20.6: Summary

20.6.1: Key Takeaways

Batteries are usually formed from a collection of electrochemical cells. Batteries provide a constant electric potential difference across their terminals, usually sustained by a chemical reaction, as long as the current through the battery is not too large (or the chemical reactions cannot be sustained). An ideal battery has no resistance and can be modeled as a simple potential difference in a circuit. A real battery includes an internal resistance and be modeled in a circuit as an ideal battery in series with a resistor. The voltage across the terminals of a real battery is equal to the voltage across the terminals of the ideal battery only when no current flows through the internal resistance.

Circuits are modeled using circuit diagram that include components (such as batteries and resistors) and wires. Wires are always modeled as having no resistance, since their resistance can be included by placing the appropriate resistor along the wire. The electric potential is always constant along a wire with no resistance. When modeling a circuit, **one always models the direction of conventional current**; that is, current is always indicated as the direction in which positive charges flow (even if in reality, it is negative electrons that flow in the opposite direction).

Circuits should be thought of in terms of conservation of energy. Components produce a potential difference between sections of wire. Batteries correspond to an increase in potential (if going from the negative to the positive terminal), whereas resistors corresponds to a decrease in potential (if going in the same direction as current through the resistor).

Kirchhoff's rules allow us to model complex circuits:

The junction rule states that: **The current entering a junction must be equal to the current exiting a junction.** This is a statement about conservation of charge. If charges are flowing into a junction, then the same amount of charges must flow back out of the junction per unit time.

The loop rule states that: **The net voltage drop across a loop must be zero.** This is a statement about conservation of energy indicating that as the potential energy of a positive charge increases as it goes through a battery, it will decrease by the same amount if it goes through a resistor that is connected to the terminals of that battery.

In order to **apply the loop rule**, we strongly suggest using the following procedure, after having made a clear, labeled diagram showing battery arrows and currents in the circuit:

1. Identify the loop, including starting position and direction.
2. Start at the beginning of the loop, and trace around the loop.
3. Each time a battery is encountered, **add the battery voltage if you are tracing the loop in the same direction as the corresponding battery arrow**, subtract the voltage otherwise.
4. Each time a resistor is encountered, **subtract the voltage across that resistor (RI, from Ohm's Law) if tracing the loop in the same direction as the current**, add the the voltage otherwise.
5. Once you have traced back to the starting point, the resulting sum must be zero.

In general, we suggest the following procedure in order to use Kirchhoff's rules to model any circuit:

1. Make a good diagram of the circuit.
2. Simplify any resistors that can easily be combined into effective resistors (in series or in parallel).
3. Make a new diagram with the effective resistors, showing battery arrows, and labeling all of the nodes so that loops can easily be described.
4. Make a **guess** for the directions of the current in each segment.
5. Write the junction rule equations. Usually, you will get $M-1$ independent equations for M loops.
6. Write the loop equations. Usually, you will get $M-1$ independent equations for M loops.
7. This will lead to N independent equations that one can solve for the N different currents in the circuit.
8. Once you have determined all of the currents, if some of them are negative numbers, switch the direction of those currents in the diagram (they will be negative if you guessed the direction incorrectly).

Current and voltage measuring devices (ammeters and voltmeters, respectively) can be constructed from a galvanometer, which measures small currents. An ammeter is constructed by placing a small shunt resistor in parallel with the galvanometer so that most of the current passes through the shunt resistor. The resulting ammeter must be placed in series with a component in order to measure the current through that component.

A voltmeter is constructed by placing a resistor in series with the galvanometer in order to reduce the current through the galvanometer. The resulting voltmeter must be placed in parallel with a component in a circuit in order to measure the voltage across that component. Note that because voltmeters and ammeters have a non-zero resistance, they will affect the circuit once they are connected.

When a capacitor is placed in a circuit, the current in the circuit will no longer be constant in time. If an uncharged capacitor with capacitance, C, is placed in a series circuit with a battery and a resistor of resistance, R, the capacitor will charge until the voltage across the capacitor is equal to that across the battery. Once the capacitor is charged, current ceases to flow in the circuit. The charges on a capacitor accumulate with a rate that decays exponentially; it will take an infinite amount of time for the capacitor to become fully charged. It will be charged to about 63% of maximum charge after a period of time, $\tau = RC$, called the time constant of the capacitor.

20.6.2: Important Equations

20.6.2.1: Ohm's Law:

$$\Delta V = IR$$

20.6.2.2: Junction Rule:

$$\sum I_{in} = \sum I_{out}$$

20.6.2.3: Loop Rule:

$$\sum_{loop} \Delta V = 0$$

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