Introduction to Circuit Analysis

**Key Question**

What are the tools we need to model and analyze systems as circuits?

**Key Terms**

- Voltage
- Current
- Resistance
- Wire
- Open Circuit
- Voltage Source
- Node
- Current Source
- Resistor
- Conductor
- Insulator
- Passive
- Sign Convention
- Ohm’s Law

In this class, we will learn how to design and build devices and systems.

**The Process**

- Analog Real World (External Environment)
  - Sensors (Analog)
  - Classical Signals
  - Processing (Algorithms)
    - Make a model and predict
  - Analog Real World (External Environment)

**Example: Self-Driving Car**

- Example: Turn on a fan when the temperature in a room is too high, and turn it off when the temperature reaches a desired state.

- Example: Start a pancake-making machine when sunlight is detected and stop when 10 pancakes are made.

How do we make models?

There is a level of abstraction involved, but let’s start with the tools we need.
Our world is made up of tiny particles we call atoms.

### Atom

An atom consists of three types of subatomic particles:

- **Protons**: positive electrical charge
- **Neutrons**: electrically neutral (no charge)
- **Electrons**: negative electrical charge

- Like charges repel each other and unlike charges attract.

#### Let's talk about elections in solid-state physics:

- Electrons exist in shells surrounding the nucleus of an atom and have the highest energy.
- Valence electrons are located in the outermost shell of the atom and have the highest energy.
- The valence band is the outermost electron orbital of the atom of a material. When excited, these electrons move into the conduction band.

#### Band Gap

- Energy range in a solid where no electron states can exist.

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### Summary

Conductivity is the ease with which electrons can flow through a material.
Our electronic devices depend on the movement of charges through material.

**Current**: represented as \( Q \)
- measured in Coulombs (C)
- \( 1 \text{C} \approx 6.2415 \times 10^{18} \text{e}^- \)

The movement of this charge over time, or the rate of flow, is called **current**. \( \frac{\text{d}Q}{\text{d}t} = I \)

What is driving these electrons to move? **Voltage** (like pressure or a pushing force) is the potential difference between two points. Think of it like an altitude. It is defined relative to a zero, or ground, for reference.

What could oppose the path of current? **Resistance** (a property of an element) opposes the flow of current.

**The Water Pipe Analogy**
- Think of water flowing in a pipe.
- The amount of water at any cross-section of the pipe is **current**.
- The force of the flowing water is **voltage**.
- Rocks and debris obstructing the flow of water cause **resistance**.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>I</td>
<td>Ampere (A) (flows through an element)</td>
</tr>
<tr>
<td>Voltage</td>
<td>V</td>
<td>Volt (V) (applied across an element)</td>
</tr>
<tr>
<td>Resistance</td>
<td>R</td>
<td>Ohm (Ω)</td>
</tr>
</tbody>
</table>

Let’s consider the relationship between these three:

If the resistance to water flow stayed the same, but the pressure of water increased, the flow rate would increase.

\[ V \uparrow \Rightarrow I \uparrow \text{ when } R \text{ is unchanged.} \]

If the pressure stayed the same, but the resistance increased, then the flow rate would decrease.

\[ R \uparrow \Rightarrow I \downarrow \text{ when } V \text{ is unchanged.} \]

If the flow rate stayed the same, but the resistance decreased, the pressure required to move the water would decrease.

\[ R \downarrow \Rightarrow V \downarrow \text{ when } I \text{ is unchanged.} \]
This relationship is described by Ohm's law.

\[ V = IR \]

How does this all fit together? **Circuit**

A circuit is a closed loop or complete path for electricity to flow through.

There are different kinds of elements that make up a circuit, each of which has a voltage across it and a current flowing through it.

- **Resistor Element**: \( I_{\text{elem}} + V_{\text{elem}} - \) or \( + V_{\text{elem}} - I_{\text{elem}} \)

When labeling, we follow passive sign convention, which means current flows from positive voltage to negative voltage (+ to -)

**Circuit Elements**

1. **Wire**
   \[ V_{\text{elem}} = 0 \]
   \( I_{\text{elem}} \) is set by the external circuit.

2. **Open Circuit**
   \[ V_{\text{elem}} = 0 \]
   \( I_{\text{elem}} \) is set by the external circuit.
3. **Voltage Source**

![Battery Diagram](image)

\[ V_{elem} = V_s \]

*\( I_{elem} \) is set by the external circuit.

4. **Current Source**

\[ I_{elem} = I_s \]

*\( V_{elem} \) is set by the external circuit.

5. **Resistor**

\[ V_{elem} = I_{elem} \cdot R \]

*Ohm's law*

\[ I_{elem} = \frac{V_{elem}}{R} \]

Remember that \( V_{elem} \) and \( I_{elem} \) can be positive or negative.

- \( I_{elem} = -5\text{A} \)
- \( I_{elem} = 5\text{A} \)
A closed path for electrons to flow is a closed circuit.

(A loop - we will end up where we started, and current is the same throughout the loop).

Node: region between circuit elements with the same potential.
(everything you can connect without lifting your pen)

Let's put together some elements in a circuit. Let's use this diagram to understand voltage better.

The Mountain Climbing Analogy
If following the purple path from zero:

OV, xV, and 5V are node potentials

The voltage across an element is the difference in potential from the + to - terminal.

\[ V_{V_1} = \text{green} - \text{green} = 5V - 0V = 5V = V_s \]
\[ V_{V_{R_1}} = \text{red} - \text{red} = 5V - xV \]
\[ V_{V_{R_2}} = \text{yellow} - \text{green} = xV - 0V = xV \]