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18-1 The Electric Battery

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

This is a simple electric cell.

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.
18-2 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.

\[ 1 \text{ A} = 1 \text{ C/s} \]
18-2 Electric Current

A complete circuit is one where current can flow all the way around. Note that the schematic drawing doesn’t look much like the physical circuit!
In order for current to flow, there must be a path from one battery terminal, through the circuit, and back to the other battery terminal. Only one of these circuits will work:
By convention, current is defined as flowing from + to −. Electrons actually flow in the opposite direction, but not all currents consist of electrons.
18-3 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.

The ratio of voltage to current is called the resistance:

\[ V = IR. \]  
(18-2)
18-3 Ohm’s Law: Resistance and Resistors

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.

\[ 1 \, \Omega = 1 \, \text{V/A} \]
Example (1)

- What is the current in amperes if 1200 Na⁺ ions flow across the cell membrane in 3.1 µs?

Solution strategy: \[ I = \frac{\Delta Q}{\Delta t} \]

What is \( \Delta Q \)? This is the charge of 1200 ions of sodium. Since each sodium atom has lost only 1 electron, then

\[ \Delta Q = 1200 \times 1.6 \times 10^{-19} C = 1.92 \times 10^{-16} C \]

Now we can find \( I \):

\[ I = \frac{1.92 \times 10^{-16} C}{3.1 \times 10^{-6} s} = 0.62 \times 10^{-10} A \]
Examples (2)

(1) What is the resistance of a toaster if 120 V produces a current of 4.6 A?

Solution:

\[ V = I \cdot R \quad \Rightarrow \quad R = \frac{V}{I} = \frac{120V}{4.6A} = 26.1\Omega \]

(2) A bird stands on a dc electric transmission line carrying 4100A. The line has 2.5x10^{-5} resistance per meter, and the bird’s feet are 4 cm apart. What is the potential difference between the bird’s feet?

Solution:

What is R? R is 0.04 of the resistance per meter (4 cm = 0.04 m)

\[ V = I \cdot R = 4100A \cdot 0.04 \cdot 2.5 \cdot 10^{-5} \Omega = 4.1 \times 10^{-3}V \]
Standard resistors are manufactured for use in electric circuits; they are color-coded to indicate their value and precision.

<table>
<thead>
<tr>
<th>Resistor Color Code</th>
<th>Color</th>
<th>Number</th>
<th>Multiplier</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>0</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Brown</td>
<td>1</td>
<td></td>
<td>$10^1$</td>
<td>1%</td>
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<tr>
<td>Red</td>
<td>2</td>
<td></td>
<td>$10^2$</td>
<td>2%</td>
</tr>
<tr>
<td>Orange</td>
<td>3</td>
<td></td>
<td>$10^3$</td>
<td></td>
</tr>
<tr>
<td>Yellow</td>
<td>4</td>
<td></td>
<td>$10^4$</td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>5</td>
<td></td>
<td>$10^5$</td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td>6</td>
<td></td>
<td>$10^6$</td>
<td></td>
</tr>
<tr>
<td>Violet</td>
<td>7</td>
<td></td>
<td>$10^7$</td>
<td></td>
</tr>
<tr>
<td>Gray</td>
<td>8</td>
<td></td>
<td>$10^8$</td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>9</td>
<td></td>
<td>$10^9$</td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td></td>
<td></td>
<td>$10^{-1}$</td>
<td>5%</td>
</tr>
<tr>
<td>Silver</td>
<td></td>
<td></td>
<td>$10^{-2}$</td>
<td>10%</td>
</tr>
<tr>
<td>No color</td>
<td></td>
<td></td>
<td></td>
<td>20%</td>
</tr>
</tbody>
</table>
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.
18-4 Resistivity

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

\[ R = \rho \frac{l}{A} \]  \hspace{1cm} (18-3)

The constant \( \rho \), the resistivity, is characteristic of the material.
## TABLE 18-1 Resistivity and Temperature Coefficients (at 20°C)

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity, $\rho$ (Ω · m)</th>
<th>Temperature Coefficient, $\alpha$ (°C$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conductors</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>$1.59 \times 10^{-8}$</td>
<td>0.0061</td>
</tr>
<tr>
<td>Copper</td>
<td>$1.68 \times 10^{-8}$</td>
<td>0.0068</td>
</tr>
<tr>
<td>Gold</td>
<td>$2.44 \times 10^{-8}$</td>
<td>0.0034</td>
</tr>
<tr>
<td>Aluminum</td>
<td>$2.65 \times 10^{-8}$</td>
<td>0.00429</td>
</tr>
<tr>
<td>Tungsten</td>
<td>$5.6 \times 10^{-8}$</td>
<td>0.0045</td>
</tr>
<tr>
<td>Iron</td>
<td>$9.71 \times 10^{-8}$</td>
<td>0.00651</td>
</tr>
<tr>
<td>Platinum</td>
<td>$10.6 \times 10^{-8}$</td>
<td>0.003927</td>
</tr>
<tr>
<td>Mercury</td>
<td>$98 \times 10^{-8}$</td>
<td>0.0009</td>
</tr>
<tr>
<td>Nichrome (Ni, Fe, Cr alloy)</td>
<td>$100 \times 10^{-8}$</td>
<td>0.0004</td>
</tr>
<tr>
<td><strong>Semiconductors</strong>‡</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon (graphite)</td>
<td>$(3–60) \times 10^{-5}$</td>
<td>$–0.0005$</td>
</tr>
<tr>
<td>Germanium</td>
<td>$(1–500) \times 10^{-3}$</td>
<td>$–0.05$</td>
</tr>
<tr>
<td>Silicon</td>
<td>$0.1–60$</td>
<td>$–0.07$</td>
</tr>
<tr>
<td><strong>Insulators</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>$10^9–10^{12}$</td>
<td></td>
</tr>
<tr>
<td>Hard rubber</td>
<td>$10^{13–10^{15}}$</td>
<td></td>
</tr>
</tbody>
</table>

‡ Values depend strongly on the presence of even slight amounts of impurities.
18-4 Resistivity

For any given material, the resistivity increases with temperature:

$$\rho_T = \rho_0[1 + \alpha(T - T_0)]$$  \hspace{1cm} (18-4)

Semiconductors are complex materials, and may have resistivities that decrease with temperature.
Example (3)

• A certain copper wire has a resistance of $15 \, \Omega$. At what point along its length must the wire be cut so that the resistance of one piece is 4 times the resistance of the other? What is the resistance of each piece?

• Answer: 4:1; $12 \, \Omega$ and $3 \, \Omega$
18-5 Electric Power

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

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

The unit of power is the watt, W.

For ohmic devices, we can make the substitutions:

\[ P = IV = I(IR) = I^2R \quad (18-6a) \]

\[ P = IV = \left(\frac{V}{R}\right)V = \frac{V^2}{R} \quad (18-6b) \]
18-5 Electric Power

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 x 10^6 J
18-6 Power in Household Circuits

The wires used in homes to carry electricity have very low resistance. However, if the current is high enough, the power will increase and the wires can become hot enough to start a fire.

To avoid this, we use fuses or circuit breakers, which disconnect when the current goes above a predetermined value.

Fuses are one-use items—if they blow, the fuse is destroyed and must be replaced.
18-6 Power in Household Circuits

Circuit breakers, which are now much more common in homes than they once were, are switches that will open if the current is too high; they can then be reset.
Example (4)

- You want to design a portable electric blanket that runs on a 1.5 V battery. If you use 0.5 mm diameter copper wire as the heating element, how long should be the wire if you want to generate 18 W?
  - Answer: 1.5 m; Hint: use these formulas:

\[
R = \rho \frac{\ell}{A} = \rho \frac{\ell}{\pi r^2} = \frac{4\rho \ell}{\pi d^2}; \quad P = \frac{V^2}{R} = \frac{V^2}{4\rho \ell / \pi d^2}
\]

- 220 V is applied to two different conductors made of the same material. One conductor is twice as long and twice the diameter of the second. What is the ratio of the power transformed in the first relative to the second?
  - Answer: The ratio is = 2
Current from a battery flows steadily in one direction (direct current, DC). Current from a power plant varies sinusoidally (alternating current, AC).
The voltage varies sinusoidally with time:

\[ V = V_0 \sin 2\pi ft = V_0 \sin \omega t \]  \hspace{1cm} (18-7a)

as does the current:

\[ I = \frac{V}{R} = \frac{V_0}{R} \sin \omega t = I_0 \sin \omega t. \]  \hspace{1cm} (18-7b)
Multiplying the current and the voltage gives the power:

\[ P = I^2R = I_0^2R \sin^2 \omega t. \]  

Average power:

\[ \bar{P} = \frac{1}{2} I_0^2R \]

\[ \bar{P} = \frac{1}{2} \frac{V_0^2}{R} \]
The current and voltage both have average values of zero, so we square them, take the average, then take the square root, yielding the root mean square (rms) value.

\[ I_{\text{rms}} = \sqrt{I^2} = \frac{I_0}{\sqrt{2}} = 0.707 I_0 \]  
\[ V_{\text{rms}} = \sqrt{V^2} = \frac{V_0}{\sqrt{2}} = 0.707 V_0. \]
Example (5)

- An 1800-W arc welder is connected to a 660-V\textsubscript{rms} ac line. Calculate (a) the peak voltage and (b) the peak current.

- Answer: a) 930 V
  b) 3.9 A
Electrons in a conductor have large, random speeds just due to their temperature. When a potential difference is applied, the electrons also acquire an average drift velocity, which is generally considerably smaller than the thermal velocity.
18-8 Microscopic View of Electric Current

This drift speed is related to the current in the wire, and also to the number of electrons per unit volume.

\[ \Delta Q = (\text{number of charges, } N) \times (\text{charge per particle}) \]
\[ = (nV)(e) = (nA\nu_d \Delta t)(e). \]

\[ I = \frac{\Delta Q}{\Delta t} = neA\nu_d \quad (18-10) \]
In general, resistivity decreases as temperature decreases. Some materials, however, have resistivity that falls abruptly to zero at a very low temperature, called the critical temperature, $T_C$. 
Experiments have shown that currents, once started, can flow through these materials for years without decreasing even without a potential difference.

Critical temperatures are low; for many years no material was found to be superconducting above 23 K.

More recently, novel materials have been found to be superconducting below 90 K, critical temperatures as high as 160K have been reported.
18-10 Electrical Conduction in the Human Nervous System

The human nervous system depends on the flow of electric charge.

The basic elements of the nervous system are cells called neurons.

Neurons have a main cell body, small attachments called dendrites, and a long tail called the axon.
Signals are received by the dendrites, propagated along the axon, and transmitted through a connection called a synapse.
18-10 Electrical Conduction in the Human Nervous System

This process depends on there being a dipole layer of charge on the cell membrane, and different concentrations of ions inside and outside the cell.
This applies to most cells in the body. Neurons can respond to a stimulus and conduct an electrical signal. This signal is in the form of an action potential.
The action potential propagates along the axon membrane.
Summary of Chapter 18

• A battery is a source of constant potential difference.

• Electric current is the rate of flow of electric charge.

• Conventional current is in the direction that positive charge would flow.

• Resistance is the ratio of voltage to current:

\[ V = IR. \]
Summary of Chapter 18

• Ohmic materials have constant resistance, independent of voltage.

• Resistance is determined by shape and material:
  • $\rho$ is the resistivity.
  • Power in an electric circuit:

\[ R = \rho \frac{\ell}{A} \]

\[ P = IV. \]
Summary of Chapter 18

• Direct current is constant

• Alternating current varies sinusoidally

The average (rms) current and voltage:

\[ I = \frac{V}{R} = \frac{V_0}{R} \sin \omega t = I_0 \sin \omega t \]

\[ I_{\text{rms}} = \sqrt{I^2} = \frac{I_0}{\sqrt{2}} = 0.707 I_0 \]

\[ V_{\text{rms}} = \sqrt{V^2} = \frac{V_0}{\sqrt{2}} = 0.707 V_0 \]

\[ I = \frac{\Delta Q}{\Delta t} = ne A v_d \]