Ch. 18 Electric Currents

These slides are not to be disseminated on the internet, or by email.
Electricity

- The Electric Battery
- Electric Current (direct current or DC)
- Ohm’s Law: Resistance and Resistors
- Resistivity - resistance, materials and temperature
- Electric Power - in Household appliances
- Alternating Current (AC)
- Microscopic View of Electric Current
- Superconductivity
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.
18.1 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.
18.1 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.
Essentially one rod is undergoing a reaction that releases electrons, while the other rod undergoes a reaction that requires electrons.

Any pair of metals that have different ionization potentials can be used to make a battery.
The Electric Battery

Several cells connected together make a battery, although now we refer to a single cell as a battery as well.
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. Which of these circuits will work?
DEFINING Electric Current

Electric current \((I)\) is the rate of flow of charge through a conductor.

\[
I = \frac{\Delta Q}{\Delta t}
\]  

Charge flows from a high potential to a low potential, and the amount of charge that flows depends on: the potential difference (voltage), and how freely the charges can move.

\[I \propto V \quad \text{and} \quad I \propto \frac{1}{R}\]

\[\implies I = \frac{V}{R}\]

Or \[V = IR\] \textbf{(Ohm’s Law)}

We define current \((I)\) as “charge per unit time”, i.e. coulombs per second. This has a special unit: “Ampere” (abbr. amp or A)

The constant \(R\) is called the RESISTANCE and has the unit “Ohm”
DIRECTION of Electric Current Flow

By convention (thanks Ben Franklin!) current is defined as flowing from + to -. Electrons actually flow in the opposite direction, but not all currents consist of electrons. (Just all the ones we encounter in electrical wiring!)
Batteries can be connected in Series or Parallel

Which bulb will shine brighter?
A    B    C (neither)

**Series**
(voltages add)

**Parallel**
(same voltage)
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 Ω = 1 V/A.

\[
\frac{\Delta I}{\Delta V} = \frac{1}{R}
\]
18.3 Ohm’s Law: Resistance and Resistors

Standard resistors are manufactured for use in electric circuits; they are color-coded to indicate their value and precision.

2538 = NNM ± T

25 x 10^3 ± 10%
Ohm’s Law: Resistance and Resistors

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 – conservation of charge.
18.4 Resistivity

What does the electrical resistance a wire, a bulb, a heating element, etc, depend on?

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 a characteristic of the material, and can also depend on temperature, pressure, etc.

Charge flowing along a wire is a bit like water flowing through a pipe, (but not exactly)
Resistivity and Temperature

For most materials, the resistivity increases linearly with temperature:

$$\rho = \rho_0 + \rho_0 \alpha \Delta T$$

Where $\alpha$ is the temperature coefficient

(This is the same way we write thermal expansion or heat capacity for example)

(Note: Semiconductors like silicon are complex materials, and may have resistivities that decrease with temperature.)

### 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</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.

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18.5 Electric Power

The unit of power is the watt, W, otherwise known as Joules per Second. In practice we can assume all devices and materials are ohmic unless told otherwise.

So the product of Voltage and Current give the Power consumed by any device (Kettle, Microwave, Mixer, Drill, Router, Oven, Computer, etc…)

\[ P = IV = I(IR) = I^2R \] \hspace{1cm} (18-6)

\[ P = IV = \left(\frac{V}{R}\right)V = \frac{V^2}{R} \]

Voltage (V) = Joules per Coulomb
Current (I) = Coulombs per second

So: \[ V \times I = \frac{J \times C}{C \times S} = \frac{J}{S} = \text{Watts} \]

Watts = Amps x Volts
ConcepTest 18.4

Dimmer

When you rotate the knob of a light dimmer, what is being changed in the electric circuit?

1) the power
2) the current
3) the voltage
4) both (1) and (2)
5) both (2) and (3)
The voltage is provided at 120 V from the outside. The light dimmer increases the resistance and therefore decreases the current that flows through the lightbulb.

ConcepTest 18.4

Dimmer

When you rotate the knob of a light dimmer, what is being changed in the electric circuit?

1) the power
2) the current
3) the voltage
4) both (1) and (2)
5) both (2) and (3)

Follow-up: Why does the voltage not change?
Wires have a resistance, so they dissipate power. This is called “line loss”

\[ P_{\text{trans}} = VI \] is the total transmitted power

\[ P_{\text{lost}} = I^2R \] is the lost power.

**Why is power transported at high voltage?**

Transmitting 100 kW at domestic voltage (110v)

\[ P_{t1} = VI \quad \rightarrow \quad I = \frac{100 \times 10^3}{110} = 909 \text{ A} \]

Transmitting 100 kW at 1100 volts (1.1 kV)

\[ P_{t2} = VI \quad \rightarrow \quad I = \frac{100 \times 10^3}{1000} = 90.9 \text{ A} \]

\[ P_{\text{lost}_1} = 909^2 R \]

\[ P_{\text{lost}_2} = 90^2 R \]

So: \[ \frac{P_{\text{lost}_1}}{P_{\text{lost}_2}} = 100 \]

Stepping up the voltage (and hence stepping the current down), improves efficiency by the square of the change in voltage (or current). In this case raising V by a factor of 10, cut the line loss by a factor of 100!

Long distance power lines (110kV) lose about 3% per 1000 km

Local power lines are closer to 1% per mile
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 × 10^6 J
18.6 Power in Household Circuits - Fuses and Breakers

The (normally copper) 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 (Usually 15A).

See Problem 18.65 in Giancoli

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

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.

Made of two metals with different thermal expansion coefficients: Strip bends when warmed by the current passing through
18.9 Superconductivity

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, $T_C$. 

![Graph showing resistivity, $\rho$, as a function of temperature, $T$, with a sharp drop at $T_C$.]
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, and work on higher temperature superconductors is continuing.
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 (ideally) a source of constant potential difference.

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

• Charge can only flow around a completed, closed circuit.

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

• Electrons drift along with the current at a very slow speed. \( I = nAve \)

• Resistance is the ratio of voltage to current: \( V = IR \) (Ohm’s law)

• Resistance is determined by shape, material, (AND temperature):

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

\[
\rho = \rho_0 + \rho_0 \alpha \Delta T
\]

• Power in an electric circuit: \( P = VI \) (Watts = Volts X Amps)

• “Line Loss” is \( P = I^2R \) so long distance power lines use low current (and hence high voltage)
War of the Currents

How we came to use alternating current (AC) for electrical power supply.
18.7 Alternating Current

- Current from a battery flows steadily in one direction (direct current, DC).
- Current from a power plant varies sinusoidally (alternating current, AC).
18.7 Alternating Current

The voltage varies sinusoidally with time:

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

as does the current:

\[ I = \frac{V}{R} = \frac{V_0}{R} \sin \omega t = I_0 \sin \omega t \] (18-7)
RMS Voltage and 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.

\[ I_{\text{rms}} = \sqrt{I^2} = \frac{I_0}{\sqrt{2}} = 0.707I_0 \]  \hspace{1cm} (18-8a)

\[ V_{\text{rms}} = \sqrt{V^2} = \frac{V_0}{\sqrt{2}} = 0.707V_0 \]  \hspace{1cm} (18-8b)

- So the RMS voltage is about 2/3 of the peak voltage, and the peak-to-peak voltage is double that.
- In the USA we use 110 volts RMS at 60 Hz
- Europe uses 230 volts RMS at 50 Hz
Power and Alternating Current

Multiplying the current and the voltage gives the power: \( P = VI \) (just like for DC electricity)

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

Not so helpful…

So we really want the time averaged value.

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

Which can be written in terms of the load and peak voltage or load and peak current

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

\[
\bar{P} = \frac{1}{2} \frac{V_0^2}{R}
\]
### Comparing Direct and Alternating Current

<table>
<thead>
<tr>
<th>DC</th>
<th>AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batteries naturally produce DC</td>
<td>AC Generation is efficient and simple</td>
</tr>
<tr>
<td>Resistance ( \propto ) cross section (A) of wire</td>
<td>R complicated by the skin effect, and extra radiative losses</td>
</tr>
<tr>
<td>Cannot be efficiently stepped up/down.</td>
<td>Transformers readily convert voltage between high (10-1000 kV) for transmission and 120v for use.</td>
</tr>
<tr>
<td>Circuits obey relatively simple rules</td>
<td>Complex, dynamic circuits, but obey the same rules, with some modifications.</td>
</tr>
<tr>
<td>Electricity is dangerous</td>
<td>Additional risk to heart rhythm</td>
</tr>
<tr>
<td>Charge flows though the circuit</td>
<td>Charge oscillates back and forth (50/60 Hz)</td>
</tr>
</tbody>
</table>
Summary of Chapter 18

• A battery is (ideally) a source of constant potential difference.
• Electric current is the rate of flow of electric charge.
• Charge can only flow around a completed, closed circuit.
• Conventional current is in the direction that positive charge would flow.
• Resistance is the ratio of voltage to current:  \( V = IR \) (Ohm’s law)
• Resistance is determined by shape, material (AND temperature):
  \[ R = \frac{\rho L}{A} \]
  \[ \rho = \rho_0 + \rho_0 \alpha \Delta T \]
• Power in an electric circuit:  \( P = VI \) (Watts = Volts X Amps)
• Alternating Current (AC)
  • RMS vs Peak voltage and current
  • AC Frequency (60 Hz)
  • Key differences between AC and DC