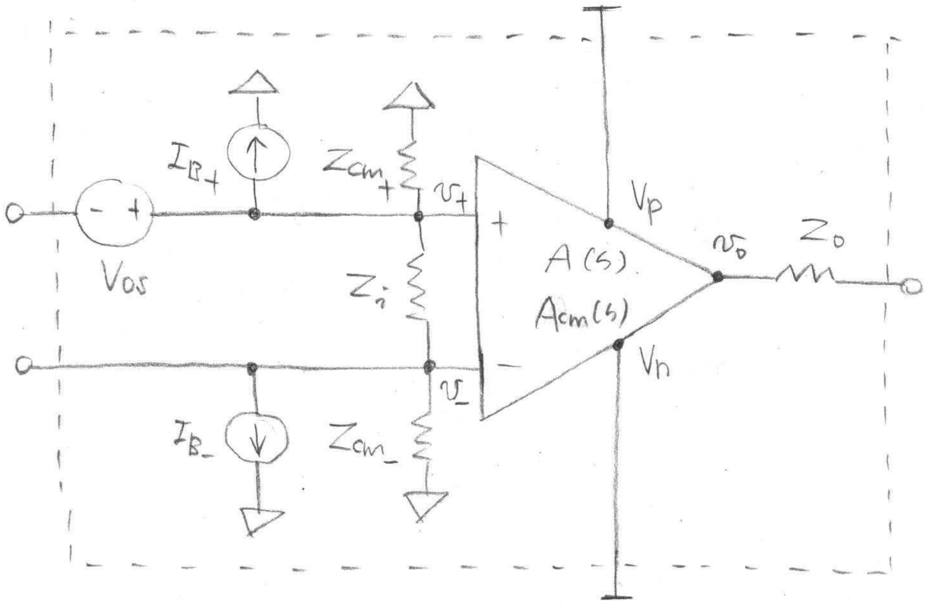
< Nonidealities of Op-Amps & In-Amps >

So far, we studied various nonidealities of op-amps / In-amps.

Today's lecture will summarize those, and introduce some more.



<u>Note</u> :

Many of them can be modeled as <u>linear</u> elements.

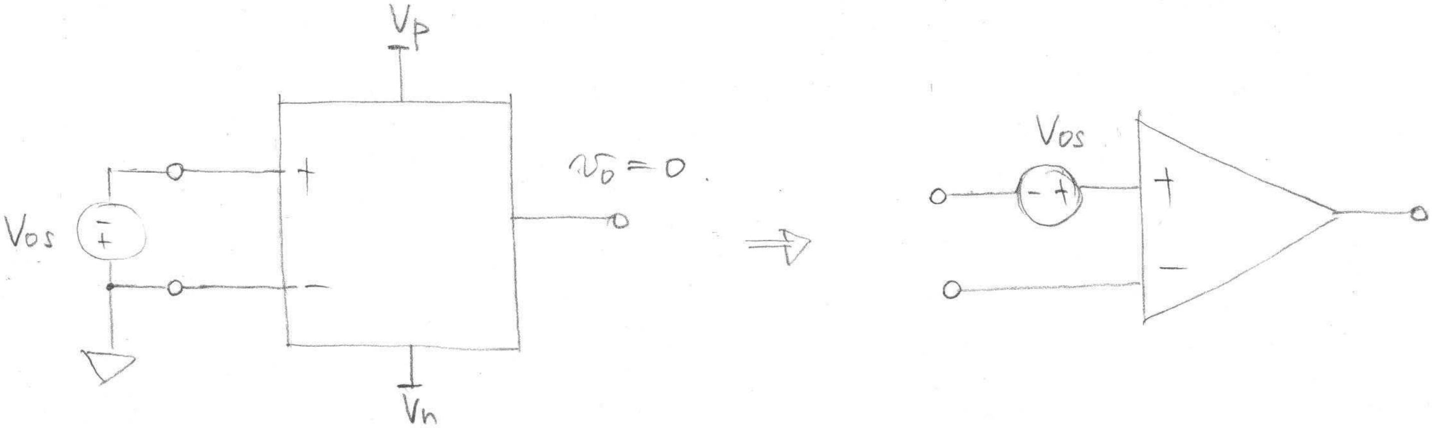
① Voltage Gains & Voltage Ranges.

$$v_o = A(v_+ - v_-) + A_c\left(\frac{v_+ + v_-}{2}\right) + \underbrace{A_p \Delta V_p + A_n \Delta V_n}_{= A_s \Delta V_s \text{ if perturbed symmetrically.}}$$

- open-loop gain $A(j\omega)$
- Common-mode rejection ratio $CMRR = \dfrac{A(j\omega)}{A_c(j\omega)}$
- power-supply rejection ratio $\begin{cases} PSRR_+ = \dfrac{A(j\omega)}{A_p(j\omega)} \\ PSRR_- = \dfrac{A(j\omega)}{A_n(j\omega)} \end{cases}$
- Input voltage range : $V_{min} < v_+, v_- < V_{max}$
- Output voltage rang : $V_{min} < v_o < V_{max}$

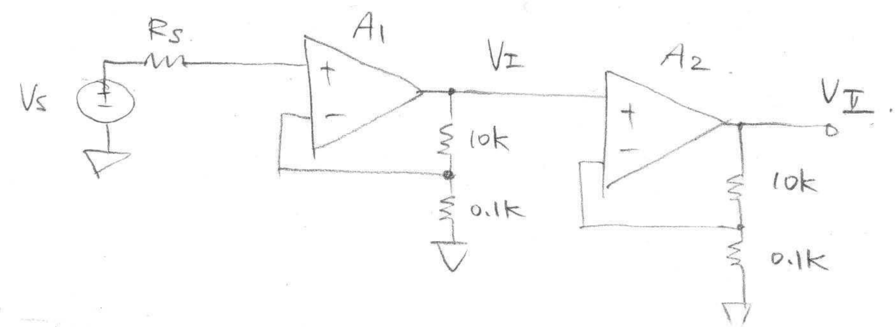
$\Rightarrow$ Cause "Clipping"

② Input offset Voltage (V_{os})



- Actual op-amp requires small non-zero differential input voltage to make the output voltage zero.
- This can be modeled as a small internal voltage V_{os} opposing the external voltage.
- It occurs due to mismatches in the internal circuits.
- It can saturate op-amp circuits with high DC gain.

<u>Example</u> Microphone Amplifier.

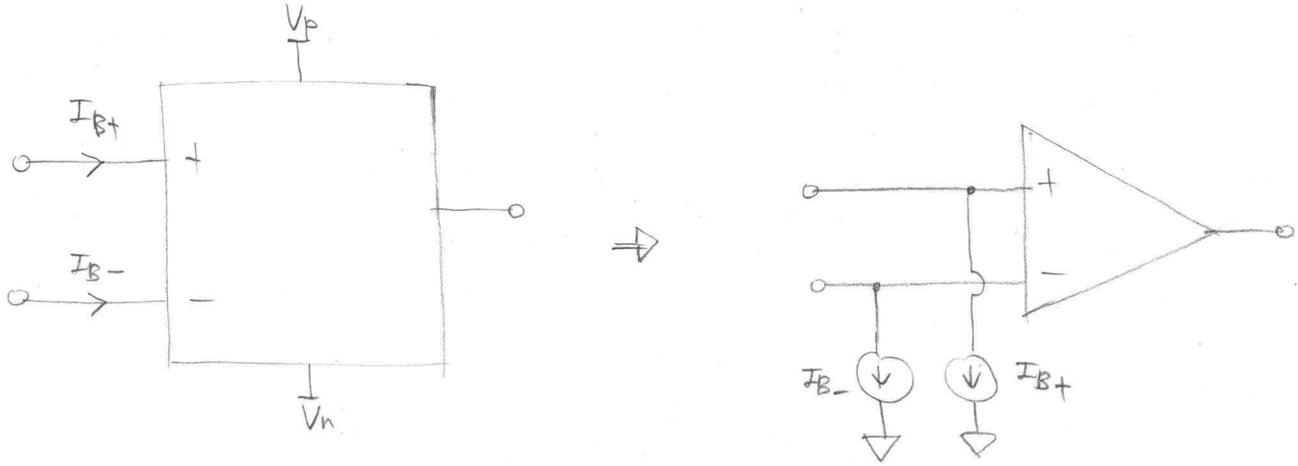


- If A_1 has $V_{os} = 2mV$ $V_I = 200mV$ $V_{II} = 20V$.

Saturates!

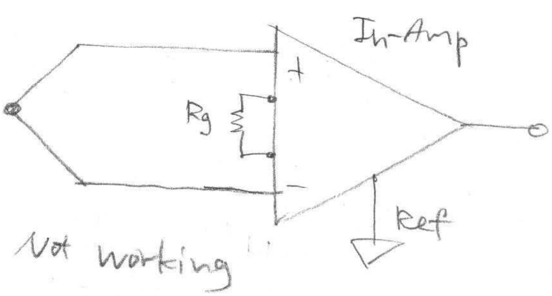
- Some op-amps provide pins for trimming V_{os}
- Implementing AC coupling (e.g. 1st order high-pass filter) between two stages can resolve the issue.

③ Input Bias Current : (I_{B+} , I_{B-})



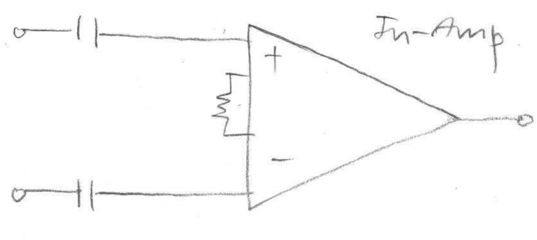
- Input terminals of an actual op-amp must draw. (or source) small DC currents.
- For example, those op-amps with bipolar transistors at the input stage, input bias currents correspond to the base currents.
- If circuits around an op-amp cannot conduct I_B, the op-amp does not work. (It cannot breath!)

Example : Thermo couple Amplifier

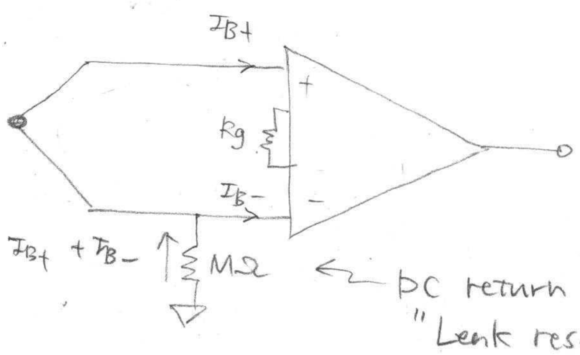


Not working

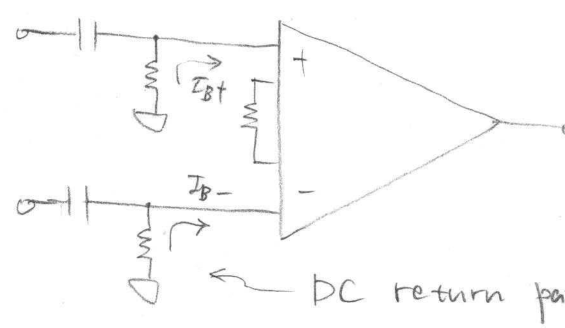
Example : AC-coupled Amplifier.



Not working !



← DC return path "Leak resistor"



← DC return path.

- Bias current compensation

- Many of modern op-amps have built-in circuits that provide the bias currents internally. (e.g. op 27)
- These are called bias current compensated op-amps.
- Therefore, the external bias current requirements are very low.
- Such op-amps can be quickly identified from the datasheet by looking at the "± (plus and minus)" sign for I_B.

④ Input Offset Current (I_{OS})

- A small difference between I_{B+} and I_{B-} is called "Input offset current" $I_{OS} = I_{B+} - I_{B-}$

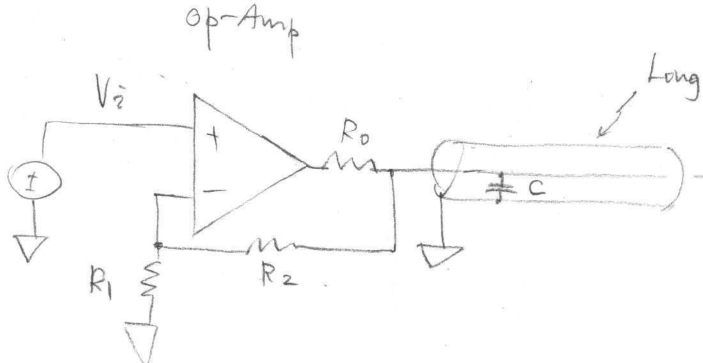
- For those op-amps with bias current compensation, the values for I_B and I_{OS} are the same or similar in the order of magnitude.

(5) Impedances.

- Output impedance : Z_o.

  - In most cases. Z_o is resistive (R_o) and small.

  - It can affect stability when driving a capacitive load. (e.g. coax cable capacitance), as it forms an RC low-pass filter in the feedback path.



Assuming $R_1, R_2 \gg R_o$

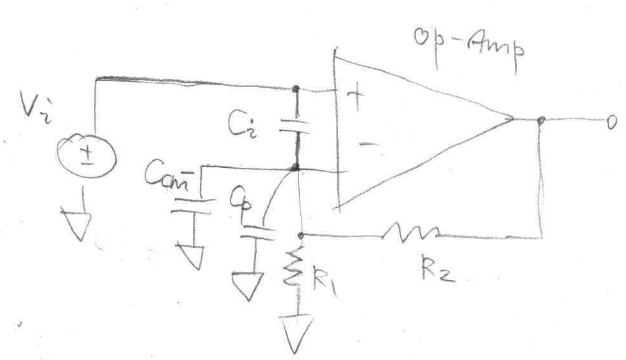
$$f(s) = \underbrace{\left(\frac{1}{R_o C s + 1}\right)}_{\text{phase lag in the loop}} \frac{R_1}{R_1 + R_2}$$

- Input impedance : Z_i, Z_{cmt}, and Z_{cm-}

  - In most cases. these are large resistances ($M\Omega - G\Omega$) in parallel with small capacitances.

  - The intrinsic values (as in the datasheet) can be affected by parasitic resistance / capacitances between the PCB and chip. (leakage path)

  - The net input capacitance C_{net} can affect the loop stability.



$$C_{net} = C_i + C_{cm^-} + C_p$$

$$f(s) = \frac{R_1}{R_1 + R_2} \underbrace{\left(\frac{1}{R_1 \| R_2 \cdot C_{net}\, s + 1}\right)}_{\text{phase lag in the loop.}}$$

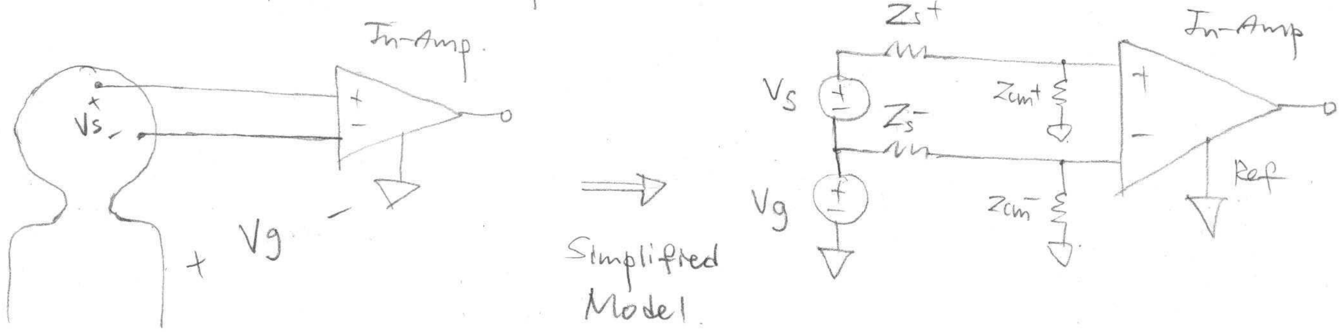
- Z_{cm+} and Z_{cm-} are important for In-amps.

They need to be 1) High and

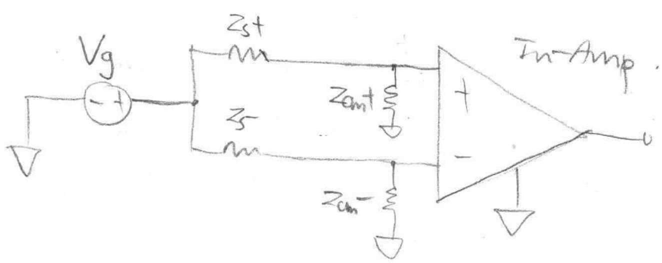
2) Well-matched ($Z_{cm+} \simeq Z_{cm-}$)

for a good interference rejection.

<u>Example</u> Biopotential Amplifier



Consider a case where $V_d = 0$.



Seen from the in-amp:

$$\begin{cases} v_{cm} = \frac{1}{2}(v_+ + v_-) \\ v_{dm} = v_+ - v_- \end{cases}$$

i) $Z_s^+ = Z_s^-$ (matched), $Z_{cm}^+ = Z_{cm}^-$ (matched)

$$v_+ = \frac{Z_{cm}}{Z_s + Z_{cm}} V_g$$

$$v_- = \frac{Z_{cm}}{Z_s + Z_{cm}} V_g$$

$$\Rightarrow \boxed{v_+ = v_-}$$

$$v_{dm} = 0$$

$$v_{cm} = \frac{Z_{cm}}{Z_s + Z_{cm}} V_g$$

↳ will be attenuated by $\underline{A_{cm}}$

ii) $Z_s+ \neq Z_s-$ (mismatched) $Z_{cm}+ = Z_{cm}-$ (matched)

$\boxed{v_+ \neq v_-}$ $v_{dm} = v_+ - v_-$ will be amplified through $A(s)$.

iii) $Z_s+ \neq Z_s-$ (mismatch), $Z_{cm}^+ = Z_{cm}^-$ (matched) and ☆ $Z_{cm} \gg Z_s$.

$$v_+ = \frac{Z_{cm}}{\cancel{Z_s+} + Z_{cm}} V_g \simeq V_g$$

$$v_- = \frac{Z_{cm}}{\cancel{Z_s-} + Z_{cm}} V_g \simeq V_g$$

$$\Rightarrow \boxed{v_+ \simeq v_-}$$

Large Z_{cm} can accomodate mismatch between Z_s+ & Z_s-

⑥ Slew Rate (SR)

- $\max\left\{\frac{dv_o}{dt}\right\} \leq SR$.

- Slew rate effectively limits the "power bandwidth"

Let $v_o(t) = V_o \cdot \sin\omega t$. $V_o = \text{const}$.

$$\frac{dv_o}{dt} = \omega V_o \cdot \cos\omega t$$

$$\max\left\{\frac{dv_o}{dt}\right\} = \omega V_o \leq SR$$

$\therefore$ $\omega \leq \frac{SR}{V_o}$ to avoid distortion.

$\therefore$ $\omega_{max} = \frac{SR}{V_o}$ "power bandwidth"

For an op-amp generating a sinusoidal output with a fixed amplitude V_o, the maximum frequency it can deliver without distorting the output is called power bandwidth. : $\omega_{max} = \frac{SR}{V_o}$.

(Perhaps) Better Illustration.