EECS 16A
More Op-amps
Admin

- Happy April, Fools (day)!
Previously on EECS 16A...
Op-amps
Last time: Playing Music

Digital to Analog Converter (DAC):
Digital music → output is 0-3.3V

Speaker: voltage in, sound out
input should be 0-10V

Digital music

R_{DAC}=1k\Omega

doesn't work! need to amplify by 3x

R_{Speaker}=8.2

cause gain is not 3x, and is not stable.

Negative Feedback: output stabilizes around input system 'Corrects itself', so that error = 0

\[
V_{in} \rightarrow A_{V_{in}} \rightarrow A_{V_{out}} \rightarrow V_{out}
\]

Negative feedback

A_{V_{out}} = \frac{1}{1 + A}

if A very large \rightarrow V_{out} = \frac{1}{A} \cdot V_{in}

can choose A,f to get any output!

Vin

Op-amp in negative feedback: (assume V_{ob}=-V_{os}) op-amp gain is very large!

V_{out} = A(V_{+} - V_{-})
\[= A V_{in} - A V_{out} \]
\[= \frac{V_{in}}{1 + A} \]
\[= \frac{1}{A + 1} \cdot V_{in} \]

"Buffer Circuit" negative feedback, gain=1

as long as A \rightarrow \infty

V_{out} = Vin

System gain is f=1
Now we can use our buffer circuit in our music player:

Cons: I actually want $V_{out} = 3V_{DAC}$, to make speaker loud enough? So need $\frac{V}{4} = 3$.
So this won’t work either! 😞

Solution: add resistors to set $f = \frac{1}{3}$

But FIRST:

**Golden Rules of op-amps:**

For an ideal op-amp, there is no current (open circuit).

### Golden Rule 1

No current (open circuit): $I_+ = I_- = 0$ (always true)

### Golden Rule 2

Only if you are in negative feedback (in steady state): $V_+ = V_-$ (also assumes infinite gain)

#### Input to the op-amp

$V_i = V_i^+ - V_i^-$

#### Negative feedback

If $V_{out}$ goes up, then $(V_+ - V_-)$ goes down, then $V_{out} = A(V_+ - V_-)$ goes down

Pros:

$\rightarrow V_{out} = V_{DAC}$, not $\frac{1}{4}V_{DAC}$
$\rightarrow$ gets rid of ‘loading effects’
Instead of a buffer (gain=1), I can use a \textbf{non-inverting op-amp} circuit to get gain=3.

\[ V_{fb} = \frac{R_2}{R_1 + R_2} \cdot V_{out} \quad V_+ = V_{fb} \]

op-amp: \( V_{out} = A \left( V_+ - V_- \right) \)

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

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

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

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

as \( A \to \infty \), \( V_{out} = \frac{1}{\left( \frac{R_2}{R_1 + R_2} \right)} \cdot V_{in} \)

\textbf{Non-inverting amplifier:} \( V_{out} = \frac{R_1 + R_2}{R_2} \cdot V_{in} \)

"Wiggle output" to check neg. feedback: if \( V_{out} \) gets disturbed and increases ↑, then \( V_{fb} \uparrow \), so \( V_+ \uparrow \), and \( V_{out} = A \left( V_+ - V_- \right) \downarrow \) so disturbance gets corrected → Yes, Negative feedback!

\[ \text{DAC} \quad \text{Non-inverting Amplifier (feedback gain=3)} \quad \text{Speaker} \]

\[ V_{DAC} \quad \text{This WORKS! :)} \quad \text{yay!} \]

\textbf{Now we can use this to finalize our music player design!}
Inverting amplifier → amplifies & switches sign of voltage

What is \( V_{\text{out}} \) as a function of \( V_s, R_1, R_2 \)?

**Node A: KCL:** \( I_1 = 0 \), so \( I_1 = I_2 \)

\[
\begin{align*}
I_1 &= \frac{V_1}{R_1} = \frac{V_s - V_+}{R_1} \\
I_2 &= \frac{V_- - V_{\text{out}}}{R_2}
\end{align*}
\]

So

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

or

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

Golden Rules:

- \( I^+ = I^- = 0 \)
- \( V^+ = V^- \) (if in negative feedback)

**Need to get rid of this. Can we use golden rule 2?**

Is it in negative feedback?
- if \( V_{\text{out}} \uparrow \), then \( V_- \uparrow \) because \( V_s \) constant, which makes \( V_{\text{out}} = A(V_s - V_-) \)
- Yes! Negative feedback, so \( V^+ - V^- = 0 \)

\[
\frac{V_s}{R_1} + \frac{V_{\text{out}}}{R_2} = 0
\]

General eqn for inverting amplifier \( w/ V_{\text{in}} = 0 \)

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

**Example:** Want to design \( V_{\text{out}} = -3V_{\text{in}} \)

\[
\text{amp w/ flipped sign} \rightarrow \text{Inverting Amplifier}
\]

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

\[
- \frac{R_2}{R_1} = -3 \quad \text{many solutions!}
\]

Pick \( R_2 = 3k\Omega, R_1 = 1k\Omega \)

**Recall:**

\[
V_{\text{out}} = \frac{-R_2}{R_1} V_s
\]
Cascading circuit blocks:

- Problem: can't connect directly, or loading effect will change behavior.
- Solution: add a buffer!

Op-amp in neg. feedback with gain = 1 "Buffer circuit".

The safe way to connect two circuit blocks is with buffers in between.

Inverting Summing Amplifier: an inverting amplifier whose input is a sum of signals.

First, apply first golden rule \( I^+ = I^- = 0 \).

KCL: \( I_1 + I_2 = I^+ + I_3 \) where
- \( I_1 = \frac{V_1 - U^+}{R_1} = \frac{V_i}{R_i} \)
- \( I_2 = \frac{V_2 - U^-}{R_2} = \frac{V_v}{R_e} \)
- \( I_3 = \frac{V_3^{(0)} - V_{out}^-}{R_3} = -\frac{V_{out}^+}{R_3} \)

Note: could have also solved with superposition.

\( V_{out}^+ = -\frac{R_3}{R_1} V_1 -\frac{R_3}{R_2} V_2 \)

Can make \( = 1 \) for summer.