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BTU 1113 Physics

Chapter 7: Electric

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Chapter Description

- Aims
  - Describe electric resistance and Ohm's Law.
  - Apply Coulomb's Law in electric.
  - Measures the electric field.
  - Calculate the electric field produced by a point charge using Gauss Law.
  - Determine internal resistance of a battery.
  - Discuss the relationship of electric power and energy.

- Expected Outcomes
  - Students should be able to describe electric resistance and Ohm's Law.
  - Students should be able to apply Coulomb's Law in electric.
  - Students should be able to measures the electric field.
  - Students should be able to calculate the electric field produced by a point charge using Gauss Law.
  - Students should be able to determine internal resistance of a battery.
  - Students should be able to discuss the relationship of electric power and energy.

- References

  - Giancoli, D.C., 2008. Physics for Scientists & Engineers. 4th edition. Prentice Hall, USA.
  - Jones, E., 2002. Contemporary College Physics. 3rd Ed, McGraw-Hill, Singapore.
  - Young, H. D. and Freedman, R. A., 2012. University Physics with Modern Physics. 13th edition, Pearson, San Francisco

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1^{st} aim:
Describe electric resistance and Ohm's Law.

Ohm's Law

Current through an ideal conductor is proportional to the applied voltage

- Conductor is also known as a *resistor*
- An *ideal conductor* is a material whose resistance does not change with temperature

For an ohmic device,

$$Voltage = Current \times Resistance$$

$$V = I \times R$$

V = Voltage (Volts = V)
I = Current (Amperes = A)
R = Resistance (Ohms = Ω)

Current and Voltage Defined

Current: (the current in electrical circuits)

Flow of current from positive terminal to the negative terminal.

- has units of Amperes (A) and is measured using *ammeters*.

Voltage:

Energy required to move a charge from one point to another.

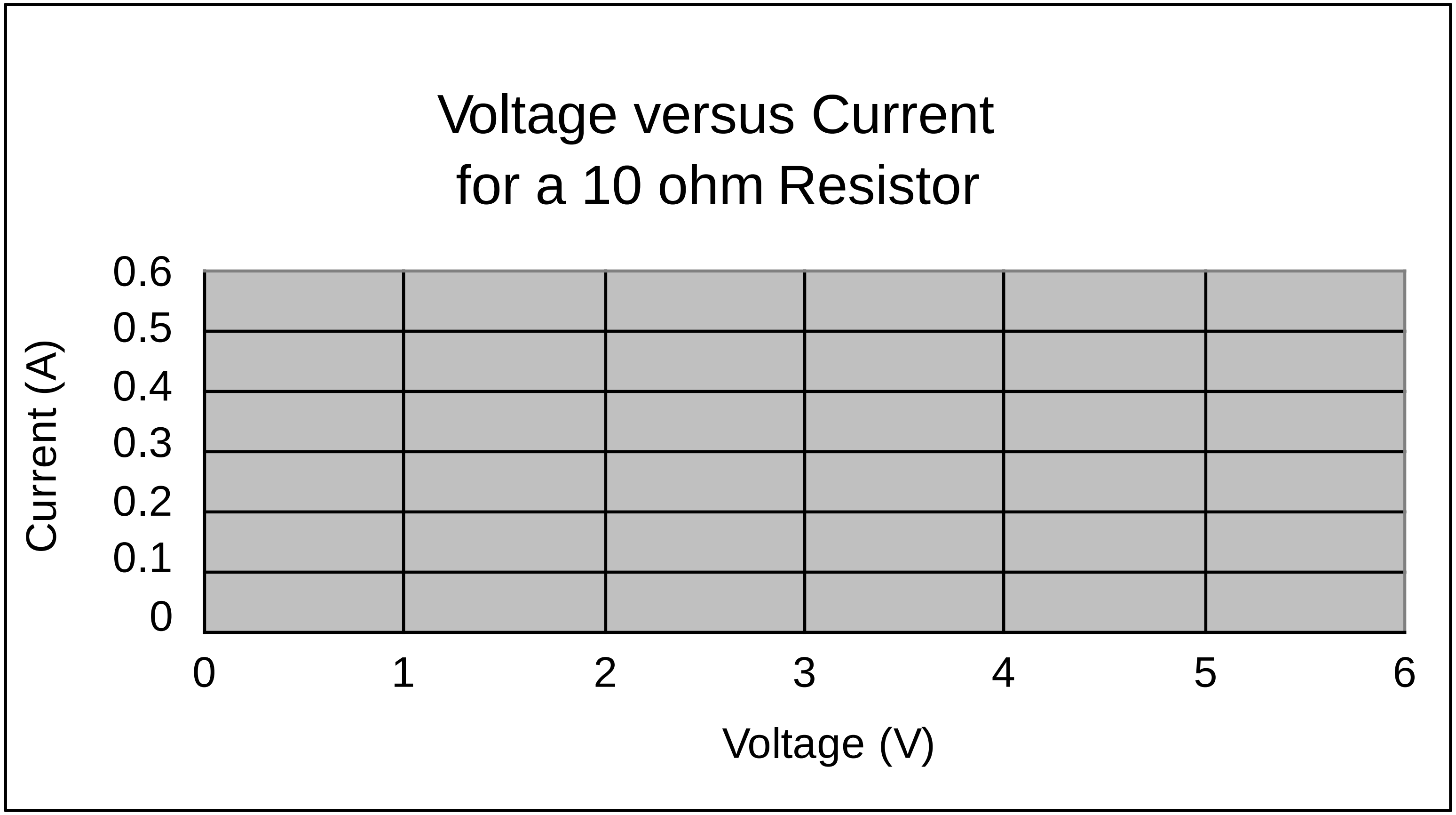
- has units of Volts (V) and is measured using *voltmeters*.

Think of voltage as what ***pushes*** *the electrons along in the circuit, and current as a group of electrons that are constantly trying to reach a state of* ***equilibrium****.*

Ohmic Resistors

- Metals
  their temperature is held constant
  - Their resistance values do not fluctuate with temperature
    - i.e. the resistance for each resistor is a constant

Voltage and Current Relationship for Linear Resistors



Ohm's Law continued

The total resistance of a circuit is dependant the *number* of resistors in the circuit and their *configuration*

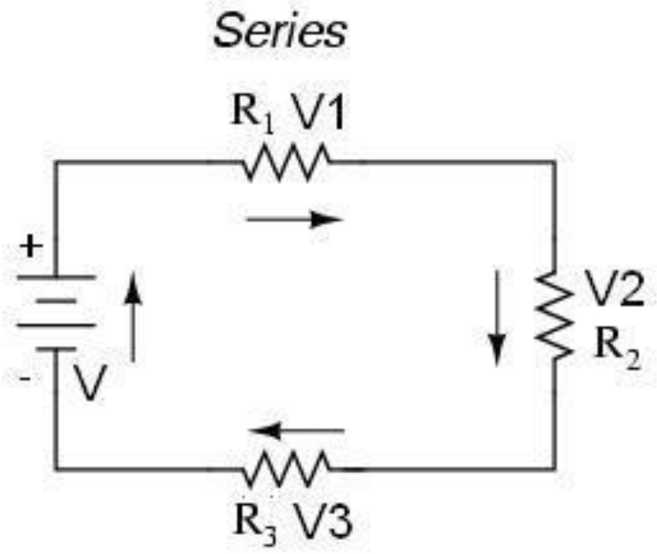
Series Circuit $$R_{total} = R = R_1 + R_2 + \ldots$$

Parallel Circuit $$\frac{1}{R_{total}} = \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

Series Circuit

Current is constant

- Why?
  - Only one path for the current to take



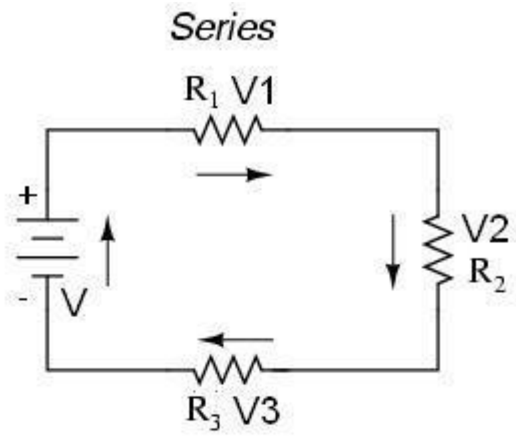
$$V = I \times R$$

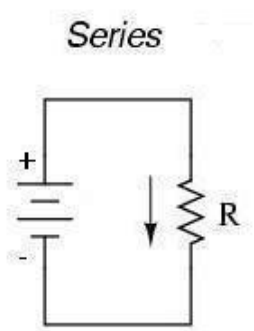
$$V = V_1 + V_2 + V_3$$

$$I = I_1 = I_2 = I_3$$

$$R = R_1 + R_2 + R_3$$

Series Equivalent Circuit





$$V_1 = I \times R_1 \quad V_2 = I \times R_2 \quad V_3 = I \times R_3$$

$$R = R_1 + R_2 + R_3$$

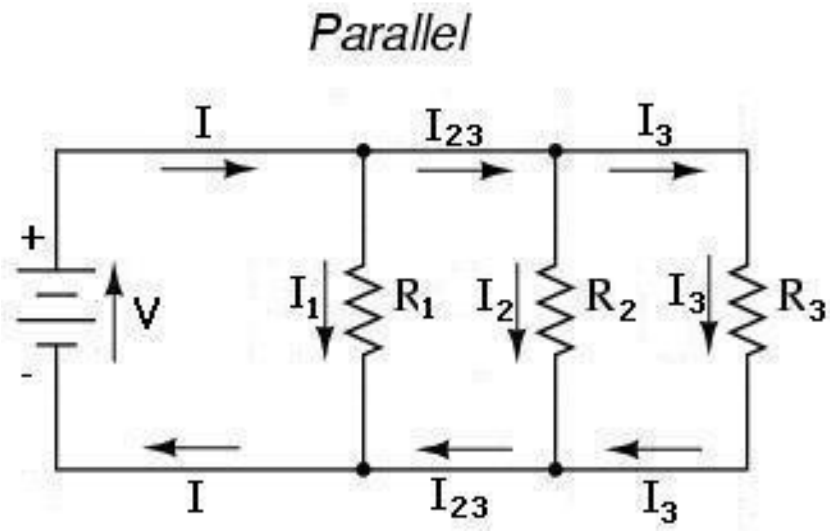
$$V = V_1 + V_2 + V_3$$

$$V = I \times R_1 + I \times R_2 + I \times R_3$$

$$V = I \times (R_1 + R_2 + R_3)$$

$$V = I \times R$$

Parallel Circuit



- $V = I \times R$

- $V = V_1 = V_2 = V_3$
- $I = I_1 + I_2 + I_3 = I_1 + I_{23}$

Voltage is constant

where $I_{23} = I_2 + I_3$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

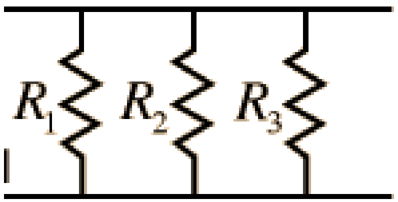
- Why?
  - There are 3 *closed loops* in the circuit

Series

$$R_{equivalent} = R_1 + R_2 + R_3 + \ldots$$

$$R_{equivalent} = \frac{V}{I} = \frac{V_1 + V_2 + V_3 + \ldots}{I} = \frac{V_1}{I_1} + \frac{V_2}{I_2} + \frac{V_3}{I_3} + \ldots = R_1 + R_2 + R_3 + \ldots$$

Series key idea: The current is the same in each resistor by the current law.



Parallel

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

Parallel:

$$\frac{V}{R_{equivalent}} = I = I_1 + I_2 + I_2 + \ldots = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \ldots$$

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

Parallel key idea: The voltage is the same across each resistor by the voltage law.

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2^{nd} aim:
Apply Coulomb's Law in electric.

Coulomb’s Law

Coulomb's law states that the **electrical force** between two charged objects is **directly proportional** to the product of the **quantity of charge** on the objects and **inversely proportional** to the **square of the separation distance** between the two objects.

Coulomb's law:

$$F_e = k_e \frac{q_1 q_2}{r^2}$$

- The SI unit of charge is the **coulomb** (C)
- k_e is called the **Coulomb constant**
  - k_e = 8.9876 x 10^9 N·m²/C² = $1/(4\pi\varepsilon_0)$
  - ε_0 is the **permittivity of free space**
  - ε_0 = 8.8542 x 10^{-12} C² / N·m²

Coulomb's Law

$$F_e = k_e \frac{q_1 q_2}{r^2}$$

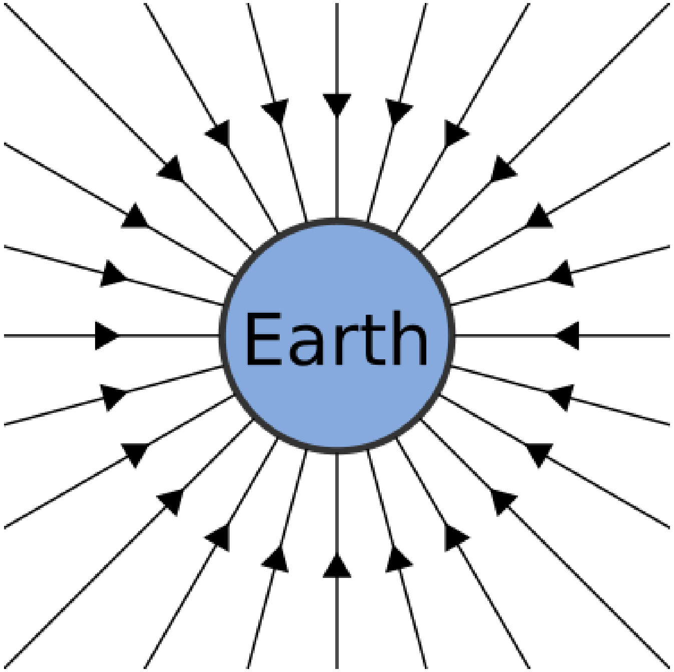
This equation gives the magnitude of the electric force.

The force is along the line connecting the charges, and is attractive if the charges are opposite, and repulsive if they are the same.

3^{rd} aim:
Measures the electric field.

Electric Field

- a region around a charged particle or object within which a force would be exerted on other charged particles or objects.



Gravitational Field

Electric Field

Electric field is defined as the **electric** force per unit charge. The direction of the **field** is taken to be the direction of the force it would exert on a positive test charge.

$$\vec{\mathbf{E}} = \frac{\vec{\mathbf{F}}}{q}$$

The electric field is radially outward from a positive charge and radially in toward a negative point charge.

Electric Field

For a point charge:

$$E = k\frac{Q}{r^2}$$

$$E = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2}$$

4th aim:

Calculate the electric field produced by a point charge using Gauss Law.

Gauss's Law

The electric flux
through any closed surface
equals ☑ enclosed charge / ε_0

$$\oint \underline{E} \bullet \underline{dA} = \frac{\sum_{inside} q}{\varepsilon_0}$$

This is always true.
Occasionally, it provides a very easy way to find the electric field (for highly symmetric cases).

Calculate the electric field produced by a point charge using Gauss Law

We choose for the gaussian surface a sphere of radius **r**, centered on the charge **Q**.

Then, the electric field **E**, has the same magnitude everywhere on the surface (radial symmetry)

Furthermore, at each point on the surface, the field **E** and the surface normal **dA** are parallel (both point radially outward).

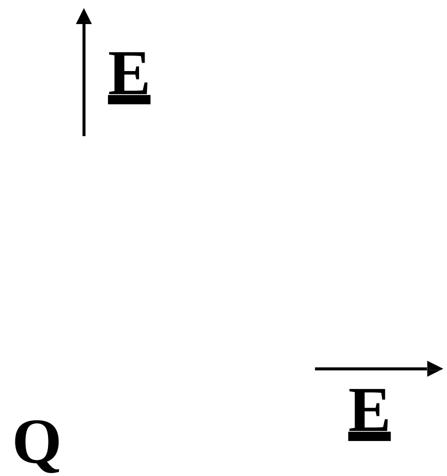
$$\mathbf{E} \cdot d\mathbf{A} = E\, dA \quad [\cos\theta = 1]$$

Electric field produced by a point charge

$$\int \underline{E} \cdot \underline{dA} = Q / \varepsilon_0$$

$$\int \underline{E} \cdot \underline{dA} = E \int dA = E A$$

$$A = 4 \pi r^2$$



$$E A = E \; 4 \pi r^2 = Q / \varepsilon_0$$

$$E = \frac{1}{4\pi\varepsilon_0} \frac{Q}{r^2}$$

$k = 1 / 4 \pi \varepsilon_0$

ε_0 = permittivity

$\varepsilon_0 = 8.85 \times 10^{-12}\ C^2/Nm^2$

Is Gauss's Law more fundamental than Coulomb's Law?

- No! Here we derived Coulomb's law for a point charge from Gauss's law.
- One can instead derive Gauss's law for a general (even very nasty) charge distribution from Coulomb's law.   The two laws are equivalent.
- Gauss's law gives us an easy way to solve a few very symmetric problems in electrostatics.
- It also gives us great insight into the electric fields in and on conductors and within voids inside metals.

Gauss's Law

The total flux within a closed surface …

… is proportional to the enclosed charge.

$$\Phi = \oint \vec{\mathbf{E}} \bullet d\vec{\mathbf{A}} = \frac{Q_{enclosed}}{\varepsilon_0}$$

Gauss's Law is always true, but is only useful for certain very simple problems with great symmetry.

Power

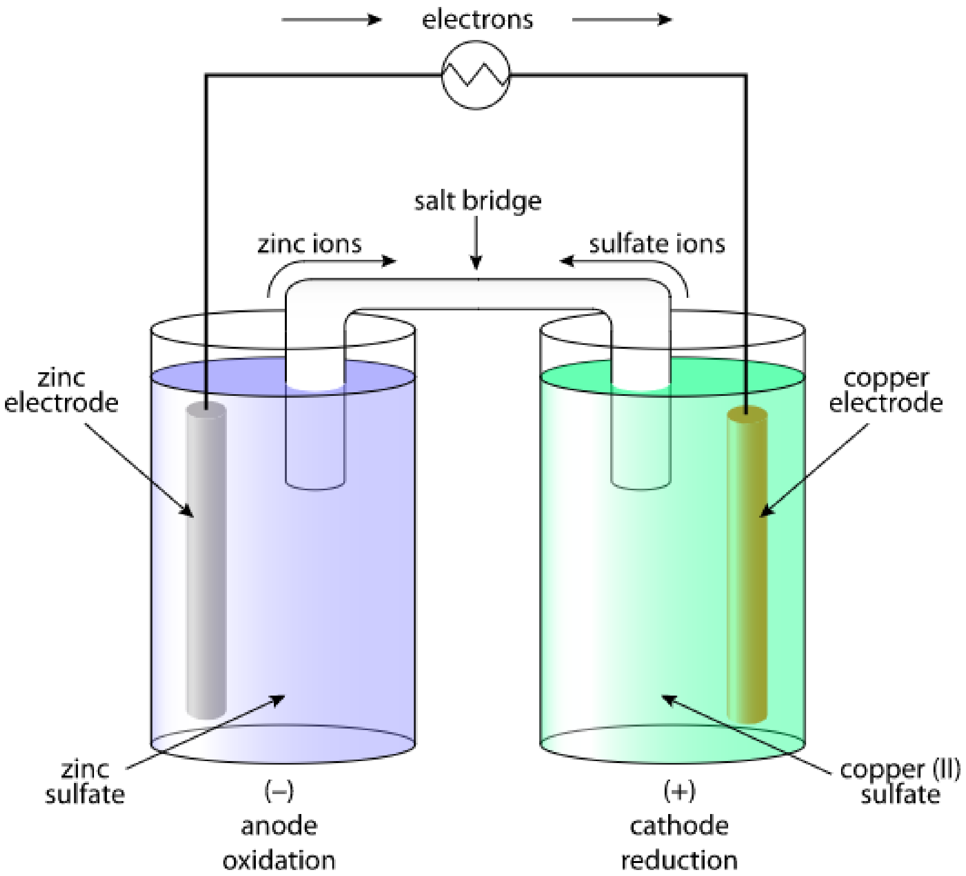
- The power rating of an appliance or a component is defined as the amount of energy used by the component / appliance in one second

5th aim:
Determine internal resistance of a battery.

The Electric Battery

Volta discovered that electricity could be created if dissimilar metals were connected by a conductive solution called an electrolyte.

The Electric Battery



This is a simple electric cell.

The Electric Battery

A battery transforms chemical energy into electrical energy.

Chemical reactions within the cell create a potential difference between the terminals by slowly dissolving them. This potential difference can be maintained even if a current is kept flowing, until one or the other terminal is completely dissolved.

Several cells connected together make a battery, although now we refer to a single cell as a battery as well.

Electric Current

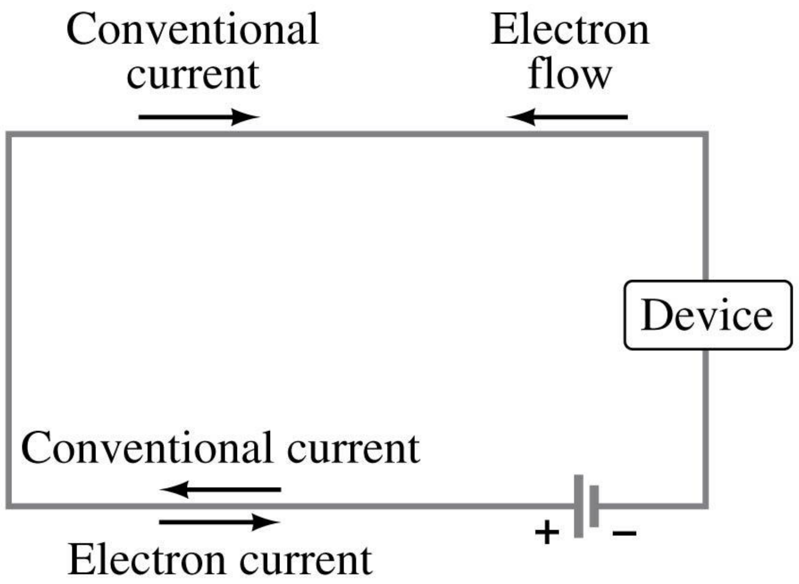
Electric current is the rate of flow of charge through a conductor:

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

Unit of electric current: the ampere, A.

$$1\ \text{A} = 1\ \text{C/s}$$

By convention, current is defined as flowing from + to –. Electrons actually flow in the opposite direction, but not all currents consist of electrons.



Ohm's Law: Resistance and Resistors

Experimentally, it is found that the current in a wire is proportional to the potential difference between its ends:

$$I \propto V$$

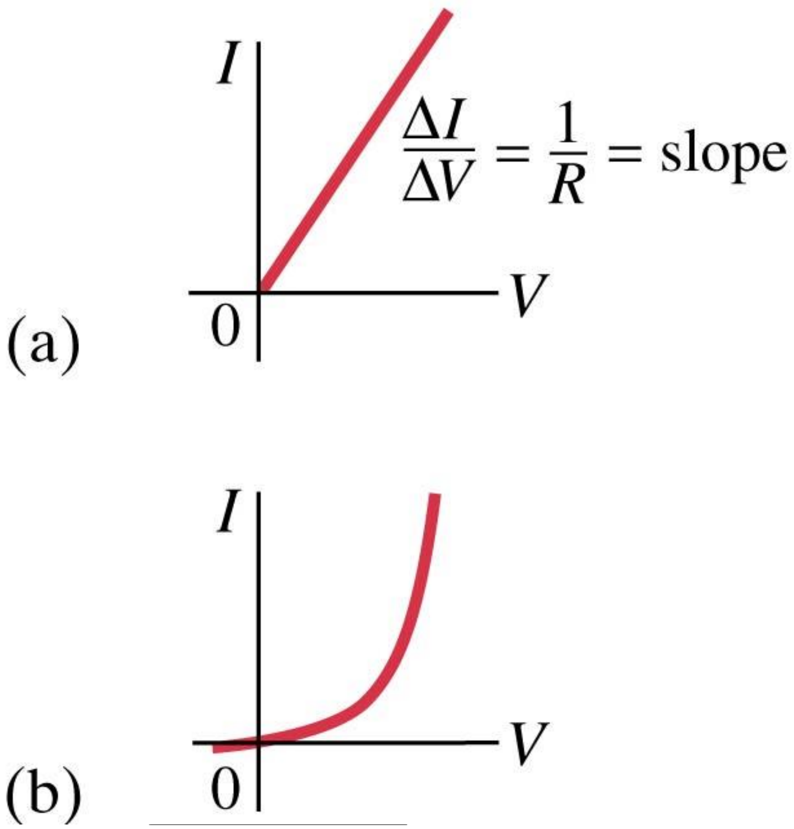
The ratio of voltage to current is called the resistance:

$$V = IR.$$

In many conductors, the resistance is independent of the voltage; this relationship is called Ohm's law. Materials that do not follow Ohm's law are called nonohmic.

Unit of resistance: the ohm, Ω.

$$1\ \Omega = 1\ \mathrm{V/A}$$



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Some clarifications:

- Batteries maintain a (nearly) constant potential difference; the current varies.
- Resistance is a property of a material or device.
- Current is not a vector but it does have a direction.
- Current and charge do not get used up. Whatever charge goes in one end of a circuit comes out the other end.

Resistivity

The resistance of a wire is directly proportional to its length and inversely proportional to its cross-sectional area:

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

The constant ρ, the resistivity, is characteristic of the material.

For any given material, the resistivity increases with temperature:

$$\rho_T = \rho_0[1 + \alpha(T - T_0)]$$

TABLE 18–1 Resistivity and Temperature Coefficients (at 20°C)

Material	Resistivity, ρ ($\Omega \cdot m$)	Temperature Coefficient, α $(C°)^{-1}$
Conductors		
Silver	1.59×10^{-8}	0.0061
Copper	1.68×10^{-8}	0.0068
Gold	2.44×10^{-8}	0.0034
Aluminum	2.65×10^{-8}	0.00429
Tungsten	5.6×10^{-8}	0.0045
Iron	9.71×10^{-8}	0.00651
Platinum	10.6×10^{-8}	0.003927
Mercury	98×10^{-8}	0.0009
Nichrome (Ni, Fe, Cr alloy)	100×10^{-8}	0.0004
Semiconductors‡		
Carbon (graphite)	$(3–60) \times 10^{-5}$	−0.0005
Germanium	$(1–500) \times 10^{-3}$	−0.05
Silicon	0.1 – 60	−0.07
Insulators		
Glass	$10^{9}–10^{12}$	
Hard rubber	$10^{13}–10^{15}$	

‡ Values depend strongly on the presence of even slight amounts of impurities.

6^{th} aim:
Discuss the relationship of electric power and energy.

Electric Power

Power, as in kinematics, is the energy transformed by a device per unit time:

$$P = \frac{\text{energy transformed}}{\text{time}} = \frac{QV}{t}.$$

$$P = IV.$$

The unit of power is the watt, W.

For ohmic devices, we can make the substitutions:

$$P = IV = I(IR) = I^2R$$

$$P = IV = \left(\frac{V}{R}\right)V = \frac{V^2}{R}$$

What you pay for on your electric bill is not power, but energy—the power consumption multiplied by the time.

We have been measuring energy in joules, but the electric company measures it in kilowatt-hours, kWh.

One kWh = (1000 W)(3600 s) = 3.60×10^6 J

Conclusion of The Chapter

This chapter explains about the physics of electricity and electronics. It includes circuits, Ohm's law, resistance and electrical energy and power. Meanwhile, its application in a battery was discussed in details as battery is a source of constant potential difference.

Reference

Giancoli, D.C., 2008. Physics for Scientists & Engineers. 4th edition. Prentice Hall, USA.