Today, we will:

- Do a review example problem – filters and digital data acquisition
- Begin to review the pdf module: **Operational Amplifiers (Op-Amps)**, and do examples
- Discuss some additional items not in the pdf notes about op-amps

Example: Digital data acquisition and filters

Given: Annalee is testing an electronics circuit in the lab. There is some pesky high frequency noise at around 3600 Hz with an amplitude around ±0.3 V. She uses a 12-bit A/D converter to sample data from the circuit. The data acquisition system is set up with a range of -10 to 10 V, and she builds a low-pass filter to filter out the high frequency noise.

To do:

(a) Calculate the gain (G) necessary to attenuate the 3600 Hz noise to a level that is below the quantizing error of the A/D converter.

(b) Annalee builds a passive first-order low-pass filter using just a resistor (R = 10.0 kΩ) and a capacitor (C = 0.653 μF). Calculate the cutoff frequency (in Hz) of her filter.

(c) Calculate the gain (G) of this filter at the noise frequency (3600 Hz). Is the noise amplitude attenuated enough to completely remove the noise?

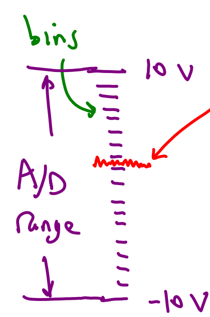
Solution:

(a) A/D Quantizing (quantization) error $= \pm \dfrac{V_{max} - V_{min}}{2^{N+1}} = \pm \dfrac{10-(-10)\text{ V}}{2^{12+1}} = \pm 0.0024414 \text{ V}$

- So, the required gain of the filter is $G = \dfrac{|V_{out}|}{|V_{in}|}$ ← set to quantizing error ← set to input amplitude (of the noise)

- Recall, we want to attenuate the noise so much that it gets "lost" in the resolution or quantizing error of the A/D.

[In other words, we set G small enough that the noise fits inside one bin of the A/D converter!]



Force the noise amplitude to be within one bin (then it can no longer be measured)

- $G = \dfrac{|\pm 0.0024414 \text{ V}|}{|\pm 0.3 \text{ V}|} = \boxed{0.008138 = G_{required}}$

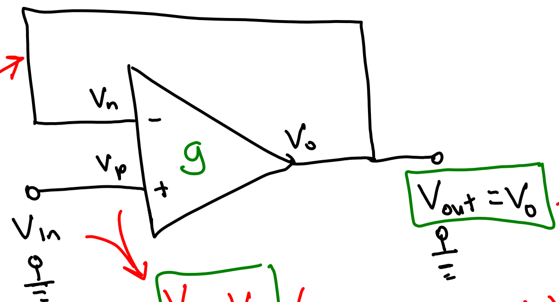
(b) $f_{cutoff} = \dfrac{1}{2\pi RC} = \dfrac{1}{2\pi(10{,}000\,\Omega)(0.653\times10^{-6}\text{ F})}\left(\dfrac{\text{F}\cdot\text{V}}{\text{C}}\right)\left(\dfrac{\text{C}}{\text{s}\cdot\text{A}}\right)\left(\dfrac{\Omega\cdot\text{A}}{\text{V}}\right) = 24.3729 \text{ Hz}$

$\boxed{f_{cutoff} \text{ of her filter} = 24.4 \text{ Hz}}$

(c) At $f = 3600$ Hz (noise), $G = \dfrac{1}{\sqrt{1+\left(\dfrac{3600}{24.3729}\right)^2}} = \boxed{0.00677 = G_{actual}}$

Thus, since $G_{actual} < G_{required}$, $\boxed{\text{THIS FILTER WILL DO THE JOB}}$ Yes

DETAILED ANALYSIS OF A BUFFER (REAL OP-AMP)



$\boxed{V_p = V_{in}}$ (connected by a wire)

- Eq. for the op-amp:

$$\boxed{V_o = g(V_p - V_n)} \quad ☆ \quad (1)$$

Similarly, $\boxed{V_{out} = V_o}$ (connected by a wire)

- So, Eq. (1) becomes $V_o = V_{out} = g(V_{in} - V_n)$

But $\boxed{V_n = V_o = V_{out}}$, since these are all connected by a wire!

- Thus, $\underline{V_{out} = g(V_{in} - V_{out})}$ $[\text{or } V_o = g(V_{in} - V_o)]$

- Do some algebra $\longrightarrow$ $V_{out}(1+g) = V_{in}$ $\rightarrow$ $\boxed{V_{out} = \dfrac{g}{1+g} V_{in}}$ ☆

Exact equation for a buffer (op-amp has internal gain g)

Example numbers: For $V_{in} =$ exactly 5 V & $g = 1 \times 10^6$ (typical g)

Then $V_{out} = \dfrac{1\times10^6}{1+1\times10^6}(5\text{ V}) = \underline{4.999995\text{ V}}$

This is so close to 5 that any voltmeter would read $\underline{5.0000\text{ V}}$

CONCLUSION: $\boxed{\text{For a buffer, } \boxed{V_{out} \approx V_{in}} \text{ and } \boxed{V_n \approx V_p}}$ (the error is negligible)

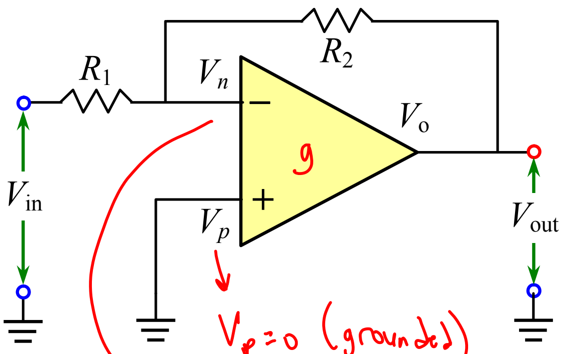
But, the exact relationship is $\boxed{V_{out} = \dfrac{g}{1+g} V_{in}}$

Example: Op-amps

Given: The circuit shown, with

- $R_1 = 20\ \text{k}\Omega$
- $R_2 = 80\ \text{k}\Omega$

The supply voltages to the op-amp are +15 V and −15 V (not shown).



$V_p = 0$ (grounded)

$V_n \approx V_p = 0$

To do:

(***a***) If the input voltage is V_{in} = 1.50 V DC and the op-amp is *ideal*, calculate the value of voltage V_n.

Solution:

- $V_p = 0$ since it is grounded
- For an ideal op-amp, $V_n = V_p$, so $\boxed{V_n = 0}$
- For a real op-amp, $V_n \simeq V_p \simeq 0$ because g is not ∞ (g typically $\sim 10^6$)

[V_n will be a very small voltage — millivolts or microvolts, depending on g]

(***b***) If the input voltage is V_{in} = 2.50 V DC and the op-amp is *real* (a type 741), calculate V_{out} (to 3 significant digits). [*Note*: You may still make the approximation $V_n \approx V_p$.]

Solution:

- This is an $\boxed{\text{inverting amplifier}}$

(I remember it because the input goes into V_n not into V_p — a noninverting amp is the opposite)

- $G = -\dfrac{R_2}{R_1} = \dfrac{-80}{20} = -4$
- $V_{out} = G\,V_{in} = (-4)(2.50\text{ V}) = -10.0\text{ V}$ (DC)

$\boxed{\text{Answer: } V_{out} \simeq 10\text{ V}}$

(actually a little smaller since $g \neq \infty$, but the error is negligible)

(***c***) If the input voltage is V_{in} = 4.50 V DC and the op-amp is *real* (a type 741), calculate V_{out} (to 2 significant digits). [*Note*: You may still make the approximation $V_n \approx V_p$.]

Solution:

- Here, $G = -4$ still, so $V_{out} = -4(4.50\text{V}) = \underline{-18.0\text{ V}}$
- But, the op-amp cannot put out this large of a negative voltage since $V^-_{supply} = -15\text{ V}$ [The op-amp will saturate]
- Actual $\boxed{V_{out} \simeq -14\text{ V}}$ (about a volt different than V^-_{supply})