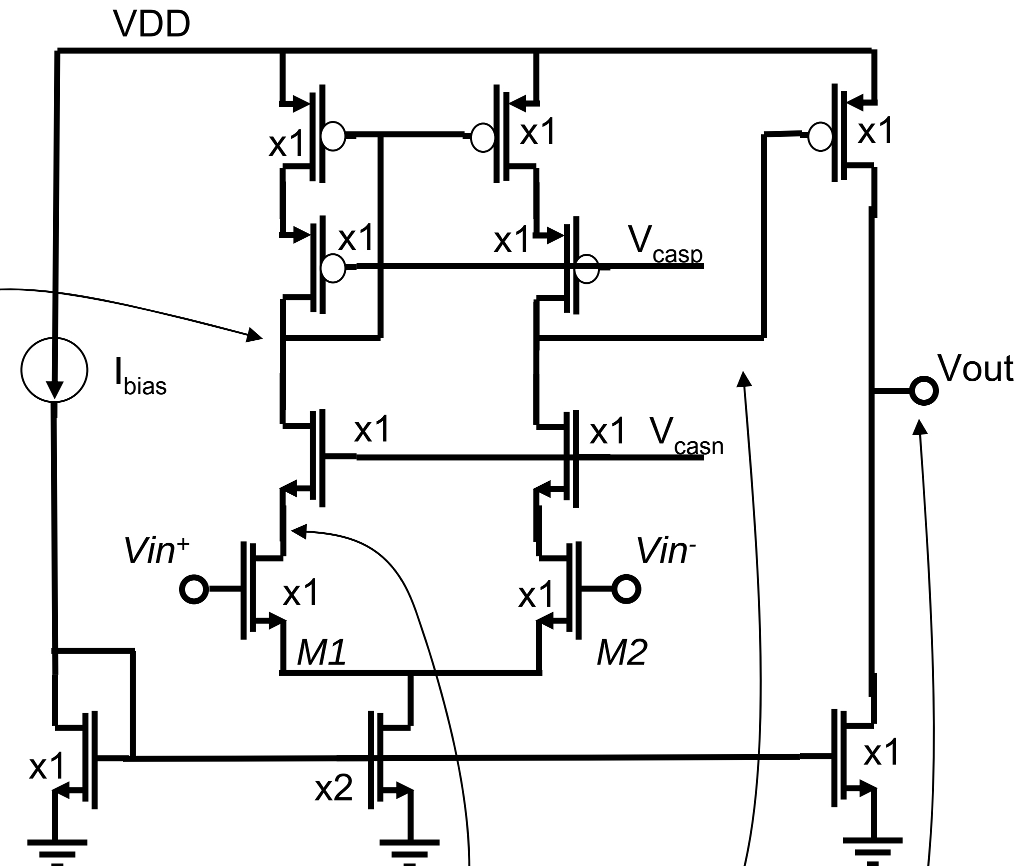
Lecture 20

Compensation and stabilization

Example: telescopic, 2-stage Op-Amp

- What are gain, poles?



Gain:

$$A_o = g_{mn}\left(g_{mn}r_{on}^2 \parallel g_{mp}r_{op}^2\right)g_{mp}\left(r_{on} \parallel r_{op}\right)$$

1st stage output pole (dominant):

$$p_1 = \frac{1}{\left(g_{mn}r_{on}^2 \parallel g_{mp}r_{op}^2\right)\left(C_{gs} + 2C_{db}\right)}$$

2nd stage output pole (depends on load):

$$p_2 = \frac{1}{\left(r_{on} \parallel r_{op} \parallel R_L\right)\left(C_L + 2C_{db}\right)}$$

mirror pole:

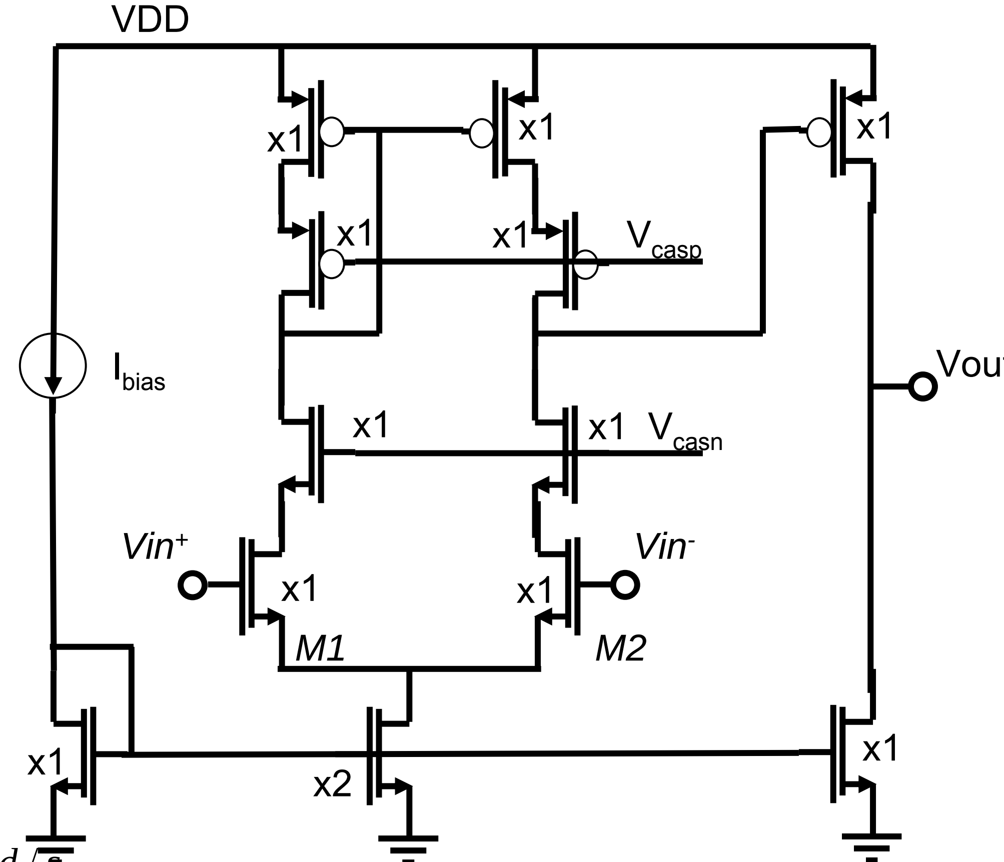
$$p_3 = \frac{g_{mp}}{\left(2C_{gs} + 2C_{db}\right)}$$

cascode pole:

$$p_4 = \frac{g_{mn}}{\left(C_{gs} + C_{db} + C_{sb}\right)}$$

Example: telescopic, 2-stage Op-Amp

- Make up some reasonable numbers:
  - Set $g_m r_o$=10
  - Set ω_T = 100Grad/s (16GHz): $\omega_T \sim g_m/C_{gs}$ (note, in real life n- and p-fets have different ω_T's)
  - Set $C_{db}=C_{gs}/2$
- Set $R_L=\infty$, C_L=0
- Now:



$$A_o = \left(g_m r_o\right)^3 / 4$$

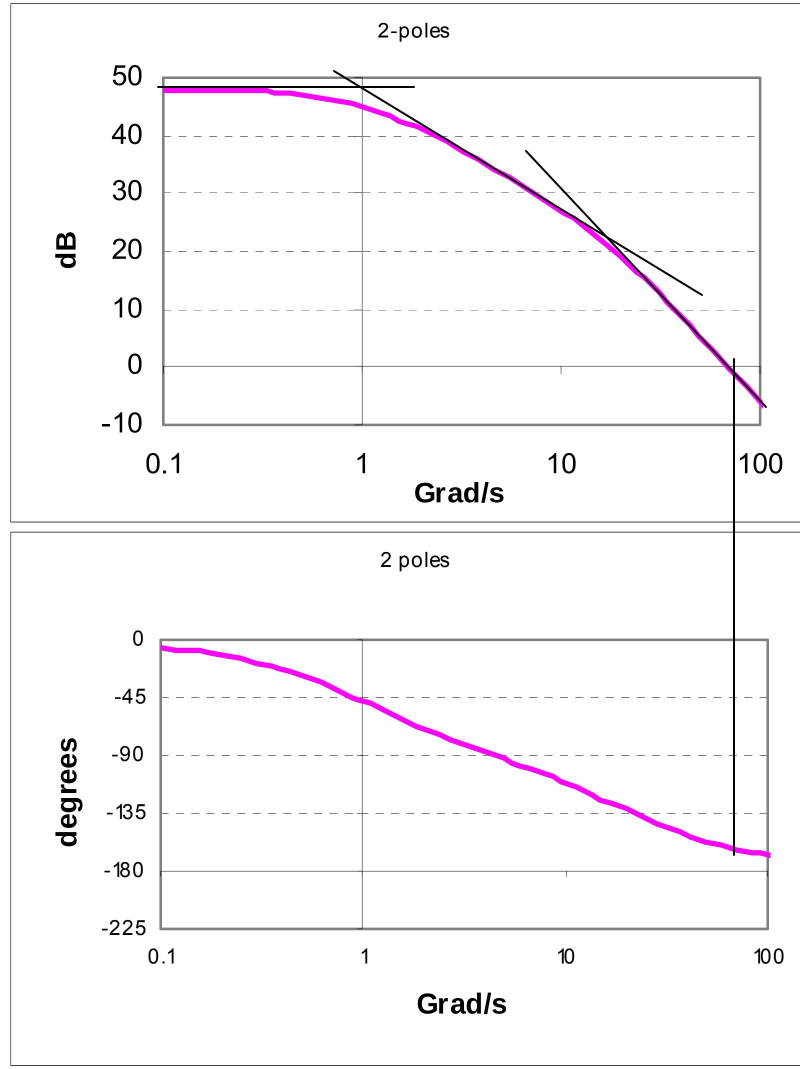
$$p_1 = \frac{1}{\left(g_m r_o^2/2\right)\left(2C_{gs}\right)} = \frac{g_m}{\left(g_m r_o\right)^2 C_{gs}} = \frac{\omega_T}{100} = 1Grad/s$$

$$p_2 = \frac{1}{r_o C_{db}} = \frac{2g_m}{\left(g_m r_o\right) C_{gs}} = \frac{\omega_T}{5} = 20Grad/s$$

Example: telescopic, 2-stage Op-Amp

- Find UGBW in this case (just looking at 2 poles)
- For $p_1<\omega<p_2$,
  - $A(\omega) = A_o*p_1/\omega$
  - So at $\omega=p_2$, $A(p_2) \sim A_o*p_1/p_2$
  - In this case, $A(p_2) \sim$ 250*1G/20G = 12.5 (22dB)
- For $\omega>p_2$,
  - $A(\omega) = A(p_2)*p_2^2/\omega^2$
- UGBW where $A(\omega) =1$
  - $A(p_2)*p_2^2/\omega^2 = 1$
  - $\omega_{UG}=(A(p_2)*p_2^2)^{½}$
  - In this case:

    ω_{UG}= 20Grad/s*$(12.5)^{½}$
  - UGBW=70Grad/s



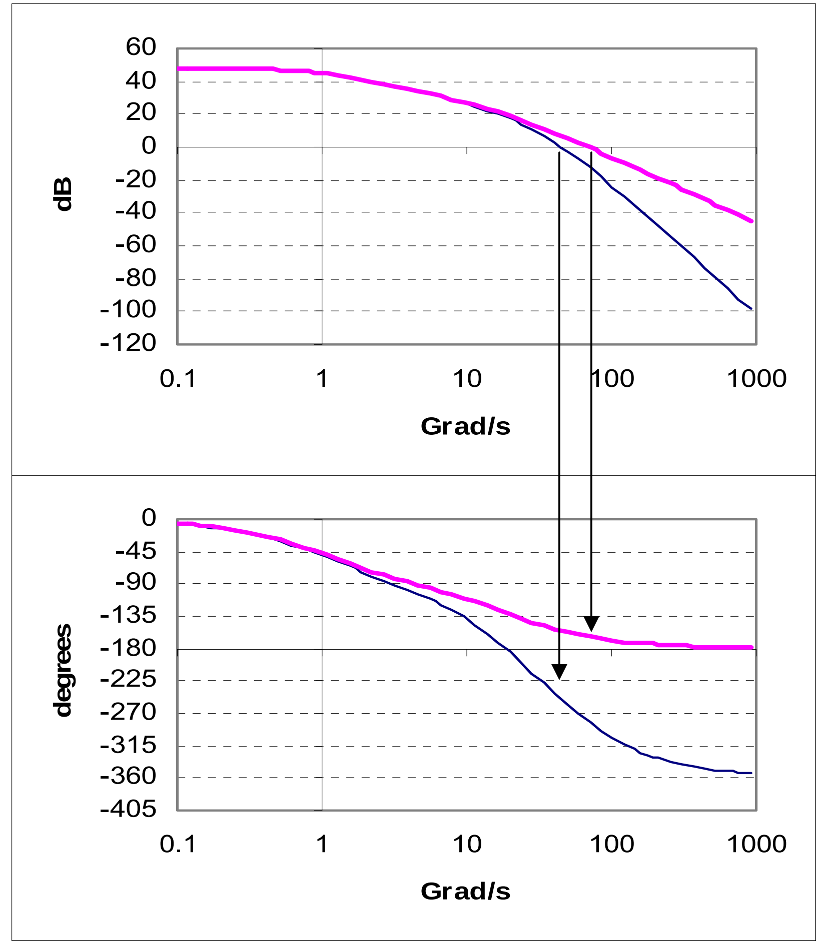
Example: telescopic, 2-stage Op-Amp

- So make a Bode plot:
  - PM is ~17º
- But we *know* there are more poles:

$$p_3 = \frac{g_m}{(2C_{gs} + 2C_{db})} = \frac{\omega_T}{3} = 33 Grad/s$$

$$p_4 = \frac{g_{mn}}{(C_{gs} + 2C_{db})} = \frac{\omega_T}{2} = 50 Grad/s$$

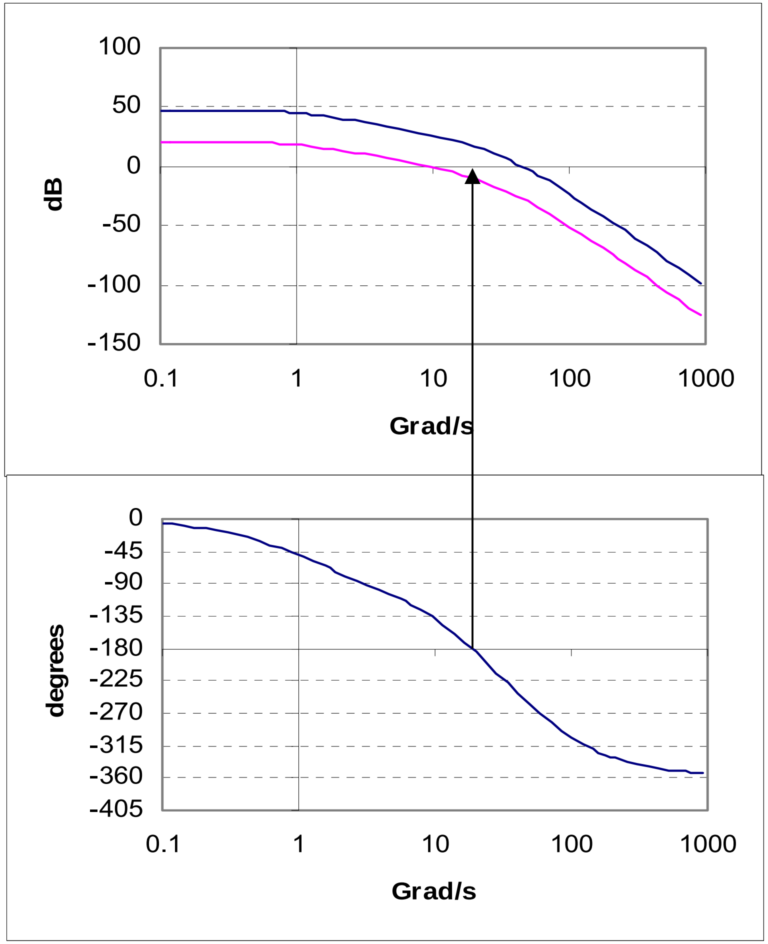
- These will have marginal effects on UGBW,
  - From 70Grad/s to 45 Grad/s
- But big effect on PM
  - 17º shifts to -70º



This is A(s)… if we set Bo =1 (unity gain) this will NOT be STABLE!

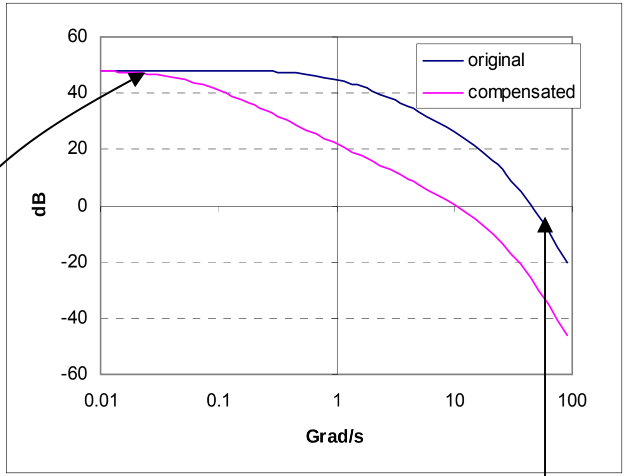
How stabilize?

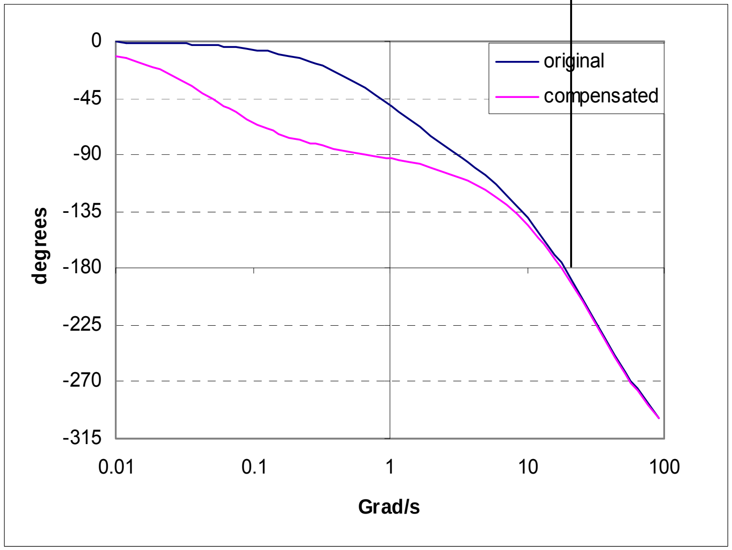
- 1st way: reduce gain:
- If know can use Bo<1, do so
  - remember Ho ~ 1/Bo
- If don't need large Ao, reduce gain other ways: lower gm of diff pair, etc.
- Try to get UGBW < p_2 :
  - $A(p_2)$=22dB
  - So reduce gain by at least 22dB
- Alternately reduce AoBo to get 10dB gain margin
  - Here, GM = -17dB
  - So reduce AoBo by 27dB
- Problem is, of course, that this kills your gain!



Compensation

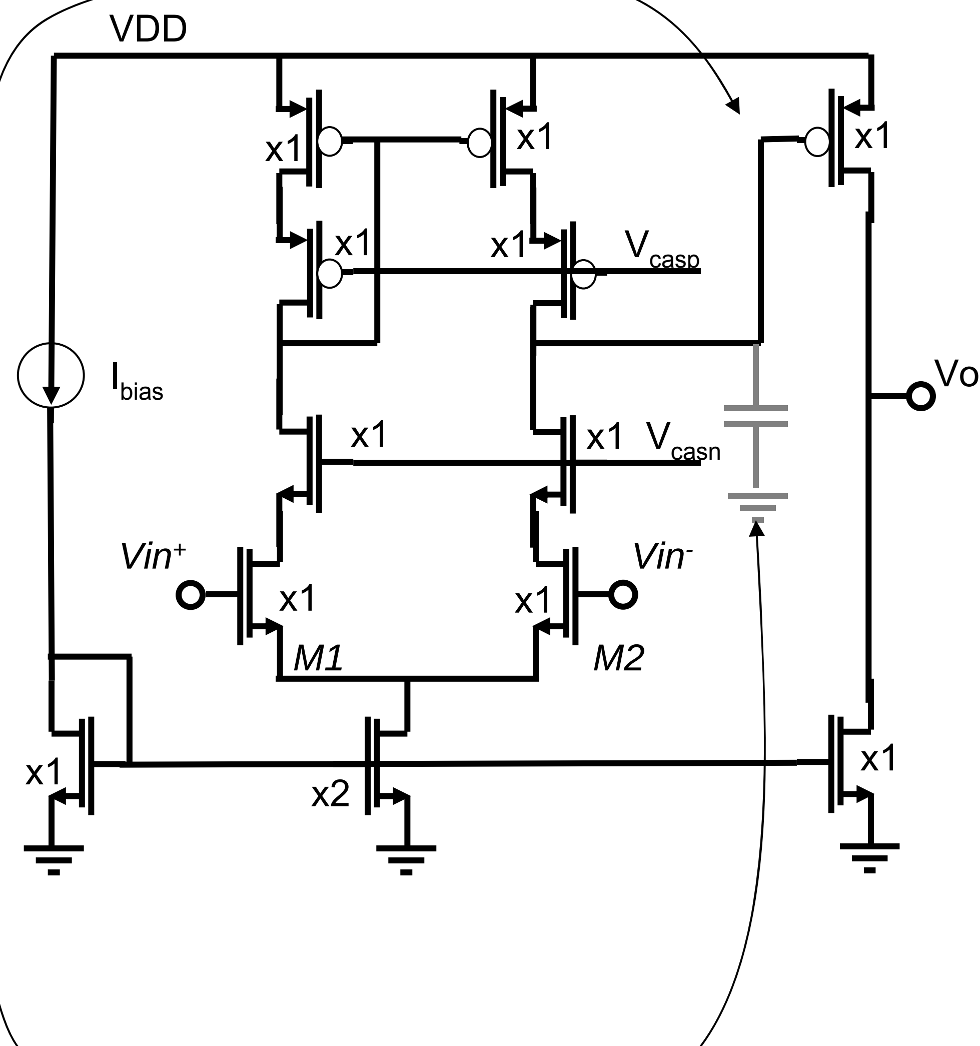
- 2^{nd} way: reduce dominant pole location:
- Every factor of ten lower is 20dB less gain at high frequencies
  – Reduce $A(p_2)$ by 22dB:
  – implies lower p_1 by 22dB (12.5)
- Or reduce pole for a 10dB GM:
  – Here GM =-17
  – So reduce by 27dB: a factor of ~20
  – Move p_1 to 50Mrad/s
  – Note HF phase barely changes, but gain drops





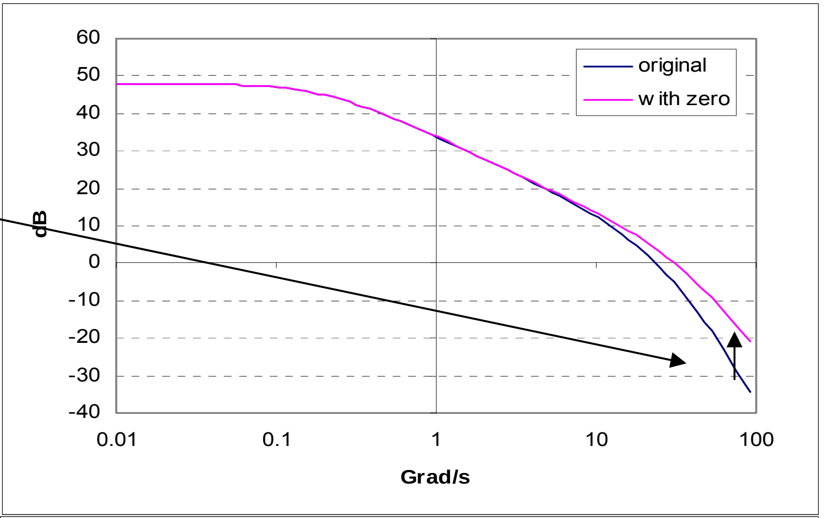
Compensation: how?

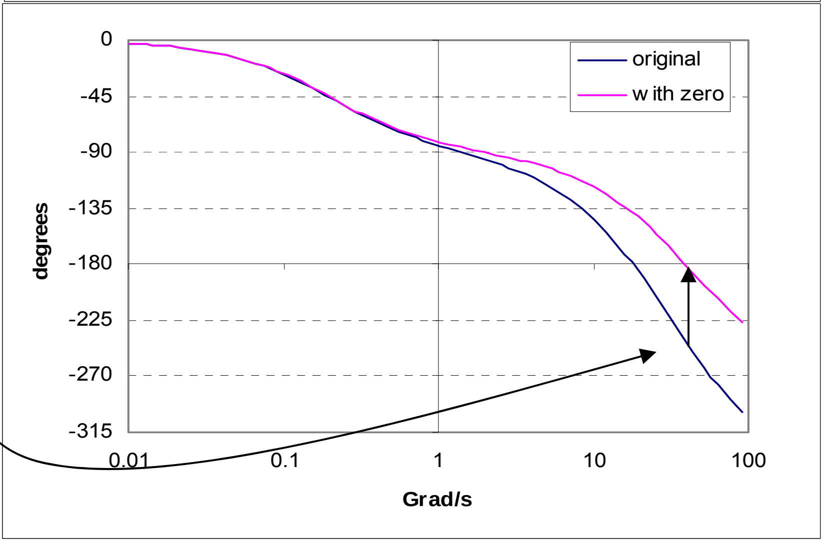
- Need to reduce dominant pole frequency
  - In example by a factor of ~20
  - How?
- Easiest way: add capacitance to dominant pole node
  - R is highest here, so least C required.
  - Add a capacitor with C =19x the parasitic cap
  - Can do this with an PFET with large W, L to make a MOS Cap.
- This costs bandwidth.
- (Note, for better PSRR in this case, would tie cap to VDD)



Adding a zero

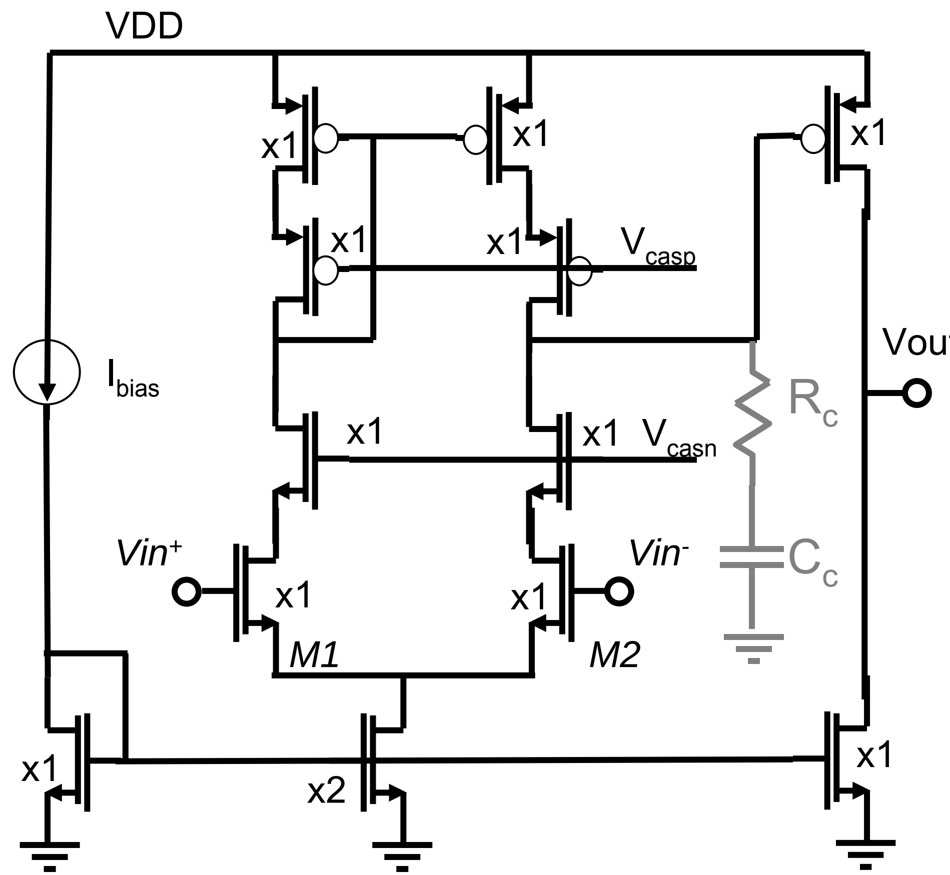
- 3rd trick: add a zero:
  - Increases HF gain by 20dB/dec(Bad)
  - But also increases HF phase by up to 90º (good)
  - Can place zero near 2nd pole to cancel phase effects while still keeping 1 pole of roll-off
  - Usually have to combine with compensation (see next slide)
- Here,
  - move $p_1 \rightarrow$ 200Mrad/s
  - Add zero at 20Grad/s
  - GM from -5dB to 4dB
  - PM from -20º to 15º
- Less of a BW hit.





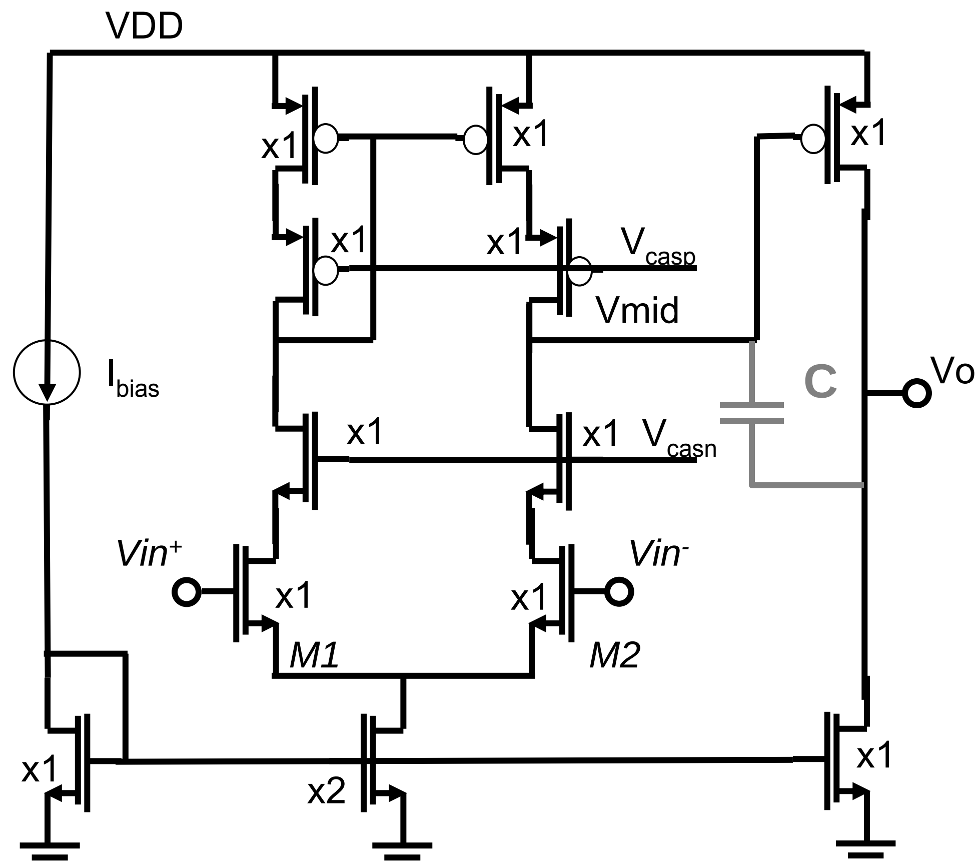
Adding a zero: how?

- Put a resistor in series with dominant capacitor
  - Changes Z_C from $1/j\omega C_c$
  - To $(1+j\omega R_c C_c)/j\omega C_c$
- Pole at $2/(g_m r_o^2 C_c)$
- Zero at $1/R_c C_c$
- 2^{nd} pole at $1/R_c\ (C_{gs}+2C_{db})$
- For $R_c << g_m r_o^2$ the 2^{nd} pole doesn't matter.



Miller Compensation

- Big capacitors take up a lot of space.
  - Can build effectively larger cap with Miller effect.
  - Ceff = $C(1+gm(R_L||ro/2)$
- But really more complicated than that.
- Get transmission zero (RHP)
- Get interactions between midpoint, output
- Get, instead:



$$C_{mid} = C_{gs} + 2C_{db}$$
$$C_L' = 2C_{db} + C_L$$
$$R_L' = R_L \,||\, \frac{r_o}{2}$$

$$\frac{Vout}{Vin} = \frac{g_m\left(\frac{g_m r_o^2}{2}\right)R_L'(sC - g_m)}{1 + s\left(R_L'(C_L'+C) + \left(\frac{g_m r_o^2}{2}\right)(C_L'+C_{mid}+C(1+g_m R_L'))\right) + s^2\left(\frac{g_m r_o^2}{2}\right)R_L'(C_L'C_{mid} + CC_{mid} + C_L'C)}$$

Miller Compensation

$$\frac{Vout}{Vin}=\frac{g_m\left(\frac{g_m r_o^2}{2}\right)R_L'(sC-g_m)}{1+s\left(R_L'(C_L'+C)+\left(\frac{g_m r_o^2}{2}\right)(C_L'+C_{mid}+C(1+g_mR_L'))\right)+s^2\left(\frac{g_m r_o^2}{2}\right)R_L'(C_L'C_{mid}+CC_{mid}+C_L'C)}$$

- What a mess! But we can interpret: assume
  - $C_{mid}<<C$, $g_m r_o^2>>RL'$

$$\frac{Vout}{Vin}=\frac{g_m\left(\frac{g_m r_o^2}{2}\right)R_L'(sC-g_m)}{1+s\left(\left(\frac{g_m r_o^2}{2}\right)(C_L'+C(1+g_mR_L'))\right)+s^2\left(\frac{g_m r_o^2}{2}\right)R_L'(CC_{mid}+C_L'C)}$$

  - $g_mR_L>1$, $g_mR_L'C>>C_L'$

$$\frac{Vout}{Vin}=\frac{g_m\left(\frac{g_m r_o^2}{2}\right)R_L'(sC-g_m)}{1+s\left(\left(\frac{g_m r_o^2}{2}\right)(C(g_mR_L'))\right)+s^2\left(\frac{g_m r_o^2}{2}\right)R_L'(CC_{mid}+C_L'C)}$$

  - 1st pole where
    Just Rout of OTA and Millerized cap

$$1\approx s\left(\left(\frac{g_m r_o^2}{2}\right)(C(g_mR_L'))\right)\Rightarrow p_1\approx\frac{1}{\frac{g_m r_o^2}{2}C(g_mR_L')}$$

  - 2nd pole where:
    Basically original output pole increased by gmRL

$$s\left(\left(\frac{g_m r_o^2}{2}\right)(C(g_mR_L'))\right)\approx s^2\left(\frac{g_m r_o^2}{2}\right)R_L'(CC_{mid}+C_L'C)$$

$$p_2=\frac{\left(\frac{g_m r_o^2}{2}\right)(C(g_mR_L'))}{\left(\frac{g_m r_o^2}{2}\right)R_L'(CC_{mid}+C_L'C)}=\frac{(g_mR_L')}{R_L'(C_{mid}+C_L')}$$

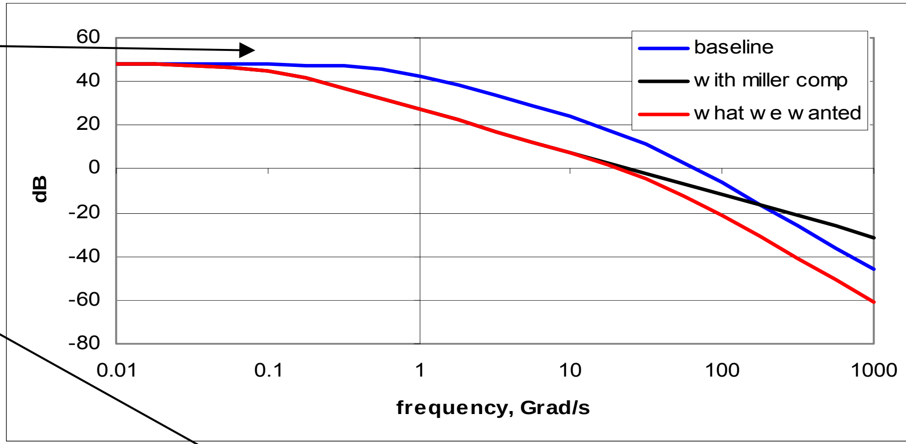
  - So for large enough C, p1 moves in as 1/gmRL, p2 moves out as gmRL: “pole splitting”

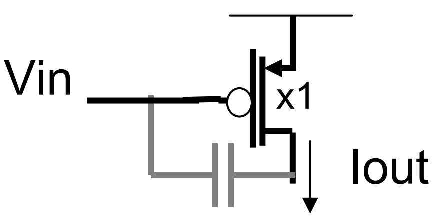
Vo

That pesky RHP zero

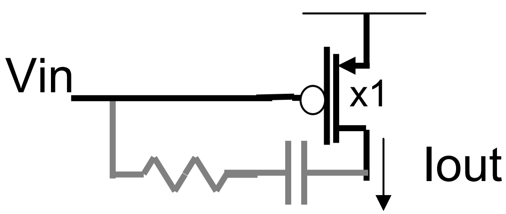
$$\frac{Vout}{Vin}=\frac{g_m\left(\frac{g_m r_o^2}{2}\right)R_L'(sC-g_m)}{1+s\left(R_L'(C_L'+C)+\left(\frac{g_m r_o^2}{2}\right)(C_L'+C_{mid}+C(1+g_mR_L'))\right)+s^2\left(\frac{g_m r_o^2}{2}\right)R_L'(C_L'C_{mid}+CC_{mid}+C_L'C)}$$

- Miller compensation lowers dominant pole
  - But PM not much better
  - RHP zero adds phase
  - may increase UGBW too
- Can cancel with series R





$$\frac{Iout}{Vin}=-gm+sC$$



$$\frac{Iout}{Vin}=-gm-sgmRC+sC$$

If gmR >1 → zero moves to LHP