Lecture 4, 7/17/2017

- The Electric Battery
- Electric Current
- Ohm’s Law, Resistance, Resistivity
- Electric Power
- Alternating Current
- Resistors in Series and in Parallel
- Kirchhoff’s Rules
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.
The Electric Battery

A battery transforms chemical energy into electrical energy.

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

\[ 1 \text{ A} = 1 \text{ C/s} \]
A complete circuit is one where current can flow all the way around.
Electric Current

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:
Electric Current

By convention, current is defined as flowing from + to −. Electrons actually flow in the opposite direction, but not all currents consist of electrons.
Ohm’s Law: Resistance and Resistors

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

\[ I \propto V \]

The ratio of voltage to current is called the resistance:

\[ V = IR. \]
Ohm’s Law

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 Ω = 1 V/A
Some clarifications:

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

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

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

The constant \( \rho \), the resistivity, is characteristic of the material.

For any given material, the resistivity increases with temperature:

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

Semiconductors are complex materials, and may have resistivities that decrease with temperature.
# Resistivity

## 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>

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$^{\dagger}$ Values depend strongly on the presence of even slight amounts of impurities.
Electric Power

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

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

The unit of power is the watt, W.

For ohmic devices (V=IR), we can make the substitutions:

\[ P = IV = I(IR) = I^2R \]

\[ P = IV = \left( \frac{V}{R} \right)V = \frac{V^2}{R} \]
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
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 (P=IV) 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.
Power in Household Circuits

Fuses are one-use items—if they blow, the fuse is destroyed and must be replaced.

(a) Types of fuses
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.
Current from a battery flows steadily in one direction (direct current, DC).

Current from a power plant varies sinusoidally (alternating current, AC).
Alternating Current

The voltage varies sinusoidally with time:

\[ V = V_0 \sin 2\pi f t = V_0 \sin \omega t \]

as does the current:

\[ I = \frac{V}{R} = \frac{V_0}{R} \sin \omega t = I_0 \sin \omega t. \]
Multiplying the current and the voltage gives the power:

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

Usually we are interested in the average power:

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

$$\bar{P} = \frac{1}{2} \frac{V_0^2}{R}$$
Alternating Current

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.

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

\[ V_{\text{rms}} = \sqrt{V^2} = \frac{V_0}{\sqrt{2}} = 0.707 V_0 \]
**EMF and Terminal Voltage**

Electric circuit needs battery or generator to produce current—these are called sources of emf.

Battery is a nearly constant voltage source, but does have a small internal resistance, which reduces the actual voltage from the ideal emf:

\[ V_{ab} = \mathcal{E} - Ir. \]
EMF and Terminal Voltage

This resistance behaves as though it were in series with the emf.

\[ V_{ab} = \text{terminal voltage} \]
A series connection has a single path from the battery, through each circuit element in turn, then back to the battery.
Resistors in Series and in Parallel

The current through each resistor is the same; the voltage depends on the resistance. The sum of the voltage drops across the resistors equals the battery voltage.

\[ V = V_1 + V_2 + V_3 = IR_1 + IR_2 + IR_3 \]
Resistors in Series and in Parallel

From this we get the equivalent resistance (that single resistance that gives the same current in the circuit).

\[ R_{eq} = R_1 + R_2 + R_3. \]
Resistors in Series and in Parallel

A parallel connection splits the current; the voltage across each resistor is the same:
Resistors in Series and in Parallel

The total current is the sum of the currents across each resistor:

\[ I = \frac{V}{R_{eq}} \]

\[ I = I_1 + I_2 + I_3, \]

\[ \frac{V}{R_{eq}} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \]
Resistors in Series and in Parallel

This gives the reciprocal of the equivalent resistance:

\[
\frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}.
\]
Kirchhoff’s Rules

Some circuits cannot be broken down into series and parallel connections.

We can use conservation of energy and conservation of charge!
Kirchhoff’s Rules

Kirchhoff’s rules:

Junction rule (conservation of charge): The sum of currents entering a junction equals the sum of the currents leaving it.

\[ \sum I_{\text{in}} = \sum I_{\text{out}} \]

Loop rule (conservation of energy): The sum of the changes in potential around a closed loop is zero.

\[ \sum_{\text{Closed Loop}} \Delta V = 0 \]
Kirchhoff’s Rules

Problem Solving: Kirchhoff’s Rules

1. Label each current (if the label direction is wrong you will get a negative current after solving the equations which means the current flows in the opposite direction).

2. Identify unknowns.

3. Apply junction (conservation of charge) and loop (conservation of energy) rules (for a full solution you will need as many independent equations as there are unknowns).

4. Solve the equations, being careful with signs.