Welcome to EECS 16A!
Designing Information Devices and Systems I

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Module 2
Lecture 11
Op-amp circuit analysis (Note 19)
Last Lecture...

**Toolbox**

- Resistors
- Capacitors
- Open-circuits
- Voltage Dividers/Summers
- Op-Amps
- Thevenin and Norton Equivalence
- KCL/KVL
- Element Definitions
- DAC
- Negative Feedback
- Op-Amp in Negative Feedback
- “Golden Rules” for Op-Amps

\[ A_V = \frac{V_{out}}{V_{in}} \]
Today

Voltage Divider:

\[ V_{R2} = V_S \left( \frac{R_2}{R_1 + R_2} \right) \]

Voltage Summer:

\[ V_{\text{out}} = V_1 \left( \frac{R_2}{R_1 + R_2} \right) + V_2 \left( \frac{R_1}{R_1 + R_2} \right) \]

Unity Gain Buffer:

\[ \frac{v_{\text{out}}}{v_{\text{in}}} = 1 \]

Inverting Amplifier:

\[ v_{\text{out}} = v_{\text{in}} \left( -\frac{R_f}{R_s} \right) + v_{\text{REF}} \left( R_f + R_s \right) \]

Non-inverting Amplifier:

\[ v_{\text{out}} = v_{\text{in}} \left( 1 + \frac{R_{\text{top}}}{R_{\text{bottom}}} \right) - v_{\text{REF}} \left( \frac{R_{\text{top}}}{R_{\text{bottom}}} \right) \]

Transresistance Amplifier:

\[ v_{\text{out}} = i_{\text{in}} (-R) + v_{\text{REF}} \]
Checking for Negative Feedback

**Step 1** – Zero out all independent sources: replacing voltage sources with wires and current sources with open circuits as in superposition.

**Step 2** – Wiggle the output and check the loop – to check how the feedback loop responds to a change.
- If the error signal decreases, the output must also decrease. The circuit is in negative feedback.
- If the error signal increases, the output must also increase. The circuit is in positive feedback.

Now let's solve it...
NFB \implies \text{GR\#2 applies} \quad U^+ = U^-

V_{in} = U_1 = I_1 R_1
V_{out} = U_3 = I_2 R_2
I_1 + I_2 = 0
\frac{V_{in}}{R_1} + \frac{V_{out}}{R_2} = 0
V_{out} = R_2 \cdot \left( - \frac{V_{in}}{R_1} \right)

V_{out} = - \frac{R_2}{R_1} \cdot V_{in}

\text{Inverting Amplifier}

\text{Av} = \frac{V_{out}}{V_{in}} = - \frac{R_2}{R_1}

\text{Element Definitions:}
V_{R1} = I_1 R_1
V_{R2} = I_2 R_2
V_{R1} = U_1 - U_2 = U_1 = V_{in}
V_{R2} = U_3 - U_2 = U_3 = V_{out}
A faster way...

**GR2:** \( U^+ = U^- \)
\[ U_2 = U^- \]
\[ U^+ = 0 \implies U_2 = 0 \]

**GR1 + KCL:** \( I_1 = I_2 + I^- \)
\[ \frac{U_2 - U_1}{R_1} = \frac{U_3 - U_2}{R_2} + I^- \]

\[ -\frac{U_1}{R_1} = \frac{U_3}{R_2} \]

\[ \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \]
Example circuit 2 (trans-resistance amplifier)

\[ i_t = 0 \Rightarrow u_1 = u_2 \]

Invert polarity

\[ \Rightarrow \]

Step 1

\[ R \]

Step 2: Check for NFB

Increase output \( \Rightarrow \)

\[ + \] moves up

output increases

by a lot

\[ X \] Not in NFB
The input is current; output is voltage; we use this model in the lab for photo sensors!
Example circuit 3 -

Check NFB:

\[ (-V_f) \]
Voltage Divider

\[ V_{S} = \frac{R_{2}}{R_{1} + R_{2}} \cdot V_{out} \]

NFB (GR=2)

\[ U^{-} = U^{+} \]

\[ V_{in} = -V_{S} \]

\[ V^{-} = U^{+} \]

\[ V_{in} = -\frac{R_{2}}{R_{1} + R_{2}} \cdot V_{out} \Rightarrow \frac{V_{in}}{V_{out}} = -\frac{R_{2}}{R_{1} + R_{2}} \]

\[ A_{V} = \frac{V_{out}}{V_{in}} = -\frac{R_{1} + R_{2}}{R_{2}} = -(1 + \frac{R_{1}}{R_{2}}) \]
Artificial Neuron

• Neurons in our brain are interconnected.
• The output of a single-neuron is dependent on inputs from several other neurons.
• This idea is represented with vector-vector multiplication – the output is a linear combination of several inputs.
• An artificial neuron circuit must perform addition and multiplication.

\[
\begin{bmatrix}
a_1 \\
a_2
\end{bmatrix} \cdot \begin{bmatrix}
v_1 \\
v_2
\end{bmatrix} = a_1 v_1 + a_2 v_2
\]
Artificial Neuron

- Neurons in our brain are interconnected.
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- This idea is represented with vector-vector multiplication – the output is a linear combination of several inputs.
- An artificial neuron circuit must perform addition and multiplication.
\[-\frac{V_1}{R_1} - \frac{V_2}{R_2} = \frac{V_{out}}{R_3}\]

\[V_{out} = -\frac{R_3}{R_1} V_1 + \left(-\frac{R_3}{R_2} V_2\right) + \ldots + \left(-\frac{R_3}{R_n} V_n\right)\]

only negative weights
\[a_{11} v_1, a_{12} v_2, \ldots, a_{1n} v_n\]

All weights are negative: How can we make \(a_1\) and \(a_2\) positive?

Add another inverting amplifier circuit.
\[ V_{out+} = - \frac{R_2}{R_1} \cdot V_{in} \]

\[ \frac{V_{out+}}{V_{in}} = - \frac{R_2}{R_1} \]

A result from inverting amplifier

\[ V_{out+} = - \frac{R_3}{R_1} \cdot V_{in} - \frac{R_3}{R_2} \cdot V_2 \] (V_{in})

\[ V_{out+} = - V_{in} \text{ (when } R_1 \text{ and } R_2 \text{ are the same)} \]
Unity Gain Buffer

\[
V_{\text{in}} \rightarrow + \rightarrow V_{\text{out}}
\]

- Allows us to isolate circuits

\[
U^+ = V_{\text{in}} \\
U^- = V_{\text{out}}
\]

Gain (\(G\))

\[
U^+ = U^- \\
V_{\text{in}} = V_{\text{out}}
\]

Speaker Design

\[
V_{\text{DAC}} \quad \text{loading}
\]

\[
V_{\text{speaker}} = \frac{V_{\text{DAC}}}{126}
\]

\[
I_t = 0 \Rightarrow U^+ = V_{\text{DAC}} \\
V_{\text{out}} = V_{\text{speaker}} = U^- \Rightarrow U^+ = U^-
\]

\[
V_{\text{DAC}} = V_{\text{speaker}}
\]