified circuit diagram

Problem-Solving Strategy, 3

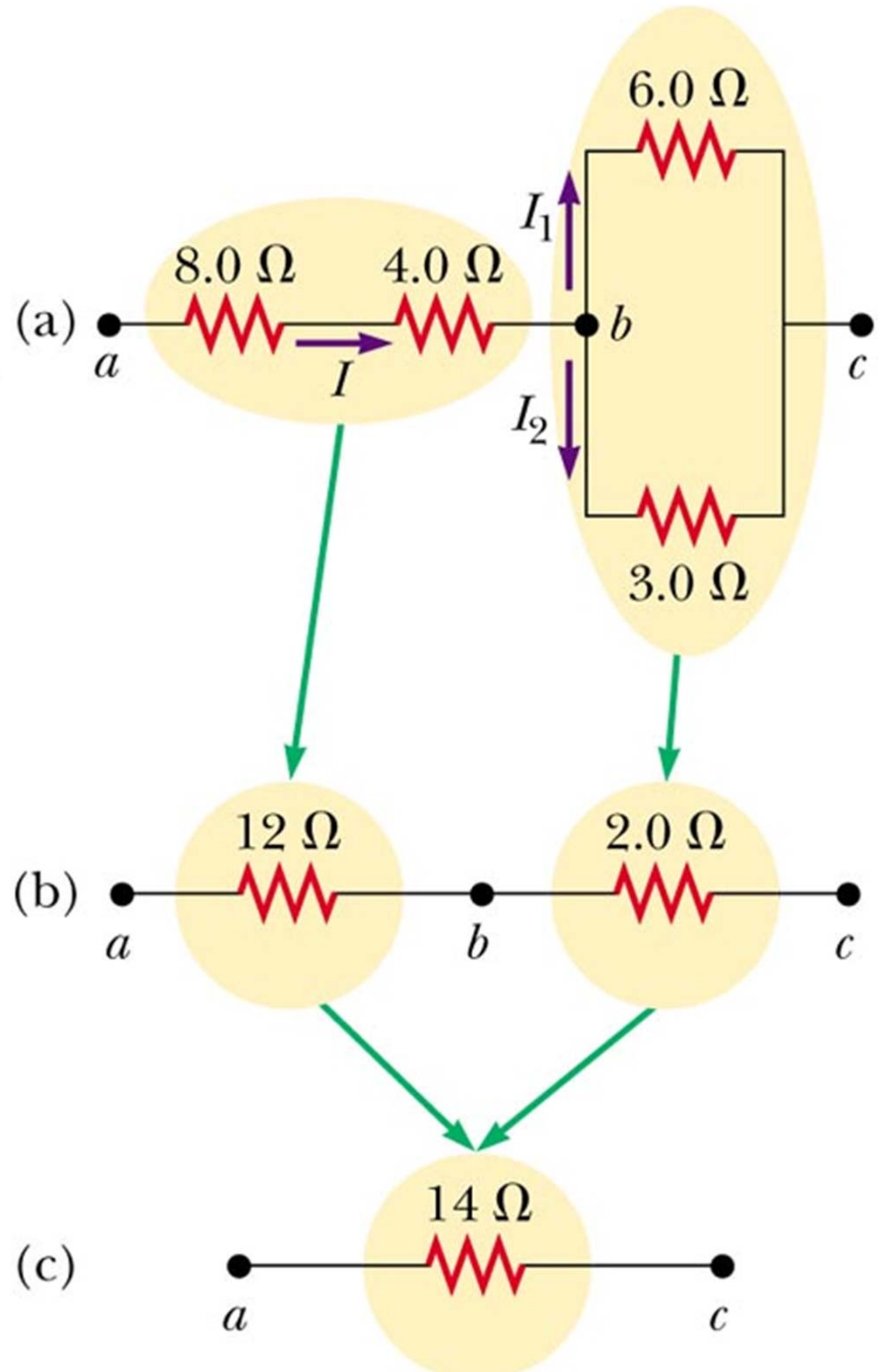
- A complicated circuit consisting of several resistors and batteries can often be reduced to a simple circuit with only one resistor
  - Replace any resistors in series or in parallel using steps 1 or 2.
  - Sketch the new circuit after these changes have been made
  - Continue to replace any series or parallel combinations
  - Continue until one equivalent resistance is found

Problem-Solving Strategy, 4

- If the current in or the potential difference across a resistor in the complicated circuit is to be identified, start with the final circuit found in step 3 and gradually work back through the circuits
  - Use $\Delta V = I R$ and the procedures in steps 1 and 2

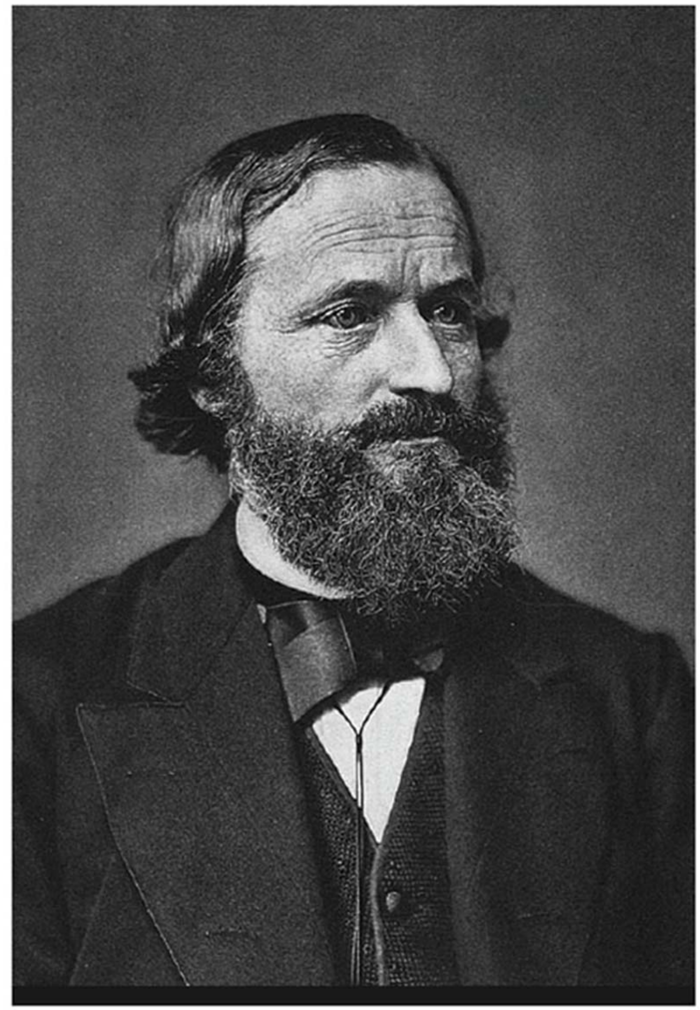
Example

- Complex circuit reduction
  - Combine the resistors in series and parallel
    - Redraw the circuit with the equivalents of each set
  - Combine the resulting resistors in series
  - Determine the final equivalent resistance



Gustav Kirchhoff

- 1824 – 1887
- Invented spectroscopy with Robert Bunsen
- Formulated rules about radiation



Kirchhoff's Rules

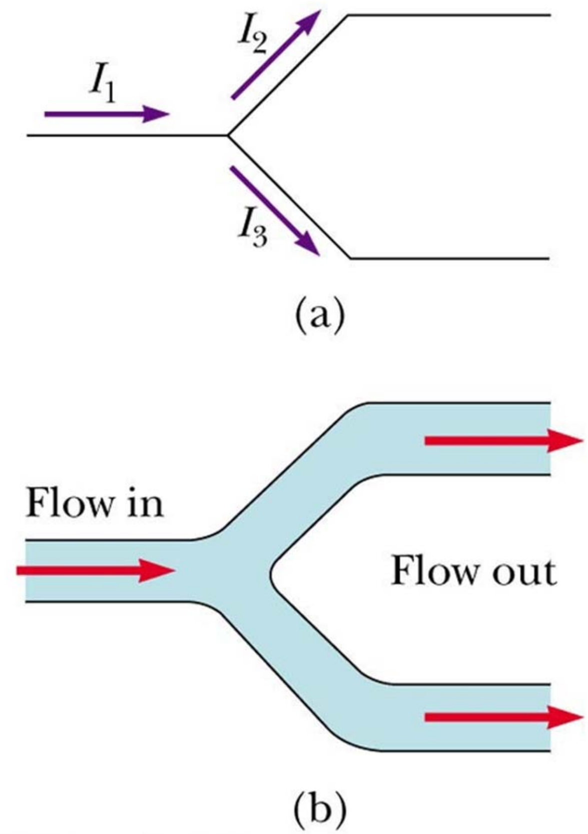
- There are ways in which resistors can be connected so that the circuits formed cannot be reduced to a single equivalent resistor
- Two rules, called Kirchhoff's Rules can be used instead

Statement of Kirchhoff's Rules

- Junction Rule
  - The sum of the currents entering any junction must equal the sum of the currents leaving that junction
    - A statement of Conservation of Charge
- Loop Rule
  - The sum of the potential differences across all the elements around any closed circuit loop must be zero
    - A statement of Conservation of Energy

More About the Junction Rule

- $I_1 = I_2 + I_3$
- From Conservation of Charge
- Diagram b shows a mechanical analog

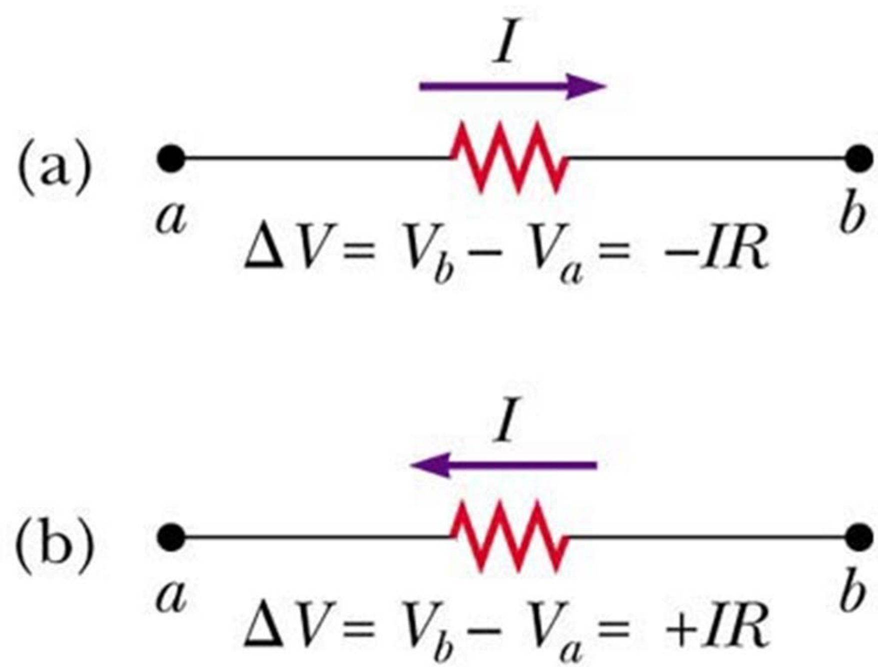


Loop Rule

- A statement of Conservation of Energy
- To apply Kirchhoff's Rules,
  - Assign symbols and directions to the currents in all branches of the circuit
    - If the direction of a current is incorrect, the answer will be negative, but have the correct magnitude
  - Choose a direction to transverse the loops
    - Record voltage rises and drops

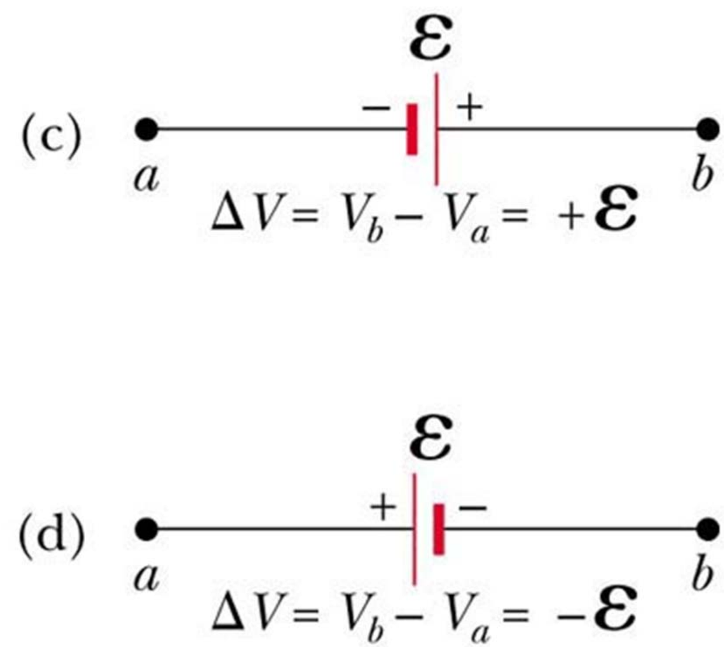
More About the Loop Rule

- Traveling around the loop from a to b
- In a, the resistor is transversed in the direction of the current, the potential across the resistor is –IR
- In b, the resistor is transversed in the direction opposite of the current, the potential across the resistor is +IR



Loop Rule, final

- In c, the source of emf is transversed in the direction of the emf (from – to +), the change in the electric potential is +ε
- In d, the source of emf is transversed in the direction opposite of the emf (from + to -), the change in the electric potential is -ε



Junction Equations from Kirchhoff's Rules

- Use the junction rule as often as needed, so long as, each time you write an equation, you include in it a current that has not been used in a previous junction rule equation
  - In general, the number of times the junction rule can be used is one fewer than the number of junction points in the circuit

Loop Equations from Kirchhoff's Rules

- The loop rule can be used as often as needed so long as a new circuit element (resistor or battery) or a new current appears in each new equation
- You need as many independent equations as you have unknowns

Problem-Solving Strategy – Kirchhoff’s Rules

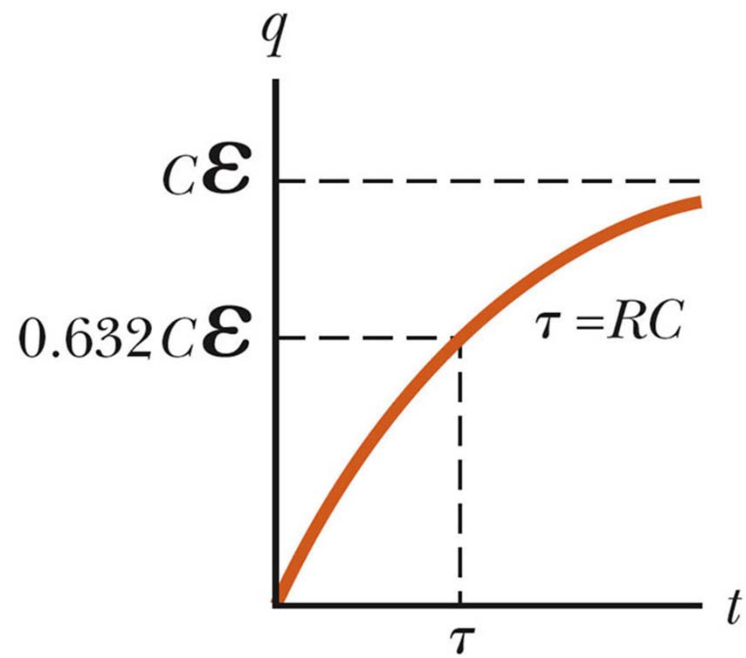
- Draw the circuit diagram and assign labels and symbols to all known and unknown quantities
- Assign directions to the currents.
- Apply the junction rule to any junction in the circuit
- Apply the loop rule to as many loops as are needed to solve for the unknowns
- Solve the equations simultaneously for the unknown quantities
- Check your answers

RC Circuits

- When a direct current circuit contains capacitors and resistors, the current will vary with time
- When the circuit is completed, the capacitor starts to charge
- The capacitor continues to charge until it reaches its maximum charge ($Q = C\varepsilon$)
- Once the capacitor is fully charged, the current in the circuit is zero

Charging Capacitor in an RC Circuit

- The charge on the capacitor varies with time
  - $q = Q(1 - e^{-t/RC})$
  - The *time constant*, $\tau = RC$
- The time constant represents the time required for the charge to increase from zero to 63.2% of its maximum



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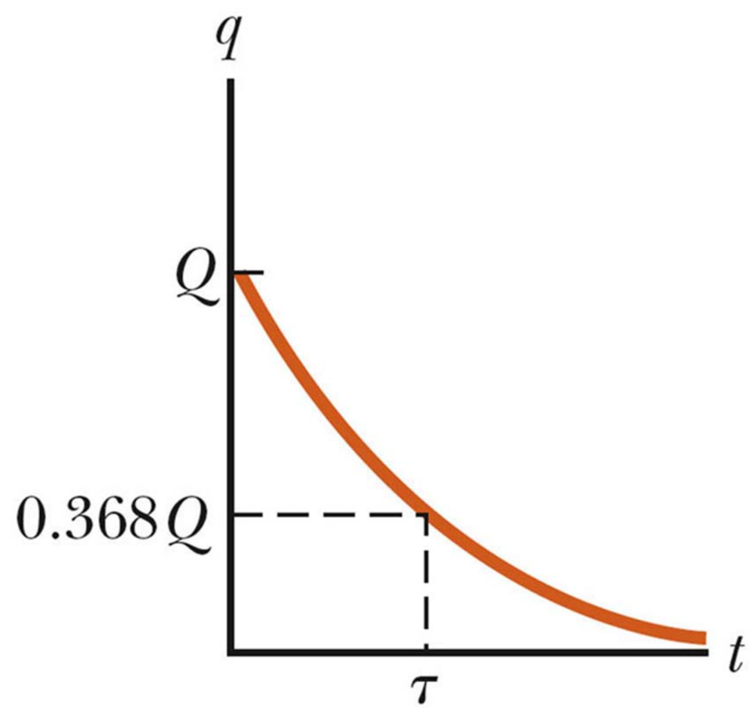
Notes on Time Constant

- In a circuit with a large time constant, the capacitor charges very slowly
- The capacitor charges very quickly if there is a small time constant
- After $t = 10\ \tau$, the capacitor is over 99.99% charged

Discharging Capacitor in an RC Circuit

- When a charged capacitor is placed in the circuit, it can be discharged
  - $q = Qe^{-t/RC}$
- The charge decreases exponentially
- At $t = \tau = RC$, the charge decreases to 0.368 Qmax
  - In other words, in one time constant, the capacitor loses 63.2% of its initial charge



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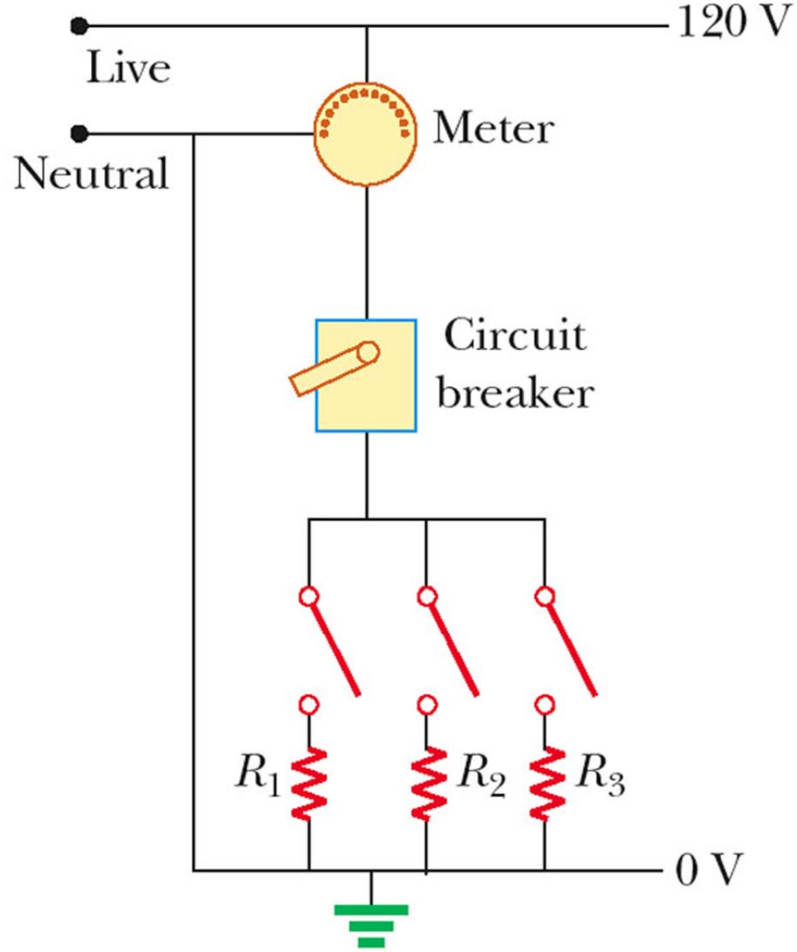
Household Circuits

- The utility company distributes electric power to individual houses with a pair of wires
- Electrical devices in the house are connected in parallel with those wires
- The potential difference between the wires is about 120V

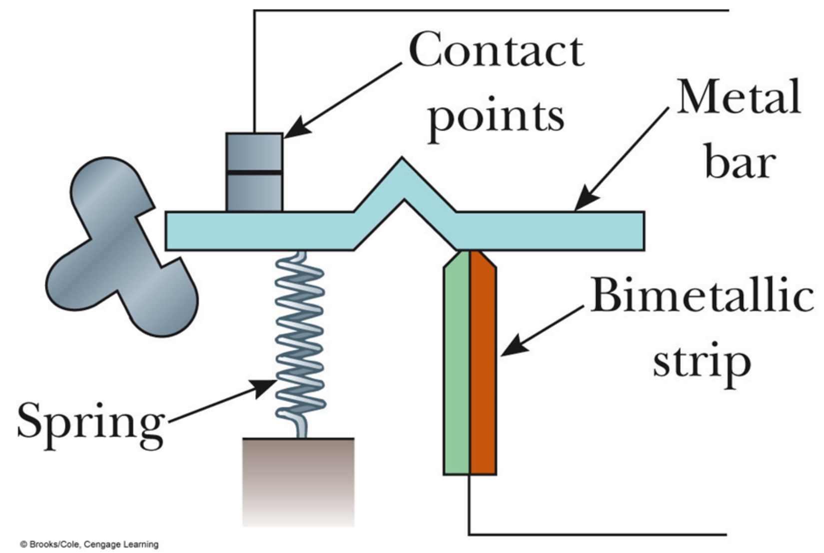


Household Circuits, cont.

- A meter and a circuit breaker are connected in series with the wire entering the house
- Wires and circuit breakers are selected to meet the demands of the circuit
- If the current exceeds the rating of the circuit breaker, the breaker acts as a switch and opens the circuit
- Household circuits actually use alternating current and voltage

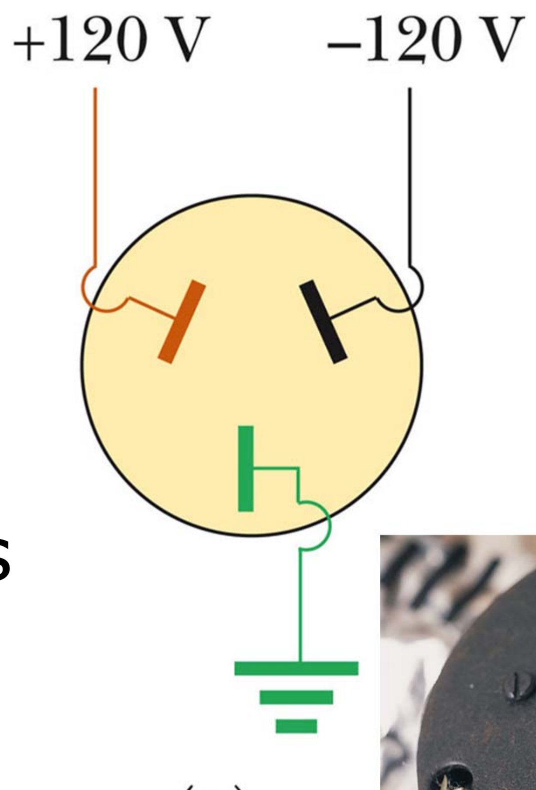
Circuit Breaker Details

- Current passes through a bimetallic strip
  - The top bends to the left when excessive current heats it
  - Bar drops enough to open the circuit
- Many circuit breakers use electromagnets instead



240-V Connections

- Heavy-duty appliances may require 240 V to operate
- The power company provides another wire at 120 V below ground potential



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Electrical Safety

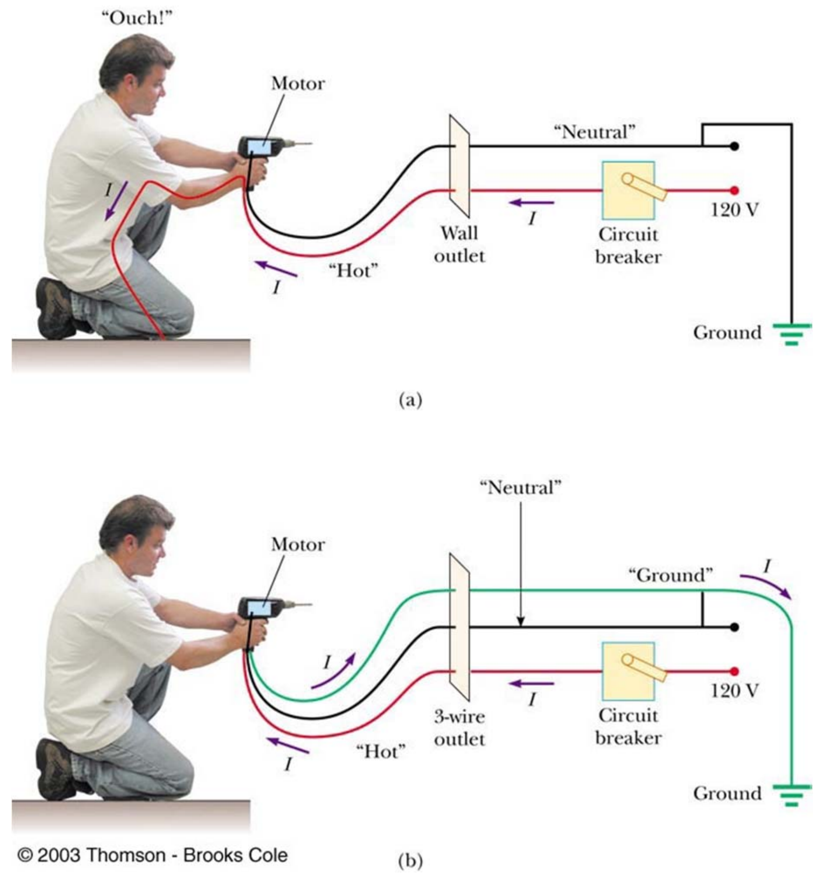
- Electric shock can result in fatal burns
- Electric shock can cause the muscles of vital organs (such as the heart) to malfunction
- The degree of damage depends on
  - The magnitude of the current
  - The length of time it acts
  - The part of the body through which it passes

Effects of Various Currents

- 5 mA or less
  - Can cause a sensation of shock
  - Generally little or no damage
- 10 mA
  - Hand muscles contract
  - May be unable to let go of a live wire
- 100 mA
  - If passes through the body for just a few seconds, can be fatal

Ground Wire

- Electrical equipment manufacturers use electrical cords that have a third wire, called a *case ground*
- Prevents shocks



Ground Fault Interrupts (GFI)

- Special power outlets
- Used in hazardous areas
- Designed to protect people from electrical shock
- Senses currents (of about 5 mA or greater) leaking to ground
- Shuts off the current when above this level

Electrical Signals in Neurons

- Specialized cells in the body, called *neurons*, form a complex network that receives, processes, and transmits information from one part of the body to another
- Three classes of neurons
  - Sensory neurons
    - Receive stimuli from sensory organs that monitor the external and internal environment of the body
  - Motor neurons
    - Carry messages that control the muscle cells
  - Interneurons
    - Transmit information from one neuron to another

Diagram of a Neuron