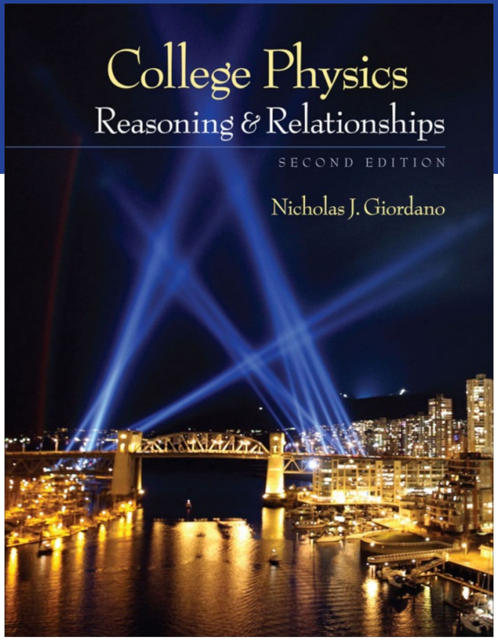

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Chapter 19

Electric Currents and Circuits

Marilyn Akins, PhD • Broome Community College

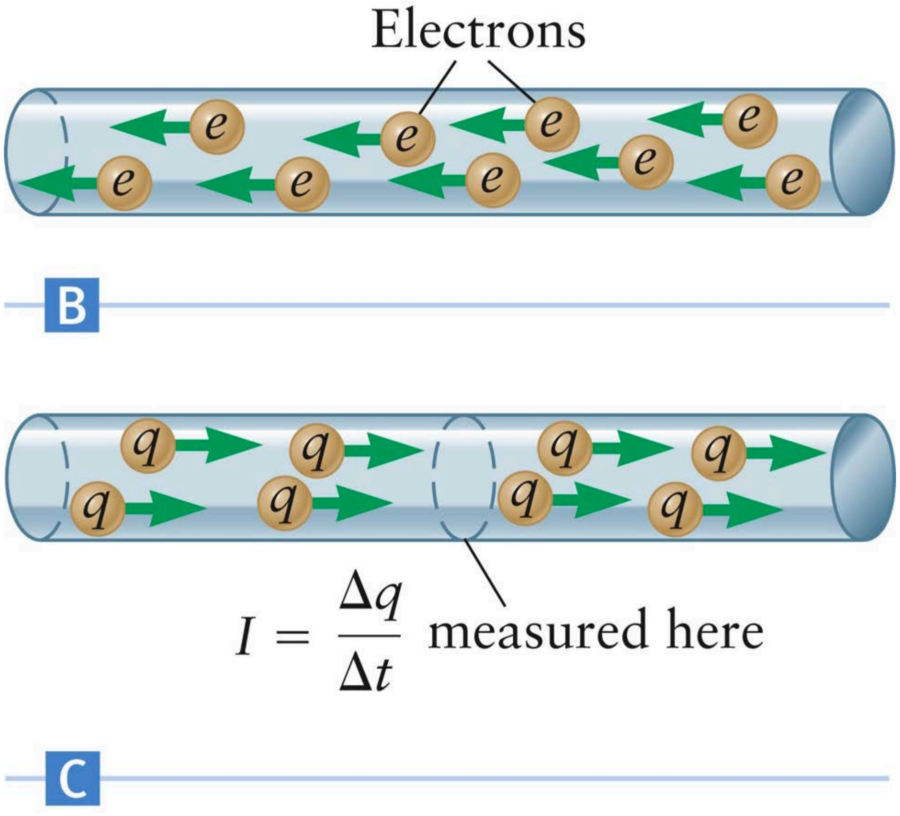
Electric Circuits

- The motion of charges leads to the idea of electric circuits
  - A circuit occurs when charge can flow in a closed path
- Also examine circuit components
  - Resistors
  - Capacitors
- Conservation principles will be useful
  - Conservation of Charge
  - Conservation of Energy

Electric Current

- Electrons can move easily through a wire
- The magnitude of the current is measured by the amount of charge that moves along the wire
- Current, I, is defined as

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



Electric Current, cont.

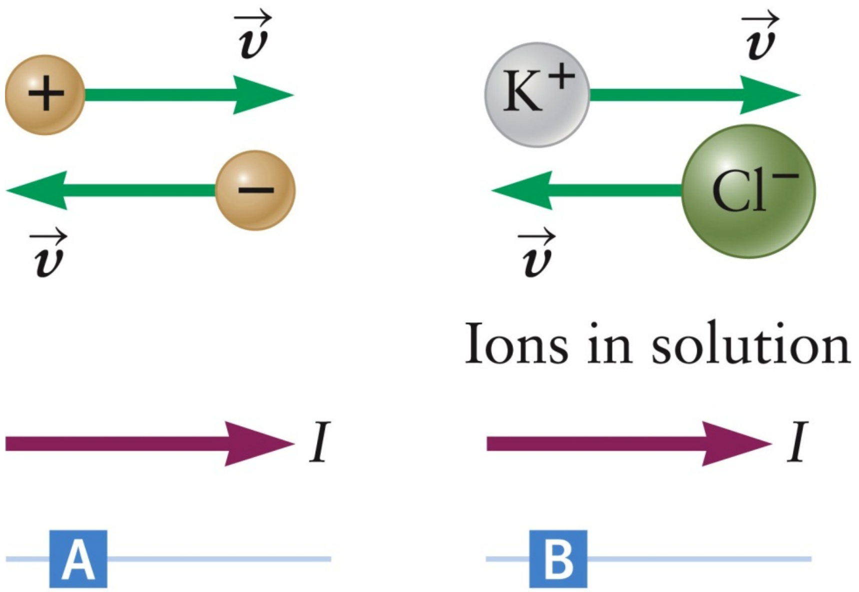
- Current is defined in terms of net positive charge flow
  - Historical reasons
- SI unit is Ampere (A)
  - In honor of André-Marie Ampère
  - 1 A = 1 C / s
- In the SI system, the ampere is a primary unit
  - Coulomb and volt, for example, are defined in terms of the ampere

Movement of Charges

- The definition of current uses the net charge, Δq, that passes a particular point during a time interval, Δt
- The amount of charge could be the result of many possible configurations, including
  - A few particles each with a large charge
  - Many particles each with a small charge
  - A combination of positive and negative charges

Movement of Charges, cont.

- If the current is carried by positive charges moving with a given velocity, the direction of the current is parallel to the velocity
- If current is carried by negative charges, the direction of the current is opposite the charges' velocity



Movement of Charges, final

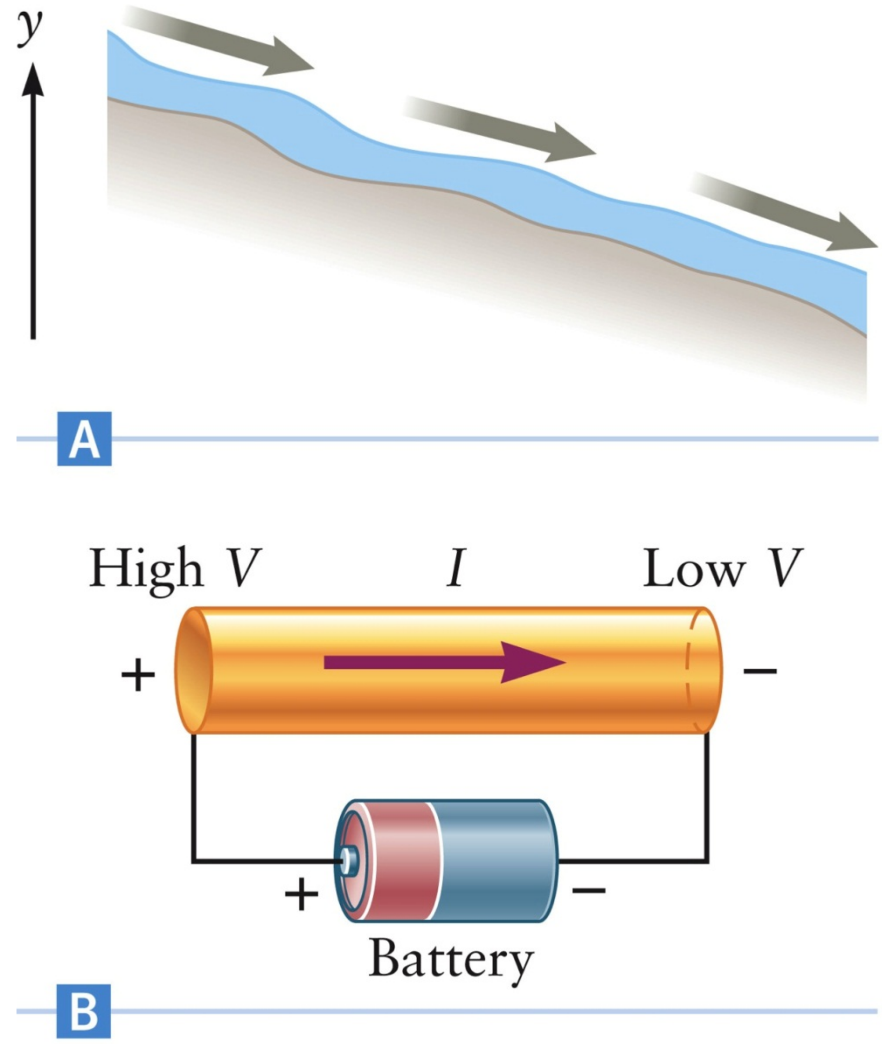
- A positive electric current can be produced by
  - Positive charges moving in one direction
  - Negative charges moving in the opposite direction
- Current in a metal is carried by electrons
- In a liquid or gas, the current is generally carried by a combination of positive ions moving in one direction and negative ions moving in the opposite direction

Current and Potential Energy

- For charge to move along a wire, the electric potential energy at one end of the wire must be higher than the electric potential energy at the other end
- Electric potential is related to electric potential energy by $V = PE_{elec} / q$
  - The potential is referred to simply as "voltage"

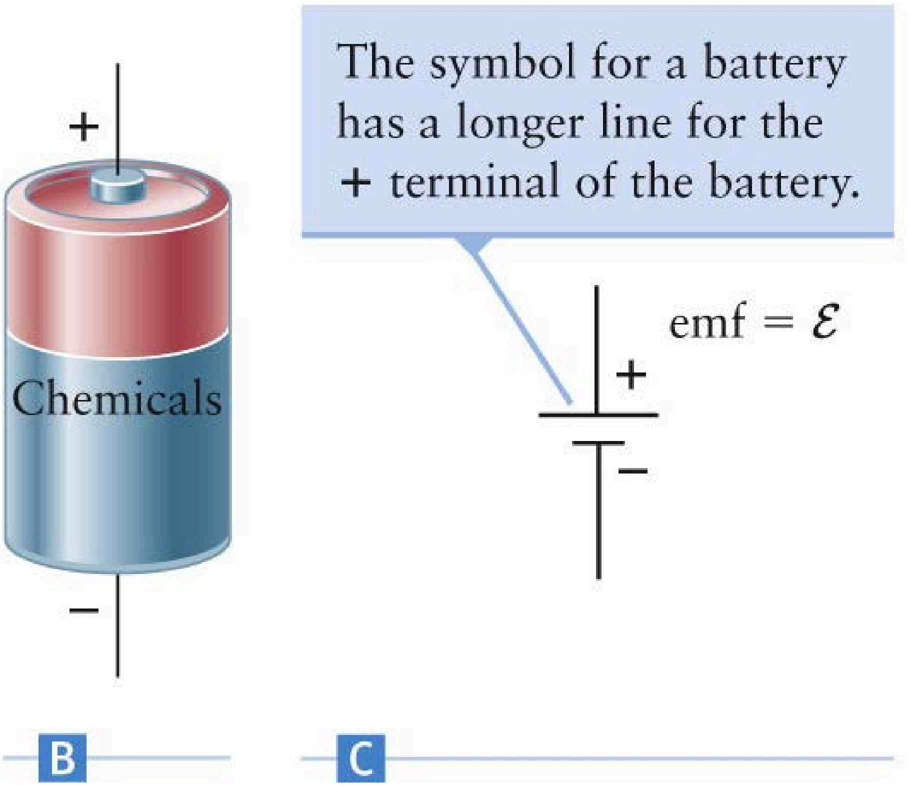
Current and Voltage

- The current is directed from a region of higher potential to a region of lower potential
  - Or higher to lower voltage
- The direction of I is always from high to low potential, regardless if the current is carried by positive or negative charges
- The potential difference may be supplied by a battery



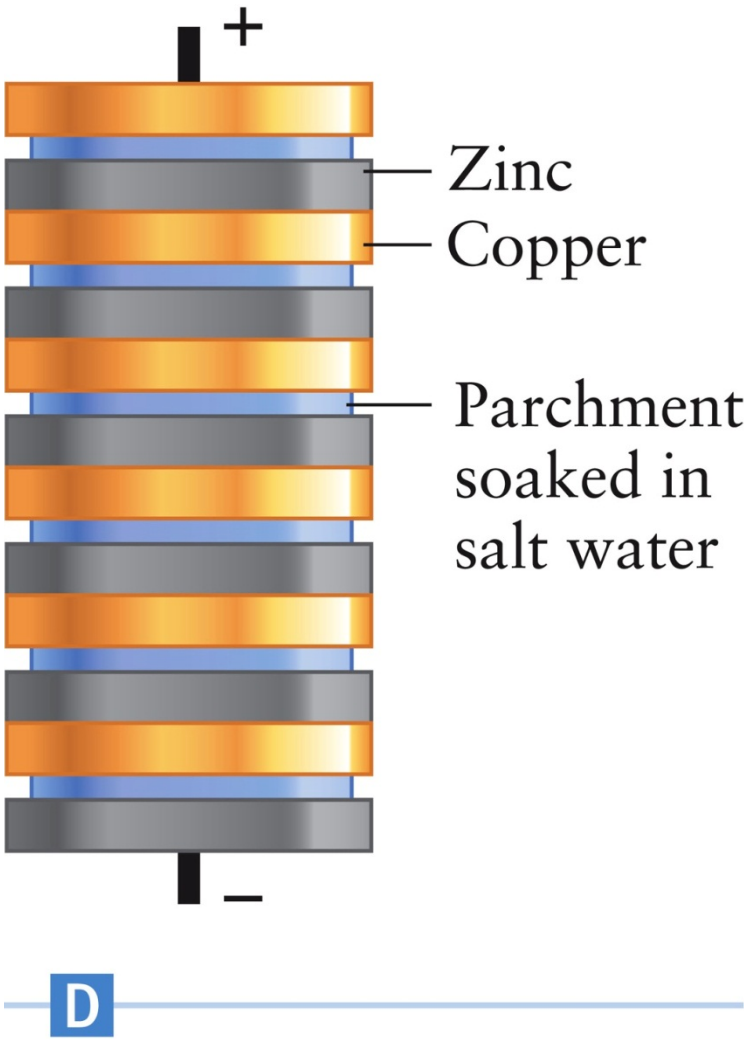
Construction of a Battery

- Alessandro Volta and his contemporaries developed the first batteries
- Batteries convert chemical energy to electrical energy
- In drawing an electric circuit the terminals of any type of battery are labeled with + and -



Volta's Battery

- Volta's first batteries consisted of alternating sheets of zinc and copper
- These were separated by a piece of parchment soaked with salt water

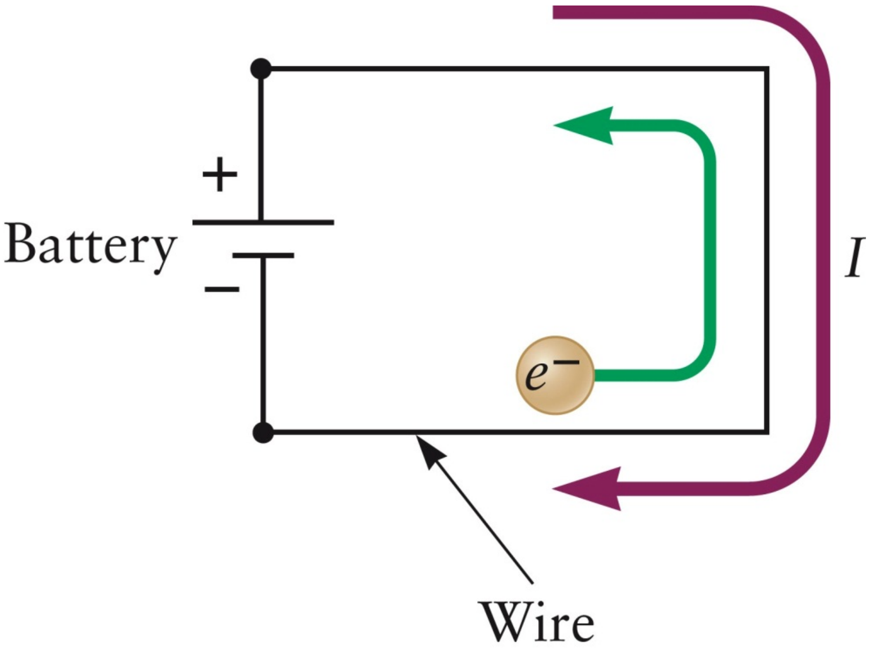


EMF

- The potential difference between a battery's terminals is called an ***electromotive force***, or ***emf***
  - The term was adopted before it was understood that batteries produce an electric potential difference, not a force
- The emf is denoted with ε and referred to as voltage
- The value of the emf depends on the particular chemical reactions it employs and how the electrodes are arranged

Simple Circuit

- If the battery terminals are connected to two ends of a wire, a current is produced
- The electrons move out of the negative terminal of the battery through the wire and into the positive battery terminal



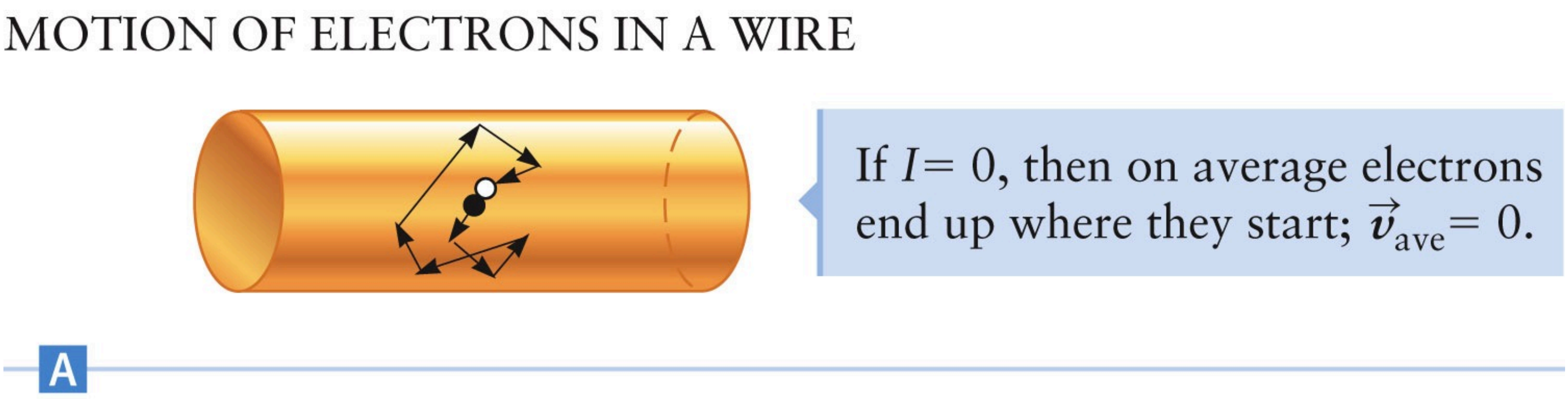
Simple Circuit, cont.

- The charge moves from one terminal to the other through a circuit
- The chemical reaction moves charge internally between the electrodes
- No net charge accumulates on the battery terminals while the current is present

Ideal vs. Real Batteries

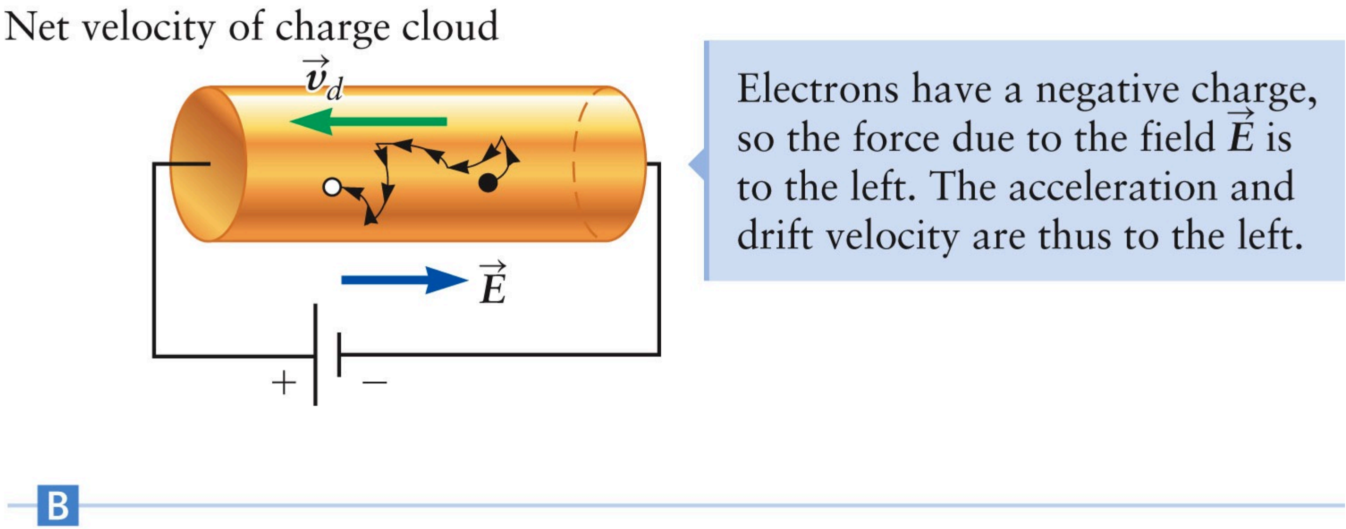
- An ideal battery has two important properties
  - It always maintains a fixed potential difference between its terminals
  - This emf is maintained no matter how much current flows from the battery
- Real batteries have two practical limitations
  - The emf decreases when the current is very high
    - The electrochemical reactions do not happen instantaneously
  - The battery will "run down"
    - It will not work forever

Current



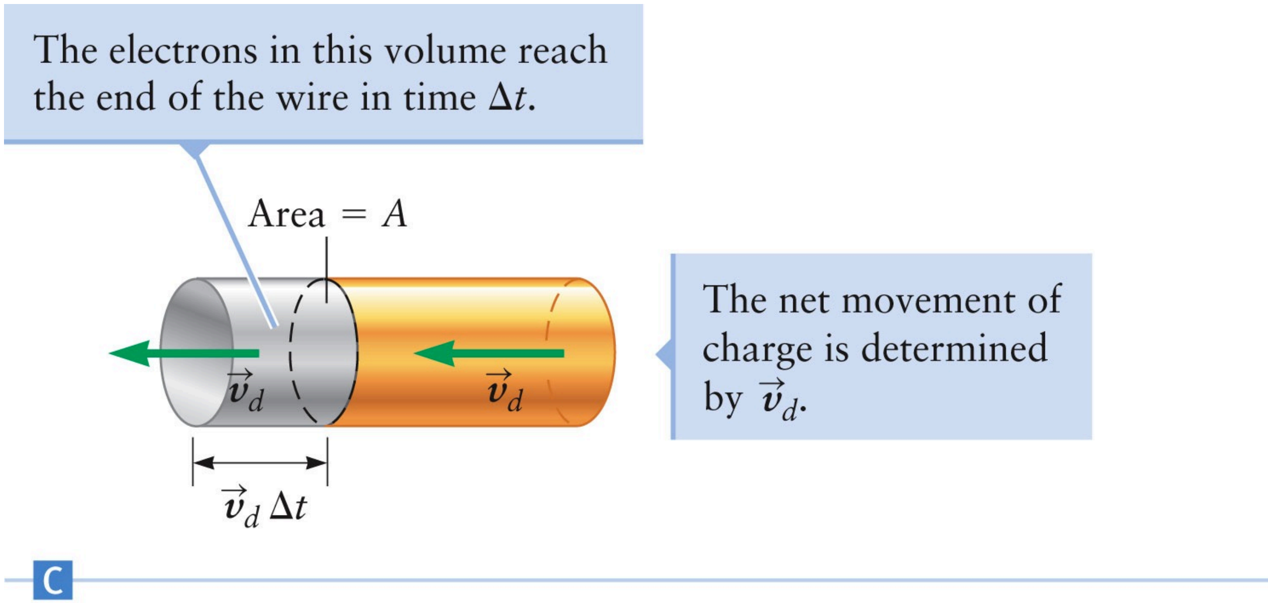
- The electrons moving in a wire collide frequently with one another and with the atoms of the wire
- This results in the zigzag motion shown
- When no electric field is present, the average electron displacement is zero
  - There is no net movement of charge
  - There is no current

Current, cont.



- With a battery connected, an electric potential is established
- There is an electric field in the wire: E = V / L
- The electric field produces a force that gives the electrons a net motion
- The velocity of this motion is the ***drift velocity***

Current and Drift Velocity



- The current is equal to the amount of charge that passes out the end of the wire per unit time
- Let *n* be the density of electrons per unit volume
- Let *A* be the cross-sectional area of the wire
- $I = - n\, e\, A\, v_d$

Ohm's Law

- The drag force on electrons leads to a drift velocity proportional to the force pushing the electrons through the metal
- The force is proportional to the electric field, so the drift velocity is proportional to the field
- The electric field is proportional to the potential difference, so the drift velocity is proportional to the potential difference
- The current is proportional to the drift velocity, so the current is proportional to the potential difference
- In summary, $v_d \propto E \rightarrow v_d \propto V \rightarrow I \propto V$

Ohm's Law, cont.

- The constant of proportionality between I and V is the electrical resistance, R

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

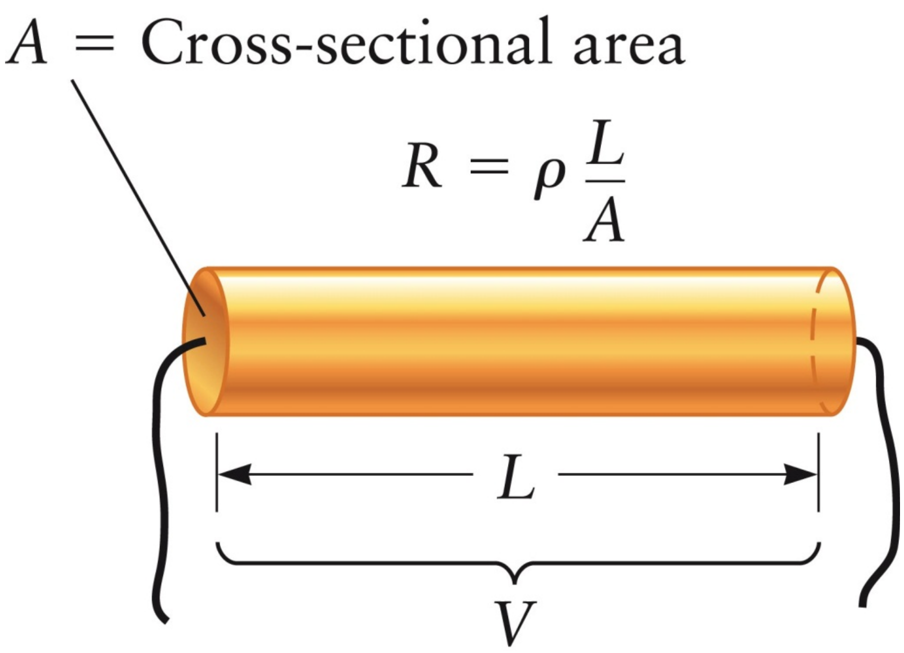
- This relationship is called ***Ohm's Law***
- The unit of resistance is an Ohm, Ω
  - Ω = Volt / Ampere
- The value of the resistance of a wire depends on its composition, size, and shape

Resistivity

- The resistivity, ρ, depends only on the material used to make the wire
- The resistance of a wire of length L and cross-sectional area A is given by

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

  - The resistivities of some materials are given in table 19.1

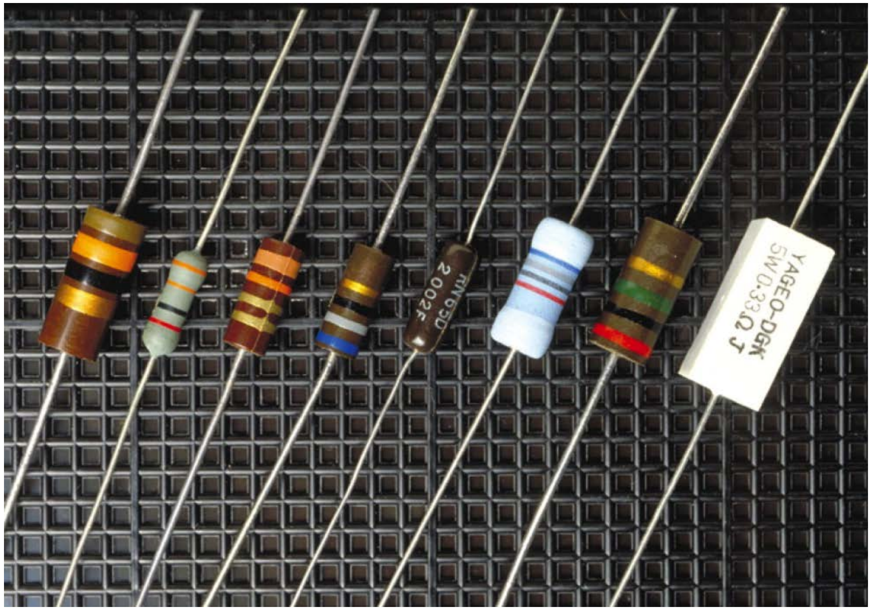


Ohm's Law: Final Notes

- Ohm's Law predicts a linear relationship between current and voltage
- Ohm's Law is not a fundamental law of physics
- Many, but not all, materials and devices obey Ohm's Law
- Resistors do obey Ohm's Law
  - Resistors will be used as the basis of circuit ideas

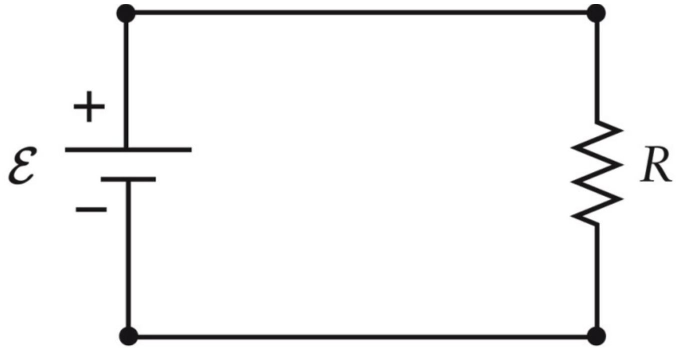
Resistors

- Resistors can be made in many shapes and sizes
- Each will have a resistance proportional to the current through and the potential across the resistor

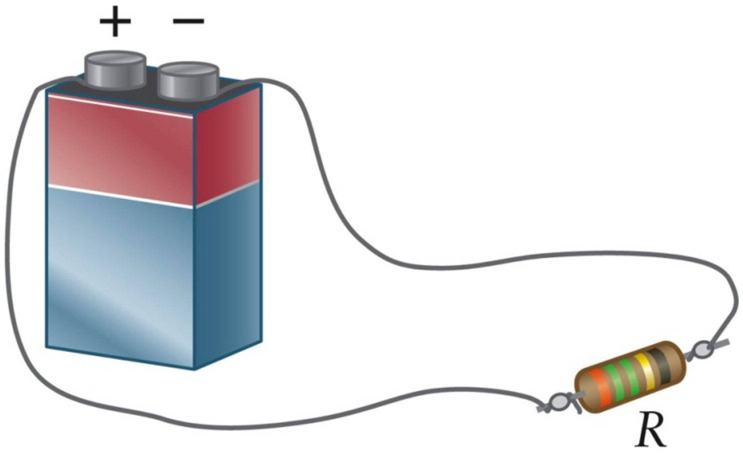


Circuit Schematic

- The circuit diagram (A) shows the symbols for the resistor and the battery
- Since the resistance of the wires is much smaller than that of the resistors, a good approximation is $R_{wire}=0$



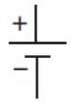
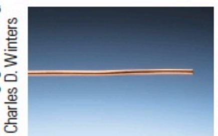
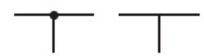
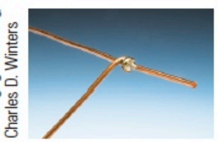
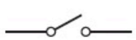
A



B

Circuit Symbols

TABLE 19.2 Symbols for Some Commonly Used Circuit Elements

Circuit Element	Symbol	Actual Appearance	Circuit Element	Symbol	Actual Appearance
Battery		© Cengage Learning/ Charles D. Winters 	Lightbulb		© David Graeme-Baker/Alamy  © Anton Prado/Alamy 
Resistor		© INSADCO Photography/Alamy 	Wire		© Cengage Learning/ Charles D. Winters 
Capacitor		© Hemera Technologies/Photo Objects/Jupiterimages 	Connection between wires		© Cengage Learning/ Charles D. Winters 
Switch		© Hemera Technologies/Photo Objects/Jupiterimages 	Electrical ground		

Current and Drift Velocity

- Current is related to the drift velocity

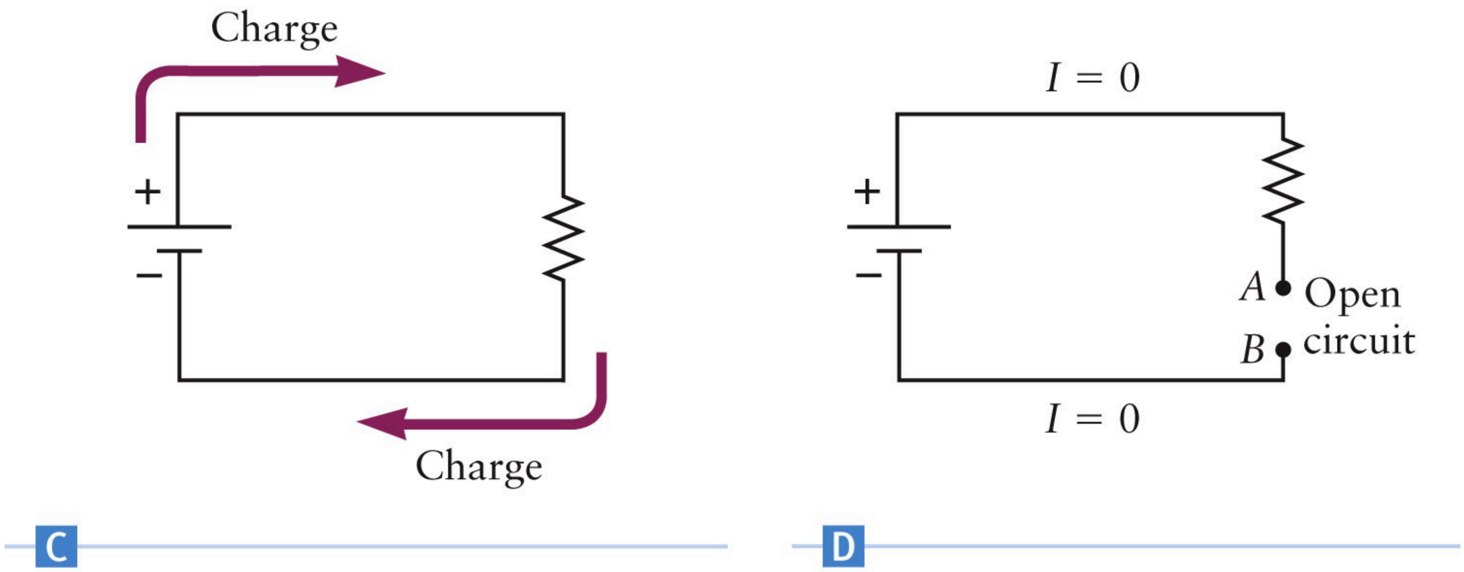
$$v_d = -\frac{I}{neA}$$

- For a household size copper wire carrying 1 A of current, the drift velocity is about -0.01 m/s
- There is no perceptible time delay between when you push a switch and when the light comes on
- The speed of the electric current is equal to the speed of electromagnetic radiation in the wire
  - This is nearly the speed of light

DC Circuits

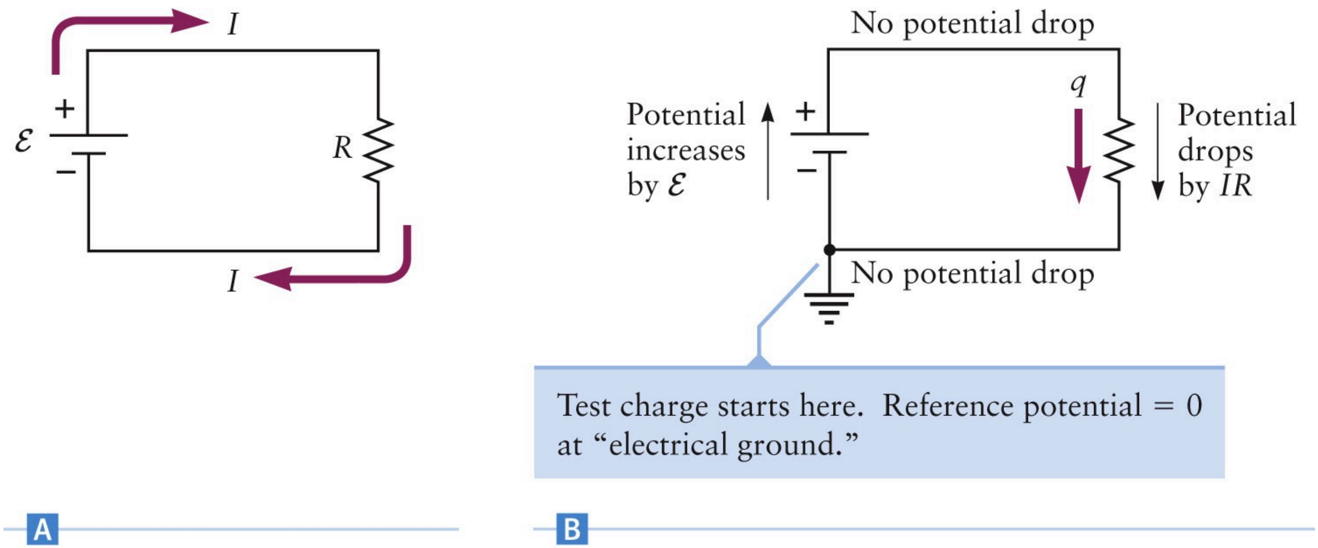
- An electric circuit is a combination of connected elements forming a complete path through which charge is able to move
- Calculating the current in the circuit is called ***circuit analysis***
- DC stands for *direct current*
  - The current is constant
- The current can be viewed as the motion of the positive charges traveling through the circuit
- The current is the same at all points in the circuit

Circuits, cont.



- There must be a complete circuit for charge flow
  - There must be a return path from the resistor for the current to return to the voltage source
- If the circuit is open, there is no current flow anywhere in the circuit

Kirchhoff's Loop Rule



- Consider the electric potential energy of a test charge moving through the circuit
- $\Delta V = \varepsilon - I R = 0$
  - For the entire circuit
  - Assumes wires have no resistance

Kirchhoff's Loop Rule, cont.

- Conservation of energy is the heart of the circuit analysis
- ***Kirchhoff's Loop Rule*** states *the change in potential energy of a charge as it travels around a complete circuit loop must be zero*
- Since $PE_{elec} = q\ V$, the loop rule also means the change in the electric potential around a closed circuit path is zero

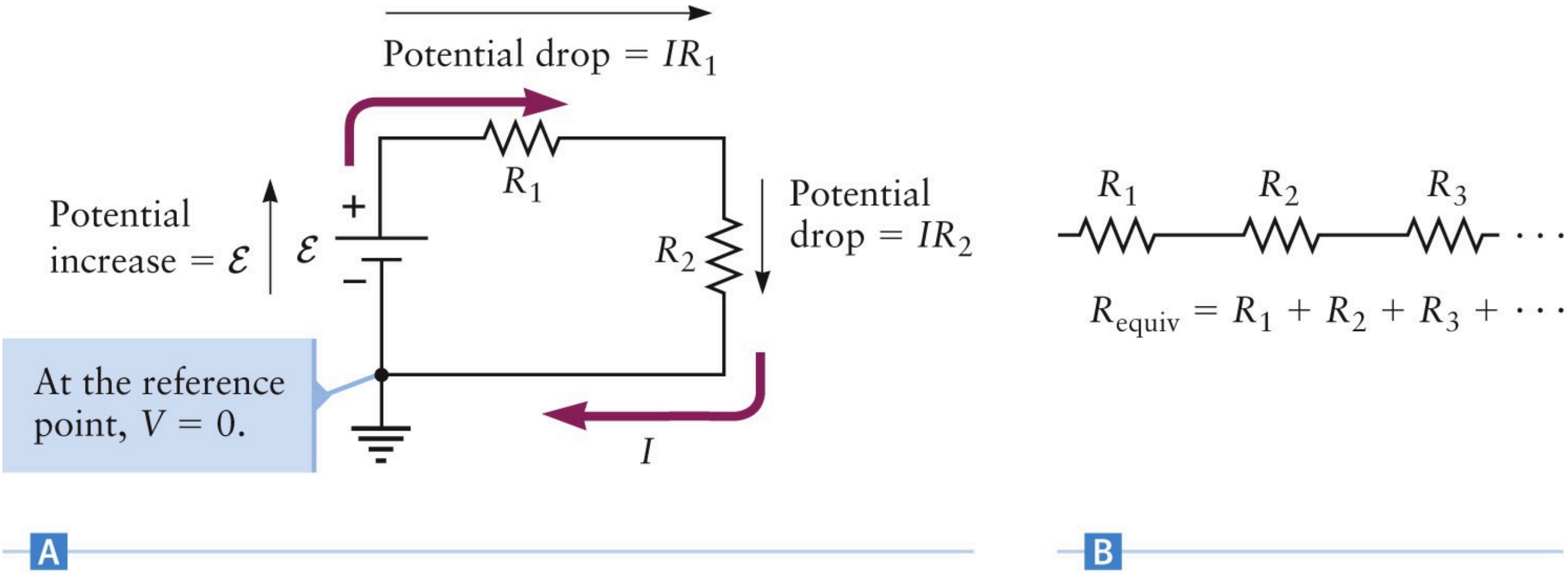
Energy in a Resistor

- The test charge gained energy when it passed through the battery
- It lost energy as it passed through the resistor
- The energy is converted into heat energy inside the resistor
  - The energy is dissipated as heat
  - It shows up as a temperature increase of the resistor and its surroundings

Power

- In the resistor, the energy decreases by q V = (I Δt) V
  - Power is energy / Δt = I V
- Applying Ohm's Law, $P = I^2 R = V^2 / R$
- The circuit converts chemical energy from the battery to heat energy in the resistors
  - Applies to all circuit elements

Resistors in Series



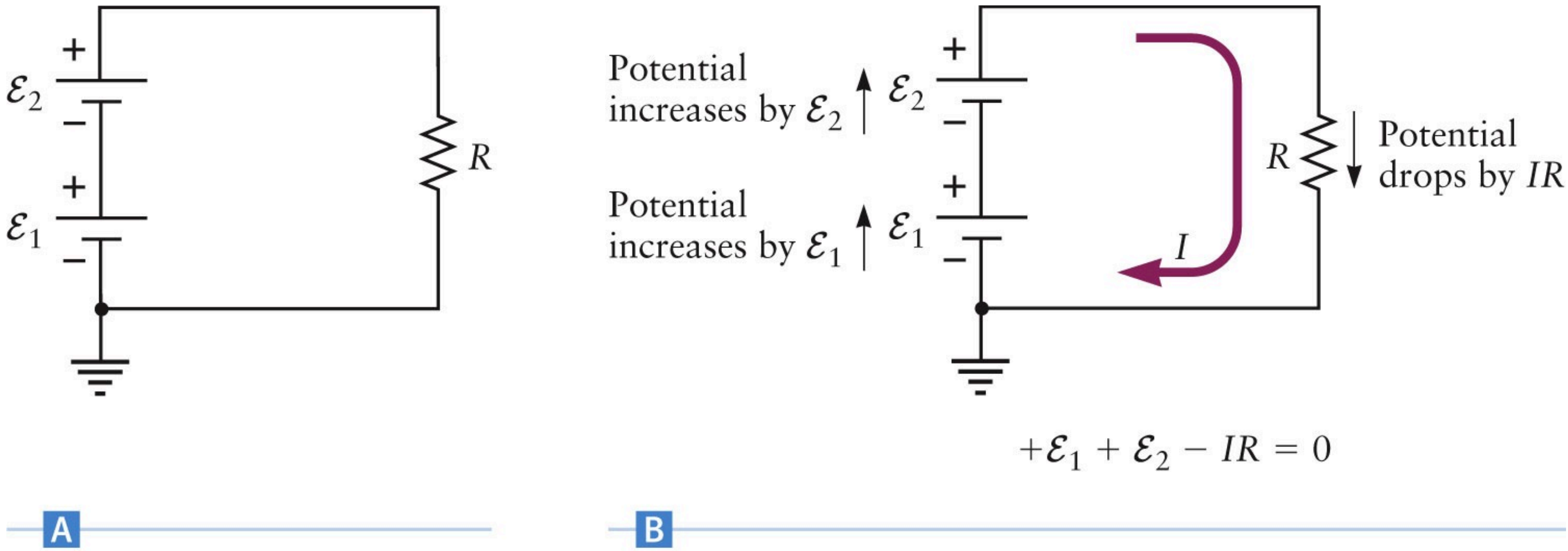
- When the current passes through one resistor and then another, the resistors are said to be in series
- Applying Kirchhoff's Loop Rule:

$$+\varepsilon - I R_1 - I R_2 = 0$$

Series Resistors – Equivalent R

- Any number of resistors can be connected in series
- The resistors will be equivalent to a single resistor with $R_{equiv} = R_1 + R_2 + R_3 + \ldots$
- An equivalent resistor means that an arrangement of resistors can be replaced by the equivalent resistance with no change in the current in the rest of the circuit
  - The idea of equivalence will apply to many other types of circuit elements

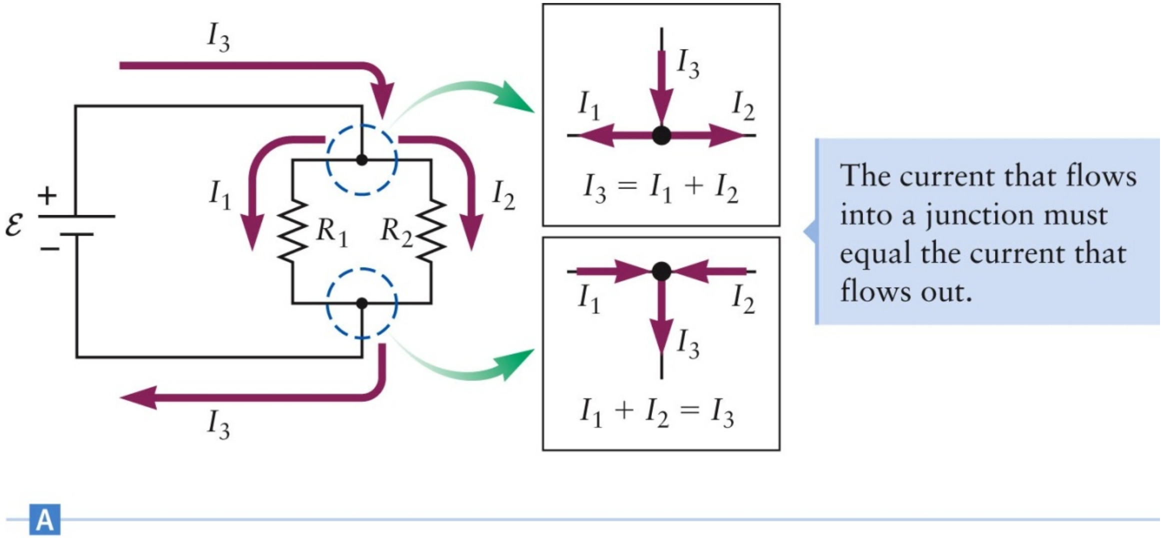
Batteries in Series



- Batteries can also be connected in series
  - The positive terminal of one battery would be connected to the negative terminal of the next battery
- The combination of two batteries in series is equivalent to a single battery with emf of

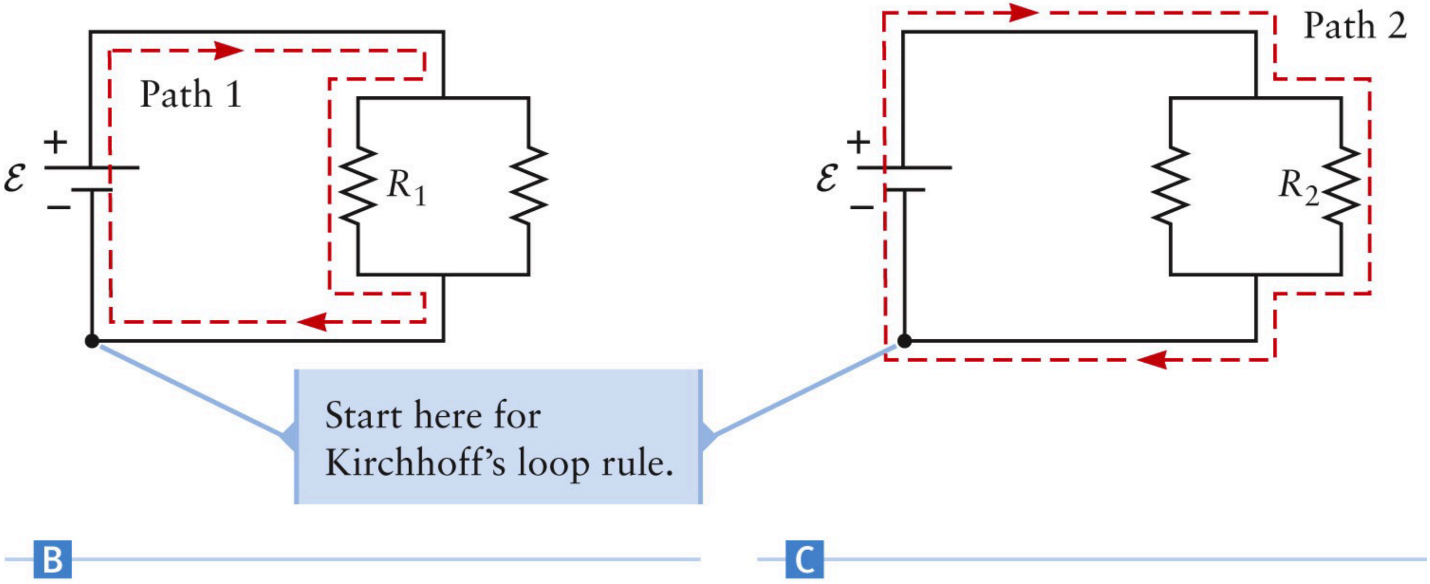
$$\varepsilon_{equiv} = \varepsilon_1 + \varepsilon_2 + \ldots$$

Resistors in Parallel



- In some circuits, the current can take multiple paths
  - The different paths are called *branches*
- The arrangement of resistors shown is called resistors in parallel
- The currents in each branch need not be equal

Resistors in Parallel, cont.



- Two unknown currents must be solved for
- Use three currents:
  - I_1 through R_1
  - I_2 through R_2
  - I_3 through the wires and other parts of the circuit
- The three currents are not independent

Kirchhoff' s Junction Rule

- The points where the currents are connected are called junctions or nodes
- Electric charge cannot be created or destroyed, so *the amount of current entering a junction much be equal to the current leaving it*
- This is called Kirchhoff' s Junction Rule
- Both of Kirchhoff' s Rules may be needed to solve a circuit
  - Any starting point can be used to make a complete loop around the circuit

Applying the Junction Rule

- For path 1, $+\varepsilon - I_1 R_1 = 0$
- For path 2, $+\varepsilon - I_2 R_2 = 0$
- The total current is

$$I_3 = I_1 + I_2 = \frac{\varepsilon}{R_1} + \frac{\varepsilon}{R_2}$$

Kirchhoff's Rules, Summary

- Kirchhoff's Loop Rule
  - The total change in the electric potential around any closed circuit path must be zero
- Kirchhoff's Junction Rule
  - The current entering a circuit junction must be equal to the current leaving the junction
- These are actually applications of fundamental laws of physics
  - Loop Rule – conservation of energy
  - Junction Rule – conservation of charge
- The rules apply to all types of circuits involving all types of circuit elements

Problem Solving Strategies

- **Recognize the principle**
  - All circuit analysis is based on Kirchhoff's loop and junction rules
- **Sketch the problem**
  - Start with a circuit diagram
  - Identify all the different circuit branches
  - The currents in the branches are generally the unknown variables in the problem

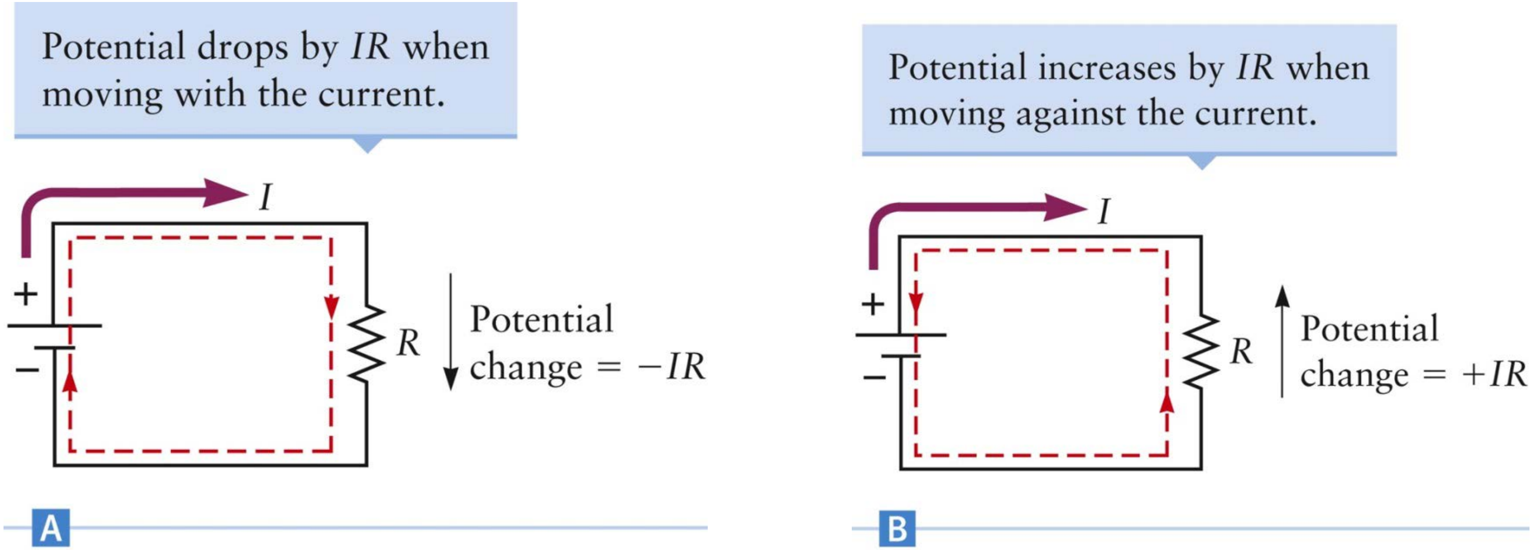
Problem Solving, cont.

- ***Identify***
  - Find all the possible closed loops and junctions in the circuit
    - Apply Kirchhoff's loop rule to each closed loop to get a set of equations involving the branch currents, battery emfs and resistances in each loop
    - Apply Kirchhoff's junction rule to each junction to get equations relating different branch currents
- ***Solve***
  - Solve the equations for the current in each branch
- ***Check***
  - Consider what your answer means
  - Does your answer make sense?

Using Kirchhoff's Rules

- The loop rule can be used as often as the resulting equation is independent of the equations from the other loop equations
  - An equation will be independent as long as it contains at least one circuit element that is not involved in other loops
- When using the loop rule, pay close attention to the sign of the voltage drop across the circuit element
  - You can go around the loop in any direction

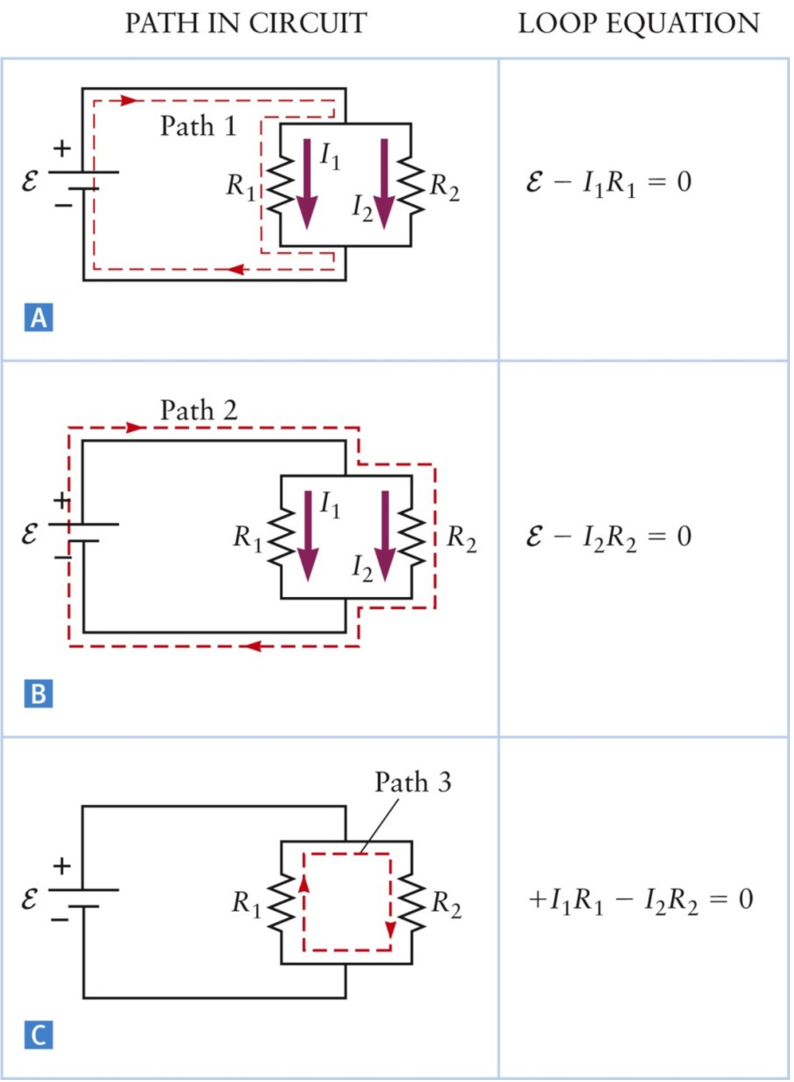
Directions in Kirchhoff's Rules



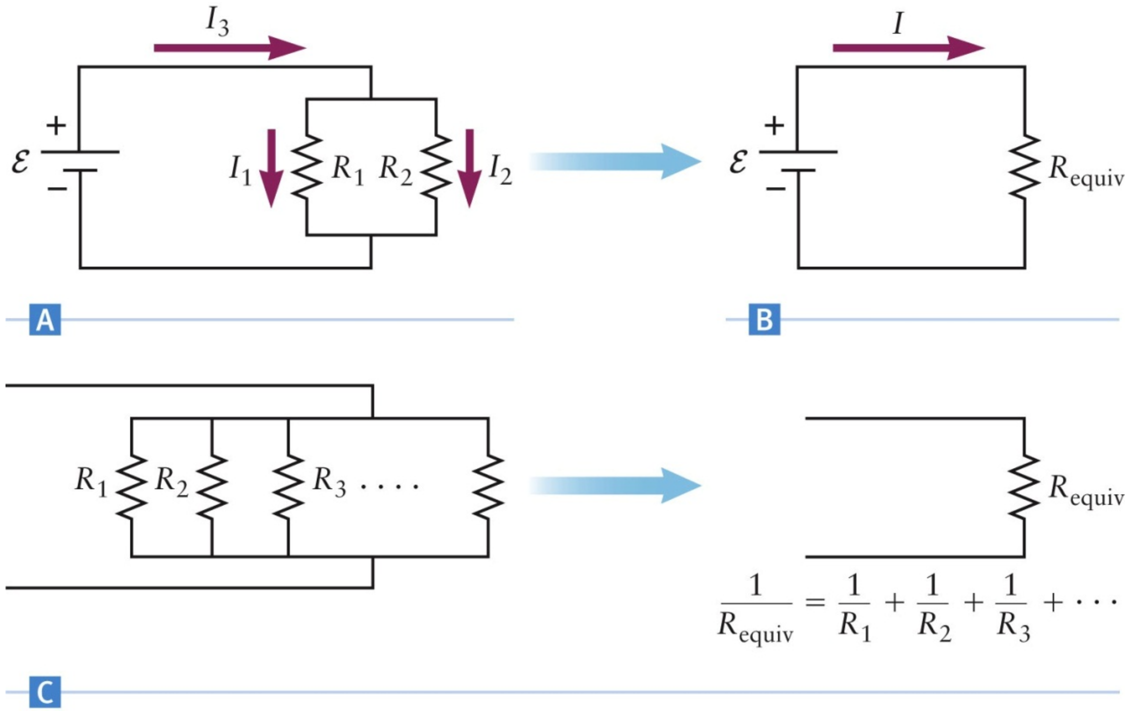
- The signs of the potentials in Kirchhoff's loop rule will depend on assumed current direction
- Moving parallel to the current produces a potential drop across a resistor
- After solving the equations, if the current is positive the assumed direction of the current is correct
- If the current is negative, the direction of the current Is opposite the assumed direction

Kirchhoff's Rules: Numbers of Equations

- In general, if a circuit has N junctions, the junction rule can be used N – 1 times
- In general, a loop equation will be independent of other loop equations if it contains at least one circuit element that is not involved in the other loops



Equivalent Resistance – Parallel



- A set of resistors in parallel can be replaced with an equivalent resistor

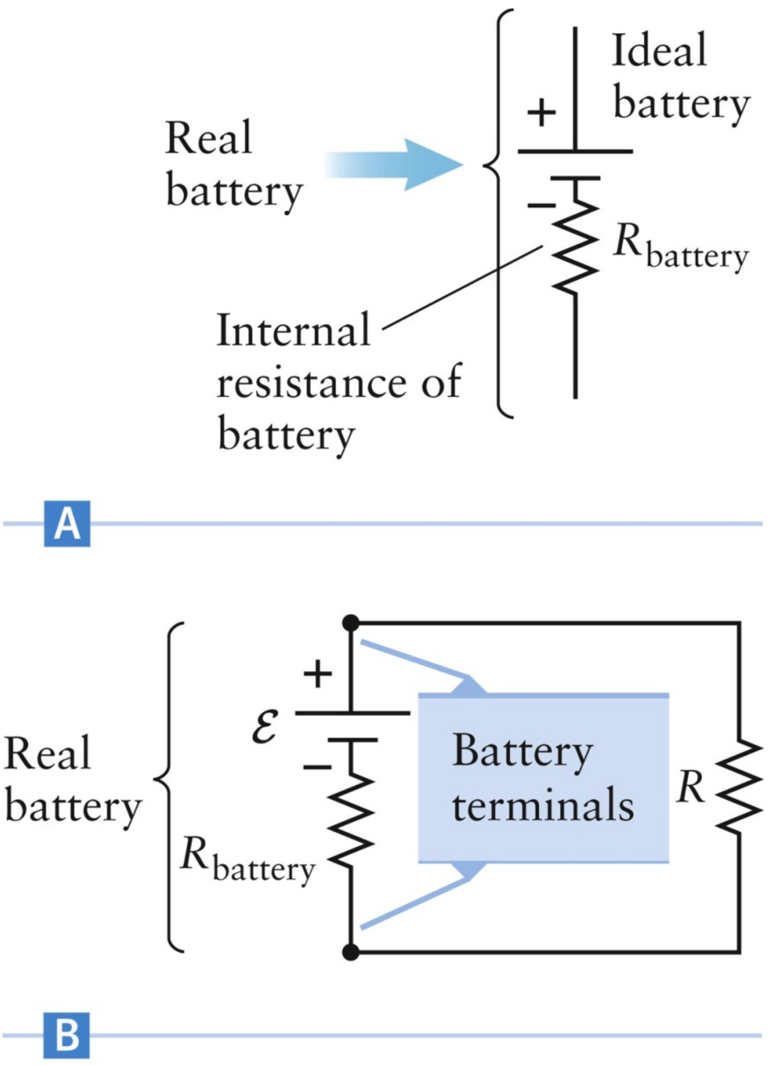
$$\frac{1}{R_{equiv}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

Circuit Analysis, Final Notes

- Some complex circuits can be solved by combinations of series and parallel rules
- Other circuits must be analyzed directly by Kirchhoff's Rules
- Connecting resistors in series always gives a total resistance larger than the resistance of any of the component resistors
- Connecting resistors in parallel always gives a total resistance smaller than the resistance of any of the component resistors

Real Batteries

- An ideal battery always maintains a constant voltage across its terminals
  - The value of the voltage is the emf of the battery
- A real battery is equivalent to an ideal battery in series with a resistor, $R_{battery}$
  - This is the internal resistance of the battery



Real Battery, cont.

- The current through the internal resistance and the external resistor is

$$I = \frac{\varepsilon}{R + R_{battery}}$$

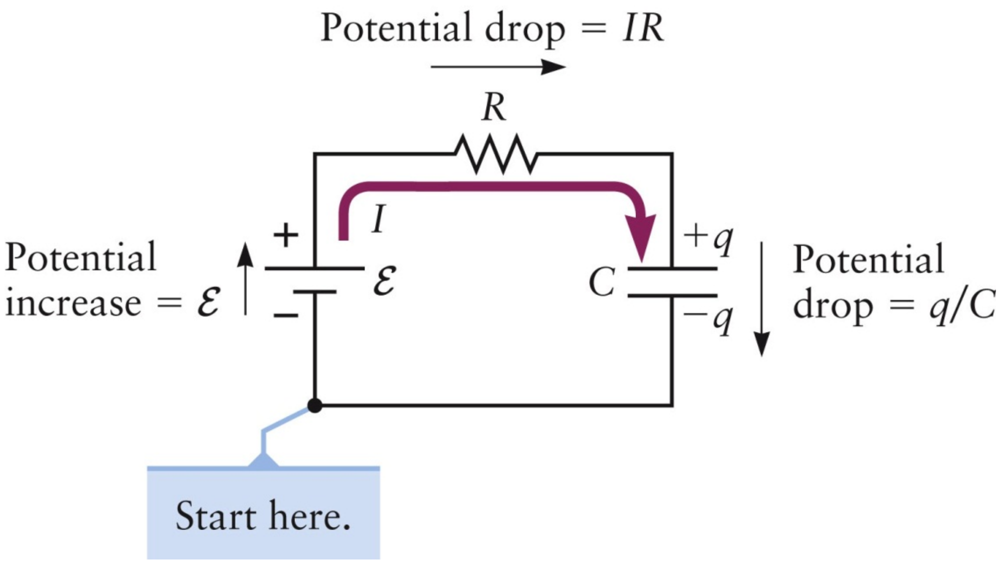
- The potential difference across the real battery's terminals is

$$potential\ of\ real\ battery = IR = \varepsilon\left(\frac{R}{R + R_{battery}}\right)$$

Kirchhoff's Rules with Capacitors

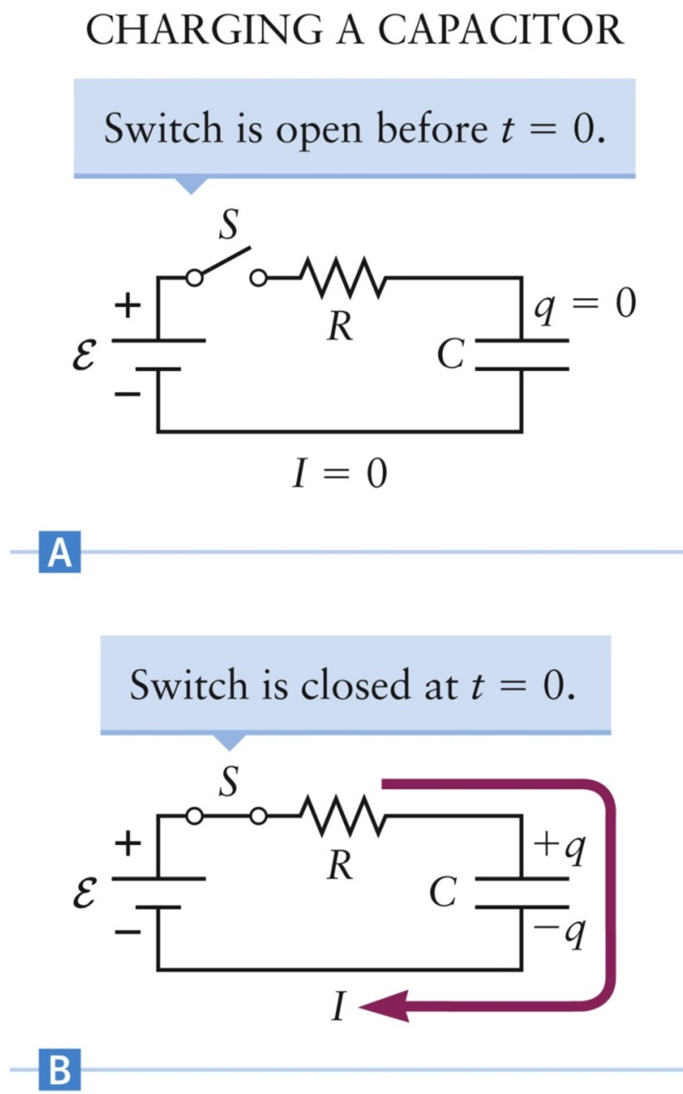
- Kirchhoff's Rules can be applied to all kinds of circuits
- The change in the potential around the circuit is

  $+\varepsilon - IR - q/C = 0$
- Want to solve for I
- I and q will be time dependent



Capacitors, cont.

- When the switch is closed, there is a current carrying a positive charge to the top plate of the capacitor
- When the capacitor plates are charged, there is a nonzero voltage across the capacitor



Charging Capacitors

- The current in the circuit is described by

$$I = \frac{\varepsilon}{R} e^{-t/\tau}$$

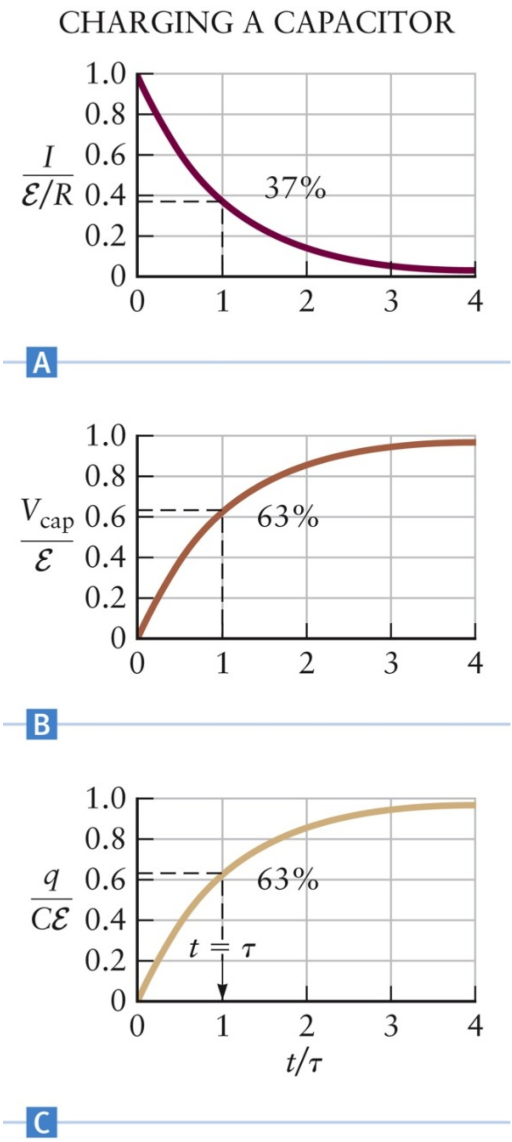
- The voltage across the capacitor is

$$V_{cap} = \varepsilon\left(1 - e^{-t/\tau}\right)$$

- The charge is given by

$$q = CV_{cap} = C\varepsilon\left(1 - e^{-t/\tau}\right)$$

- τ = RC and is called the ***time constant***



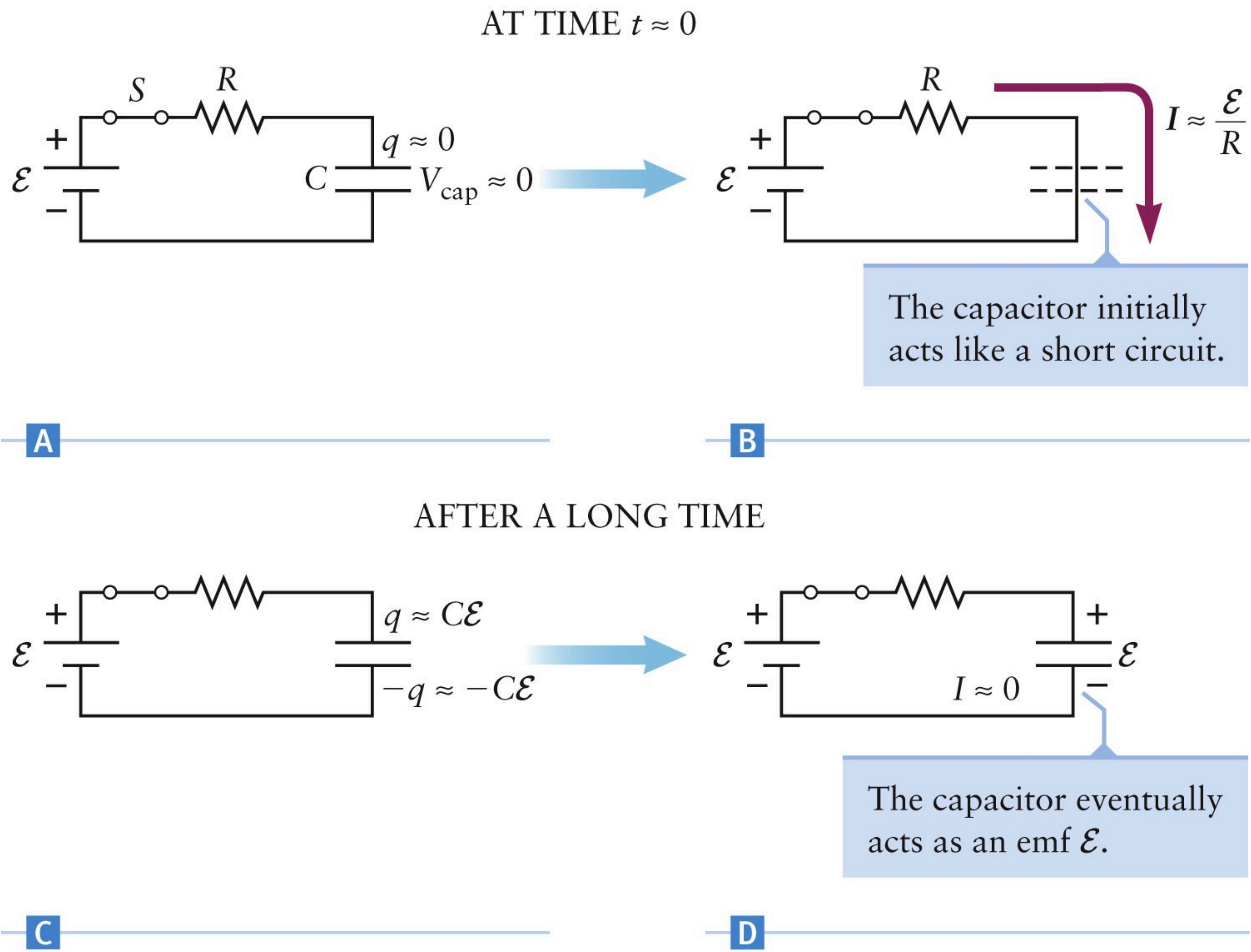
Time Constant

- Current
  - At the end of one time constant, the current has decreased to 37% of its original value
  - At the end of two time constants, the current has decreased to 63% of its original value
- Voltage and charge
  - At the end of one time constant, the voltage and current have increased 63% of their asymptotic values

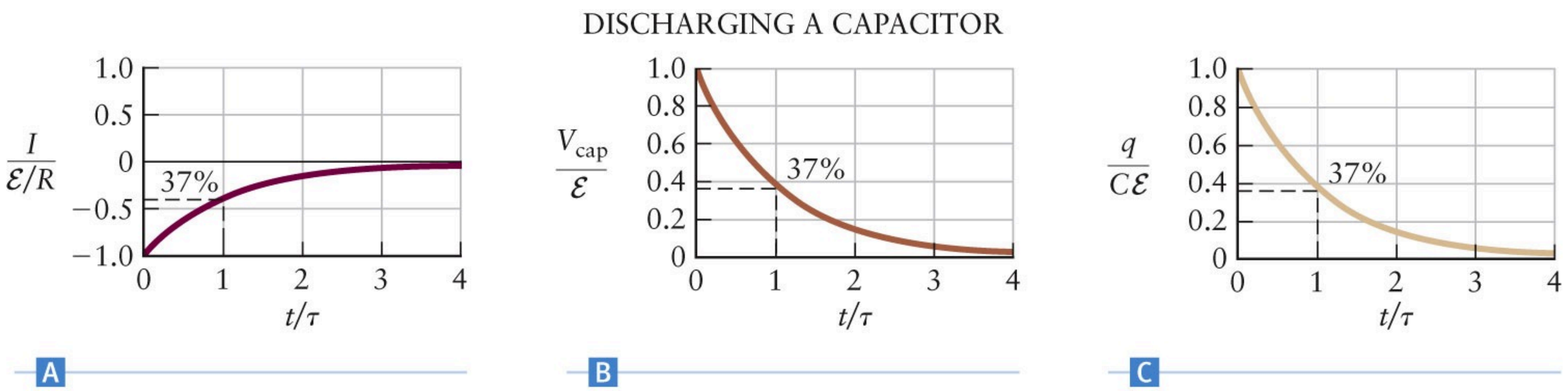
Capacitor at Various Times

- Just after the switch is closed
  - The charge is very small
  - V_{cap} is very small
  - $I = \varepsilon / R$
- When t is large
  - The charge is very large
  - $V_{cap} \approx \varepsilon$
  - The polarity of the capacitor opposes the battery emf
  - The current approaches zero

Capacitors at Various Times, Circuits



Discharging the Capacitor



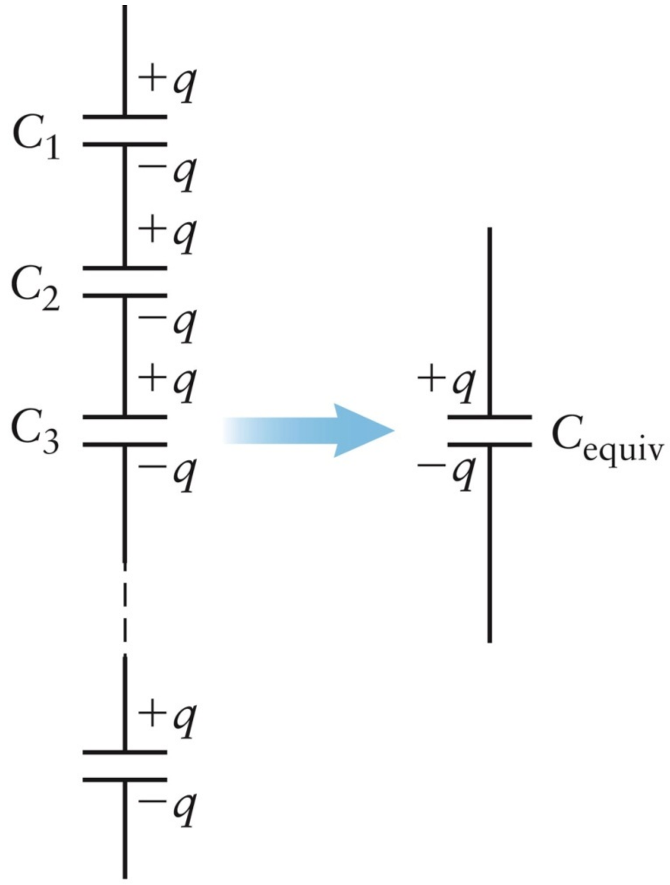
- Current: $I = -\frac{\varepsilon}{R}\left(1 - e^{-t/\tau}\right)$
- Voltage: $V_{cap} = \varepsilon\, e^{-t/\tau}$
- Charge: $q = C\,\varepsilon\, e^{-t/\tau}$
- Time constant: $\tau = RC$, the same as for charging

Capacitors in Series

- Several capacitors can be connected in series
- The equivalent capacitance is

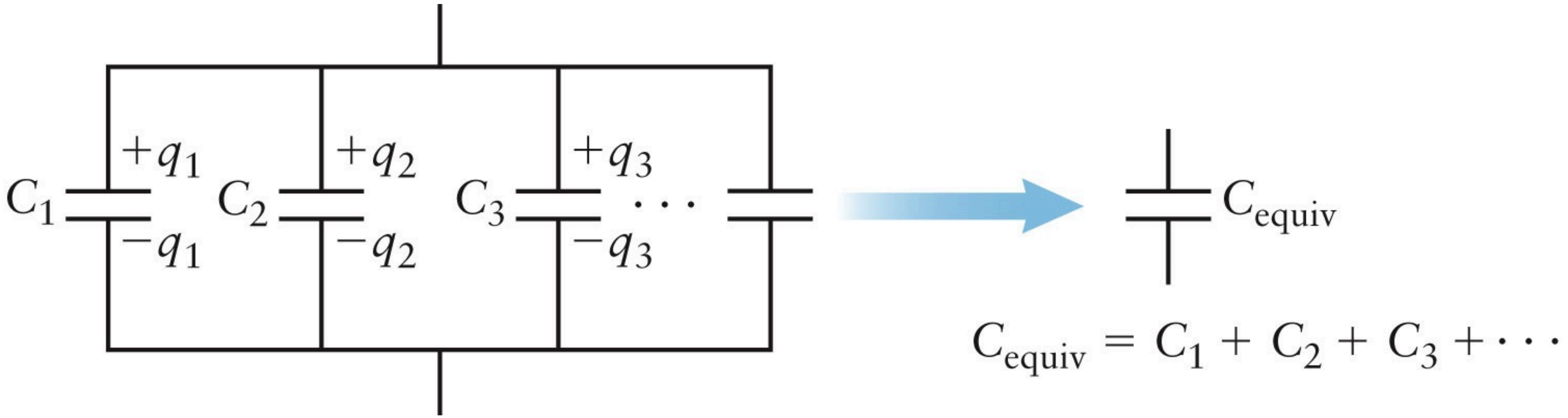
$$\frac{1}{C_{equiv}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots$$

- The equivalent capacitance is smaller than any of the individual capacitors



$$\frac{1}{C_{equiv}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots$$

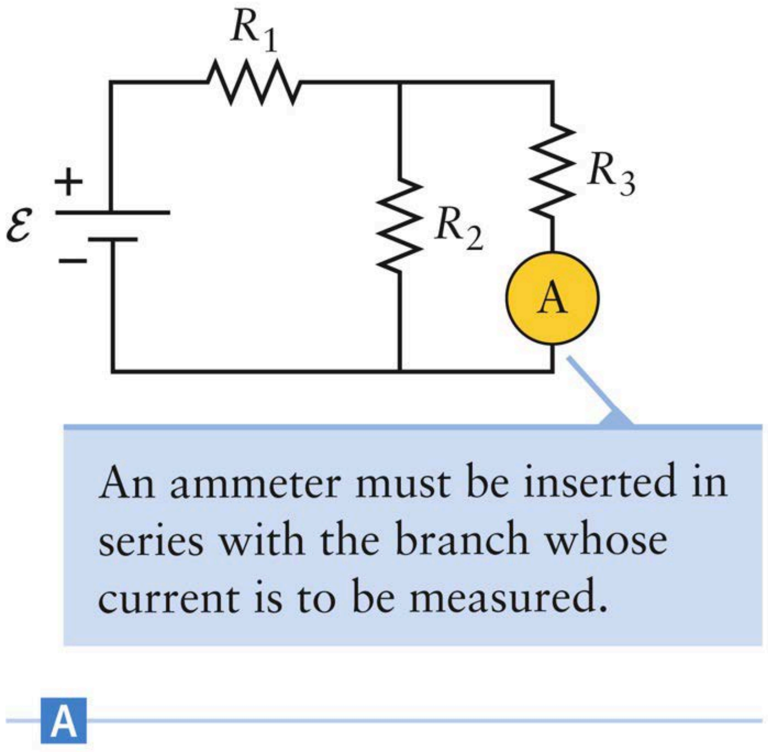
Capacitors in Parallel



- Capacitors connected in parallel also can be equivalent to a singe capacitor
- $C_{equiv} = C_1 + C_2 + C_3 + \ldots$
- The equivalent capacitance is larger than any of the individual capacitors

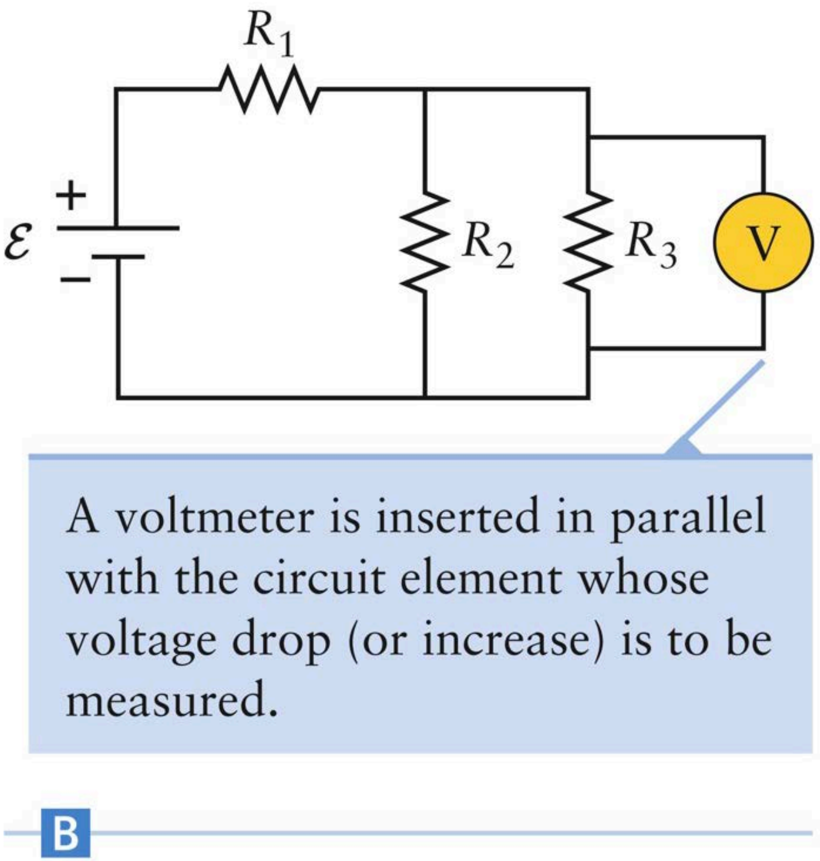
Ammeters

- An ***ammeter*** is a device that measures current
- An ammeter must be connected in series with the desired circuit branch
- An ideal ammeter will measure current without changing its value
  - Must have a very low resistance



Voltmeters

- A ***voltmeter*** measures the voltage across a circuit element
- It must be connected in parallel with the element
- An ideal voltmeter should measure the voltage without changing its value
  - The voltmeter should have a very high resistance



Filters

- It is often desirable to filter out time-dependent fluctuations in a voltage signal
- Circuits that can do so are called ***filters***
- They can be constructed with RC combinations
- A filter is useful in many applications
  - Noise in a radio signal
- The amount of filtering depends on the values of R and C

Electric Currents in Nerves

- Many nerves are long and thin, much like wires
- The conducting solution inside the fiber acts as a resistor
- The lipid layer acts as a capacitor
- The nerve fiber behaves as an RC circuit
  - Needs a small time constant
    - Small R through large radius
    - Small C through a layer of myelin increasing the distance between the capacitor plates

Electric Currents and Health

- Your body is a moderately good conductor of electricity
- The body's resistance when dry is about 1500 Ω
- When wet, the body's resistance is about 500 Ω
- Current is carried by different parts of the body
  - Skin
  - Internal organs

TABLE 19.3 Effect of Electric Current on the Human Body

Current (mA)	Effect on Body
1	Threshold for sensing (can "feel it tingle")
5	Harmless
10–20	Involuntary muscle contraction
50	Pain
100–200	Disrupts the heart
300	Burns

Household Currents

- The voltage in your home is an AC voltage oscillating at a certain frequency
  - Frequency is 60 Hz in the US
- Most modern outlets and plugs have three connections
  - Two are flat
  - One is round and connects to ground
  - Polarized plugs have flat connectors of different sizes
    - The larger connects to the lower potential

Fuses and Circuit Breakers

- In a fuse, current passes through a thin metal strip
  - This strip acts as a resistor with a small resistance
  - If a failure causes the current to become large, the power causes the strip to melt and the current stops
- A circuit breaker also stops the current when it exceeds a predetermined limit
  - The circuit breaker can be reset for continued use

Temperature Dependence of Resistance

- As temperature increases, the ions in a metal vibrate with larger amplitudes
  - This causes more frequent collisions and an increase in resistance
- For many metals near room temperature,

  $\rho = \rho_o\,[1 + \alpha(T - T_o)$
- α is called the ***temperature coefficient of the resistivity***
- The resistivity and resistance vary linearly with temperature

Superconductivity

- At very low temperatures, the linearity of resistance breaks down
- The resistivity of metals approach a nonzero value at very low temperatures
- In some metals, resistivity drops abruptly and is zero below a critical temperature
- Metals for which the resistivity goes to zero are called ***superconductors***