Lecture 15: High Gain Op Amps

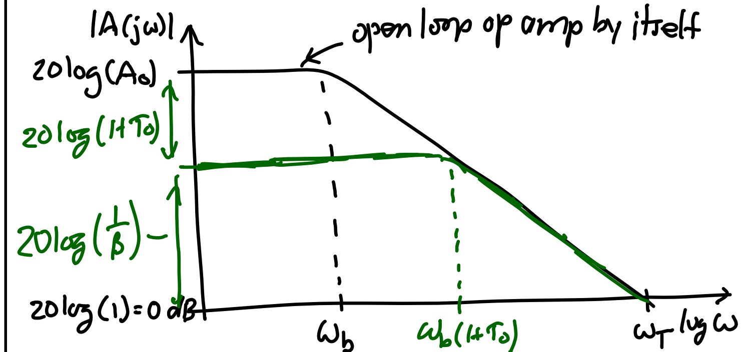
- **Announcements**:
  - ↳ Midterm will be on the date specified in your syllabus: Thursday, Oct. 31, 9:00-11 a.m. in this room
  - ↳ HW#7 online
  - ↳ 240A students should be working on HW#1A, too
- **Lecture Topics**:
  - ↳ Finish offset Voltage (bipolar)
  - ↳ Finite Gain BW
  - ↳ Effect of FB (a first pass)
  - ↳ High Gain Op Amps
- ------------------------------------
- **Last Time**:
- SCP input offset voltage
- Go through offset voltage handout (skim in lecture, then you should go through it more slowly later)

over

Finite Op Amp Gain & Bandwidth

For an ideal op amp, $A=\infty$.

In reality, the gain is given by: $A(s)=\dfrac{A_o}{1+s/\omega_b}$



$\omega_T \triangleq$ unity gain frequency = freq. @ which $|A(j\omega)|=1$ (= 0dB)

At ω_T:

$$|A(j\omega_T)|=1=\frac{A_o}{\sqrt{1+\left(\frac{\omega_T}{\omega_b}\right)^2}}$$

$$[\omega_T \gg \omega_b] \Rightarrow \frac{A_o}{\frac{\omega_T}{\omega_b}}=1 \rightarrow \underbrace{\boxed{\omega_T=A_o\omega_b}}_{\text{Gain-Bandwidth Product}}$$

For $\omega \gg \omega_b$:

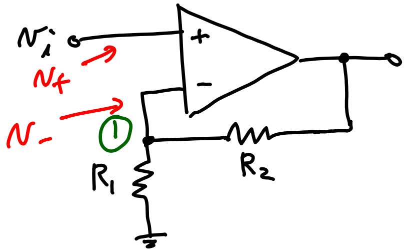
$$A(s)\approx\frac{A_o}{\frac{s}{\omega_b}}=\frac{A_o\omega_b}{s}=\frac{\omega_T}{s}=\frac{f_T}{f}$$

[Integrator w/ time constant $\tau=\frac{1}{\omega_T}$]

The unity gain bandwidth f_T is usually specified on op amp data sheets. Knowing f_T, one can easily determine the op amp gain at a given frequency f.

Frequency Response of Closed Loop Amplifiers

Example. Non-Inverting Amplifier



$v_o = A(s)(v_+ - v_-)$

$v_- = v_+ - \frac{v_o}{A(s)}$

$v_- = v_i - \frac{v_o}{A(s)}$

Find an expression for the gain as a function of frequency.

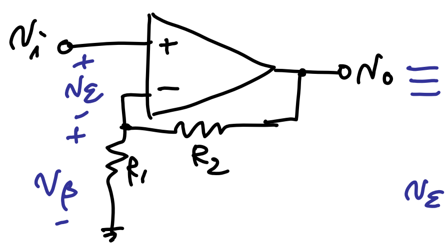
(1) Brute force derivation:

KCL(1): $\frac{v_o - v_-}{R_2} = \frac{v_-}{R_1} \rightarrow \frac{v_o}{R_2} = v_-\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$

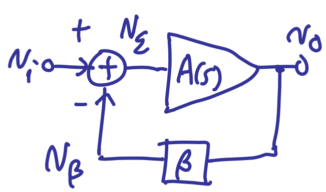
$\frac{v_o}{R_2} = \left(v_i - \frac{v_o}{A(s)}\right)\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \rightarrow \frac{v_o}{v_i}(s) = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{1}{A(s)}\left(1 + \frac{R_2}{R_1}\right)}$ = *

$\left[A(s) = \frac{A_o}{1 + \frac{s}{\omega_b}}\right] \Rightarrow \boxed{\frac{v_o}{v_i}(s) = \left(1 + \frac{R_2}{R_1}\right) \frac{1}{1 + \frac{s}{A_o \omega_b \left(\frac{R_1}{R_1 + R_2}\right)}}}$

(2) More insightful way to do this:

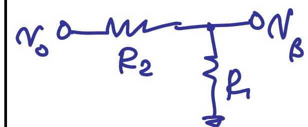


≡



$v_\varepsilon = v_i - v_\beta \rightarrow \frac{v_o}{v_i} = \frac{A(s)}{1 + \beta A(s)}$

What is β?



$\boxed{\beta = \frac{v_\beta}{v_o} = \frac{R_1}{R_1 + R_2}}$ ← feedback factor

Recall f/ previous FB analysis:

$\frac{v_o}{v_i}(s) = \frac{A(s)}{1 + \beta A(s)}$

$\left[A(s) = \frac{A_o}{1 + \frac{s}{\omega_b}}\right] \rightarrow \frac{v_o}{v_i}(s) = \frac{\frac{A_o}{1 + (s/\omega_b)}}{1 + \beta\left(\frac{A_o}{1 + (s/\omega_b)}\right)}$

$$\frac{v_o}{v_i}(s) = \underbrace{\frac{A_o}{1 + \beta A_o}}_{\text{closed loop dc gain term}} \; \underbrace{\frac{1}{1 + \frac{s}{\omega_b(1 + \beta A_o)}}}_{\text{frequency shaping term}}$$

$T_o = \beta A_o \triangleq$ "loop gain" @ $\omega = 0$ (i.e., @ dc)

If $A_o \rightarrow \infty$,
or if $\beta A_o \gg 1$ } ⇒ dc gain $= \frac{1}{\beta}$

Plug in β: [for $\beta A_o \gg 1$]

$\frac{v_o}{v_i}(s) \cong \frac{1}{\beta} \frac{1}{1 + \frac{s}{\omega_b \beta A_o}} = \left(1 + \frac{R_2}{R_1}\right) \frac{1}{1 + \frac{s}{\omega_b A_o \left(\frac{R_1}{R_1 + R_2}\right)}}$ *

Observations:

① Closed loop DC gain $= \frac{A_o}{1+\beta A_o} = \frac{A_o}{1+T_o} \approx \frac{A_o}{T_o}$ $[T_o \gg 1]$

i.e., the closed loop gain is reduced from the open loop gain by $1+T_o$ → show this on graph

② Alternatively, closed loop DC gain $\approx \frac{A_o}{\beta A_o} = \frac{1}{\beta}$ $[T_o \gg 1]$

③ ω_{-3dB} has increased from $\omega_b \rightarrow \omega_b(1+A_o\beta) = \omega_b(1+T_o)$

To draw the Bode plot, just find the dc gain, draw a horizontal line across, then follow the open loop response after running into it!

④ Gain-BW Product $= \frac{A_o}{1+\beta A_o}\omega_b(1+\beta A_o) = A_o\omega_b = \omega_T$

∴ the Gain-BW product remains the same for the open & closed loop FB cases!

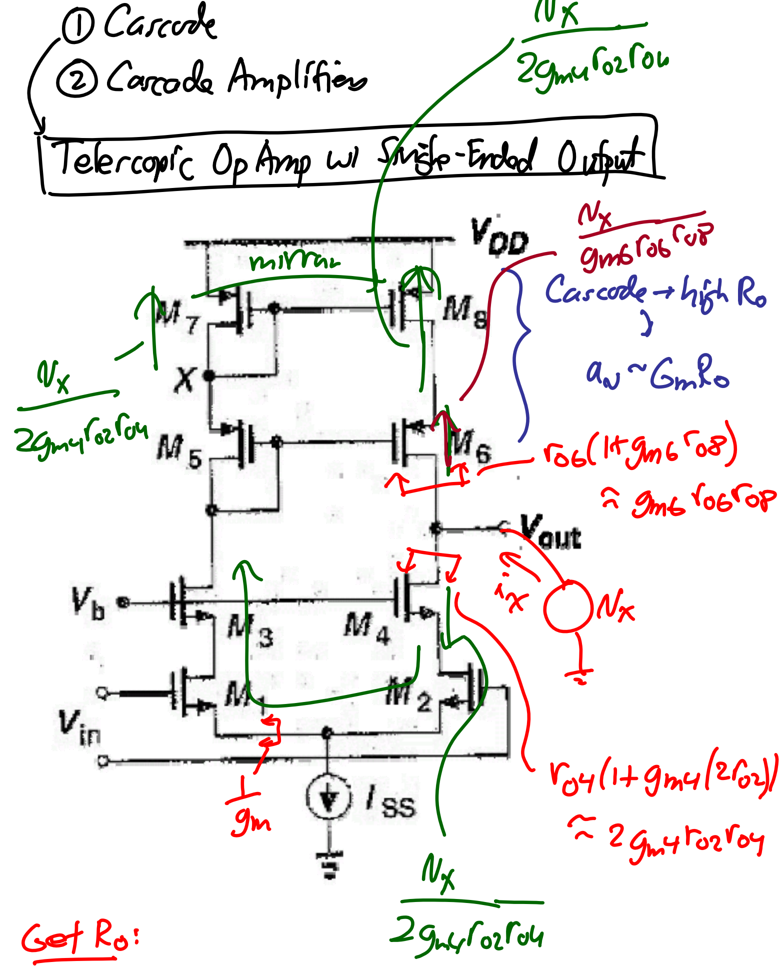
High Gain Op Amps

How can we increase gain?

① Cascode

② Cascode Amplifier

Telescopic Op Amp w/ Single-Ended Output



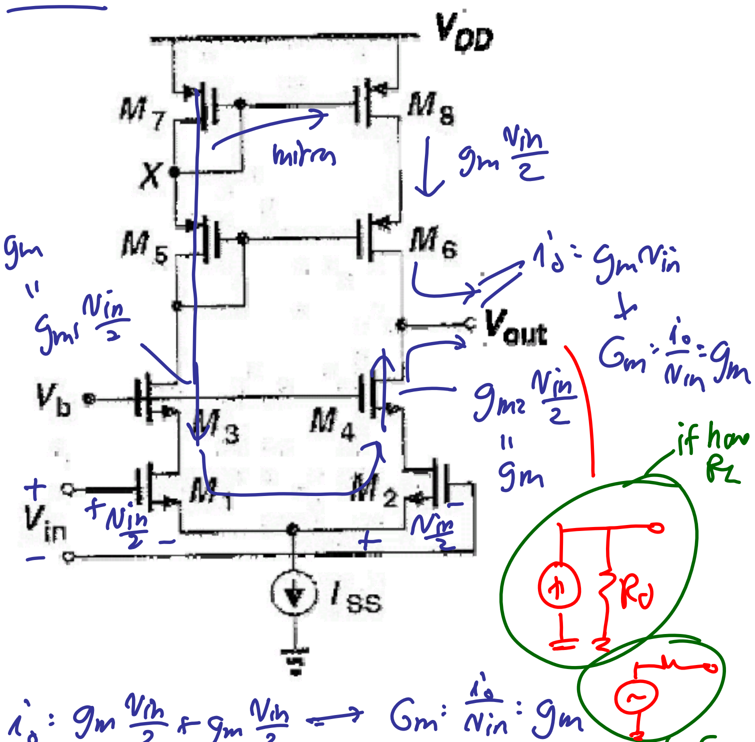
Get R_o:

$$i_x = \frac{v_x}{g_{m6}r_{o6}r_{op}} + \frac{v_x}{2g_{m4}r_{o2}r_{o4}} + \frac{v_x}{2g_{m4}r_{o2}r_{o4}}$$

$R_o = \frac{v_x}{i_x} = (g_{m6} r_{o6} r_{o8}) \| (g_{m4} r_{o2} r_{o4})$

$= (g_{mp} r_{op}^2) \| (g_{mN} r_{oN}^2)$

Get G_m:



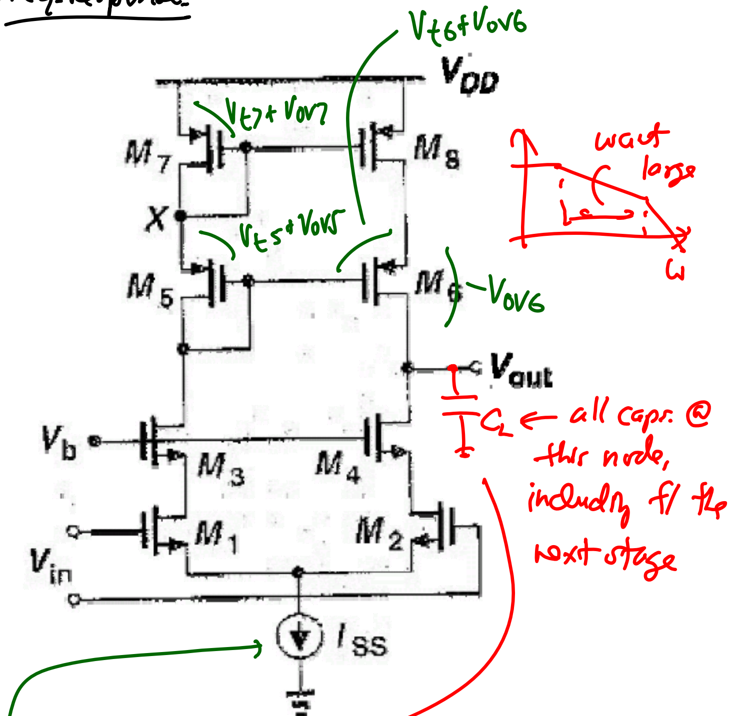
$i_o = g_m \frac{v_{in}}{2} + g_m \frac{v_{in}}{2} \longrightarrow G_m = \frac{i_o}{v_{in}} = g_m$

$\therefore$ Gain: $A_v = g_{mN} [(g_{mN} r_{oN}^2) \| (g_{mp} r_{op}^2)]$

huge R! huge R!

gain will be BIG!

Freq. Response:



→ This contributes the dominant pole since R_o = huge:

$\omega_H = \frac{1}{R_o C_L}$

Problems/Issues:

① Limited output swing:

$V_{omax} = V_{DD} - |V_{t7}| - |V_{ov7}| - |V_{t5}| - |V_{ov5}| + |V_{t6}| + \cancel{|V_{ov6}|} - \cancel{|V_{ov6}|}$

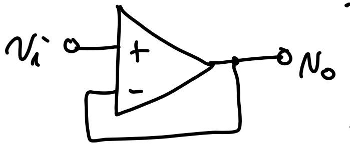
$V_{omin} = V_{ovSS} + V_{ov2} + V_{ov4}$

current source V_{ov}

$V_{oswing} = V_{omax} - V_{omin}$

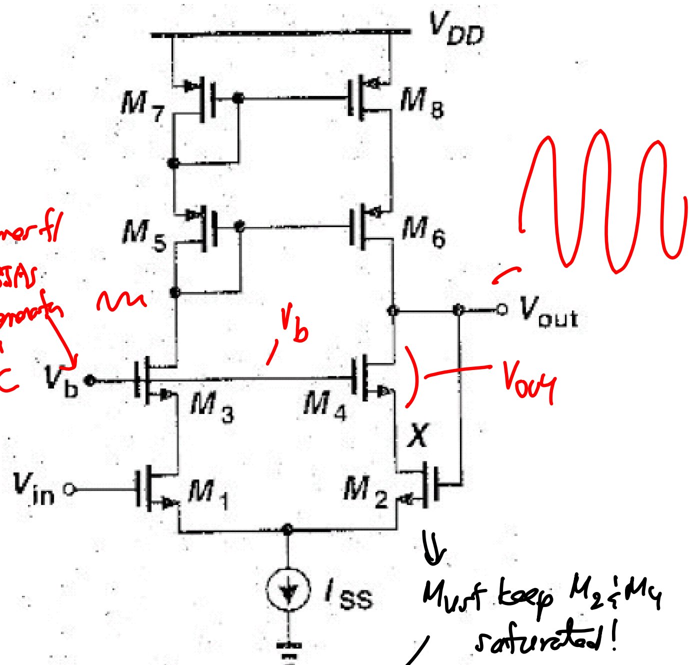
Problem: Not so large!

Problem ②: Difficult to tie the input to output!



unity gain buffer (very useful)

Common-fl VBIAS Generator = DC



Must keep M_2 & M_4 saturated!

M_4: