Ch.26: Current and Resistance

Physics 104: Electricity and Magnetism

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Outline

Remember From Previous Chapters

Classical Mechanics

- Equations of motion:

$$\vec{\boldsymbol{v}}_f = \vec{\boldsymbol{v}}_i + \vec{\boldsymbol{a}}t$$

$$\vec{\boldsymbol{r}}_f = \vec{\boldsymbol{r}}_i + \vec{\boldsymbol{v}}_i t + \frac{1}{2}\vec{\boldsymbol{a}}t^2$$

$$\vec{\boldsymbol{v}}_f^2 = \vec{\boldsymbol{v}}_i^2 + 2\vec{\boldsymbol{a}} \cdot \left(\vec{\boldsymbol{r}}_f - \vec{\boldsymbol{r}}_i\right)$$

- Newton's Second Law:

$$\sum \vec{\boldsymbol{F}} = m\vec{\boldsymbol{a}}$$

- Work-Energy Theorem:

$$W = \Delta K$$

$$W = \vec{\boldsymbol{F}} \cdot \vec{\boldsymbol{d}}$$

$$K = \frac{1}{2}m\vec{\boldsymbol{v}}^2$$

Electric Field

- Coulomb's Law:

$$\vec{\boldsymbol{F}}_e = k_e \frac{q_1 q_2}{r^2}\hat{\boldsymbol{r}}$$

- Electric Field:

$$\vec{\boldsymbol{E}} = \frac{\vec{\boldsymbol{F}}_e}{q_0} = k_e \frac{q}{r^2}\hat{\boldsymbol{r}}$$

$$\vec{\boldsymbol{a}} = \left(\frac{q}{m}\right)\vec{\boldsymbol{E}}$$

Flux

- Gauss's Law:

$$\Phi_E = \oint \vec{\boldsymbol{E}} \cdot \vec{\boldsymbol{A}} = \frac{q_{\text{in}}}{\varepsilon_0}$$

Remember From Previous Chapters

Electric Potential and Energy

- Electric Potential:

$$V = k_e \frac{q}{r}$$

- Potential Energy:

$$U_E = k_e \frac{q_1 q_2}{r}$$

- Relation to Electric Field:

$$\Delta V = -\vec{\boldsymbol{E}} \cdot \vec{\boldsymbol{d}}$$

- Potential and Energy:

$$\Delta U_E = q \Delta V$$

Capacitance and Dielectrics

- Capacitance:

$$C = \frac{Q}{\Delta V} = \frac{\varepsilon_0 A}{d}$$

- Capacitors in Parallel:

$$C_{\text{eq}} = \sum C_i$$

- Capacitors in Series:

$$\frac{1}{C_{\text{eq}}} = \sum \left(\frac{1}{C_i} \right)$$

- Energy Stored in Capacitor:

$$U_E = \frac{Q^2}{2C} = \frac{1}{2} Q \Delta V$$

$$= \frac{1}{2} C (\Delta V)^2$$

Remember From Previous Chapters

- Energy Density of Electric Field:

$$u_E = \frac{U_E}{V} = \frac{1}{2}\varepsilon_0 E^2$$

- Dielectric Constant:

$$\Delta V = \Delta V_0/\kappa$$

$$C = \kappa C_0$$

$$Q = \kappa Q_0$$

$$U_E = U_0/\kappa$$

1. Electric Current

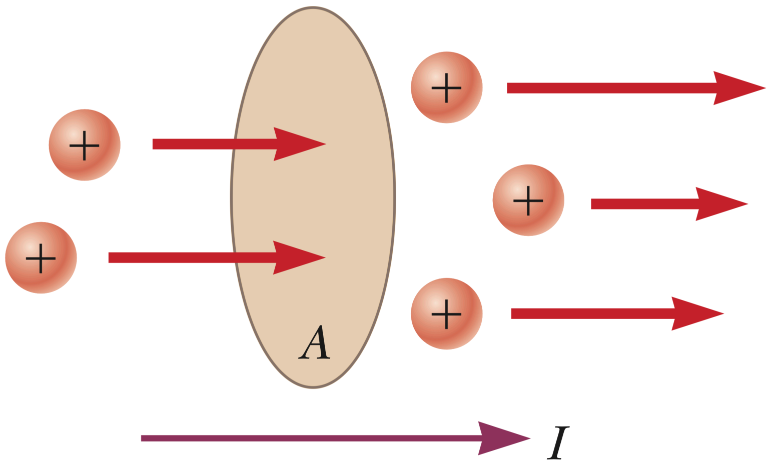
2. Resistance

3. Resistance and Temperature

4. Electrical Power

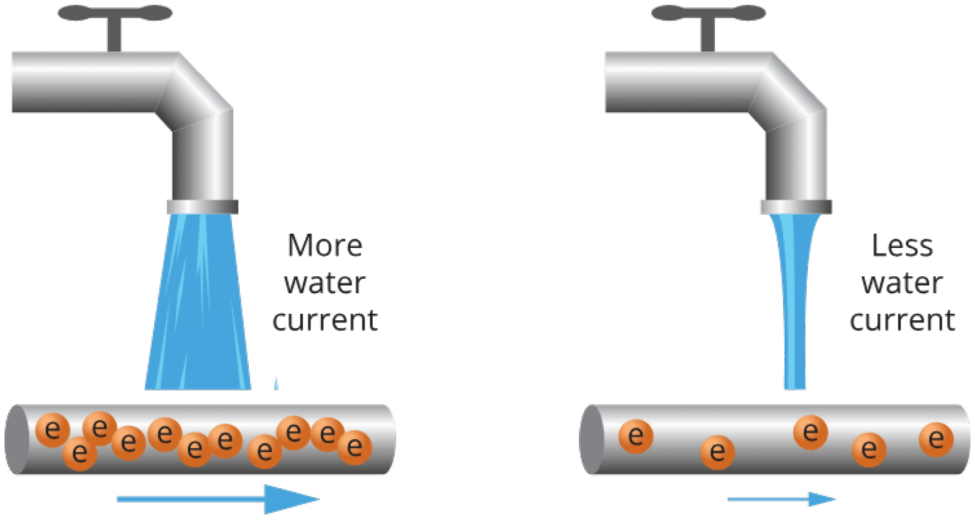
5. Problems

1.1 Definition of electric Current



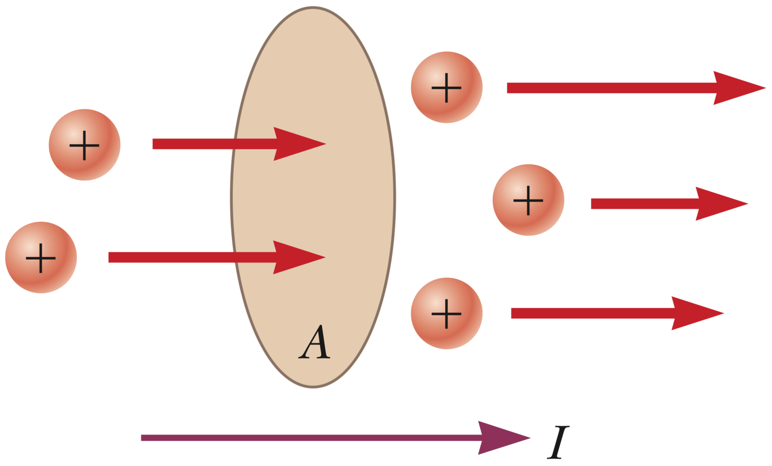
Electric **current** is the flow rate of electric charge. The average current is:

$$I_{\text{avg}} = \frac{\Delta Q}{\Delta t}$$



The larger the flow of charges, the larger the current.

1.1 Definition of electric Current

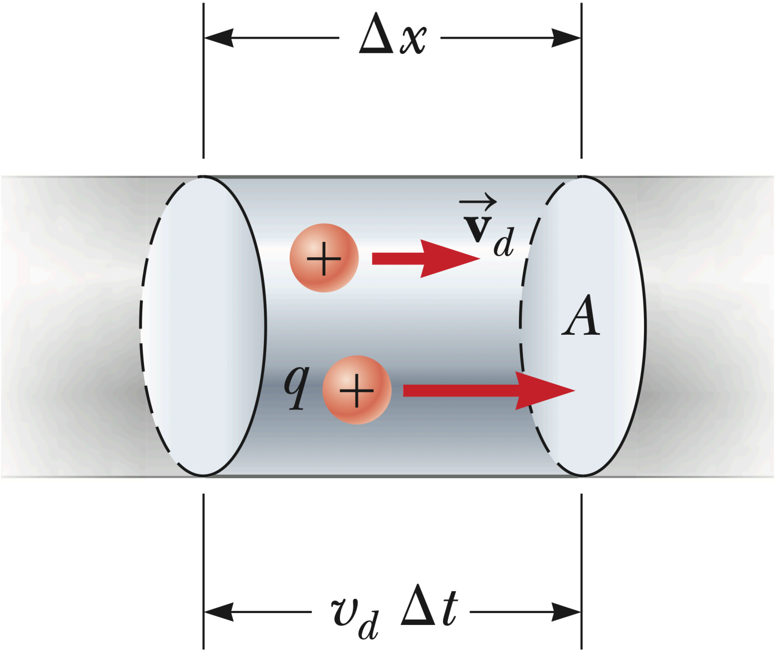


The instantaneous current I is the limit as $\Delta t \to 0$ of the average current,

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

- The SI unit of current is the ampere (A), which is defined as one coulomb per second (C/s).
- A current of 1 ampere means that 1 coulomb of charge is flowing through a surface every second.
- The direction of current is defined as the direction of positive charge flow.

1.2 Microscopic Model of current



When number of charges q per unit volume (n) move with an average drift velocity v_d through a cross-sectional area A, the amount of charge ΔQ that passes through the area in a time interval Δt can be expressed as:

$$\Delta Q = (nAv_d\Delta t)q.$$

Since $I_{\text{avg}} = (\Delta Q)/(\Delta t)$, the current can be expressed as:

$$I_{\text{avg}} = nAv_dq$$

1.2 Microscopic Model of current

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Example 1.1

The 12-gauge copper wire in a typical residential building has a cross-sectional area of $3.31 \times 10^{-6} \mathrm{m}^2$. It carries a constant current of 10 A.

What is the drift speed of the electrons in the wire?

Assume each copper atom contributes one free electron to the current. The density of copper is $\rho = 8.92 \ \mathrm{g/cm^3}$ and its molar mass is $M = 63.5 \ \mathrm{g/mol^{-1}}$. (Use $N_A = 6.02 \times 10^{23} \mathrm{mol}^{-1}$ for Avogadro's number.)

1.2 Microscopic Model of current

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Solution 1.1

$$v_d = \frac{I}{nAq}$$

n is the number of free electrons per unit volume,

$$n = \frac{N_A}{V} = \frac{N_A \rho}{M}$$

Therefore,

$$v_d = \frac{IM}{N_A \rho A q}$$

Substituting the given values in SI units,

$$v_d = 2.23 \times 10^{-4} \text{ m/s}$$

1. Electric Current

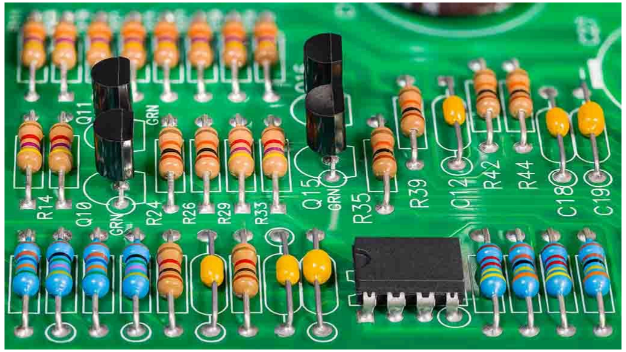
2. Resistance

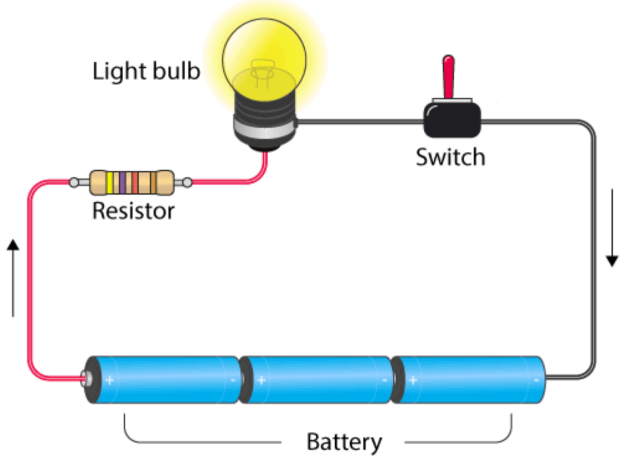
3. Resistance and Temperature

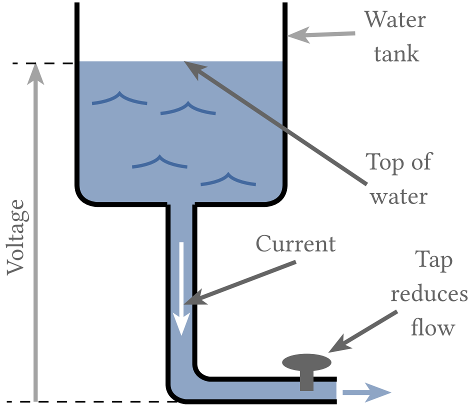
4. Electrical Power

5. Problems

2.1 Have you seen this part before?

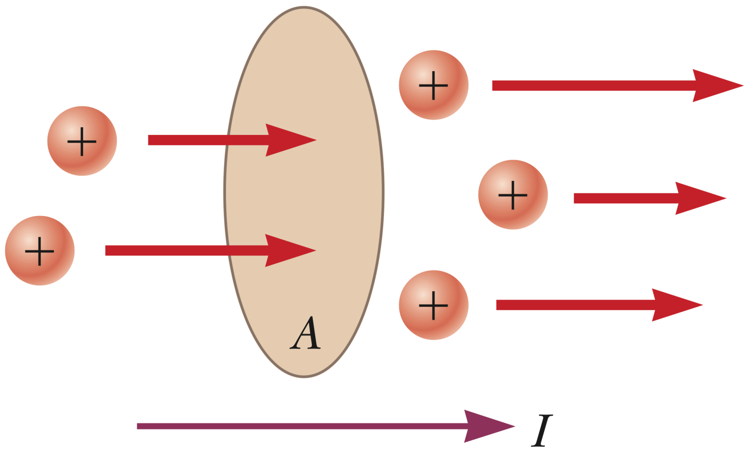






This is a resistor. A resistor is a device that resists the flow of electric current.

2.2 Ohm's Relation



The **Current density** J is defined as the current per unit area,

$$J = \frac{I}{A} = nqv_d$$

Ohm's relation states the following:

"For many materials (including most metals), the ratio of the current density to the electric field is a constant σ that is independent of the electric field producing the current."

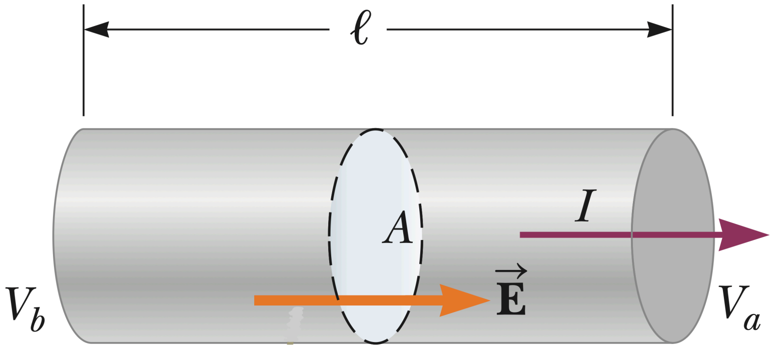
$$\sigma = \frac{J}{E}$$

σ is called the **conductivity** of the material.

$$\rho = \frac{1}{\sigma}$$

ρ is called the **resistivity** of the material.

2.2 Ohm's Relation



When an electric potential difference ΔV is applied across a wire of length ℓ and cross-sectional area A, the electric field in the wire is approximately uniform such that

$$\Delta V = E\ell = \left(\frac{J}{\sigma}\right)\ell = \left(\frac{\rho\ell}{A}\right)I$$

Therefore, the current I and the potential difference ΔV are proportional to each other, and the constant of proportionality is

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

2.2 Ohm's Relation

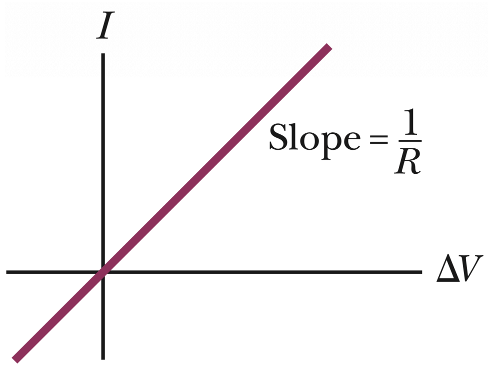
R is called the **resistance** of the conductor and has SI unit of ohms (Ω).

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

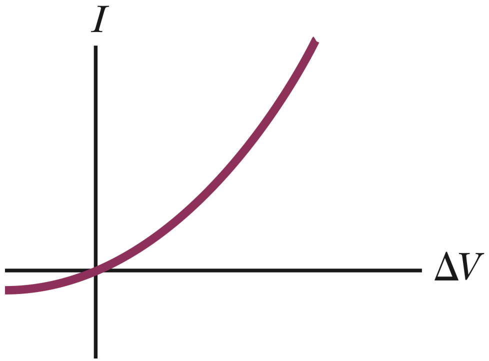
Notice that ρ has a unit of (Ω.m).

Therefore, **Ohm's relation** becomes,

$$\boxed{\Delta V = IR}$$



Ohmic materials



Non-ohmic materials

2.2 Ohm's Relation

Material	Resistivity[a] ($\Omega \cdot m$)	Temperature Coefficient[b] α [$(°C)^{-1}$]
Silver	1.59×10^{-8}	3.8×10^{-3}
Copper	1.7×10^{-8}	3.9×10^{-3}
Gold	2.44×10^{-8}	3.4×10^{-3}
Aluminum	2.82×10^{-8}	3.9×10^{-3}
Tungsten	5.6×10^{-8}	4.5×10^{-3}
Iron	10×10^{-8}	5.0×10^{-3}
Platinum	11×10^{-8}	3.92×10^{-3}
Lead	22×10^{-8}	3.9×10^{-3}
Nichrome[c]	1.00×10^{-6}	0.4×10^{-3}
Carbon	3.5×10^{-5}	-0.5×10^{-3}
Germanium	0.46	-48×10^{-3}
Silicon[d]	2.3×10^{3}	-75×10^{-3}
Glass	10^{10} to 10^{14}	
Hard rubber	$\sim 10^{13}$	
Sulfur	10^{15}	
Quartz (fused)	75×10^{16}	

2.2 Ohm's Relation

The colored bands on this resistor are yellow, violet, black, and gold.

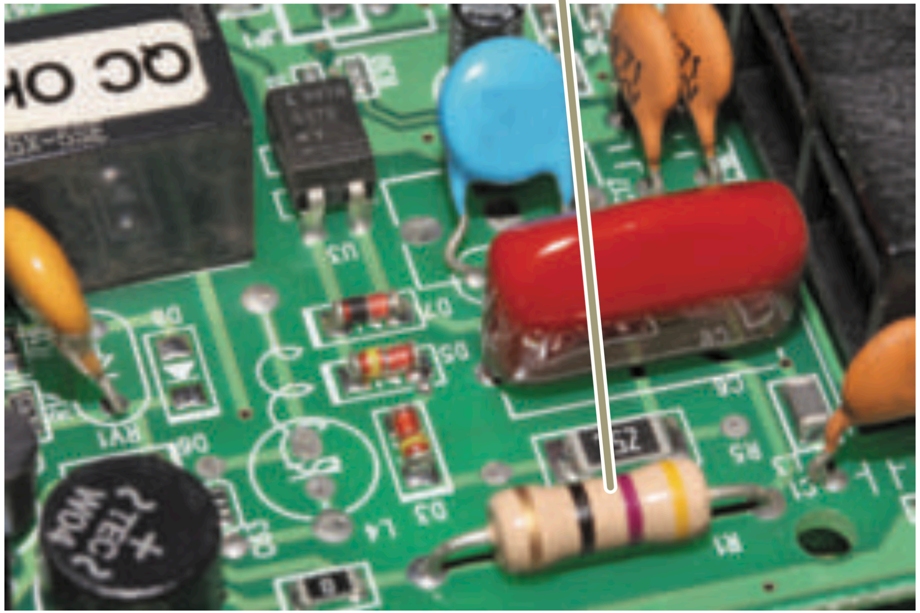


TABLE 26.1 Color Coding for Resistors

Color	Number	Multiplier	Tolerance
Black	0	1	
Brown	1	10^1	
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	
Gold		10^{-1}	5%
Silver		10^{-2}	10%
Colorless			20%

$$R = (\text{Color1 Color2}) \times \text{Color3} \pm \text{Color4} \quad \Omega$$

$$R = 47 \times 1 \pm 5\% \quad \Omega$$

2.3 Example

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Example 2.2

The radius of 22-gauge Nichrome wire is 0.32 mm.

(A) Calculate the resistance per unit length of this wire. ($\rho = 1 \times 10^{-6}\ \Omega.\text{m}$)

Solution 2.2

$$\frac{R}{\ell} = \frac{\rho}{A} = \frac{\rho}{\pi r^2} = \frac{1 \times 10^{-6}}{\pi (0.32 \times 10^{-3})^2} = 3.1\ \Omega/\text{m}$$

2.3 Example

Example 2.3

(B) If a potential difference of 10 V is maintained across a 1 m length of the Nichrome wire, what is the current in the wire?

Solution 2.3

$$I = \frac{\Delta V}{R} = \frac{\Delta V}{(R/\ell)\ell} = \frac{10 \text{ V}}{(3.1 \ \Omega/\text{m})1 \text{ m}} = 3.2 \text{ A}$$

2.3 Example

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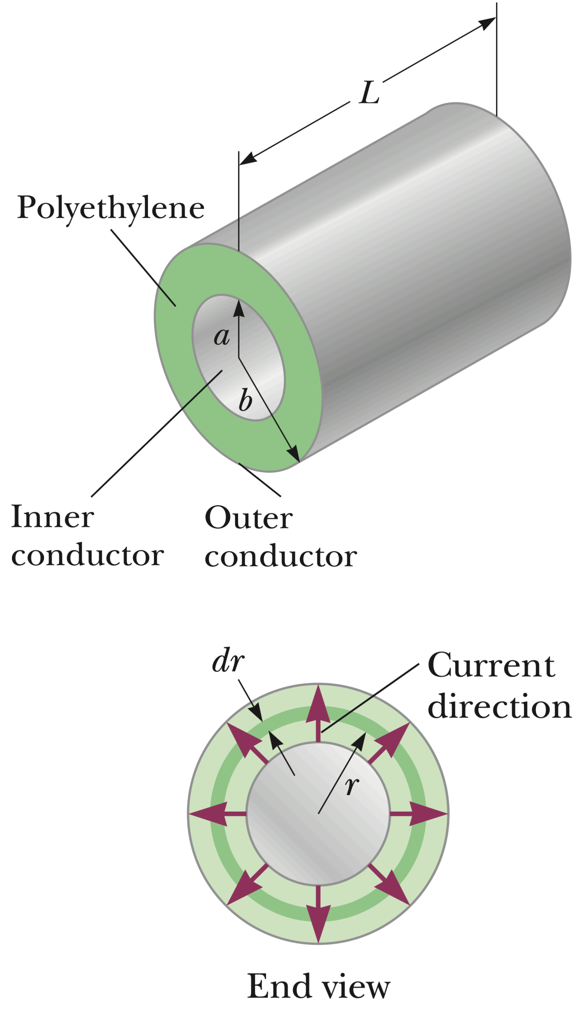
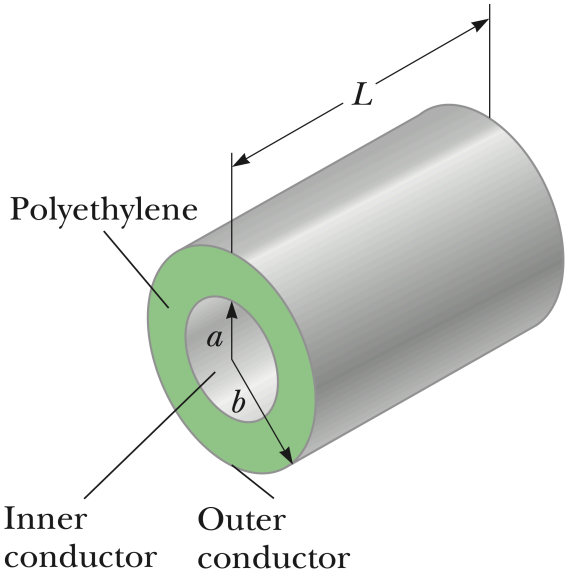
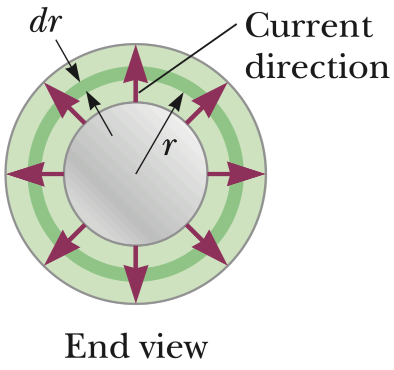
Example 2.4

A coaxial cable consists of two concentric cylindrical conductors. The region between the conductors is completely filled with polyethylene plastic to prevent leakage through the plastic. The radius of the inner conductor is $a = 0.5$cm, the radius of the outer conductor is $b = 1.75$cm, and the length is $L = 15$cm. The resistivity of the plastic is 10^{13} Ω.m. Calculate the radial resistance of the plastic between the two conductors.



2.3 Example





Solution 2.4

$$dR = \frac{\rho}{A}\,dr = \frac{\rho}{2\pi r L}\,dr$$

$$R = \frac{\rho}{2\pi L}\int_a^b \frac{1}{r}\,dr = \frac{\rho}{2\pi L}\ln\left(\frac{b}{a}\right)$$

$$R = \frac{10^{13}}{2\pi(0.15)}\ln\left(\frac{1.75}{0.5}\right) = 1.33\times 10^{13}\ \Omega$$

1. Electric Current

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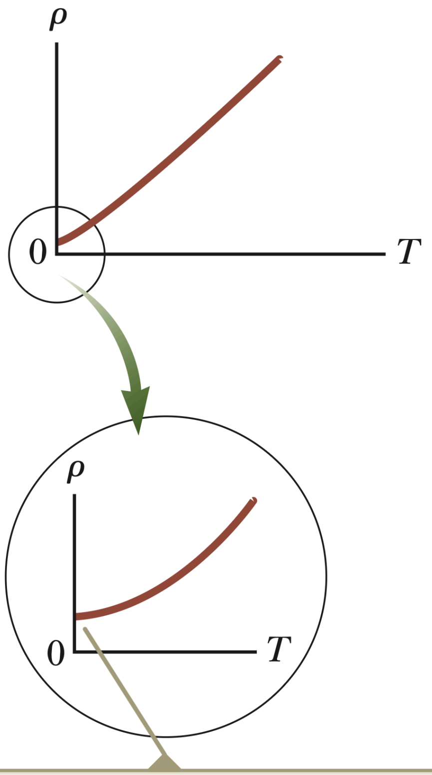
5. Problems

3.1 Temperature Coefficient of Resistivity



As T approaches absolute zero, the resistivity approaches a nonzero value.

- The resistivity ρ of a material generally changes with temperature T as:

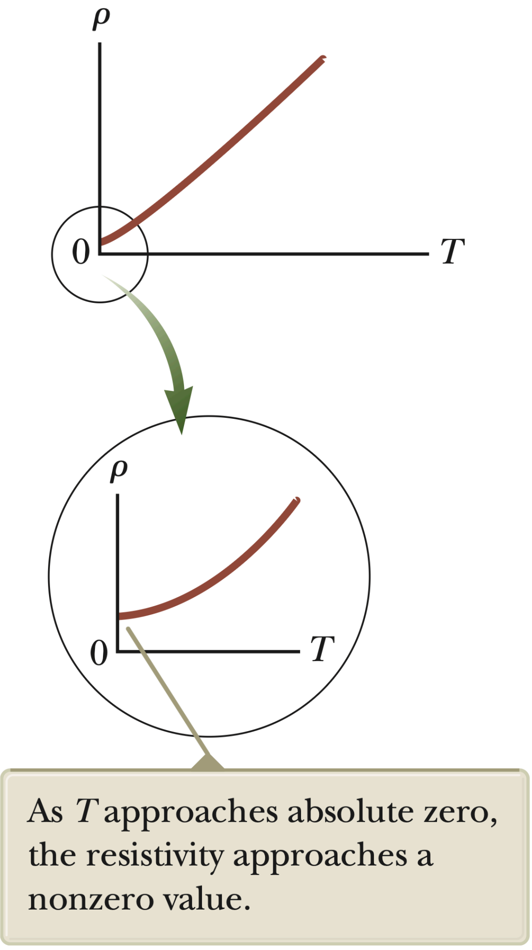
$$\rho = \rho_0[1 + \alpha(T - T_0)]$$

where ρ_0 is the resistivity at a reference temperature T_0, and α is the **temperature coefficient of resistivity**.

- Since the resistance R is proportional to the resistivity ρ, the resistance also changes with temperature as:

$$R = R_0[1 + \alpha(T - T_0)]$$

3.1 Temperature Coefficient of Resistivity



- From the above equations, we can express α as:

$$\alpha = \frac{\rho - \rho_0}{\rho_0(T - T_0)} = \frac{R - R_0}{R_0(T - T_0)}$$

- The unit of α is typically the inverse of degrees Celsius (C^{-1}).
- The temperature coefficient α is normally positive, but can be negative for some materials (such as semiconductors).

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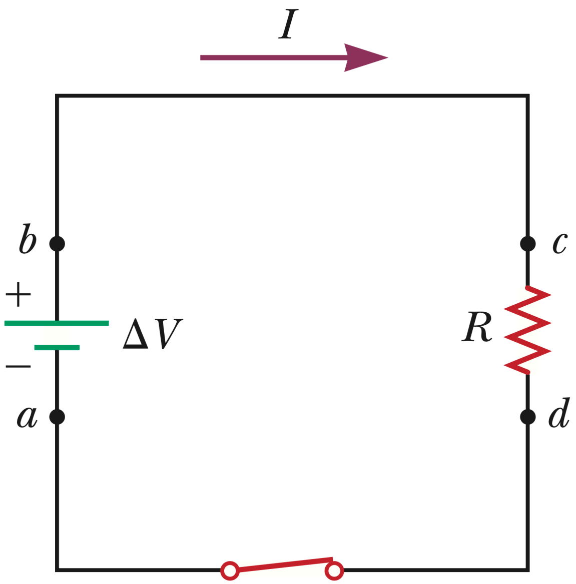
4.1 Electrical Power

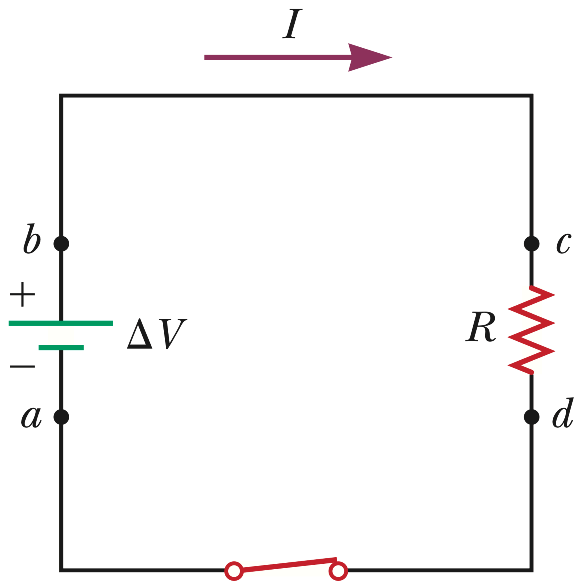


- The electric power P delivered by a power source in a circuit is the rate at which energy is transferred to electric parts, such as resistors,

$$P = \frac{\mathrm{d}U_E}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}(Q\Delta V) = \frac{\mathrm{d}Q}{\mathrm{d}t}\Delta V$$

$$\boxed{P = I\Delta V}$$

4.2 Power on a Resistor



- The power consumed by a resistor ($R = \Delta V / I$) is converted into thermal energy and other forms of energy, and can be calculated as:

$$P = I^2 R = \frac{(\Delta V)^2}{R}$$

- The electric energy consumed by a resistor over a time interval Δt can be calculated as:

$$\text{Energy} = P \Delta t$$

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Example 4.5

An electric heater is constructed by applying a potential difference of 120 V across a Nichrome wire that has a total resistance of 8Ω. Find the current carried by the wire and the power rating of the heater.

Solution 4.5

$$I = \frac{\Delta V}{R} = \frac{120 \text{ V}}{8\Omega} = 15 \text{ A}$$

$$P = I\Delta V = (15 \text{ A})(120 \text{ V}) = 1800 \text{ W}$$

4.3 Example

Example 4.6

An immersion heater must increase the temperature of 1.5 kg of water from 10°C to 50°C in 10 min while operating at 110 V.

(A) What is the required resistance of the heater?

4.3 Example

Solution 4.6

The energy required to heat the water is:

$$H = mc\Delta T,$$

where m is the mass, c is the specific heat capacity, and ΔT is the change in temperature. Therefore, the power the resister has to provide is:

$$P = \frac{(\Delta V)^2}{R} = \frac{H}{\Delta t}$$

Solving for R gives:

$$R = \frac{(\Delta V)^2 \Delta t}{mc\Delta T} = \frac{(110\ \text{V})^2(600\ \text{s})}{(1.5\ \text{kg})(4184\ \text{J/kg.C})(40\ \text{C})} = 28.9\ \Omega$$

4.3 Example

(B) Estimate the cost of heating the water.

Solution 4.6

$$\text{Energy} = P\Delta t = \frac{(\Delta V)^2}{R}\Delta t = \frac{(110\ \text{V})^2}{28.9\ \Omega}(10\ \text{min})\left(\frac{1\ \text{h}}{60\ \text{min}}\right) = 0.07\ \text{kWh}$$

$$\text{Cost} = \text{Energy} \times \text{Cost/kWh} = (0.07\ \text{kWh})\left(\frac{0.18\ \text{ريال}}{\text{kWh}}\right) = 0.013\ \text{ريال}$$

Suggested Problems

4, 6, 10, 13, 17, 18, 23, 28, 30, 35

Book: Serway, R. A., & Jewett, J. W. (2018). Physics for Scientists and Engineers (10th ed.)

Chapter: 26 - Current and Resistance

1. Electric Current

2. Resistance

3. Resistance and Temperature

4. Electrical Power

5. Problems

5.1 Electric Current

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Problem 5.1

4. **Q|C** A copper wire has a circular cross section with a radius of 1.25 mm. (a) If the wire carries a current of 3.70 A, find the drift speed of the electrons in this wire. (b) All other things being equal, what happens to the drift speed in wires made of metal having a larger number of conduction electrons per atom than copper? Explain.

5.1 Electric Current

Answer 5.1

(A) The drift speed of the electrons can be calculated using the formula:

$$v_d = \frac{I}{nAq}$$

Where the area of the wire is $A = \pi r^2$. The number of free electrons per unit volume (similar to example 1):

$$n = \frac{N_A \rho}{M} = \frac{6.02 \times 10^{23}\text{mol}^{-1}(8.92\ \text{g/cm}^3)}{63.5\ \text{g/mol}^{-1}} = 8.46 \times 10^{28}\text{m}^{-3}$$

Therefore, the drift speed is:

$$v_d = \frac{3.7\ \text{C/s}}{(8.46 \times 10^{28}\text{m}^{-3})\left(\pi(1.25 \times 10^{-3})^2\right)(1.6 \times 10^{-19}\ \text{C})} = 5.6 \times 10^{-5}\ \text{m/s}$$

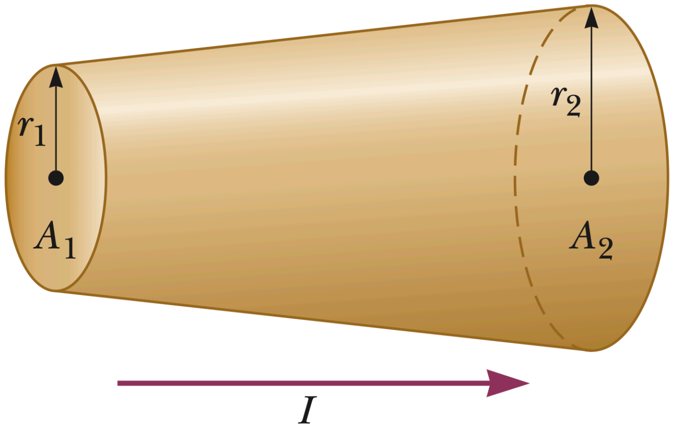
5.1 Electric Current

(B) The drift speed of the electrons is inversely proportional to the number of free electrons per unit volume. Therefore, the more free electrons in a conductor, the slower they move on average.

5.1 Electric Current

Problem 5.2

6. QIC V Figure P26.6 represents a section of a conductor of nonuniform diameter carrying a current of $I = 5.00$ A. The radius of cross-section A_1 is $r_1 = 0.400$ cm. (a) What is the magnitude of the current density across A_1? The radius r_2 at A_2 is larger than the radius r_1 at A_1. (b) Is the current at A_2 larger, smaller, or the same? (c) Is the current density at A_2 larger, smaller, or the same? Assume $A_2 = 4A_1$. Specify the (d) radius, (e) current, and (f) current density at A_2.



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Answer 5.2

(A)

$$J = \frac{I}{A} = \frac{5\ \text{A}}{\pi(4\times 10^{-3})^2} = 99.5\ \text{kA/m}^2$$

(B) The current (I) does not change with the radius of the wire.
(C) The current density (J) decreases as the radius increases.
(D)

$$A_2 = 4A_1 \Rightarrow \pi r_2^2 = 4\pi r_1^2 \Rightarrow r_2 = 2r_1 = 8\ \text{mm}$$

(E) $I = 5\ \text{A}$ everywhere in the wire.
(F) $J_2 = J_1/4$ because J is inversely proportional to the area.

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Problem 5.3

10. **T** A wire 50.0 m long and 2.00 mm in diameter is connected to a source with a potential difference of 9.11 V, and the current is found to be 36.0 A. Assume a temperature of 20.0°C and, using Table 26.2, identify the metal out of which the wire is made.

5.2 Resistance

Answer 5.3

We can identify the metal by calculating the resistivity ρ using the formula:

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

using ($A = \pi r^2 = \pi(d/2)^2 = \pi d^2/4$) and ($R = \Delta V/I$), we get:

$$\rho = \frac{\Delta V}{I}\frac{\pi d^2/4}{\ell} = 1.59 \times 10^{-8}\ \Omega.\text{m}$$

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Problem 5.4

13. **T** Suppose you wish to fabricate a uniform wire from 1.00 g of copper. If the wire is to have a resistance of $R = 0.500\ \Omega$ and all the copper is to be used, what must be (a) the length and (b) the diameter of this wire?

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Answer 5.4

(A)
$$R = \frac{\rho \ell}{A} \implies \ell = \frac{RA}{\rho}$$

Since R is given and ρ is known for the copper material, we only need to find the area A of the wire. From the volume of the wire, we can find the area as $V = A\ell$, so $A = V/\ell$. The volume can be calculated from the mass M (which is given) and density ρ_M (constant for copper) as $V = M/\rho_M$. Therefore, the length of the wire is:

$$\ell = \frac{R(V/\ell)}{\rho} = \frac{R(M/\rho_M)}{\ell\ \rho}$$

$$\implies \ell = \sqrt{\frac{RM}{\rho\rho_M}} = \sqrt{\frac{(10^{-3}\ \ \mathrm{Kg})(0.5\ \Omega)}{(1.7\times 10^{-8}\ \Omega.\mathrm{m})(8.92\times 10^{3}\ \mathrm{Kg/m^3})}} = 1.82\ \mathrm{m}$$

5.2 Resistance

(B) From Part (A) we found that the area can be calculated as

$$A = \frac{V}{\ell} = \frac{M/\rho_M}{\ell}$$

Also, we know that $A = \pi r^2$, therefore,

$$A = \frac{M}{\ell\ \rho_M} = \pi r^2$$

$$\Longrightarrow r = \sqrt{\frac{M}{\pi\ \ell\ \rho_M}} = 1.4 \times 10^{-4}\ \text{m}$$

Finally, the diameter of the wire is:

$$\Longrightarrow D = 2r = 2.8 \times 10^{-4}\ \text{m}$$

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Problem 5.5

17. What is the fractional change in the resistance of an iron filament when its temperature changes from 25.0°C to 50.0°C?

5.3 Resistance and Temperature

Answer 5.5

The resistance at T can be calculated using the formula:

$$R = R_0[1 + \alpha(T - T_0)] = R_0 + R_0\alpha(T - T_0)$$

The fractional change in resistance is:

$$\frac{R - R_0}{R_0} = \alpha(T - T_0) = (5 \times 10^{-3}\text{C}^{-1})(50\ \text{C} - 25\ \text{C}) = 0.12$$

The value of α for iron is taken from the table of temperature coefficients for different materials (see your book).

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Problem 5.6

18. A certain lightbulb has a tungsten filament with a resistance of 19.0 Ω when at 20.0°C and 140 Ω when hot. Assume the resistivity of tungsten varies linearly with temperature even over the large temperature range involved here. Find the temperature of the hot filament.

5.3 Resistance and Temperature

Answer 5.6

$$R = R_0[1 + \alpha(T - T_0)] = R_0 + R_0\alpha(T - T_0)$$

$$T - T_0 = \frac{R - R_0}{R_0\alpha}$$

$$T = \frac{R - R_0}{R_0\alpha} + T_0$$

$$T = 1.44 \times 10^3\ {}^\circ\mathrm{C}$$

Problem 5.7

23. Assume that global lightning on the Earth constitutes a constant current of 1.00 kA between the ground and an atmospheric layer at potential 300 kV. (a) Find the power of terrestrial lightning. (b) For comparison, find the power of sunlight falling on the Earth. Sunlight has an intensity of 1 370 W/m^2 above the atmosphere. Sunlight falls perpendicularly on the circular projected area that the Earth presents to the Sun.

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Answer 5.7

(a)

$$P = \Delta V \ I = 3 \times 10^8 \ \text{W}$$

(b)

$$I = \frac{P}{A} = \frac{P}{\pi r^2}$$

$$P = I(\pi r^2) = (1370 \ \text{W/m}^2)\left[\pi(6.37 \times 10^6 \ \text{m})^2\right] = 1.75 \times 10^{17} \ \text{W}$$

5.4 Electrical Power

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Problem 5.8

28. Q|C V Residential building codes typically require the use of 12-gauge copper wire (diameter 0.205 cm) for wiring receptacles. Such circuits carry currents as large as 20.0 A. If a wire of smaller diameter (with a higher gauge number) carried that much current, the wire could rise to a high temperature and cause a fire. (a) Calculate the rate at which internal energy is produced in 1.00 m of 12-gauge copper wire carrying 20.0 A. (b) **What If?** Repeat the calculation for a 12-gauge aluminum wire. (c) Explain whether a 12-gauge aluminum wire would be as safe as a copper wire.

5.4 Electrical Power

Answer 5.8

(A)

$$R = \frac{\rho \ell}{A} = \frac{\rho \ell}{\pi \left(\frac{d}{2}\right)^2} = 5.2 \times 10^{-3}\ \Omega$$

$$P = I\Delta V = I^2 R = (20\ \text{A})^2 (5.2 \times 10^{-3}\ \Omega) = 2.1\ \text{W}$$

(B) Similar to Part (A), we can calculate the power for aluminum, and we get:

$$P = 3.42\ \text{W}$$

(C) Copper is safer to use than aluminum because it has a lower resistivity, which means it will dissipate less power (and thus generate less heat) for the same current.

5.4 Electrical Power

Problem 5.9

30. An 11.0-W energy-efficient fluorescent lightbulb is designed to produce the same illumination as a conventional 40.0-W incandescent lightbulb. Assuming a cost of $0.110/kWh for energy from the electric company, how much money does the user of the energy-efficient bulb save during 100 h of use?

5.4 Electrical Power

Answer 5.9

For the 11W bulb, the current can be calculated as:

$$\text{Energy} = P\Delta t = 3.96 \times 10^6 \;\; \text{J}$$

The cost of energy can be calculated as:

$$\text{Cost} = \text{Energy} \times \text{Cost/kWh} = (3.96 \times 10^6 \;\; \text{J})\left(\frac{\$0.11}{3.6 \times 10^6 \;\; \text{J}}\right) = \$0.121$$

Repeating the calculation for the 40 W bulb, we get the cost to be \$ 0.44.
Therefore, the savings from using the 11 W bulb instead of the 40 W bulb is:

$$\text{Savings} = \$0.44 - \$0.121 = \$0.32$$

5.4 Electrical Power

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Problem 5.10

35. **V** One wire in a high-voltage transmission line carries 1 000 A starting at 700 kV for a distance of 100 mi. If the resistance in the wire is 0.500 Ω/mi, what is the power loss due to the resistance of the wire?

5.4 Electrical Power

Answer 5.10

The power consumed by the wire is:

$$P = I^2 R = I^2 \left(\frac{R}{\ell}\right)\ell = (1000\ \mathrm{A})^2 \left(\frac{0.5\ \Omega}{1\ \mathrm{mi}}\right)(100\ \mathrm{mi}) = 50\ \mathrm{MW}$$