Operational Amplifiers (Op-Amps)

- Active element for amplifying an electric signal
- Very common (and inexpensive) component
- Best understood as 3-terminal circuit element: 2 inputs and 1 output

SOIC 14 Op-amp: $0.90 each
Op-Amps

- Op-amps contain the following key components:
  - Resistor connecting input voltages
  - Voltage-controlled voltage source generating output
  - Power supply on top & bottom
Op-Amps

• Amplification factor typically very large (100,000 or more)
• Input resistance generally very large (1 MΩ or greater)
• Thus, very common for open-loop circuit to saturate output voltage
Ideal Op-Amps

- To simplify prior problem, assume resistance becomes arbitrarily large – then,
  - Negligible current flows between inputs (since $I = V_d/R_i \to 0$)
  - Both input currents become zero (since $I = I_+ = -I_-$)
Ideal Op-Amps

• Create a closed loop configuration and let the amplification factor diverge – then,
  – Output voltage is bounded: \( V_+ = A(V_+ - V_-) \)
  – Thus, \( V_- = \left( \frac{A-1}{A} \right) V_+ \)
  – In limit \( A \to \infty \), \( V_- \to V_+ \)
Ideal Op-Amps

• Golden rules:
  – Both input currents are zero
  – For closed loops: both input voltages are equal
Example #1

• Quantitatively predict the behavior of this circuit:
Solution

- Since \( I_+ = I_- = 0 \), all current flows directly from output to ground.
- Thus, \( I = \frac{V_{\text{out}}}{(R_f + R_i)} \)
- With feedback, \( V_+ = V_- = IR_i = V_{\text{out}} \frac{R_i}{(R_f + R_i)} \)
- Amplification \( A = \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{R_f+R_i}{R_i} = 1 + \frac{R_f}{R_i} \)
Example #2

• What’s the amplification of this circuit? What’s the most important difference from the last example?

\[ A = -\frac{R_f}{R_i} = -10 \]
Example #3

• What is the output voltage of this circuit, and what could it be used for?
Solution

- Calculate total current: \[ I = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \]
- Calculate the output voltage: \[ -V_{\text{out}} = IR_f = \frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3 \]
- Applications:
  - Audio mixer
  - Digital to analog conversion
Example #4

• How will this circuit behave? What might you use it for?
Solution

• Calculate branch currents: \( I_1 = \frac{V_1 - V_x}{R_1} \); \( I_2 = \frac{V_2 - V_x}{R_2} \)

• No input current implies \( I_1 = -I_2 \), or \( \frac{V_1 - V_x}{R_1} = -\frac{V_2 - V_x}{R_2} \)

Thus, \( R_2 (V_1 - V_x) = R_1 (V_x - V_2) \)

\[
V_x = \frac{R_2 V_1 + R_1 V_2}{R_1 + R_2}
\]
Solution

Given that \( V_x = \frac{R_2V_1 + R_1V_2}{R_1 + R_2} \), 3 solution regimes

<table>
<thead>
<tr>
<th>Region Name</th>
<th>Input Values</th>
<th>Output Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive saturation</td>
<td>( AV_x &gt; V_{sat} )</td>
<td>( V_{sat} )</td>
</tr>
<tr>
<td>Active</td>
<td>( -V_{sat} &lt; AV_x &lt; V_{sat} )</td>
<td>( AV_x )</td>
</tr>
<tr>
<td>Negative saturation</td>
<td>( AV_x &lt; -V_{sat} )</td>
<td>( -V_{sat} )</td>
</tr>
</tbody>
</table>
Homework

• HW #24 due today by 4:30 pm in EE 325B
• HW #25 due Fri.: DeCarlo & Lin, Chapter 9:
  – Problem 38 [Plot $v_c(t)$ and $i_L(t)$ for $0 < t < 0.16$ sec]