Chapter 17

Current and Resistance
1. Three charged particles are arranged on corners of a square as shown in Figure MCQ15.12, with charge \(-Q\) on both the particle at the upper left corner and the particle at the lower right corner, and charge \(+2Q\) on the particle at the lower left corner. What is the direction of the electric field at the upper right corner which is a point in empty space? (a) upward and to the right (b) to the right (c) downward (d) downward and to the left (e) The field is exactly zero at that point.

2. If more electric field lines leave a Gaussian surface than enter it, what can you conclude about the net charge enclosed by that surface?

3. Why is it important to avoid sharp edges or points on conductors used in high-voltage equipment?

4. Rank the potential energies of the four systems of particles shown in Figure from largest to smallest. Include equalities if appropriate.

MCQ15.12, with charge \(Q\) on both the particle at the lower right corner, and charge \(+2Q\) on the particle at the lower left corner. What is the direction of the electric field at the upper right corner? Which is a point in empty space? (a) upward and to the right (b) to the right (c) downward (d) downward and to the left (e) The field is exactly zero at that point.

Three charged particles are arranged on corners of a square as shown in Figure MCQ15.12.
Quiz 3

(Must show work to get full credit)

1. If three unequal capacitors, initially uncharged, are connected in series across a battery, which of the following statements is true?

(a) The equivalent capacitance is greater than any of the individual capacitances.
(b) The largest voltage appears across the capacitor with the largest capacitance.
(c) The largest voltage appears across the capacitor with the smallest capacitance.
(d) The capacitor with the largest capacitance has the greatest charge.
(e) The capacitor with the smallest capacitance has the smallest charge.
Consider positive and negative charges moving horizontally through the four regions in Figure. Rank the magnitudes of the currents in these four regions from lowest to highest.
Introducjon

Practical applications were based on static electricity.

A steady source of electric current allowed scientists to learn how to control the flow of electric charges in circuits.

Current
Electric Current

The current is the rate at which the charge flows through a surface.

- Look at the charges flowing perpendicularly through a surface of area \( A \).

- The SI unit of current is Ampere (A).

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

- 1 A = 1 C/s
The instantaneous current is the limit of the average current as the interval goes to zero:

$$\lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = I$$

If there is a steady current, the average and instantaneous currents will be the same.

SI unit: A
Electric Current, Cont.

- The direction of the current is the motion of the negatively charged particles.

- In a common conductor, such as copper, the direction of the current is due to the motion of the negatively charged electrons. This is known as conventional current.

- A charge carrier can be positive or negative.

- It is common to refer to a moving charge as a mobile charge carrier.

- The direction of the current is the direction of the negative charge flow.
Power

• In a conductor carrying a current, the electric potential of the charges is continually decreasing.

• Positive charges move from regions of high potential to regions of low potential.

\[ \Delta U_{\text{charges}} = q \Delta V \]

• The power delivered to the circuit element is the energy divided by the elapsed time.

• The power delivered to the circuit element is negative—often only the magnitude is desired.

\[ q \Delta V_{\text{charges}} = q \Delta V \]

Section 17.1
Current and Drift Speed

- Charged particles move through a conductor of cross-sectional area $A$.
- $n$ is the number of charge carriers per unit volume.
- $n$ is the total number of charge carriers.

\[ I = \int_{A} n \, v \, \Delta x \]

Section 17.2
Current and Drift Speed, Cont.

- Finally, current, \( I = \frac{\Delta Q}{\Delta t} = n q v^p A \)

  - Rewritten: \( \Delta Q = (n A v^p \Delta t) q \)

  - \( v^p = \frac{\Delta x}{\Delta t} \)

  - The drift speed, \( v^p \), is the speed at which the carriers move.

- The total charge is the number of carriers times the charge per carrier, \( q \)

- \( \Delta Q = (n A \Delta x) q \)
If the conductor is isolated, the electrons undergo random motion.

When an electric field is set up in the conductor, it creates an electric force on the electrons and hence a current.
Charge Carrier Motion in a Conductor

• The zig-zag black line represents the motion of a charge carrier in a conductor. The net drift speed is small.
• The sharp changes in direction are due to collisions.
• The net motion of electrons is opposite the direction of the electric field.

Although electrons move with average velocity \( \vec{v}_d \), collisions with atoms cause sharp, momentary changes of direction.
Electrons in a Circuit

• Assume you close a switch to turn on a light.
• A battery in a circuit supplies energy (not charge) to the electric field set up in the completed circuit.
• The electrons already in the bulb move in response to the electric field.
• The electrons do not travel from the switch to the bulb.

The circuit: A battery in a circuit supplies energy (not charge) to the electric field set up in the completed circuit.

The electrons already in the bulb move in response to the electric field.

The electrons do not travel from the switch to the bulb.

Electrons in a Circuit
The amount of charge that passes through the filament of a certain lightbulb in 2.00 s is 1.67 C. Find (a) the average current in the lightbulb and (b) the number of electrons that pass through the filament in 5.00 s. (c) If the current is supplied by a 12.0-V battery, what total energy is delivered to the lightbulb filament? (d) What is the average power? (e) The number of electrons that pass through the filament in 5.00 s is 1.67 C. Find (a) the average current in the lightbulb and (b) the amount of charge that passes through the filament of a certain lightbulb in 2.00 s.
\[ \tfrac{10.0}{W} = \frac{s}{2.00} \quad \frac{2.00}{\Omega} = \frac{\nabla}{\Omega} = \frac{\lambda_{\beta}}{\bar{l}} \]

\[ \int_{10.0}^{2.00} = (\Lambda 0.12 \Omega C) (1.67 \times 10^{19}) = \lambda b \quad \Omega \nabla \quad (2) \]

2.61 \times 10^{19} \text{ electrons} = \Lambda \nabla \quad (0.835 \text{ A})(5.00 \text{ s})

(0.10-19 C/electron) = (0.835 \text{ A})(5.00 \text{ s})

\[ I \nabla \lambda_{\beta} = b \nabla \quad (1) \]

\[ 0.835 \text{ A} = \frac{s}{2.00} \quad \frac{2.00}{1.67 \Omega} = \frac{\nabla}{\Omega} = \frac{\lambda_{\beta}}{I} \]
Electrons in a Circuit, Cont.

- The drift speed is much smaller than the average speed between collisions.
- Although the drift speed is on the order of 10^{-4} m/s, the effect of the electric field is felt on the order of 10^8 m/s.
- When a circuit is completed, the electric field travels with a speed close to the speed of light.

Section 17.2
A copper wire of cross-sectional area $3.00 \times 10^{-2}$ m$^2$ carries a current of 10.0 A. (a) Assuming a copper wire of cross-sectional area $3.00 \times 10^{-2}$ m$^2$ carries a current of 10.0 A. (a) Assuming 

copper is 8.92 g/cm$^3$, and its atomic mass is 63.5 u.

An electron would have at 20.0°C. The density of an electron would have at 20.0°C. The density of copper is 8.92 g/cm$^3$, and its atomic mass is 63.5 u.

Each copper atom contributes one free electron to the metal, find the drift speed of the electrons in this wire. (b) Use the ideal gas model to compare the drift speed with the random rms speed.

Assuming each copper atom contributes one free electron to the metal, find the drift speed of the electrons in this wire. (b) Use the ideal gas model to compare the drift speed with the random rms speed.
\[
\frac{s/m_{10-6} \times 0.001 \times 8.46 \times 10^{6} \times \text{electrons/mole}}{10^{12} \text{ electrons/mole}} = \frac{V_{bu}}{I} = p_{\alpha}
\]

\[
\frac{8.46 \times 10^{6} \times 10^{9} \times 10^{12} \times \text{electrons/mole}}{6.02 \times 10^{23} \times 10^{-6} \text{ electrons/mole}} = u
\]

\[
\left(\frac{\text{cm}}{m_{10-6}}\right)_{10^{12} \text{ cm}^{-1}} = \frac{10^{9} \text{ cm}}{m_{10-6}} = \frac{8.46 \times 10^{23} \text{ cm}^{-1}}{6.02}
\]

\[
\frac{8.46 \times 10^{23} \text{ cm}^{-1}}{6.02} = \frac{d}{m} = \Lambda
\]
\[
\frac{s/m_{10^9} \times 1.15 \times 1.15}{(\frac{K}{10^{-18}})(\frac{K}{L^{\frac{1}{2}}}) \times 88.1 \times 88.1} = \sum_{\Omega}
\]

\[
\frac{e^{-\mu}}{L^{\frac{1}{2}} \gamma_{\Omega}} = \sum_{\Omega}
\]
A circuit is a closed path of some sort around which current circulates.

Quantities of interest are generally current and potential difference.

A circuit diagram can be used to represent the circuit which current circulates.

A circuit is a closed path of some sort around.
An ammeter is used to measure current. In line with the bulb, all the charge passing through the bulb also must pass through the meter.
A voltmeter is used to measure voltage (potential difference). It connects to the two contacts of the bulb.
In a conductor, the voltage applied across the ends of the conductor is proportional to the current through the conductor. The constant of proportionality is the resistance of the conductor.

\[ \frac{I}{V} = R \]
Resistence, cont.

Resistance in a circuit arises due to collisions between the electrons carrying the current with the fixed atoms inside the conductor. Units of resistance are ohms (Ω).

\[ V = I \times R \]

- \( V \) is voltage [V]
- \( I \) is current [A]
- \( R \) is resistance [Ω]
Ohm's Law

- Materials that obey Ohm's law are said to be ohmic.

- This statement has become known as Ohm's Law.

\[ \Delta V = I R \]

- Materials that obey Ohm's law are said to be ohmic.

- Only for certain materials, Ohm's law is an empirical relationship that is valid over a wide range of applied voltages or currents. Most metals, including some materials, show that for many materials, including...
Ohm's Law, Cont.

- An ohmic device
- The resistance is constant over a wide range of voltages.
- The slope is related to the current and voltage is linear.
- The relationship between resistance is constant.

\[ \frac{V}{I} = \text{Slope} \]
Figure 17.7

The potential difference, \( \Delta V \), is proportional to the current, \( I \), and the cross-sectional area, \( A \), of the conductive material.

\[ \frac{\Delta V}{\Delta t} = \frac{q}{A} \]

Where

- \( I \) is the current
- \( A \) is the cross-sectional area
- \( \Delta V \) is the potential difference
- \( \Delta t \) is the time interval

The electric field, \( E \), is defined as:

\[ E = \frac{\Delta V}{\Delta L} \]

Where

- \( \Delta L \) is the length of the conductor

The electric field is induced by the current in the conductor.
Ohm's Law, Final

Section 17.4

• Non-ohmic materials are those whose resistance changes with voltage or current.
• The current-voltage relationship is nonlinear.
• A diode is a common example of a non-ohmic device.

ΔV

I
The resistance of an ohmic conductor is proportional to its length, \( L \), and inversely proportional to its cross-sectional area, \( A \). The resistance of the material, \( \rho \), is the constant of proportionality and is called the resistivity.

\[
\frac{A}{L} = \rho
\]
<table>
<thead>
<tr>
<th>Material</th>
<th>$\alpha$ at 20°C</th>
<th>Resistivity (Ω·m)</th>
<th>Temperature Coefficient of Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz (fused)</td>
<td>$7.5 \times 10^{-16}$</td>
<td>6.40</td>
<td>0.46</td>
</tr>
<tr>
<td>Sulfur</td>
<td>$10^{-15}$</td>
<td>0.5</td>
<td>10^{-13}</td>
</tr>
<tr>
<td>Hard Rubber</td>
<td>$10^{-14}$</td>
<td>3.5</td>
<td>10^{-5}</td>
</tr>
<tr>
<td>Glass</td>
<td>$10^{-14}$</td>
<td>150</td>
<td>10^{-8}</td>
</tr>
<tr>
<td>Silicon</td>
<td>$10^{-14}$</td>
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<td>10^{-8}</td>
</tr>
<tr>
<td>Germanium</td>
<td>$10^{-14}$</td>
<td>11</td>
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<tr>
<td>Carbon</td>
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<tr>
<td>Nichrome</td>
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<td>Lead</td>
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</tr>
<tr>
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<tr>
<td>Tungsten</td>
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</tr>
<tr>
<td>Aluminum</td>
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</tr>
<tr>
<td>Cold Copper</td>
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<td>0.5</td>
<td>10^{-8}</td>
</tr>
<tr>
<td>Silver</td>
<td>$10^{-14}$</td>
<td>0.3</td>
<td>10^{-8}</td>
</tr>
</tbody>
</table>
Temperature Variation of Resistivity

For most metals, resistivity increases with increasing temperature. With a higher temperature, the metal's constituent atoms vibrate with increasing amplitude. The electrons find it more difficult to pass through the atoms. For most metals, resistivity increases with increasing temperature.
Temperature Variation of Resistivity, Cont.

For most metals, resistivity increases approximately linearly with temperature over a limited temperature range. The temperature coefficient of resistivity, $\alpha$, is given by:

$$[(\rho - \rho_0)/\rho_0]d = d$$

where $\rho_0$ is the resistivity at some reference temperature $T_0$, $\rho$ is the resistivity at some temperature $T$, and $T_0$ is usually taken to be $20^\circ\text{C}$. 

- For most metals, resistivity increases linearly with temperature over a limited temperature range.
Since the resistance of a conductor with uniform cross-sectional area is proportional to the resistivity, you can find the effect of temperature on resistance.

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

Temperature Variation of Resistance.
• In a circuit, as a charge moves through the battery, the electrical potential energy of the system is increased by the battery.

$\Delta E = \Delta Q V$.

• As the charge moves through a resistor, it loses this potential energy during collisions with atoms in the resistor.

The temperature of the resistor will increase.

• The chemical potential energy of the battery decreases by the same amount.

$\Delta E = \Delta Q V$.
(a) Calculate the resistance per unit length of a 22-gauge Nichrome wire of radius 0.321 mm.

(b) If a potential difference of 10.0 V is maintained across a 1.00-m length of the Nichrome wire, what is the current in the wire?

(c) The wire is melted down and recast with twice its original length. Find the new resistance $R_N$ as a multiple of the old resistance $R_O$.

(d) Calculate the resistance per unit length of a 22-gauge Nichrome wire of radius 0.321 mm.
\[ \begin{align*}
^0 \phi \Psi &= \frac{^0 \mathcal{A}}{^0 \zeta \phi} = \frac{\zeta / ^0 \mathcal{A}}{(\zeta / ^0 \mathcal{A})^d} = \frac{^N \mathcal{A}}{^N \zeta \phi} = \frac{N \phi}{N \Psi}
\end{align*} \]

\[ \begin{align*}
\zeta / ^0 \mathcal{A} &= (\zeta / ^0 \mathcal{A})^0 \mathcal{A} = ^N \mathcal{A} \\
(\zeta / ^0 \mathcal{A})^0 \mathcal{A} &= ^N \mathcal{A} \leftrightarrow ^0 \mathcal{A}^0 \mathcal{A} = ^N \zeta ^N \mathcal{A} \leftrightarrow ^0 \Lambda = ^N \Lambda
\end{align*} \]

\[ \begin{align*}
\mathcal{A} \zeta \Psi &= \frac{\mathcal{U} \zeta \Psi}{\Lambda 0. \mathcal{A} \zeta \Psi} = \frac{\mathcal{U}}{\Lambda \mathcal{A} \zeta \Psi} = I
\end{align*} \]

\[ \begin{align*}
\text{w} / \mathcal{U} \zeta \Psi &= \frac{\text{w} \zeta \Psi}{\text{w} \cdot \mathcal{U} \zeta \Psi 10 \cdot \text{w} \zeta \Psi 10} \times \frac{\text{w} \zeta \Psi}{\text{w} \cdot \mathcal{U} \zeta \Psi 10} = \frac{\mathcal{A} \zeta \Psi}{\mathcal{A} \zeta \Psi} = \frac{\zeta \Psi}{\mathcal{A} \zeta \Psi}
\end{align*} \]

\[ \text{w} \zeta \Psi 10 \times \Psi \zeta \Psi = \zeta (\text{w} \zeta \Psi 10 \times \mathcal{U} \zeta \Psi 0. \mathcal{A} \zeta \Psi) = \frac{\mathcal{A} \zeta \Psi}{\mathcal{A} \zeta \Psi} = \mathcal{A} \]
Energy Transfer in the Circuit

Consider the circuit shown.

Imagine a quantity of positive charge, $Q$, moving around the circuit from point A back to point A.

A.

Positive current $I$ travels clockwise from the positive to the negative terminal of the battery.
Energy Transfer in the Circuit,

Cont.

Section 17.6

- The chemical energy of the battery decreases by the same amount.
- The potential energy of the system increases by \[ \Delta V \].

A to B, the potential energy of the system increases by \[ \Delta V \].

As the charge moves through the battery from zero to B, it is grounded and its potential is taken to be zero.

- Point A is the reference point.

- Point A is the reference point.

Cont.
Energy Transfer in the Circuit, Final

• As the charge moves through the resistor, from C to D,
  it loses energy in collisions with the atoms of the resistor.

• When the charge returns to A, the net result is that
  the energy is transferred to internal energy.

• As the charge moves through the resistor, some chemical energy of the battery has been delivered to the resistor and caused its temperature to rise.

Section 17.6
Electrical Energy and Power, Cont.

- The rate at which the energy is lost is the power.

\[ \frac{P}{\sqrt{V}} = R^2 I = \rho \]

From Ohm's law, alternate forms of power are

\[ \frac{V}{\sqrt{\Omega}} = \frac{I}{\sqrt{\Omega}} = \rho \]

section 17.6
• The SI unit of power is Watt (W).

1 kWh = 3.60 x 10^6 J

and the amount of time it is supplied.

This is defined in terms of the unit of power—is the kilowatt-hour.

The unit of energy used by electric companies—1 must be in Amperes, R in ohms and V in Volts.

Electrical Energy and Power, Final
Superconductors

- A class of materials and compounds whose resistances suddenly drop to zero at a certain temperature, \( T^\ast \) – \( T^\ast \) is called the critical temperature, \( T^\ast \) is less than zero.

- The graph is the same as a normal metal above \( T^\circ \) but suddenly drops to zero at \( T^\ast \) at \( T^\ast \) below zero.

Section 17.7
Superconductors, Cont.

- The value of $T_c$ is sensitive to:
  - Chemical composition
  - Crystallographic structure
  - Pressure
- Once a current is set up in a superconductor, it persists without any applied voltage. Since $R = 0$.
Superconductor Timeline

• 1911 – Superconductivity discovered by H. Kamerlingh Onnes
• 1986 – High temperature superconductivity discovered by Bednorz and Müller
• 1987 – Superconductivity at 96 K and 105 K
• 1987 – Current
• 1986 – High temperature superconductivity discovered by H. Kamerlingh Onnes
• 1986 – Superconductivity near 30 K

More materials and more applications
Superconductors do not necessarily exhibit superconductivity. One application is the construction of superconducting magnets.

Good conductors do not necessarily exhibit superconductivity.
Every action involving the body’s muscles is initiated by electrical activity.

Voltage pulses cause the heart to beat.

These voltage pulses are large enough to be detected by equipment attached to the skin.
The sinoatrial (SA) node initiates the heartbeat.

The electrical impulses cause the right and left atrial muscles to relax.

When the impulse reaches the atrioventricular (AV) node, the muscles of the atria begin to relax.

The ventricles relax and the cycle repeats.
Electrocardiogram (EKG)

- A normal EKG

- P occurs just before the atria begin to contract.
- QRS pulse occurs in the ventricles just before they begin to contract.
- The T pulse occurs when the cells in the ventricles begin to recover.
• Abnormal EKG, I
  - The QRS portion is wider than normal.
  - This indicates the possibility of an enlarged heart.
  - The QRS pulse is too wide for an enlarged heart.
Abnormal EKG, 2

There is no constant relationship between P and QRS pulse.

This suggests a blockage in the electrical conduction path between the SA and AV nodes.

This leads to inefficient heart pumping.
Abnormal EKG

- Abnormal EKG
- No P pulse and an irregular spacing between the QRS pulses
- Symptomatic of irregular atrial contraction, called fibrillation
- The atrial and ventricular contraction are irregular.

Section 17.8
Implanted Cardiotomy Defibrillator (ICD) devices can monitor, record, and logically process heart signals. Then supply different corrective signals to hearts that are not beating correctly. Device signals record and logically process second 17.8.
Functions of an ICD

- Monitor atrial and ventricular chambers
- Distinguish between arrhythmias
- Store heart signals for read out by a physician
- Easily reprogrammed by an external magnet

Section 17.8
More Functions of an ICD

- Perform signal analysis and comparison
- Supply repetitive pacing signals to speed up or slow down a malfunctioning heart
- Adjust the number of pacing pulses per minute to match patient’s activity

Section 17.8