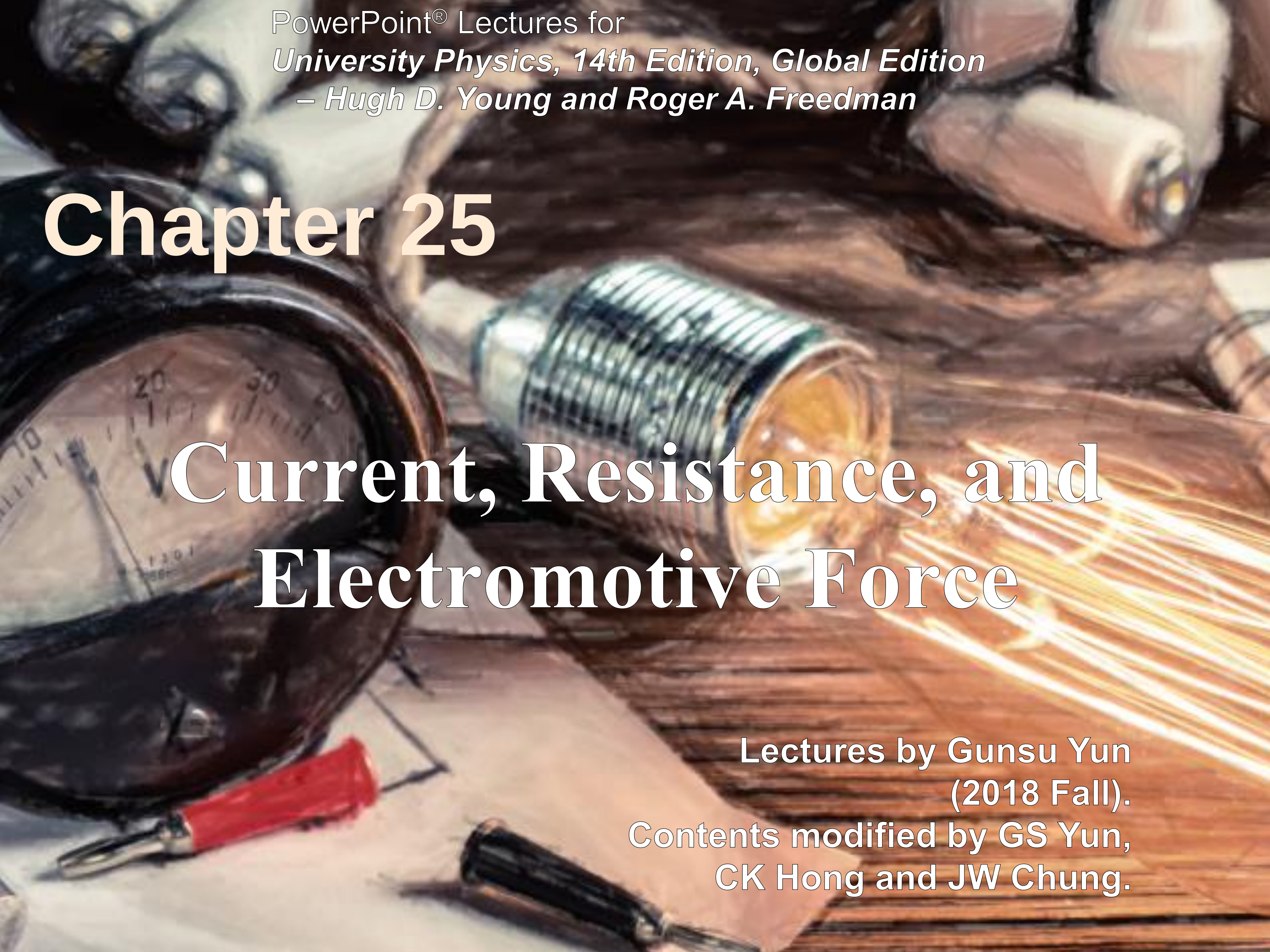

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Chapter 25

Current, Resistance, and Electromotive Force

Lectures by Gunsu Yun
(2018 Fall).
Contents modified by GS Yun,
CK Hong and JW Chung.

Goals for Chapter 25

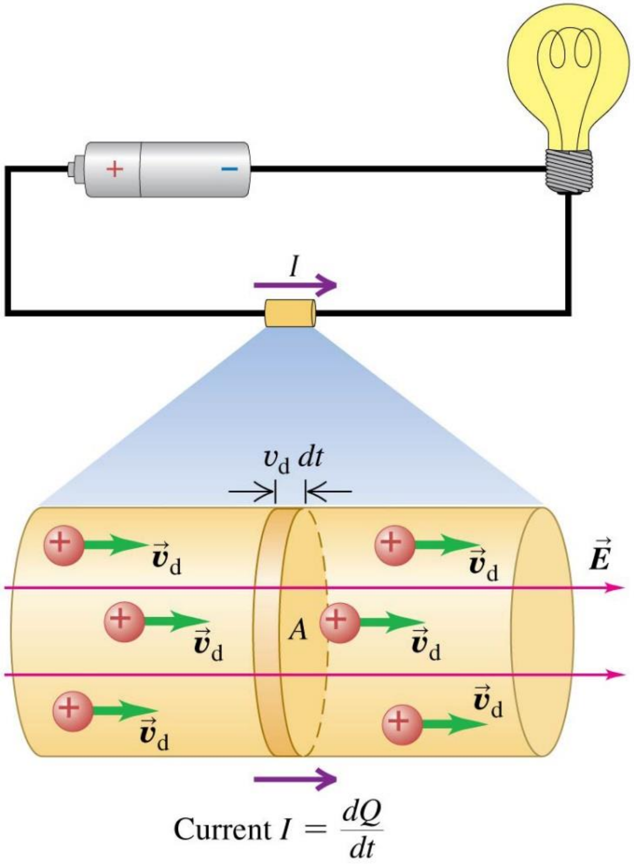
- **Electric current**
- **Resistivity** and **conductivity**
- **Resistance**
- **Electromotive force**
- **Energy and power in electric circuits**

25.1 Current

- A **current** is any motion of charge from one region to another.

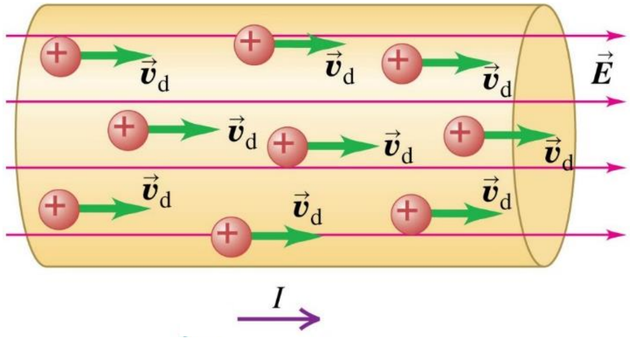
$$I = \frac{dQ}{dt}$$

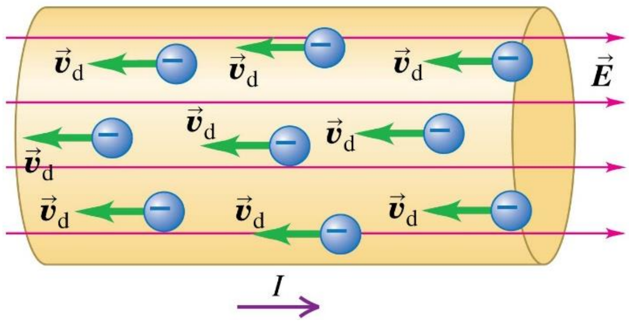
- SI unit of current: **ampere, A** = C/s



Direction of current flow

- A current can be produced by positive or negative charge flow.

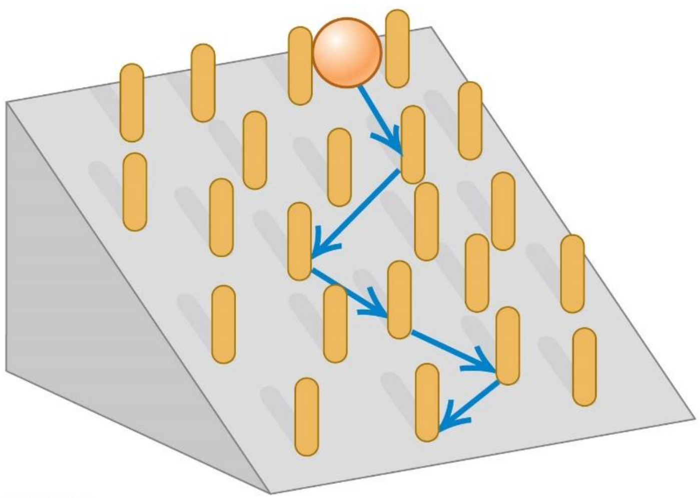


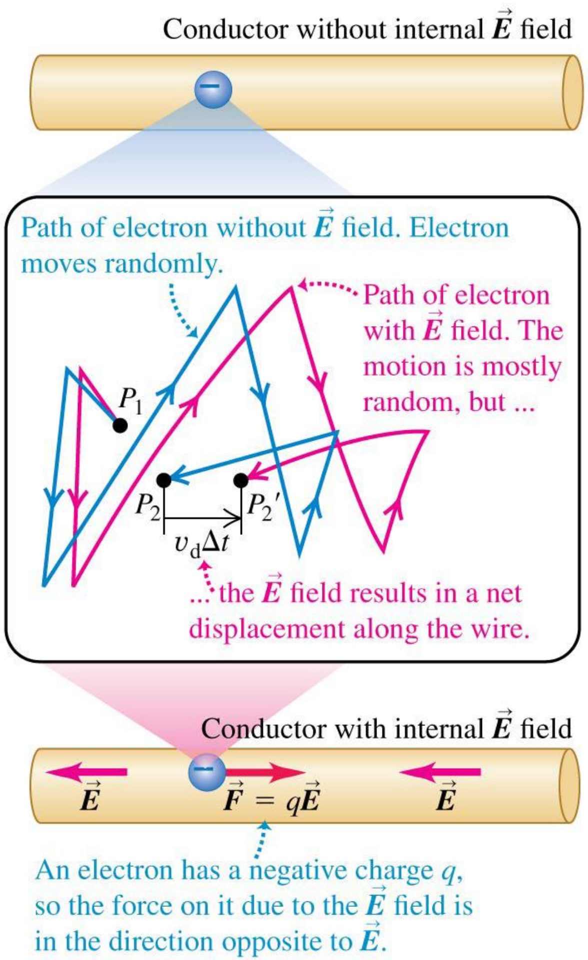


- Conventional **current** is treated as a **flow of positive charges**.
- In a metallic conductor, the moving charges are electrons — but the current still points in the direction positive charges would flow.

25.6 Metallic conduction*

- **Electrons in a conductor** are free to move, colliding at intervals with the stationary positive ions.
- The motion of the electrons is analogous to the motion of a ball rolling down a pinball machine.





$\vec{v}_d$: drift velocity $\quad v_d \propto E$

Drift velocity and current density

- We can define a **vector current density** that includes the direction of the **drift velocity**:

Vector current density

$$\vec{\boldsymbol{J}} = nq\vec{\boldsymbol{v}}_{\mathrm{d}}$$

Drift velocity

Concentration of moving charged particles

Charge per particle

- The vector current density is always in the same direction as the electric field, no matter what the signs of the charge carriers are.

$$I = \int \vec{J} \cdot d\vec{A} = nqv_d A$$

Current through an area

$$I = \overbrace{\frac{dQ}{dt}}^{\text{Rate at which charge flows through area}} = n|q|v_{\mathrm{d}}A$$

Drift speed

Cross-sectional area

Concentration of moving charged particles

Charge per particle

25.2 Resistivity

- The **resistivity** $\boldsymbol{\rho}$ of a material is the ratio of the electric field in the material to the current density it causes:

- The **conductivity** $\boldsymbol{\sigma}$ is the reciprocal of the resistivity.

Resistivity of a material

$$\rho = \frac{E}{J}$$

Magnitude of electric field in material

Magnitude of current density caused by electric field

$$\vec{J} = \rho^{-1}\vec{E}$$

$$\vec{J} = \sigma\vec{E}$$

Resistivities at room temperature (20°C)

TABLE 25.1 Resistivities at Room Temperature (20°C)

	Substance	ρ ($\Omega \cdot$ m)	Substance	ρ ($\Omega \cdot$ m)
Conductors			**Semiconductors**	
Metals	Silver	1.47×10^{-8}	Pure carbon (graphite)	3.5×10^{-5}
	Copper	1.72×10^{-8}	Pure germanium	0.60
	Gold	2.44×10^{-8}	Pure silicon	2300
	Aluminum	2.75×10^{-8}	**Insulators**	
	Tungsten	5.25×10^{-8}	Amber	5×10^{14}
	Steel	20×10^{-8}	Glass	10^{10}–10^{14}
	Lead	22×10^{-8}	Lucite	$>10^{13}$
	Mercury	95×10^{-8}	Mica	10^{11}–10^{15}
Alloys	Manganin (Cu 84%, Mn 12%, Ni 4%)	44×10^{-8}	Quartz (fused)	75×10^{16}
	Constantan (Cu 60%, Ni 40%)	49×10^{-8}	Sulfur	10^{15}
	Nichrome	100×10^{-8}	Teflon	$>10^{13}$
			Wood	10^{8}–10^{11}

Resistivity and temperature*

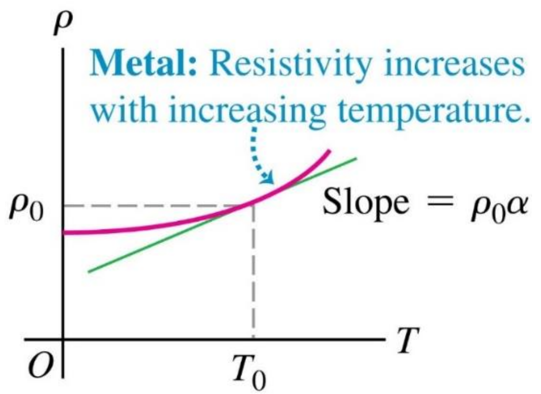
- The resistivity of a metallic conductor nearly always increases with increasing temperature.

Temperature dependence of resistivity:

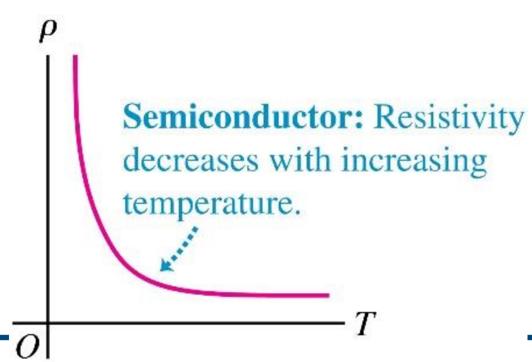
Resistivity at temperature T — Temperature coefficient of resistivity

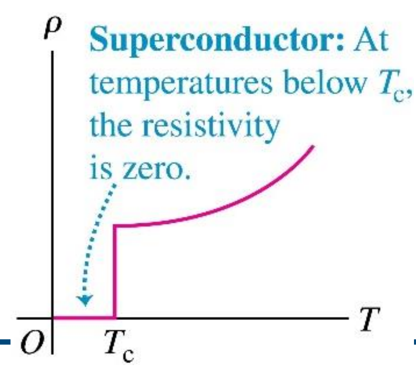
$$\overbrace{\rho(T)}^{\text{Resistivity at temperature } T} = \rho_0[1 + \alpha(T - T_0)]$$

Resistivity at reference temperature T_0



Material	α [(°C)$^{-1}$]
Aluminum	0.00039
Carbon (graphite)	−0.0005
Copper	0.00393
Iron	0.0050
Lead	0.0043
Silver	0.0038
Tungsten	0.0045



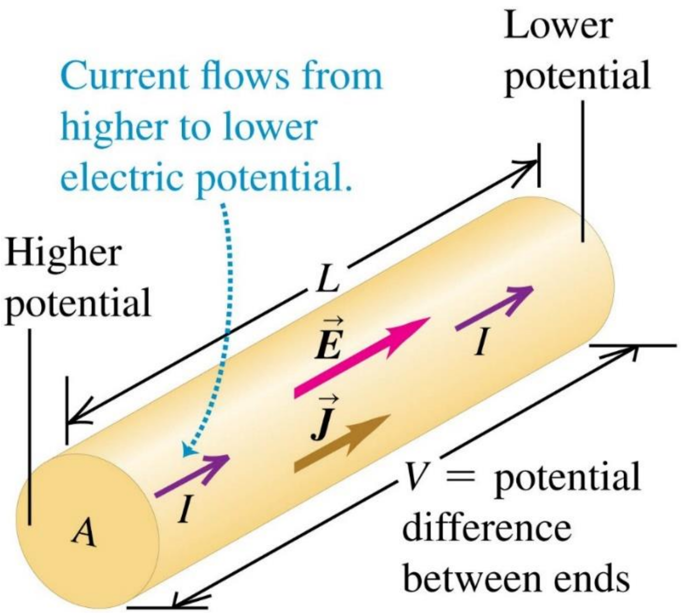


25.3 Resistance

- **Ohm's law**:

  voltage drop $(V) \propto$ current (I)

  $$V = RI \;\rightarrow\; R \equiv \frac{V}{I}$$



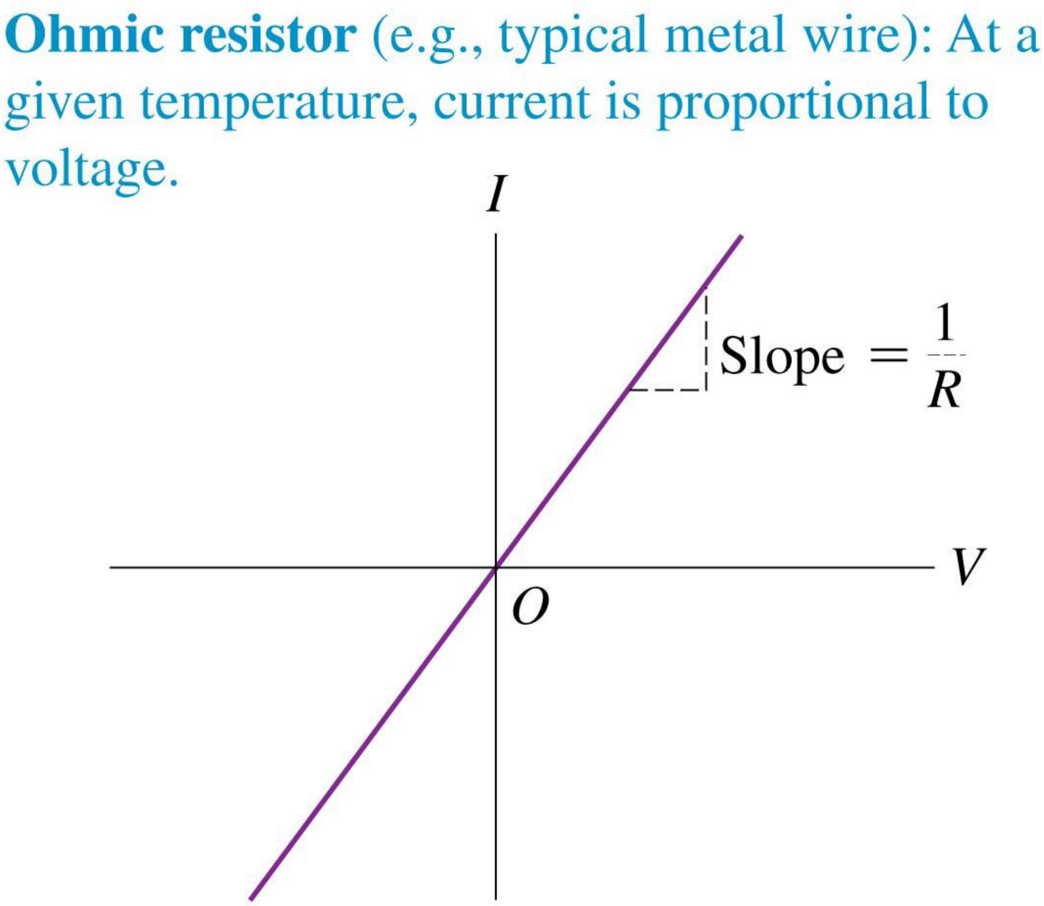
- **Resistance *R*** of a (cylindrical) conductor:

  $$R = \frac{V}{I} = \frac{EL}{JA} = \rho\frac{L}{A} \quad (\because E = \rho J)$$

- SI unit of resistance: **ohm, Ω**

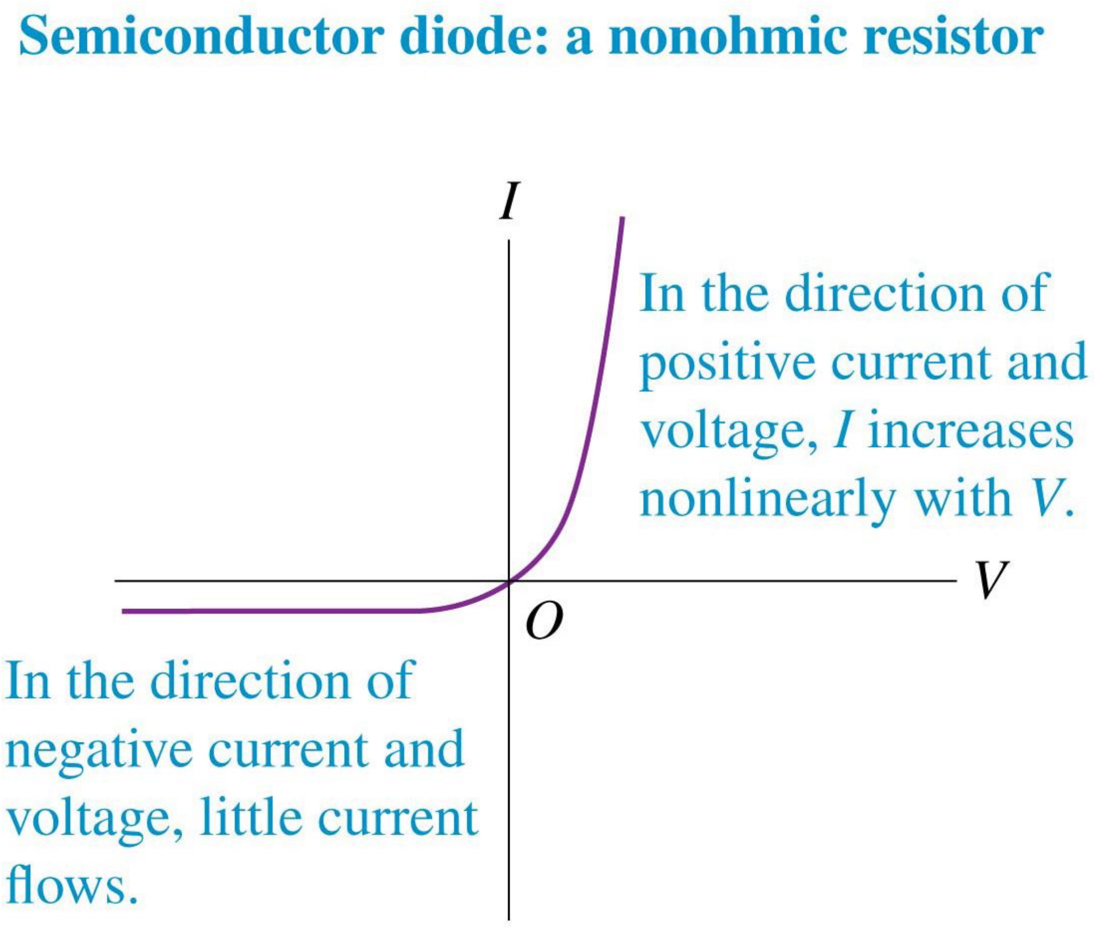
Ohmic resistors

- Resistors that obey the Ohm's law.
- Current vs. potential difference (voltage) is linear. $I = V/R$



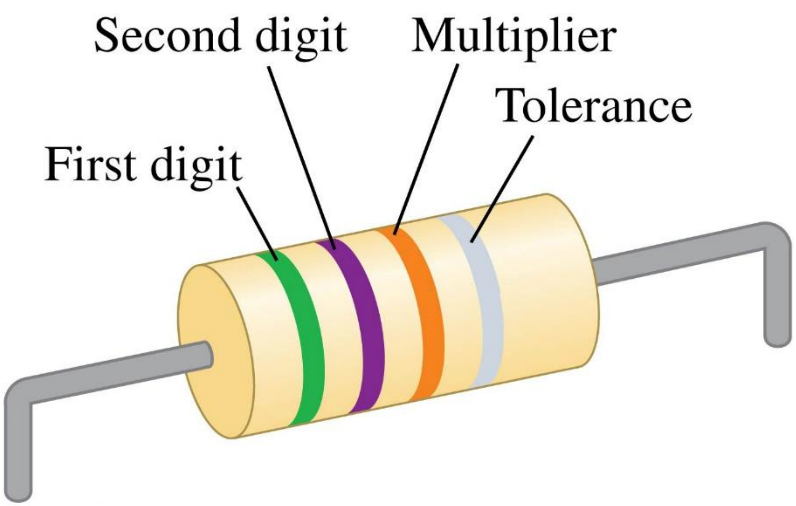
Non-Ohmic resistors*

- Example: semiconductor **diode**



Color-code for resistors*

Color	Value as Digit	Value as Multiplier
Black	0	1
Brown	1	10
Red	2	10^2
Orange	3	10^3
Yellow	4	10^4
Green	5	10^5
Blue	6	10^6
Violet	7	10^7
Gray	8	10^8
White	9	10^9



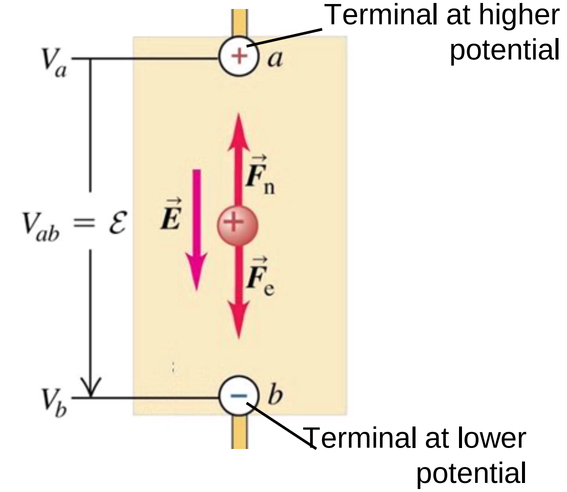
- 5.7 kΩ with a tolerance of ±10%.

25.4 Electromotive force and circuits

- **Electromotive force** (**emf, $\mathcal{E}$**) is the influence ("pump") which makes current flow from lower to higher potential. A circuit element that provides emf is called a **source of emf**.
- "emf" is ***not* a force but similar to potential**.
- SI unit of emf: V (= J/C). "Volt"
- For ideal source of emf (or in open-circuit condition),

$$\mathcal{E} = \frac{\text{Work done on } q \text{ by } F_n}{q} = \frac{qV_{ab}}{q} = V_{ab}$$

V_{ab}: termal voltage (diffence)



F_n: Nonelectrostatic force *moving* charge to higher potential
F_e: Force due to electric field
For open circuit (no net motion of charge), $F_n = F_e$.

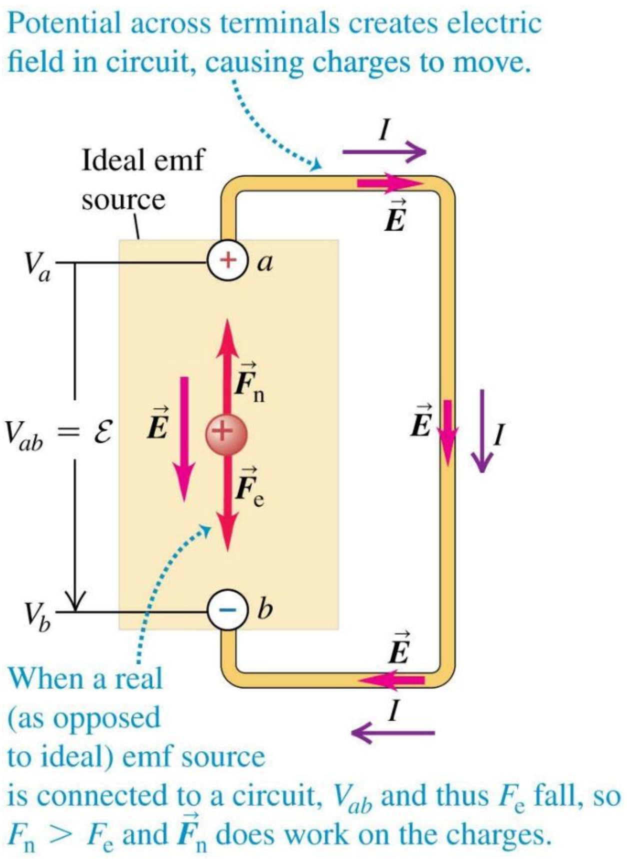
Internal resistance

- Real sources of emf contain some **internal resistance *r***. When the circuit is closed and a current (I) flows, a voltage drop (rI) corresponding to the resistive loss of energy occurs within the emf source.

$$(\text{Work done on } q \text{ by } F_n) = qV_{ab} + (\text{Resistive energy loss})$$

$$\mathcal{E} = V_{ab} + rI$$

Note that the **terminal voltage** becomes less than the emf (= open-circuit terminal voltage).



- The current through the source:

$$V_{ab} = \mathcal{E} - rI = IR \quad \rightarrow \quad I = \frac{\mathcal{E}}{R + r}$$

Alessandro Volta (☼1745, †1827)

Inventor of battery

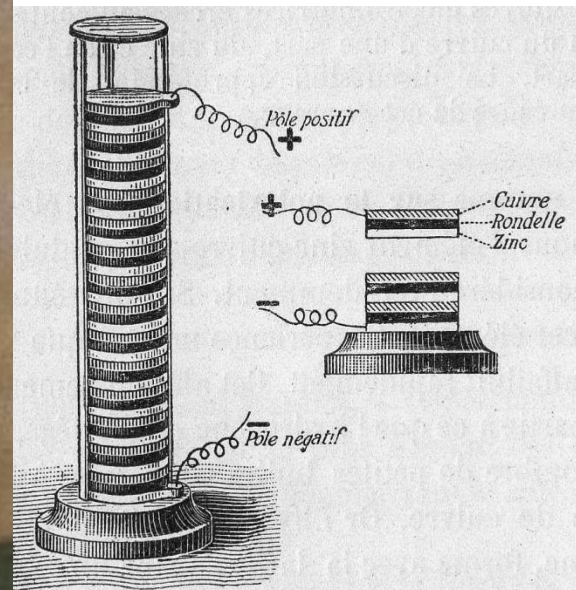
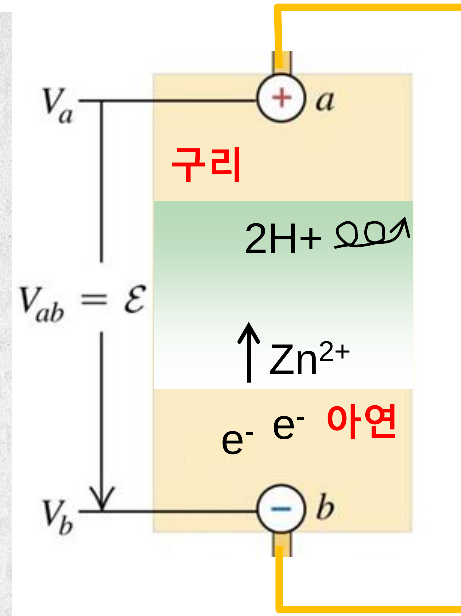


Fig. 283. — Pile de Volta.



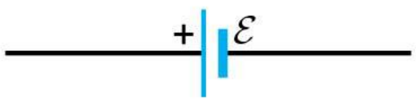
The nonelectrostatic force F_n comes from chemical (redox) reactions:

[Zn] Anode(-): $Zn \rightarrow Zn^{2+} + 2e^-$
[Cu] Cathode(+): $2H^+ + 2e^- \rightarrow H_2$

Table 25.4 — Symbols for circuit diagrams

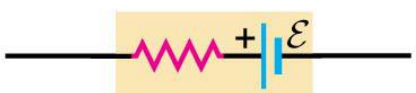
Conductor with negligible resistance

Resistor

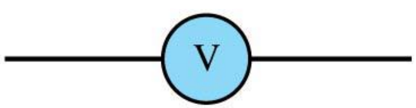


Source of emf (longer vertical line always represents the positive terminal, usually the terminal with higher potential)

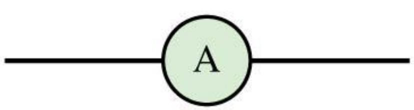
or



Source of emf with internal resistance *r* (*r* can be placed on either side)



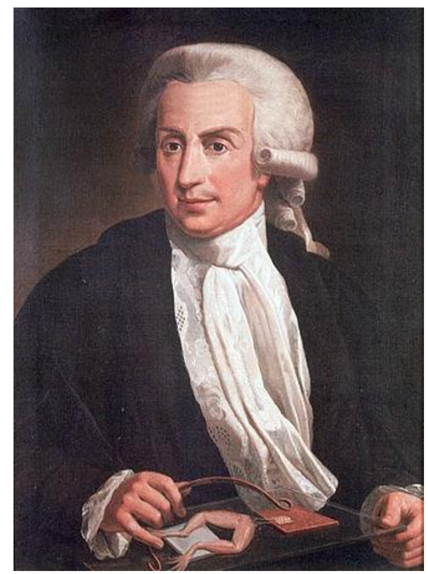
Voltmeter (measures potential difference between its terminals)



Ammeter (measures current through it)

Listen to learned men, but do so only with one ear.
Let the other be always ready to receive the sweet accents of the voice of your heavenly Friend.

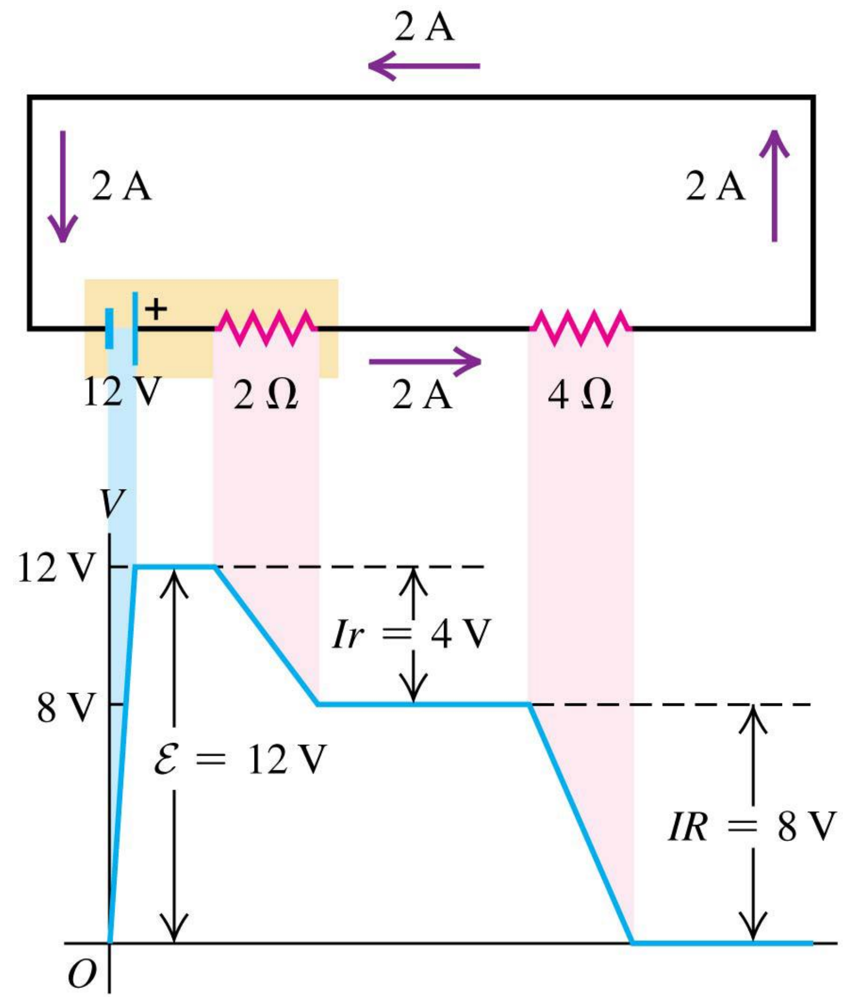
André-Marie Ampère (☼1775, †1836)
electromagnetism



Luigi Galvani (☼1737, †1798)
Bioelectricity

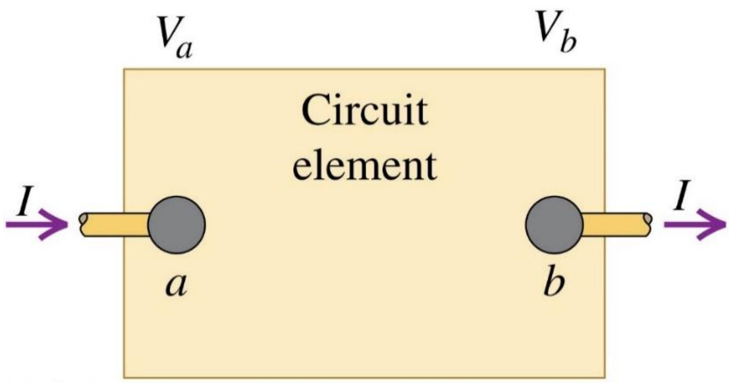
Potential changes around a circuit

- The potential **rises** when the current goes through a battery, and **drops** when it goes through a resistor.
- Going all the way around the loop brings the potential back to where it started.



25.5 Energy and power in electric circuits

- A circuit element with potential difference $V_{ab} = V_a - V_b$ between its terminals and current I passing through it in the direction from a toward b.



- The time rate of energy transfer is **power *P***:

Power delivered to or extracted from a circuit element $\rightarrow$ $P = V_{ab} I$

Voltage across circuit element

Current in circuit element

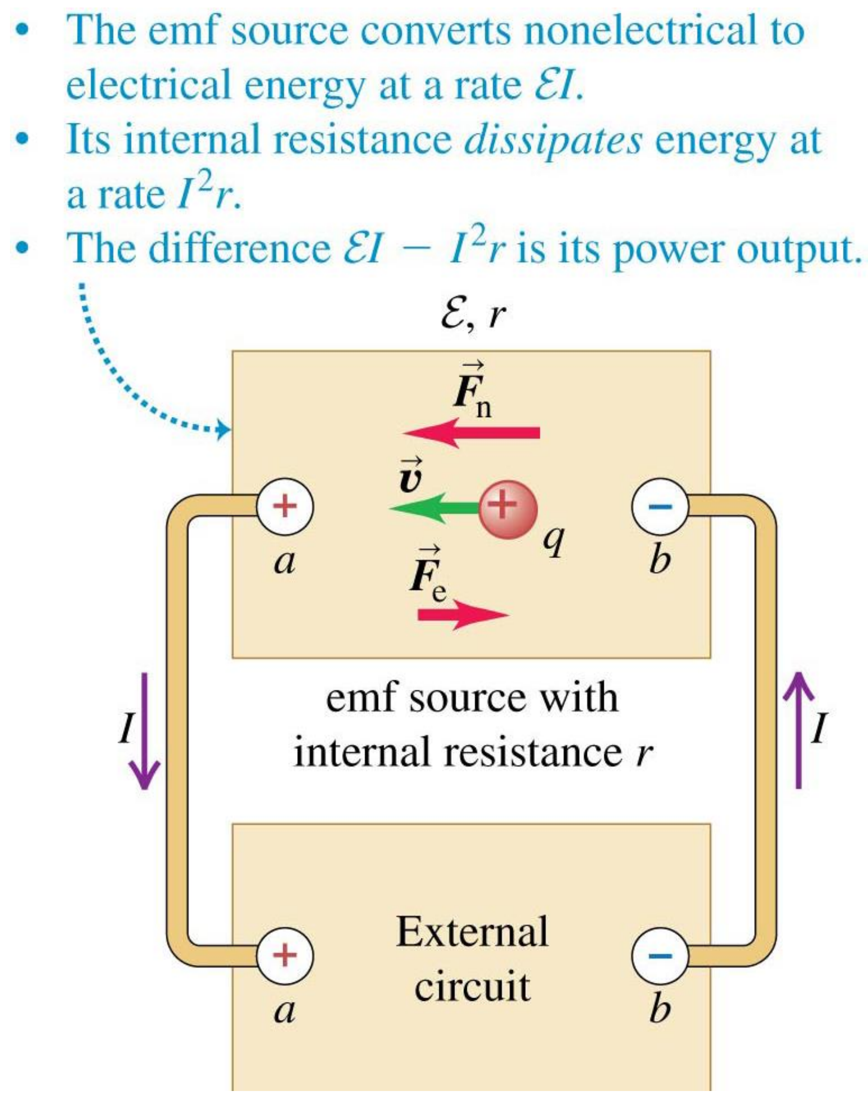
$$W = V_{ab} Q \rightarrow \frac{dW}{dt} = V_{ab} \frac{dQ}{dt}$$

$$P \equiv \frac{dW}{dt} = V_{ab} I = \frac{V_{ab}^2}{R} = I^2 R$$

in case of resistive circuit

Power output of an emf source

- A source with emf $\mathcal{E}$ and internal resistance r connected by ideal wires to an external circuit
- $V_a > V_b \rightarrow V_{ab} > 0$
- Power generated by the emf source: $P_{\text{emf}} = \mathcal{E} I$
- Power delivered to the external circuit: $P = V_{ab} I$
- Power dissipated in the internal resistance: $P_r = I^2 r = P_{\text{emf}} - P$



$$P = \mathcal{E}I - I^2 r$$

25 Summary

- **Current and current density**

- **Resistivity and resistors**

- **Circuits and emf**

- **Energy and power in electric circuits**