EE 105 | Discussion 3

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Discussion Outline

- Finite gain & bandwidth
- Gain error
- Introduce slew rate, offset voltage & input bias nonidealities

Nonideal Op Amps | Finite Gain & Bandwidth

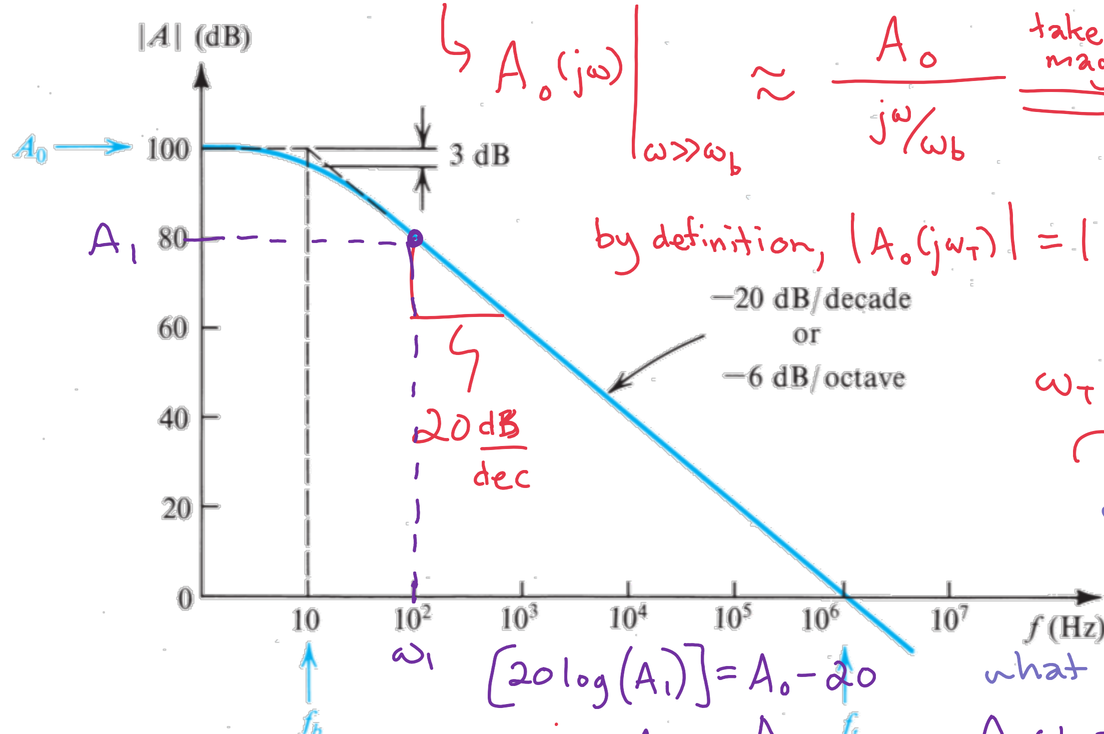
- Op amps without any feedback have open-loop gain $A_o(s)$

$$A_o(s) = \frac{A_o}{1+\frac{s}{\omega_b}}$$ (Low pass STC)

$$\hookrightarrow A_o(j\omega)\Big|_{\omega\gg\omega_b} \approx \frac{A_o}{j\omega/\omega_b} \xrightarrow[\text{mag}]{\text{take}} |A_o(j\omega)|\Big|_{\omega\gg\omega_b} = \frac{A_o\omega_b}{\omega}$$

by definition, $|A_o(j\omega_T)| = 1 = \frac{A_o\omega_b}{\omega_T}$

$$\omega_T = A_o\omega_b$$



$[20\log(A_1)] = A_o - 20$

$A_1 = \frac{A_o}{10}$

Say $A_o \downarrow 20\,dB = A_1$

$\omega \uparrow 10\times = \omega_1$

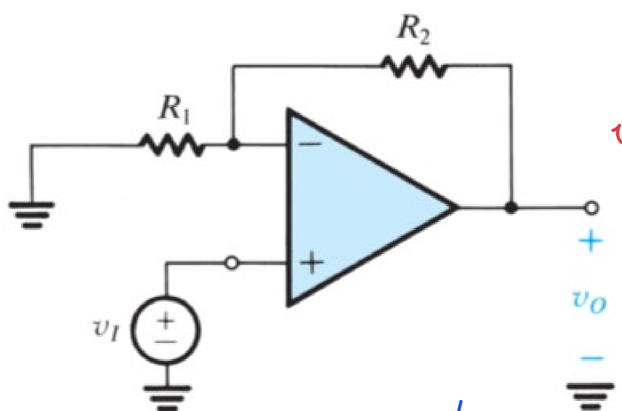
what happens to $(A_o\omega_b)$?

$A_1\omega_1 = \left(\frac{A_o}{10}\right)(10\omega_b) = A_o\omega_b$

GBW constant!

Nonideal Op Amps | Finite Gain & Bandwidth

- At DC, $|A_o(s)| = A_o$, which is finite in real op amps
- When we close the loop, this results in a deviation from the expected gain



$v_o = A_o(v^+ - v^-)$

$v^+ = v_i$

$v^- = \frac{R_1}{R_1 + R_2} v_o$

$= A_o\left(v_i - \frac{R_1}{R_1+R_2} v_o\right)$

$v_o\left(1 + \frac{R_1}{R_1+R_2} A_o\right) = A_o v_i$

$A_{v,actual} = \frac{v_o}{v_i} = \frac{A_o}{1 + \frac{R_1}{R_1+R_2} A_o} = \frac{1 + R_2/R_1}{1 + \frac{1 + R_2/R_1}{A_o}}$

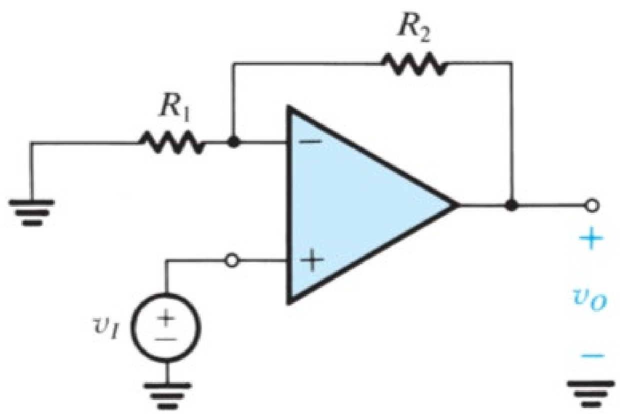
RECALL: $A_{v,ideal} = \left.\frac{v_o}{v_i}\right|_{A_o = \infty} = 1 + \frac{R_2}{R_1}$

equal when $A_o \to \infty$

$A_{v,actual} = \frac{A_{v,ideal}}{1 + A_{v,ideal}/A_o}$

Define gain error, $\epsilon = \frac{|A_{v,actual} - A_{v,ideal\cancel{0}}|}{A_{v,ideal}} \times 100$

Nonideal Op Amps | Finite Gain & Bandwidth



can swap & remove abs. val. b/c $A_{v,ideal} > A_{v,act.}$

$$\epsilon = \frac{|A_{v,actual} - A_{v,ideal}|}{A_{v,ideal}} \times 100$$

$$\varepsilon = \left(A_{v,id.} - \frac{A_{v,id.}}{1 + A_{v,id.}/A_o}\right)\left(\frac{1}{A_{v,id.}}\right) \times 100$$

$$= \frac{(1 + A_{v,id}/A_o) - 1}{1 + A_{v,id}/A_o} \times 100$$

$$= \frac{A_{v,id.}}{A_o + A_{v,id.}} \times 100$$

$$\% \ \varepsilon_{gain} = \frac{(1 + R_2/R_1)}{A_o + (1 + R_2/R_1)} \times 100$$

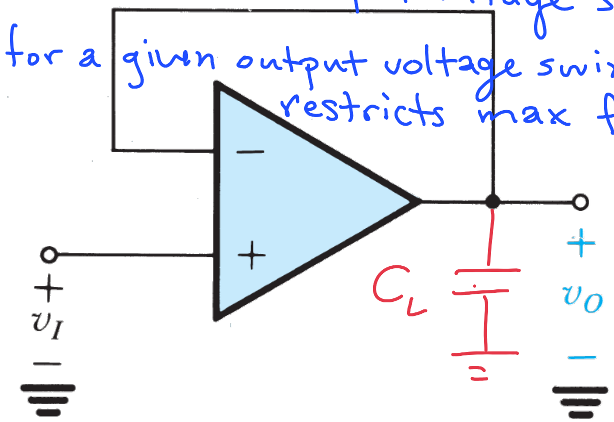
Nonideal Op Amps | Slew Rate

Slew rate (SR) refers to the max rate of change of an amplifier's output voltage

$$SR \triangleq \left.\frac{dv_o}{dt}\right|_{max}$$

This imposes two limitations on the output

1. Amplitude (i.e. ΔV_o) $\rightarrow \Delta V_o \leq SR \cdot \Delta t$ (for a given frequency, SR restricts max output voltage swing)
2. Frequency (i.e. Δt) $\rightarrow \Delta t \geq \frac{\Delta V_o}{SR}$ (for a given output voltage swing, SR restricts max frequency)



Say op amp has max output current $i_{o,max}$. For a given C_L:

$$i_{o,max} = C_L \left(\frac{dv_o}{dt}\right)_{max}$$

$\therefore SR = i_{o,max}/C_L$

Note that this $i_{o,max}$ is usually dictated by your amplifier's bias current

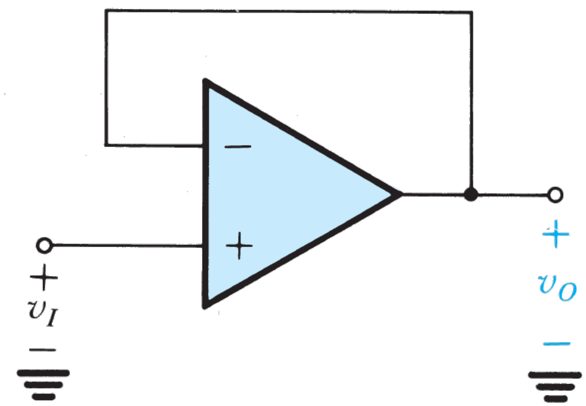
Nonideal Op Amps | Slew Rate

Limitation #1: Amplitude (i.e. ΔV_o)

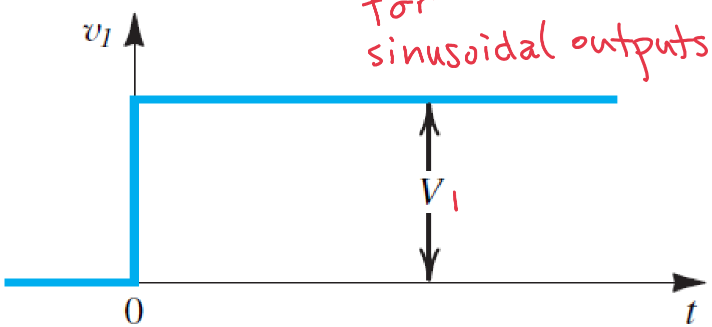
$\Delta V_o \leq SR \cdot \Delta t$

for sinusoidal outputs $\Delta t = \frac{1}{2f}$

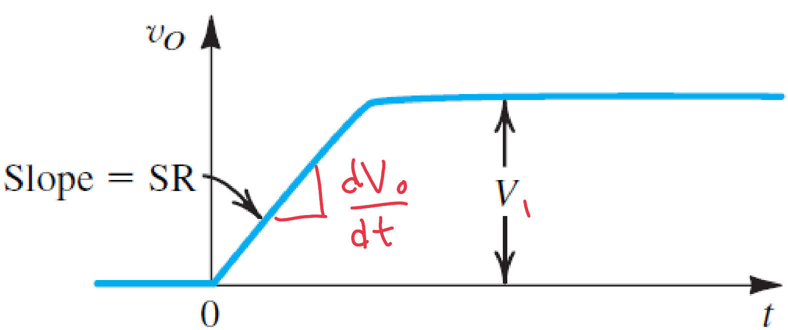
Unity-gain buffer



Input voltage step

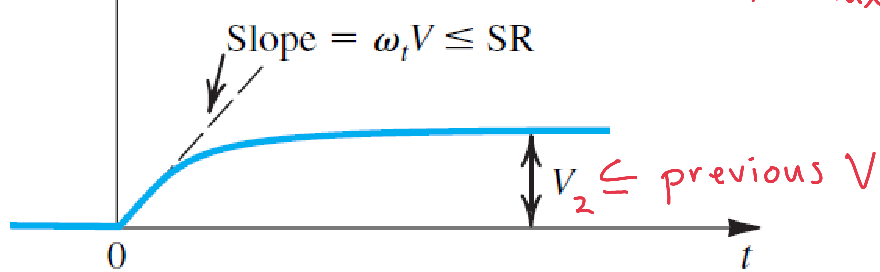


Output voltage waveform, SR-limited



Output voltage waveform, not SR-limited

i.e., slope never exceeds $\left(\frac{dV_o}{dt}\right)_{max}$



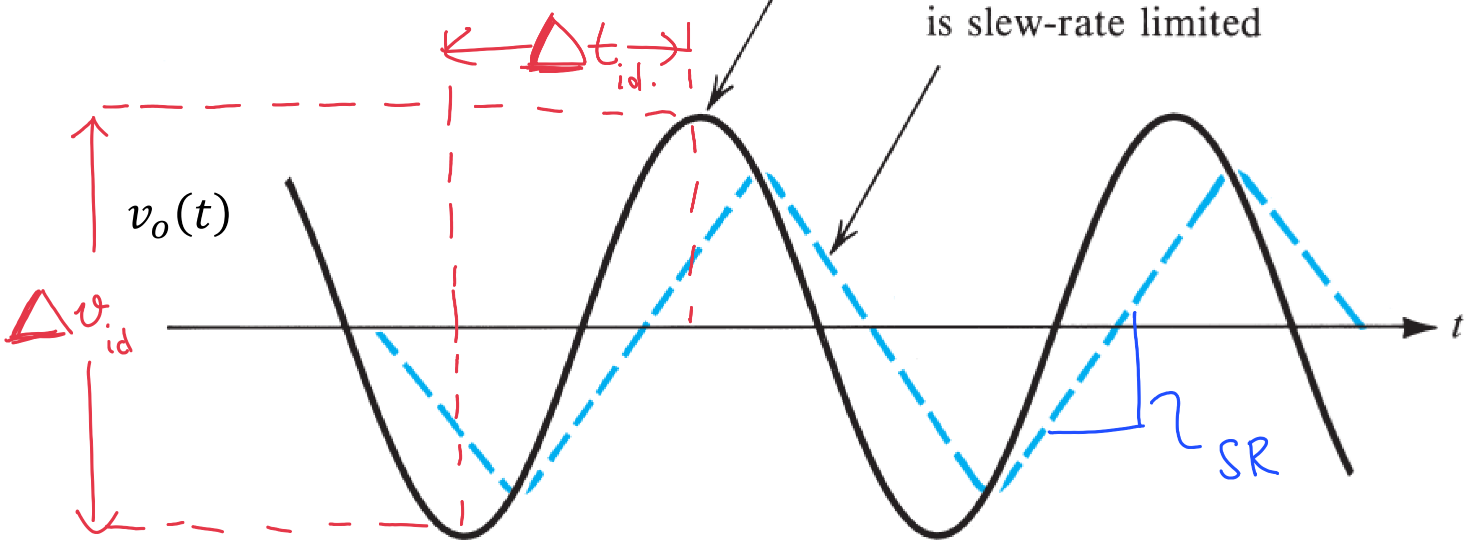
Nonideal Op Amps | Slew Rate

Limitation #2: Frequency (i.e. Δt) $\rightarrow \Delta t \geq \frac{\Delta V_o}{SR}$

$\Delta t_{ideal} = \frac{1}{2f}$

$SR < \frac{\Delta v_{ideal}}{\Delta t_{ideal}}$

<u>*Sinusoidal output waveform, SR-limited*</u>



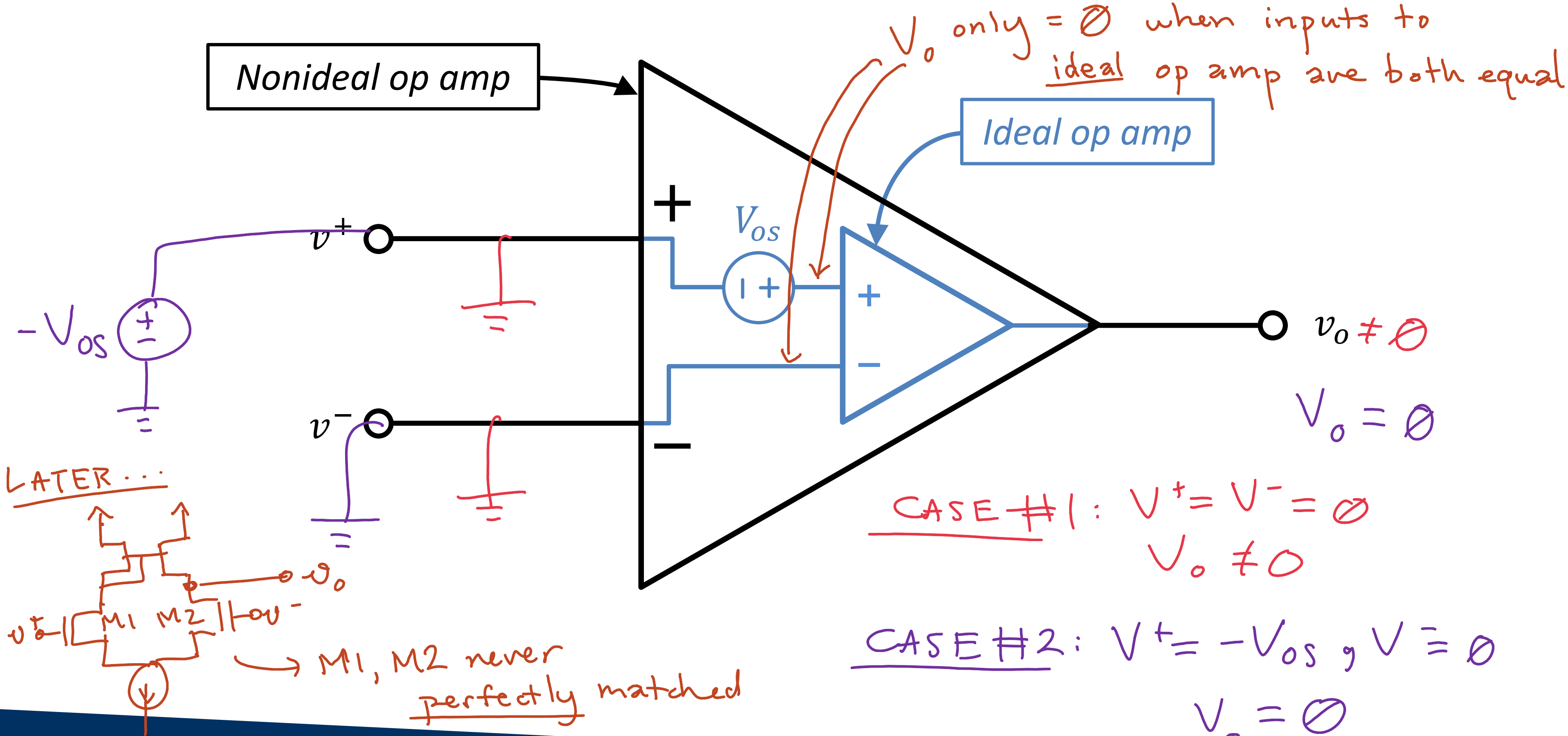
Nonideal Op Amps | Offset Voltage

$V_o = A_o (v^+ - v^-)$
(finite) (infinite) (zero)

Recall our qualitative understanding for why $v^+ = v^-$ when $A_o = \infty$

→ In actuality, setting both v^+& $v^- = 0$ will result in a nonzero v_o

→ This is due to mismatches in the op amp *differential pair* (we'll see this later)



Nonideal Op Amps | Offset Voltage

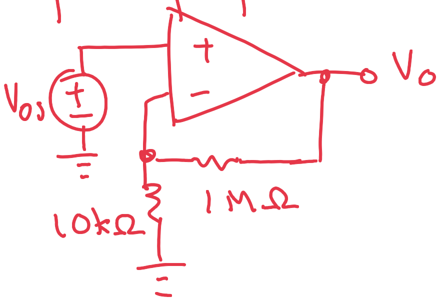
- Now consider an input offset voltage, $V_{OS} = \pm 2\ mV$
- What's the largest possible v_o when v_i is 0 V?

Given $A_{v,ideal} = 100 \frac{V}{V}$

$A_{v,ideal} = 1 + \frac{1M\Omega}{R_1}$

$R_1 \approx 10\ k\Omega$

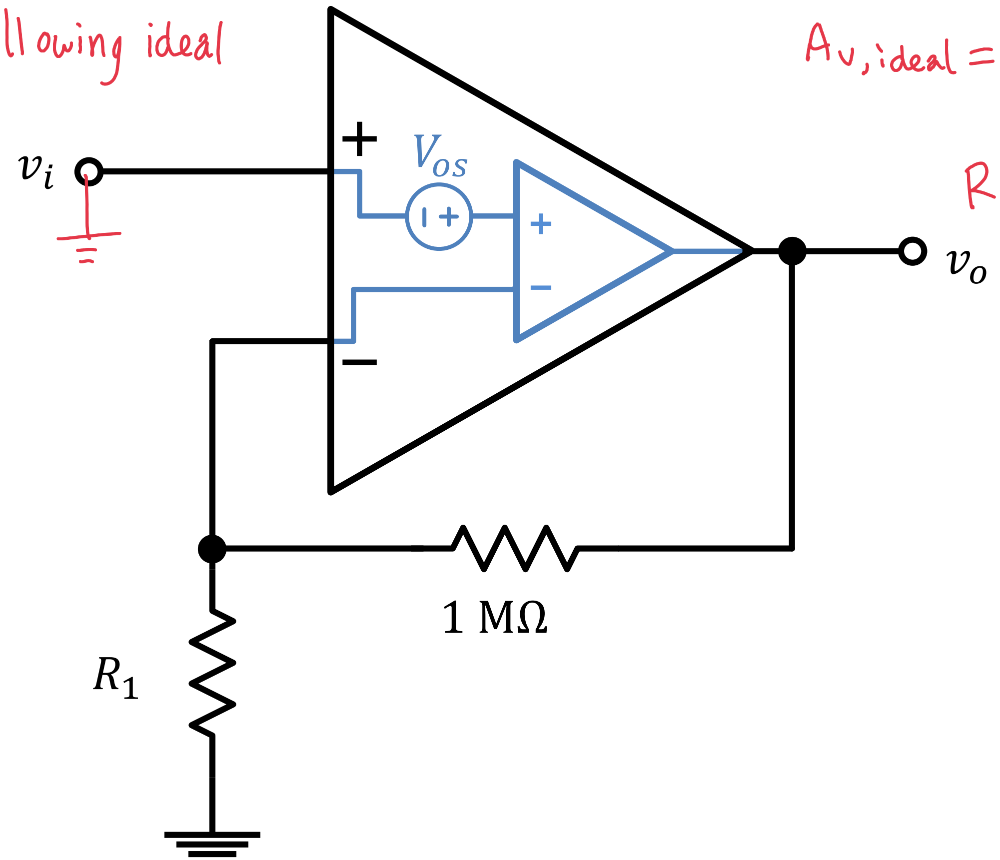
This looks just like the following ideal op amp problem:



$|V_o| = (100 \frac{V}{V})|V_{os}|$

$= (10^2)(2 \times 10^{-3})$

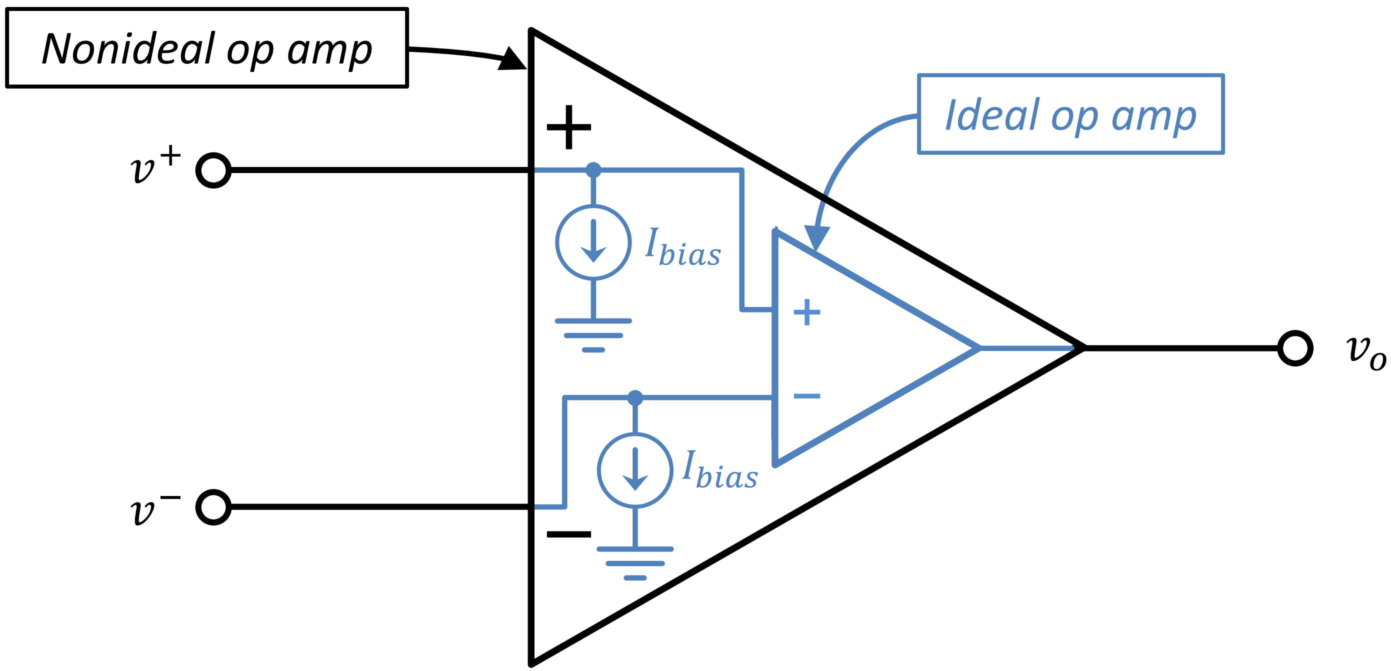
$V_o = \pm 200\ mV$



Nonideal Op Amps | Input Bias Current

If $i^+, i^- \neq 0$, what's another way to describe this nonideality?

$R_{in} \neq \infty$



Nonideal Op Amps | Input Bias Current

- The circuit below has a closed-loop gain of 100 V/V
- Input bias current, $I_{bias} = 200\ nA$
- What's v_o when v_i is 0 V?

↳ $R_1 \approx 10k\Omega$

(ignoring V_{os})

$v^+ = v_i$

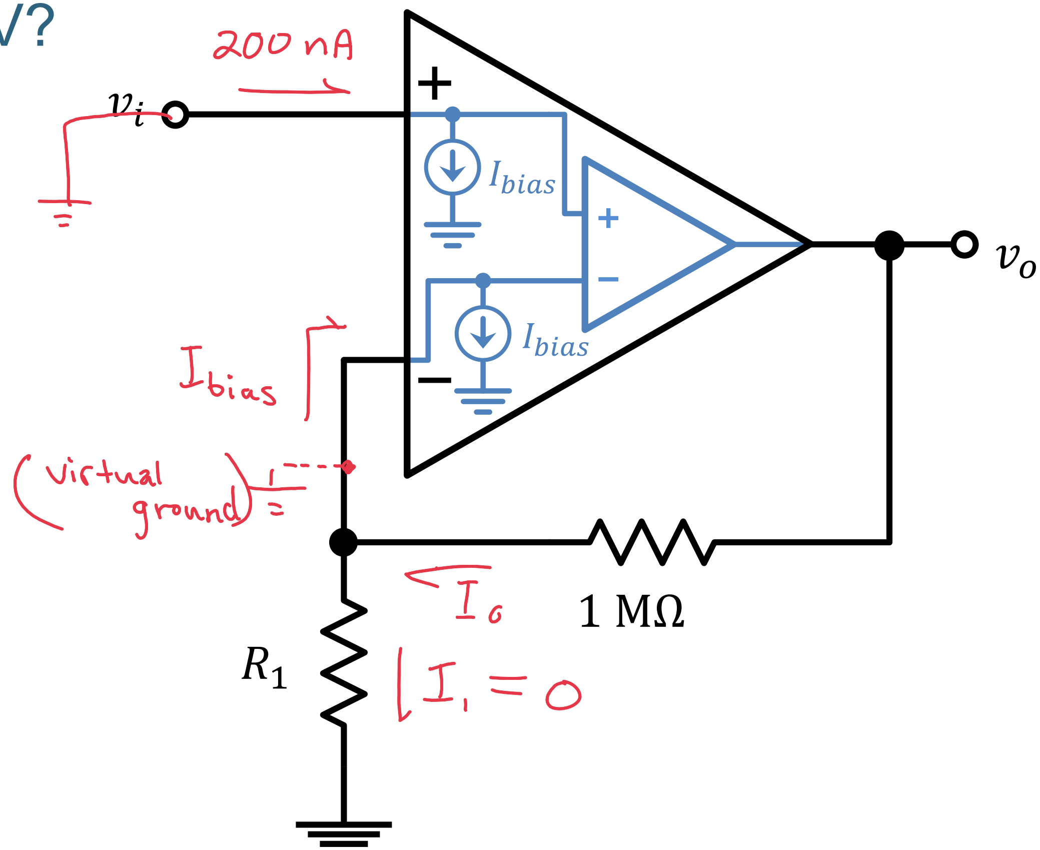
R_1 grounded on both sides, $I_1 = 0$

↳ $I_o = I_{bias}$

$\therefore V_o = I_{bias}(1M\Omega)$

$= (2\times10^{-7}A)(10^6\Omega)$

$V_o = 200\,mV$



Nonideal Op Amps | Bias Current Compensation

- Find the value of R_b required to null the effects of I_{bias} on v_o

To get $V_o = 0V$,

$$v^- = -I_o R_2$$

(b/c $V_o = v^- + I_o R_2$)

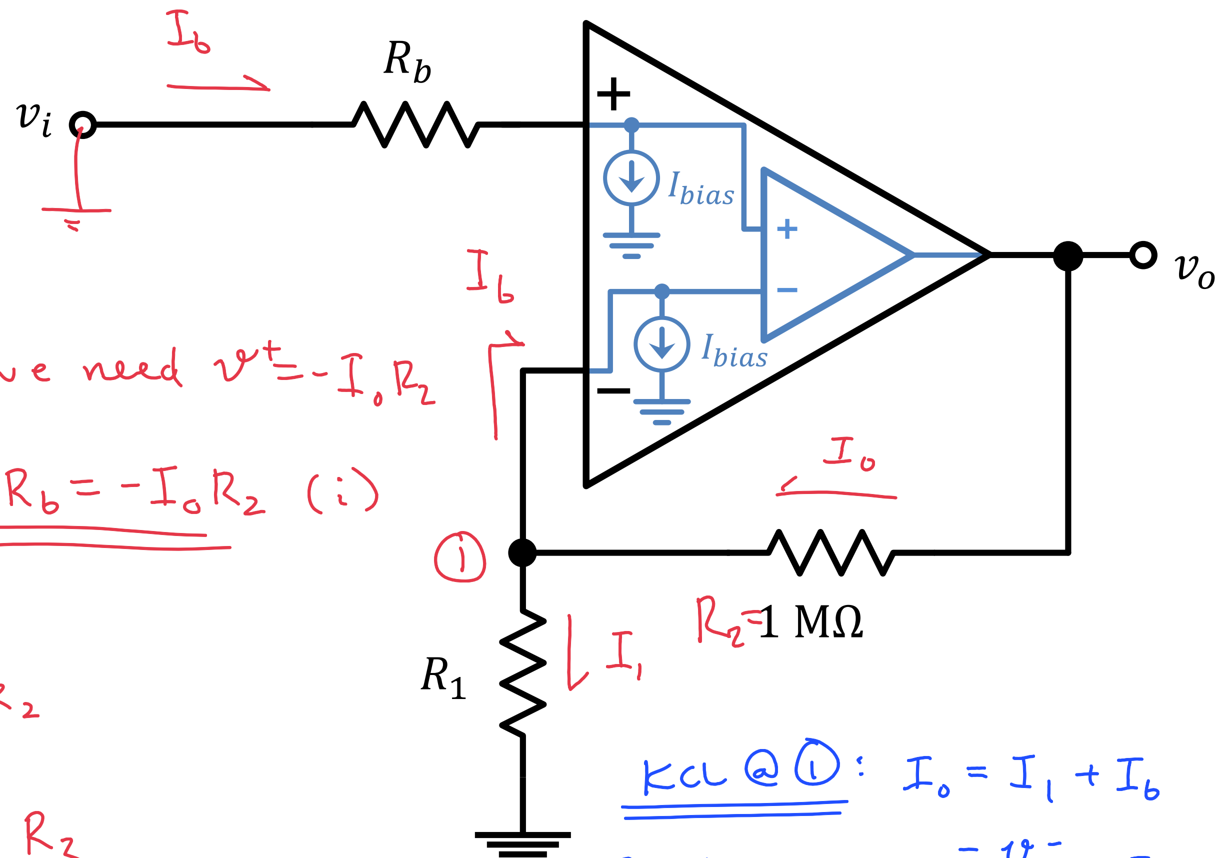
Assuming $v^- = v^+$, we need $v^+ = -I_o R_2$

$$v^+ = v_i - I_b R_b = -I_b R_b = -I_o R_2 \quad (i)$$

(ii) into (i)

$$-I_b R_b = -I_b \left(\frac{R_1}{R_1+R_2}\right) R_2$$

$$R_b = \frac{R_1 R_2}{R_1 + R_2} = R_1 \| R_2$$



KCL @ 1: $I_o = I_1 + I_b$

$$= \frac{v^-}{R_1} + I_b$$

$$\text{(ii)}\ I_o = I_b \left(\frac{R_1}{R_1+R_2}\right) \Leftarrow I_o = -I_o \frac{R_2}{R_1} + I_b$$