OUTLINE

- Inverting-amplifier circuit
- Summing-amplifier circuit
- Noninverting-amplifier circuit
- Difference-amplifier circuit

Reading
Chapter 5.3-5.7

Review: Negative Feedback

- Negative feedback is used to “linearize” a high-gain differential amplifier.

Without feedback

With feedback
**Inverting Amplifier Circuit**

\[ i_n = 0 \Rightarrow i_s = -i_f \]
\[ v_p = 0 \Rightarrow v_n = 0 \]

\[ v_o = -\frac{R_f}{R_s} v_s \]

**Analysis using Realistic Op Amp Model**

- In the analysis on the previous slide, the op amp was assumed to be ideal, *i.e.*
  \[ R_i = \infty; A = \infty; R_o = 0 \]
- In reality, an op amp has finite \( R_i \), finite \( A \), non-zero \( R_o \), and usually is loaded at its output terminals with a load resistance \( R_L \). It can be shown that

\[
    v_o = \frac{-A + \left( \frac{R_o}{R_f} \right)}{\frac{R_s}{R_f} \left( 1 + A + \frac{R_o}{R_i} + \frac{R_o}{R_L} \right) + \left( 1 + \frac{R_o}{R_i} \right) \left( 1 + \frac{R_s}{R_i} \right) + \frac{R_o}{R_f}} v_s
\]
### Summing Amplifier Circuit

\[ v_o = -\left( \frac{R_f}{R_a} v_a + \frac{R_f}{R_b} v_b + \frac{R_f}{R_c} v_c \right) \]

\[ \begin{align*}
  i_n &= 0 \Rightarrow i_a + i_b + i_c = -i_f \\
  v_p &= 0 \Rightarrow v_n = 0
\end{align*} \]

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### Application: Digital-to-Analog Conversion

A DAC can be used to convert the digital representation of an audio signal into an analog voltage that is then used to drive speakers -- so that you can hear it!

"Weighted-adder D/A converter"

<table>
<thead>
<tr>
<th>Binary number</th>
<th>Analog output (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>0</td>
</tr>
<tr>
<td>0001</td>
<td>.5</td>
</tr>
<tr>
<td>0010</td>
<td>1</td>
</tr>
<tr>
<td>0011</td>
<td>1.5</td>
</tr>
<tr>
<td>0100</td>
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</tr>
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<td>1100</td>
<td>7</td>
</tr>
<tr>
<td>1110</td>
<td>7.5</td>
</tr>
</tbody>
</table>

S1 closed if LSB = 1
S2 " if next bit = 1
S3 " if " = 1
S4 " if MSB = 1

(Transistors are used as electronic switches)
Characteristic of 4-Bit DAC

Digital Input

Noninverting Amplifier Circuit

\[ i_p = 0 \Rightarrow v_p = v_g \Rightarrow v_n = v_g \]

\[ i_n = 0 \Rightarrow R_s \& R_f \text{ form a voltage divider} \]
Difference Amplifier Circuit

\[ i_n = 0 \Rightarrow \frac{v_n - v_a + v_n - v_o}{R_a} = 0 \]
\[ i_p = 0 \Rightarrow v_p = -\frac{R_c}{R_c + R_d} v_n = v_n \quad \text{if} \quad \frac{R_a}{R_b} = \frac{R_p}{R_d}, \text{then} \quad v_o = \frac{R_c}{R_a} (v_b - v_a) \]

Difference Amplifier – Another Perspective

Redefine the inputs in terms of two other voltages:

1. differential mode input \( v_{dm} \equiv v_b - v_a \)
2. common mode input \( v_{cm} \equiv \frac{(v_a + v_b)}{2} \)

so that

\[ v_a = v_{cm} - \frac{(v_{dm})}{2} \quad \text{and} \quad v_b = v_{cm} + \frac{(v_{dm})}{2} \]

Then it can be shown that

\[ v_o = A_{cm} v_{cm} + A_{dm} v_{dm} \]

where \( A_{cm} = \frac{R_a R_d - R_b R_c}{R_a (R_c + R_d)} \) and \( A_{dm} = \frac{R_d (R_a + R_b) + R_p (R_c + R_d)}{2 R_d (R_c + R_d)} \)

“common mode gain” “differential mode gain”
Difference Amplifier (cont’d)

If \( \frac{R_a}{R_b} = \frac{R_c}{R_d} \), then \( v_{cm} = 0 \) and \( v_{dm} = \frac{R_b}{R_a} \)

- An ideal difference amplifier amplifies only the differential mode portion of the input voltage, and eliminates the common mode portion.
  - provides immunity to noise (common to both inputs)
- If the resistors are not perfectly matched, the common mode rejection ratio (CMRR) is finite:

\[
CMRR \equiv \left| \frac{A_{dm}}{A_{cm}} \right| \approx \frac{1 + R_b / R_a}{\varepsilon} \quad \text{if} \quad \frac{R_a}{R_b} = (1 - \varepsilon) \frac{R_c}{R_d}
\]

Summary

- Voltage transfer characteristic of op amp:

- A feedback path between an op amp’s output and its inverting input can force the op amp to operate in its linear region, where \( v_o = A (v_p - v_n) \)
- An ideal op amp has infinite input resistance \( R_i \), infinite open-loop gain \( A \), and zero output resistance \( R_o \). As a result, the input voltages and currents are constrained:
  \( v_p = v_n \) and \( i_p = -i_n = 0 \)