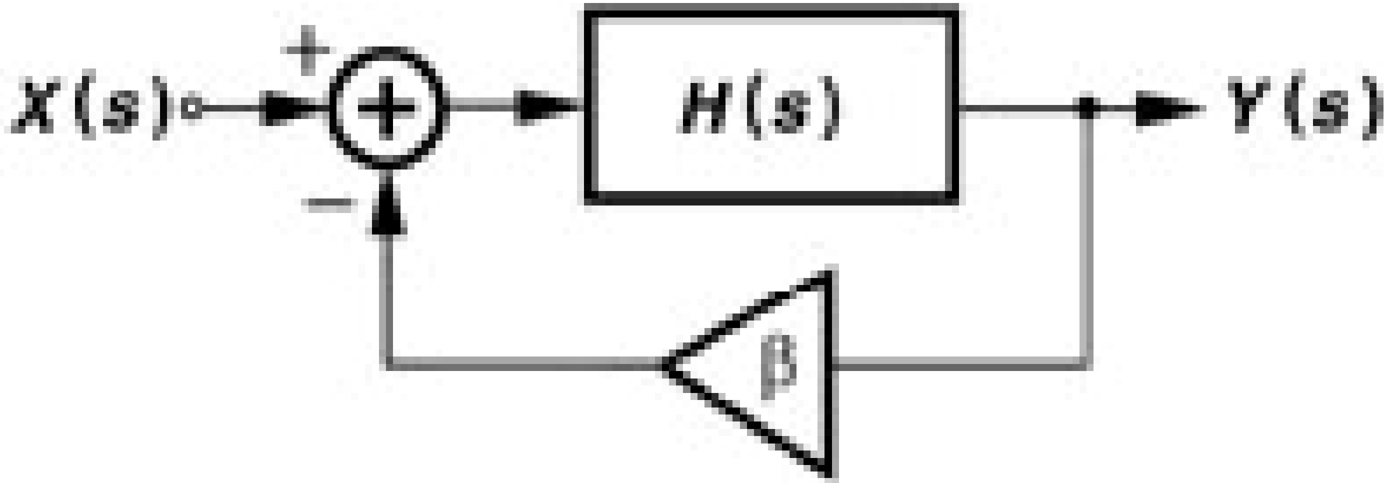
Chapter 10
Stability and Frequency Compensation

Basic Stability

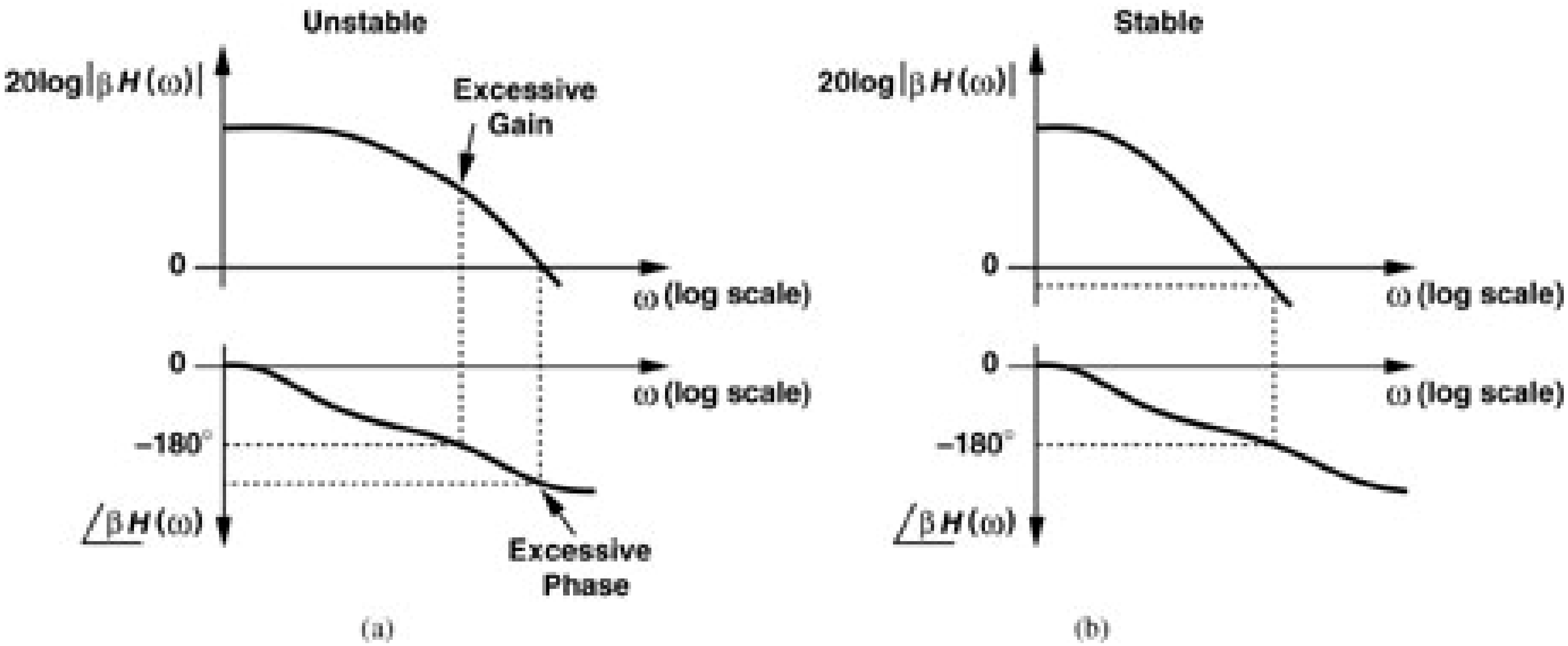


$$\frac{Y}{X}(s) = \frac{H(s)}{1+\beta H(s)}$$

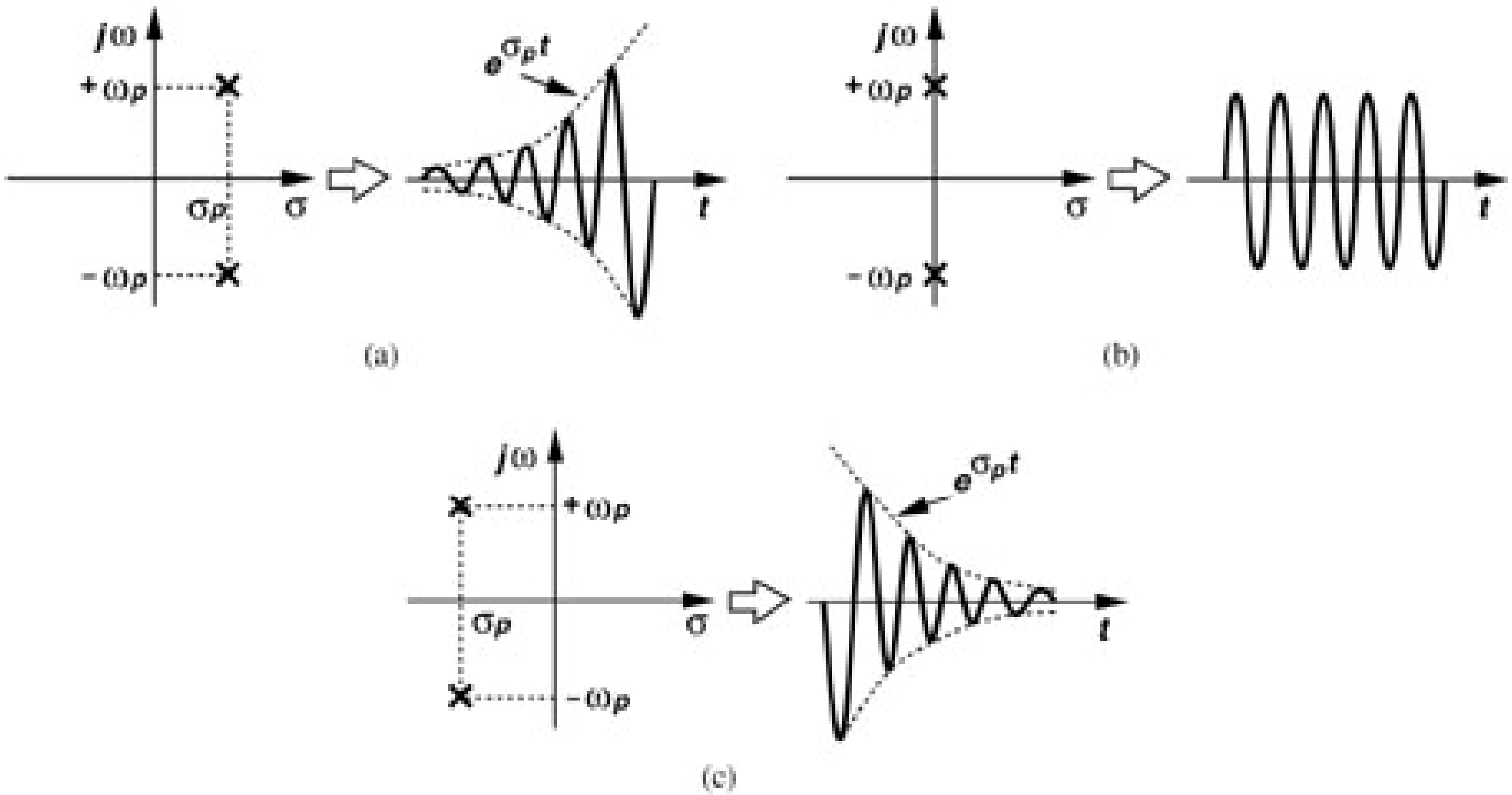
$$May\ \ oscillate\ \ at\ \ \omega\ \ if\ \ |\beta H(j\omega)| = 1\ \ and$$

$$\angle \beta H(j\omega) = -180\ \ (Barkhausen\ \ criteria)$$

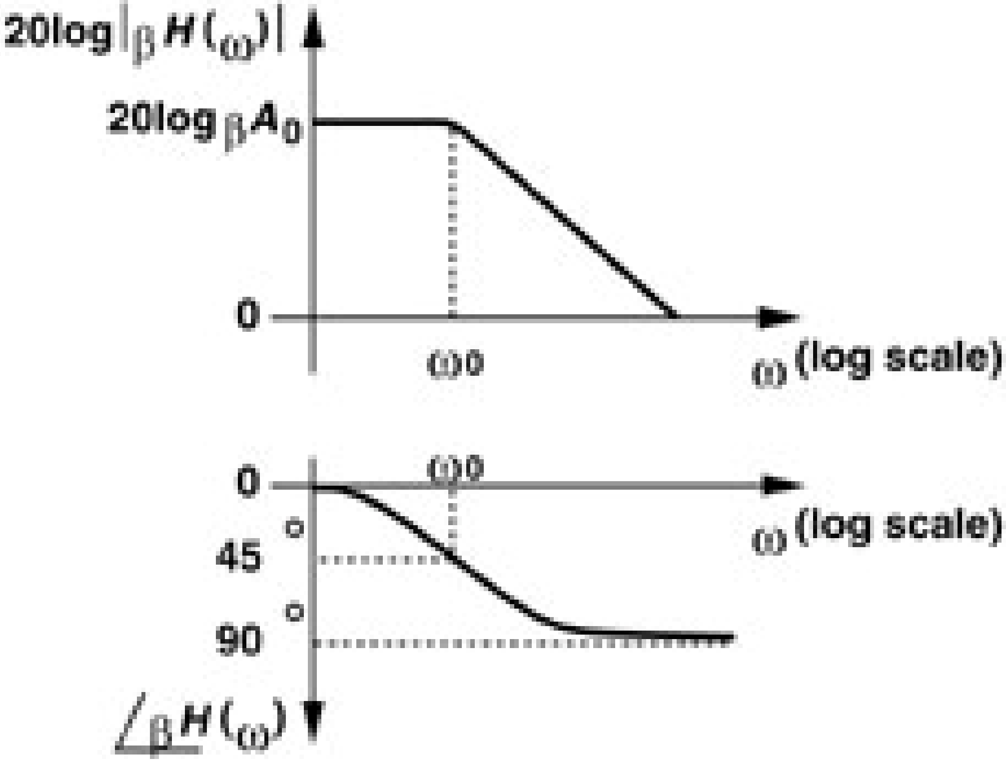
Stable and Unstable Systems

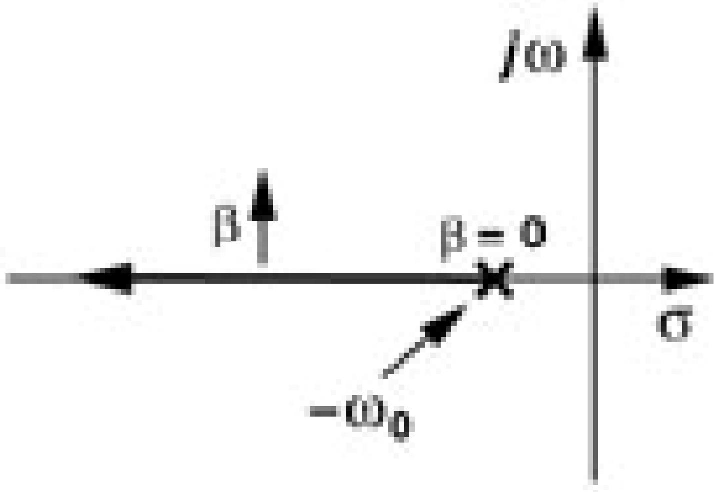


Stability and Complex Poles

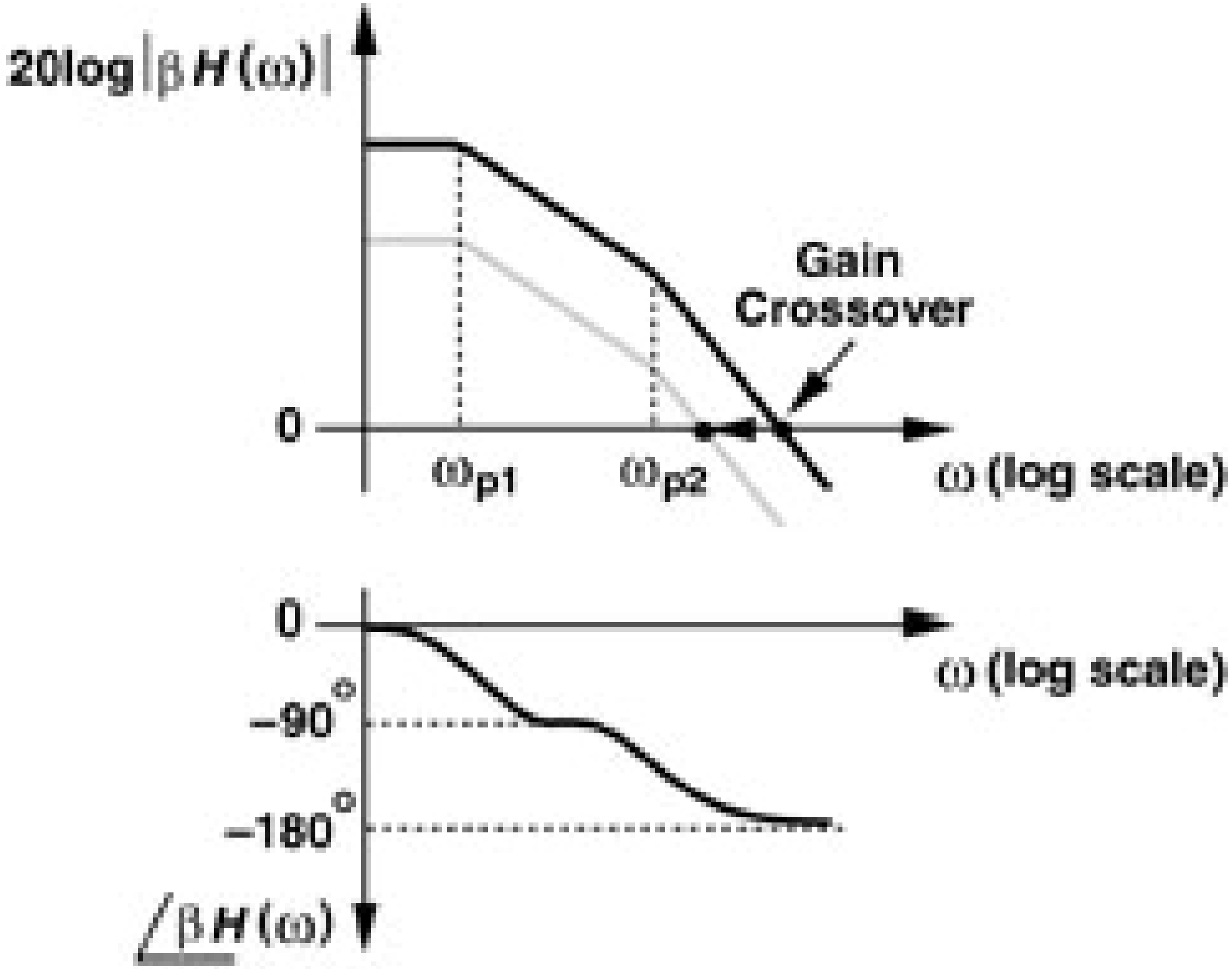


Basic One Pole Bode Plot

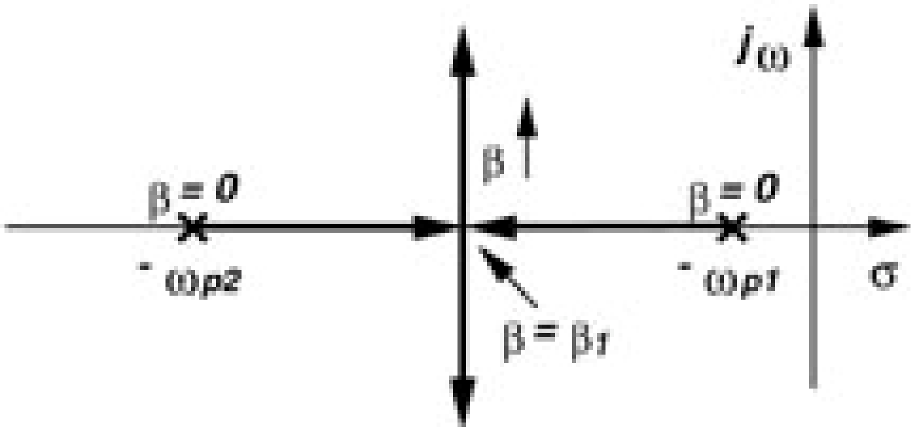




Multipole Systems



Loot Locus for a 2-Pole System



$$H_{open}(s) = \frac{A_0}{\left(1 + s/\omega_{p1}\right)\left(1 + s/\omega_{p2}\right)}$$

$$H_{closed}(s) = \frac{H_{open}(s)}{1 + \beta H_{open}(s)} = \frac{A_0 \omega_{p1} \omega_{p2}}{s^2 + \left(\omega_{p1} + \omega_{p2}\right) s + \left(1 + \beta A_0\right) \omega_{p1} \omega_{p2}}$$

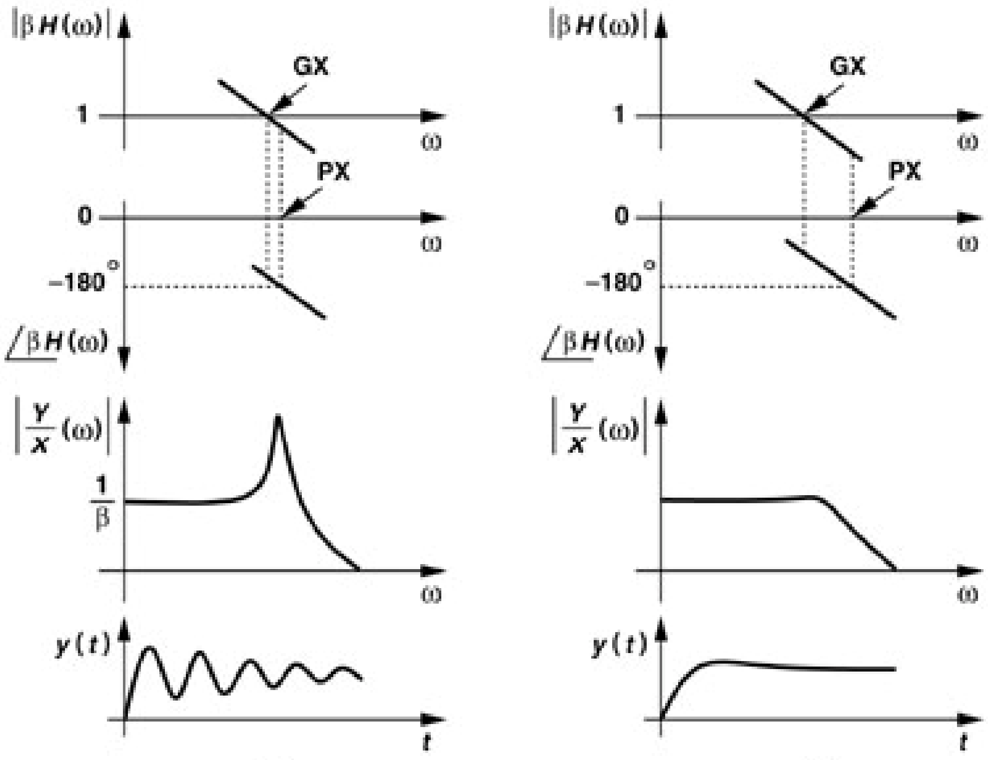
$$s_{1,2} = -\frac{1}{2}\left(\omega_{p1} + \omega_{p2}\right) \pm \frac{1}{2}\sqrt{\left(\omega_{p1} + \omega_{p2}\right)^2 - 4\left(1 + \beta A_0\right) \omega_{p1} \omega_{p2}}$$

$$s_{1,2}\Big|_{\beta = 0} = -\omega_{p1}, \; -\omega_{p2}$$

$$s_{1,2}\Big|_{\beta = \beta_1 = \frac{(\omega_{p1} - \omega_{p2})^2}{4 A_0 \omega_{p1} \omega_{p2}}} = -\frac{1}{2}\left(\omega_{p1} + \omega_{p2}\right)$$

$$s_{1,2}\Big|_{\beta > \beta_1} = \text{Complex Values}$$

Phase Margin

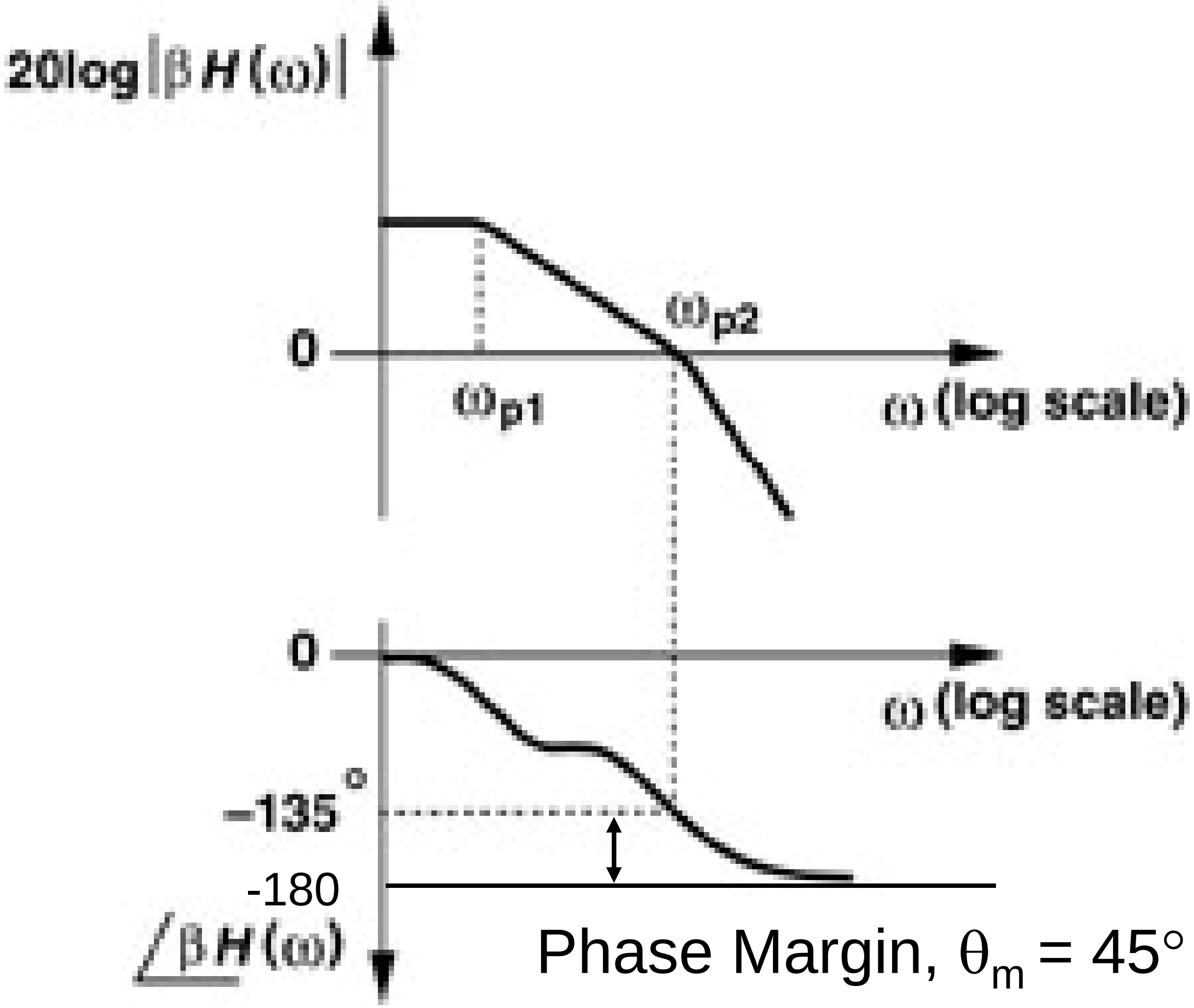


(a) (b)

$$\frac{Y}{X} = \frac{H(j\omega)}{1+\beta H(j\omega)}$$

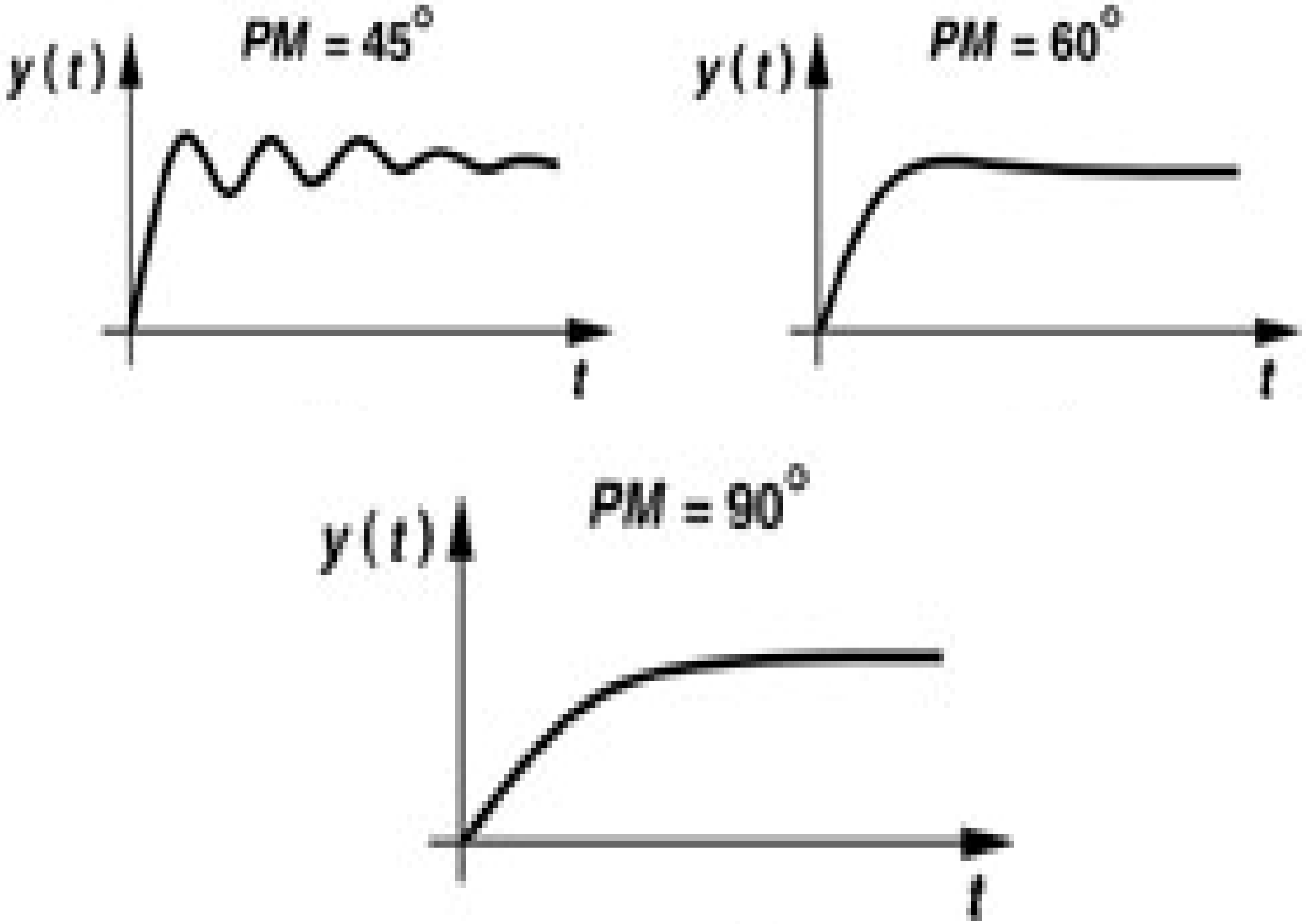
$$\begin{aligned}\left|\frac{Y}{X}\right| &= \left|\frac{H(j\omega_{GX})}{1+\beta H(j\omega_{GX})}\right| \\ &= \left|\frac{1/\beta}{1+\exp\left[j(-180^\circ + PM)\right]}\right| \\ &= \frac{1}{\beta\left|1+\cos(180^\circ - PM) - j\sin(180^\circ - PM)\right|}\end{aligned}$$

Phase Margin (cont.)

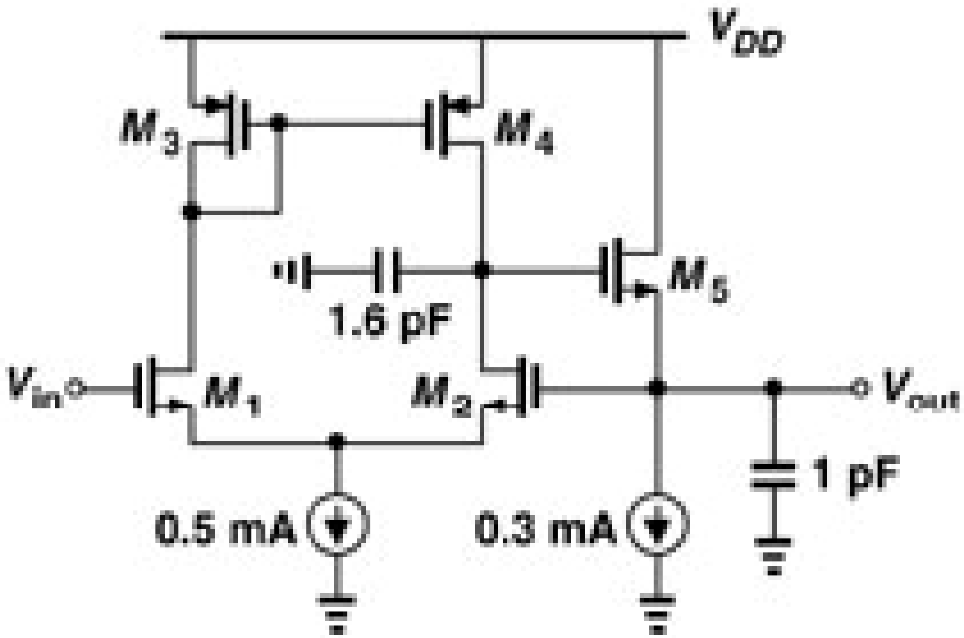


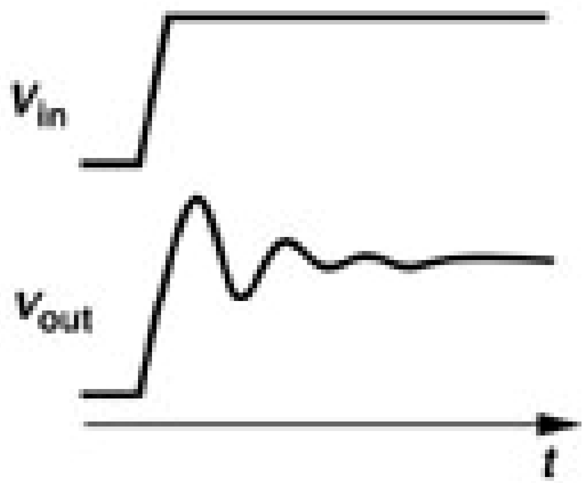
Phase Margin, $\theta_m = 45°$

Phase Margin (cont.)



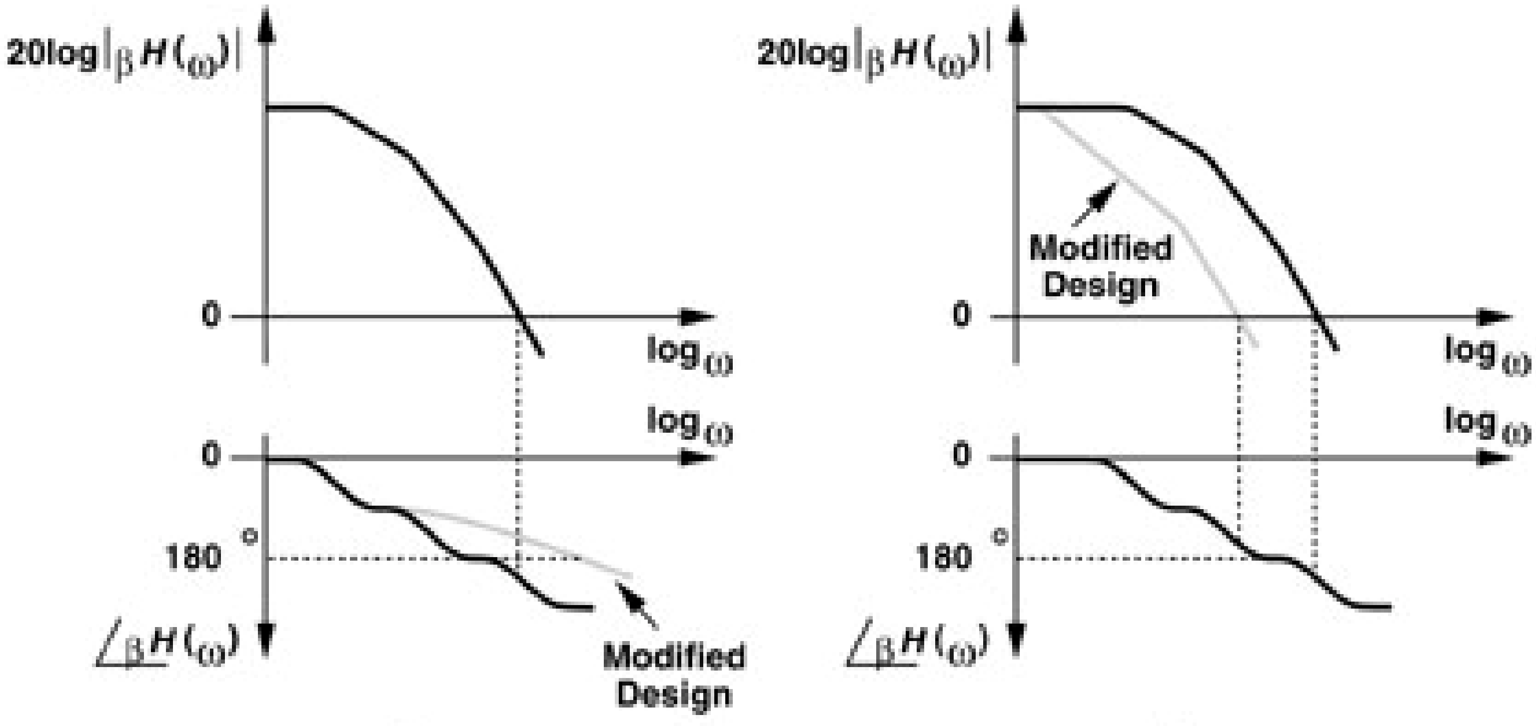
Small Signal Analysis Limitations





Small signal analysis yields 65 ° of θ_m, but large signal transient response is different. Large signal simulation includes effects not seen in small signal analysis.

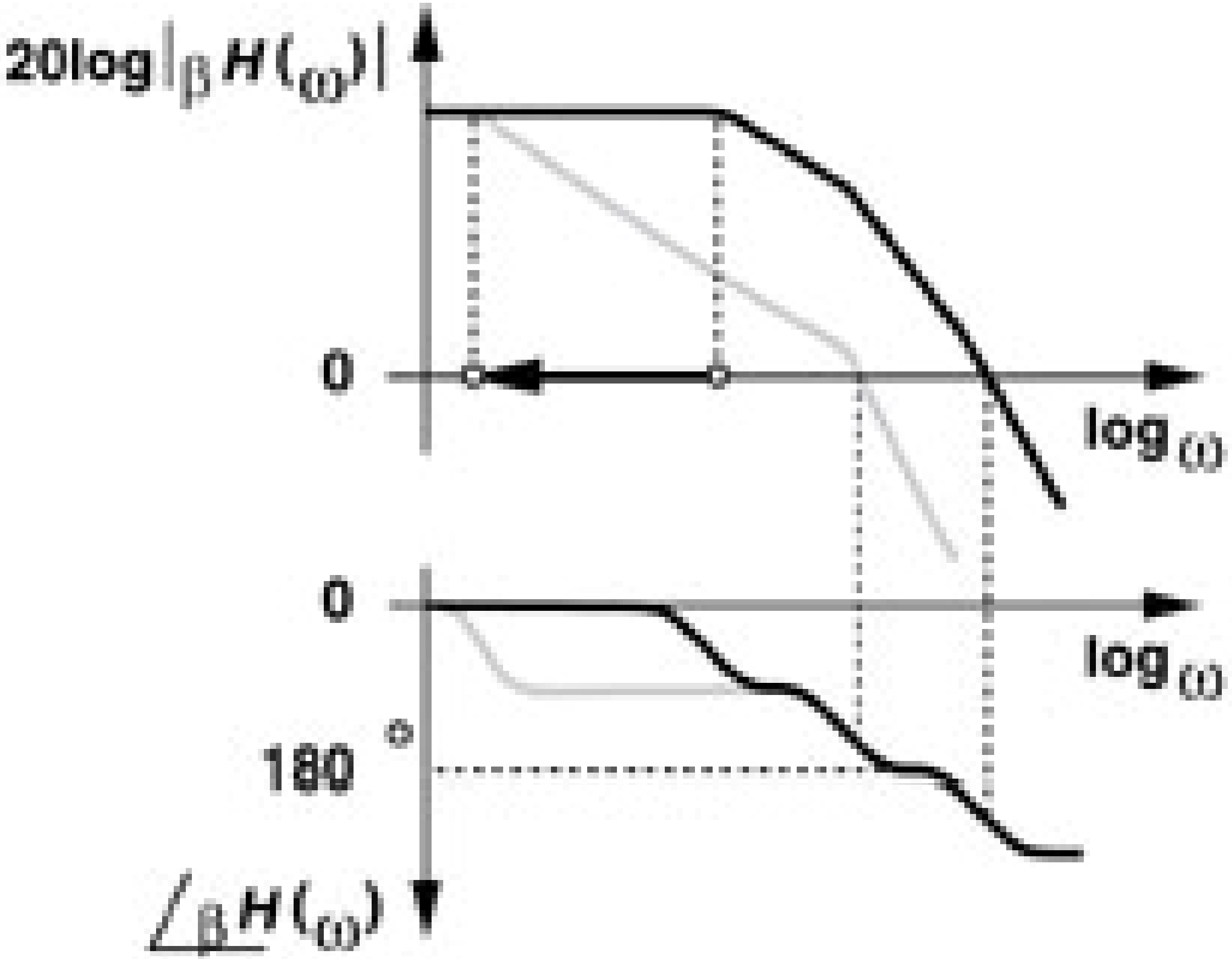
Frequency Compensation



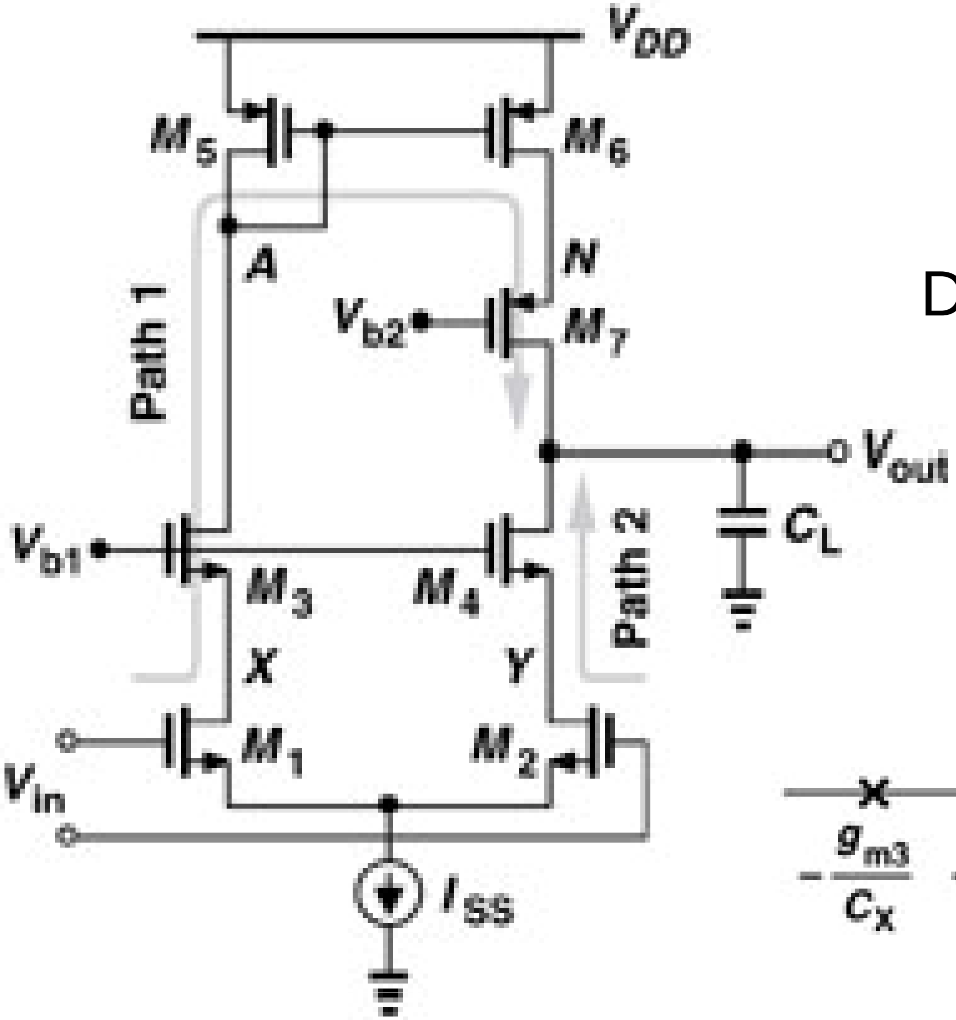
(a) (b)

Compensation is the manipulation of gain and/or pole positions to improve phase margin.

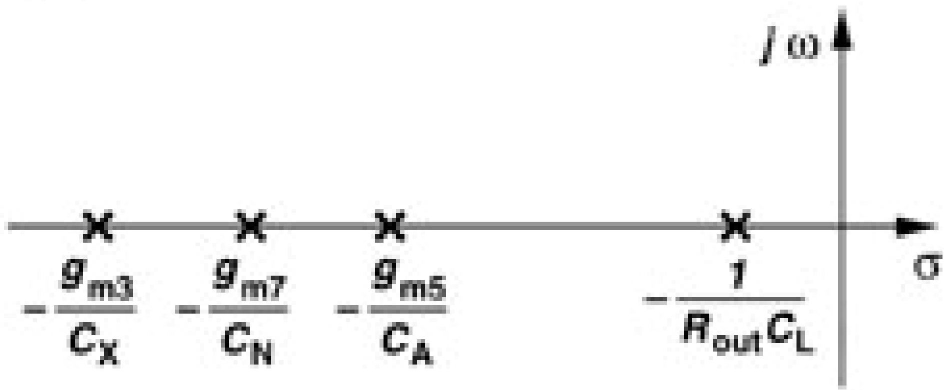
Compensation (cont.)



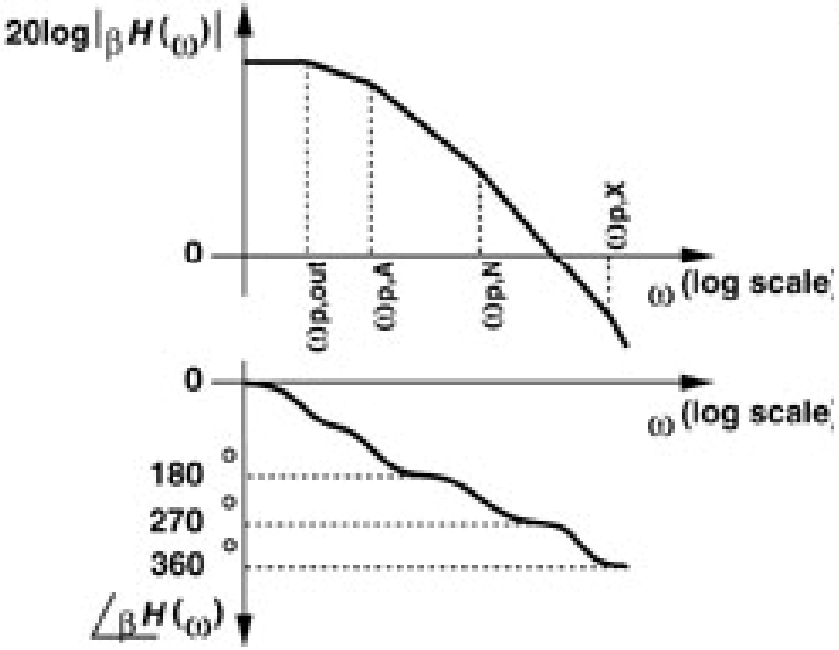
Single Ended Single Stage Amp

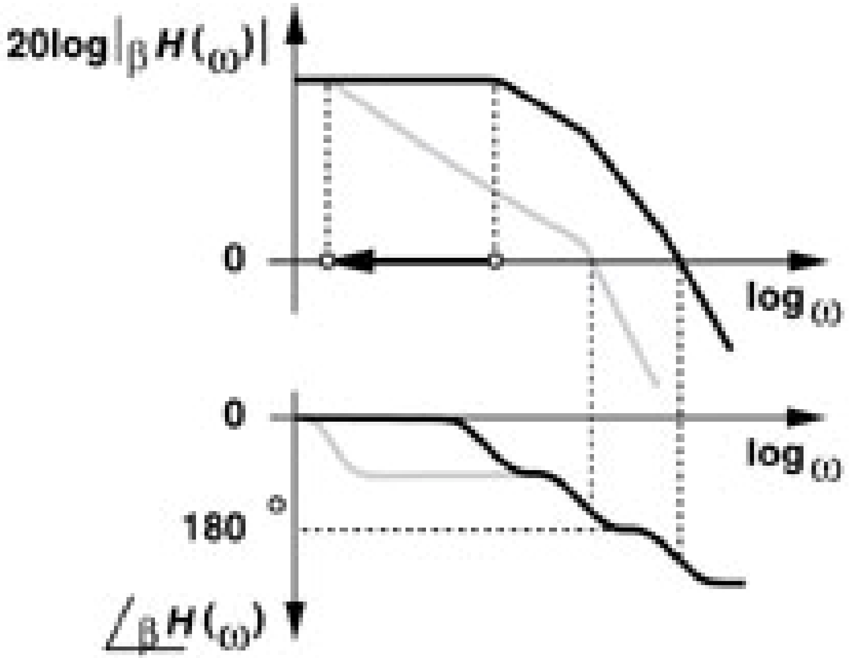


Dominant Pole at Output

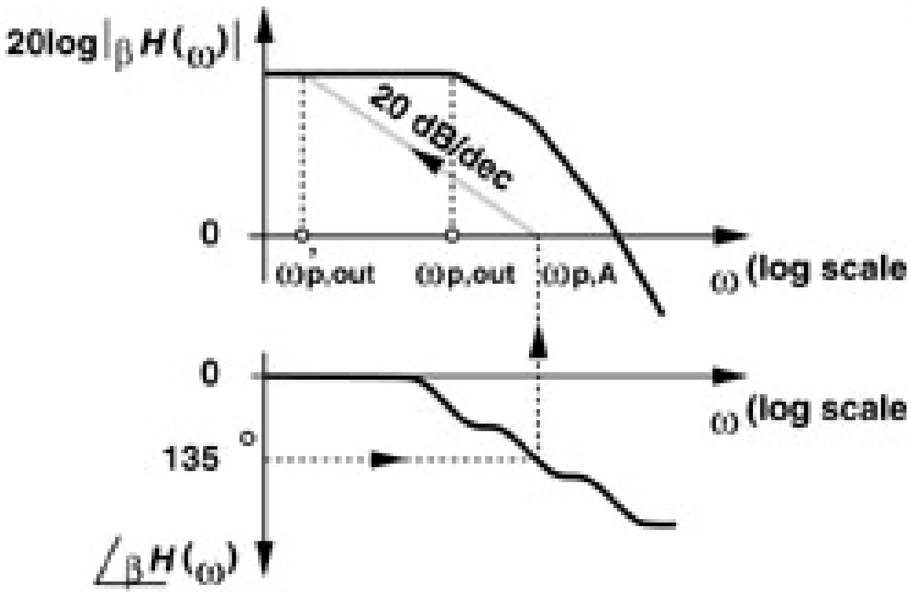


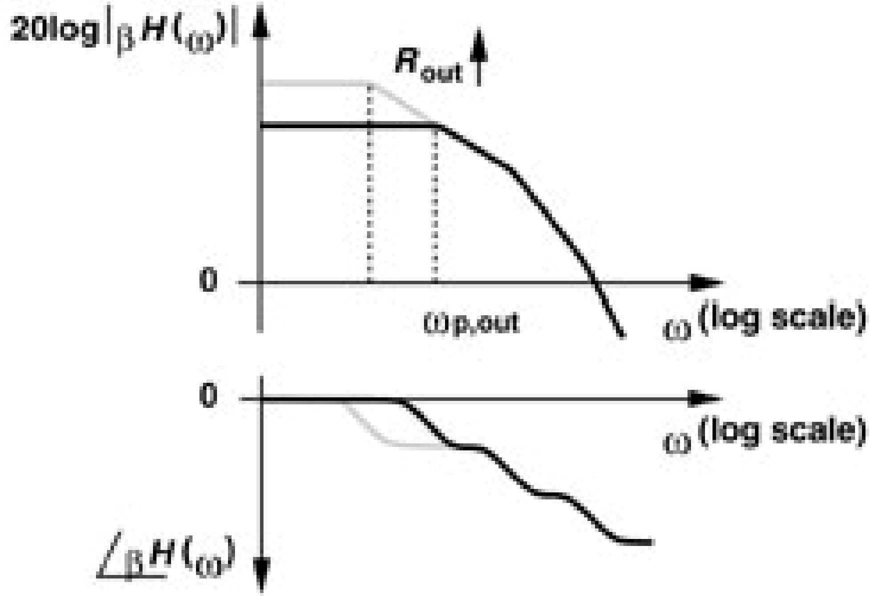
Pre- and Post-Compensation





Compensation (cont.)





Compensation Example

$Given\ \ T_0 = 5000V/V,\ \ fp1 = 2MHz,\ \ fp2 = 25MHz,\ \ fp3 = 50MHz$

$Desire\ \ \phi_m = 70°,\ \ find\ \ f_{0db}\ \ and\ \ new\ \ f_{p1}\ \therefore$

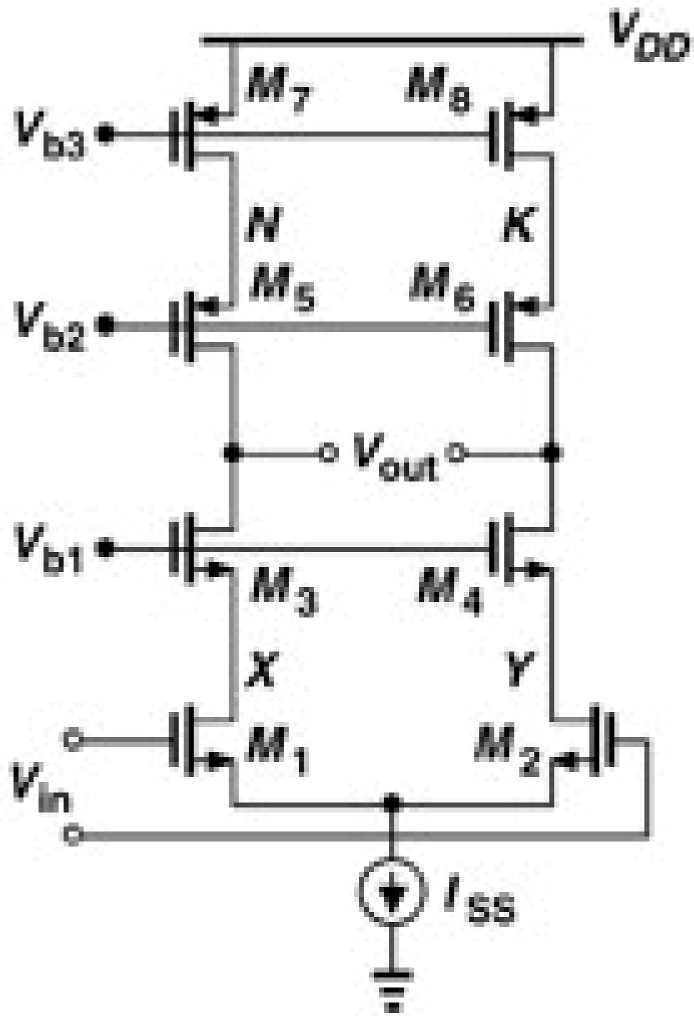
$$70° = 180° - \tan^{-1}(f_{0db}/f_{p1}) - \tan^{-1}(f_{0db}/f_{p2}) - \tan^{-1}(f_{0db}/f_{p2})$$

$$70° = 90 - \tan^{-1}(f_{0db}/f_{p2}) - \tan^{-1}(f_{0db}/f_{p2}),\ assume\ \ 90°\ \ from\ \ f_{p1}$$

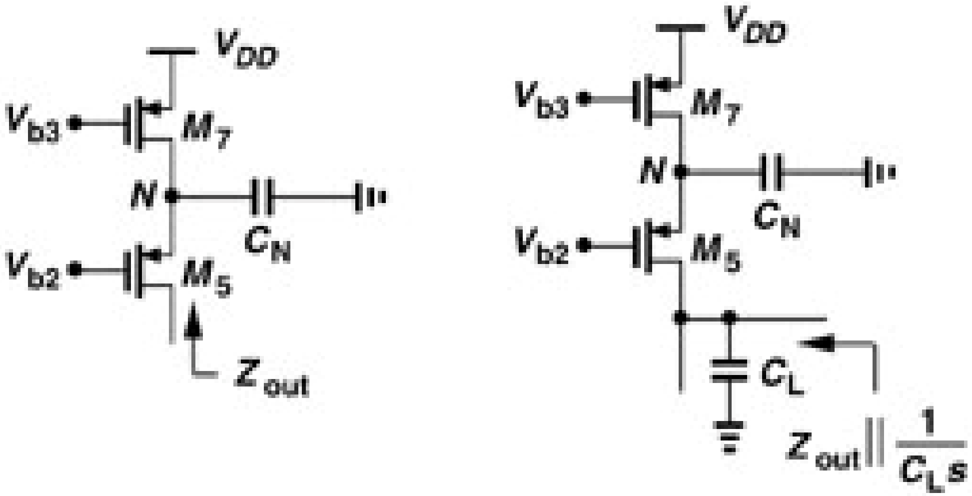
$$f_{0db} \approx 6MHz$$

$$f_{0db} = T_0 f_{p1} \quad \rightarrow \quad f_{p1} = f_{0db}/T_0 = 1.2KHz$$

Fully Differential Telescopic Op-Amp



Cascode Current Source Impedance

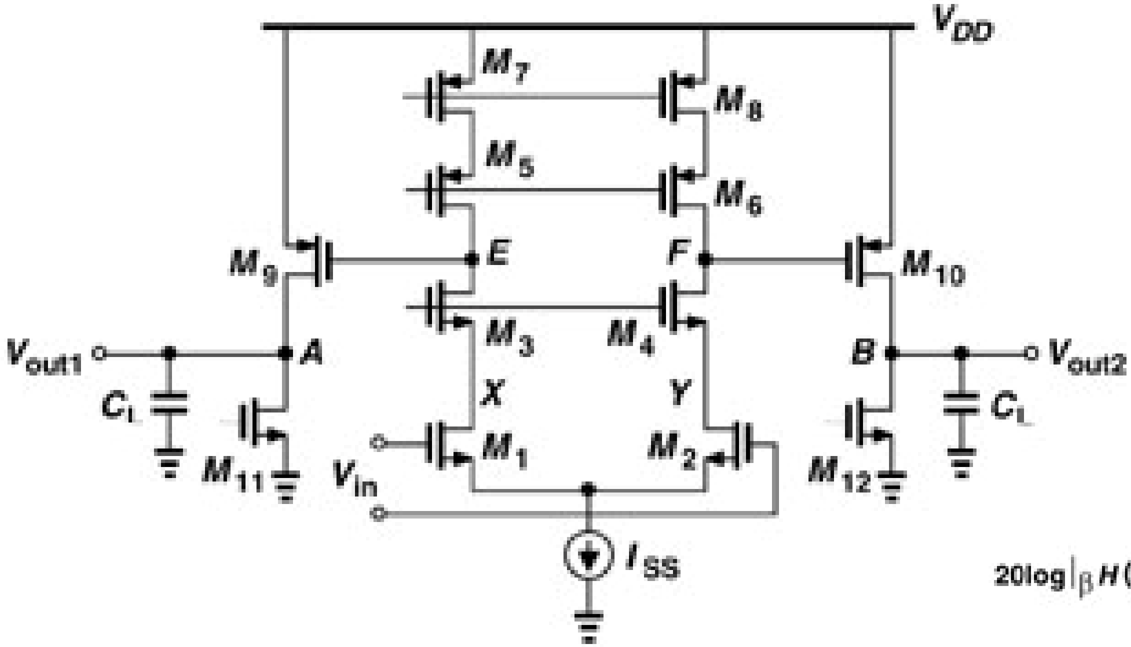


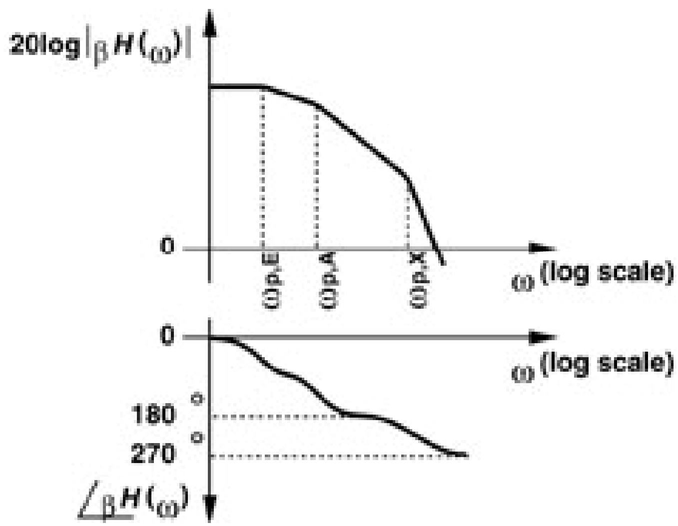
(a)

$$Z_{out} \parallel \frac{1}{sC_L} = \frac{(1+g_{m5}r_{o5})\dfrac{r_{o7}}{1+sr_{o7}C_N}\dfrac{1}{sC_L}}{(1+g_{m5}r_{o5})\dfrac{r_{o7}}{1+sr_{o7}C_N}+\dfrac{1}{sC_L}}$$

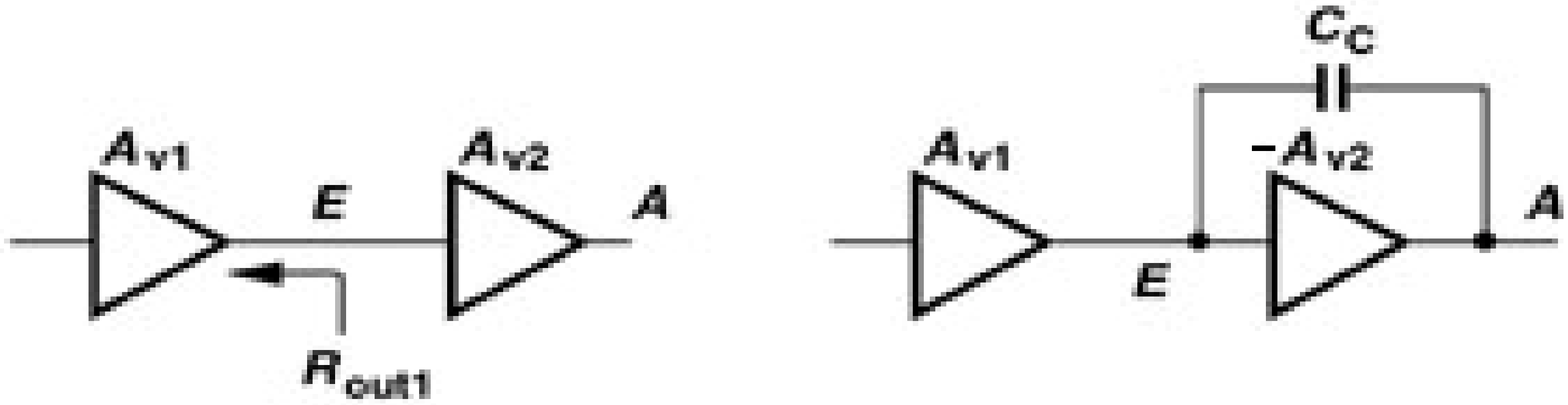
$$= \frac{(1+g_{m5}r_{o5})r_{o7}}{1+s\left[(1+g_{m5}r_{o5})r_{o7}C_L + r_{o7}C_N\right]}$$

Compensation of Two-Stage Op Amps





Compensation (cont.)



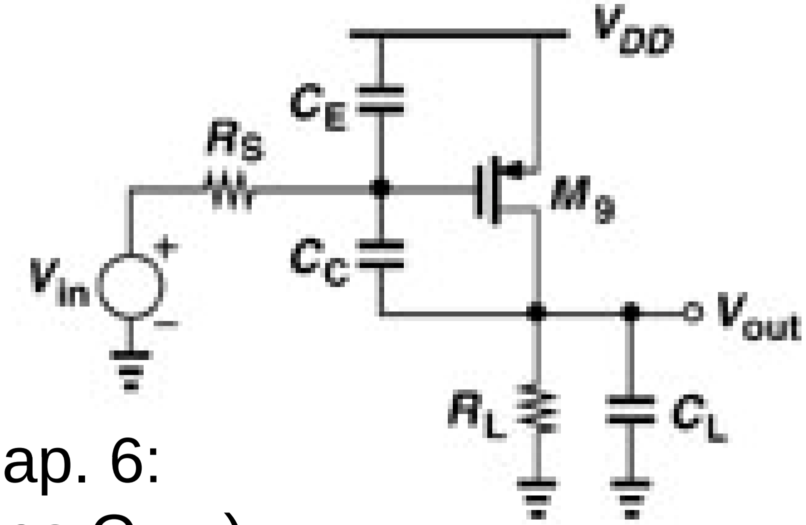
Miller Effect $C_{eq} = C_E + (1 + A_{v2}) C_C$

$$f_{pE} = \frac{1}{2\pi R_{out}[C_E + (1 + A_{v2}) C_C]}$$

Pro: Need a smaller capacitor

Con: Exact effect of bridging capacitor involve a zero. If open-loop gain is high, zero may prevent -20db/dec curve from going all the way to 0db

Compensation (cont.)



Recall, from Chap. 6:
(assume C_C includes C_{GD9})

$$f_{p,in} = \frac{1}{2\pi\left(R_S\left[C_E + (1+g_m R_L)C_C\right] + R_L(C_C + C_L)\right)}$$

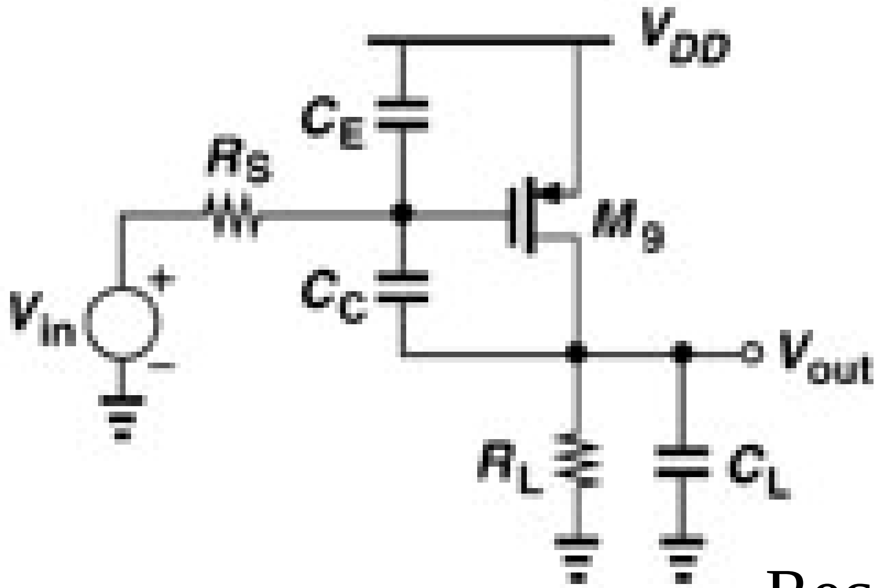
$$f_{p,in} \approx \frac{1}{2\pi R_S\left[C_E + (1+g_m R_L)C_C\right]}$$

Compensation (cont.)

$$f_{p,out} = \frac{R_S(1+g_{m9}R_L)C_C + R_S C_E + R_L(C_C + C_L)}{2\pi R_S R_L (C_E C_C + C_E C_L + C_C C_L)}$$

$$f_{p,out} \approx \frac{R_S g_{m9} R_L C_C + R_L C_C}{2\pi R_S R_L (C_E C_C + C_C C_L)} = \frac{g_{m9}}{2\pi (C_E + C_L)}$$

Compensation (cont.)

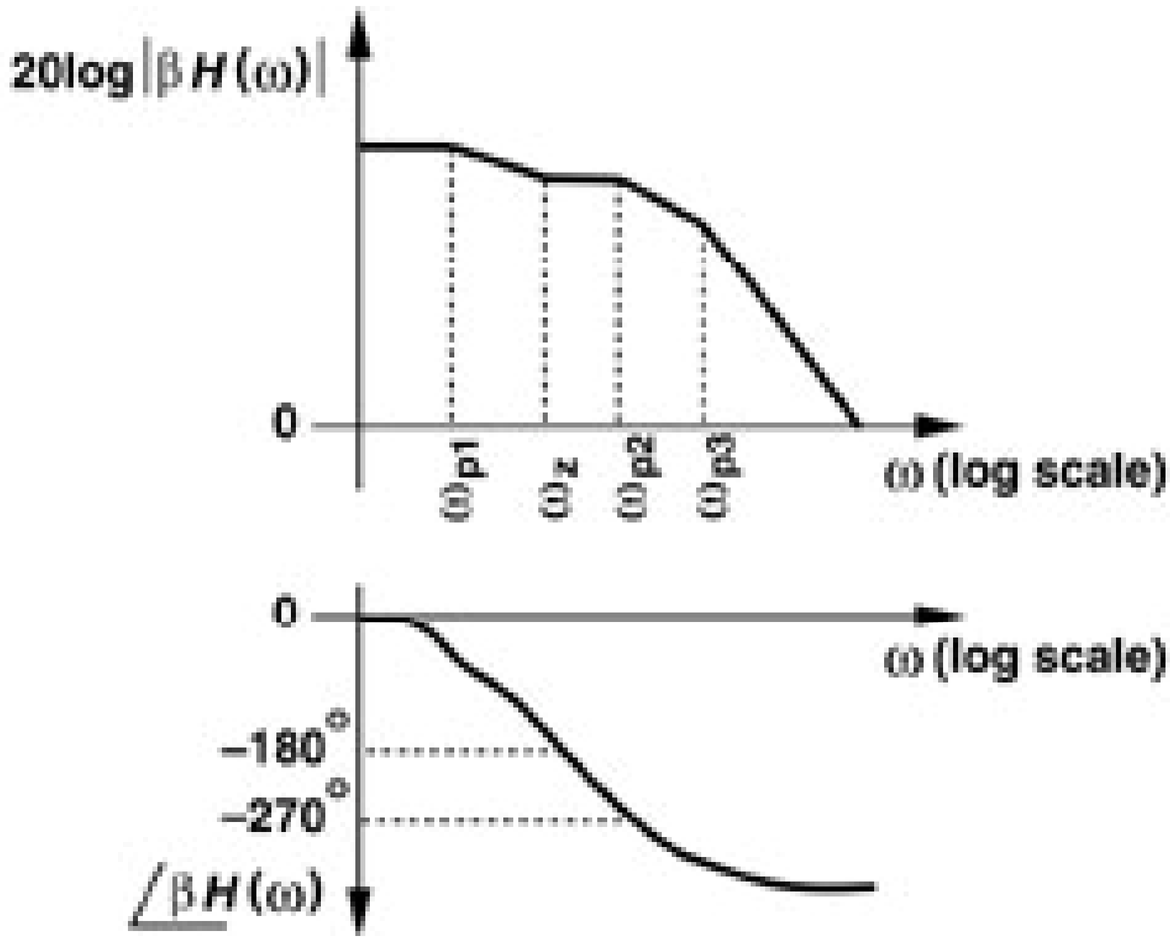


Recall, transfer function includes

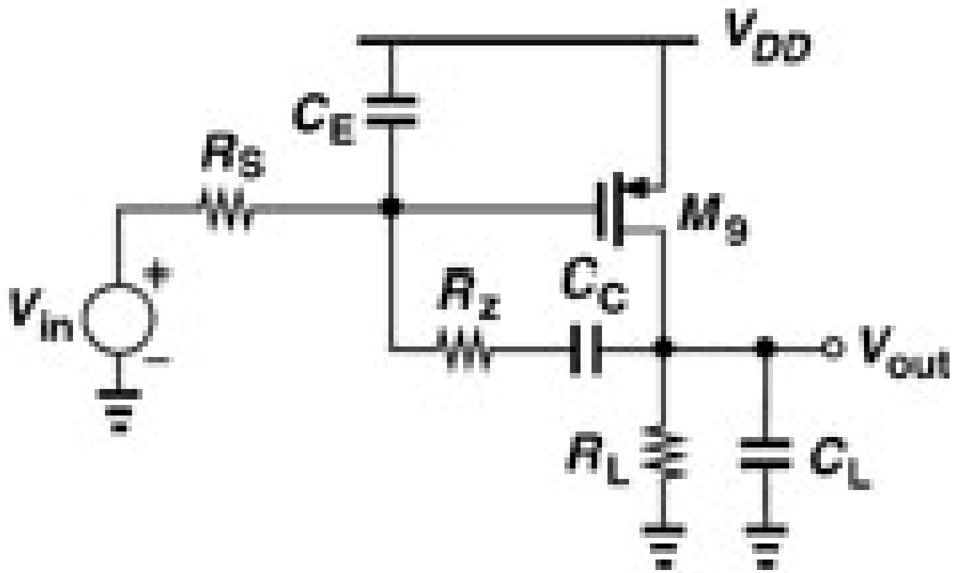
$(1 - s/\omega_z)$ numerator term and

$$f_Z(RHP) = \frac{g_{m9}}{2\pi C_C}$$

Phase and Magnitude of RHP Zero



RHP Zero Removal



$$f_Z = \frac{g_{m9}}{2\pi C_C (1/g_{m9} - R_Z)}$$

RHP Zero Removal (cont.)

$$f_Z = \frac{1}{2\pi C_C (1/g_{m9} - R_Z)}$$

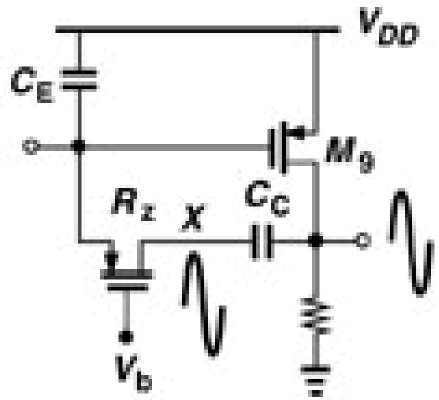
Could set $R_z = 1/g_{m9}$, or cancel

other non-dominant pole

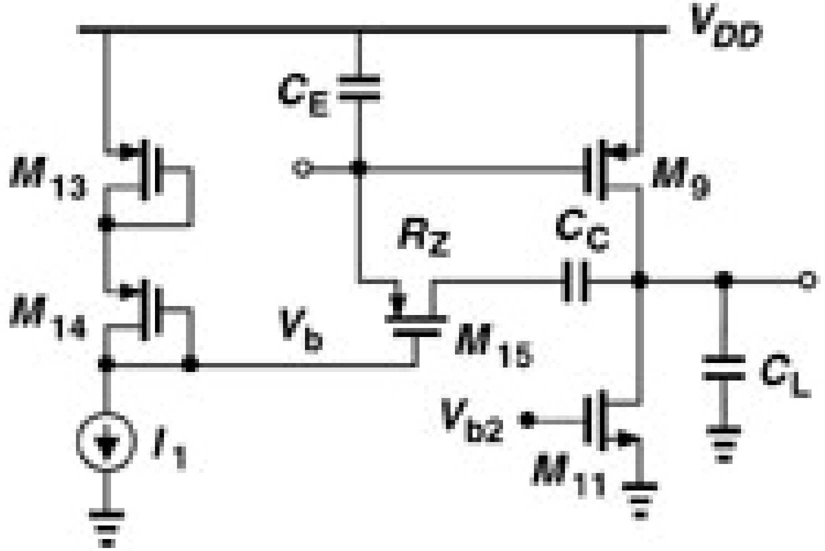
$$\frac{1}{C_C (1/g_{m9} - R_Z)} = \frac{-g_{m9}}{C_L + C_E}$$

$$R_Z = \frac{C_L + C_E + C_C}{g_{m9} C_C} \approx \frac{C_L + C_C}{g_{m9} C_C}$$

Miller Compensation (cont.)



Temp. and Process Tracking



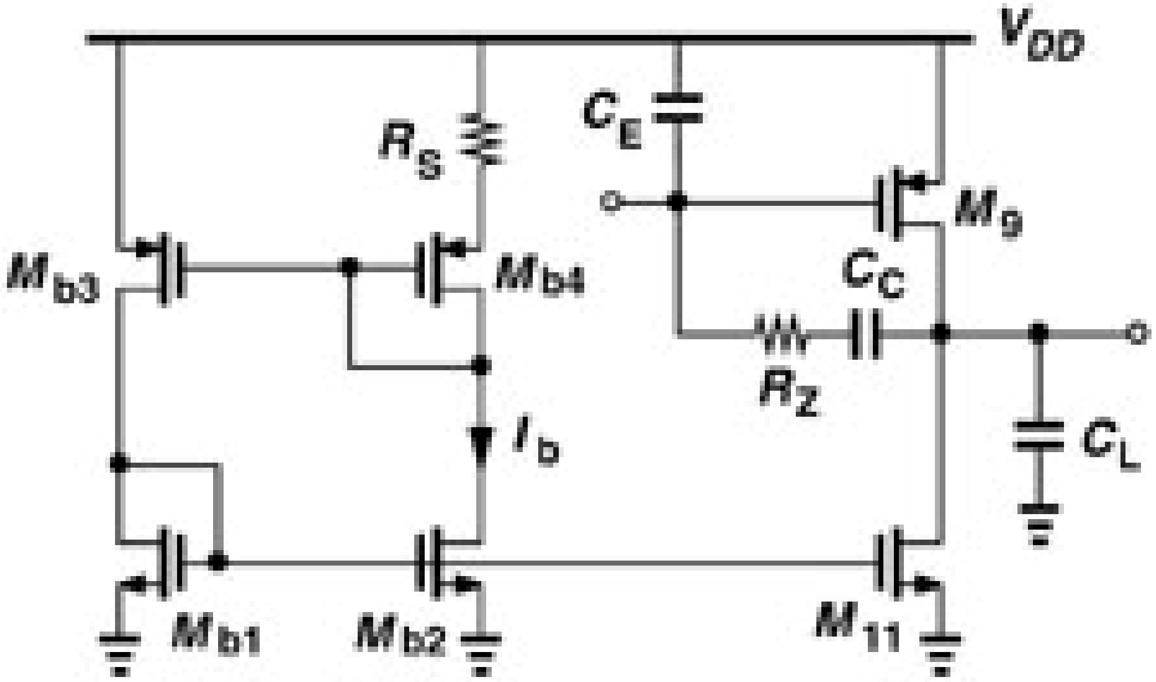
$$R_{on15} = \frac{1}{\mu_p C_{ox}\left(\frac{W}{L}\right)_{15}(V_{GS15} - V_{TH15})}$$

$$= \frac{(W/L)_{14}}{g_{m14}(W/L)_{15}} \qquad \text{because } g_{m14} = \mu_p C_{ox}\left(\frac{W}{L}\right)_{14}(V_{GS14} \quad V_{TH14})$$

$$g_{m14}^{-1}\frac{(W/L)_{14}}{(W/L)_{15}} = g_{m9}^{-1}\left(1 + \frac{C_L}{C_E}\right)$$

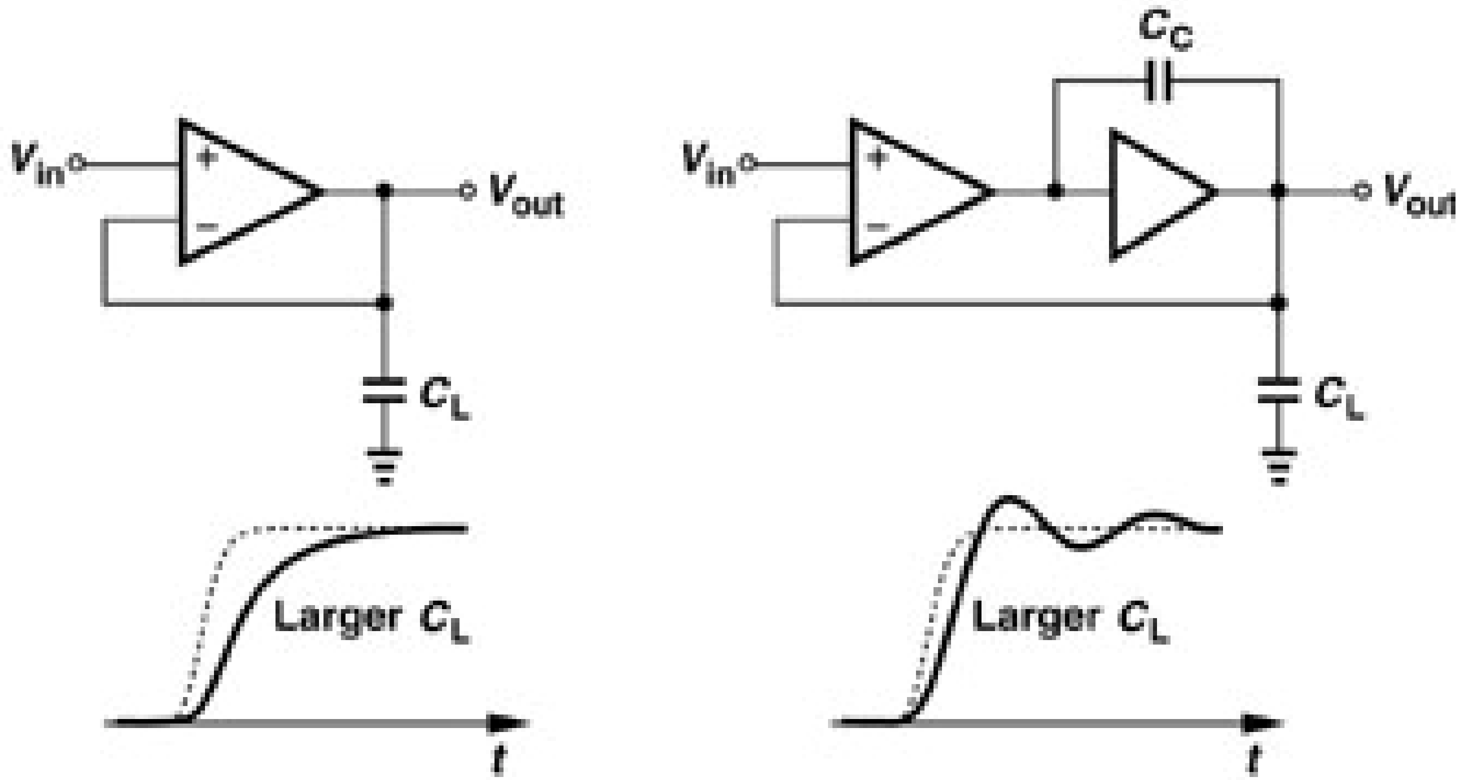
$$\left(\frac{W}{L}\right)_{15} = \sqrt{(W/L)_{14}(W/L)_9} \cdot \sqrt{\frac{I_{D9}}{I_1}} \cdot \frac{C_E}{C_E + C_L}$$

Miller Compensation (cont.)

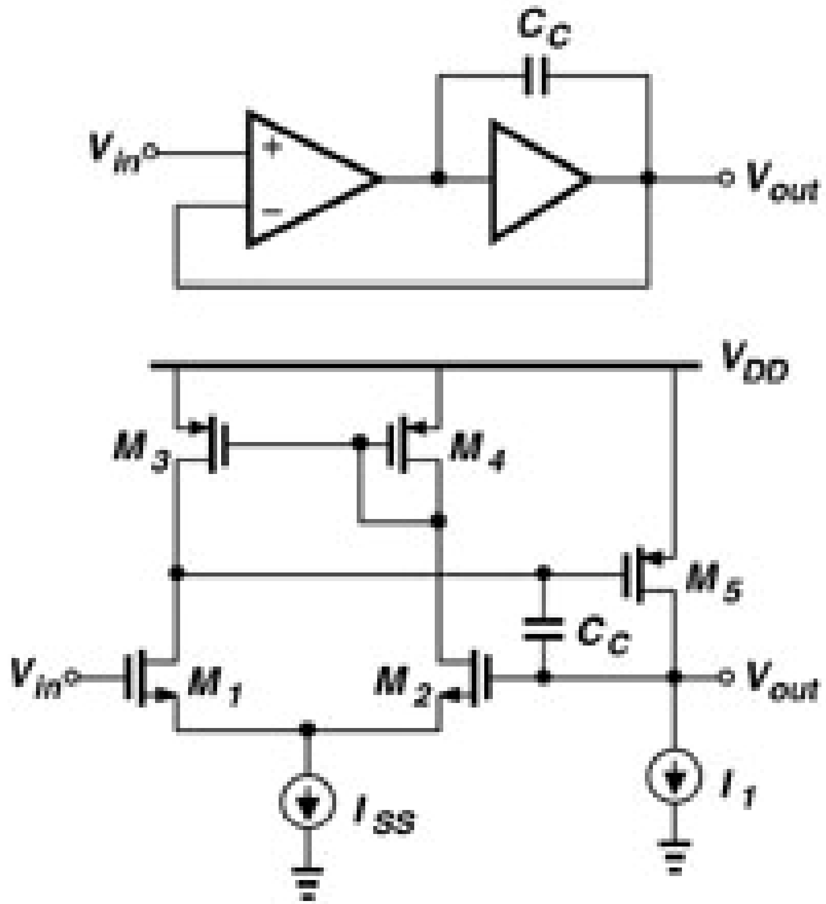


$$g_{m9} \propto \sqrt{I_{D9}} \propto \sqrt{I_{D11}} \propto 1/R_S$$

Load Capacitance Effects

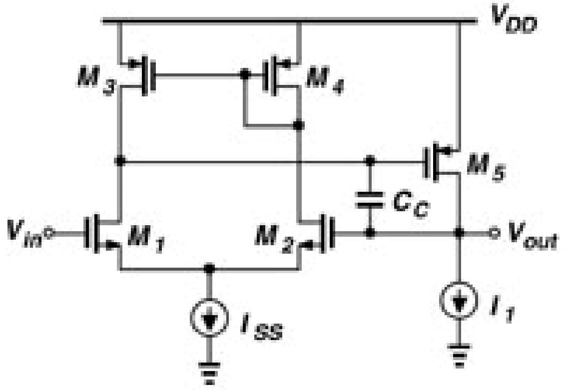


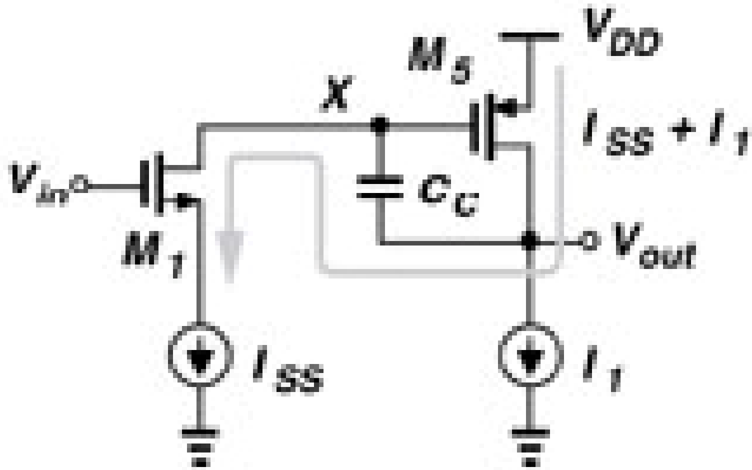
Slewing in Two-Stage Op Amps

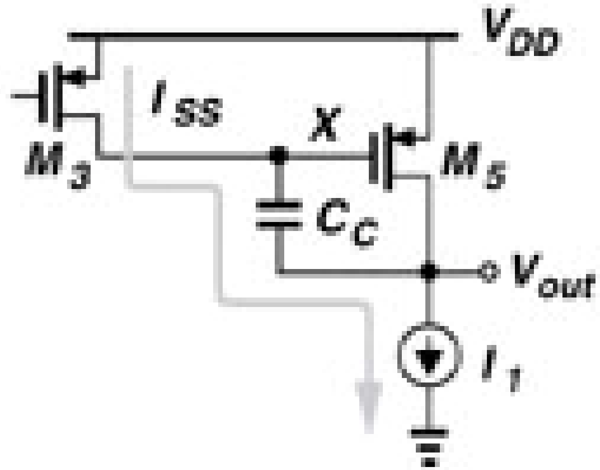


Basic Two-Stage Op Amp

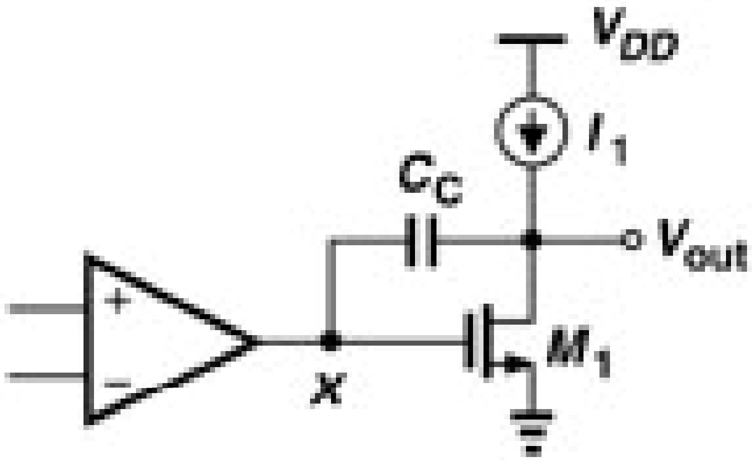
Slewing in Two-Stage Op Amp

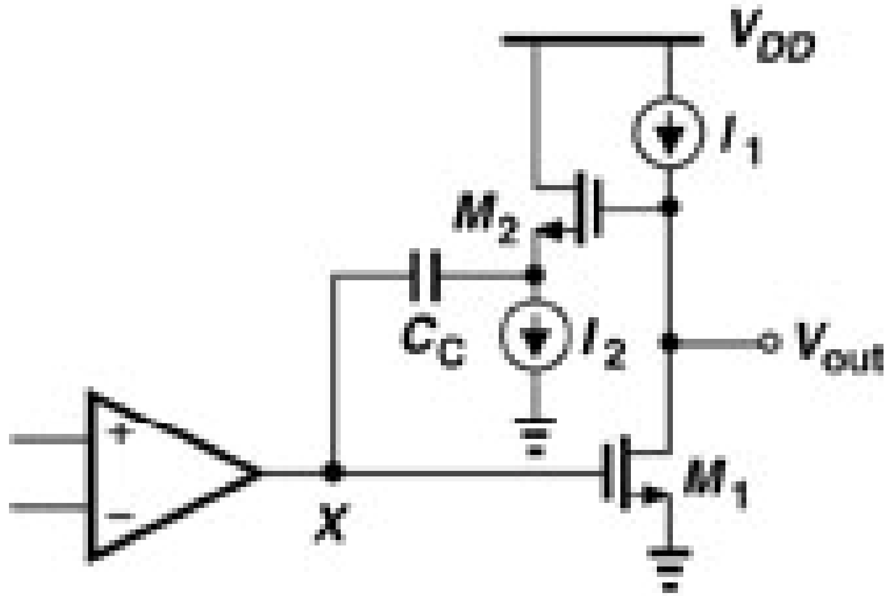




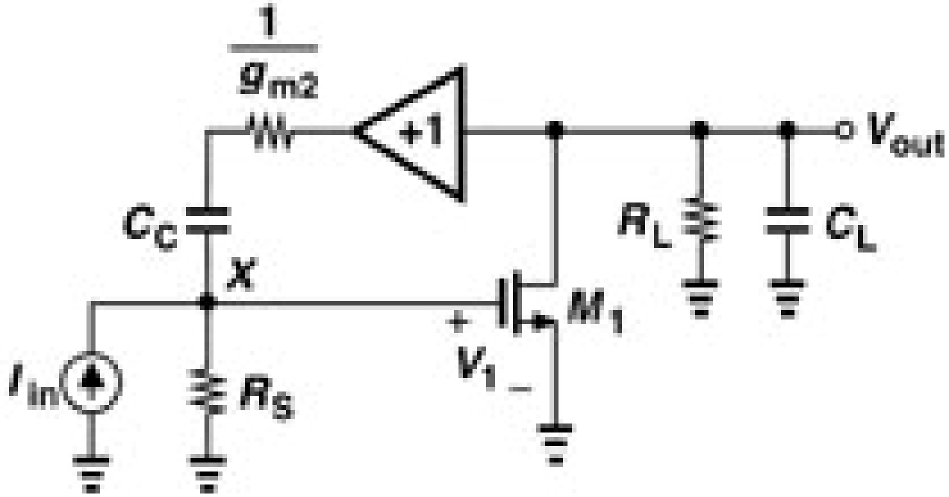


Other Compensation Techniques





Other Compensation Techniques (cont.)

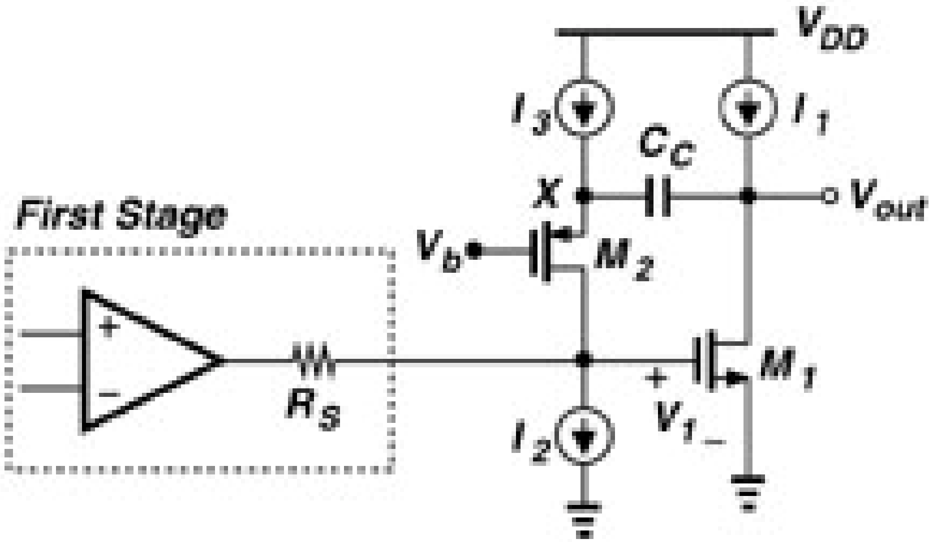


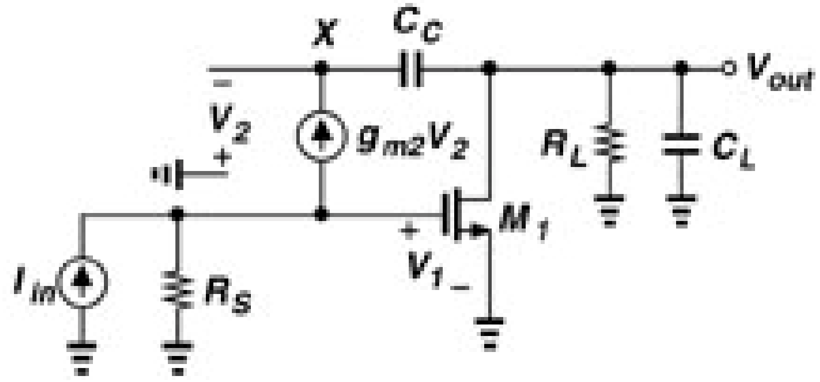
$$\frac{V_{out}}{I_{in}} = -\frac{g_{m1} R_L R_S \left(g_{m2} + C_L s\right)}{R_L C_L C_C \left(1 + g_{m2} R_S\right) s^2 + \left[\left(1 + g_{m1} g_{m2} R_L R_S\right) C_C + g_{m2} R_L C_L\right] s + g_{m2}}$$

$$1 + g_{m2} R_S \gg 1 \ , \quad \left(1 + g_{m1} g_{m2} R_L R_S\right) C_C \gg g_{m2} R_L C_L$$

$$\omega_{p1} \simeq \frac{1}{g_{m1} R_L R_S C_C} \ , \quad \omega_{p2} \simeq \frac{g_{m1}}{C_L}$$

Other Compensation Techniques (cont.)

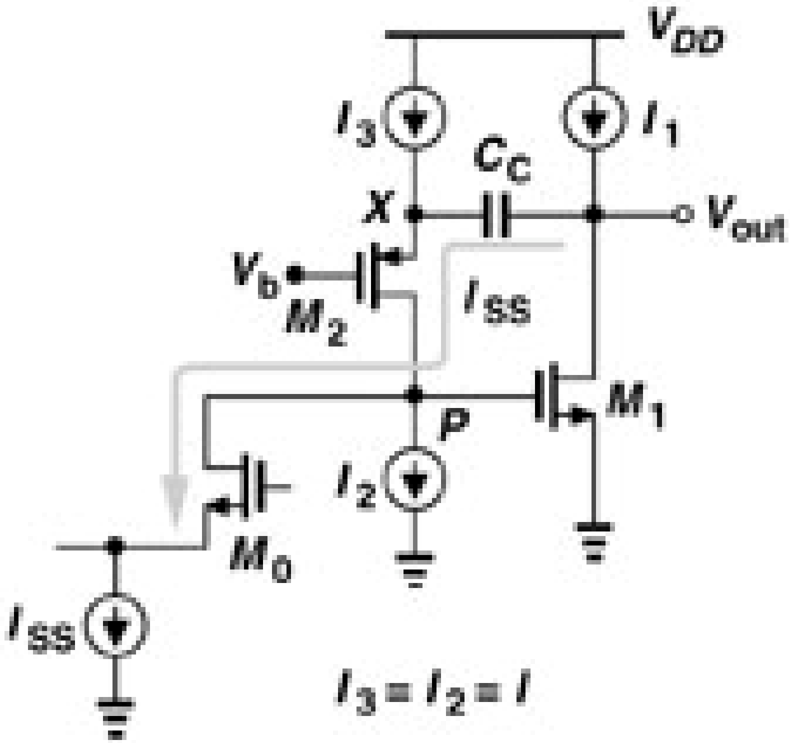




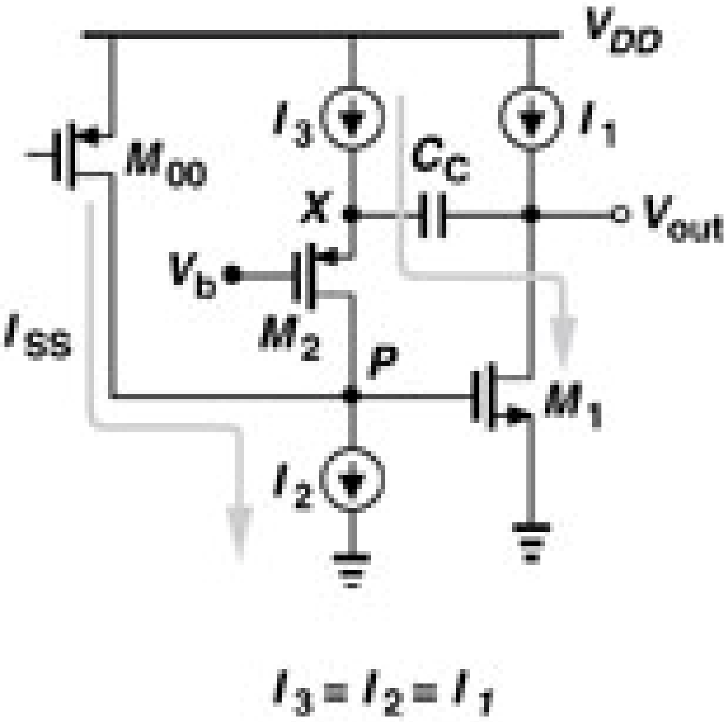
$$\frac{V_{out}}{I_{in}} = -\frac{g_{m1} R_S R_L \left(g_{m2} + C_C s\right)}{R_L C_L C_C s^2 + \left[\left(1 + g_{m1} R_S\right) g_{m2} R_L C_C + C_C + g_{m2} R_L C_L\right] s + g_{m2}}$$

$$\omega_{p1} \simeq \frac{1}{g_{m1} R_L R_S C_C}, \quad \omega_{p2} \simeq \frac{g_{m2} R_S g_{m1}}{C_L}$$

Slewing with Common-Gate Compensation

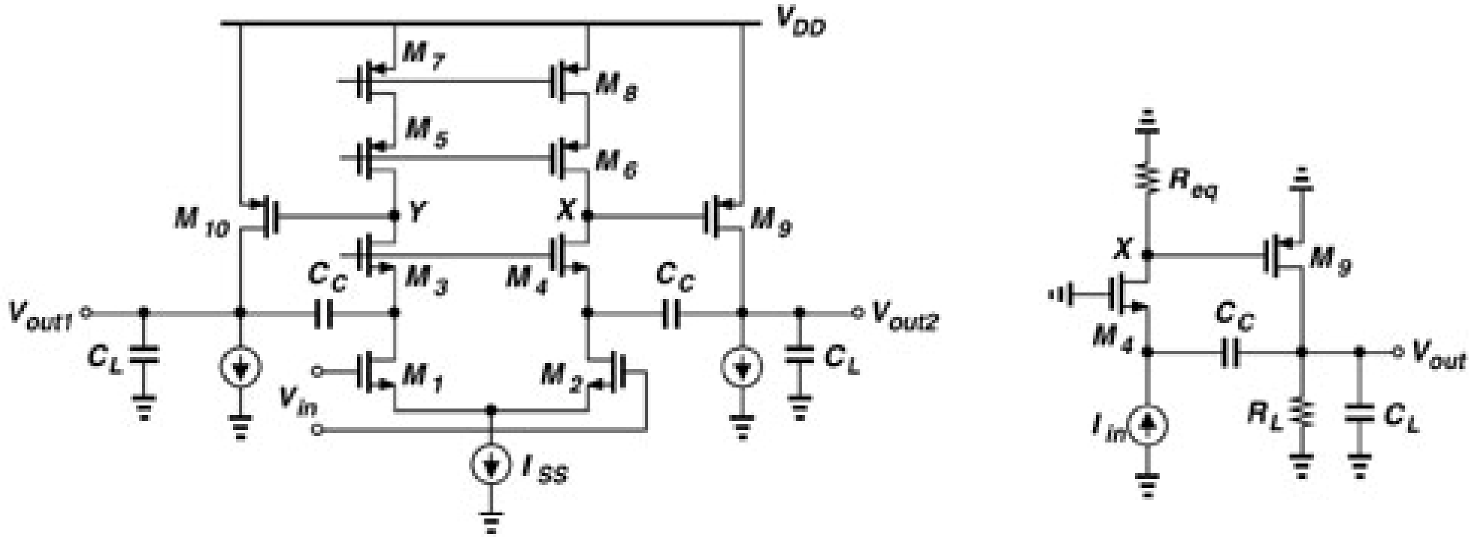


(a)



(b)

Other Compensation Techniques (cont.)



(a) (b)

$$\omega_z \simeq g_{m4} R_{eq} \cdot \frac{g_{m9}}{C_C}$$

$$\omega_{p1} \simeq \frac{1}{g_{m9} R_{eq} R_L C_C}$$

$$\omega_{p2} \simeq \frac{g_{m4} R_{eq} g_{m9}}{C_L}$$