Chapter 13
Electric Circuits
What is Electric Current?

How does it resemble the flow of water in a pipe?
Can you get a flashlight bulb to light, with a battery and a single wire?
Electric Circuits and Electric Current

- A flashlight, an electric toaster, and a car’s starting motor all involve electric circuits and electric current.

- For the flashlight bulb to light, there must be a closed or complete path from the bulb to both ends of the battery.
- Such a path is called a circuit.
Electric Circuits and Electric Current

- A flashlight, an electric toaster, and a car’s starting motor all involve electric circuits and electric current.

- In this circuit, the battery is the energy source, using energy from chemical reactions to separate positive and negative charges.
- This leads to a voltage difference, with an excess of positive charges at one end of the battery and an excess of negative charges at the other.
- These charges will tend to flow from one terminal to the other if we provide an external conducting path (the circuit).
A flow of electric charge is an **electric current**:

\[ I = \frac{q}{t} \]

where \( I \) is electric current, \( q \) is charge, and \( t \) is time.

The standard unit for electric current is the **ampere**:

\[ 1 \text{ A} = 1 \text{ C} / \text{s} \]

For example, if 3 C of charge flow through a wire in 2 s, then the electric current \( I \) is \( 3 \text{ C} / 2 \text{ s} = 1.5 \text{ A} \).

Positive charges moving to the right have the same effect as negative charges moving to the left.
A flow of electric charge is an **electric current**:  

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The standard unit for electric current is the **ampere**:  

1 A = 1 C / s

The direction of current is defined as the direction that positive charges would flow.

In reality, the charge carriers in a metal wire are negatively charged electrons.
In addition to an energy source and a conducting path, a circuit also includes some resistance to the current.

- In the flashlight bulb, a very thin wire filament restricts the current because of its very small cross-sectional area.
- The wire filament gets hot as charges are forced through this constriction.
- Its high temperature makes it glow, and we have light.
Two arrangements of a battery, bulb, and wire are shown below. Which of the two arrangements will light the bulb?

a) Arrangement (a)
b) Arrangement (b)
c) Both
d) Neither

The bulb will light in arrangement A in which the filament of the bulb is connected to the two sides of the battery for a closed circuit. In B there is no voltage across the filament and thus no current in the filament.
Water flowing in a pipe is similar to electric current flowing in a circuit.

- The battery is like the pump.
- The electric charge is like the water.
- The connecting wires are like the thick pipe.
- The filament is like the nozzle or narrow pipe.
- The switch is like the valve.
In a water-flow system, a high pressure difference will produce a large rate of water flow or current.

- High pressure can be produced by raising the storage tank: this pressure is related to the gravitational potential energy.
- Likewise, a large difference in potential energy between the charges at the two ends of a battery is associated with a high voltage and a greater tendency for charge to flow.
In the circuit shown, the wires are connected to either side of a wooden block as well as to the light bulb. Will the light bulb light in this arrangement?

a) Yes  
b) No  
c) Maybe  
d) Impossible to tell from the picture

The bulb will not light since (dry) wood is a very poor conductor. The resistance will be so high that virtually no current is in the lamp circuit.
In the circuit shown, could we increase the brightness of the bulb by connecting a wire between points A and B?

a) Yes  
b) No  
c) Maybe  
d) Impossible to tell from the picture

No. Connecting A and B will provide a **short circuit** for the battery that will damage it while allowing virtually no current in the bulb.
Which of the two circuits shown will cause the light bulb to light?

- a) Arrangement (a)
- b) Arrangement (b)
- c) Both
- d) Neither

Diagram B will allow the light bulb to light since there is a **closed circuit** providing current from the battery through the bulb. Whether the switch is open or closed is immaterial here since it is in parallel with another conductor. In diagram A **no potential difference is in the closed circuit.**
Suppose we use an uncoated metal clamp to hold the wires in place in the battery-and-bulb circuit shown. Will this be effective in keeping the bulb burning brightly?

a) Yes  
b) No  
c) Maybe  
d) Impossible to tell from the picture

No. The metal clamp will provide a conducting path across the battery causing the battery to discharge. If we want to use a clamp we can put insulating tape between one of its jaws and the electrical connection.
Ohm’s Law and Resistance

- The electric current flowing through a given portion of a circuit is directly proportional to the voltage difference across that portion and inversely proportional to the resistance:

  \[ I = \frac{\Delta V}{R} \]

  - **Resistance** \( R \) is the ratio of the voltage difference to the current for a given portion of a circuit, and is in units of ohms:
    \[ 1 \text{ ohm} = 1 \, \Omega = 1 \text{ V} / \text{A}. \]
  - The resistance of a wire is proportional to the length of the wire, inversely proportional to the cross-sectional area of the wire, and inversely proportional to the **conductivity** of the material.
  - It also depends on the temperature of the material.
Consider the two signs shown, located in different physics labs. Which of the two would be reason for greater concern?

We had better pay attention to the high voltage warning. The other is a practical joke. The danger to the body, and even to life, comes from electrical current in the body, which could occur if you accidentally make contact with a large potential difference across parts of your body. The effect of a high resistance is to limit current in a circuit if a voltage source is present; it is not dangerous at all.

- a) The one on the left.
- b) The one on the right.
- c) Both
- d) Neither
If we know the resistance of a given portion of a circuit and the applied voltage, we can calculate the current through that portion of the circuit.

For example, consider a 1.5-V battery connected to a light bulb with a resistance of 20 ohms. If the resistance of the battery itself is negligible, the current can be found by applying Ohm’s Law:

\[ I = \frac{1.5 \text{ V}}{20 \Omega} \]

\[ = 0.075 \text{ A} \]

\[ = 75 \text{ mA} \]
However, we ignored the resistance of the battery itself, as well as the very small resistance of the connecting wires.

- If the battery is fresh, its internal resistance is small and can often be neglected.
- As the battery is used, its internal resistance gets larger.

The voltage of the battery, 1.5 V, is called the electromotive force $\mathcal{E}$: the increase in potential energy per unit charge provided by the chemical reactions in the battery.

Loop equation: $\mathcal{E} = I R$
If the internal resistance of the battery is $5 \ \Omega$, then the total resistance of the circuit is:

$$R = R_{\text{battery}} + R_{\text{bulb}} = 5 \ \Omega + 20 \ \Omega = 25 \ \Omega$$

Then the total current in the circuit is:

$$I = \frac{\mathcal{E}}{R} = \frac{1.5 \ \text{V}}{25 \ \Omega} = 0.06 \ \text{A} = 60 \ \text{mA}$$

And the voltage difference across the light bulb is:

$$\Delta V = IR = (0.06 \ \text{A})(20 \ \Omega) = 1.2 \ \text{V}$$

If we measure the voltage difference across the battery or the light bulb, we will get 1.2 V.
If we disconnect the bulb and measure the voltage across the battery terminals, we will get 1.5 V again.

As a battery gets older, its internal resistance gets larger.

The total resistance of the circuit increases and reduces the current flowing through the circuit.

As the current gets smaller, the bulb gets dimmer.

In a dead battery, the internal resistance has become so large that the battery can no longer produce a measurable current.

A good voltmeter does not draw much current, so it can still measure approximately the electromotive force of the battery, even if the battery has too much internal resistance to produce a measurable current.
Series and Parallel Circuits

- In a series circuit, there are no points in the circuit where the current can branch into secondary loops.
  - All the elements line up on a single loop.
  - The current that passes through one element must also pass through the others.
In a \textit{series} combination of resistances, each resistance contributes to restricting the flow of current around the loop.

- The total series resistance of the combination \( R_{\text{series}} \) is the sum of the individual resistances:
  \[
  R_{\text{series}} = R_1 + R_2 + R_3
  \]

- A common mistake is to think the current gets used up in passing through the resistances in a series circuit.
- The same current must pass through each component much like the continuous flow of water in a pipe.
It is the voltage that changes as the current flows through the circuit.

- Voltage decreases by Ohm’s Law: \( \Delta V = I R \) as the current passes through each resistor.

The total voltage difference across the combination is the sum of these individual changes.

- If two light bulbs are connected in series with a battery, the current will be less than with a single bulb, because the total series resistance is larger.
- The bulbs will glow less brightly.
Two resistors are connected in series with a battery as shown. $R_1$ is less than $R_2$. Which of the two resistors has the greater current flowing through it?

a) $R_1$

b) $R_2$

c) Both

d) Neither

The current is the same in each, since it is a series circuit.
Two resistors are connected in series with a battery as shown. $R_1$ is less than $R_2$. Which of the two resistors has the greatest voltage difference across it?

a) $R_1$
b) $R_2$
c) Both
d) Neither

The voltage difference is greater across $R_2$. According to Ohm's Law, $V = IR$, so for the same current, the larger the resistance the greater the potential difference.
In the circuit shown, the 1-Ω resistance is the internal resistance of the battery and can be considered to be in series with the battery and the 9-Ω load. What is the current flowing through the 9-Ω resistor?

a) 0.1 A  
b) 0.3 A  
c) 0.9 A  
d) 3 A  
e) 10 A

\[ R_{\text{series}} = 9 \, \Omega + 1 \, \Omega = 10 \, \Omega \]

\[ I_{\text{series}} = \frac{V_{\text{total}}}{R_{\text{series}}} = \frac{3 \, \text{V}}{10 \, \Omega} = 0.3 \, \text{A} \]
In the circuit shown, the $1\text{-}\Omega$ resistance is the internal resistance of the battery and can be considered to be in series with the battery and the $9\text{-}\Omega$ load. What is the voltage across the $9\text{-}\Omega$ resistor?

a) 0.1 V  
b) 0.3 V  
c) 1.0 V  
d) 2.7 V  
e) 3.0 V

Since $I_{9\Omega} = I_{\text{series}}$:

$V_{9\Omega} = I_{\text{series}}R_{9\Omega} = (0.3 \text{ A})(9 \text{ }\Omega) = 2.7 \text{ V}$
Three resistors are connected to a 6-V battery as shown. The internal resistance of the battery is negligible. What is the current through the 15-Ω resistance?

- a) 0.1 A
- b) 0.15 A
- c) 0.4 A
- d) 1.5 A
- e) 4.0 A

\[ R_{\text{series}} = 15 \, \Omega + 20 \, \Omega + 25 \, \Omega = 60 \, \Omega \]

\[ I_{15\Omega} = I_{\text{series}} = \frac{V_{\text{total}}}{R_{\text{series}}} = \frac{6 \, V}{60 \, \Omega} = 0.1 \, \text{A} \]
Does this same current flow through the 25-Ω resistance?

a) Yes.
b) No.
c) It depends on various things.

Yes. Since all the resistors are in series, the same current must flow through all three. There is no other path for the current through the 15-Ω resistor to follow, except to go through the 20-Ω resistor and then the 25-Ω resistor.
What is the voltage difference across the 25-Ω resistance?

(a) 0.1 V  
(b) 2.5 V  
(c) 6 V  
(d) 25 V  
(e) 60 V

Since $I_{25Ω} = I_{\text{series}}$:

$$V_{25Ω} = I_{\text{series}}R_{25Ω} = (0.1 \text{ A})(25 \text{ Ω}) = 2.5 \text{ V}$$
In a **parallel circuit**, there are points at which the current can branch or split up into different paths.

- The flow divides and later rejoins.
- The total cross-sectional area the current (or water) flows through is **increased**, therefore **decreasing the resistance** to flow:

\[
\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}
\]
In a parallel combination of resistances, the voltage difference across each resistance is the same, since they are all connected between the same two points.

- The currents can be different, since they divide: they add to give the total current through the combination.
- A portion of the total current flows through each branch.
Parallel combinations decrease the resistance and increase the amount of current that will flow.

Increased current causes the bulbs to burn more brightly than in a series circuit but also depletes the batteries more quickly.

The energy available from the batteries is the same in either case.
Two 10-Ω light bulbs are connected in parallel to one another, and this combination is connected to a 6-V battery. What is the total current flowing around the loop?

a) 0.6 A  

b) 1.2 A  

c) 6 A  

d) 12 A  

e) 60 A

\[ \frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} \]

\[ = \frac{1}{10 \, \Omega} + \frac{1}{10 \, \Omega} \]

\[ = \frac{2}{10 \, \Omega} = \frac{1}{5 \, \Omega} \]

\[ R_{\text{parallel}} = 5 \, \Omega \]

\[ I = \frac{\varepsilon}{R} \]

\[ = \frac{6 \, \text{V}}{5 \, \Omega} \]

\[ = 1.2 \, \text{A} \]
How much current passes through each light bulb?

a) 0.6 A  b) 1.2 A  c) 6 A  d) 12 A  e) 60 A

\[ I = \frac{\Delta V}{R} \]
\[ = \frac{6 \text{ V}}{10 \Omega} \]
\[ = 0.6 \text{ A} \]
Three identical resistors, each 24 Ω, are connected in parallel with one another as shown. The combination is connected to a 12-V battery whose internal resistance is negligible. What is the equivalent resistance of this parallel combination?

a) 0.0417 Ω  
b) 0.125 Ω  
c) 8 Ω  
d) 24 Ω  
e) 72 Ω

\[
\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{24 \, \Omega} + \frac{1}{24 \, \Omega} + \frac{1}{24 \, \Omega} = \frac{3}{24 \, \Omega} = \frac{1}{8 \, \Omega}
\]

\[R_{\text{parallel}} = 8 \, \Omega\]
What is the total current through the combination?

- a) 0.5 V
- b) 1.0 V
- c) 1.2 V
- d) 1.5 V
- e) 12 V

\[ I_{\text{total}} = \frac{V_{\text{total}}}{R_{\text{parallel}}} = \frac{12 \text{ V}}{8 \Omega} = 1.5 \text{ V} \]
How much current flows through each resistor in the combination?

a) 0.5 V  
b) 1.0 V  
c) 1.2 V  
d) 1.5 V  
e) 12 V

The resistors are identical and are in parallel, so the same current must flow through each resistor.

The total current is split into three identical parts:

\[
I_{\text{one 24-\Omega resistor}} = \frac{1}{3} I_{\text{total}} = \frac{1}{3} (1.5 \text{ V}) = 0.5 \text{ V}
\]
In the circuit shown, \( R_3 \) is greater than \( R_2 \), and \( R_2 \) is greater than \( R_1 \). \( \varepsilon \) is the electromotive force of the battery whose internal resistance is negligible. Which of the three resistors has the greatest current flowing through it?

\[
a) R_1 \\
b) R_2 \\
c) R_3 \\
d) R_1 \text{ and } R_2 \text{ are equal, and greater than } R_3 \\
e) They are all equal
\]

\( R_3 \) has the greatest current since the current in it is the sum of the currents in \( R_1 \) and \( R_2 \).
A voltmeter measures the voltage difference between two points in a circuit, or across an element in a circuit.

- It is inserted *in parallel* with the element whose voltage difference is being measured.
- A voltmeter should have a large resistance, so that it does not divert much current from the component whose voltage is being measured.
In the circuit shown, the circle with a \( V \) in it represents a voltmeter. Which of the following statements is correct?

a) The voltmeter is in the correct position for measuring the voltage difference across \( R \).

b) No current will flow through the meter, so it will have no effect.

c) The meter will draw a large current.

The correct statement is (a). A voltmeter is a high-resistance device connected in parallel with whatever circuit element it is desired to measure the voltage across.
An **ammeter** measures the electric current flowing through a point in a circuit.

- It is inserted *in series* into the circuit whose current is being measured, so that all the current flows *through* it.
- An ammeter should have a small resistance, so that its effect on the current is small.
- If you place an ammeter directly across the terminals of a battery, you could damage the meter and the battery.

![Diagram of a circuit with an ammeter](image-url)
In the circuit shown, the circle with an $A$ in it represents an ammeter. Which of the following statements is correct?

a) The meter is in the correct position for measuring the current through $R$.
b) No current will flow through the meter, so it will have no effect.
c) The meter will draw a significant current from the battery.

The answer is (c). An ammeter is a low-resistance device and is to be placed in series in the circuit, just as a flow-meter is placed in a fluid circuit.
Electric Energy and Power

- Energy is supplied to a water-flow system by the pump, which increases the gravitational potential energy of the water by lifting it up to a higher tank.

- As the water flows down through pipes to a lower tank, gravitational potential energy is transformed into kinetic energy of the moving water.
- Once the water comes to rest in the lower tank, the kinetic energy is dissipated by frictional or viscous forces which generate heat.
Similarly, in an electric circuit energy is supplied by a battery, which draws its energy from the potential energy stored in its chemical reactants.

- The battery increases the potential energy of electric charges as it moves positive charges toward the positive terminal and negative charges toward the negative terminal.
- When we provide an external conducting path from the positive to the negative terminal, charge flows from points of higher potential energy to points of lower potential energy.

- As potential energy is lost, kinetic energy is gained by the electrons.
- This kinetic energy is converted to heat by collisions with other electrons and atoms.
Energy source → potential energy → kinetic energy → heat

- Since voltage is potential energy per unit charge, multiplying a voltage difference by charge yields energy.
- Since current is the rate of flow of charge, multiplying a voltage difference by current yields power, the rate of energy use.
- The power supplied by a source must equal the power dissipated in the resistances.

\[
P = \mathcal{E}I
\]

\[
= \Delta VI; \quad \Delta V = IR \Rightarrow 
\]

\[
P = (IR)R = I^2R
\]

\[
\mathcal{E}I = I^2R
\]
What is the power dissipated in a 20-Ω light bulb powered by two 1.5-V batteries in series?

- a) 0.15 W
- b) 0.45 W
- c) 3.0 W
- d) 6.67 W
- e) 60 W

\[ E = E_1 + E_2 = 3 \text{ V} \]

\[ R = 20 \ \Omega \]

\[ E = IR \]

\[ I = \frac{E}{R} = \frac{3 \text{ V}}{20 \ \Omega} = 0.15 \ \text{A} \]

\[ P = EI = I^2R = (0.15 \ \text{A})^2(20 \ \Omega) = 0.45 \ \text{W} \]

**check:**

\[ P = EI = (3 \ \text{V})(0.15 \ \text{A}) = 0.45 \ \text{W} \]
The ease with which electric power can be transmitted over considerable distances is one of its main advantages over other forms of energy.

- The source of the energy might be gravitational potential energy of water, chemical potential energy stored in fossil fuels, or nuclear potential energy stored in uranium.
- Power plants all use electric generators that convert mechanical kinetic energy produced by turbines to electric energy.
- These generators are the source of the electromotive force.
The unit of energy commonly used to discuss electric energy is the **kilowatt-hour**, which is a unit of power (the kilowatt) multiplied by a unit of time (an hour).

- 1 kilowatt equals 1000 watts
- 1 hour = 3600 seconds
- 1 kilowatt-hour equals 3.6 million joules

The kilowatt-hour is a much larger unit of energy than the joule, but it is a convenient size for the amounts of electrical energy typically used in a home.
How much does it cost to light a 100-watt light bulb for one day? Assume an average rate of cost of 10 cents per kilowatt-hour.

a) 0.24 cents  b) 2.4 cents  c) 24 cents  d) $2.40  e) $24

Energy used = power x time
= (100 W)(24 hr)
= 2400 Wh
= 2.4 kWh

Cost = energy used x rate of cost
= (2.4 kWh)(10 cents / kWh)
= (2.4 kWh)(10 cents / kWh)
= 24 cents
Alternating Current and Household Circuits

- The current we draw from a wall outlet is **alternating current (ac)** rather than **direct current (dc)**.
  - *Direct current* implies that the current flows in a single direction from the positive terminal of a battery or power supply to the negative terminal.
  - *Alternating current* continually reverses its direction -- it flows first in one direction, then in the other, then back again.
  - In North America the ac goes through 60 cycles each second (60 Hz).
The plot of electric current as a function of time for an alternating current is a **sinusoidal curve**.

- The average value of an ordinary alternating current is zero.
- The power dissipated in a resistance is proportional to the square of the current.
- The **effective current** or **rms current** is obtained by squaring the current, averaging this value over time, and taking the square root of the result.
- The effective current $I_{\text{eff}}$ is 0.707 times the peak current $I_{\text{peak}}$. 

![Diagram showing sinusoidal current waveform with $I_{\text{eff}} = 0.707 I_p$]
If we plot the voltage across an electrical outlet as a function of time, we get another sinusoidal curve.

- The effective value of this voltage is typically between 110 and 120 volts in North America.
- The standard household power supplied in this country is 115 volts, 60 hertz ac.
- Household circuits are wired in parallel so that different appliances can be added to or removed from the circuit without affecting the voltage available.
A 60-W light bulb is designed to operate on 120 V ac. What is the effective current drawn by the bulb?

a) 0.2 A
b) 0.5 A
c) 2.0 A
d) 72 A
e) 7200 A

\[
P = 60 \text{ W} \\
\Delta V_{\text{effective}} = 120 \text{ V} \\
P = I \Delta V \Rightarrow \\
I = \frac{P}{\Delta V} \\
= \frac{60 \text{ W}}{120 \text{ V}} \\
= 0.5 \text{ A}
\]
Household circuits are wired in parallel so that different appliances can be added to or removed from the circuit without affecting the voltage available.

- As you add more appliances, the total current drawn increases, because the total effective resistance of the circuit decreases when resistances are added in parallel.
- Since too large a current could cause the wires to overheat, a fuse or circuit breaker in series with one leg of the circuit will disrupt the circuit if the current gets too large.
- Appliances with larger power requirements (stoves, clothes dryers, etc) are usually connected to a separate 220-V line.