CIRCUIT THEORY I

Lecture 1

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ELECTRICAL QUANTITIES, UNITS, AND SYMBOLS

Why Units Matter in Electronics

In electronics, all concepts are tied to **measurable quantities**. To analyze, design, and troubleshoot circuits, you must be able to:

- State **how many volts** are present at a certain test point.
- Determine **how much current** is flowing through a conductor.
- Measure **how much power** an amplifier delivers.

Without standard units, these values would be meaningless and could not be communicated effectively.

ELECTRICAL QUANTITIES, UNITS, AND SYMBOLS

Standard Units and Symbols

Each electrical quantity is expressed in terms of a **standard unit** defined by the International System of Units (SI).

Along with the unit, a **symbol** is used in equations and schematics to represent that quantity clearly and consistently.

Example:

QUANTITY	SYMBOL	SI UNIT	SYMBOL
capacitance	C	farad	F
charge	Q	coulomb	C
conductance	G	siemens	S
current	I	ampere	A
energy or work	W	joule	J
frequency	f	hertz	Hz
impedance	Z	ohm	Ω
inductance	L	henry	H
power	P	watt	W
reactance	X	ohm	Ω
resistance	R	ohm	Ω
voltage	V	volt	V

ELECTRICAL QUANTITIES, UNITS, AND SYMBOLS

Metric Prefixes in Engineering

Electrical quantities often span **very large** or **very small** values. To avoid writing long numbers in scientific notation, engineers use **metric prefixes** with powers of ten:
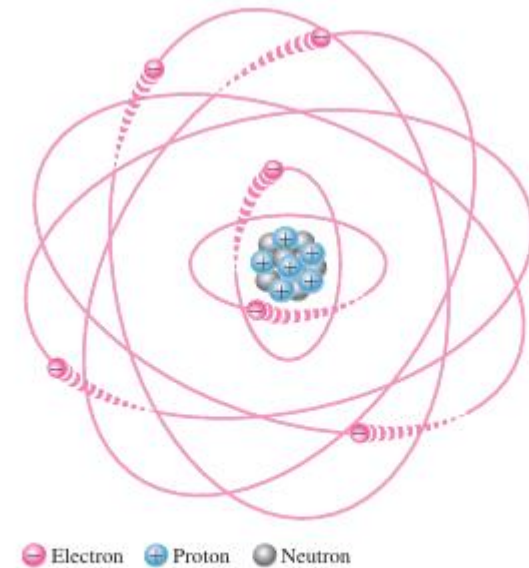
METRIC PREFIX	SYMBOL	POWER OF TEN	VALUE
femto	f	10^{-15}	one-quadrillionth
pico	p	10^{-12}	one-trillionth
nano	n	10^{-9}	one-billionth
micro	μ	10^{-6}	one-millionth
milli	m	10^{-3}	one-thousandth
kilo	k	10^{3}	one thousand
mega	M	10^{6}	one million
giga	G	10^{9}	one billion
tera	T	10^{12}	one trillion

ELECTRICAL QUANTITIES, UNITS, AND SYMBOLS

Metric Prefixes in Engineering

Electrical quantities often span **very large** or **very small** values. To avoid writing long numbers in scientific notation, engineers use **metric prefixes** with powers of ten:

Engineering Notation

- Engineering notation is a form of scientific notation where the **exponent is always a multiple of 3.**
- This makes it easy to pair with metric prefixes.

- Example:
    - $4.7 \times 10^3 \Omega \rightarrow$ written as **4.7 kΩ**
    - $2.2 \times 10^{-6} F \rightarrow$ written as **2.2 μF**

ATOMIC STRUCTURE

Introduction to Atomic Structure

- All matter is made of atoms, which consist of protons, neutrons, and electrons.

- The Bohr model describes the atom like a miniature solar system: a nucleus (protons & neutrons) surrounded by orbiting electrons.

- Protons (+) and electrons (−) carry the smallest possible isolated charges.

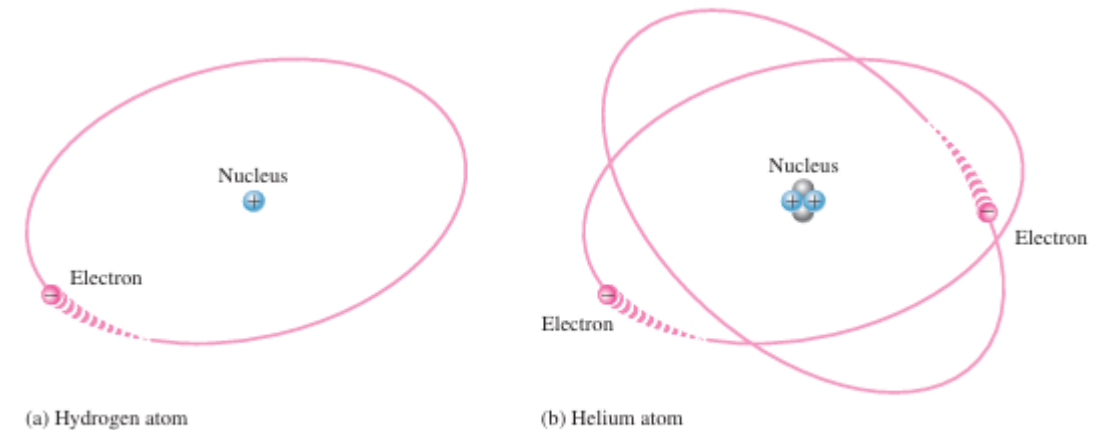- The arrangement of electrons determines how well a material conducts electricity

⊖ Electron   ⊕ Proton   ◯ Neutron

▲ **FIGURE 2–1**

The Bohr model of an atom showing electrons in circular orbits around the nucleus. The "tails" on the electrons indicate they are in motion.

ATOMIC STRUCTURE

Atomic Number

- The **atomic number** equals the number of protons in the nucleus.
- It distinguishes one element from another (e.g., hydrogen has 1 proton, helium has 2).

- In a neutral atom, the number of protons = number of electrons, so the charges balance
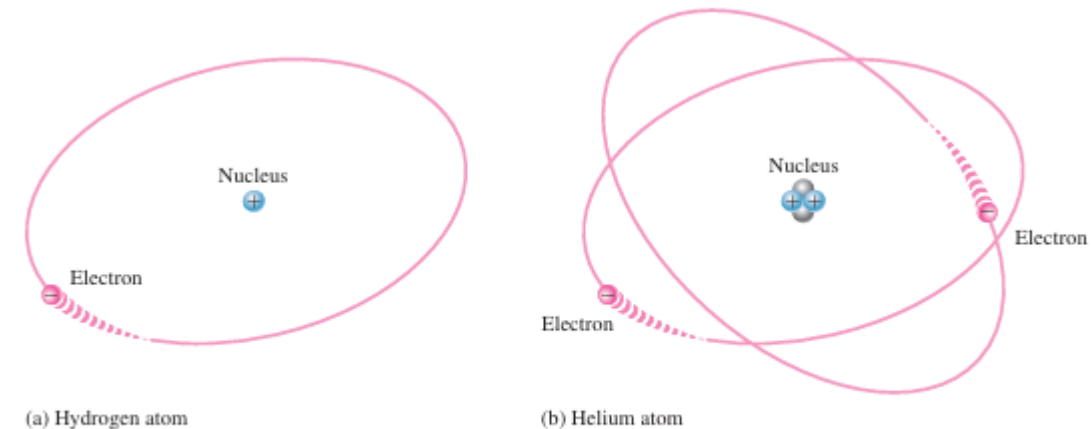

(a) Hydrogen atom
(b) Helium atom

▲ **FIGURE 2–2**

The two simplest atoms, hydrogen and helium.

ATOMIC STRUCTURE

Shells, Orbits, and Energy Levels

- Electrons orbit at specific **energy levels (shells),** numbered outward from the nucleus (n=1 is closest).

- Electrons in outer shells have **higher energy.**

- Electrons can move between shells by **absorbing or emitting photons** equal to the difference in energy levels.

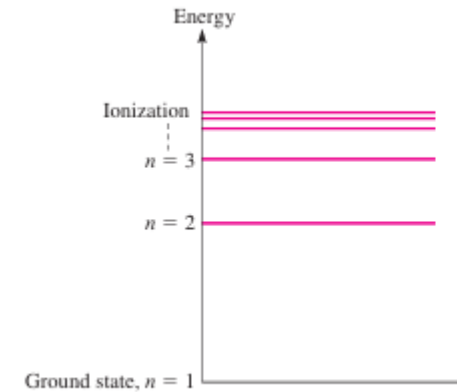- Example: hydrogen's electron can absorb energy to jump from ground state (n=1) to n=2 or higher

Nucleus

Nucleus

Electron

Electron

Electron

(a) Hydrogen atom

(b) Helium atom

▲ **FIGURE 2-2**

The two simplest atoms, hydrogen and helium.

ATOMIC STRUCTURE

Energy Levels and Ionization

- If an electron absorbs enough energy, it can **escape the atom**, becoming a **free electron.**

- The atom left behind is an **ion:**
  - Loss of electron → **positive ion**
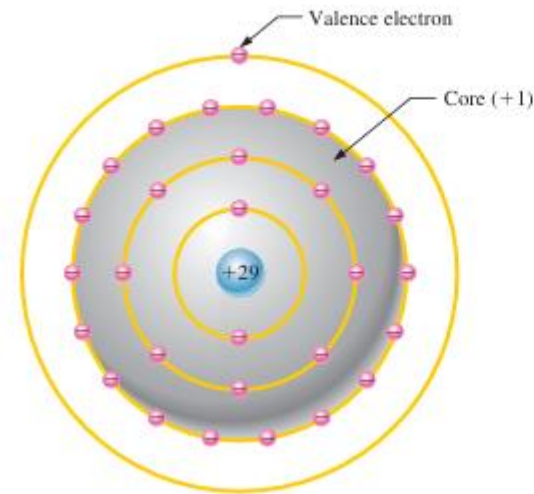 - Gain of electron → **negative ion**

Energy

Ionization

$n = 3$

$n = 2$

Ground state, $n = 1$

◄ FIGURE 2–3

Energy levels in hydrogen.

ATOMIC STRUCTURE

The Copper Atom

- Copper (common in circuits) has **29 electrons** across 4 shells.

- The **outer shell** (valence shell) has **1 valence electron**, which can easily become a free electron.

- At room temperature, many free electrons form a "**sea**" inside copper, making it an excellent conductor
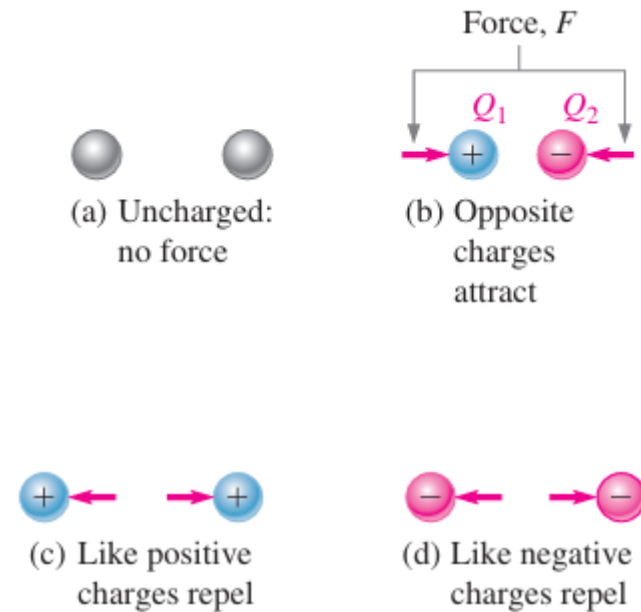

► FIGURE 2–4
The copper atom.

ATOMIC STRUCTURE

Categories of Materials

- **Conductors:** 1–3 valence electrons, many free electrons (e.g., silver, copper).

- **Semiconductors:** 4 valence electrons, fewer free electrons, basis for electronic devices (e.g., silicon, germanium).

- **Insulators:** tightly bound valence electrons, no free electrons, block current (e.g., glass, teflon, polyethylene)

ELECTRICAL CHARGE

Concept of Electrical Charge

- **Electrons** carry the smallest unit of **negative charge.**

- **Excess of electrons** → net negative charge.

- **Deficiency of electrons** → net positive charge.

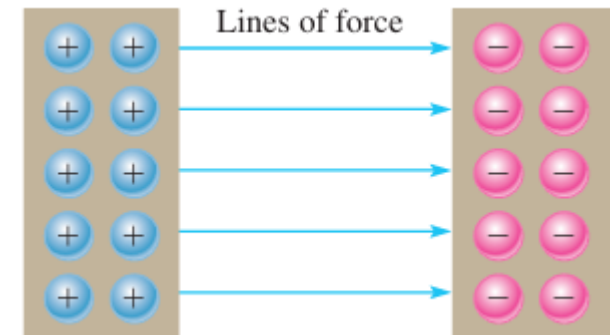- Electrical charge is a **property of matter** caused by this imbalance

Force, F

(a) Uncharged: no force

(b) Opposite charges attract

Q_1 Q_2

(c) Like positive charges repel

(d) Like negative charges repel

Attraction and repulsion of electrical charges.

ELECTRICAL CHARGE

Concept of Electrical Charge

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- **Excess of electrons** → net negative charge.

- **Deficiency of electrons** → net positive charge.

- Electrical charge is a **property of matter** caused by this imbalance

- Oppositely charged plates → there will be an electric field between the plates due to all of the charges present.

Electric field between two oppositely charged surfaces as represented by lines of force.

ELECTRICAL CHARGE

Coulomb's Law

- A **force (F)** exists between two point charges (**Q1, Q2**).

- Proportional to the **product of charges.**

- Inversely proportional to the **square of the distance (d)** between them:

$$F = k\frac{Q_1 Q_2}{d^2}$$

- Explains attraction and repulsion between charges

ELECTRICAL CHARGE
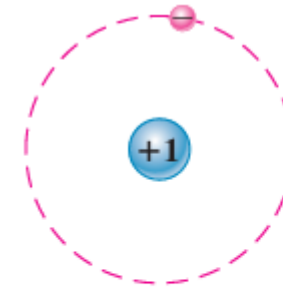
Coulomb: The Unit of Charge

- Electrical charge is measured in coulombs (C).

- 1 coulomb = total charge of 6.25×10^{18} electrons.

- A single electron carries a charge of $1.6 \times 10^{-19}\ C$.

- Formula for total charge (for a given number of electrons):

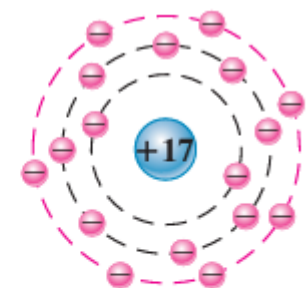$$Q = \frac{\text{number of electrons}}{6.25 \times 10^{18} \text{ electrons/C}}$$

ELECTRICAL CHARGE

Positive and Negative Charge

• A neutral atom has equal protons and electrons.

• Losing a valence electron → positive ion.

• Gaining an electron → negative ion.

• Illustrated with hydrogen chloride (HCl) formation: hydrogen loses an electron, chlorine gains one, forming H^+ and Cl^- ions
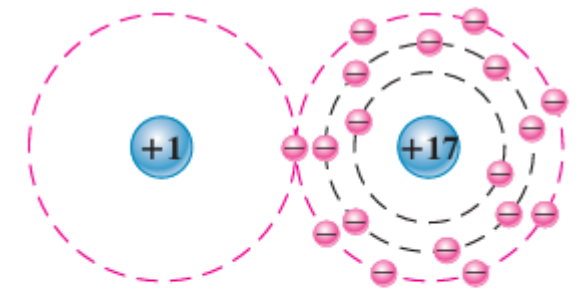

Hydrogen atom
(1 proton, 1 electron)

Chlorine atom
(17 protons, 17 electrons)

(a) The neutral hydrogen atom has a single valence electron.

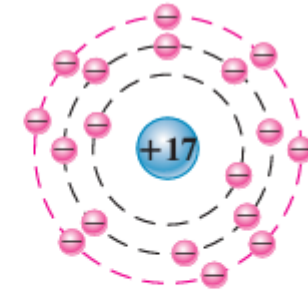(b) The atoms combine by sharing the valence electron to form gaseous hydrogen chloride (HCl).

ELECTRICAL CHARGE

Positive and Negative Charge

- A neutral atom has equal protons and electrons.

- Losing a valence electron → positive ion.

- Gaining an electron → negative ion.

- Illustrated with hydrogen chloride (HCl) formation: hydrogen loses an electron, chlorine gains one, forming H⁺ and Cl⁻ ions

Positive hydrogen ion
(1 proton, no electrons)

Negative chloride ion
(17 protons, 18 electrons)

(c) When dissolved in water, hydrogen chloride gas separates into positive hydrogen ions and negative chloride ions. The chlorine atom retains the electron given up by the hydrogen atom forming both positive and negative ions in the same solution.

VOLTAGE

Definition of Voltage

- Voltage is the **potential difference** between two points.

- It represents **energy (work) per unit charge:**

$$V = \frac{W}{Q}$$

- Voltage is also called **electromotive force (emf)** and is the driving force that establishes current in circuits

The Volt

The unit of voltage is the volt, symbolized by V. One volt is the potential difference (voltage) between two points when one joule of energy is used to move one coulomb of charge from one point to the other.
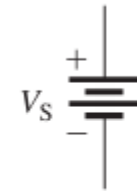
VOLTAGE

Voltage Sources

•Provide **electrical energy (emf)** from different forms of energy:

- **Chemical energy** → batteries.
- **Light energy** → solar cells.
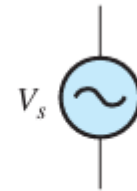- **Magnetic + mechanical motion** → generators.

V_S

(a) DC voltage source

V_s

(b) AC voltage source

Ideal vs Practical Sources

Ideal source: supplies constant voltage regardless of current.
Practical source: voltage decreases slightly as current increases

VOLTAGE

Ideal vs Practical Sources

Ideal source: supplies constant voltage regardless of current.
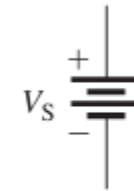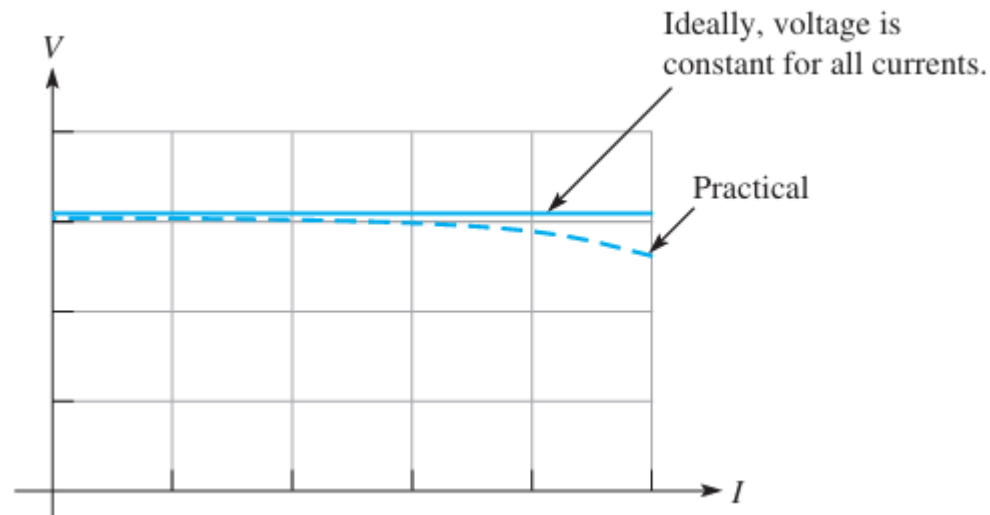**Practical source:** voltage decreases slightly as current increases

(a) DC voltage source   (b) AC voltage source
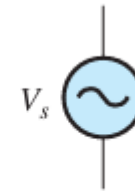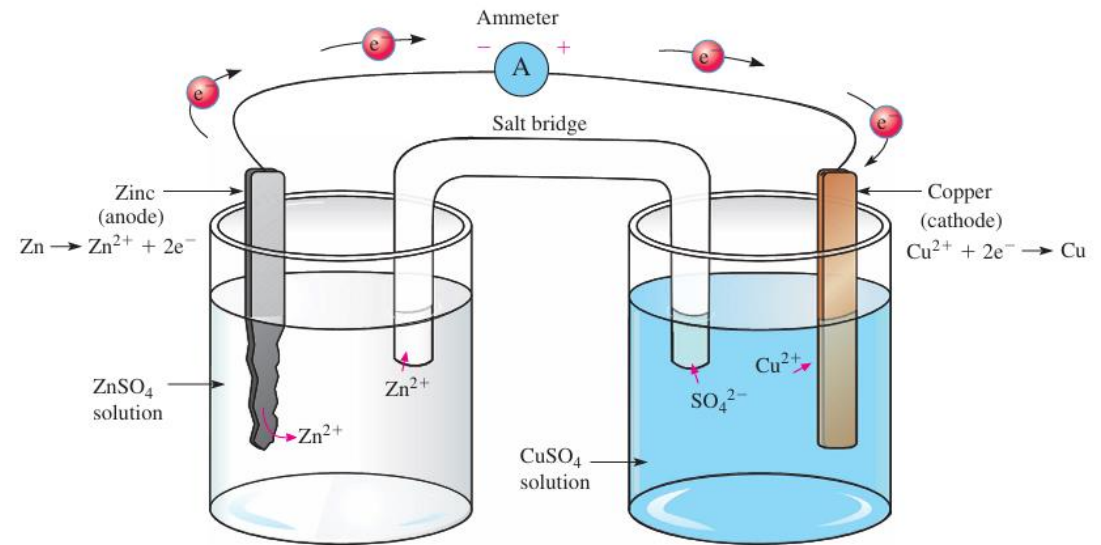

Ideally, voltage is constant for all currents.

Practical

VOLTAGE

Types of DC Voltage Sources

- **Batteries**: convert chemical energy to electrical energy.
  - Consist of **cells** (e.g., copper–zinc, lead–acid, lithium-ion).

  - Connected in **series** → higher voltage.

  - Connected in **parallel** → higher current capacity

  - Primary batteries: single-use (alkaline, carbon-zinc, silver oxide).

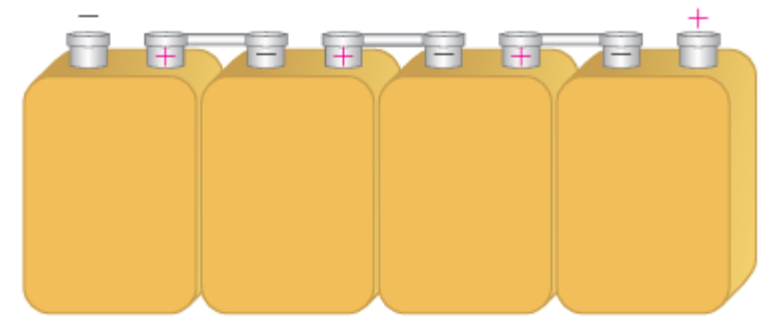 - Secondary batteries: rechargeable (lead-acid, lithium-ion, NiMH).

A copper-zinc battery. The reaction can only occur if an external path is provided for the electrons. As the reaction proceeds, the Zn anode is eaten away and Cu2+ ions combine with electrons to form copper metal on the cathode.

VOLTAGE

Types of DC Voltage Sources

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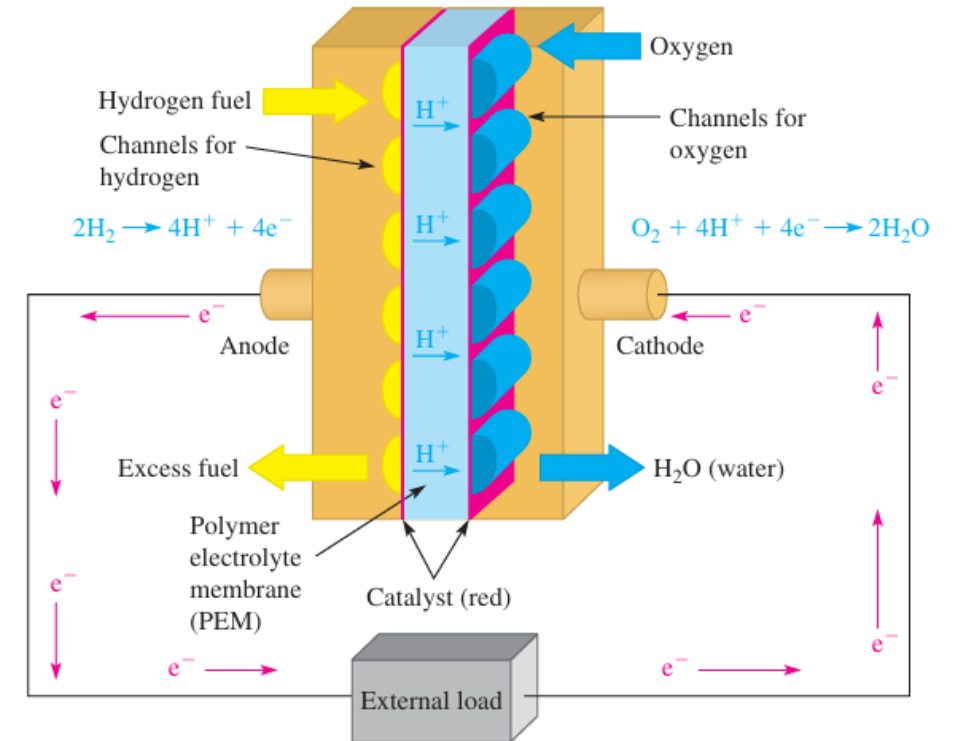(a) Series-connected cells increase voltage.

(b) Parallel-connected cells increase current capacity.

VOLTAGE

Fuel Cells

- Convert **hydrogen + oxygen** directly into electricity (dc voltage).

- By-product: **water**.

- Clean, efficient, and scalable—used in vehicles, power plants, and portable devices
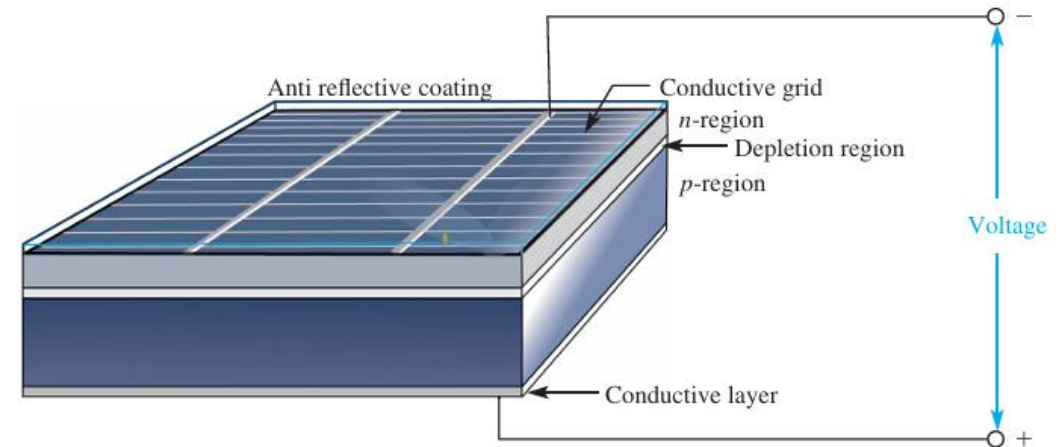

Hydrogen fuel

Channels for hydrogen

$2H_2 \longrightarrow 4H^+ + 4e^-$

Anode

Excess fuel

Polymer electrolyte membrane (PEM)

Catalyst (red)

Oxygen

Channels for oxygen

$O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O$

Cathode

H_2O (water)

e^-

External load
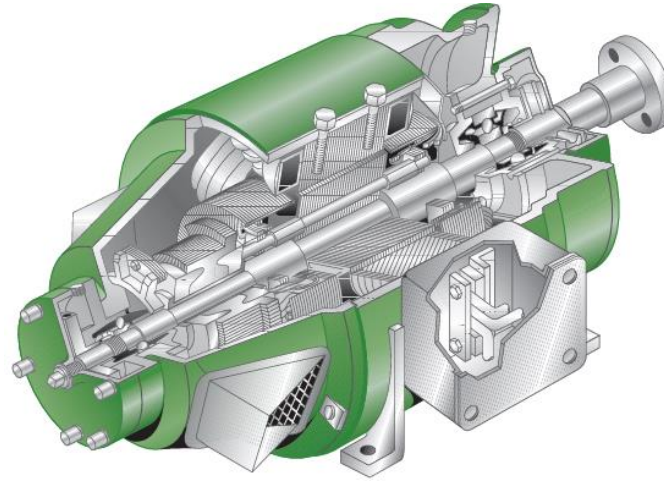
H^+

Simplified diagram of a fuel cell.

VOLTAGE

Solar Cells

- Work via the **photovoltaic effect** (light → electricity).

- Made from **semiconductor layers** (n-type and p-type).

- When sunlight excites electrons, they move across a **depletion region,** creating current.

- Widely researched for improving **efficiency** and clean energy generation
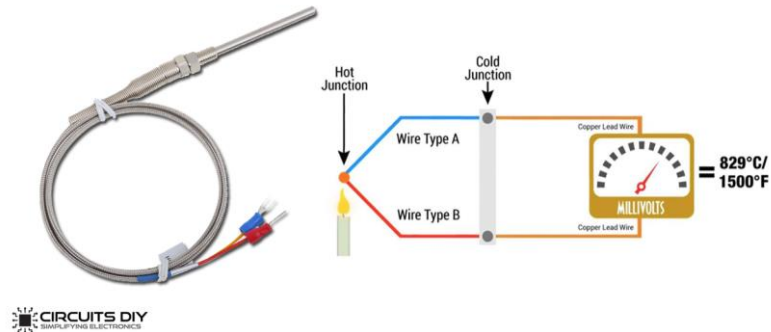
A crystalline silicon cell.

VOLTAGE

DC Generator

The Electronic Power Supply

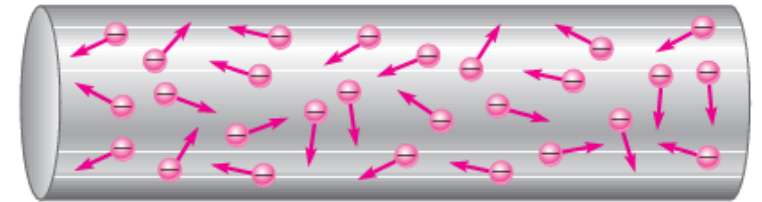Thermocouples

Piezoelectric Sensors

PZT

Metal Plate

Compressing Produces Electricity

Hot Junction

Cold Junction

Wire Type A

Wire Type B

Copper Lead Wire

Copper Lead Wire

MILLIVOLTS

= 829°C/ 1500°F

CIRCUITS DIY
SIMPLIFYING ELECTRONICS
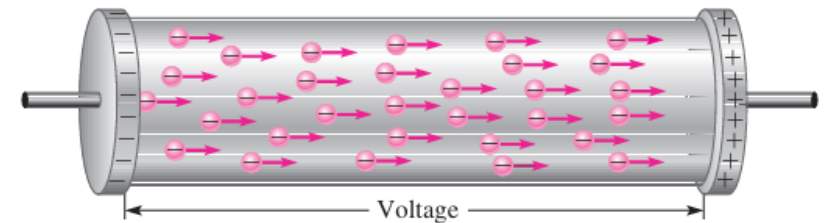
CURRENT

Definition of Current

- **Electric current** is the **flow of electric charge** in a conductor.

- It results from **free electrons** moving under the influence of an electric field.

- Symbol: **I** (from the French word *intensité*).

Random motion of free electrons in a material.

Direction of Current Flow

- **Conventional current flow**: current flows from **positive → negative terminal**.

- **Electron flow**: actual flow of electrons is from **negative → positive**.

Electrons flow from negative to positive when a voltage is applied across a conductive or semiconductive material.

CURRENT

Unit of Current
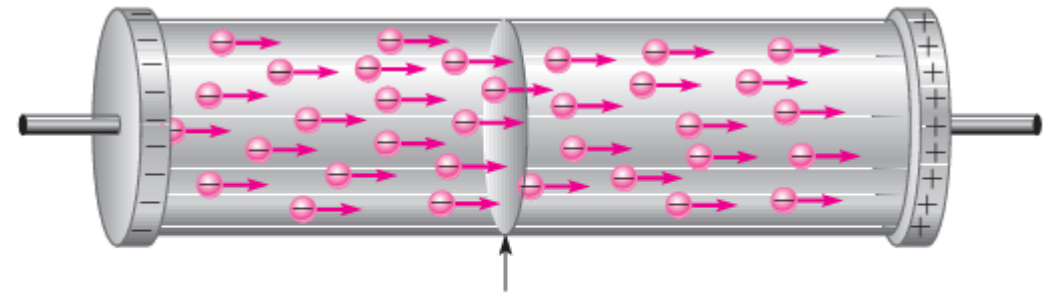
- The **ampere (A)** is the SI unit of current.

- **1 ampere** = flow of **1 coulomb of charge per second.**

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

Q is charge in coulombs (C),
t is time in seconds (s).

When a number of electrons having a total charge of 1 C pass through a cross-sectional area in 1 s, there is 1 A of current.

==One ampere (1 A) is the amount of current that exists when a number of electrons having a total charge of one coulomb (1 C) move through a given cross-sectional area in one second (1 s).==

- Smaller units: **milliampere (mA)** and **microampere (µA)**
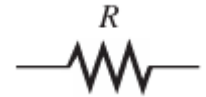
CURRENT

Drift Velocity

•Although electrons move very fast randomly, their **net drift velocity** due to electric field is relatively **slow** (fractions of mm/s).

•The actual signal (electric field propagation) travels at a **significant fraction of the speed of light.**

RESISTANCE

- ==Resistance== is the property of a material that opposes the flow of electric current. It arises from collisions between free electrons and atoms/ions in a conductor.

- Symbol: **R**, measured in **ohms (Ω)**.

- ==One ohm (1 Ω) of resistance exists if there is one ampere (1 A) of current in a material when one volt (1 V) is applied across the material.==

- Resistance is defined by Ohm's law: $R = \dfrac{V}{I}$ where *V* is voltage and *I* is current.

- ==Conductance:== The reciprocal of resistance is conductance, symbolized by G.

- It is a measure of the ease with which current is established. The formula is $G = \dfrac{1}{R}$

- The unit of conductance is the siemens, abbreviated S
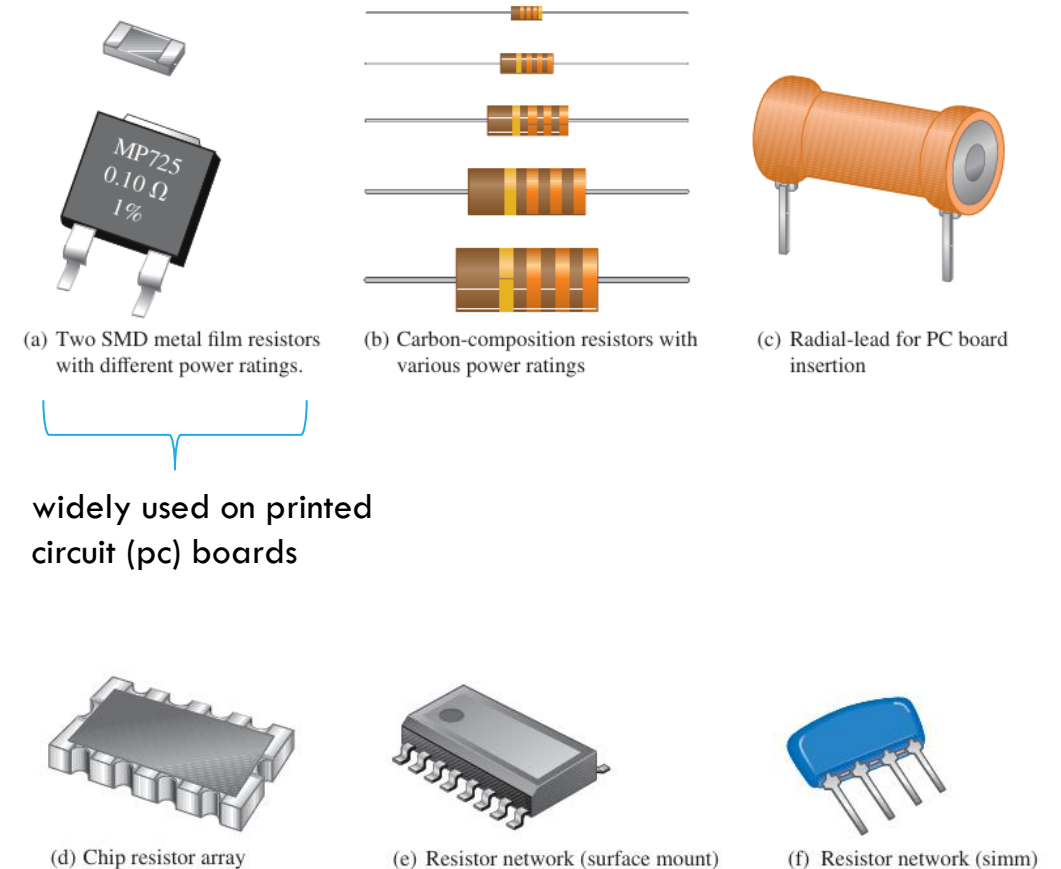
R

Resistance symbol.

RESISTANCE

Resistors: A component that is specifically designed to have a certain amount of resistance.
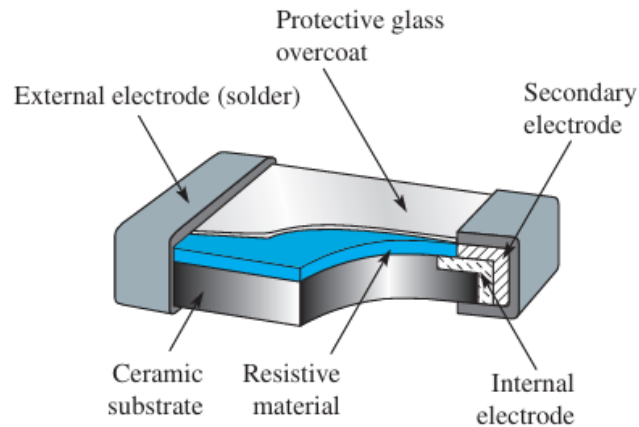
Principal applications:

- To limit current in a circuit,
- To divide voltage, and,
- To generate heat (in certain cases).

<mark>Fixed Resistors:</mark> available with a large selection of resistance values that are set during manufacturing and cannot be changed easily.

(a) Two SMD metal film resistors with different power ratings.

(b) Carbon-composition resistors with various power ratings

(c) Radial-lead for PC board insertion

widely used on printed circuit (pc) boards

(d) Chip resistor array

(e) Resistor network (surface mount)

(f) Resistor network (simm)

Typical fixed resistors.

RESISTANCE

(a) Cutaway view of an SMD metal film resistor

Protective glass overcoat
External electrode (solder)
Secondary electrode
Ceramic substrate
Resistive material
Internal electrode

(b) Cutaway view of a carbon-composition resistor

Color bands
Resistance material (carbon composition)
Insulated coating
Leads
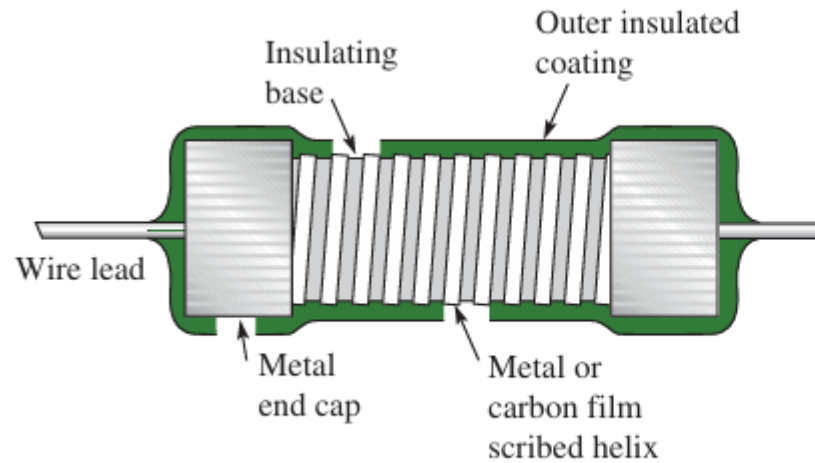
SMD Metal Film Resistor:

- Made with a resistive film on a substrate, covered by an insulating glass layer.
- End caps provide electrical connections.
- Resistance depends on the film's **resistivity** and **dimensions**.
- Precision versions are **laser-trimmed** for accuracy.
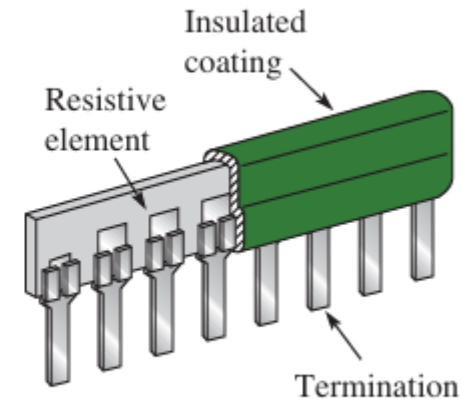
Carbon-Composition Resistor:

- Composed of **carbon powder + insulating filler + resin binder**.
- Resistance set by the **carbon-to-filler ratio**.
- Shaped into rods with conductive leads attached.
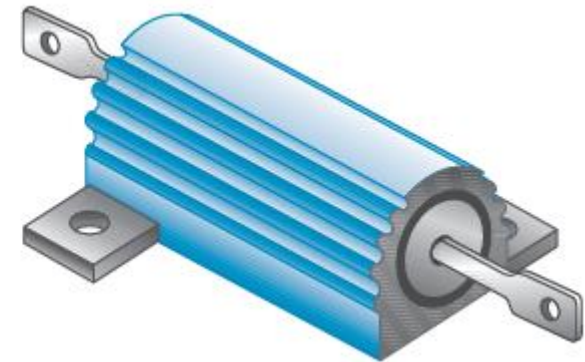- Protected by an insulating coating.

RESISTANCE

Carbon-Film Resistors

Construction views of typical film resistors.

- A thin carbon film is deposited on a ceramic substrate.
- Resistance controlled by **film thickness and spiral cut pattern.**
- More stable and reliable than carbon-composition.
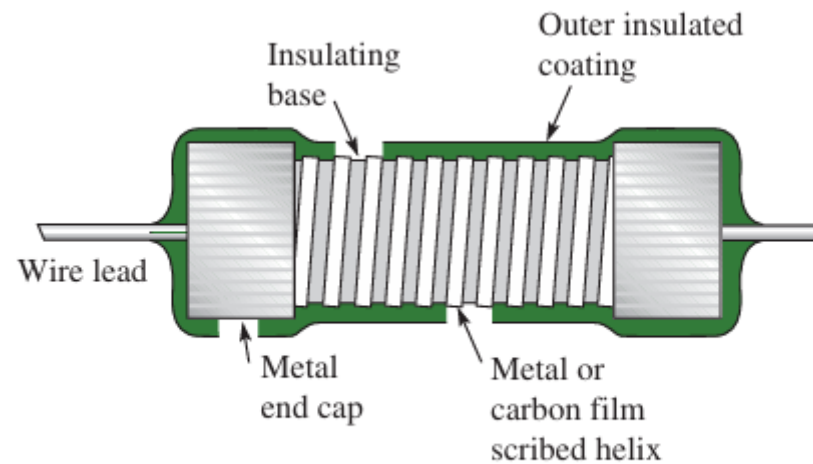
RESISTANCE

Wirewound Resistors

Typical wirewound power resistors.

- Resistance wire (nichrome) wound around a ceramic core.
- Can handle high power dissipation.
- Accurate, but inductive effects limit use in high-frequency circuits.

RESISTANCE

Metal-Oxide Resistors

(a) Film resistor showing spiraling technique

- The metal oxide film resistor is made by coating the ceramic core with metal oxide such as tin oxide.
- The antimony oxide is added to the tin oxide to increase its resistivity.
- The resistivity of the metal oxide film mainly depends on the amount of antimony oxide added to the tin oxide.
- Good stability and ability to withstand **high temperatures.**

RESISTANCE

Factors Affecting Resistance

Material Type
 Conductors (copper, silver): very low resistance (free electrons are abundant).
 Semiconductors (silicon, germanium): moderate resistance, depends on doping and temperature.
 Insulators (glass, rubber): extremely high resistance (electrons tightly bound).
Length (L)
 Longer conductors = more collisions = higher resistance.
 $R \propto L$.
Cross-sectional Area (A)
 Larger area = more room for electrons = lower resistance.
 $R \propto \frac{1}{A}$.
Temperature
 Metals: resistance **increases** as temperature rises.
 Semiconductors: resistance **decreases** with temperature (more free carriers).

RESISTANCE

Resistivity (ρ)

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

ρ (rho): material-dependent constant (Ω·m).

Examples:,

- Copper: very low ρ (~$1.7×10−8$ Ω·m) → excellent conductor.
- Nichrome (alloy): higher ρ → used for heating elements.

RESISTANCE

Temperature Dependence

Expressed using the **temperature coefficient of resistance (α):**

$$R_T = R_0 \left[1 + \alpha(T - T_0) \right]$$

- R_T: resistance at temperature T.
- R_0: resistance at reference temperature T_0.
- Metals → positive α (resistance rises).
- Semiconductors → negative α (resistance drops).

RESISTANCE

Variable Resistors

Variable resistors allow the **resistance to be adjusted** manually or automatically.
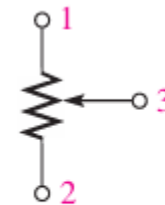
Types of Variable Resistors

Potentiometer (Pot)
    Three-terminal device.
    Works as a **voltage divider**.
    Common uses: **volume control, tuning, calibration.**

Rheostat
    Two-terminal version of a potentiometer.
    Used to **control current** by varying resistance in series.

(a) Potentiometer   (b) Rheostat   (c) Potentiometer connected as a rheostat

RESISTANCE

Variable Resistors

Typical potentiometers and construction views.

RESISTANCE

Variable Resistors

1. Quarter turn   2. Half turn   3. Three-quarter turn

(a) Linear

1. Quarter turn   2. Half turn   3. Three-quarter turn

(b) Tapered (nonlinear)

Linear Potentiometer
- Resistance changes proportionally with the movement of the wiper (moving contact).
- Example: Half the rotation → half the total resistance; three-quarters → three-quarters of resistance.

Tapered (Nonlinear) Potentiometer
- Resistance changes in a nonlinear way with wiper movement.
- Example: Half the rotation does not equal half the total resistance.
- Used when a nonlinear control response is desired (e.g., audio volume controls).

RESISTANCE

Variable Resistance Sensors

Many sensors work by converting a **physical quantity into a resistance change**.
The resistance variation can be measured directly or by observing its effect on **voltage or current** in a circuit.

Examples

Thermistors → resistance varies with **temperature.**
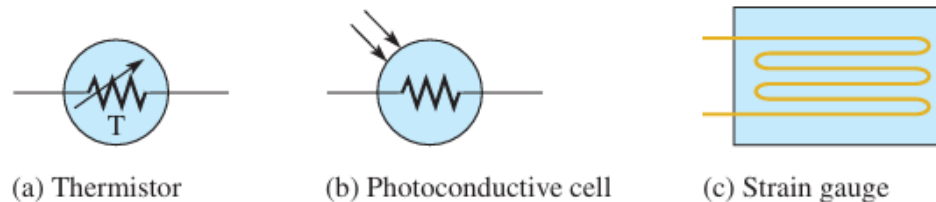**Photoconductive cells (LDRs)** → resistance varies with light intensity.
Strain gauges → resistance changes when force or mechanical strain is applied.
　　Very small resistance changes, so sensitive instruments are needed.
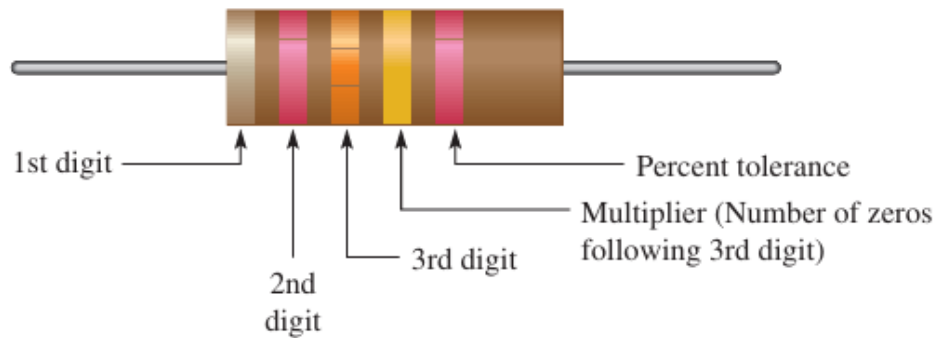　　Commonly used in scales and motion detection systems.

(a) Thermistor　　　(b) Photoconductive cell　　　(c) Strain gauge

Symbols for resistance sensors.

RESISTANCE

Resistor Color Codes

Resistors are often marked with **colored bands** that indicate their resistance value and tolerance.

Example: **Red – Violet – Orange – Gold**

Red = 2

Violet = 7

Orange = ×1,000

Gold = ±5%

→ Resistance = **27 kΩ ± 5%**

	DIGIT	COLOR
Resistance value, first	0	Black
three bands:	1	Brown
	2	Red
First band—1st digit	3	Orange
Second band—2nd digit	4	Yellow
Third band—3rd digit	5	Green
Fourth band—multiplier	6	Blue
(number of zeros	7	Violet
following 3rd digit)	8	Gray
	9	White
Fourth band—multiplier	0.1	Gold
	0.01	Silver
	±2%	Red
	±1%	Brown
Fifth band—tolerance	±0.5%	Green
	±0.25%	Blue
	±0.1%	Violet

RESISTANCE

Resistor Color Codes

Find the resistance value in ohms and the percent tolerance for each of the color-coded resistors shown in Figure 2–30.

(a)   (b)   (c)

RESISTANCE

Resistor Color Codes

Find the resistance value in ohms and the percent tolerance for each of the color-coded resistors shown in Figure 2–30.

(a)   (b)   (c)

Solution   **(a)** First band is red = 2, second band is violet = 7, third band is black = 0, fourth band is gold = ×0.1, fifth band is red = ±2% tolerance.

$$R = 270 \times 0.1 = \mathbf{27\ \Omega\ \pm 2\%}$$

(b) First band is yellow = 4, second band is black = 0, third band is red = 2, fourth band is black = 0, fifth band is brown = ±1% tolerance.

$$R = \mathbf{402\ \Omega\ \pm 1\%}$$

(c) First band is orange = 3, second band is orange = 3, third band is red = 2, fourth band is orange = 3, fifth band is green = ±0.5% tolerance.
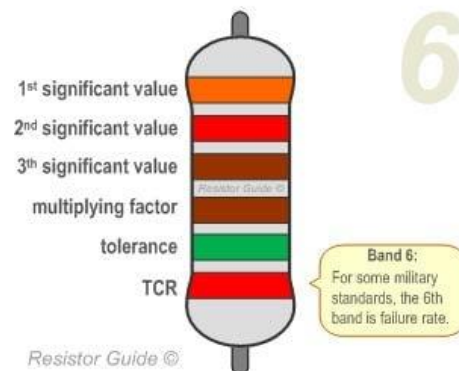
$$R = \mathbf{332{,}000\ \Omega\ \pm 0.5\%}$$

RESISTANCE

Zero Ohm Resistor

Exceptions to Resistor Color Codes

- **Zero-ohm resistor:**
    - Marked with a single black band.
    - Used as a **jumper** on printed circuit boards (PCBs).
    - Advantage: can be machine-placed like other resistors.

- **Military resistors:**
    - May include an **extra reliability band.**
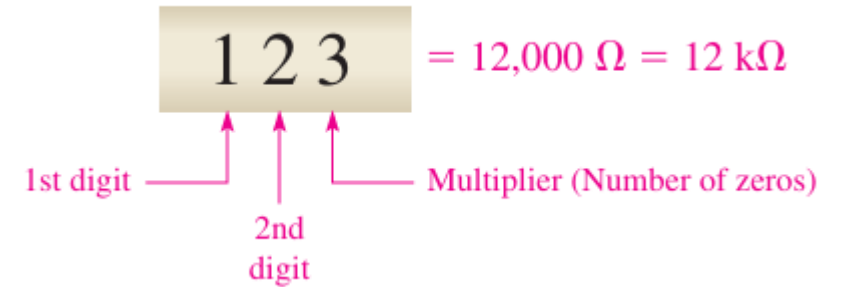   - Always check the manufacturer's datasheet for details.

1st significant value
2nd significant value
3th significant value
multiplying factor
tolerance
TCR

Band 6:
For some military standards, the 6th band is failure rate.

Resistor Guide ©

RESISTANCE

Exceptions to Resistor Color Codes

Not all resistors use color bands; many use **printed label codes**, especially **surface-mount resistors (SMDs)**.

Types of Label Codes

- **Numeric codes**
  - Use **3 digits**:
    - First two digits = significant figures.
    - Third digit = multiplier (number of zeros).
  - Example:
    - 100 → 10 Ω
    - 101 → 100 Ω
  - Note: works only for resistances ≥ **10 Ω**.

1 2 3   = 12,000 Ω = 12 kΩ

1st digit ——   —— Multiplier (Number of zeros)

2nd digit

Example of three-digit labeling for a resistor.

RESISTANCE

Exceptions to Resistor Color Codes

Not all resistors use color bands; many use **printed label codes**, especially **surface-mount resistors (SMDs)**.

Types of Label Codes

- **Alphanumeric codes**
    - Use letters and numbers to indicate value and tolerance.
    - In some larger resistors, the **full resistance value and tolerance** are printed directly.

22R	= 22 Ω

1st digit —
2nd digit
Decimal point and multiplier

2M2	= 2.2 MΩ

1st digit —
Decimal point and multiplier
2nd digit

220K	= 220 kΩ

1st digit —
2nd digit
3rd digit
Decimal point and multiplier

0R1	= 0.1 Ω

1st digit —
Decimal point and multiplier
2nd digit

RESISTANCE

Resistor Color Codes

Interpret the following alphanumeric resistor labels:

(a) 470   **(b)** 471   **(c)** 68K   **(d)** 10M   **(e)** 5R6

RESISTANCE

Resistor Color Codes

Interpret the following alphanumeric resistor labels:

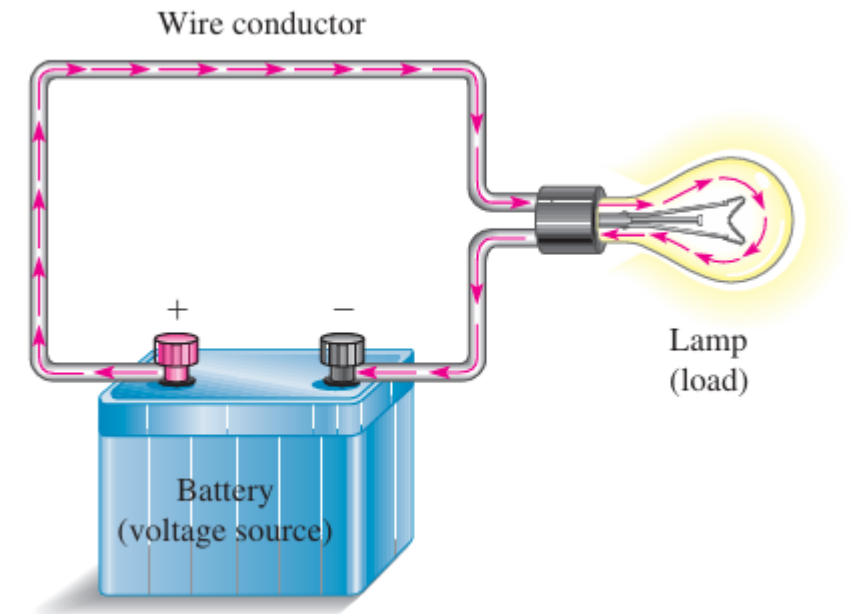(a) 470   (b) 471   (c) 68K   (d) 10M   (e) 5R6

Solution   (a) 470 = **47 Ω**   (b) 471 = **470 Ω**   (c) 68K = **68 kΩ**

                  (d) 10M = **10 MΩ**   (e) 5R6 = **5.6 Ω**

THE ELECTRIC CIRCUIT

Definition of an Electric Circuit

- An **electric circuit** is a **complete conducting path** that allows electric current to flow.

- For current to exist:
    - A **voltage source** must be present (battery, generator, etc.).
    - There must be a **closed conducting path** (wires, conductors).
    - A **load** (resistor, lamp, motor, etc.) should be in the path to use the electrical energy.

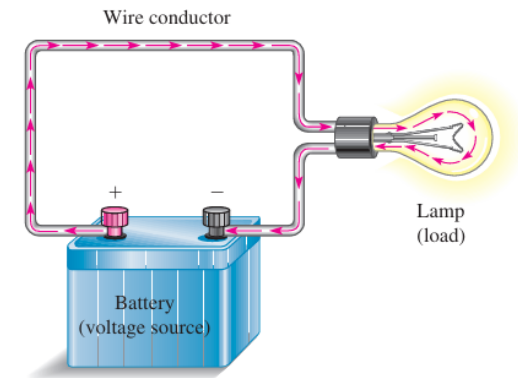If the circuit is **open** (broken path), current cannot flow.

Wire conductor

Lamp (load)

Battery (voltage source)

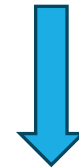A simple electric circuit.

THE ELECTRIC CIRCUIT

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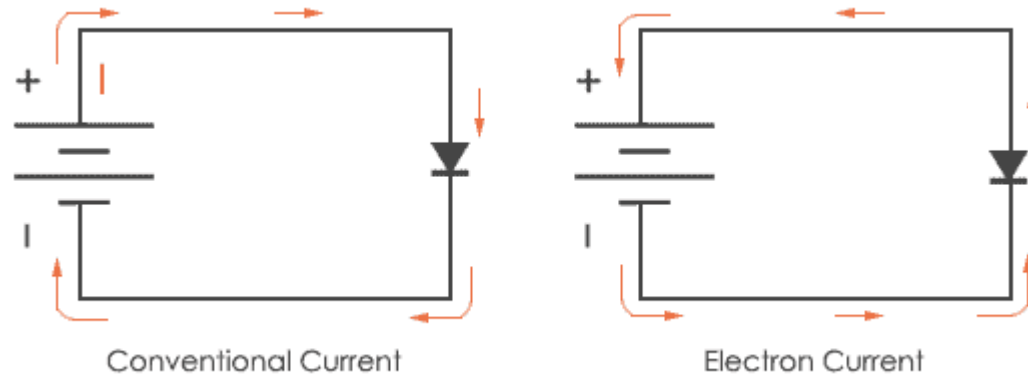

A simple electric circuit.

Schematic for the circuit above

THE ELECTRIC CIRCUIT

Conventional vs Electron Flow

Conventional Current Flow: Assumes current flows **from positive to negative** (historical convention).

Electron Flow: Actual flow of electrons is **from negative to positive**.
Both are correct representations, but **conventional flow** is used in most circuit diagrams and analysis.

Conventional Current   Electron Current

THE ELECTRIC CIRCUIT

Practical Considerations

Circuits must be designed to handle the **expected current** without overheating.
Fuses and circuit breakers are included for protection against overloads or short circuits.

Real-world circuits often include **control elements** (switches, relays) and **measuring instruments** (ammeters, voltmeters).

THE ELECTRIC CIRCUIT
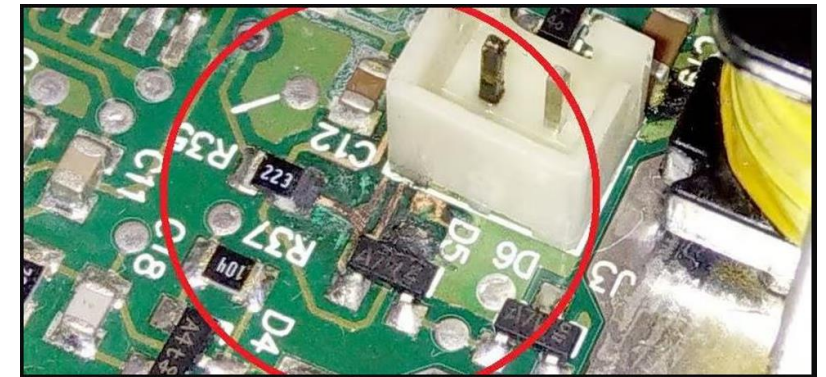
Why Current Control is Necessary

Current in a circuit must be regulated to **prevent damage** to components and ensure **safe operation.**

Too much current can cause:

Overheating of wires and components.
Fire hazards in household or industrial circuits.
Permanent failure of sensitive electronic parts (e.g., ICs, LEDs).

THE ELECTRIC CIRCUIT

Switches

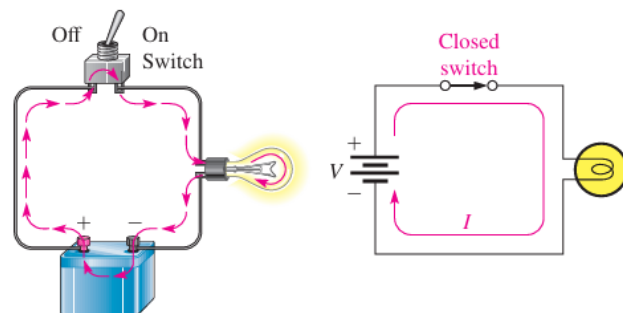Simple devices used to **manually open or close** a circuit.

Types:
   SPST (Single-Pole Single-Throw): Basic ON/OFF switch.
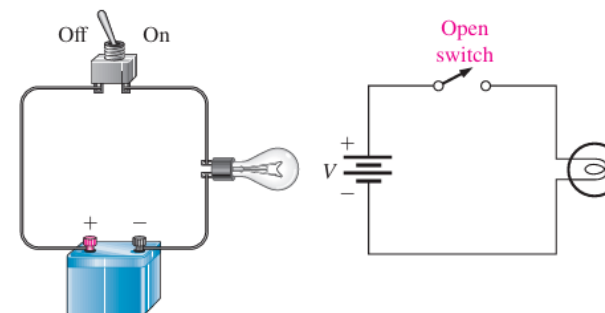   **SPDT and DPDT:** Allow switching between two circuits or reversing polarity.
   Push-button, toggle, slide, rotary switches → used in different applications.
Example: Light switch at home.

SPST (Single-Pole Single-Throw):

(a) There is current in a *closed* circuit because there is a complete current path (switch is ON or in the *closed* position). Current is almost always indicated by a red arrow in this text.
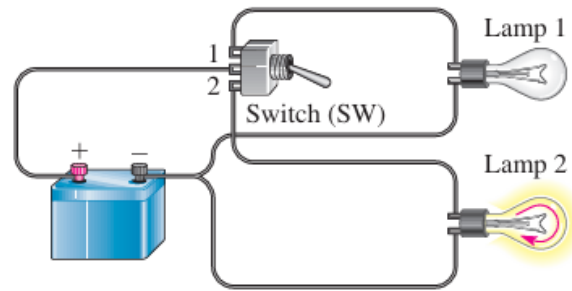
(b) There is no current in an *open* circuit because the path is broken (switch is OFF or in the *open* position).
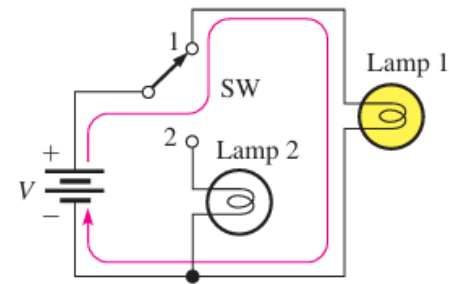
THE ELECTRIC CIRCUIT
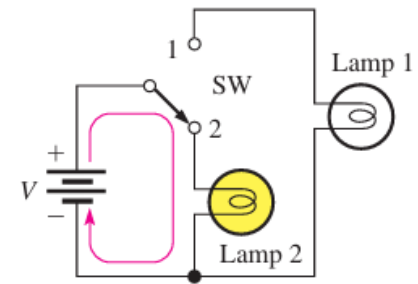
Switches

SPDT and DPDT:

When one lamp is on, the other is off, and vice versa.

(a) Pictorial

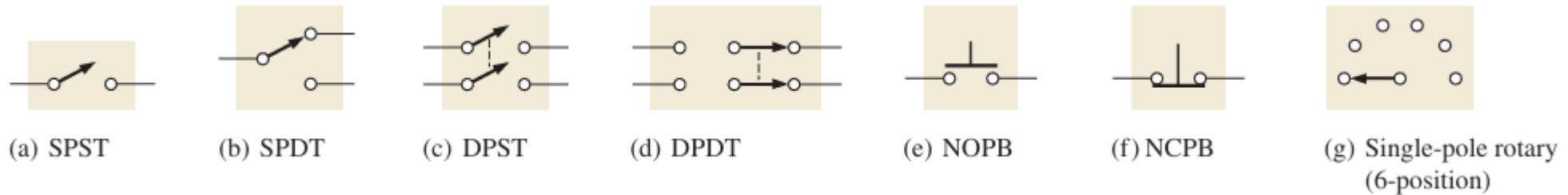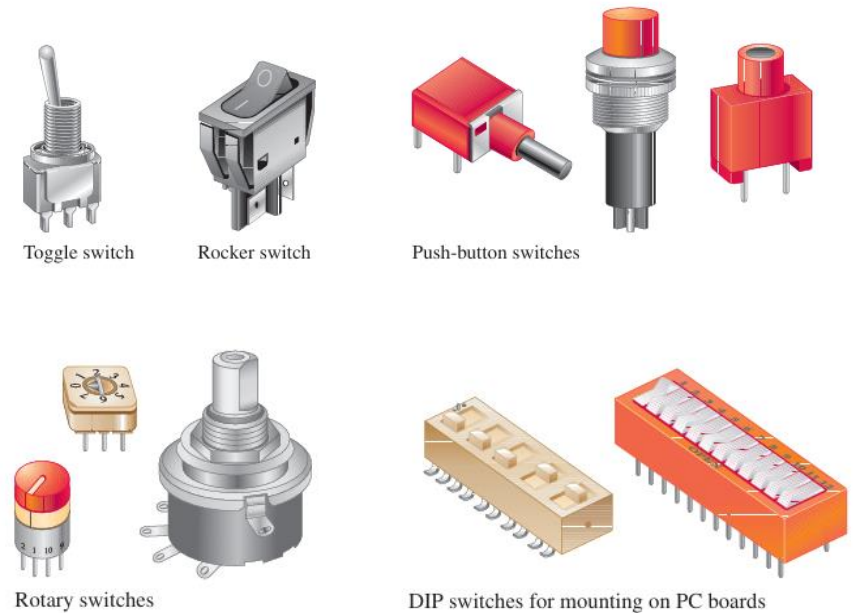(b) A schematic showing Lamp 1 on and Lamp 2 off

(c) A schematic showing Lamp 2 on and Lamp 1 off

THE ELECTRIC CIRCUIT

Other Switches

- **DPST**: One action, two circuits ON/OFF together.
- **DPDT**: Two inputs, each can connect to two outputs (often used for polarity/motor control).
- **Push-buttons**: Momentary control (either N.O. or N.C.).
- **Rotary switch**: Selects one of many possible connections with a knob.

Toggle switch   Rocker switch   Push-button switches

Rotary switches   DIP switches for mounting on PC boards

(a) SPST   (b) SPDT   (c) DPST   (d) DPDT   (e) NOPB   (f) NCPB   (g) Single-pole rotary (6-position)

Switch symbols.

THE ELECTRIC CIRCUIT

Protection Devices

Fuses

- Thin wire element that **melts** when current exceeds a safe limit.
- Permanently opens the circuit to stop current flow.
- Must be **replaced** after blowing.
- Used in low-cost and simple protection schemes.

Circuit Breakers

- Automatically **open the circuit** during overload or short-circuit conditions.
- Unlike fuses, they can be **reset** (manually or automatically).
- Widely used in residential, commercial, and industrial wiring.
- Types:
  - **MCB (Miniature Circuit Breaker):** Protects against overloads in home wiring (1 A – 125 A).
  - **MCCB (Molded Case Circuit Breaker):** For higher current ratings in industries (63 A-1000 A).

(a) Cartridge fuses

(b) Plug fuse

(c) Circuit breakers

(d) Fuse symbol

(e) Circuit breaker symbol

MCCB - MCB

THE ELECTRIC CIRCUIT

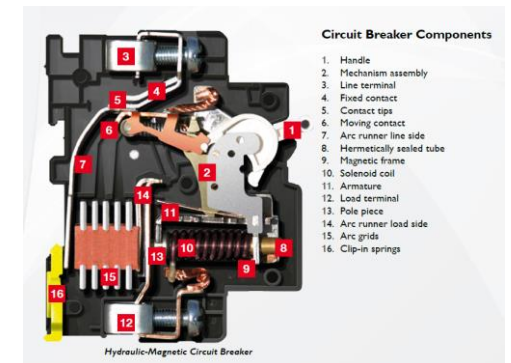Normal Conditions   Thermal Trip

Protection Devices

Circuit Breaker Operation

Purpose: A circuit breaker protects circuits by **automatically disconnecting power** when excessive current flows.

Two Common Operating Principles

1.Thermal (Heating Effect) Circuit Breaker

1. Excess current causes a **bimetallic strip/spring** to heat and bend.
2. This mechanical action **opens the contacts.**
3. Once tripped, the contacts stay open until the breaker is **manually reset.**

MCCB - MCB
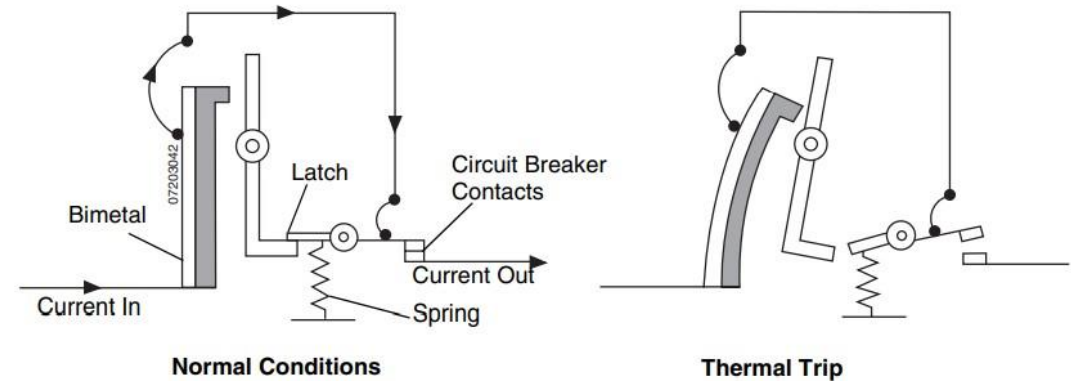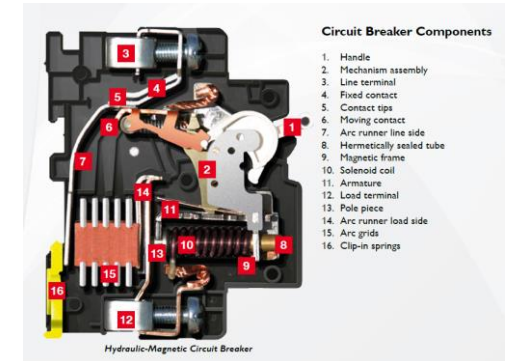
THE ELECTRIC CIRCUIT

Protection Devices

Circuit Breaker Operation

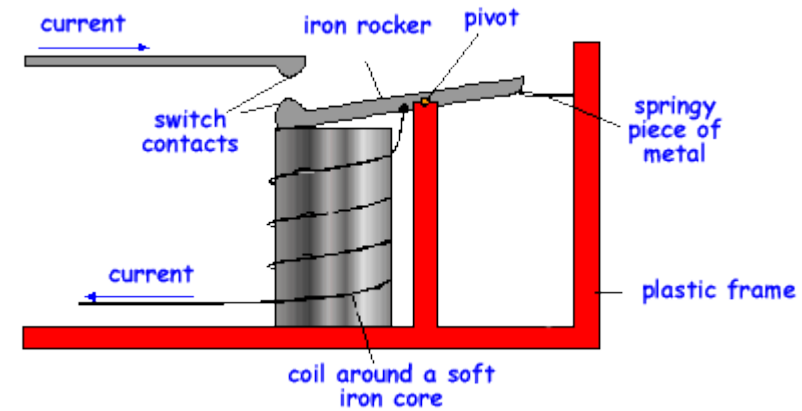**Purpose:** A circuit breaker protects circuits by **automatically disconnecting power** when excessive current flows.

Two Common Operating Principles

1.Magnetic Circuit Breaker

1. Excess current produces a **strong magnetic field** around a coil.
2. The magnetic force pulls a mechanism that **opens the contacts.**
3. Also requires **manual resetting** after tripping.

MCCB - MCB

THE ELECTRIC CIRCUIT

Protection Devices

GFCI (Ground-Fault Circuit Interrupter) or Residual Current Devices (RCDs)
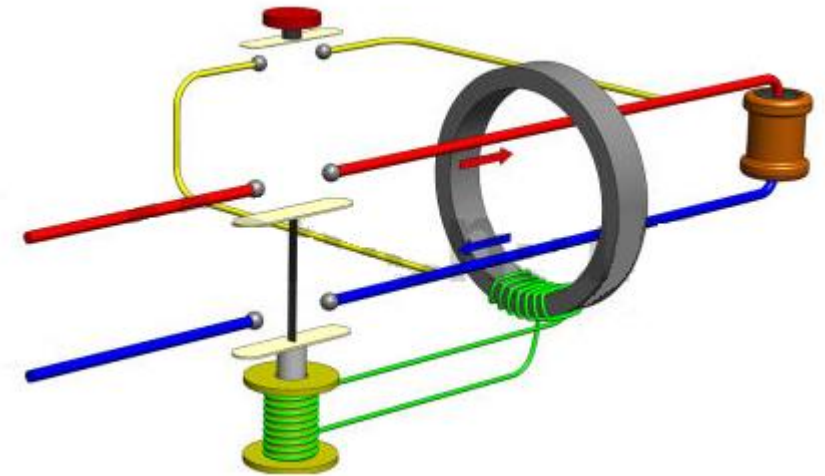
- **Basic Function**

RCDs continuously compare the currents in the **phase (line)** and **neutral** conductors.
Any difference indicates **leakage current** flowing to ground.
When the leakage exceeds the rated sensitivity, the RCD **quickly disconnects**

- **Protection of Human Life**

When current through the human body reaches about **30 mA or more**, it becomes dangerous (muscle contraction, inability to let go, respiratory paralysis, heart fibrillation).
Therefore, RCDs with a **rated residual current of 30 mA** are chosen to provide **personal protection**.
Commonly used in **residential, office, and small facility installations.**

THE ELECTRIC CIRCUIT

Protection Devices

GFCI (Ground-Fault Circuit Interrupter) or Residual Current Devices (RCDs)

- **Protection Against Fire**

Leakage currents of around **300 mA** can produce sufficient **heating** to cause **fire hazards**.
For this reason, RCDs with a **rated residual current of 300 mA** are used in **industrial or large facilities** to reduce the risk of fire.

- Prevents **electric shock hazards.**
- Common in bathrooms, kitchens, and outdoor circuits.

THE ELECTRIC CIRCUIT

Wires and Conductors

Function of Wires in Circuits

Wires are the physical medium through which current flows in an electric circuit. They connect sources, loads, and components, forming the complete conductive path necessary for operation. While they may seem simple, their design and selection are crucial because factors like **material, size, insulation, and resistance** affect circuit performance.

THE ELECTRIC CIRCUIT

Wires and Conductors

Common Conductor Materials

- **Copper** is the most widely used conductor due to its excellent electrical conductivity, durability, and relatively low cost. It has a low resistance, which minimizes energy losses and heating.

- **Aluminum** is sometimes used, particularly in power transmission lines, because it is lighter and less expensive than copper. However, its conductivity is lower, requiring thicker wires for the same current-carrying capacity.

- **Silver** has the highest electrical conductivity of all metals but is rarely used in wiring because of its high cost. It may, however, be applied in specialized circuits (e.g., aerospace or high-frequency systems).

THE ELECTRIC CIRCUIT

American Wire Gauge (AWG) sizes and resistances for solid round copper.

AWG #	AREA (CM)	RESISTANCE (Ω/1000 FT AT 20°C)	AWG #	AREA (CM)	RESISTANCE (Ω/1000 FT AT 20°C)
0000	211,600	0.0490	19	1,288.1	8.051
000	167,810	0.0618	20	1,021.5	10.15
00	133,080	0.0780	21	810.10	12.80
0	105,530	0.0983	22	642.40	16.14
1	83,694	0.1240	23	509.45	20.36
2	66,373	0.1563	24	404.01	25.67
3	52,634	0.1970	25	320.40	32.37
4	41,742	0.2485	26	254.10	40.81
5	33,102	0.3133	27	201.50	51.47
6	26,250	0.3951	28	159.79	64.90
7	20,816	0.4982	29	126.72	81.83
8	16,509	0.6282	30	100.50	103.2
9	13,094	0.7921	31	79.70	130.1
10	10,381	0.9989	32	63.21	164.1
11	8,234.0	1.260	33	50.13	206.9
12	6,529.0	1.588	34	39.75	260.9
13	5,178.4	2.003	35	31.52	329.0
14	4,106.8	2.525	36	25.00	414.8
15	3,256.7	3.184	37	19.83	523.1
16	2,582.9	4.016	38	15.72	659.6
17	2,048.2	5.064	39	12.47	831.8
18	1,624.3	6.385	40	9.89	1049.0

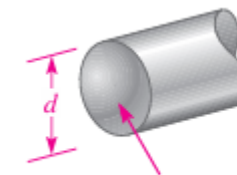**Wires and Conductors**

Wire Sizes and Gauge Systems

The **cross-sectional area** of a wire determines how much current it can safely carry without overheating. In the United States, wire sizes are typically designated using the **American Wire Gauge (AWG)** system:

- A **smaller AWG number** means a **thicker wire** with less resistance per unit length.
- For example, AWG 12 is thicker and carries more current than AWG 22.
- Resistance per unit length decreases as wire diameter increases, which improves efficiency in transmitting current.
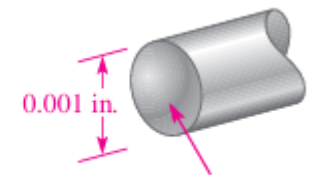
For very large conductors (such as busbars or transmission cables), sizes are often expressed directly in **circular mils** (a unit of cross-sectional area).

Cross-sectional area

$$A = d^2$$

where A is the cross-sectional area in circular mils and d is the diameter in mils.

THE ELECTRIC CIRCUIT

Wires and Conductors

Resistance of Wires

Even though conductors like copper have low resistance, **all wires possess some resistance.** The resistance of a wire depends on three main factors:

1.**Length** – longer wires have higher resistance.
2.**Cross-sectional area** – thicker wires have lower resistance.
3.**Material** – copper and silver have low resistivity, while aluminum is higher.

Each type of conductive material has a characteristic called its resistivity, ρ. For each material, ρ is a constant value at a given temperature. The formula for the resistance of a wire of length l and cross-sectional area A is:
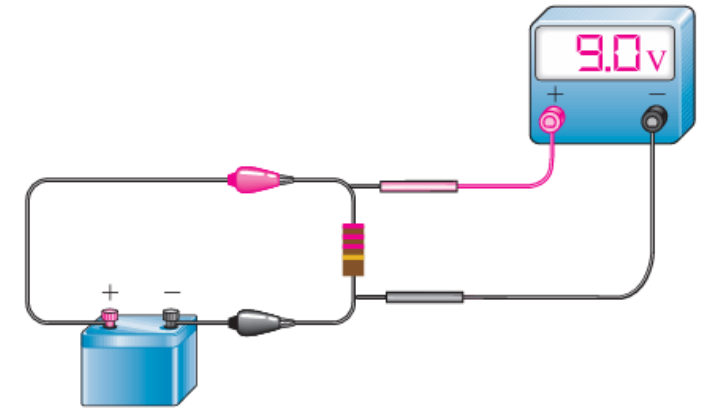
$$R = \frac{\rho l}{A}$$

The resistance produces heat when current flows (Joule heating), which must be considered in high-current applications to prevent overheating or fire.
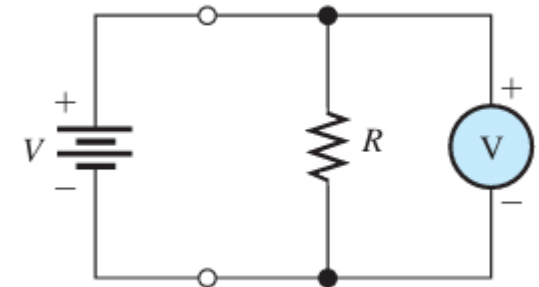
THE ELECTRIC CIRCUIT

Measuring Voltage

- **Definition:** Voltage is the potential difference between two points in a circuit.
- **Instrument:** A **voltmeter** or the voltmeter function of a digital multimeter (DMM).

- **Connection:**
  - Always placed **in parallel** with the component or section of the circuit across which the voltage is being measured.
  - This ensures the meter measures the difference in potential directly.

- **Precautions:**
  - The meter has a very high internal resistance so that it draws negligible current.
  - Reversing the leads will only reverse the polarity indication, not damage the meter (in modern digital instruments).
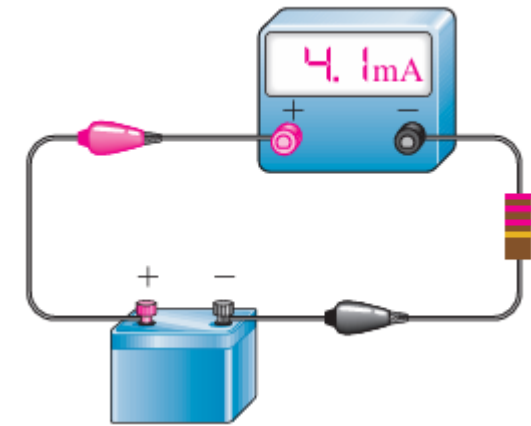
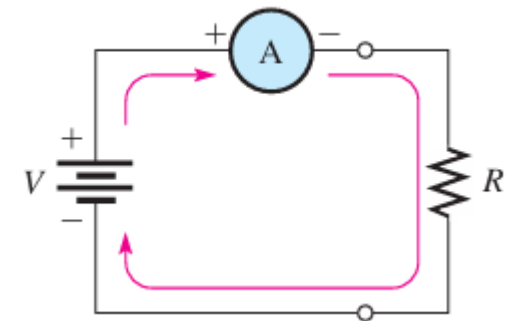Example of a voltmeter connection in a simple circuit to measure voltage.

THE ELECTRIC CIRCUIT

Measuring Current

- **Definition:** Current is the rate of flow of electric charge through a conductor.
- **Instrument:** An **ammeter** or the ammeter function of a DMM.
- **Connection:**
  - Always placed **in series** with the component whose current is to be measured.
  - This allows all charge flowing through the circuit to also flow through the meter.
- **Precautions:**
  - The meter must have very low internal resistance so as not to alter the circuit operation.
  - Care must be taken not to connect the ammeter across a voltage source directly, as this may create a short circuit and damage the meter.
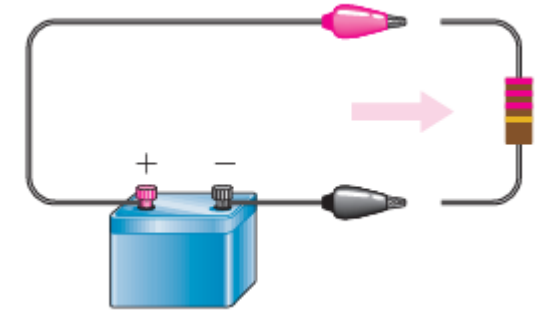

Install the ammeter in the current path with polarity as shown (negative to negative, positive to positive).
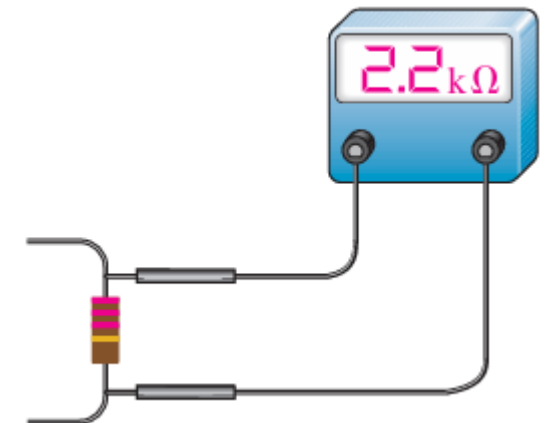
THE ELECTRIC CIRCUIT

Measuring Resistance

- **Definition:** Resistance opposes current flow and is determined by material, length, and cross-sectional area.
- **Instrument:** An **ohmmeter** or the ohmmeter function of a DMM.

- **Connection:**
  - The resistance to be measured must be **isolated from the circuit** to avoid false readings caused by parallel paths.
  - The meter applies a small internal voltage and measures the resulting current to calculate resistance.
- **Precautions:**
  - Never attempt to measure resistance in a live circuit. Voltage or current present may damage the meter or give erroneous results.

Disconnect the resistor from the circuit to avoid damage to the meter and/or incorrect measurement.
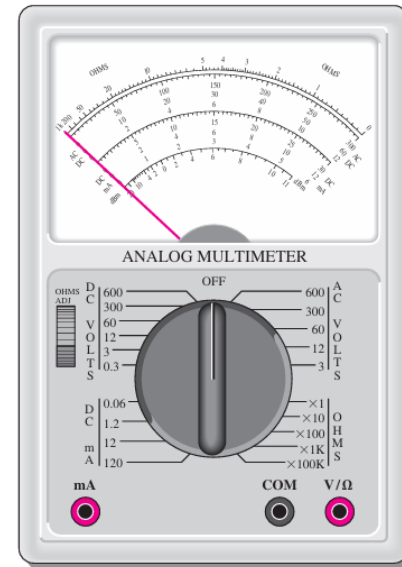
Measure the resistance. (Polarity is not important.)

THE ELECTRIC CIRCUIT

Multimeters

- **Digital Multimeter (DMM):**
  - Combines voltmeter, ammeter, and ohmmeter functions in one instrument.
  - Modern DMMs are versatile, accurate, and widely used in electronics.
  - Typical features include autoranging, polarity indication, and overload protection.

- **Analog Multimeter (VOM):**
  - Uses a moving-coil meter movement.
  - Once standard, now largely replaced by DMMs due to lower accuracy and higher sensitivity to user error.
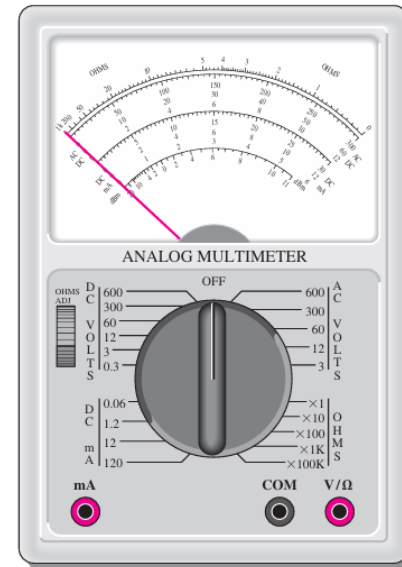
THE ELECTRIC CIRCUIT

Multimeters

Measurement Practices

- **Proper Range Selection:** Always begin with the highest range, then step down for accuracy.

- **Polarity Awareness:** Observe meter lead polarity, especially on analog instruments.

- **Safety First:** Ensure circuits are de-energized when measuring resistance; confirm meter settings before connecting.

THE ELECTRIC CIRCUIT

Electrical Safety

Introduction

Electricity is useful but can also be **hazardous** if not handled properly. Even relatively low voltages can be dangerous under certain conditions, especially if they allow current to pass through the human body. Safety practices and protective devices are essential in every electrical environment.

Electric Shock

- **Cause:** Shock occurs when the body becomes part of an electrical circuit and current flows through it.
- **Severity depends on:**
  - **Amount of current** (in amperes).
  - **Path through the body** (hand-to-hand, hand-to-foot, etc.).
  - **Duration** of contact.

THE ELECTRIC CIRCUIT

Electrical Safety

Effects of Current on the Human Body

CURRENT (MA)	PHYSICAL EFFECT
0.4	Slight sensation
1.1	Perception threshold
1.8	Shock, no pain, no loss of muscular control
9	Painful shock, no loss of muscular control
16	Painful shock, let-go threshold
23	Severe painful shock, muscular contractions, breathing difficulty
75	Ventricular fibrillation, threshold
235	Ventricular fibrillation, usually fatal for duration of 5 seconds or more
4,000	Heart paralysis (no ventricular fibrillation)
5,000	Tissue burn

THE ELECTRIC CIRCUIT

Electrical Safety

Shock Hazards

- **Low Voltage Is Not Always Safe:**
  - Under the right conditions (e.g., wet skin), even **50 V** can be dangerous.

- **Current, not just voltage, is the true danger,** but voltage determines how much current will flow through body resistance.

THE ELECTRIC CIRCUIT

Electrical Safety

Protective Devices

1.Fuses and Circuit Breakers
1. Protect equipment and wiring from excessive current.
2. **Do not guarantee personal safety** from shock.

2.Grounding (Earthing)
1. Provides a **low-resistance path** for fault currents to return to ground safely.
2. Prevents exposed metal parts from rising to dangerous voltages.

3.Double Insulation
1. Many modern appliances have two layers of insulation, eliminating the need for grounding.

4.Ground-Fault Circuit Interrupter (GFCI)
1. Detects small leakage currents (as little as 5 mA) and disconnects power rapidly.
2. Common in **bathrooms, kitchens, outdoor outlets.**

THE ELECTRIC CIRCUIT

Electrical Safety

Safe Practices

- Always **disconnect power** before working on a circuit.
- Use **one hand only** when possible (to reduce chance of current across chest/heart).
- Keep work areas **dry.**
- Use **insulated tools** and wear proper protective gear.
- Verify circuits are de-energized with a tester before touching.