
- Operational Feedback
  - Current versus voltage feedback
- Op Amp
  - Properties
  - Common Op-Amp-based setups

- Op-Amps.
Type of feedback

- Convention for voltage and current feedback:

<table>
<thead>
<tr>
<th>Sample output</th>
<th>Type of input</th>
<th>Name</th>
</tr>
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<tbody>
<tr>
<td>Voltage</td>
<td>Voltage</td>
<td>Voltage feedback</td>
</tr>
<tr>
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</table>
Operational Voltage feedback

- Input impedance of A0 very large, no current can flow into the amplifier
- Input must cancel the feedback
  \[ i_{in} = -\frac{\alpha V_{out}}{R_f} \]
- Input resistor sets \( V_{in} \)
  \[ i_{in} = \frac{V_{in} - V_A}{R_i} \]
- Input current must all go through the feedback resistor
  \[ i_{in} = \frac{V_A - V_{out}}{R_f} \]
- Amplifier gain is
  \[ \frac{V_{in} - V_{out} / A_0}{R_i} = \frac{V_{out} / A_0 - V_{out}}{R_f} \]
- So
  \[ A = \frac{V_{out}}{V_{in}} = \frac{1}{(R_i/R_f)(1/A_0 - 1) + 1/A_0} \]

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Operational Current feedback

- Resistor is used to sample the output current

\[ i_{in} R_f = -(i_{in} + i_{out}) R_G \]

\[ \frac{i_{out}}{i_{in}} = -\frac{R_f + R_G}{R_G} \]
Operational Amplifier (Op. Amp.)

Transistors (we will learn about these later)
Ideal Operational Amplifier

• The ideal op-amp is characterized by 7 properties
  – Knowledge of these properties is sufficient to design and analyze a large number of useful circuits

• Basic op-amp properties
  – Infinite open-loop voltage gain
  – Infinite input impedance
  – Zero output impedance
  – Zero noise contribution
  – Zero DC output offset
  – Infinite bandwidth
  – Differential inputs that “stick together”
**Ideal Op. Amp. Properties**

- **Property No.1: Infinite Open-Loop Gain**
  - Open-Loop Gain $A_{\text{vol}}$ is the gain of the op-amp without positive or negative feedback
  - In the ideal op-amp $A_{\text{vol}}$ is infinite
    - Typical values range from 20,000 to 200,000 in real devices

- **Property No.2: Infinite Input Impedance**
  - Input impedance is the ratio of input voltage to input current
    
    $$Z_{\text{in}} = \frac{V_{\text{in}}}{I_{\text{in}}}$$
  - When $Z_{\text{in}}$ is infinite, the input current $I_{\text{in}} = 0$
    - High-grade op-amps can have input impedance in the TΩ range
    - Some low-grade op-amps, on the other hand, can have mA input currents
**Property No. 3: Zero Output Impedance**

- The ideal op-amp acts as a perfect internal voltage source with no internal resistance
  - This internal resistance is in series with the load, reducing the output voltage available to the load
  - Real op-amps have output-impedance in the 100-20Ω range

- Example

\[
V_0 = \frac{VR_2}{R_1 + R_2}
\]
Ideal Op. Amp. Properties

- **Property No.4: Zero Noise Contribution**
  - In the ideal op-amp, zero noise voltage is produced internally
    - This is, any noise at the output must have been at the input as well
  - Practical op-amp are affected by several noise sources, such as resistive and semiconductor noise
    - These effects can have considerable effects in low signal-level applications

- **Property No. 5: Zero output Offset**
  - The output offset is the output voltage of an amplifier when both inputs are grounded
  - The ideal op-amp has zero output offset, but real op-amps have some amount of output offset voltage
Ideal Op. Amp. Properties

■ Property No. 6: Infinite Bandwidth
  • The ideal op-amp will amplify all signals from DC to the highest AC frequencies
  • In real opamps, the bandwidth is rather limited
    ■ This limitation is specified by the Gain-Bandwidth product (GB), which is equal to the frequency where the amplifier gain becomes unity
    ■ Some op-amps, such as the 741 family, have very limited bandwidth of up to a few KHz

■ Property No. 7: Differential Inputs Stick Together
  • In the ideal op-amp, a voltage applied to one input also appears at the other input

- (I) The output attempts to do whatever is necessary to make the voltage difference between the two inputs zero.

- (II) The inputs draw no current

- This golden rules obscure what is really going on but they greatly simplify the analysis of circuit based on Op. Amps.

1. (+) is grounded so Rule I implies (-) is also grounded,
2. So the voltage across $R_2$ is $V_{out}$ and the voltage across $R_1$ is $V_{in}$
3. So rule II implies:
   \[ \frac{V_{out}}{R_2} = -\frac{V_{in}}{R_1} \]
   Or gain is
   \[ A = -\frac{R_2}{R_1} \]
Examples of Op. Amp. applications

- Voltage comparator
  \[ V_{\text{out}} = V_{\text{CC}} \, \text{sign}(V_{\text{in}}) \]

- Voltage follower
  - What is the main use of this circuit?
    - Buffering
Examples of Op. Amp. applications

- **Non-inverting amplifier**

\[ V_{out} = \left(1 + \frac{R_2}{R_1}\right)V_{in} \]

- **Inverting amplifier**

\[ V_{out} = -\frac{R_2}{R_1}V_{in} \]
Examples of Op. Amp. applications

- **Summing amplifier**

  
  \[ V_{out} = -\left( \frac{V_1 R_f}{R_1} + \frac{V_2 R_f}{R_2} + \cdots + \frac{V_N R_f}{R_N} \right) \]

- **Differential amplifier**

  \[ V_{out} = \frac{R_2}{R_1} (V_2 - V_1) \]

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Examples of Op. Amp. applications

- Integrating amplifier
  \[ V_{\text{out}} = -\frac{1}{j\omega CR} V_{\text{in}} = -\frac{1}{RC} \int V_{\text{in}} \, dt \]

- Differentiating amplifier
  \[ V_{\text{out}} = -\frac{R}{j\omega C} V_{\text{in}} = -RC \frac{dV_{\text{in}}}{dt} \]

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Examples of Op. Amp. applications

- **Current-to-voltage**
  
  ![Current-to-voltage schematic]

  \[ V_{out} = -I_{in}R \]

- **Voltage to current**
  
  ![Voltage to current schematic]

  \[ I_L = \frac{V_{in}}{R} \]