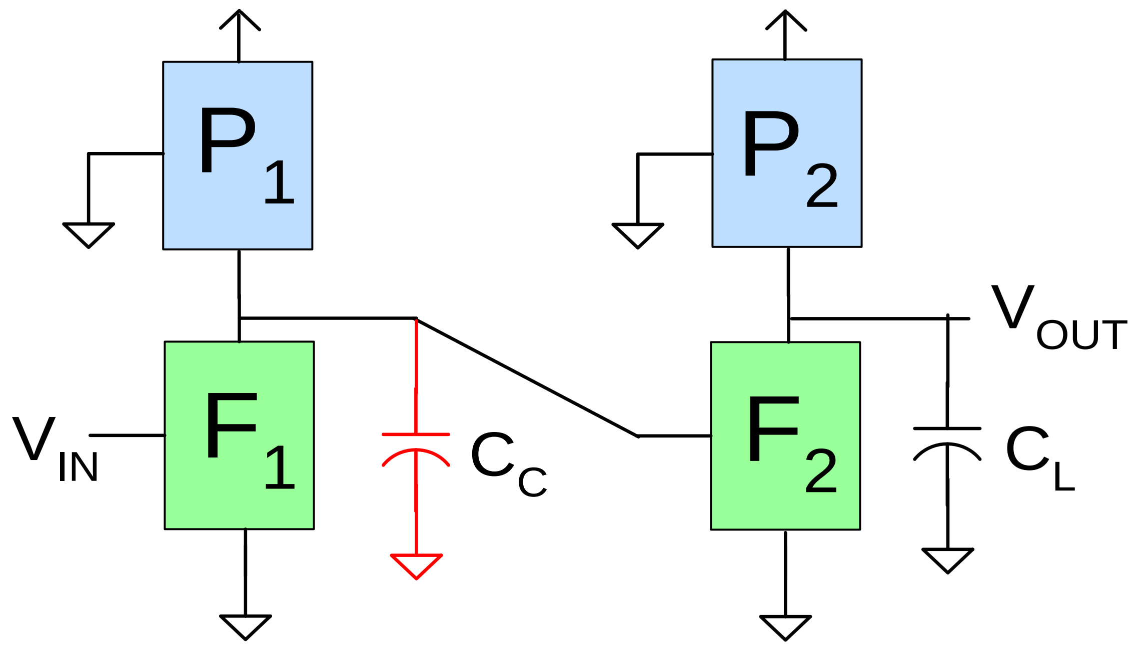
EE 435

Lecture 15

Compensation of Feedback Amplifiers

Review from Last Time

Analysis of <u>Internal Node</u> Compensated Two-Stage Op Amps



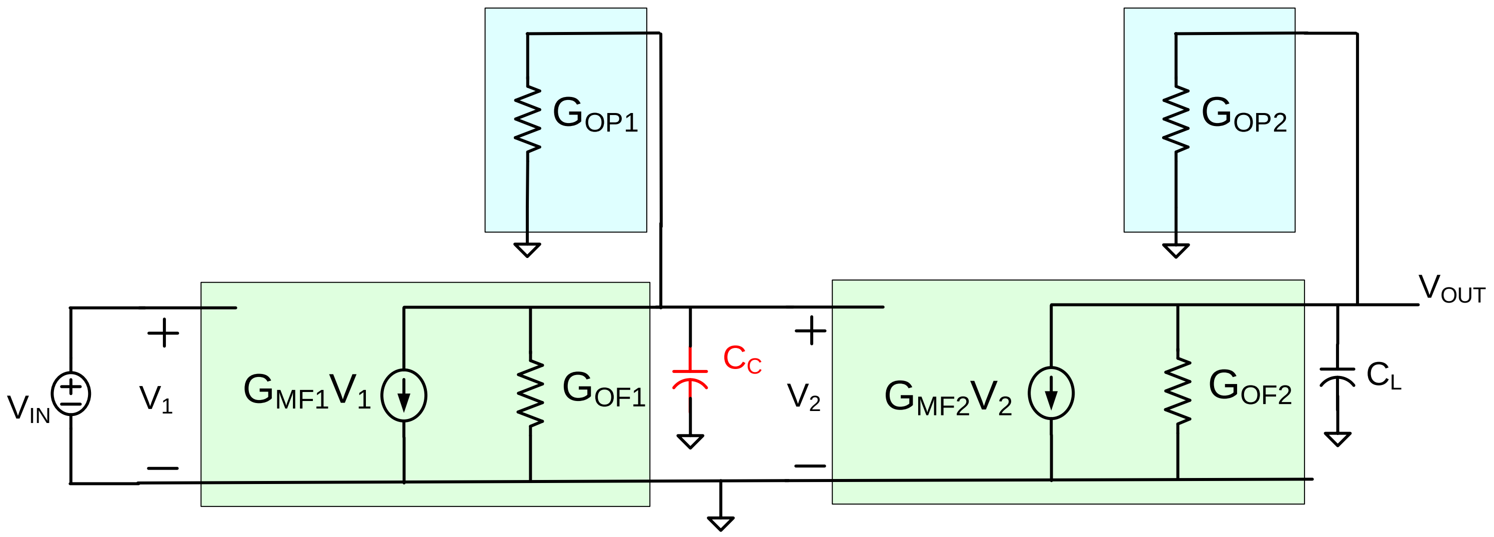
Consider single-ended input-output (differential analysis only slightly different)

Can’t get everything but can get most of the small-signal results

Since internal node compensated, must have $p_1 << p_2$

Review from Last Time

Analysis of Internal-Node Compensated Two-Stage Op Amps

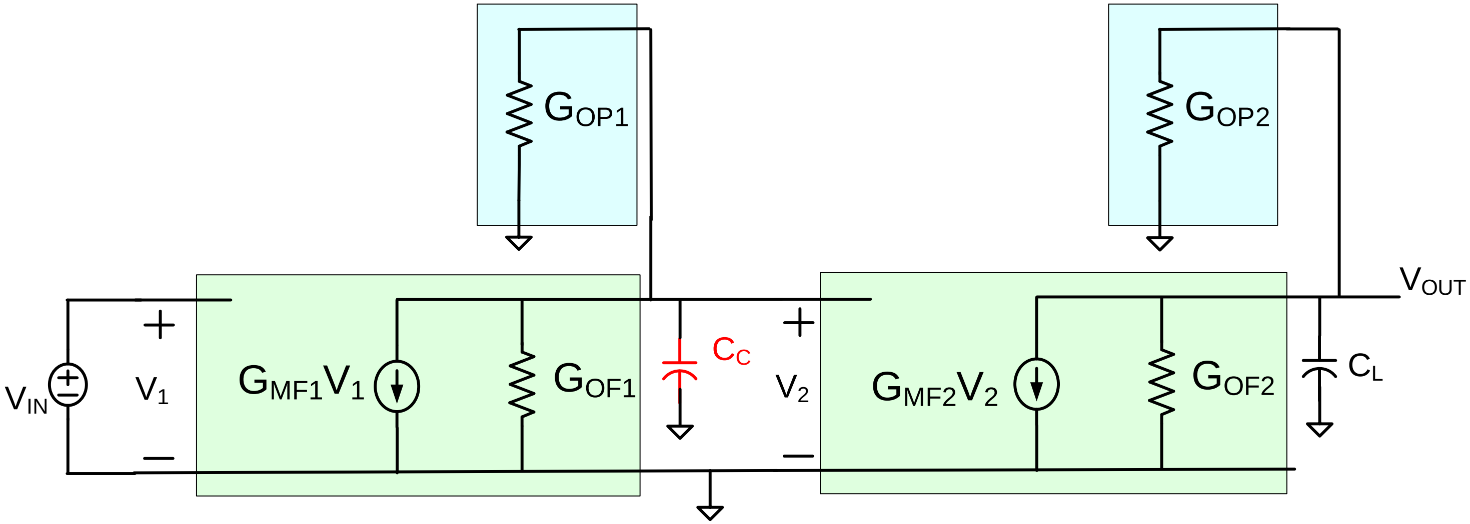


$$\left.\begin{aligned} V_2\left(sC_C + G_{OF1} + G_{OP1}\right) + G_{mF1}V_{IN} &= 0 \\ V_{OUT}\left(sC_L + G_{OP2} + G_{OF2}\right) + G_{mF2}V_2 &= 0 \end{aligned}\right\}$$

$$A_V(s) = \frac{-G_{mF1}}{sC_C + G_{OF1} + G_{OP1}} \bullet \frac{-G_{mF2}}{sC_L + G_{OP2} + G_{OF2}}$$

Review from Last Time

Analysis of Internal-Node Compensated Two-Stage Op Amps



$$A_{V0}=\left(\frac{G_{mF1}}{G_{oF1}+G_{OP1}}\right)\left(\frac{G_{mF2}}{G_{OF2}+G_{OP2}}\right)$$

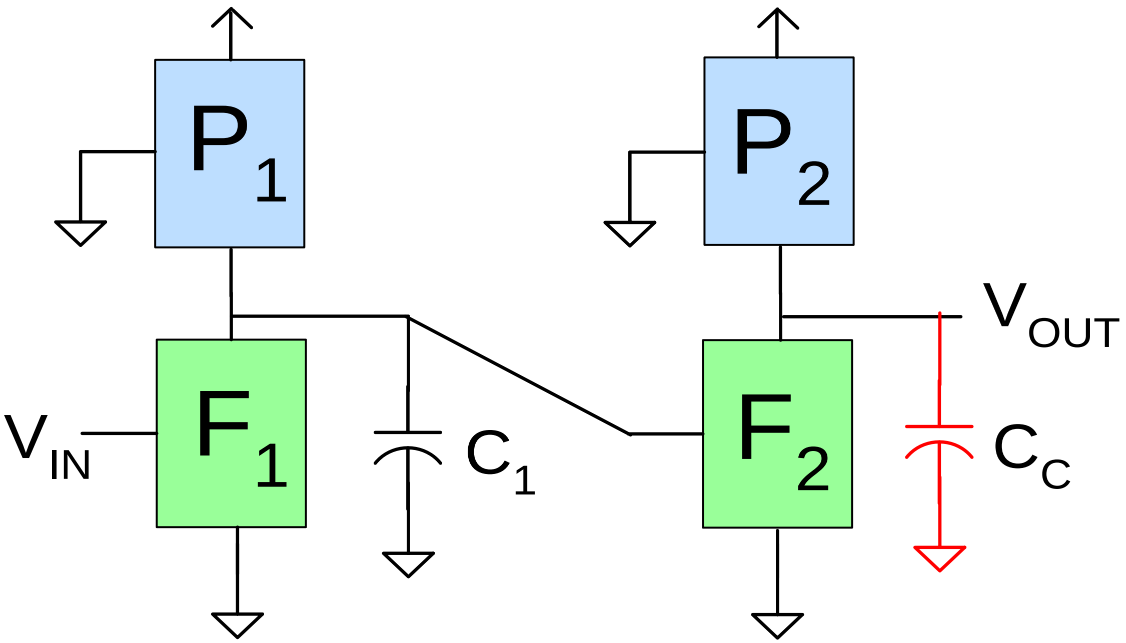
$$|p_2|=\frac{\left(G_{OF2}+G_{OP2}\right)}{C_L}$$

$$\mathbf{BW}=|\mathbf{p_1}|$$

$$|p_1|=\frac{\left(G_{OF1}+G_{OP1}\right)}{C_C}$$

$$GB=\frac{G_{mF1}G_{mF2}}{\left(G_{OF2}+G_{OP2}\right)C_C}$$

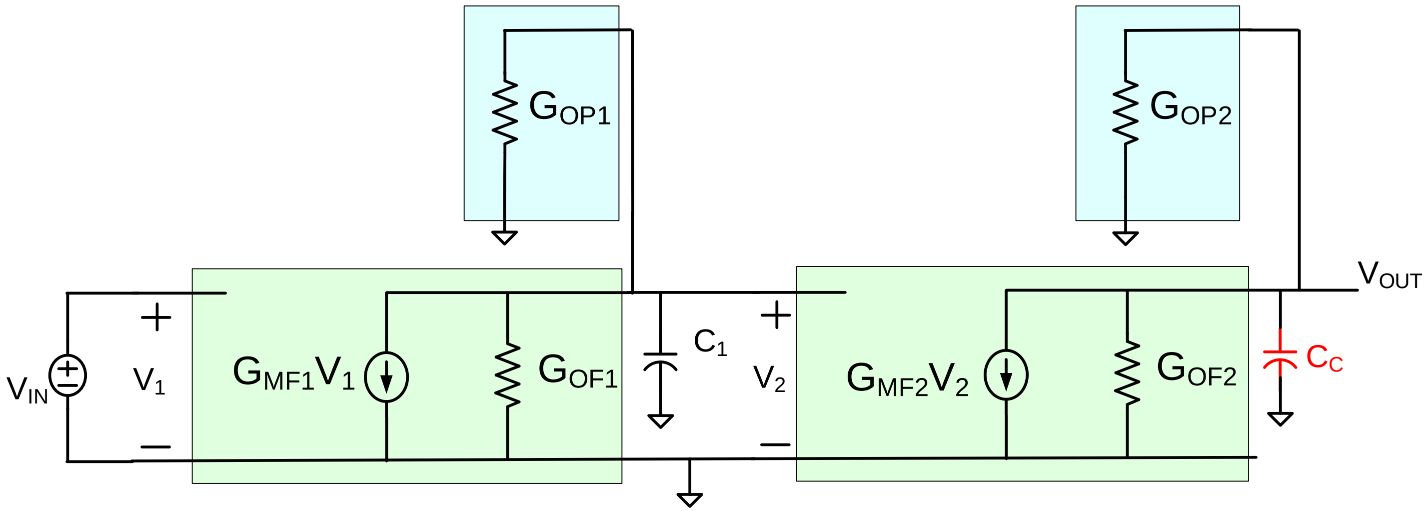
Analysis of Load Compensated Two-Stage Op Amps



Can’t get everything but can get most of the small-signal results

Review from Last Time

Analysis of Externally Compensated Two-Stage Op Amps



$$A_{V0} = \left(\frac{G_{mF1}}{G_{OF1}+G_{OP1}}\right)\left(\frac{G_{mF2}}{G_{OF2}+G_{OP2}}\right)$$

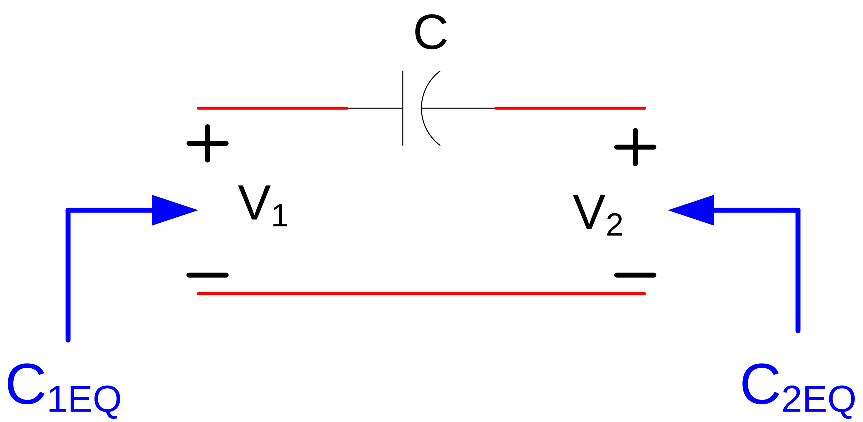
$$|p_2| = \frac{\left(G_{OF2}+G_{OP2}\right)}{C_C}$$

$$\mathbf{BW} = |\mathbf{p_2}|$$

$$|p_1| = \frac{\left(G_{OF1}+G_{OP1}\right)}{C_1}$$

$$GB = \frac{G_{mF1}G_{mF2}}{\left(G_{OF1}+G_{OP1}\right)C_C}$$

Miller Capacitance - Review



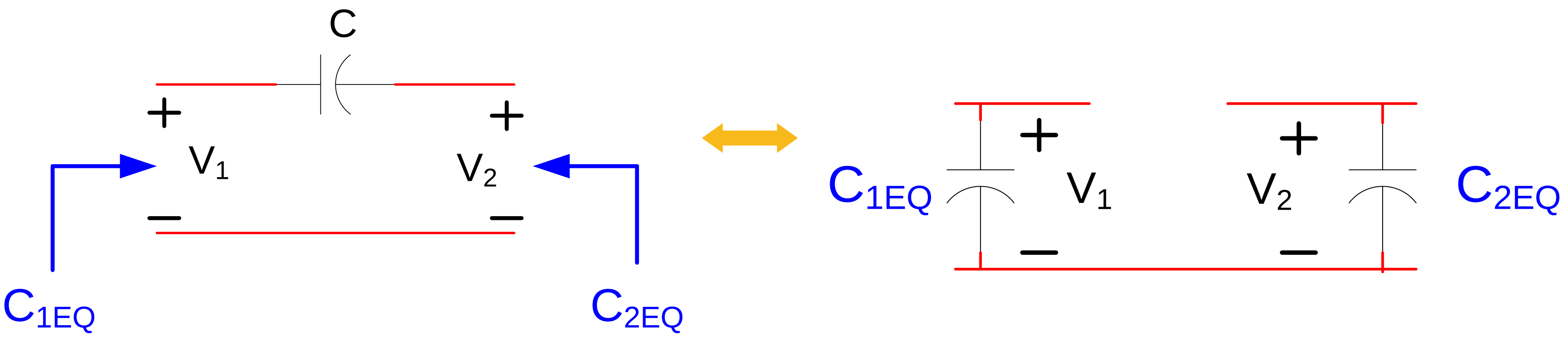
If $V_2 = -AV_1$ then for A large

$$\mathbf{C_{1EQ}} = \mathbf{C}(\mathbf{1} + \mathbf{A}) \approx \mathbf{CA} \qquad\qquad \mathbf{C_{2EQ}} = \mathbf{C}\left(\mathbf{1} + \frac{\mathbf{1}}{\mathbf{A}}\right) \approx \mathbf{C}$$

Thus, a large effective capacitance can be created with a much smaller capacitor if a capacitor bridges two nodes with a large inverting gain !!

Note: The symbol “A” used in the Miller Capacitance should not be confused with the gain of the op amp

Miller Capacitance - Review



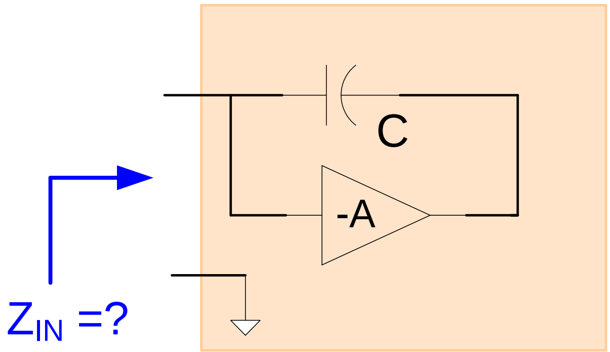
If $V_2 = -AV_1$ then for A large

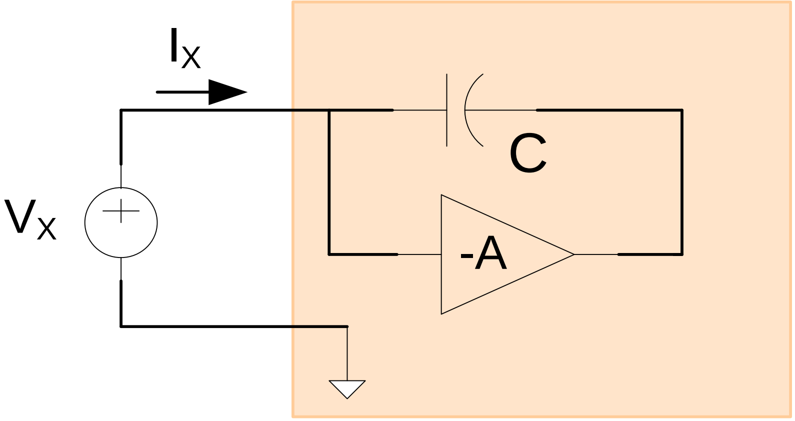
$$\mathbf{C_{1EQ}} = \mathbf{C}(\mathbf{1} + \mathbf{A}) \approx \mathbf{CA} \qquad \mathbf{C_{2EQ}} = \mathbf{C}\left(\mathbf{1} + \frac{\mathbf{1}}{\mathbf{A}}\right) \approx \mathbf{C}$$

- If A changes with frequency, C_{1EQ} and C_{2EQ} are no longer pure capacitors
- More useful for giving a concept than for accurate actual analysis because of frequency dependence of A

Miller Capacitance - Review

The Basic Concept – from capacitance multiplication





$$I_X = [V_X - (-AV_X)]sC = V_X s\left[C(1+A)\right]$$

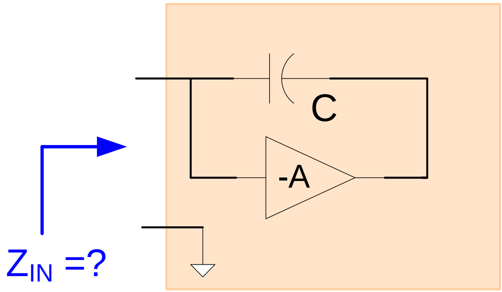
thus

$$Z_{IN} = \frac{V_X}{I_X} = \frac{1}{s\left[C(1+A)\right]}$$

So, if A is constant, input looks like a capacitor of value

$$C_{EQ} = C(1+A)$$

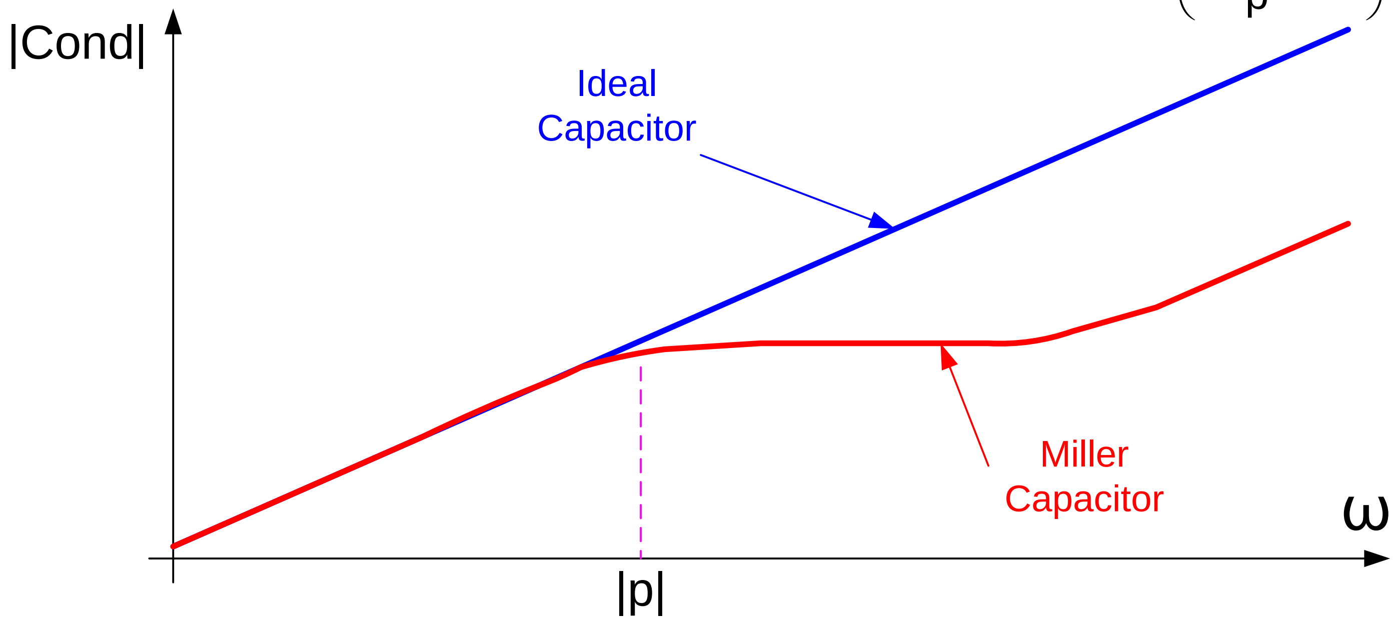
Miller Capacitance - Review



$$Z_{IN}=\frac{V_X}{I_X}=\frac{1}{s\left[C(1+A)\right]}$$

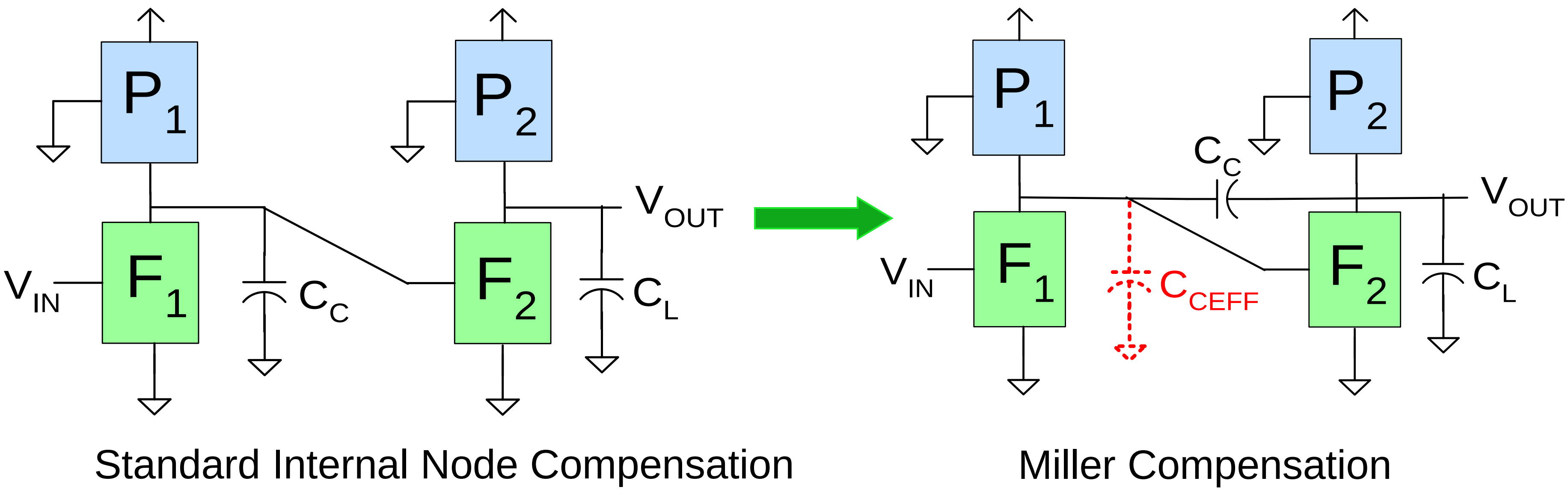
If $\quad A(s)=\frac{A_0}{\frac{s}{p}+1}$

$$G_{IN}=s\left[C(1+A)\right]=sC\left(\frac{\frac{s}{p}+1+A_0}{\frac{s}{p}+1}\right)$$



Does not behave as a capacitor for ω > p

Internal-Node Miller-Compensated Two-Stage Op Amp



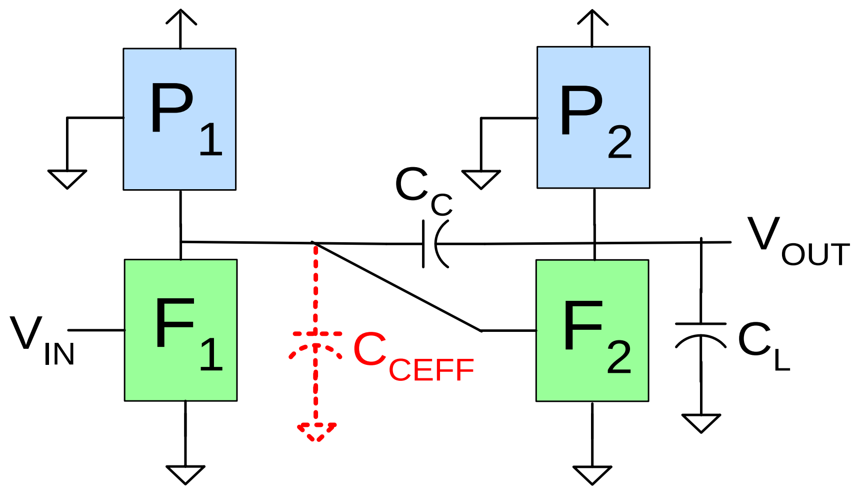
The second stage amplifier can be used to create a Miller capacitance at its input with no circuit overhead!

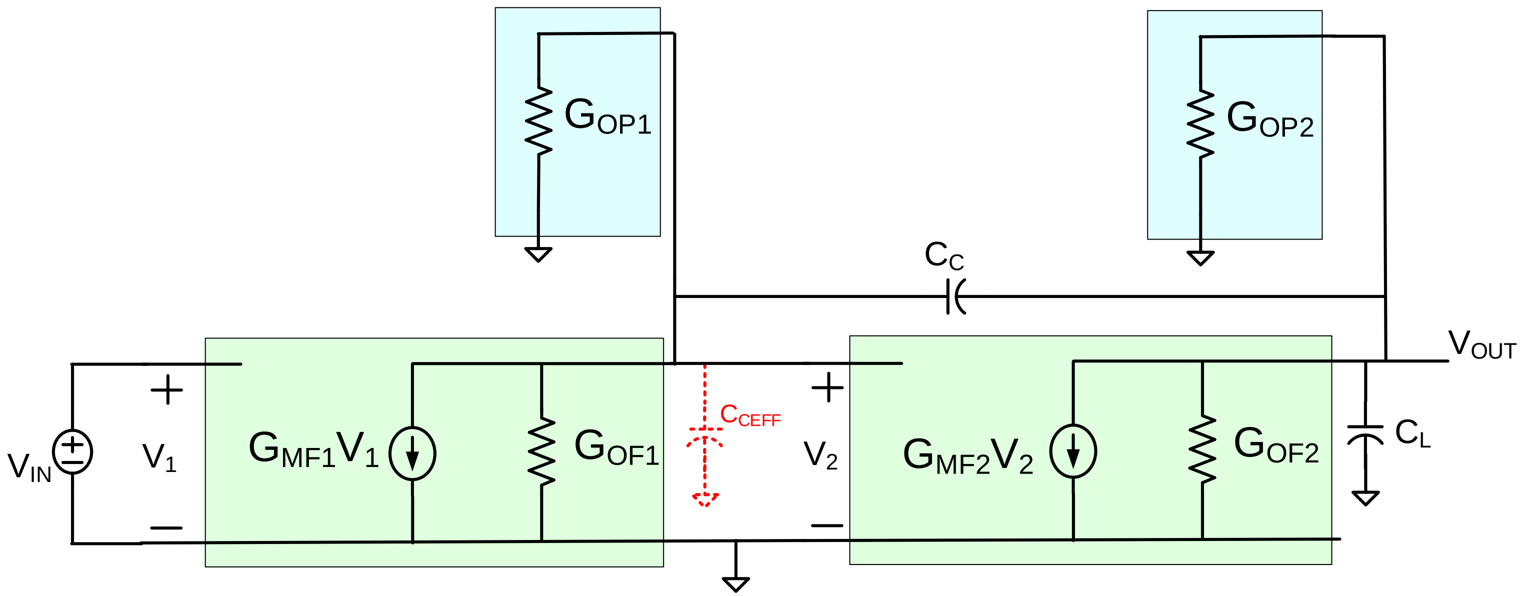
Compensation capacitance reduced by approximately the gain of the second stage! (the value of the two C_C's are not the same)

Since the gain of the second stage is not constant, however, a new analysis is needed

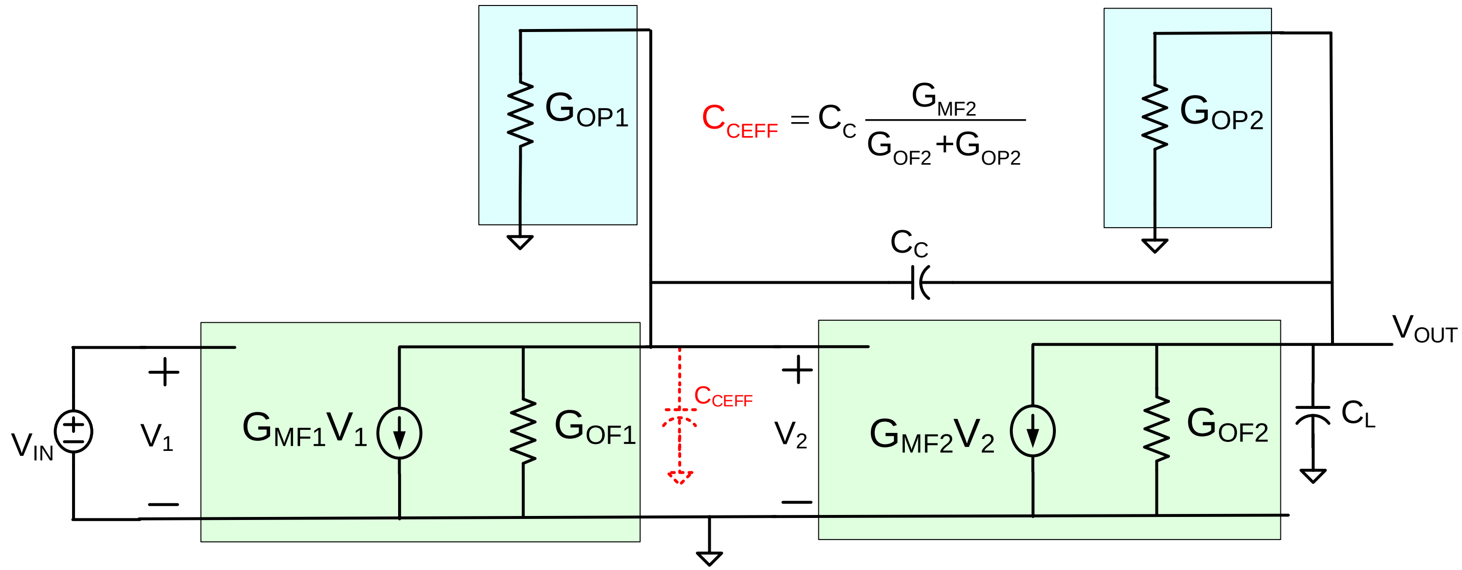
If C_C is small enough, this can become an internally compensated op amp with internal-node compensation

Intuitive Pole Analysis of Internally Miller-Compensated Two-Stage Op Amps





Intuitive Pole Analysis of Internally Miller-Compensated Two-Stage Op Amps



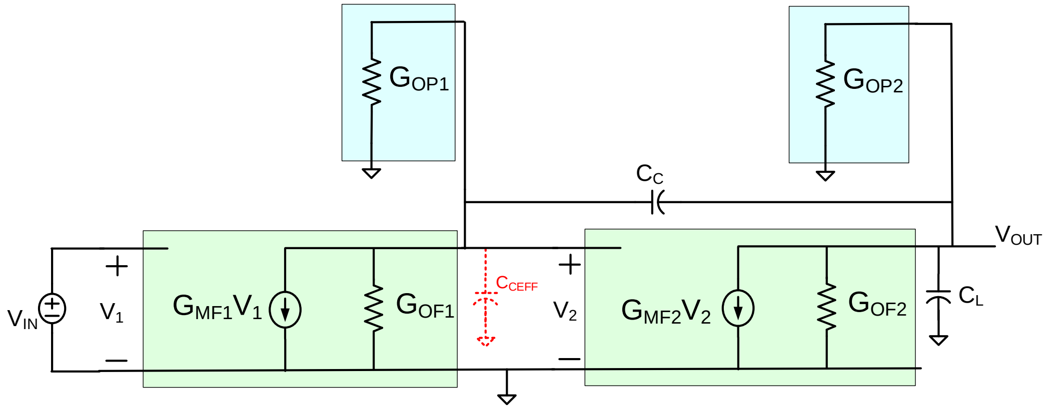
$$A_{V0} = \left(\frac{G_{MF1}}{G_{OF1}+G_{OP1}}\right)\left(\frac{G_{MF2}}{G_{OF2}+G_{OP2}}\right)$$

$$|p_1| = \frac{(G_{OF1}+G_{OP1})}{C_C} \quad \longrightarrow \quad |p_1| = \frac{G_{OF1}+G_{OP1}}{C_{CEFF}} = (G_{OF1}+G_{OP1})\left(\frac{G_{OF2}+G_{OP2}}{C_C\, G_{MF2}}\right)$$

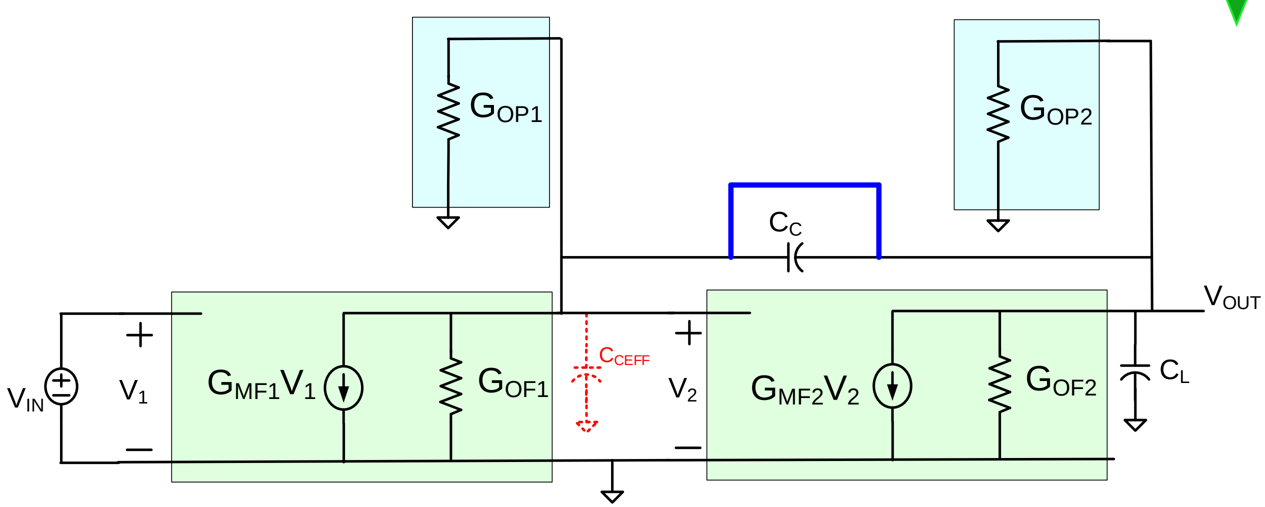
$$\mathbf{BW} = |\mathbf{p_1}|$$

(Intuitive Analysis based upon C_{CEFF} capacitance assumption)

Intuitive Pole Analysis of Internally Miller-Compensated Two-Stage Op Amps



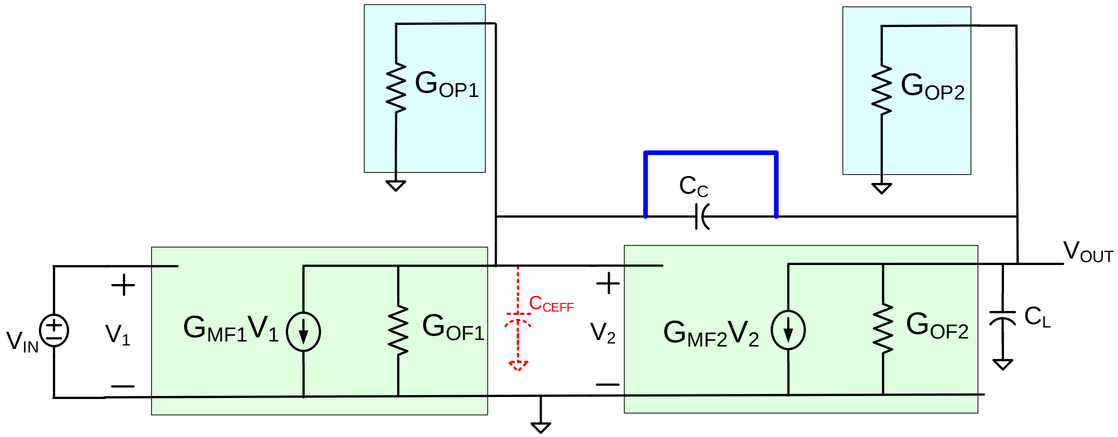
- To find the high-frequency pole p_2, the circuit has changed
- At high frequencies C_C looks like a short circuit
- Define G_2 to be conductance facing C_L for pole analysis



Note the F2 block is now "diode connected" at high frequencies

$$G_2 = G_{OP1} + G_{OF1} + G_{OP2} + G_{OF2} + G_{MF2} \simeq G_{MF2}$$

Intuitive Pole Analysis of Internally Miller-Compensated Two-Stage Op Amps



$$C_{CEFF} = C_C \frac{G_{MF2}}{G_{OF2}+G_{OP2}}$$

$$G_2 \simeq G_{MF2}$$

$$|p_2| = \frac{(G_{OF2}+G_{OP2})}{C_L} \quad \Longrightarrow \quad |p_2| = \frac{G_{MF2}}{C_L}$$

Will be shown later that C_C introduces a zero in the gain function

$$A_{V0} = \left(\frac{G_{MF1}}{G_{OF1}+G_{OP1}}\right)\left(\frac{G_{MF2}}{G_{OF2}+G_{OP2}}\right)$$

$$BW = (G_{OF1}+G_{OP1})\left(\frac{G_{OF2}+G_{OP2}}{C_C\ G_{MF2}}\right) = \frac{G_{OF1}+G_{OP1}}{C_{CEFF}}$$

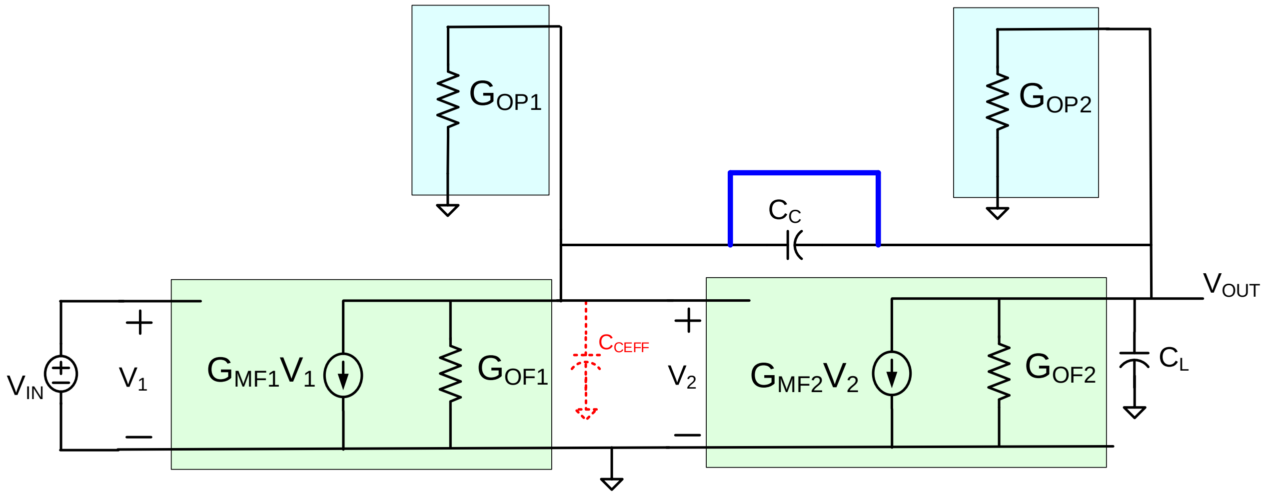
$$GB = \frac{G_{MF1}G_{MF2}}{(G_{OF2}+G_{OP2})C_C}$$

If zero does not affect GB

$$GB = \frac{G_{MF1}}{C_C}$$

$$A(s) \simeq \frac{\left(\frac{s}{z_1}+1\right)G_{MF1}G_{MF2}}{s^2C_CC_L + sC_CG_{MF2} + (G_{OF1}+G_{OP1})(G_{OF2}+G_{OP2})}$$

Intuitive Pole Analysis of Internally Miller-Compensated Two-Stage Op Amps



$$|p_2| = \frac{(G_{OF2}+G_{OP2})}{C_L} \quad \Rightarrow \quad |p_2| = \frac{G_{MF2}}{C_L}$$

$|p_2|$ has increased !

$$A_{V0} = \left(\frac{G_{MF1}}{G_{OF1}+G_{OP1}}\right)\left(\frac{G_{MF2}}{G_{OF2}+G_{OP2}}\right)$$

$$BW = (G_{OF1}+G_{OP1})\left(\frac{G_{OF2}+G_{OP2}}{C_C\ G_{MF2}}\right) = \frac{G_{OF1}+G_{OP1}}{C_{EFF}}$$

$$GB = \frac{G_{MF1}G_{MF2}}{(G_{OF2}+G_{OP2})C_C}$$

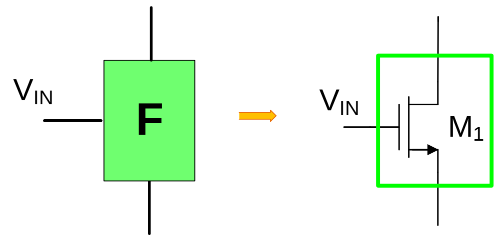
If zero does not affect GB

$$\Rightarrow \quad GB = \frac{G_{MF1}}{C_C}$$

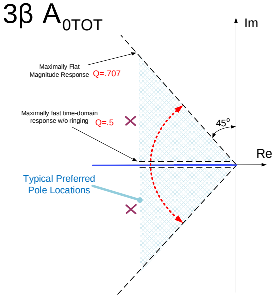
Has the GB decreased with the Miller compensation?

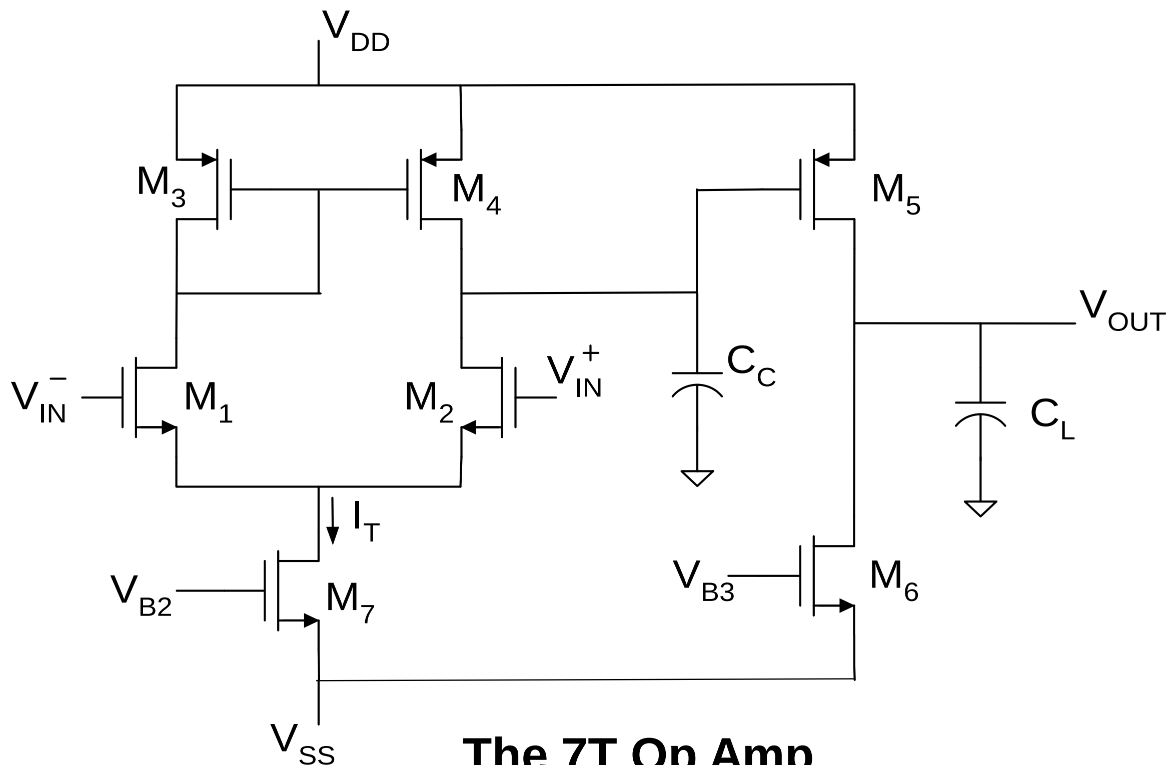
No, because the C_C decreased by the same factor!

Basic Two-Stage Op Amp



$k \cong 3\beta A_{0TOT}$



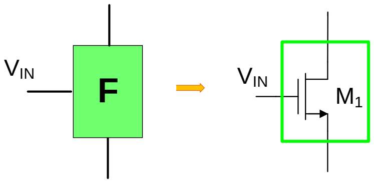


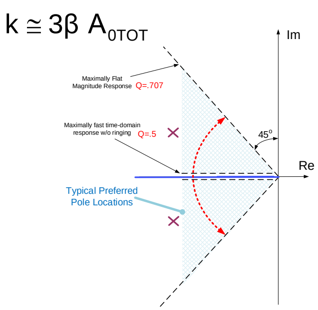
The 7T Op Amp

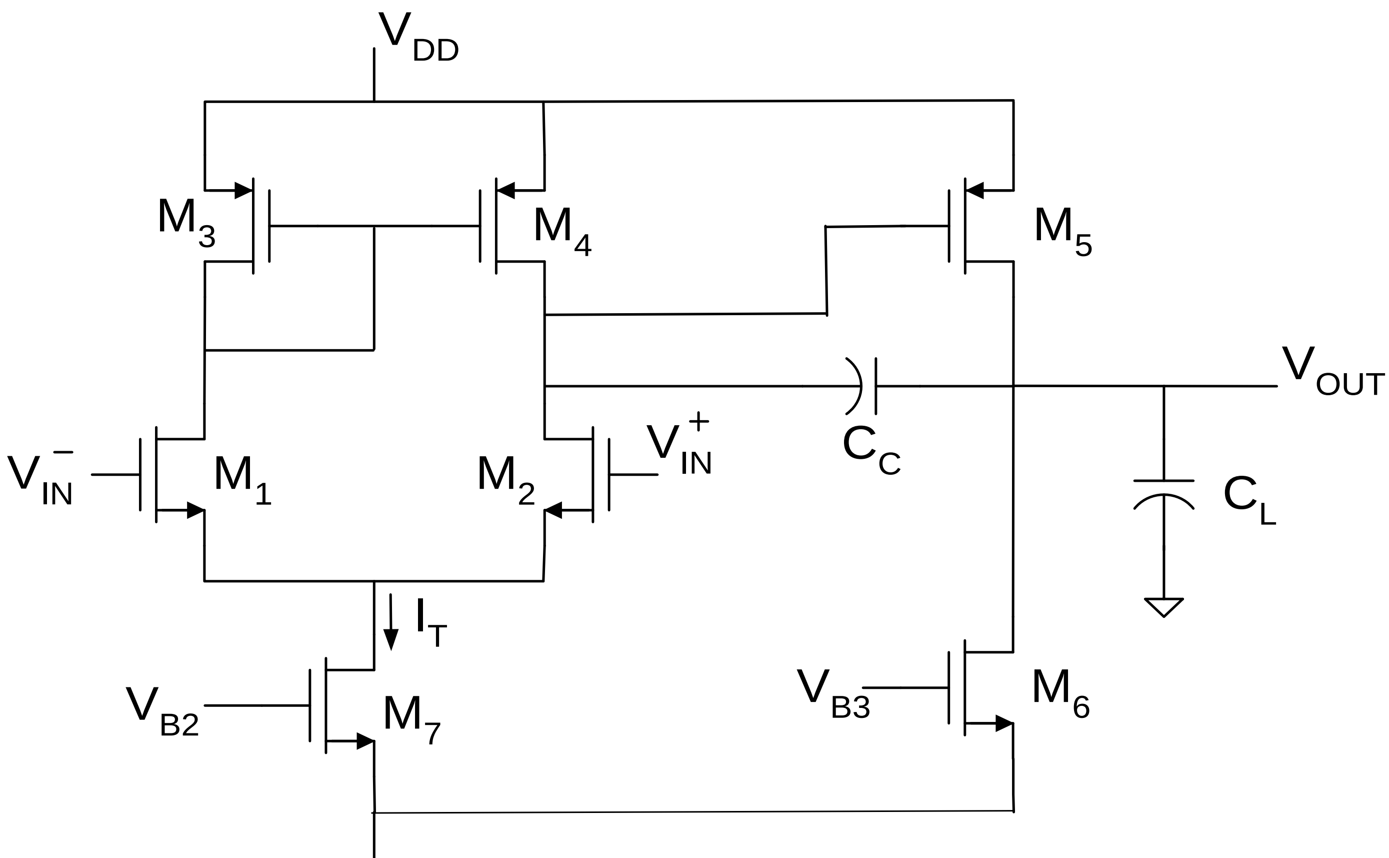
- Essentially just a cascade of two common-source stages
- Same gain and pole expressions as developed for the cascade
- Compensation Capacitor C_C used to get wide pole separation
- Two poles in amplifier
- No universally accepted strategy for designing this seemingly simple amplifier

Pole spread $\cong 3\beta A_{01} A_{02}$ makes C_C unacceptably large

Basic Two-Stage Op Amp (with Miller Compensation)



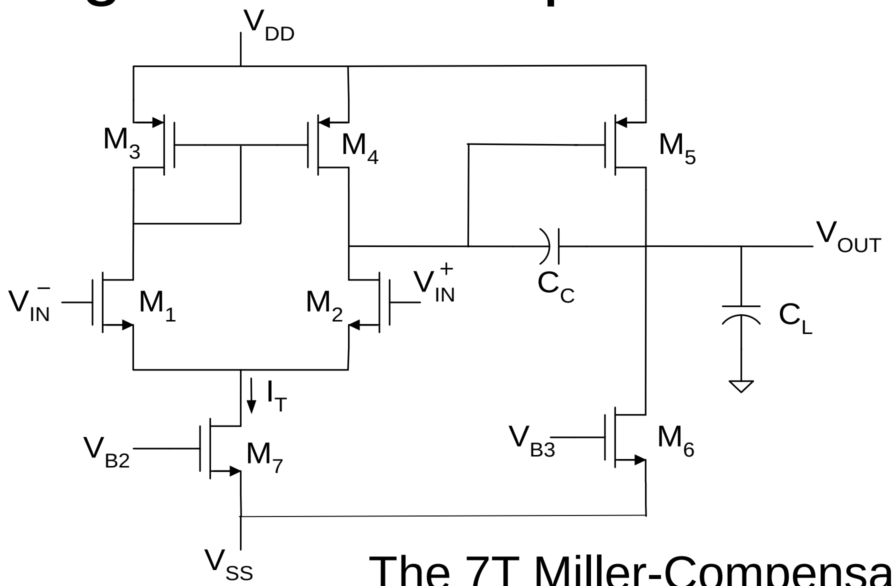




The 7T Miller-Compensated Op Amp

- o Reduces C_C by approximately A_{02}
- o Pole spread $\simeq 3\,\beta A_{01}A_{02}$ makes size of C_C manageable
- o One of the most widely used op amp architectures

Basic Two-Stage Miller Compensated Op Amp



The 7T Miller-Compensated Op Amp

By inspection (Notation: $p_1 = -\tilde{p}_1$ $p_2 = -\tilde{p}_2$)

$$\mathbf{A_o} = \left(\frac{-\mathbf{g_{m1}}}{\mathbf{g_{o2}} + \mathbf{g_{o4}}}\right)\left(\frac{\mathbf{g_{m5}}}{\mathbf{g_{o5}} + \mathbf{g_{o6}}}\right)$$

$$\tilde{p}_2 = \frac{g_{m5}}{C_L}$$

$$\tilde{p}_1 = \frac{g_{o2} + g_{o4}}{C_C\left(\frac{g_{m5}}{g_{05} + g_{o6}}\right)}$$

If zero does not affect GB

$$\mathbf{GB} = \frac{\mathbf{g_{m1}}}{\mathbf{C_C}}$$

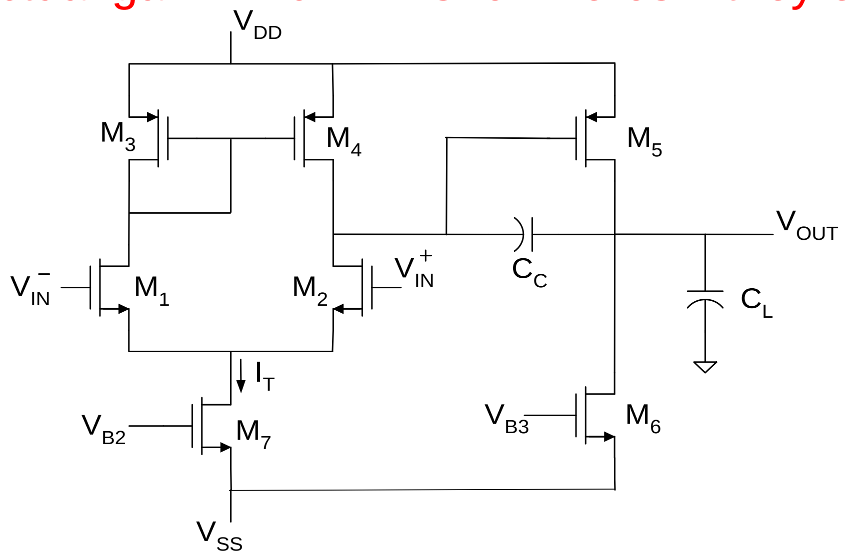
Will also get these results from a more complete (and time consuming) analysis

This analysis was based only upon finding the poles and <u>will miss zeros if they exist</u>

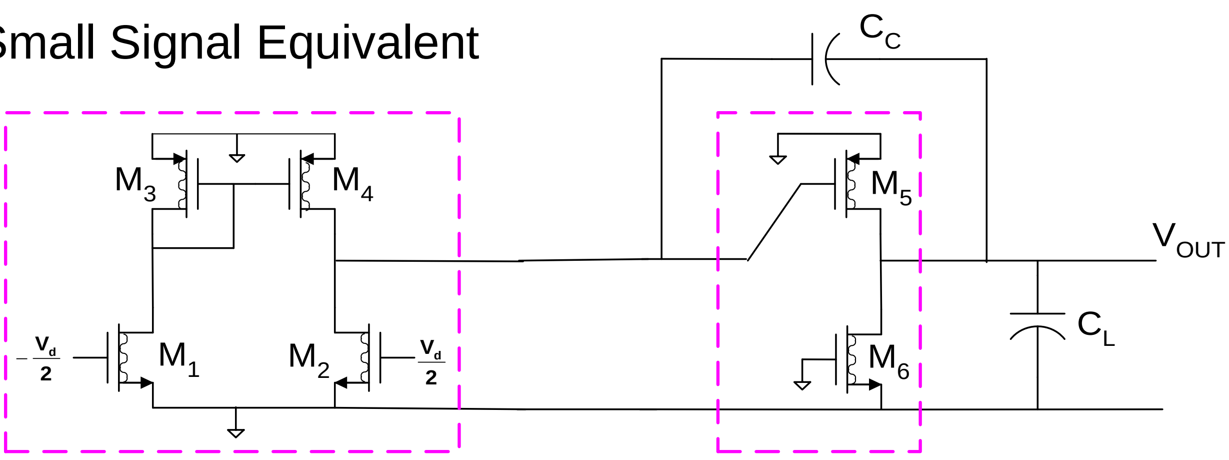
Small Signal Analysis of Basic Two-Stage Op Amp

(Will now obtain the actual gain which will show zeros if they exist)

(with Miller compensation)



Differential Small Signal Equivalent



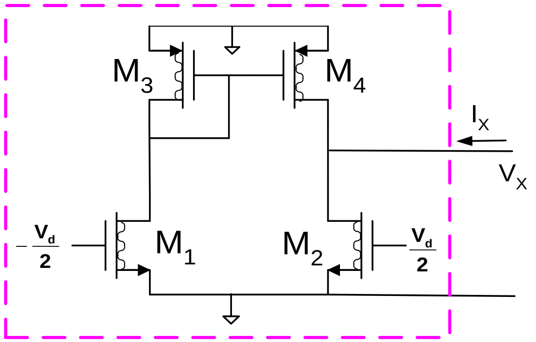
Norton Equivalent One-Port

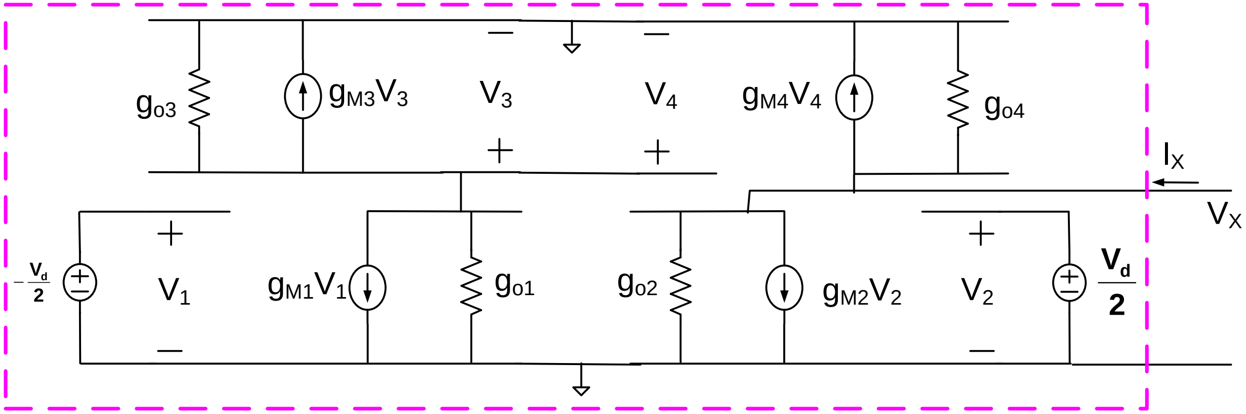
Two-Port

Small Signal Analysis of Basic Two-Stage Op Amp

(with Miller compensation)

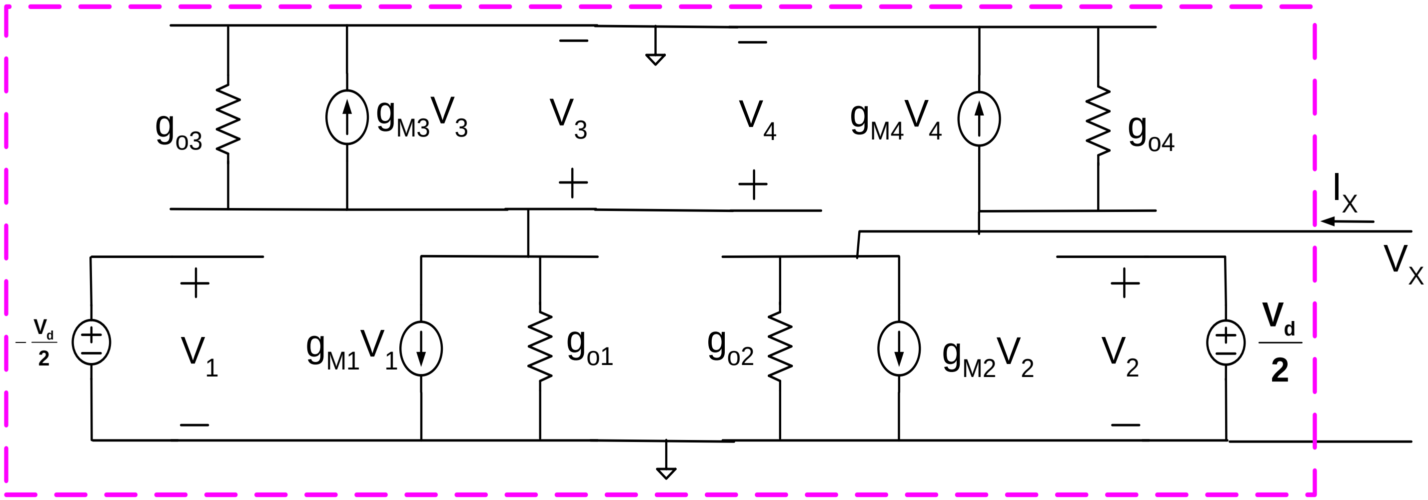
Differential Small Signal Equivalent





Small Signal Analysis of Basic Two-Stage Op Amp
(with Miller compensation)

Differential Small Signal Equivalent



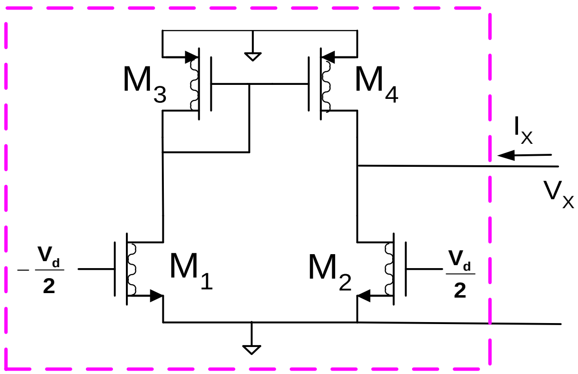
$$\left.\begin{aligned} I_X &= V_X(g_{o2}+g_{o4}) + g_{m2}\frac{V_d}{2} + g_{m4}V_4 \\ V_4&(g_{m3}+g_{o1}+g_{o3}) + g_{m1}\left(-\frac{V_d}{2}\right) = 0 \end{aligned}\right\}$$

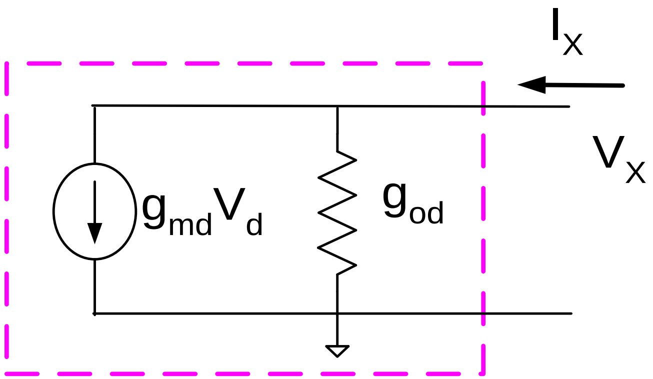
$$I_X = V_X(g_{o2}+g_{04}) + g_{m2}V_d\left(\frac{1+\frac{g_{m1}}{g_{m2}}\left(\frac{g_{m4}}{g_{m3}+g_{o2}+g_{o3}}\right)}{2}\right)$$

$$I_X \cong V_X(g_{o2}+g_{04}) + g_{m2}V_d$$

Small Signal Analysis of Basic Two-Stage Op Amp
(with Miller compensation)

Differential Small Signal Equivalent





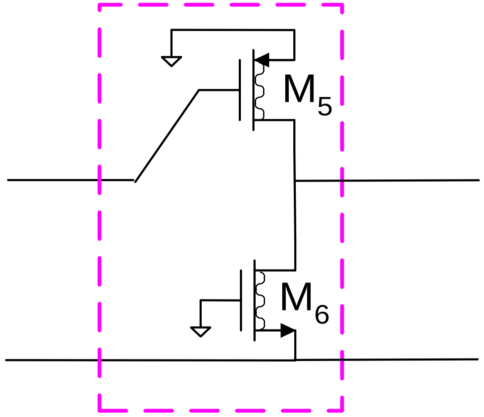
$$I_X \cong V_X\left(g_{o2}+g_{o4}\right)+g_{m2}V_d$$

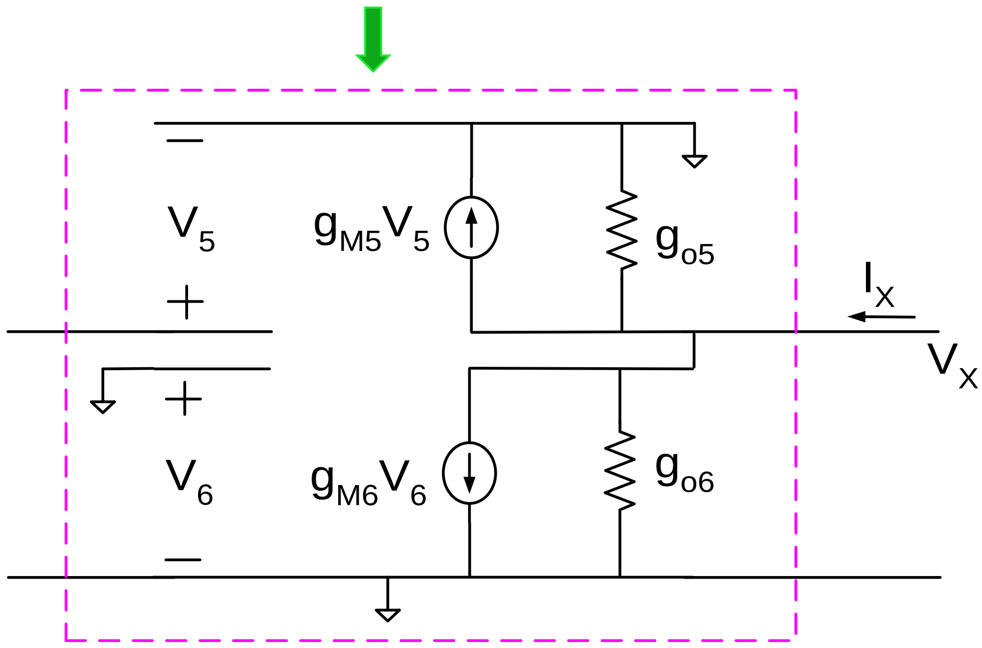
Since M_1 and M_2 are matched as are M_3 and M_4

$g_{md}=g_{m1}$
$g_{od}=g_{02}+g_{04}$

Small Signal Analysis of Basic Two-Stage Op Amp
(with Miller compensation)

Differential Small Signal Equivalent





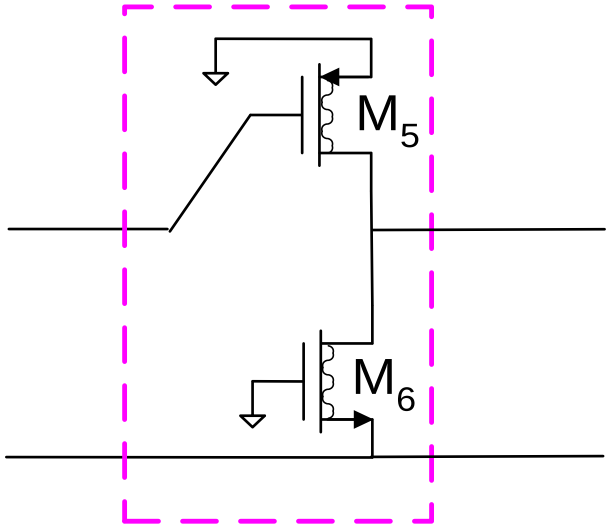
$g_{oo}=g_{o5}+g_{06}$

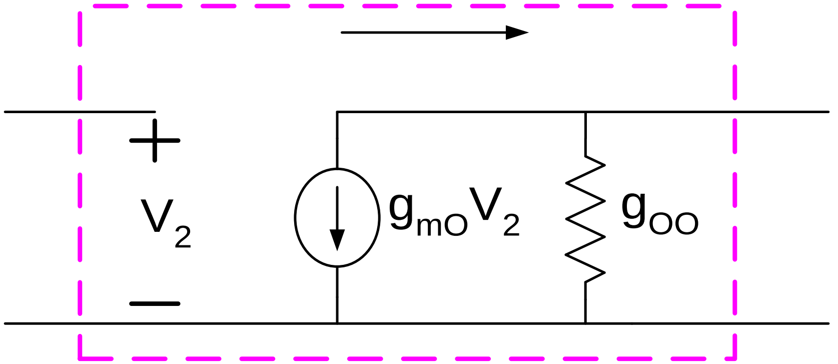
$g_{mo}=g_{m5}$

Small Signal Analysis of Basic Two-Stage Op Amp

(with Miller compensation)

Differential Small Signal Equivalent

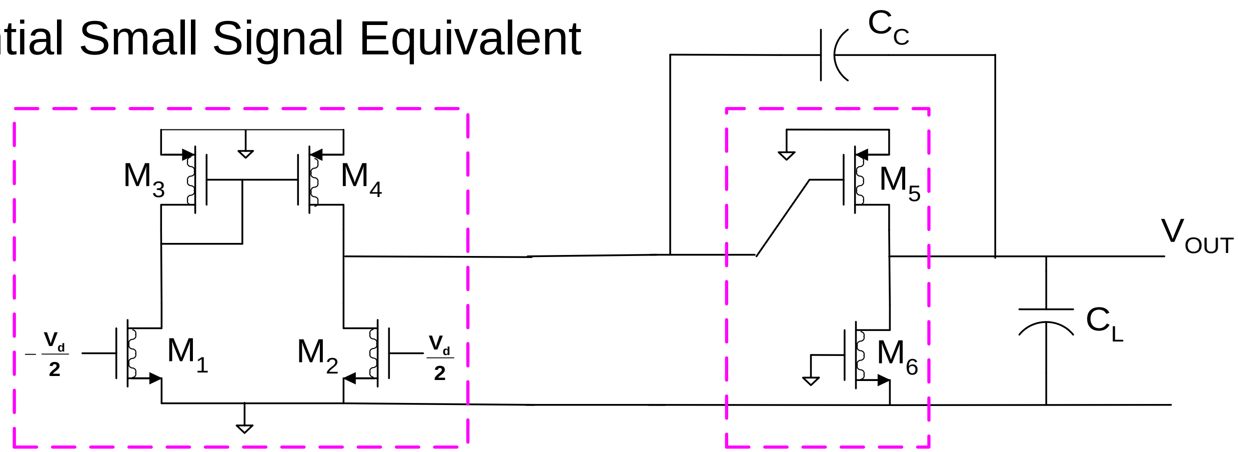


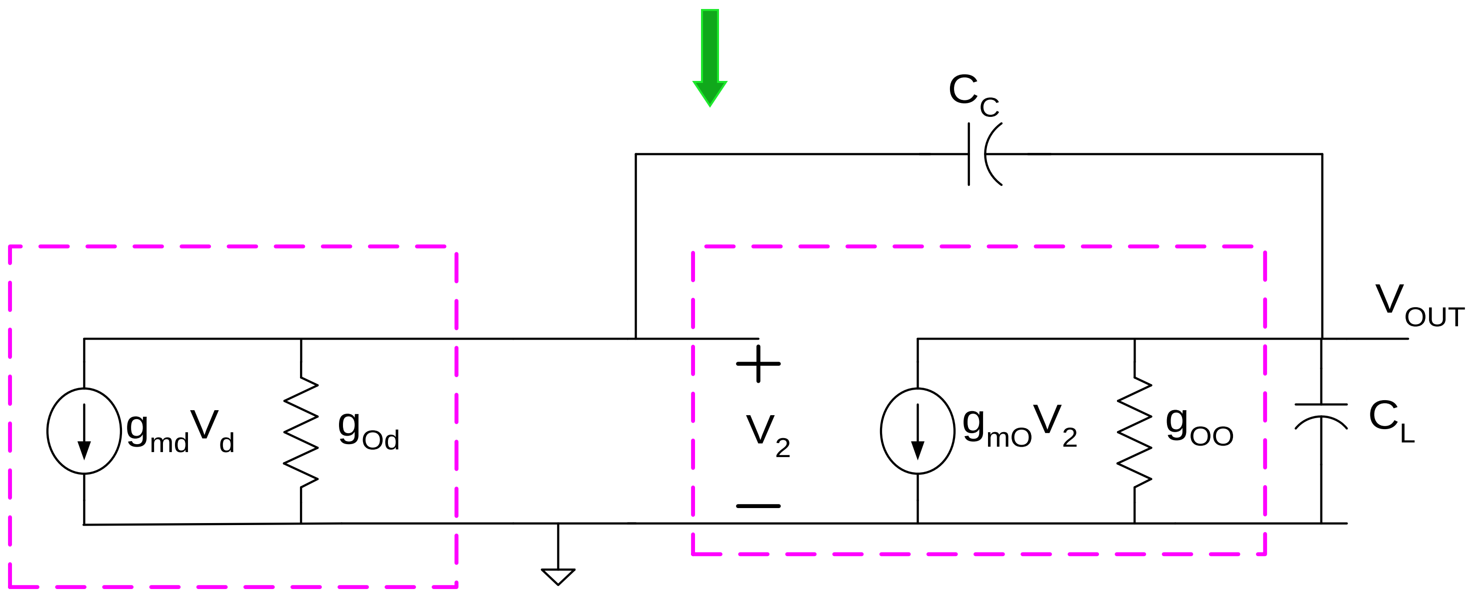


Small Signal Analysis of Basic Two-Stage Op Amp

(with Miller compensation)

Differential Small Signal Equivalent



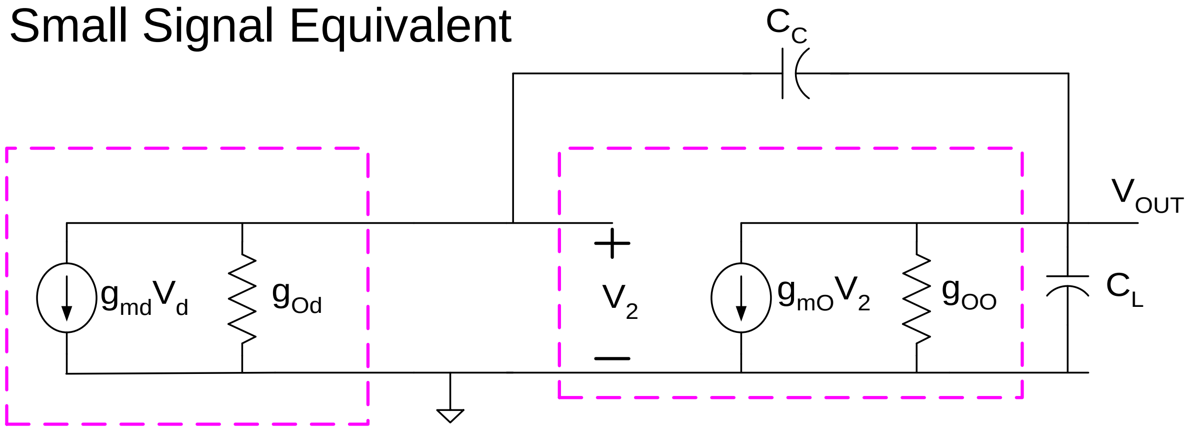


(This happens to be the general form for a two-stage structure with a quarter circuit and counterpart circuit !)

Small Signal Analysis of Basic Two-Stage Op Amp

(with Miller compensation)

Differential Small Signal Equivalent



$$\left.\begin{aligned} V_{OUT}\left(sC_C + sC_L + g_{oo}\right) + g_{mo}V_2 &= sC_C V_2 \\ V_2\left(sC_C + g_{od}\right) + g_{md}V_d &= sC_C V_{OUT} \end{aligned}\right\}$$

Solving we obtain:

$$V_{OUT} = V_d \frac{g_{md}\left(g_{mo} - sC_C\right)}{s^2 C_C C_L + s\left[g_{mo}C_C + \left(C_C\left(g_{oo} + g_{od}\right) + C_L g_{od}\right)\right] + g_{oo}g_{od}}$$

This simplifies to:

$$V_{OUT} \cong V_d \frac{g_{md}\left(g_{mo} - sC_C\right)}{s^2 C_C C_L + s g_{mo} C_C + g_{oo}g_{od}}$$

(This happens to be the general form for a two-stage structure with a quarter circuit and counterpart circuit !)

Small Signal Analysis of Basic Two-Stage Op Amp

(with Miller compensation)

Differential Small Signal Equivalent

Summary:

$$A(s)=\frac{g_{md}\left(g_{mo}-sC_C\right)}{s^2C_CC_L+sg_{mo}C_C+g_{oo}g_{od}}$$

where for the 7T implementation

$$\mathbf{g_{md}=g_{m1}=g_{m2}}$$

$$g_{mo}=g_{m5}$$

$$\mathbf{g_{od}=g_{o2}+g_{o4}}$$

$$\mathbf{g_{oo}=g_{o5}+g_{o6}}$$

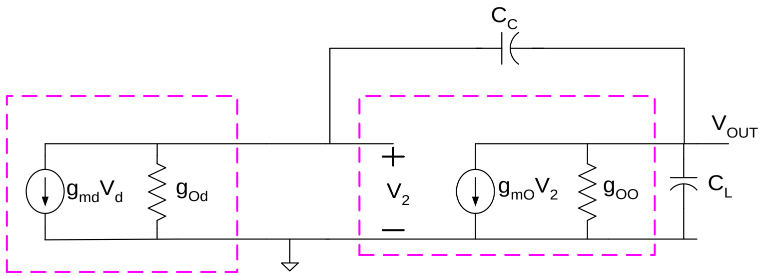
Note presence of single RHP zero!

How does this compare to the intuitive approximate analysis that obtained only the poles?

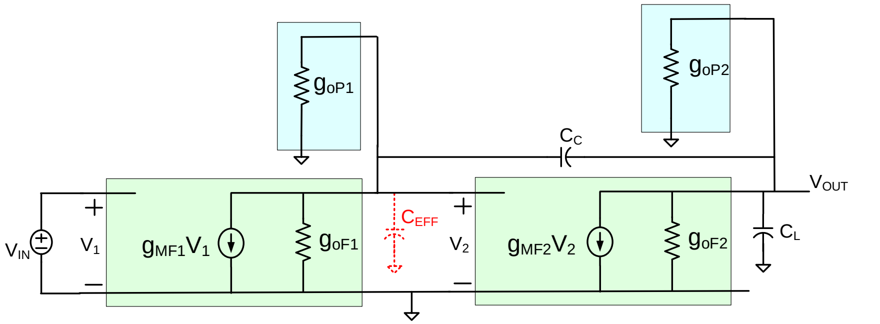
Small Signal Analysis of Basic Two-Stage Op Amp

(with Miller compensation)

Detailed analysis



Inspection Analysis



$$A(s) = \frac{g_{md}(g_{mo} - sC_C)}{s^2C_CC_L + sg_{mo}C_C + g_{oo}g_{od}}$$

$$A(s) \simeq \frac{\left(\frac{s}{\tilde{z}_1} + 1\right) g_{mF1}g_{mF2}}{s^2C_CC_L + sC_Cg_{mF2} + (g_{0F1} + g_{0P1})(g_{0F2} + g_{0P2})}$$

$$z_1 = \frac{g_{mo}}{C_C}$$

$$g_{md} = g_{mF1}$$

$$g_{m0} = g_{mF2}$$

$$g_{od} = g_{oF1} + g_{oP1}$$

$$g_{oo} = g_{oF2} + g_{oP2}$$

$$p_1 = -\frac{(g_{oF1} + g_{oP1})(g_{oF2} + g_{oP2})}{C_C\ g_{mF2}}$$

$$p_2 = -\frac{g_{mF2}}{C_L}$$

Same denominator so same poles and also same dc gain !

Small Signal Analysis of Two-Stage Miller-Compensated Op Amp

(with Miller compensation)

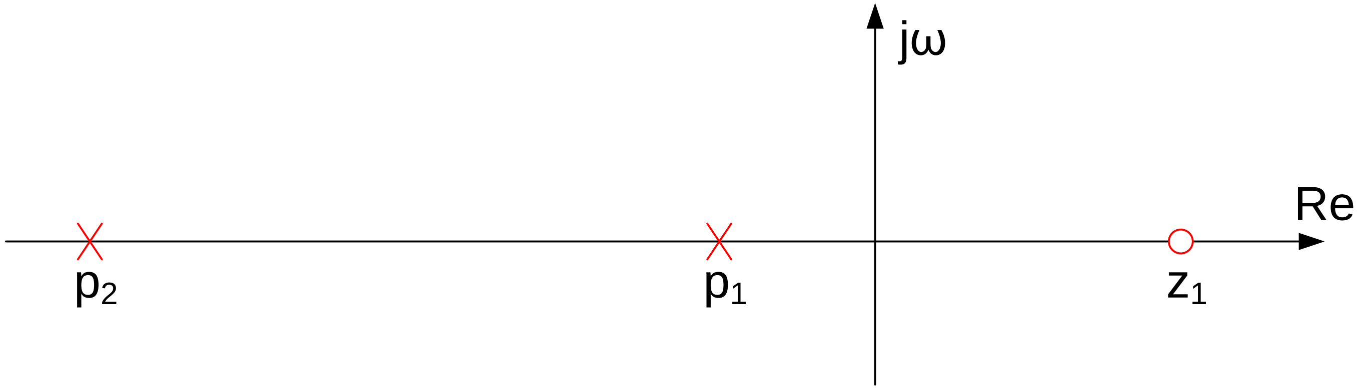
$$A(s) = \frac{g_{md}\left(g_{m0} - sC_C\right)}{s^2 C_C C_L + s g_{m0} C_C + g_{oo} g_{od}}$$

Note this is of the form:

(Notation: $p_1 = -\tilde{p}_1$ $p_2 = -\tilde{p}_2$ $z_1 = -\tilde{z}_1$)

$$A(s) = A_0 \frac{\dfrac{s}{\tilde{z}_1} + 1}{\left(\dfrac{s}{\tilde{p}_1} + 1\right)\left(\dfrac{s}{\tilde{p}_2} + 1\right)}$$

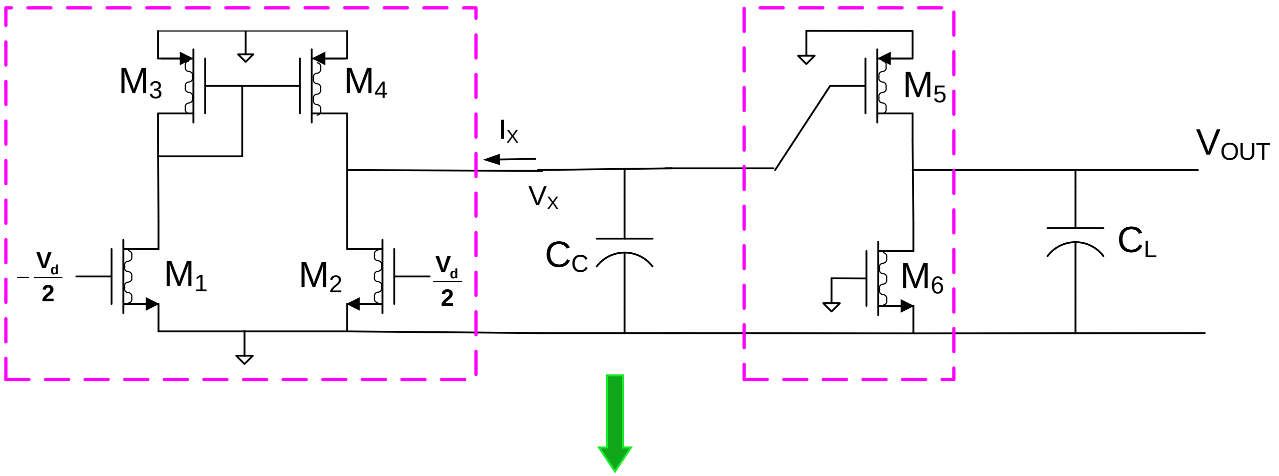
This has two negative real-axis poles and one positive real-axis zero

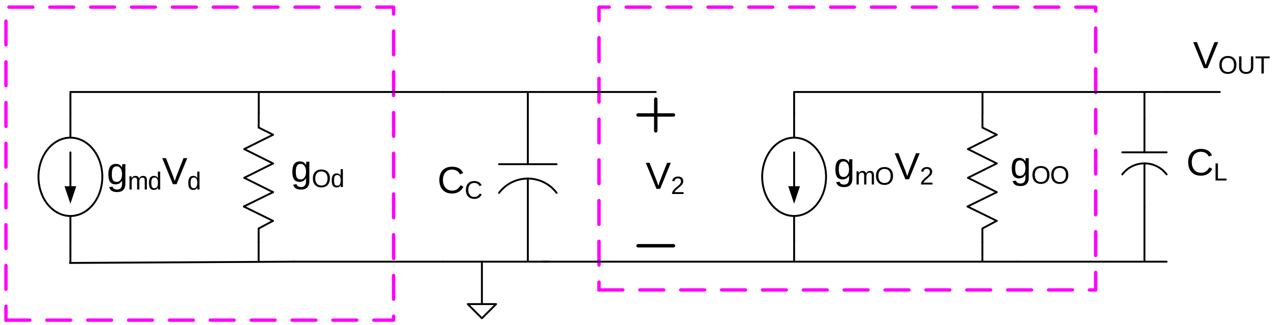


Small Signal Analysis of Basic Two-Stage Op Amp

(with Internal node compensation …. i.e. not Miller compensation)

Differential Small Signal Equivalent

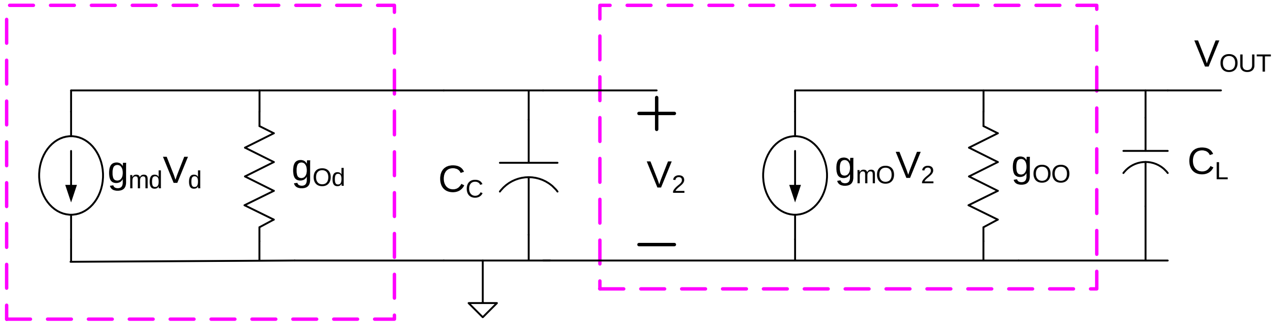




Small Signal Analysis of Basic Two-Stage Op Amp

(with Internal node compensation)

Differential Small Signal Equivalent



$$\left.\begin{aligned} V_{OUT}\left(sC_L+g_{00}\right)+g_{m0}V_2&=0\\ V_2\left(sC_C+g_{0d}\right)+g_{md}V_d&=0\end{aligned}\right\}$$

Solving we obtain:

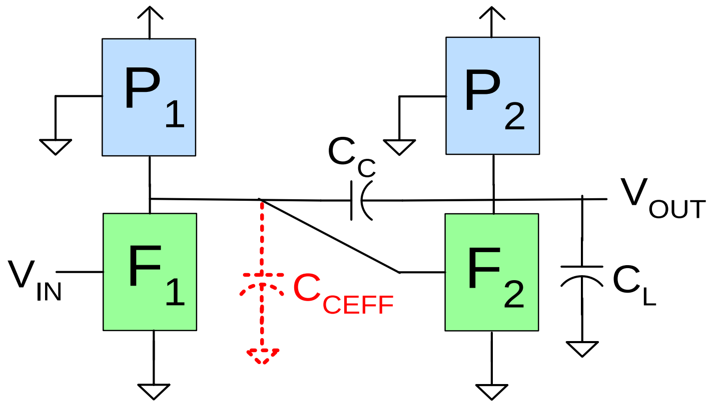
$$V_{OUT}=V_d\frac{g_{m0}g_{md}}{\left(sC_L+g_{00}\right)\left(sC_C+g_{0d}\right)}$$

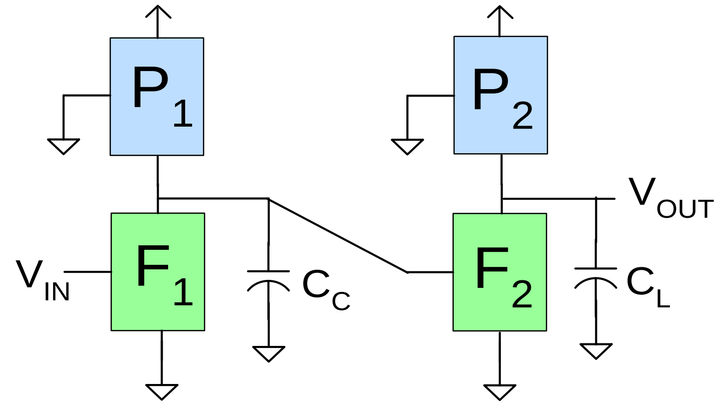
This can be approximated by :

$$V_{OUT}=V_d\frac{g_{m0}g_{md}}{s^2C_CC_L+sC_Cg_{00}+g_{00}g_{0d}}$$

Can show this is the same as was obtained by inspection !

How does the Gain of the Two-Stage Miller-Compensated Op Amp Compare with Internal Compensated Op Amp?



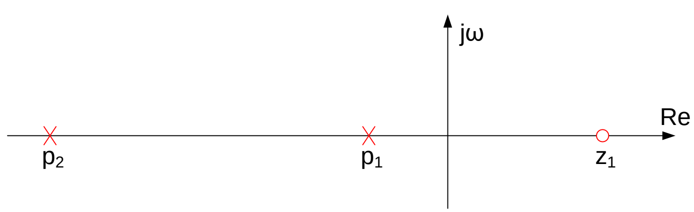


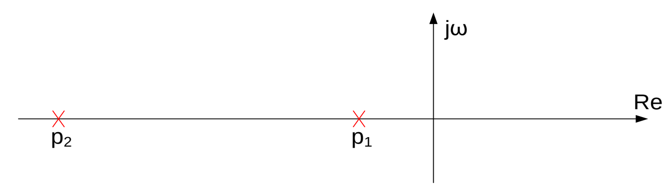
$$A(s)=\frac{g_{md}\left(g_{m0}-sC_C\right)}{s^2C_CC_L+sg_{m0}C_C+g_{oo}g_{od}}$$

$$A(s)\cong\frac{g_{md}g_{m0}}{s^2C_CC_L+sC_Cg_{oo}+g_{oo}g_{od}}$$

$$A(s)=A_0\frac{\frac{s}{\tilde{z}_1}+1}{\left(\frac{s}{\tilde{p}_1}+1\right)\left(\frac{s}{\tilde{p}_2}+1\right)}$$

$$A(s)=A_0\frac{1}{\left(\frac{s}{\tilde{p}_1}+1\right)\left(\frac{s}{\tilde{p}_2}+1\right)}$$





Compensation criteria:

must be developed

$$4\beta\, A_0 > \frac{p_2}{p_1} > 2\beta\, A_0$$

Simple pole calculations for 2-stage op amp

Since the poles of the 2-stage op amp must be widely separated, a simple calculation of the poles from the characteristic polynomial is possible.

Assume p_1 and p_2 are the poles and $|p_1| << |p_2|$

$$D(s)=s^2+a_1s+a_0$$

determines p_1

but

$$D(s)=(s-p_1)(s-p_2)=s^2-s(p_1+p_2)+p_1p_2 \approx s^2 - p_2 s + p_1 p_2$$

thus

determines p_2

p_2=- a_1 and p_1 = - a_0/a_1

Example

A feedback amplifier has a characteristic polynomial of

$$D(s) = s^2 + 9000s + 1.8E3$$

Without using the quadratic equation, determine the poles by inspection and determine the ratio of the two poles.

solution

A feedback amplifier has a characteristic polynomial of

$$D(s) = s^2 + 9000s + 1.8E3$$

$$D(s) = \underbrace{s^2 + 9000s}_{P_h=-9000} + 1.8E3$$

$$D(s) = s^2 + \underbrace{9000s + 1.8E3}_{P_L=-2}$$

Ratio = 4500

Can now use these results to calculate poles of Basic Two-stage Miller Compensated Op Amp

From small signal analysis:

$$\mathbf{A(s)} = \frac{\mathbf{g_{md}\left(g_{m5} - sC_C\right)}}{\mathbf{s^2C_CC_L + sg_{m5}C_C + g_{oo}g_{od}}}$$

$$\mathbf{g_{md} = g_{m1} = g_{m2}}$$

$$\mathbf{g_{od} = g_{o2} + g_{o4}}$$

$$\mathbf{g_{oo} = g_{o5} + g_{o6}}$$

$$p_2 = -\frac{g_{m5}}{C_L}$$

$$p_1 = -\frac{g_{oo}g_{od}}{g_{m5}C_C}$$

$$A_0 = \frac{g_{m5}g_{md}}{g_{oo}g_{od}}$$

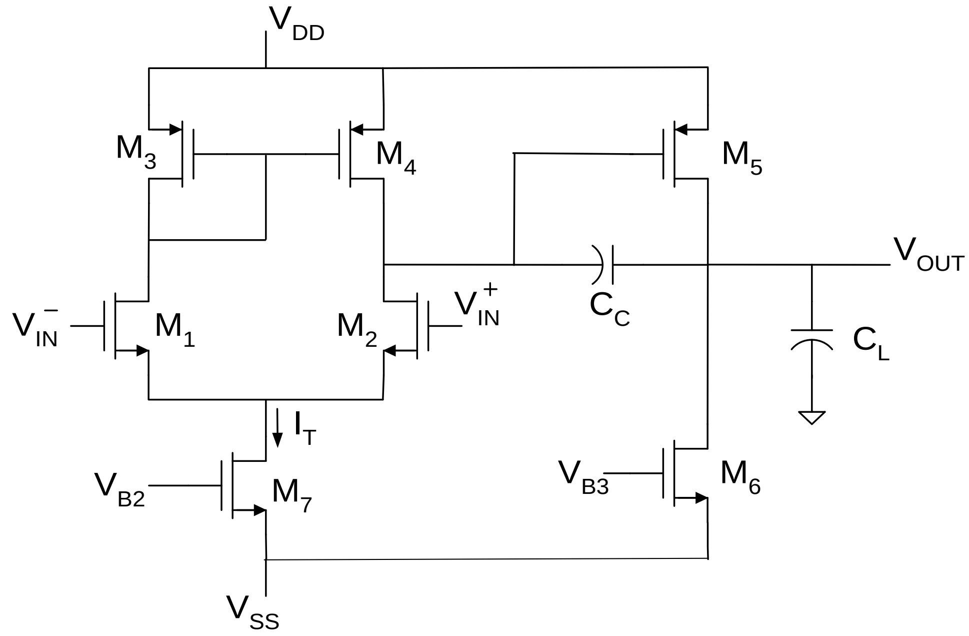
$$GB = \frac{g_{m5}g_{md}}{g_{oo}g_{od}} \bullet |p_1| = \frac{g_{m5}g_{md}}{g_{oo}g_{od}} \bullet \frac{g_{oo}g_{od}}{g_{m5}C_C} = \frac{g_{md}}{C_C}$$

From Previous Inspection

$$\mathbf{A_o} = \left(\frac{-\mathbf{g_{m1}}}{\mathbf{g_{o2}} + \mathbf{g_{o4}}}\right)\left(\frac{\mathbf{g_{m5}}}{\mathbf{g_{o5}} + \mathbf{g_{o6}}}\right)$$

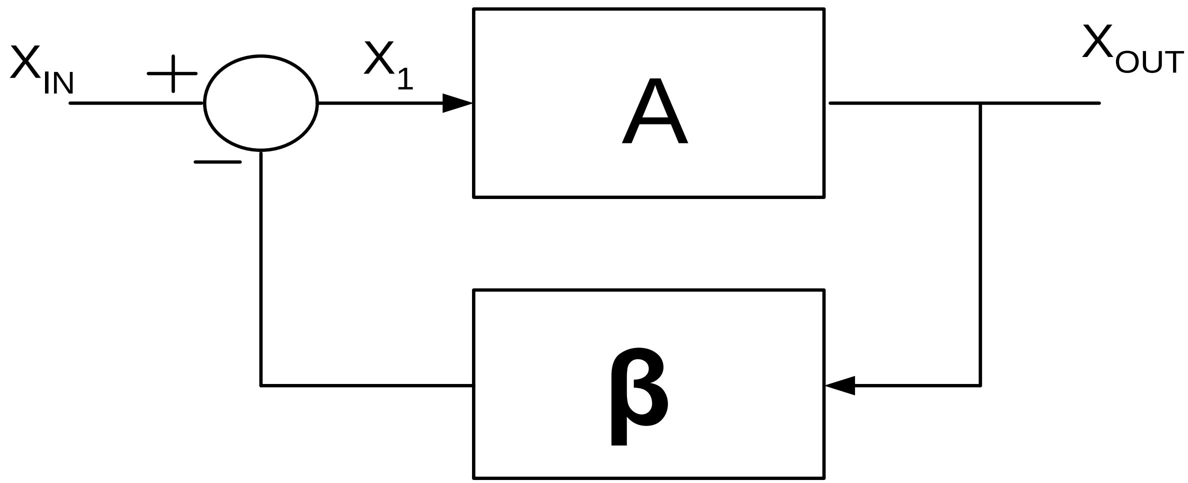
$$p_1 = -\frac{g_{o2} + g_{o4}}{C_C\left(\dfrac{g_{m5}}{g_{05} + g_{o6}}\right)} \qquad p_2 = -\frac{g_{m5}}{C_L}$$

$$\mathbf{GB} = \frac{\mathbf{g_{m1}}}{\mathbf{C_C}}$$



Note the simple results obtained from inspection agree with the more time consuming results obtained from a small signal analysis

Feedback applications of the two-stage Op Amp



How does the amplifier perform with feedback ?

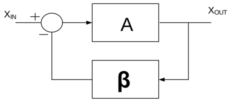
How should the amplifier be compensated?

Feedback applications of the two-stage Op Amp

Open-loop Gain

$$A(s)=\frac{N(s)}{D(s)}$$

<u>Standard</u> Feedback Gain



$$A_{FB}(s)=\frac{A(s)}{1+A(s)\beta(s)}=\frac{N(s)}{D(s)+N(s)\beta(s)}\overset{\text{defn}}{=}\frac{N_{FB}(s)}{D_{FB}(s)}$$

$$N_{FB}(s)=N(s)$$

$$D_{FB}(s)=D(s)+\beta(s)N(s)$$

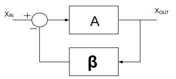
- Open-loop and closed-loop zeros identical (for standard feedback gain)
- Closed-loop poles different than open-loop poles
- Often β(s) is not dependent upon frequency
- Open-loop zeros, gain, and β play a key role in determining closed-loop poles

Feedback applications of the two-stage Op Amp

Open-loop Gain

$$A(s) = \frac{N(s)}{D(s)}$$

Standard Feedback Gain



$$A_{FB}(s) = \frac{A(s)}{1 + A(s)\beta(s)} = \frac{\frac{1}{\beta(s)}}{1 + \frac{1}{A(s)\,\beta(s)}}$$

Alternate Feedback Gain (often FB is not of "standard" form)

$$A_{FB}(s) = \frac{\frac{1}{\beta_1(s)}}{1 + \frac{1}{A(s)\,\beta(s)}} = \frac{\frac{\beta(s)}{\beta_1(s)} N(s)}{D(s) + N(s)\,\beta(s)}$$

In either case, denominators are the same and characteristic equation defined by

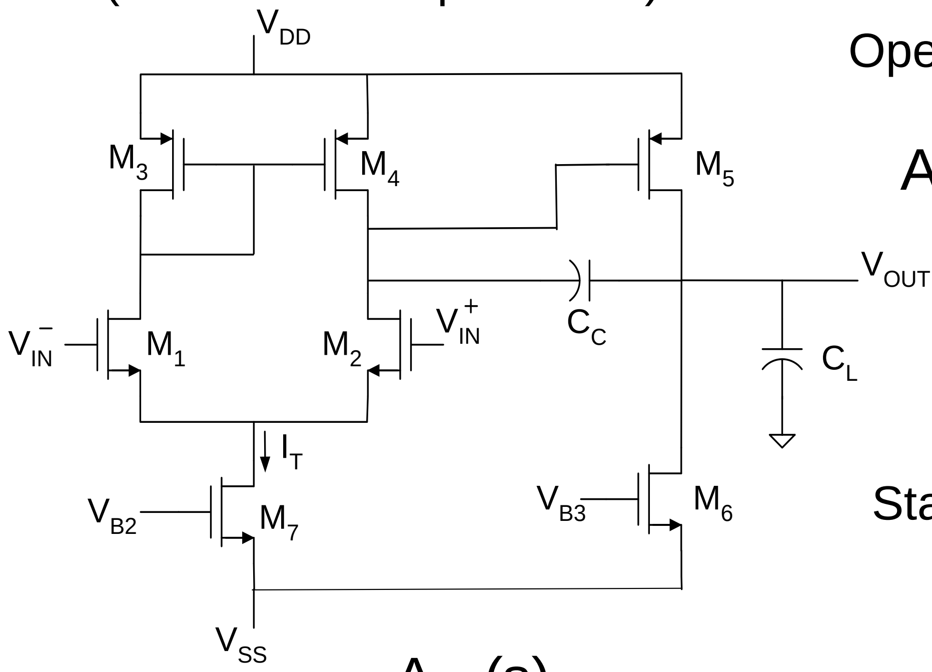
$$D_{FB}(s) = D(s) + \beta(s)N(s)$$

Often $\beta(s)$ and $\beta_1(s)$ are not dependent upon frequency and in this case

$$N_{FB}(s) = N(s)$$

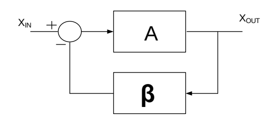
Basic Two-Stage Op Amp with Feedback

(with Miller compensation)



Open-loop gain

$$A(s)=\frac{g_{md}\left(g_{mo}-sC_c\right)}{s^2C_CC_L+sC_Cg_{mo}+g_{oo}g_{od}}$$



$$A_{FB}=\frac{A}{1+A\beta}$$

Standard feedback gain with constant β

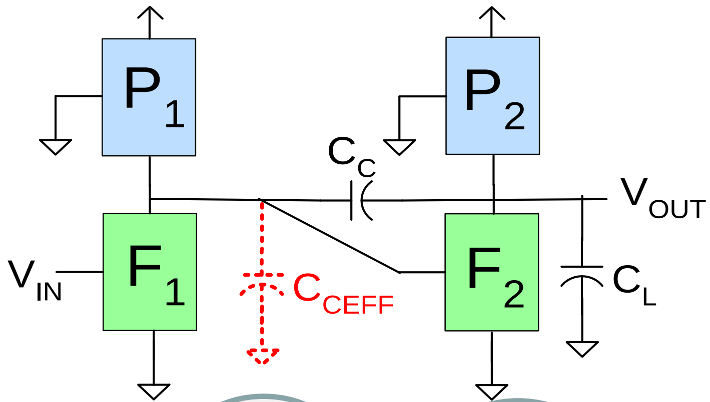
$$A_{FB}(s)=\frac{g_{md}\left(g_{mo}-sC_c\right)}{s^2C_CC_L+sC_C\left(g_{mo}-\beta g_{md}\right)+g_{oo}g_{od}+\beta g_{md}g_{mo}}$$

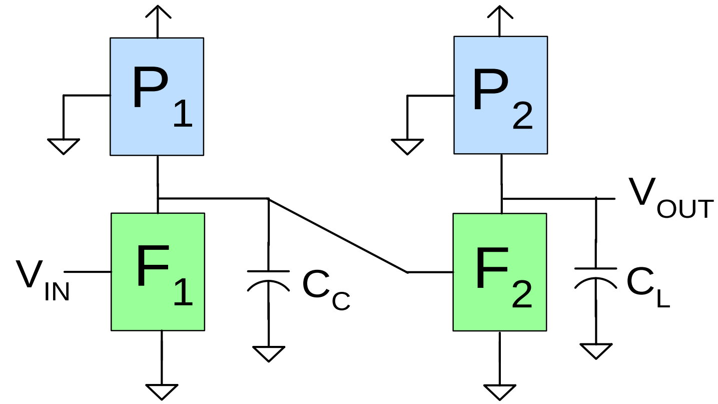
$$A_{FB}(s)\cong\frac{g_{md}\left(g_{m0}-sC_c\right)}{s^2C_CC_L+sC_C\left(g_{mo}-\beta g_{md}\right)+\beta g_{md}g_{mo}}$$

where $g_{md}=g_{m1}$ $\qquad g_{mo}=g_{m5}$

$g_{od}=g_{o2}+g_{o4}$ $\qquad g_{oo}=g_{o5}+g_{o6}$

How does the Gain of the Two-Stage Miller-Compensated Op Amp Compare with Internal Compensated Op Amp with feedback $A_{FB} = \dfrac{A}{1+A\beta}$?





$$A(s) = \frac{g_{md}(g_{m0} - sC_C)}{s^2 C_C C_L + s g_{m0} C_C + g_{oo} g_{od}}$$

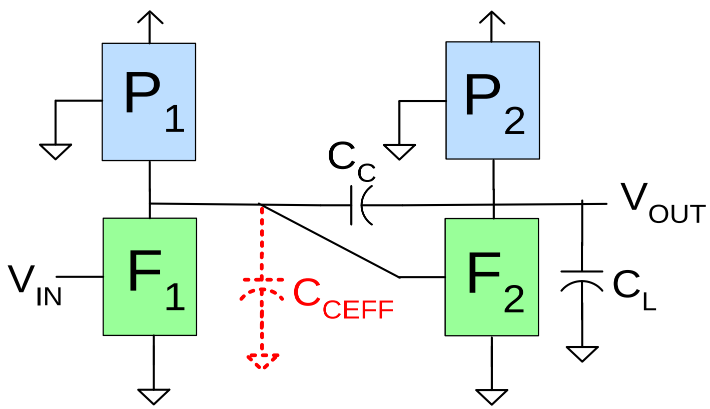
$$A(s) \cong \frac{g_{md} g_{m0}}{s^2 C_C C_L + s C_C g_{oo} + g_{oo} g_{od}}$$

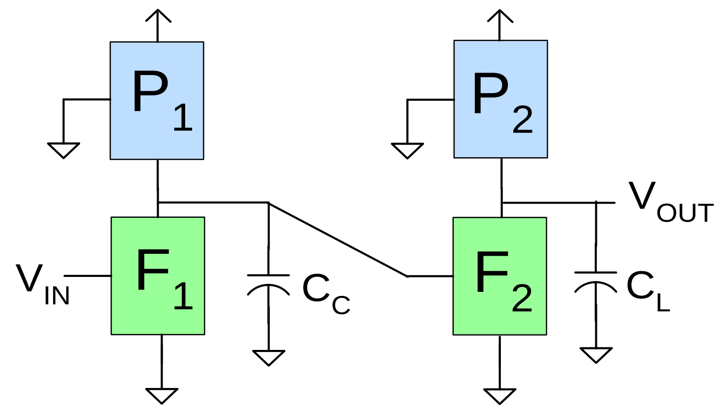
$$A_{FB}(s) \cong \frac{g_{md}(g_{m0} - sC_c)}{s^2 C_c C_L + sC_c(g_{m0} - \beta g_{md}) + \beta g_{md} g_{m0}}$$

$$A_{FB}(s) \cong \frac{g_{m0} g_{md}}{s^2 C_c C_L + sC_c g_{00} + \beta g_{m0} g_{md}}$$

Zero in open-loop gain introduces the $-\beta g_{md}$ term in FB configuration

How was compensation done before the work of Fullagar ?





$$A(s)=\frac{g_{md}(g_{m0}-sC_C)}{s^2C_CC_L+sg_{m0}C_C+g_{oo}g_{od}}$$

$$A(s)\cong\frac{g_{md}g_{m0}}{s^2C_CC_L+sC_Cg_{oo}+g_{oo}g_{od}}$$

$$A_{FB}(s)\cong\frac{g_{md}(g_{m0}-sC_c)}{s^2C_cC_L+sC_c(g_{m0}-\beta g_{md})+\beta g_{md}g_{m0}}$$

$$A_{FB}(s)\cong\frac{g_{m0}g_{md}}{s^2C_cC_L+sC_cg_{00}+\beta g_{m0}g_{md}}$$

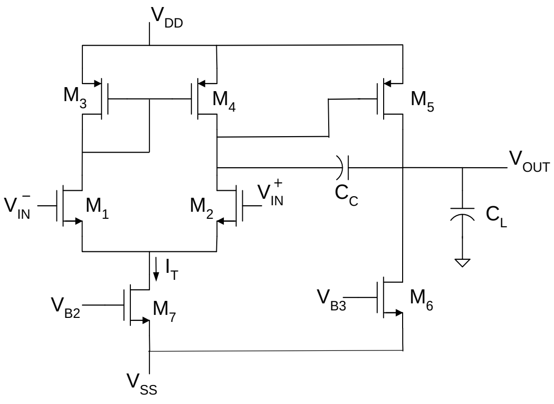
Internal node capacitor C_C or Miller C_C added externally

Or “load compensation” before output buffer added externally

Termed “externally compensated”

Basic Two-Stage Op Amp

(with Miller compensation) $A_{FB} = \dfrac{A}{1 + A\beta}$



$$A_{FB}(s) \cong \frac{g_{md}\left(g_{m0} - sC_c\right)}{s^2 C_C C_L + sC_C\left(g_{mo} - \beta g_{md}\right) + \beta g_{md} g_{mo}}$$

$$\text{Pole } Q = ?$$

Review of Basic Concepts

Consider a second-order factor of a denominator polynomial, P(s), expressed in integer-monic form

$$P(s)=s^2+a_1s+a_0$$

Then P(s) can be expressed in several alternative but equivalent ways

$$s^2+s\frac{\omega_0}{Q}+\omega_0^2$$

$$s^2+s2\zeta\omega_0+\omega_0^2$$

$$\left(s-p_1\right)\left(s-p_2\right)$$

and if complex conjugate poles,

$$\left(s+\alpha+j\beta\right)\left(s+\alpha-j\beta\right)$$

$$\left(s-re^{j\theta}\right)\left(s-re^{-j\theta}\right)$$

and if negative real-axis poles

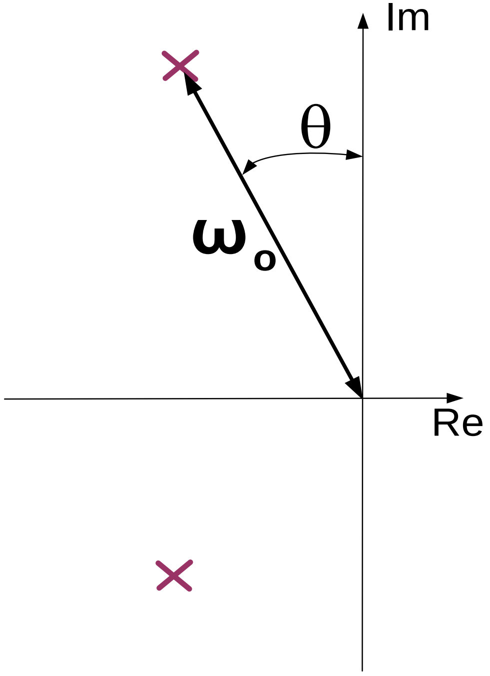
$$(s-p_1)(s-kp_1)$$

These are 7 different 2-paramater characterizations of the second-order factor and it is easy to map from any one characterization to any other !

$$\{a_1\ a_0\}\ \ \{\omega_0\ Q\}\ \ \{\omega_0\ \ \zeta\}\ \ \{p_1\ p_2\}\ \ \{\alpha\ \ \beta\}\ \ \{r\ \ \theta\}\ \ \{p_1\ \ k\}$$

Review of Basic Concepts

$$s^2 + s\frac{\omega_0}{Q} + \omega_0^2$$



$$\sin\theta = \frac{1}{2Q}$$

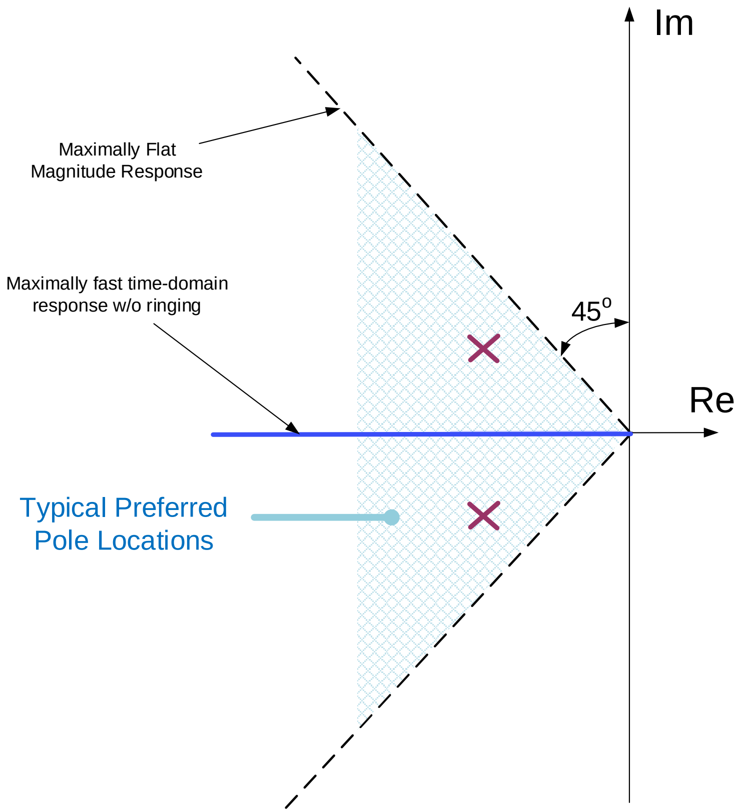
ω_o = magnitude of pole

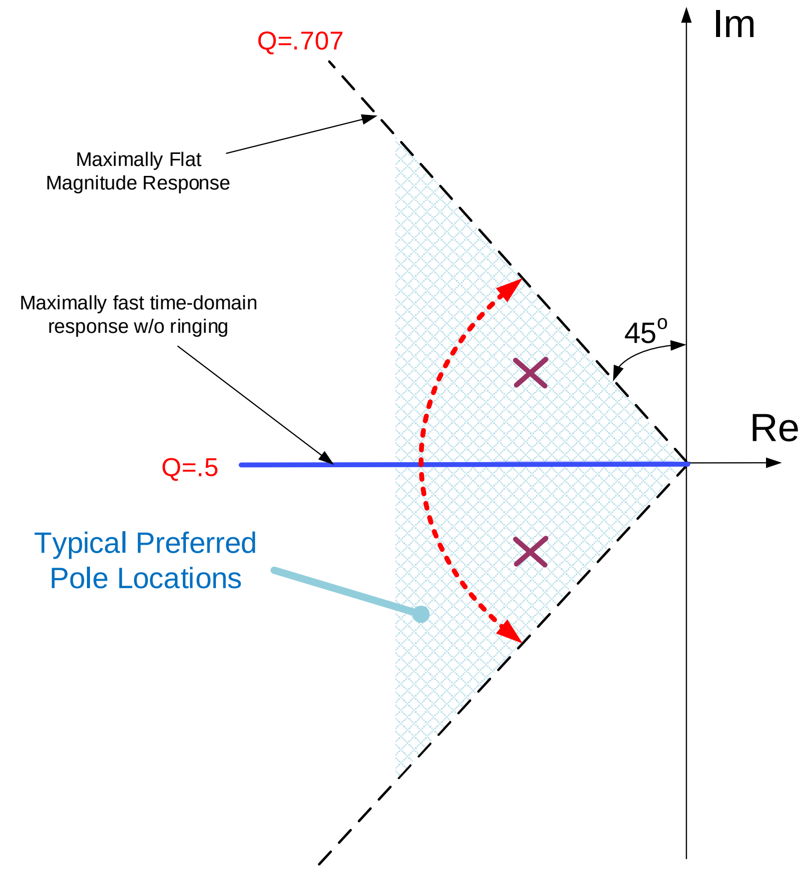
Q determines the angle of the pole

Observe: Q=0.5 corresponds to two identical real-axis poles

Q=.707 corresponds to poles making 45° angle with Im axis

What closed-loop pole Q is typically required when compensating an op amp?





Recall:

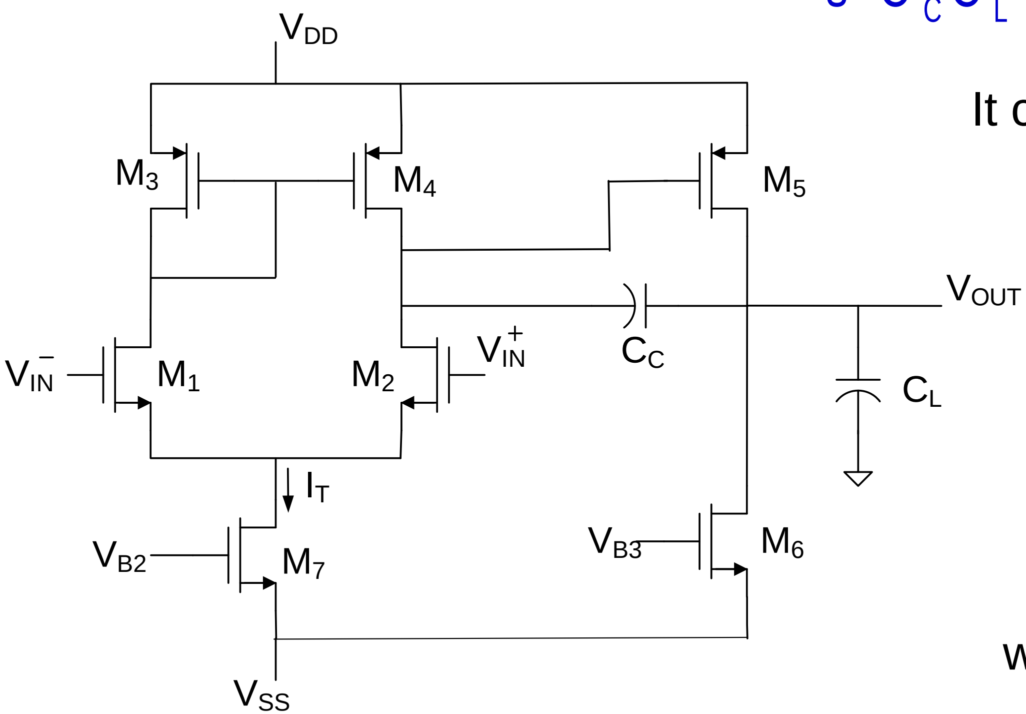
Typically compensate so closed-loop poles make angle between 45° and 90° from imaginary axis

Equivalently:

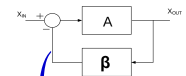
$$0.5 < Q < .707$$

Basic Two-Stage Op Amp

(with Miller compensation)



Standard Feedback Gain



$$A_{FB}(s) \cong \frac{g_{md}\left(g_{m0} - sC_c\right)}{s^2 C_c C_L + sC_C\left(g_{mo} - \beta g_{md}\right) + \beta g_{md} g_{mo}}$$

It can be shown that

$$Q = \sqrt{\frac{C_L}{C_C}} \sqrt{\beta} \frac{\sqrt{g_{mo} g_{md}}}{g_{mo} - \beta g_{md}}$$

$$C_C = \frac{C_L \beta}{Q^2} \frac{g_{mo} g_{md}}{\left(g_{mo} - \beta g_{md}\right)^2}$$

where $g_{md} = g_{m1}$ $g_{mo} = g_{m5}$

$g_{oo} = g_{o5} + g_{o6}$ and $g_{od} = g_{o2} + g_{o4}$

But what pole Q is desired? **.707< Q <0.5**

Right Half-Plane Zero in OL Gain (from Miller Compensation) Limits Performance

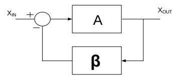
(because it increases the pole Q and thus requires a larger C_C!)

Closed-form expression for C_C!

Basic Two-Stage Op Amp

(with Miller compensation)

Standard Feedback Gain



$$A_{FB}(s) \cong \frac{g_{md}\left(g_{m0} - sC_c\right)}{s^2 C_C C_L + sC_C\left(g_{mo} - \beta\, g_{md}\right) + \beta\, g_{md} g_{mo}}$$

$$Q = \sqrt{\frac{C_L}{C_C}}\sqrt{\beta}\,\frac{\sqrt{g_{mo} g_{md}}}{g_{mo} - \beta g_{md}}$$

$$C_C = \frac{C_L \beta}{Q^2}\,\frac{g_{mo} g_{md}}{\left(g_{mo} - \beta g_{md}\right)^2}$$

Question: Can we express C_C in terms of the pole spread k instead of in terms of Q?

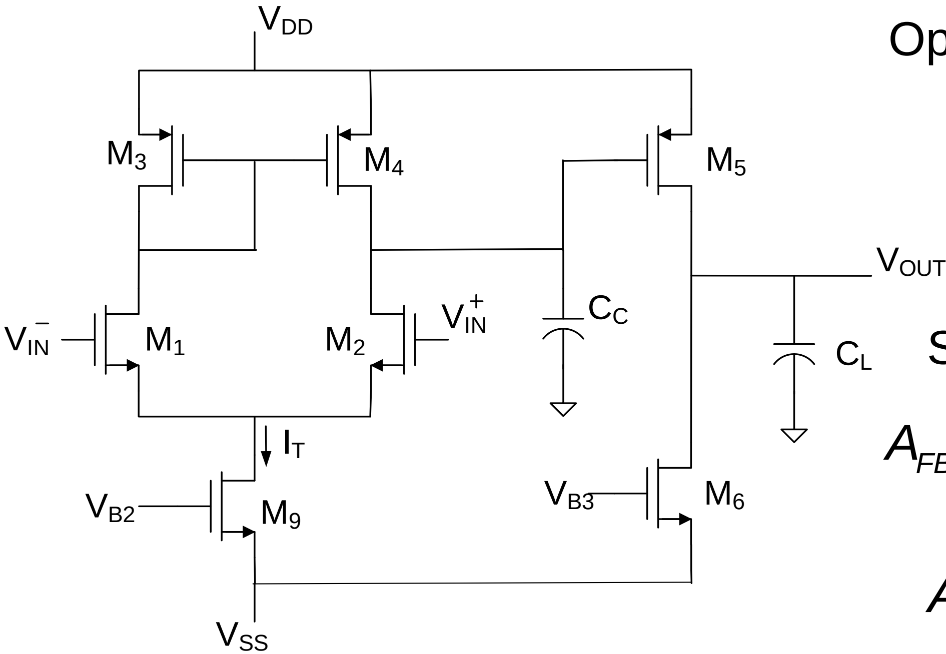
Recall when criteria $2\beta A_o < k < 4\beta A_o$ was derived (Lect 13), started with expression:

$$Q = \frac{\sqrt{k}}{(1+k)}\sqrt{\beta A_{0TOT}} \underset{k\,\mathrm{large}}{\cong} \sqrt{\frac{\beta A_{0TOT}}{k}} \quad \Longrightarrow \quad k \underset{k\,\mathrm{large}}{\cong} \frac{\beta A_{0TOT}}{Q^2}$$

No ! Relationship between k and Q was developed for 2nd-order lowpass open-loop gain (i.e. no zeros present!)

Basic Two-Stage Op Amp with Feedback

(with Internal Node compensation)



Open-loop gain

$$A(s)=\frac{g_{m0}g_{md}}{s^2C_CC_L+sC_Cg_{00}+g_{00}g_{0d}}$$

$$A_{FB}=\frac{A}{1+A\beta}$$

Standard feedback gain with constant β

$$A_{FB}(s)=\frac{g_{m0}g_{md}}{s^2C_CC_L+sC_Cg_{00}+g_{00}g_{0d}+\beta g_{m0}g_{md}}$$

$$A_{FB}(s)\cong\frac{g_{m0}g_{md}}{s^2C_CC_L+sC_Cg_{00}+\beta g_{m0}g_{md}}$$

where $g_{oo}=g_{o5}+g_{o6}$ $\quad g_{mo}=g_{m5}$

$g_{od}=g_{o2}+g_{o4}$ $\quad g_{md}=g_{m1}$

$$4\beta\ A_0>\frac{p_2}{p_1}>2\beta\ A_0 \Leftrightarrow k\cong\frac{\beta A_{0TOT}}{Q^2}$$

$$p_2=\frac{g_{00}}{C_L}\quad p_1=\frac{g_{0d}}{C_C}\quad A_0=\frac{g_{m0}g_{md}}{g_{00}g_{0d}}$$

$$C_L4\beta\frac{g_{m0}g_{md}}{g_{00}^2}>C_C>C_L2\beta\frac{g_{m0}g_{md}}{g_{00}^2}$$

OR

$$C_C=C_L\beta\frac{g_{m0}g_{md}}{Q^2g_{00}^2}=C_L\beta\frac{g_{m5}g_{m1}}{Q^2\left(g_{05}+g_{06}\right)^2}$$

Status on Compensation

Generally not needed for single-stage op amps

Analytical expressions were developed with $A_{FB} = \frac{A}{1+A\beta}$ for

- Two-stage with internal node compensation (no OL zeros)
- Two-stage with load compensation (no OL zeros)
- Two-stage with basic Miller compensation (OL zero, single series comp cap)

Will now develop a more general compensation strategy

Stay Safe and Stay Healthy !

End of Lecture 15