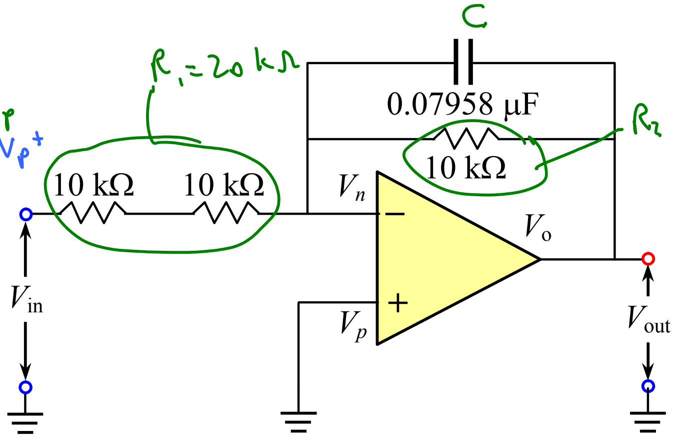
Today, we will:

- Do some more example problems and discussion about op-amp circuits
- Finish reviewing the pdf module: **op-amps (miscellaneous properties: GBP, CMRR)**

Example: Op-amp circuits

Given: Consider the circuit shown.



* Active, not passive because of the op-amp & feedback loop

(*a*) **To do**: What kind of circuit is this?

Inverting because V_{in} goes into V_n^- not V_p^+

$\boxed{\text{Active, inverting, low-pass filter/amplifier}}$

Low-pass (think about the capacitor)

(*b*) **To do**: Calculate the output voltage V_{out} when the input voltage is 2.0 V DC.

- For a DC voltage input, the DC voltage charges up the capacitor, & it acts like an open circuit after that
- Circuit becomes an inverting amplifier with $G = -\frac{R_2}{R_1} = -\frac{10}{20} = -0.5 = G_{amp}$
- Thus, $V_{out} = G_{amp} G_{filter} V_{in} = (-0.5)(1)(2.00\ V) = \boxed{-1.00\ V \quad DC}$

(*c*) **To do**: Calculate the amplitude of the output voltage V_{out} when the input voltage is a pure sine wave with amplitude 1.0 V and frequency 200 Hz.

- Since this is a low-pass filter/amplifier, $f_{cutoff} = \frac{1}{2\pi R_2 C}$ [R_2 is the resistor closest to the capacitor]
- numbers: $f_{cutoff} = \frac{1}{2\pi(10{,}000\ \Omega)(0.07958 \times 10^{-6}\ F)}\left(\frac{\Omega \cdot A}{V}\right)\left(\frac{C}{V \cdot s}\right)\left(\frac{F \cdot V}{C}\right) = 199.99\ Hz$

  (let's call it $\underline{f_{cutoff} = 200.\ Hz}$)

- Overall gain, $G_{overall} = G_{amplifier} \cdot G_{filter}$

  [The filter gain & the amplifier gain are multiplied together]

- In terms of amplitude, $|G_{overall}| = |G_{amplifier}| \cdot |G_{filter}|$

  (We use absolute value since we care only about the amplitude, not the sign)

- $|G_{overall}| = \underbrace{(0.5)}_{\text{amplifier}} \underbrace{\frac{1}{\sqrt{1+\left(\frac{f}{f_{cutoff}}\right)^2}}}_{\text{filter}} = (0.5)\frac{1}{\sqrt{1+\left(\frac{200}{199.99}\right)^2}} = 0.35355 \cong 0.354$

- Finally, $|V_{out}|$ = amplitude of output voltage $= |G_{overall}||V_{in}| = (0.35355)(1.00\ V) = \boxed{0.354\ V}$

Recall, from last lecture:

In general, we desire our electronic circuits to have ***very low output impedance*** and ***very high input impedance***.

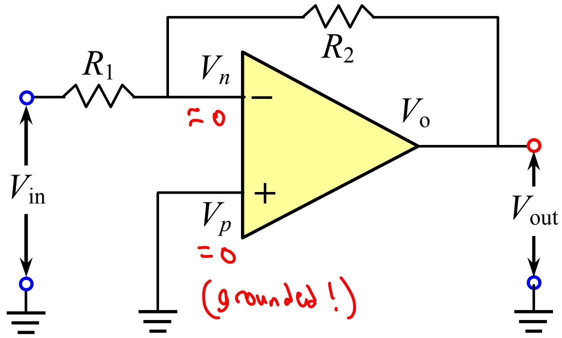
The input impedance of an inverting amplifier op-amp circuit is approximately R_1.

That is one reason why we generally want R_1 to be large (> 1 kΩ as an absolute lower limit).

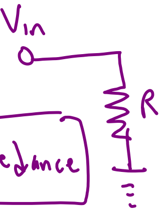
The output impedance of an inverting amplifier op-amp circuit is small, on the order of 1 Ω.

What about a *noninverting* amplifier? What are the input and output impedances?

Inverting Amplifier:



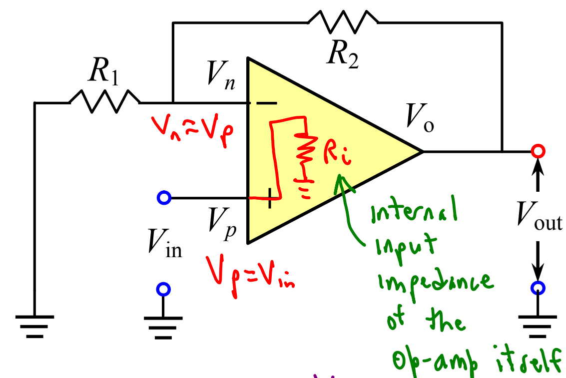
V_{in} "sees"



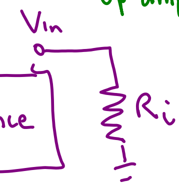
So, $\boxed{R_1 = \text{input impedance}}$

R_1 = selected by user, & typically ranges from 10 kΩ to 100 kΩ (not real huge)

Noninverting Amplifier:



V_{in} "sees"



So, $\boxed{R_i = \text{input impedance}}$

R_i = internal input impedance of the op-amp itself, which is typically tens of megaohms (huge)

BOTTOM LINE:

INVERTING AMPLIFIER:

- The input impedance of an inverting amplifier is $\approx R_1$ (not real huge)
- The output impedance of an inverting amplifier is ~ 1 Ω (small)

NONINVERTING AMPLIFIER:

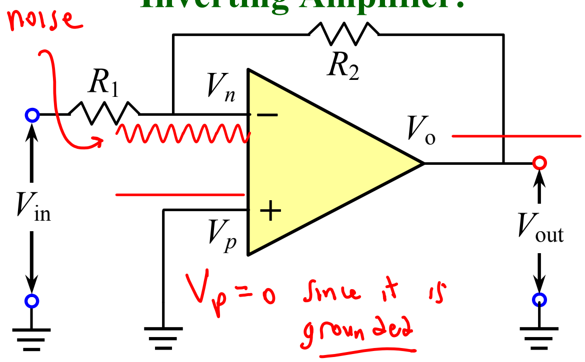
- The input impedance of a noninverting amplifier is $\approx R_i$ (huge, Mohms)
- The output impedance of a noninverting amplifier is ~ 1 Ω (small)

Which is "better"?

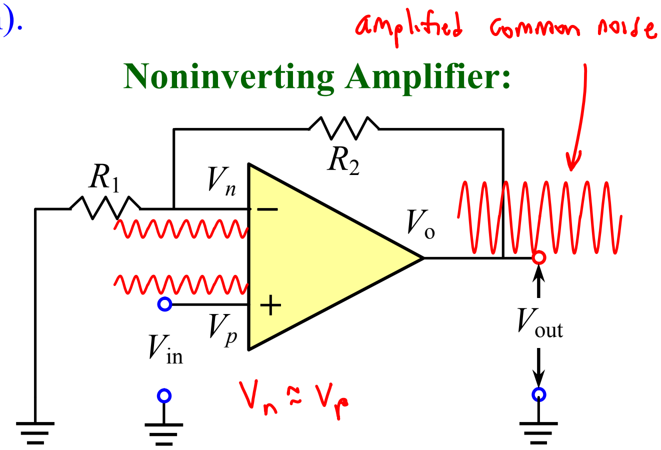
- Noninverting is "better" if primary concern is input loading.
- Inverting is "better" if primary concern is noise, especially common mode noise.

Let's compare the amplification of **common mode noise** for *inverting* and *noninverting* amplifiers (common mode noise amplification).

Inverting Amplifier:



Noninverting Amplifier:



- V_n may have noise, but $V_p = 0$
- There is no common mode noise!

[Noise in V_{in} affects only V_n]

- $V_n \approx V_p$, so if there is noise in V_{in}, there is common mode noise in both V_n & V_p
- This common mode noise gets amplified by gain G_{cm} (common mode gain)

[G_{cm} is an undesired property of the op-amp]

Comments: • In both cases, signal & noise get amplified due to amplifier gain

$\left(G = -\frac{R_2}{R_1}\right.$ for inverting & $G = 1 + \frac{R_2}{R_1}$ for noninverting$\left.\right)$

• We are talking here about additional noise amplification due to G_{CM} effects

☆

Bottom Line:

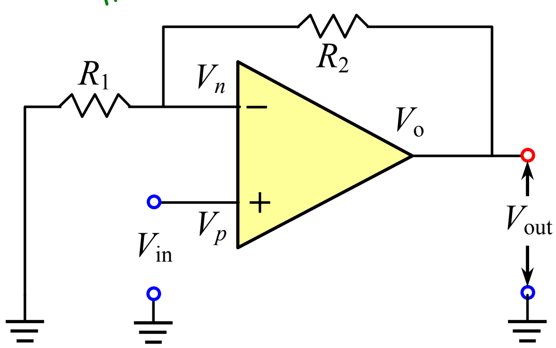
- If *input loading* is of primary concern, *noninverting* amplifiers should be used.
- If *noise reduction* and *signal-to-noise issues* are of primary concern, *inverting* amplifiers should be used.

High-end audio equipment → noise is primary concern, so use inverting amplifiers

Example: Op-amp circuits with GBP effects

Given: We need to amplify the output of a microphone (music converted into voltage) by a factor of 1000. We construct a noninverting amplifier as sketched, with:

- $R_1 = 1\ \text{k}\Omega$ (lower recommended limit)
- $R_2 = 999\ \text{k}\Omega$ (close to the upper recommended limit, which is 1 MΩ)



To do:
(***a***) Calculate the *theoretical* gain of the circuit (at any frequency) if the op-amp were ideal.
(***b***) Calculate the *actual* gain for a type 741 op-amp, with GBP = 1.0 MHz at the following frequencies of the music:

- f = 20 Hz (lower limit of human hearing)
- f = 261.63 Hz (middle C) → middle C on a piano is 261.626 Hz
- f = 4000 Hz = 4 kHz (a fairly high note)
- f = 20 kHz (upper limit of human hearing) (for healthy young people — older people lose their hearing, especially high freq.'s)

(***c***) Suggest a better circuit.

Solution:

(a) Noninverting amplifier → $G_{theory} = 1 + \frac{R_2}{R_1} = 1 + \frac{999}{1} = \boxed{1000 = G_{theory}}$

(b) • In real life, however, the actual G will be lower than this due to GBP effects. And, the reduction of G depends on the frequency component of the signal.

• Here, GBP = 1.0 MHz (given by op-amp specs)

• From the notes, $\boxed{GBP_{noninverting} = G_{theory} \cdot f_c}$ (f_c = internal cutoff frequency due to GBP effects) (internal limitations of the op-amp)

$$\boxed{f_c = \frac{GBP_{inverting}}{G_{theory}}} = \frac{1{,}000{,}000\ \text{Hz}}{1000} = 1000\ \text{Hz}$$

• The op-amp acts like a low-pass filter with $f_{cutoff} = f_c = 1000$ Hz !

$$\rightarrow G_{actual} = G_{theory} \cdot \frac{1}{\sqrt{1 + \left(\frac{f}{f_c}\right)^2}}$$

$$= (1000) \frac{1}{\sqrt{1 + (20/1000)^2}} = 999.8$$

At f = 20 Hz, GBP has very little effect; $G \approx G_{theory}$

Repeat for all the frequencies in the signal:

f (Hz)	G_{theory}	G_{actual}
20	1000	999.8
261.63	1000	967.4
4,000	1000	242.5
20,000	1000	49.9

We are losing amplification at the high frequencies! (The music would not sound so great)

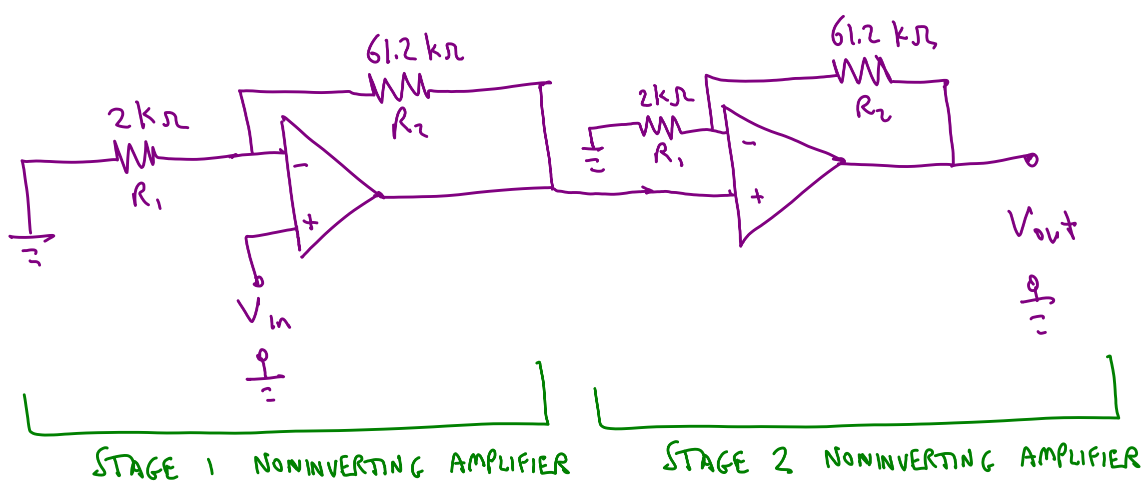
(c) Better circuit? USE A TWO-STAGE AMPLIFIER (Two instead of one in series)

- Let $G_1 = G_2 = \sqrt{1000} = 31.623$ since $G = G_1 \cdot G_2$
- Pick $R_1 = 2.00\ k\Omega$ (twice the lower recommended limit)
- Calculate R_2 (remember that this is noninverting amplification)

$$G_1 = 1 + \frac{R_2}{R_1} \longrightarrow R_2 = R_1(G-1) = 2.00\ k\Omega\,(31.623-1) = 61.2455\ k\Omega$$

- So, for each (identical) stage, use $R_1 = 2.00\ k\Omega$ & $R_2 = 61.2\ k\Omega$

- Revised two-stage noninverting amplifier circuit:



$G_{theory_1} = 31.623$ $G_{theory_2} = 31.623$

- Overall theoretical gain $= G_{theory,\,overall} = G_{theory_1} G_{theory_2} = 31.623^2 = 1000$ ✓

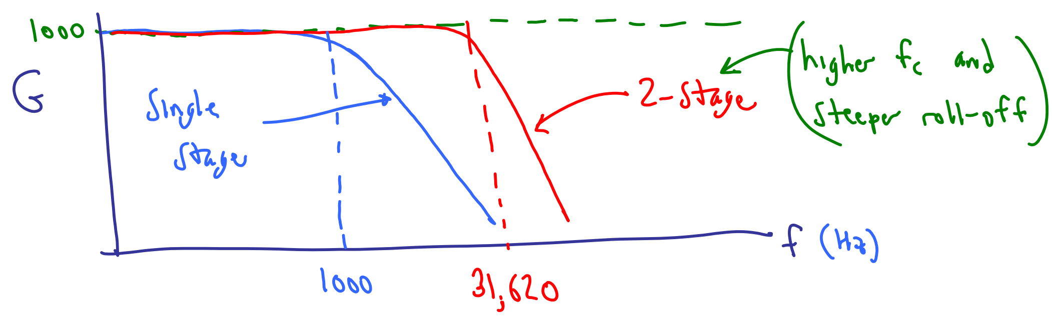
· Now let's check the GBP effects for this revised 2-stage circuit:

· For one stage, $G_{theory} = 31.62$

$$f_c = \frac{GBP_{noninverting}}{G_{theory}} = \frac{1.00 \times 10^6 \text{ Hz}}{31.62} = \underline{31.62 \text{ kHz}}$$

Notice how much larger is f_c now (31.62 kHz) compared to previously (previous f_c was 1000 Hz = 1.00 kHz)

· Bode plot:



We say that the two-stage amplifier has a <u>greater bandwidth</u>

· Re-do the table of actual gain. Here $G_{overall} = (G_{theory})^2 (G_{GBP})^2$ since there are 2 stages in series

e.g., @ f = 4000 Hz, $G_{overall} = (31.62)^2 \left[\frac{1}{\sqrt{1+\left(\frac{4000}{31620}\right)^2}}\right]^2 = 984.2$

f (Hz)	G_{theory}	G_{actual}
20	1000	≈ 1000
261.63	1000	999.9
4,000	1000	984.2
20,000	1000	714.3

(was 49.9 for the single-stage amplifier)

We still lose some amplitude at the very highest frequencies, but this music will sound much better!

Lesson: Use a 2-stage amplifier to avoid GBP filtering effects

Example: Op-amp circuits

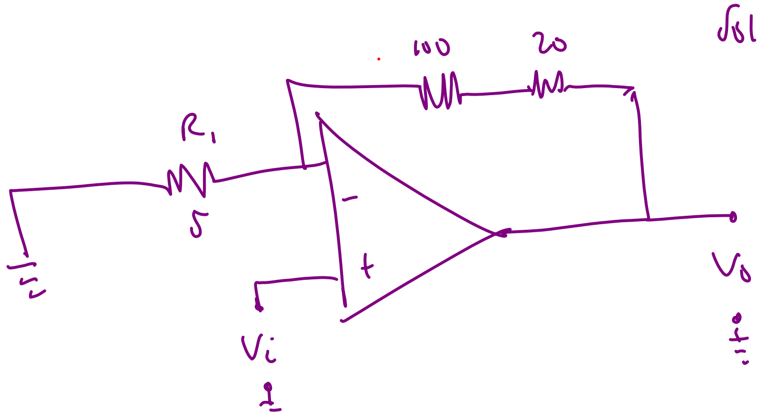
Given: We need to build an amplifier with a theoretical gain of 25 (or -25 – sign does not matter). We use a 741 op-amp with GBP = 1.0 MHz (1000 kHz). The resistors we have on hand are 5 kΩ, 10 kΩ, 20 kΩ, 50 kΩ, 100 kΩ, and 200 kΩ (we have several of each).

(*a*) To do: Draw an electrical circuit that will generate the required gain using a non-inverting amplifier. Repeat for an inverting amplifier.

Solution:

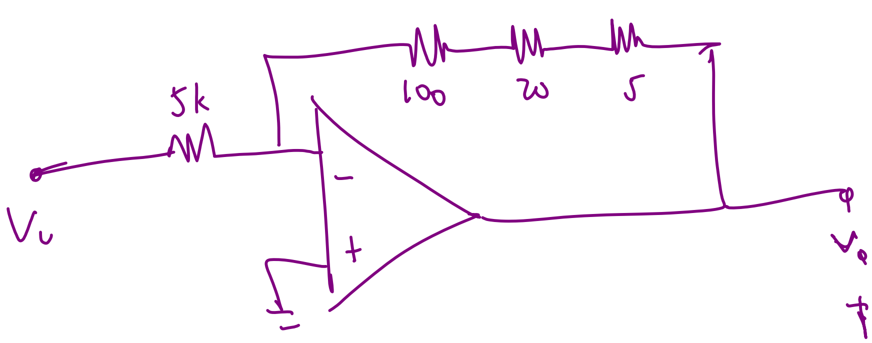
Non-inverting: $G_{theory} = 1 + \frac{R_2}{R_1} = 25$ Pick $R_1 = 5\ k\Omega$

Solve $R_2 = 120\ k\Omega$



Inverting: $G_{theory} = -\frac{R_2}{R_1} \rightarrow R_2 = -R_1 G_{theory}$

Pick $5\ k\Omega = R_1 \rightarrow R_2 = 125\ k\Omega$



☆ Solve the rest of this problem on your own, for practice (***b***) **To do**: For the non-inverting case, calculate the overall gain of the amplifier if the signal being amplified has a frequency of 20 kHz. Repeat for the inverting amplifier.

Solution:

Non-inverting:

ANSWERS:

$f_c = 40$ kHz

$\boxed{G_{overall} = 22.4}$

Inverting:

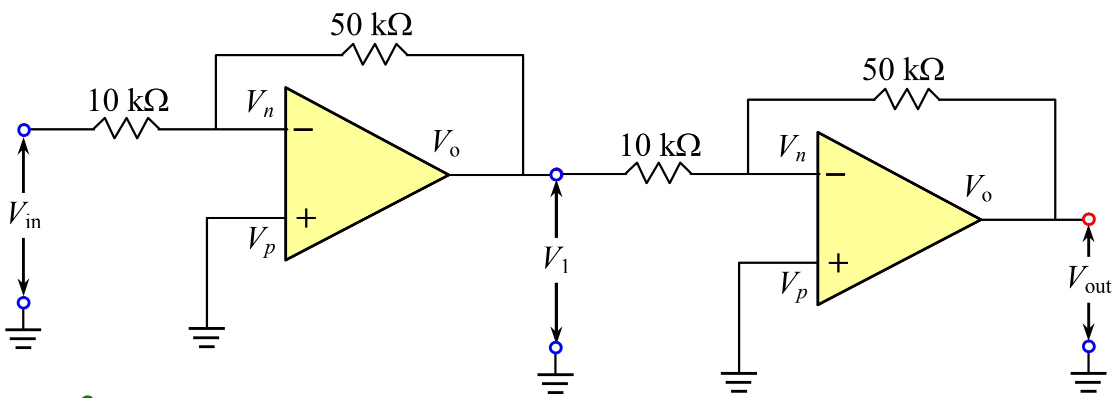
$f_c = 38.46$

$\boxed{G_{overall} = -22.2}$

(*c*) **To do**: For the inverting case, suppose we split up the gain into two stages to reduce the effect of the GBP-filtering. Calculate the overall gain of the amplifier if the signal being amplified has a frequency of 20 kHz.

★ DO THIS ON YOUR OWN FOR PRACTICE

Solution:



Stage 1 inverting amplifier

Stage 2 inverting amplifier

Combined theoretical gain = 25

However, due to GBP effects, the actual overall gain is lower

$f_c = 166.67$ kHz

$G_{overall} = (-4.964)^2 = 24.6$

[GBP effects are not significant in this problem]