Lecture 3

Operational Amplifiers:
- Ideal
- The Inverting Configuration
Our purpose is to:

- Explain the characteristics of an ideal Op-Amp.
- Identify the inverting configuration of an Op-Amp.
- Analyze op-amp circuits where the non-inverting terminal is grounded.
- Analyze the effect of a finite open-loop gain on an op-amp circuit where the non-inverting terminal is grounded.
Circuit Symbol

(a) 

(b)
741 Op Amp (Pin-Out Diagrams)
Characteristics/Properties (Ideal Op-Amp)

- **Property No.1: Infinite input impedance** \((Z_{in} \rightarrow \infty)\)
  - Input impedance is the ratio of input voltage to input current \((Z_{in} = V_{in}/I_{in})\)
  - As \(I_{in} \rightarrow 0\) \(Z_{in} \rightarrow \infty\).
  - High-grade op-amps can have input impedance in the \(T\Omega\) range.
  - Some low-grade op-amps (on the other hand) can have mA input currents.
Property No.2: Zero output impedance \( (Z_{out} \approx 0) \)

- The ideal op-amp acts as a perfect internal voltage source with no internal resistance.
- Real-life op-amps have some internal resistance which then is in series with an external load, thus reducing the output voltage available to the load.
- Example:

\[
V_0 = \frac{VR_2}{R_1 + R_2}
\]

- Real-life op-amps have output-impedance in the 100-20 \( \Omega \) range.
Property No.3: Infinite Open-Loop Gain ($A_{vol} \rightarrow \infty$)

- Open-loop gain is the gain of the op-amp **without positive or negative feedback**.

- Ideally infinite (typical values range from 20,000 to 200,000 in real-life devices; normally feedback is applied around the op-amp so that the gain of the overall circuit is defined and kept to a figure which is more usable).

- Open-loop gain falls very rapidly with **increasing frequency**.
Property No.4: Zero Common-Mode Gain (what does this mean?!?)

- An ideal op-amp only amplifies the voltage difference between its two inputs.

- If these inputs were to be shorted together (thus ensuring zero potential difference between them), there should be no change in output voltage for any amount of voltage applied between the two shorted inputs and ground.

Example:
Voltage that is common between either of the inputs and ground (as “$V_{\text{common-mode}}$” is in this case) is called **common-mode voltage**. As we vary this common voltage, the perfect op-amp's output voltage should hold absolutely steady (i.e., no observable change in output for any arbitrary change in common-mode input). This translates to a **common-mode voltage gain** of zero.

The performance of a real op-amp in this regard is most commonly measured in terms of its **differential voltage gain** (i.e., how much it amplifies the difference between two input voltages) *versus* its common-mode voltage gain (i.e., how much it amplifies a common-mode voltage). The ratio of the former to the latter is called the **common-mode rejection ratio** (CMRR):

$$CMRR = \frac{A_v(\text{Differential})}{A_v(\text{Common-Mode})}$$
Common-Mode Rejection Ratio

- An ideal op-amp, with $A_{v (Common-Mode)} = 0$ would have an infinite CMRR.

- Real-life op-amps have high CMRRs (the ubiquitous 741 having something around 70 dB, which works out to a little over 3,000 in terms of a ratio).

A note about feedback compensation…

- Because the CMRR in a typical op-amp is so high, common-mode gain is usually not a great concern in circuits where the op-amp is being used with negative feedback.

- If the common-mode input voltage of an op-amp circuit were to suddenly change (thus producing a corresponding change in the output due to common-mode gain), that change in output would be quickly corrected as negative feedback and $A_{vol}$ worked to bring the system back to equilibrium.

- Conclusion: A change might be seen at the output, but it would be a lot smaller than what you might expect!
Property No.5: Infinite Bandwidth (What does this mean?!?)

- The ideal op-amp will amplify all signals from DC to the highest AC frequencies.

- In real op-amps, the bandwidth is rather limited; this limitation is specified by the Gain-Bandwidth product (GB), which = the frequency where the amplifier gain → unity.

- Some op-amps (such as the 741 family) have very limited bandwidth of up to a few KHz.
Property No. 6: Zero Output Offset (What does this mean?!!?)

- The output offset is the output voltage of an amplifier when both inputs are grounded, i.e.;

- Ideal op-amp: Zero output offset.

- Real op-amps: Finite amount of output offset voltage
The Inverting Configuration
In-Class Analysis 1: Closed-Loop Gain

Determine the closed-loop voltage gain $v_o/v_I$ ...
In-Class Analysis 1 (Solution)

\[ A_{vol} \equiv \frac{v_o}{e_{in}} \]

\[ e_{in} = v_2 - v_1 = \frac{v_o}{A_{vol}} \approx 0 \]

\[ i_1 = \frac{v_I - v_1}{R_1} = \frac{v_I - 0}{R_1} = \frac{v_I}{R_1} \]

\[ v_o = v_1 - i_1 R_2 = 0 - i_1 R_2 \]

\[ \frac{v_o}{v_I} = -\frac{R_2}{R_1} \]
Design an inverting op-amp where the closed-loop gain is $= -10$ and the total resistance is $150\,\text{K}\Omega$. 
In-Class Analysis 2 (Solution)

\[
\frac{v_o}{v_i} = -\frac{R_2}{R_1} = -10
\]

\[
R_2 = 10R_1
\]

\[
R_2 + R_1 = 150K
\]

\[
10R_1 + R_1 = 150K
\]

\[
R_1 = 13.63K
\]

\[
R_2 = 136.3K
\]