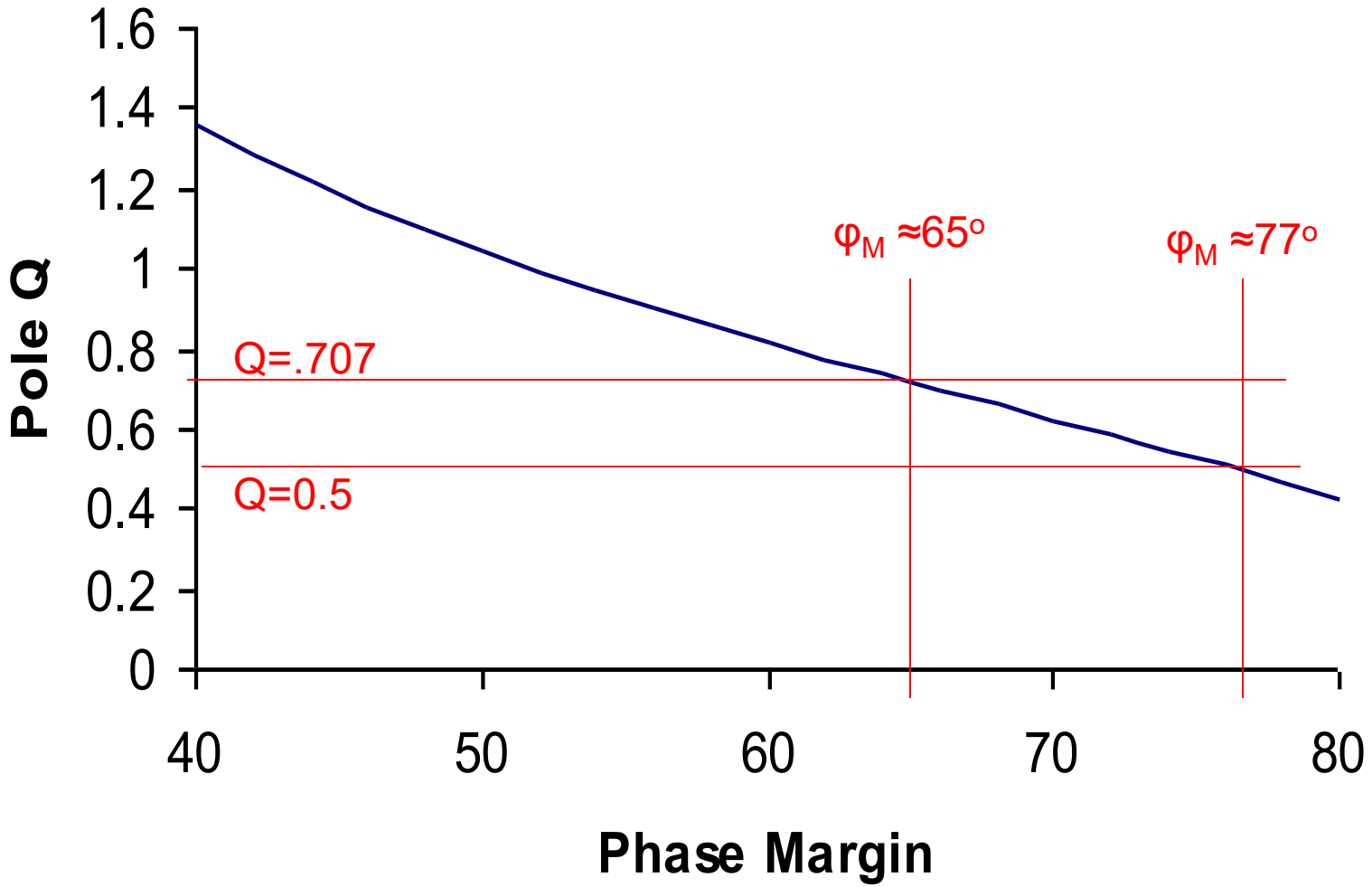
EE 435

Lecture 18

- Power Split between Stages
- Moving the RHP zero into LHP in Miller Compensated Amplifier
- Breaking the Loop for Loop Gain Analysis
- Op Amp Simulation
- Other Methods of Gain Enhancement

Phase Margin vs Q

Second-order low-pass Amplifier



.707< Q <0.5 ⇒ 65° < φ_M < 75°

Compensation Summary

- Gain and phase margin performance often strongly dependent upon architecture
- Relationship between overshoot and ringing and phase margin were developed only for 2^{nd}-order lowpass gain characteristics and differ dramatically for higher-order structures
- Absolute gain and phase margin criteria are not robust to changes in architecture or order
- It is often difficult to correctly “break the loop” to determine the loop gain Aβ with the correct loading on the loop (will discuss this more later)

Review from last lecture

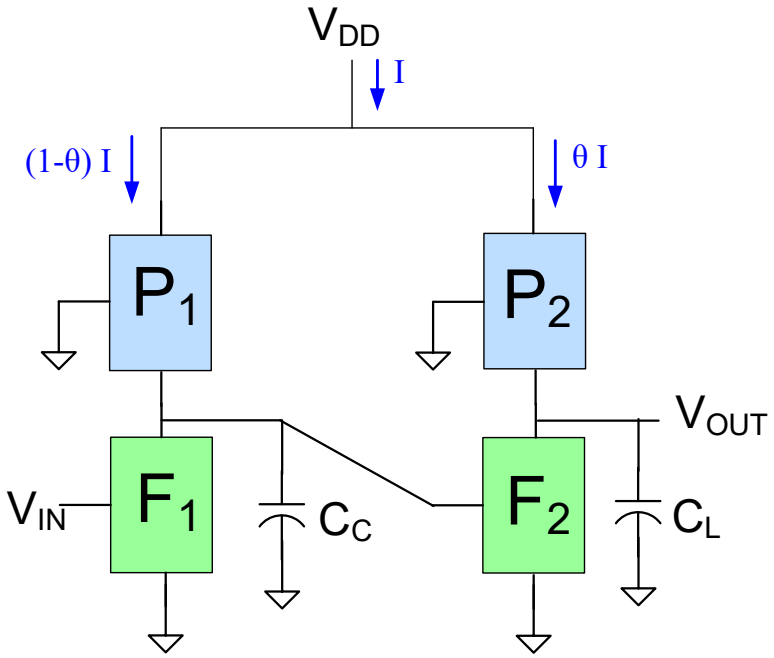
Practical Set of Design Parameters

$$S_{PRACTICAL} = \{P, \theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}\}$$

7 degrees of freedom!

- P : total power dissipation
- θ = fraction of total power in second stage
- V_{EBk} = excess bias voltage for the k^{th} transistor
- Phase margin constraint assumed (so C_C not shown in DoF)

Power distribution between stages

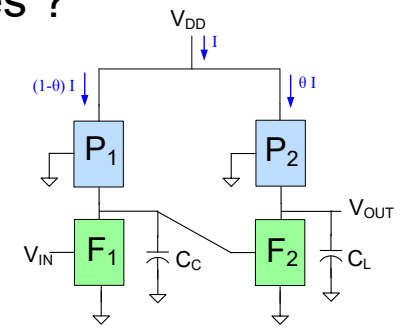


How should the power be split between the two stages ?

- Would often like to minimize power for a given speed (GB) requirement
- Optimal split may depend upon architecture

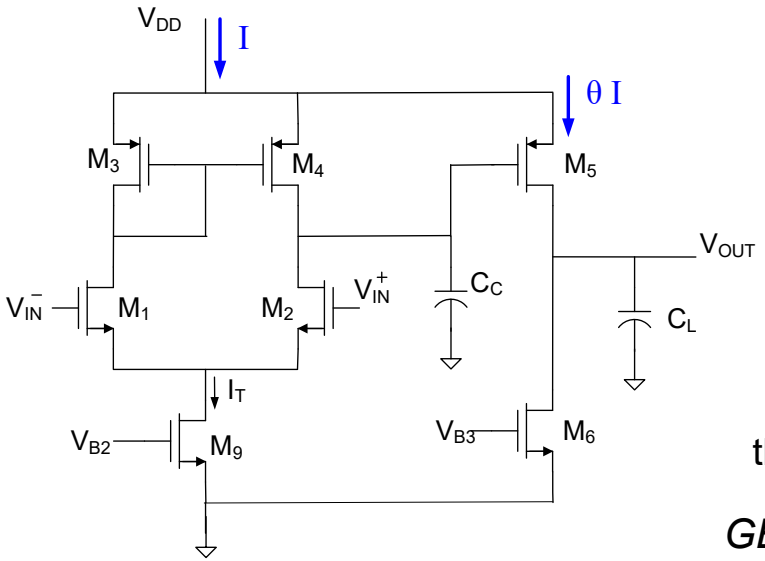
Power distribution between stages

How should the power be split between the two stages ?



Consider basic two-stage with first-stage compensation

Assume compensated with $p_2=3\beta A_0 p_1$



$$A_{10} = \frac{-g_{m1}}{g_{01}+g_{03}}$$

$$A_{20} = \frac{-g_{m5}}{g_{05}+g_{06}}$$

$$p_1 = \frac{g_{01}+g_{03}}{C_C}$$

$$p_2 = \frac{g_{05}+g_{06}}{C_L}$$

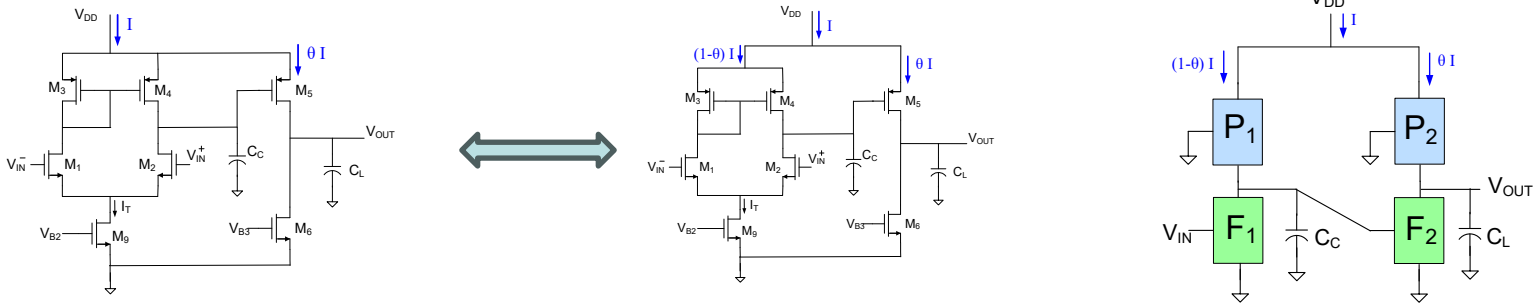
$$GB = A_{01}A_{02}p_1$$

thus

$$GB = \frac{g_{m1}}{g_{01}+g_{03}}\frac{g_{m5}}{g_{05}+g_{06}}\frac{g_{01}+g_{03}}{C_C} = \frac{g_{m1}g_{m5}}{(g_{05}+g_{06})C_C}$$

Power distribution between stages

How should the power be split between the two stages to minimize power for given GB with a fixed C_L ?



Since $p_2 = 3\beta A_0 p_1$

$$A_{10} = \frac{-g_{m1}}{g_{01} + g_{03}}$$

$$A_{20} = \frac{-g_{m5}}{g_{05} + g_{06}}$$

$$p_1 = \frac{g_{01} + g_{03}}{C_C}$$

$$p_2 = \frac{g_{05} + g_{06}}{C_L}$$

$$\frac{g_{05} + g_{06}}{C_L} = 3\beta \frac{g_{m1}}{g_{01} + g_{03}} \frac{g_{m5}}{g_{05} + g_{06}} \frac{g_{01} + g_{03}}{C_C}$$

$$\frac{g_{05} + g_{06}}{C_L} = 3\beta \frac{g_{m1} g_{m5}}{C_C (g_{05} + g_{06})}$$

Since $GB = \dfrac{g_{m1} g_{m5}}{(g_{05} + g_{06}) C_C}$

$$GB = \frac{g_{05} + g_{06}}{3\beta C_L}$$

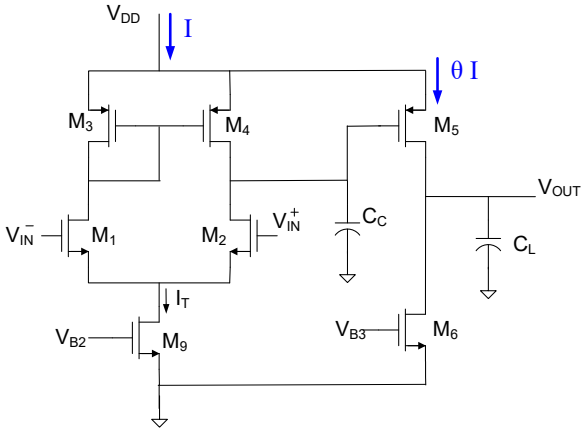
$$GB = \frac{(\lambda_p + \lambda_n)\theta I}{3\beta C_L}$$

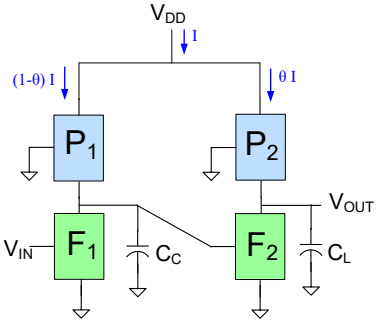
Finally $GB = \dfrac{(\lambda_p + \lambda_n)\theta P}{V_{DD} 3\beta C_L}$

Thus for given GB, for this structure want θ as close to 1 as is practical

Power distribution between stages

How should the power be split between the two stages to minimize power for given GB with a fixed C_L ?





$p_2=3\beta A_0 p_1$

$$GB = \frac{\left(\lambda_p + \lambda_n\right)\theta P}{V_{DD} 3\beta C_L}$$

Want to apply almost all power to second stage!

How does this split change with β ?

How does this split change if compensation changes to $p_2=4\beta A_0 p_1$?

How does this split change if compensation changes to $p_2=2\beta A_0 p_1$?

Power distribution between stages

Note: Optimum power split for previous example was for dominant pole compensation in first stage. Results may be different for Miller compensation or for output compensation

For first-stage compensation capacitor with compensation criteria $p_2=3\beta A_0 p_1$:

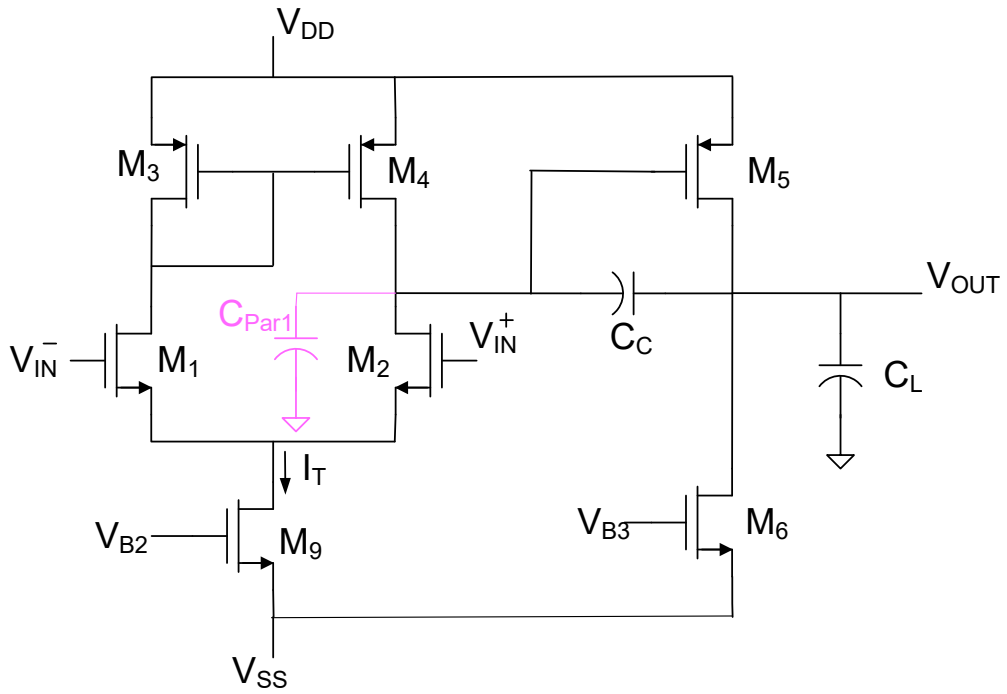
$$GB = \frac{\left(\lambda_p + \lambda_n\right)\theta P}{V_{DD} 3\beta C_L}$$

For Miller Compensation with RHP zero and arbitrary Q compensation criteria:

$$GB = \frac{P(1-\theta)}{V_{DD} V_{EB1} C_C} = \frac{PQ^2\left(2\theta V_{EB1} - \beta(1-\theta)\left|V_{EB5}\right|\right)^2}{C_L \beta 2\theta V_{EB1}^2 \left|V_{EB5}\right| V_{DD}}$$

By taking derivative of GB wrt θ, it can be easily shown that the derivative is positive in the interval $0<\theta\leq 1$ indicating that for a given P, want to make θ close to 1 to maximize GB

Basic Two-Stage Miller Compensated Op Amp



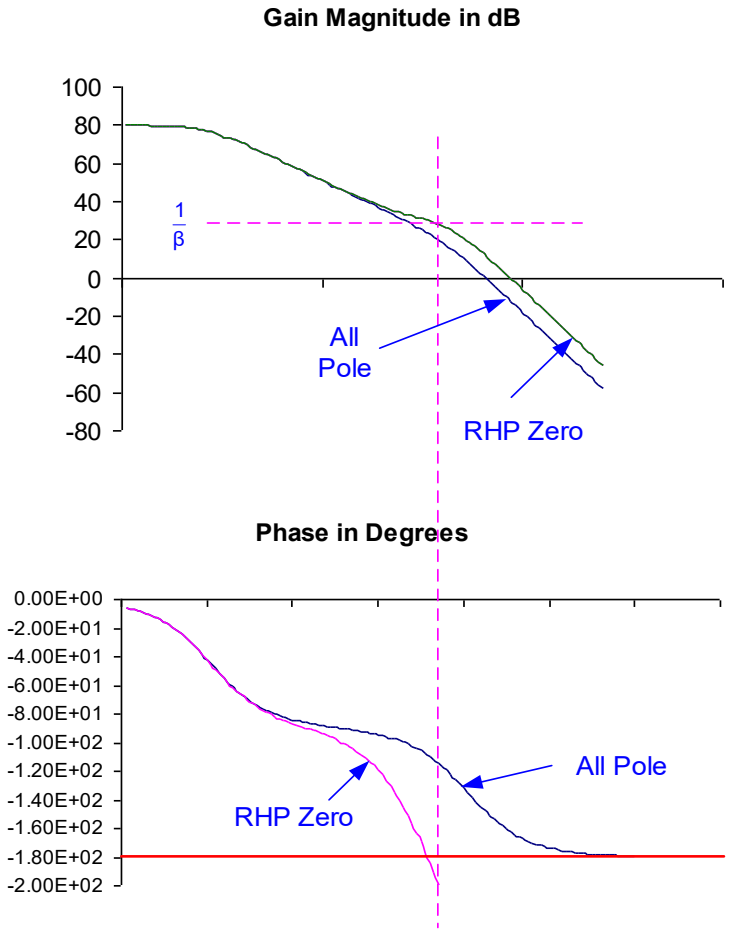
$$A_{FB}(s) \cong \frac{g_{md}(g_{m0} - sC_c)}{s^2 C_c C_L + sC_c(g_{mo} - \beta\, g_{md}) + \beta\, g_{md} g_{mo}}$$

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

Right Half-Plane Zero Limits Performance

- Why does the RHP zero limit performance ?
- Can anything be done about this problem ?
- Why is this not 3rd order since there are 3 caps ?

Why does the RHP zero limit performance ?

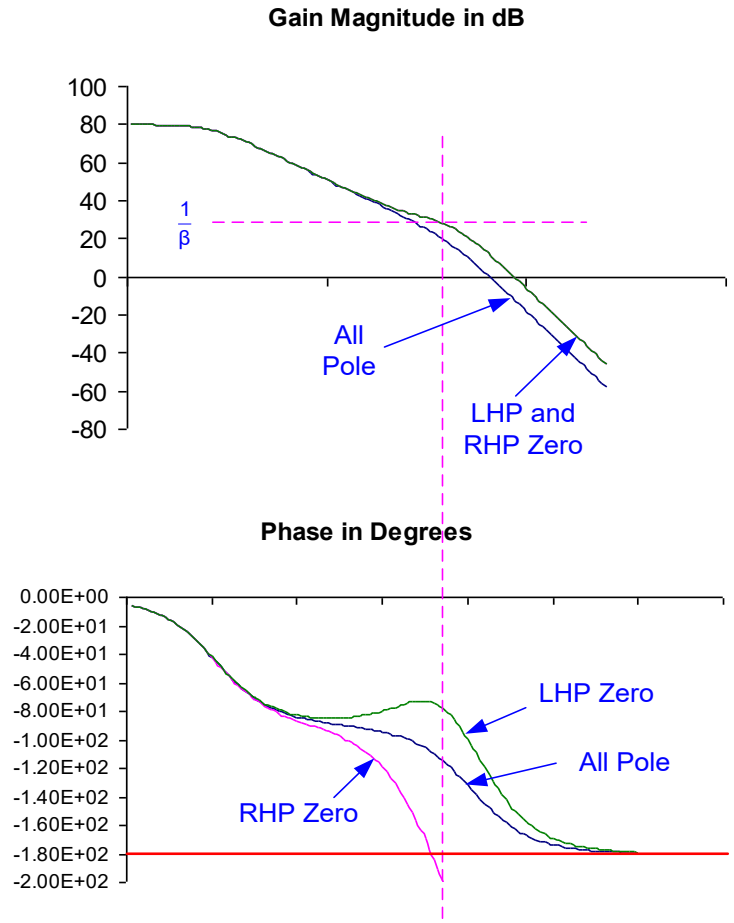


$p_1 = -1$, $p_2 = -1000$, $z_x = \{\text{none}, +250\}$

In this example:

- accumulate phase shift and slow gain drop with RHP zeros
- effects are dramatic

Why does the RHP zero limit performance ?



p_1=1, p_2=1000, z_x={none,250,-250}

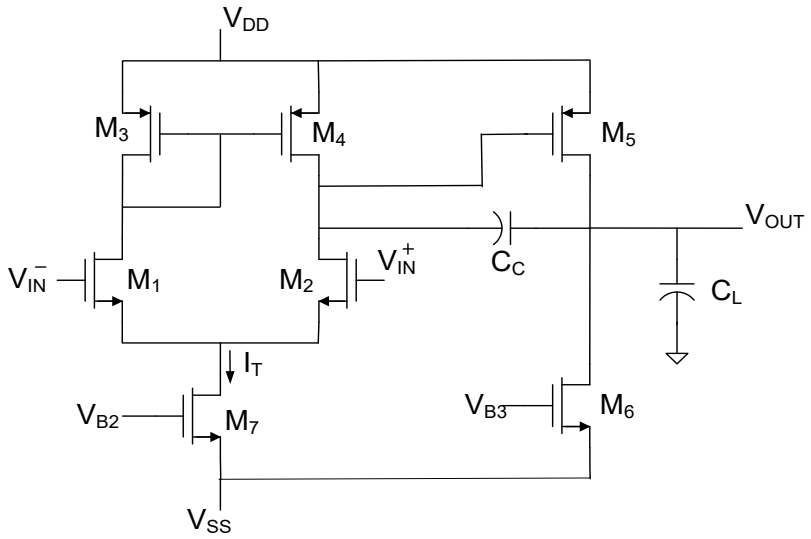
In this example:

- accumulate phase shift and slow gain drop with RHP zeros
- loose phase shift and slow gain drop with LHP zeros
- effects are dramatic

Two-stage amplifier

(with RHP Zero Compensation)

What causes the Miller compensation capacitor to create a RHP zero?



$$V_d = V_{IN}^{+} - V_{IN}^{-}$$

$$A_V = (A_0 p_1 p_2)\frac{1}{(s+p_1)(s+p_2)}$$

with Miller Compensation

$$A_V = \left(A_0 \frac{p_1 p_2}{z}\right)\frac{-s+z}{(s+p_1)(s+p_2)}$$

At low frequencies, V_{OUT}/V_d is positive but at high frequencies it becomes negative

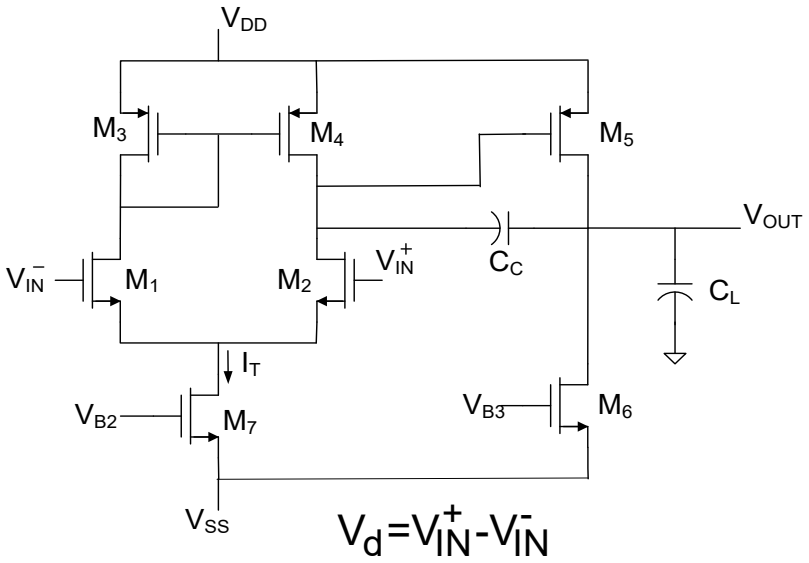
Alternately, C_C provides a feed-forward inverting signal from the input to the first stage output which also becomes the second stage output

Feed-forward paths create zeros in the gain transfer function !

Two-stage amplifier

(with RHP Zero Compensation)

What can be done to remove the RHP zero?



$$A_V = (A_0 p_1 p_2)\frac{1}{(s+p_1)(s+p_2)}$$

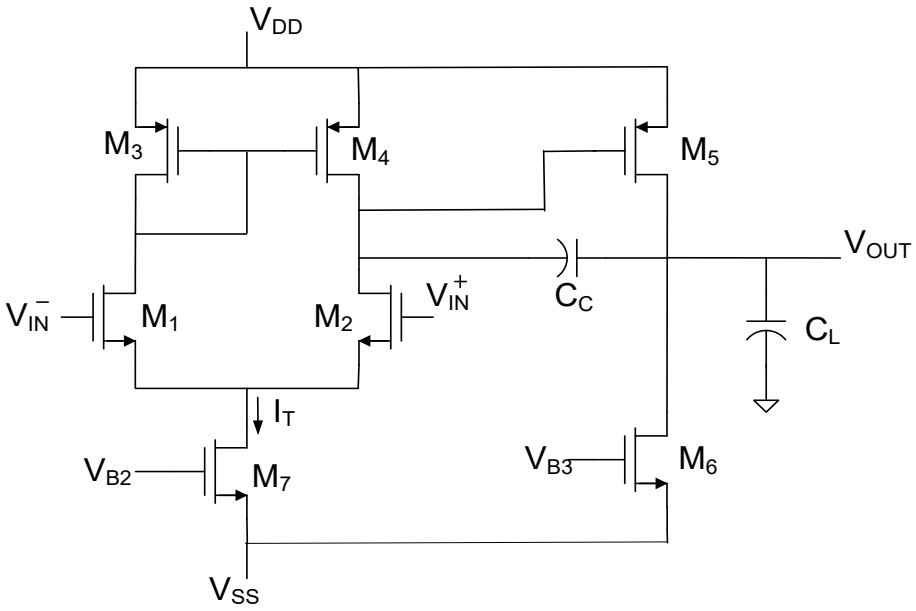
with Miller Compensation

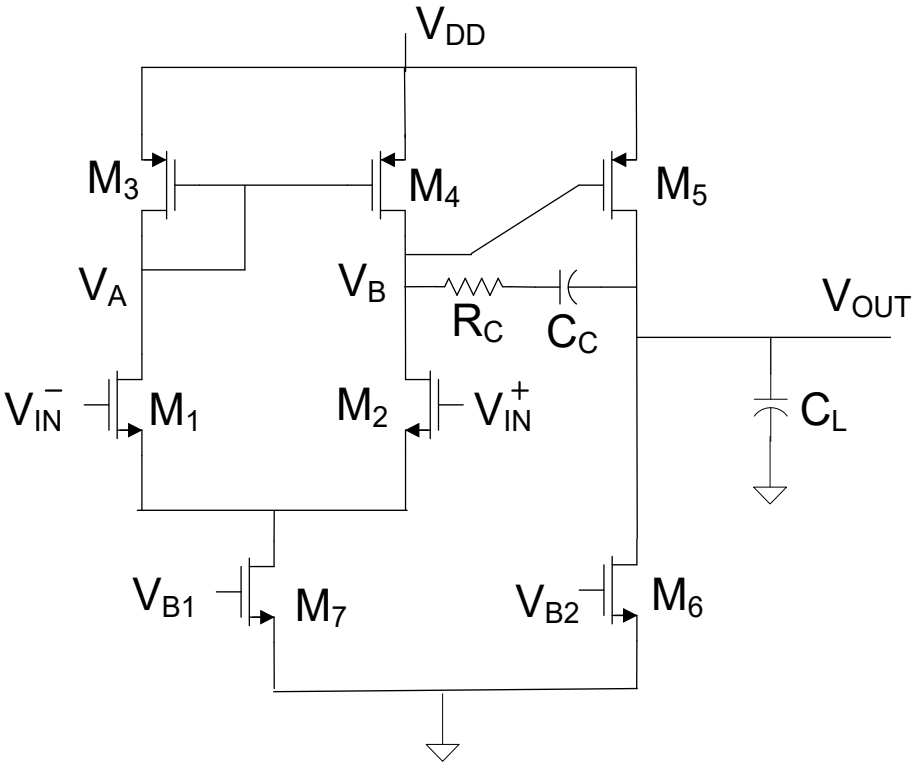
$$A_V = \left(A_0 \frac{p_1 p_2}{z}\right)\frac{-s+z}{(s+p_1)(s+p_2)}$$

Alternately, C_C provides a feed-forward inverting signal from the input to the first stage output which also becomes the second stage output

Break the feed-forward path from the output of the first stage to the output of the second stage at high frequencies

Two-stage amplifier with LHP Zero Compensation





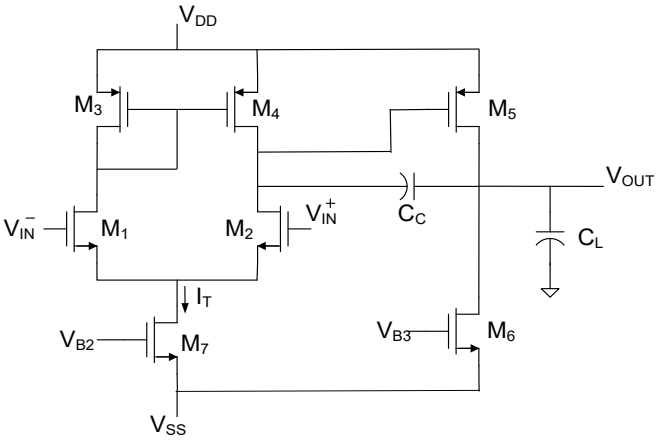
Right Half-Plane Zero Limits Performance

Will show zero can be moved to Left Half-Plane

R_C realized with single triode region device

Two-stage amplifier with LHP Zero Compensation

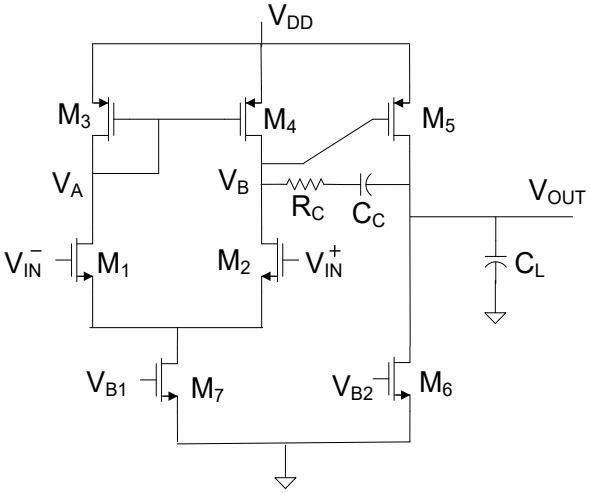
Analysis almost by inspection:



$$A(s) = \frac{g_{md}\left(g_{m5} - sC_c\right)}{s^2 C_C C_L + sC_C g_{m5} + g_{oo} g_{od}} \qquad z_1 = \frac{g_{m5}}{C_C}$$

$$\frac{1}{sC_c} \Rightarrow \frac{1}{sC_c} + R_C$$

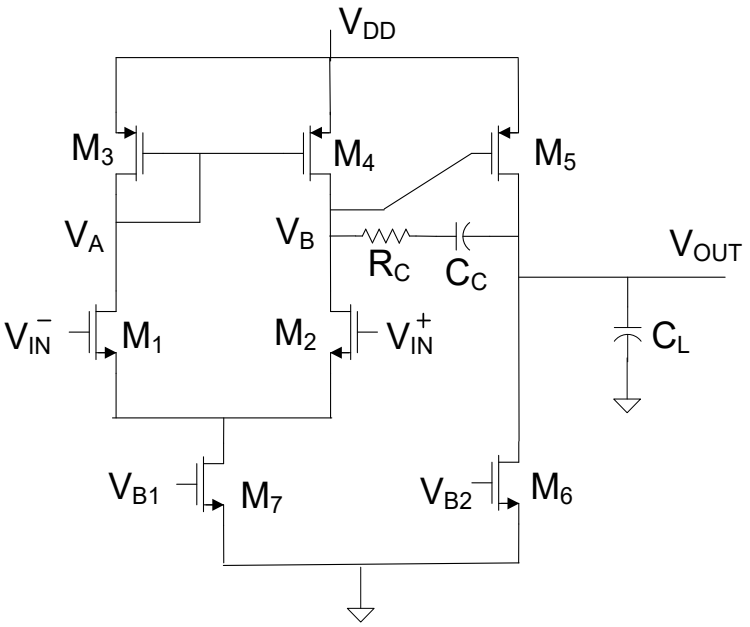
$$sC_C \Rightarrow \frac{sC_c}{1 + sC_c R_C}$$



$$A(s) = \frac{g_{md}\left(g_{m5} + sC_c\left[\frac{g_{m5}}{g_c} - 1\right]\right)}{s^2 C_C C_L + sC_C g_{m5} + g_{oo} g_{od}}$$

$$z_1 = \frac{-g_{m5}}{C_C\left[\frac{g_{m5}}{g_C} - 1\right]}$$

Two-stage amplifier with LHP Zero Compensation



$$A(s) = \frac{g_{md}\left(g_{m5} + sC_c\left[\frac{g_{m5}}{g_c} - 1\right]\right)}{s^2 C_C C_L + sC_C g_{m5} + g_{oo} g_{od}}$$

$$z_1 = \frac{-g_{m5}}{C_C\left[\frac{g_{m5}}{g_C} - 1\right]}$$

z_1 location can be programmed by R_C

If $g_c > g_{m5}$, z_1 in RHP and if $g_c < g_{m5}$, z_1 in LHP

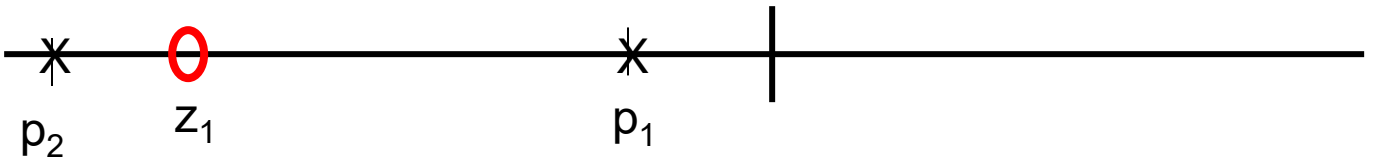
R_C has almost no effect on p_1 and p_2

Two-stage amplifier with LHP Zero Compensation

$$A(s) = \frac{g_{md}\left(g_{m5} + sC_c\left[\frac{g_{m5}}{g_c} - 1\right]\right)}{s^2 C_C C_L + sC_C g_{m5} + g_{oo} g_{od}}$$

$$z_1 = \frac{-g_{m5}}{C_C\left[\frac{g_{m5}}{g_C} - 1\right]}$$

$$p_1 = -\frac{g_{o1} + g_{o5}}{C_C\left(\frac{g_{m5}}{g_{05} + g_{o6}}\right)} \qquad p_2 = -\frac{g_{m5}}{C_L}$$

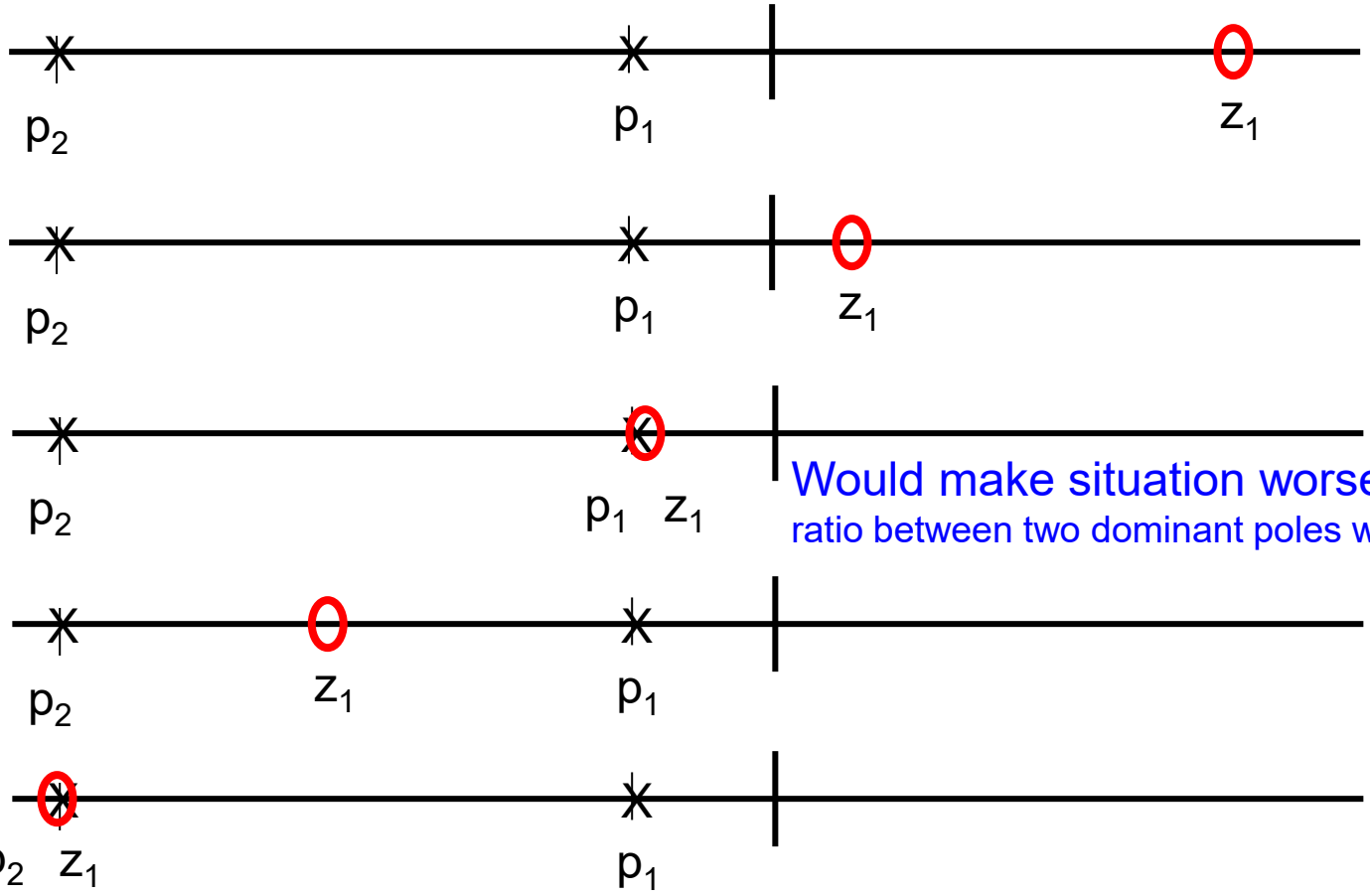


where should z_1 be placed?

Two-stage amplifier with LHP Zero Compensation

where should z_1 be placed?

$$z_1 = \frac{-g_{m5}}{C_C\left[\frac{g_{m5}}{g_C} - 1\right]}$$



$$p_1 = -\frac{g_{o1} + g_{o5}}{C_C\left(\frac{g_{m5}}{g_{05} + g_{o6}}\right)}$$

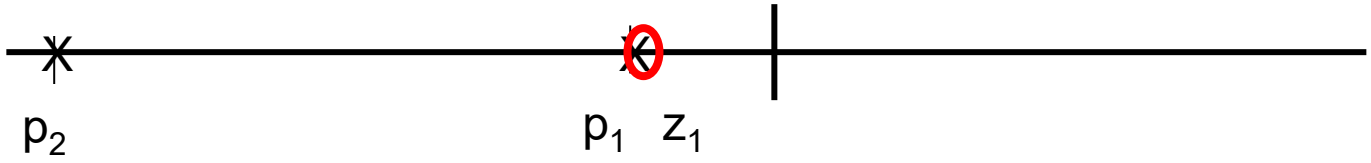
$$p_2 = -\frac{g_{m5}}{C_L}$$

Would make situation worse (because ratio between two dominant poles would be reduced !

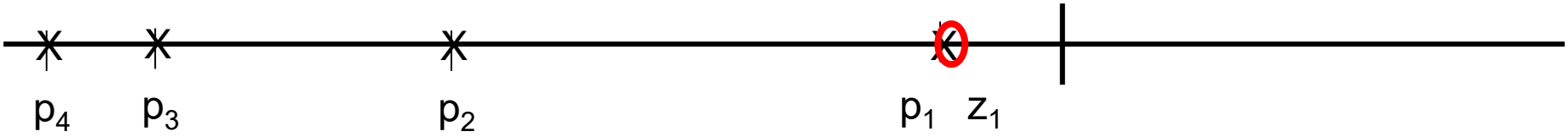
Two-stage amplifier with LHP Zero Compensation

where should z_1 be placed?

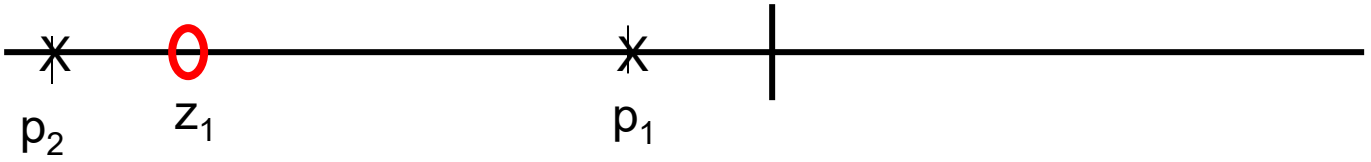
Would make situation worse (because ratio between two dominant poles would be reduced !



Other parasitic poles, at higher frequencies are present and not too much larger than p_2!



Two-stage amplifier with LHP Zero Compensation



$$z_1 = \frac{-g_{m5}}{C_C\left[\frac{g_{m5}}{g_C} - 1\right]}$$

z_1 often used to cancel p_2

Can reduce size of required compensation capacitor

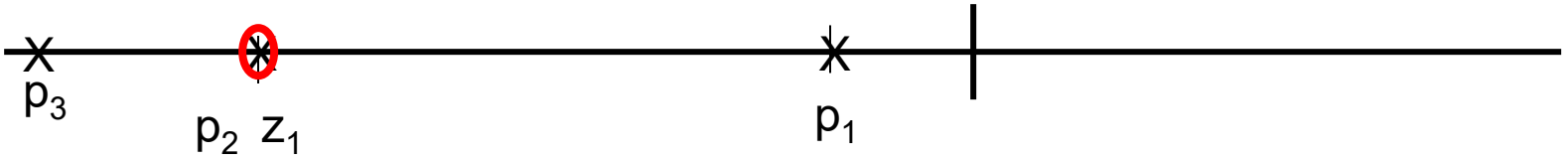
a) eliminates RHP zero

b) increases spread between p_1 and p_3

Improves phase margin

Design formulations easily extend to this structure

Two-stage amplifier with LHP Zero Compensation

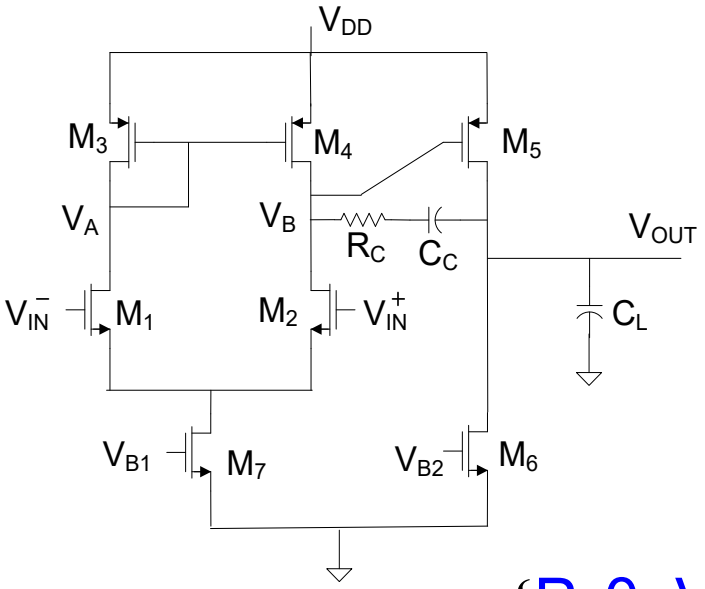


$$z_1 = \frac{-g_{m5}}{C_C\left[\frac{g_{m5}}{g_C} - 1\right]}$$

Analytical formulation for compensation requirements not easy to obtain
(must consider at least 3rd –order poles and both T(s) and poles not mathematically tractable)

C_C often chosen to meet phase margin (or settling/overshoot) requirements after all other degrees of freedom used with computer simulation from magnitude and phase plots

Basic Two-Stage Op Amp with LHP zero



8 Degrees of Freedom

$$\{P, \theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}, R_C, C_C\}$$

1 constraint (phase margin)

---

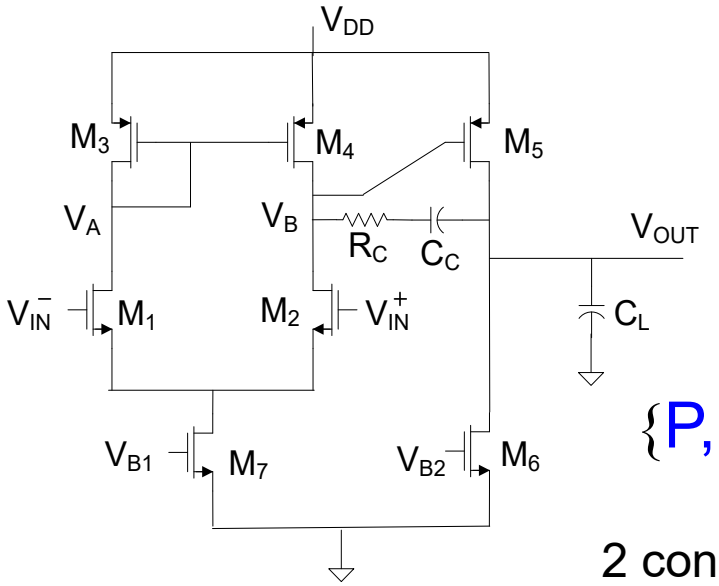
with zero cancellation of p_2

7 Degrees of Freedom

$$\{P, \theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}, R_C, C_C\}$$

2 constraints (phase margin), $z_1 = p_2 = \dfrac{-g_{m5}}{C_C\left[\dfrac{g_{m5}}{g_C} - 1\right]}$

Basic Two-Stage Op Amp with LHP zero



with zero cancellation of p_2

7 Degrees of Freedom

$$\{P, \theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB6}, V_{EB7}, R_C, C_C\}$$

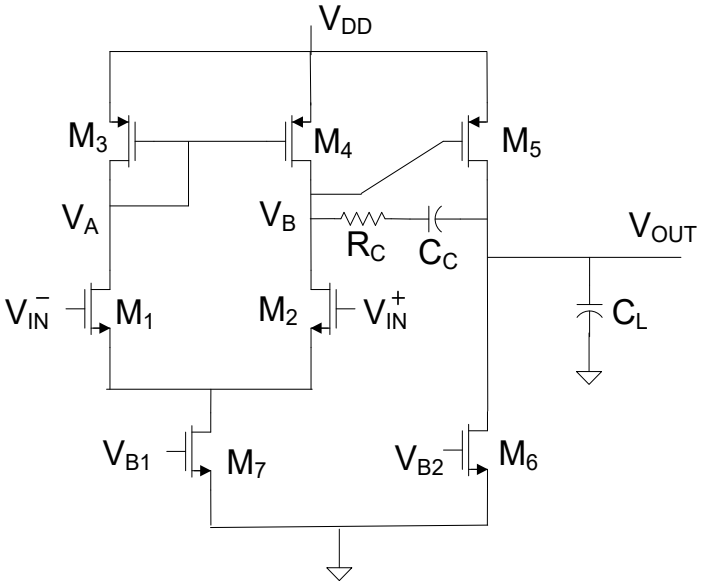
2 constraints (phase margin), $z_1 = p_2 = \dfrac{-g_{m5}}{C_C\left[\dfrac{g_{m5}}{g_C} - 1\right]}$

Design Flow:

1. Ignore R_C and design as if RHP zero is present
2. Pick R_C to cancel p_2
3. Adjust p_1 (i.e. change/reduce C_C) to achieve desired phase margin

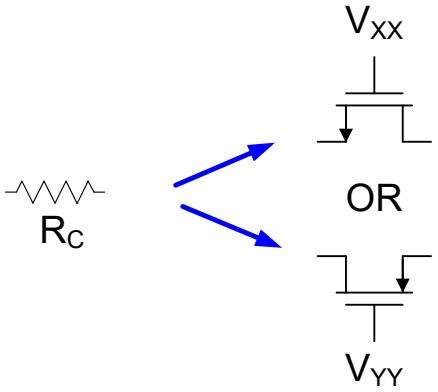
   (or preferably desired closed-loop performance for desired β)

Basic Two-Stage Op Amp with LHP zero



Realization of R_C

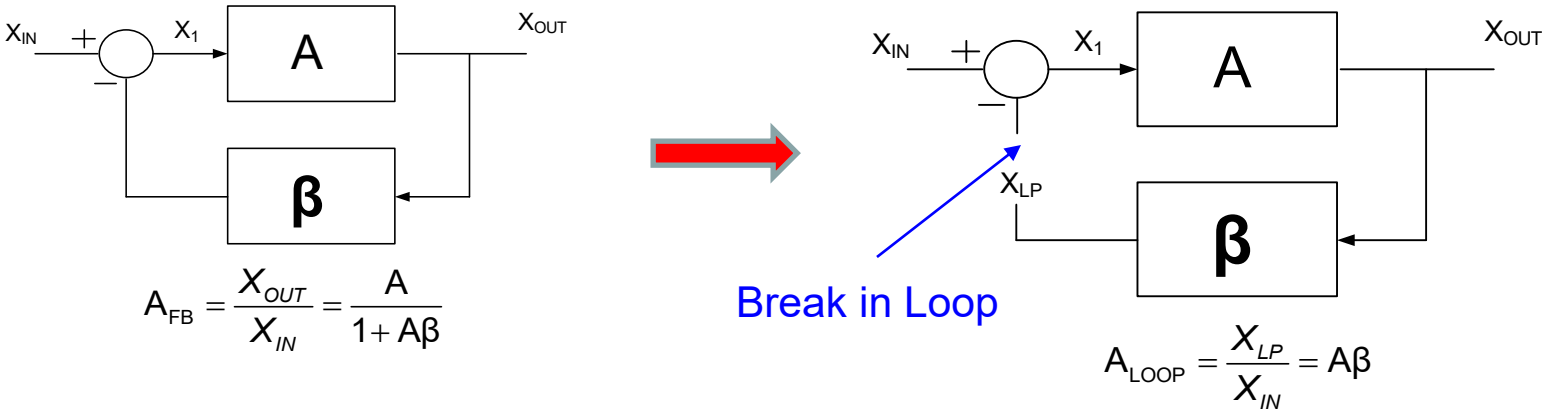
$$R_C = \frac{L}{\mu C_{OX} W V_{EB}}$$



Transistors in triode region
Very little current will flow through transistors (and no dc current)
V_{DD} or GND often used for V_{XX} or V_{YY}
V_{BQ} well-established since it determines I_{Q5}
Using an actual resistor not a good idea (will not track g_{m5} over process and temp)

Two-Stage Amplifiers

Loop Gain Analysis



- Loop Gain
  - Loading of A and β networks
  - Breaking the Loop (with appropriate terminations)
  - Biasing of Loop
  - Simulation of Loop Gain
- Open-loop gain simulations
  - Systematic Offset
  - Embedding in closed loop

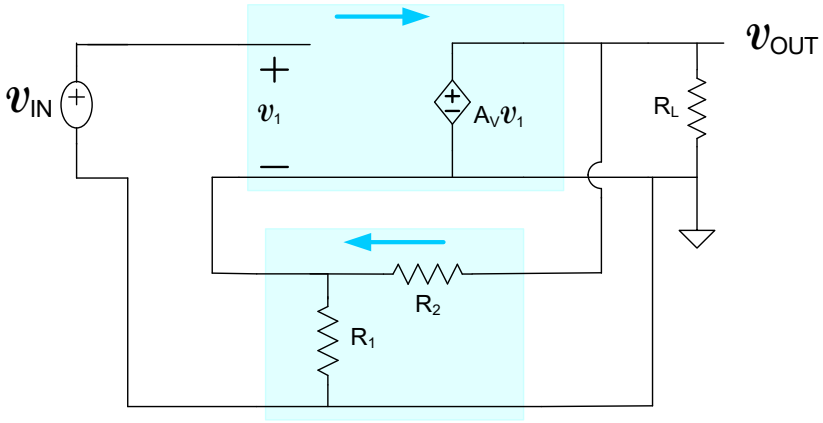
Loop Gain - Aβ

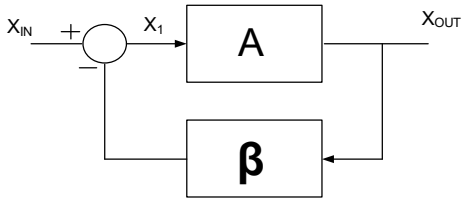
Loop Gain is a Critical Concept for Compensation of Feedback Amplifiers when Using Phase Margin Criteria (If you must!)

- Sometimes it is not obvious where the actual loop gain is at in a feedback circuit
- The A amplifier often causes some loading of the β amplifier and the β amplifier often causes some loading of the A amplifier
- Often try to “break the loop” to simulate or even calculate the loop gain or the gains A and β
- If the loop is not broken correctly or the correct loading effects on both the A amplifier and β amplifier are not included, errors in calculating loop gain can be substantial and conclusions about compensation can be with significant error

Loop Gain - Aβ

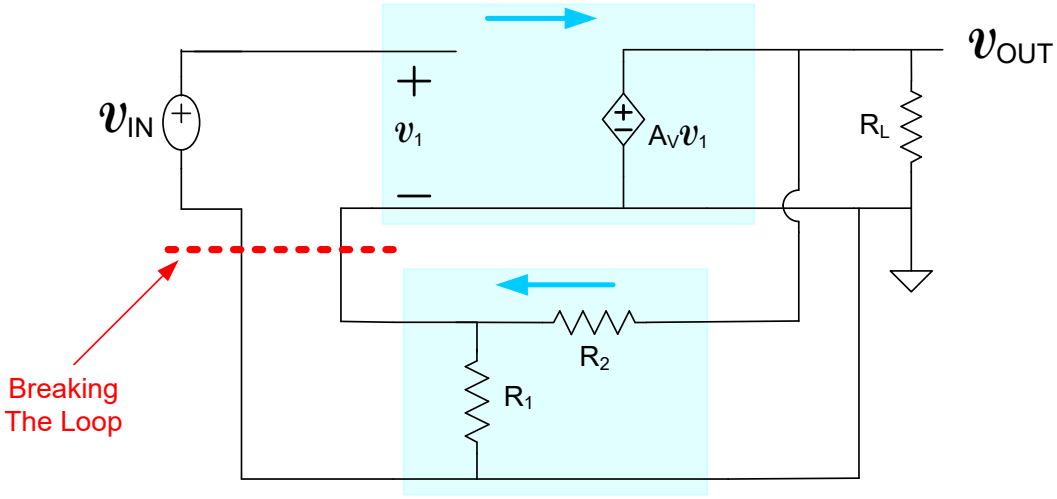
(for voltage-series feedback configuration)





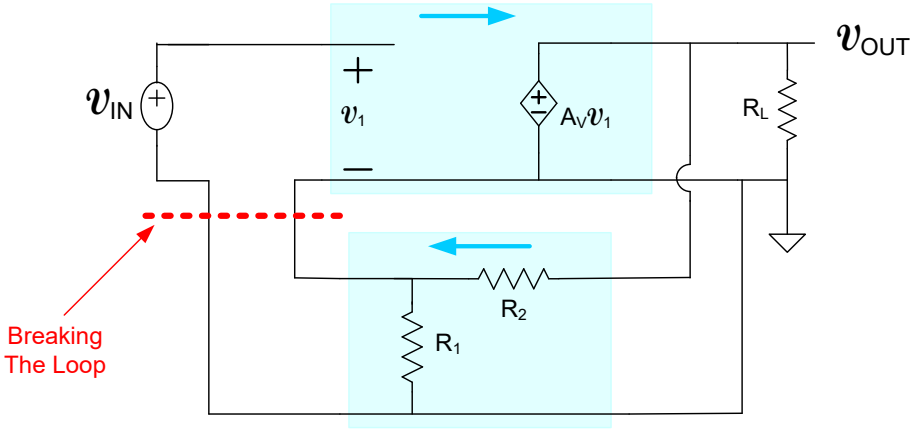
Block diagram represents small-signal feedback model

The loop is often broken on the circuit schematic to determine the loop gain



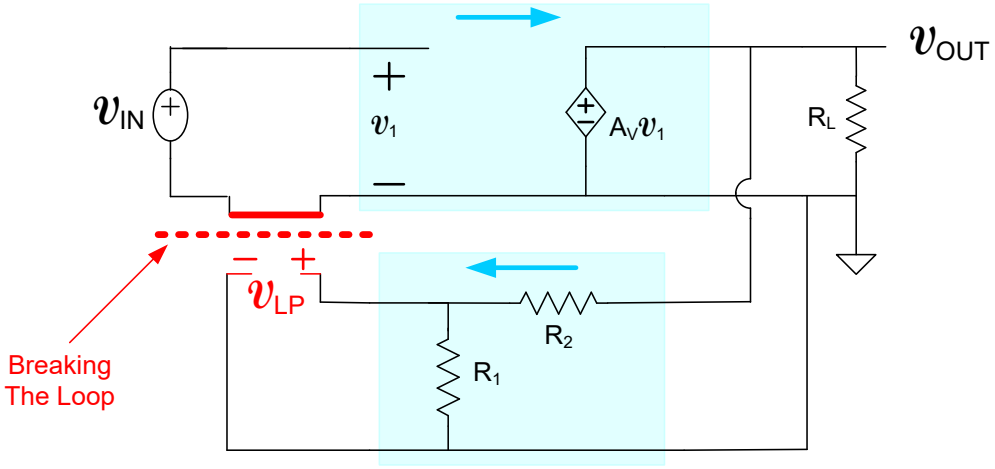
Loop Gain - Aβ

Breaking the loop to obtain the loop gain (Ideal A amplifier)



$$\beta = \frac{R_1}{R_1+R_2}$$

Note terminations where the loop is broken – open and short



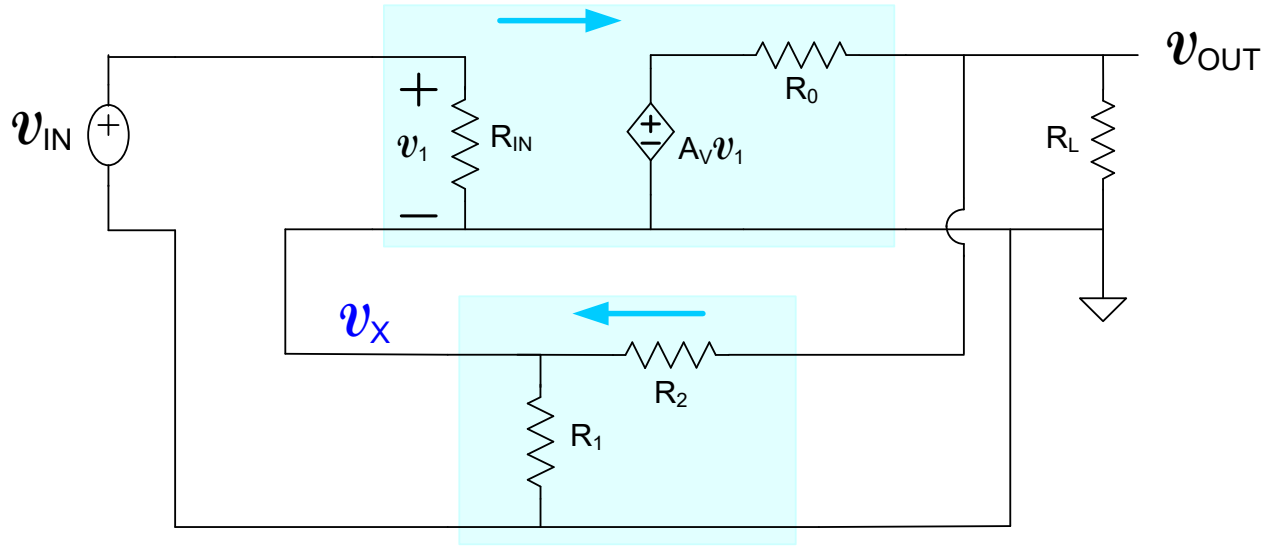
$$v_{LP} = v_{IN} A_V \frac{R_1}{R_1+R_2}$$

$$\frac{v_{LP}}{v_{IN}} = A_{LOOP} = A\beta$$

Block diagram represents small-signal feedback model

Loop Gain - Aβ

But what if the amplifier is not ideal?



For the feedback amplifier:

$$\left.\begin{aligned} v_{OUT}(G_O+G_L+G_2) &= v_X G_2 + A_V v_1\, G_O \\ v_X(G_1+G_2+G_{IN}) &= v_{OUT} G_2 + v_{IN} G_{IN} \\ v_{IN} &= v_1 + v_X \end{aligned}\right\}$$

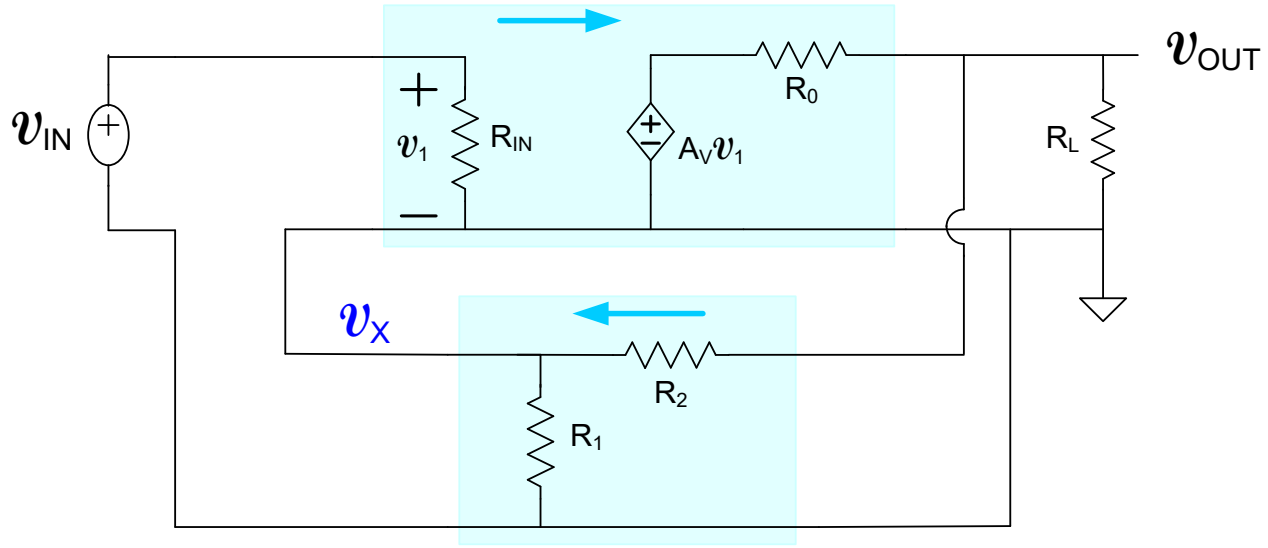
Solving, we obtain

$$A_{FB} = \frac{v_{OUT}}{v_{IN}} = \frac{G_{IN}G_2 + A_V(G_O[G_1+G_2])}{(G_O+G_L)[G_1+G_2+G_{IN}] + G_2(G_1+G_{IN}) + A_V G_2 G_O}$$

What is the Loop Gain ? Needed to obtain the Phase Margin !

Loop Gain - Aβ

But what if the amplifier is not ideal?



$$A_{FB} = \frac{v_{OUT}}{v_{IN}} = \frac{G_{IN}G_2 + A_V\left(G_O\left[G_1+G_2\right]\right)}{\left(G_O+G_L\right)\left[G_1+G_2+G_{IN}\right]+G_2\left(G_1+G_{IN}\right)+A_V G_2 G_O}$$

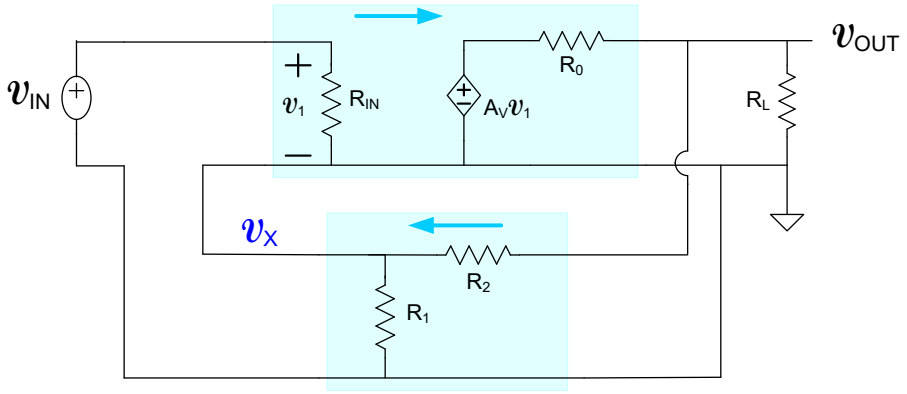
What is the Loop Gain ? Needed to obtain the Phase Margin !

Remember: $A_{FB} = \dfrac{F_1(s)}{1+A\beta}$ Characteristic Polynomial Determined by $D(s) = 1 + A\beta$

Whatever is added to “1” in the denominator is the loop gain

Loop Gain - Aβ

But what if the amplifier is not ideal?



$$\beta = \frac{R_1}{R_1+R_2}$$

$$\beta = \frac{G_2}{G_1+G_2}$$

$$A_{FB} = \frac{v_{OUT}}{v_{IN}} = \frac{G_{IN}G_2+A_V\left(G_O[G_1+G_2]\right)}{(G_O+G_L)[G_1+G_2+G_{IN}]+G_2(G_1+G_{IN})+A_V G_2 G_O}$$

Can be rewritten as

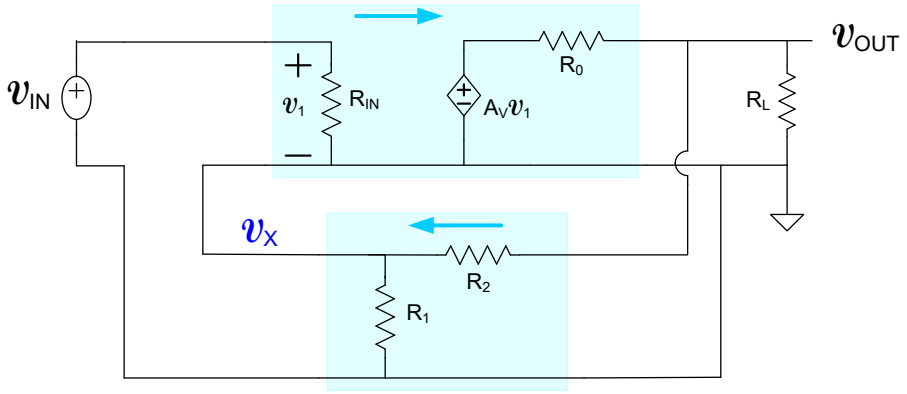
$$A_{FB} = \frac{\dfrac{G_{IN}G_2}{(G_O+G_L)[G_1+G_2+G_{IN}]+G_2(G_1+G_{IN})}+A_V\left(\dfrac{G_O[G_1+G_2]}{(G_O+G_L)[G_1+G_2+G_{IN}]+G_2(G_1+G_{IN})}\right)}{1+A_V\left[\dfrac{G_2G_O}{(G_O+G_L)[G_1+G_2+G_{IN}]+G_2(G_1+G_{IN})}\right]}$$

The Loop Gain is

$$A_{LOOP} = A_V\left[\frac{G_2G_O}{(G_O+G_L)[G_1+G_2+G_{IN}]+G_2(G_1+G_{IN})}\right]$$

Loop Gain - Aβ

But what if the amplifier is not ideal?



$$\beta = \frac{R_1}{R_1+R_2}$$

$$\beta = \frac{G_2}{G_1+G_2}$$

The Loop Gain is

$$A_{LOOP} = A_V\left[\frac{G_2 G_O}{(G_O+G_L)[G_1+G_2+G_{IN}]+G_2(G_1+G_{IN})}\right]$$

This can be rewritten as

$$A_{LOOP} = \left(A_V\left[\frac{G_O(G_1+G_2)}{(G_O+G_L)[G_1+G_2+G_{IN}]+G_2(G_1+G_{IN})}\right]\right)\left[\frac{G_2}{G_1+G_2}\right]$$

This is of the form

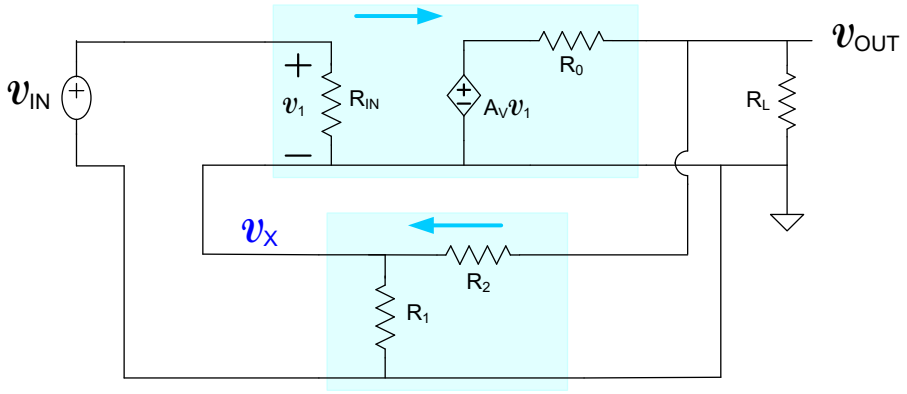
$$A_{LOOP} = (A_{VL})\left[\frac{G_2}{G_1+G_2}\right]$$

where A_{VL} is the open loop gain including loading of the load and β network !

$$A_{VL} = A_V\left[\frac{G_O(G_1+G_2)}{(G_O+G_L)[G_1+G_2+G_{IN}]+G_2(G_1+G_{IN})}\right]$$

Loop Gain - Aβ

But what if the amplifier is not ideal?



$$\beta = \frac{R_1}{R_1+R_2}$$

$$\beta = \frac{G_2}{G_1+G_2}$$

The Loop Gain is

$$A_{LOOP} = A_V\left[\frac{G_2G_O}{(G_O+G_L)[G_1+G_2+G_{IN}]+G_2(G_1+G_{IN})}\right]$$

The Forward Amplifier Gain is

$$A_{VL} = A_V\left[\frac{G_O(G_1+G_2)}{(G_O+G_L)[G_1+G_2+G_{IN}]+G_2(G_1+G_{IN})}\right]$$

Note that A_{VL} is affected by both its own input and output impedance and that of the β network

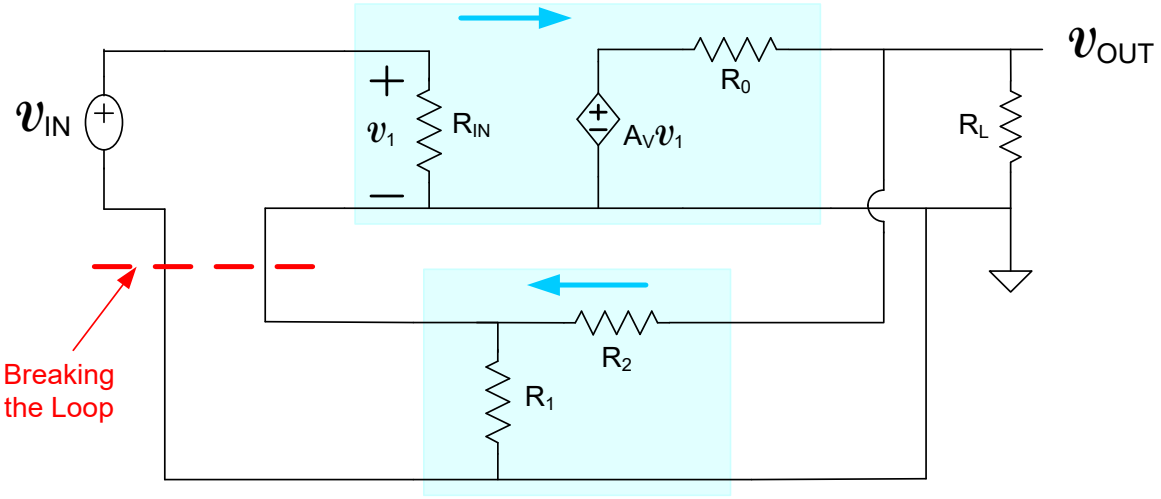
This is a really "messy" expression

Any "breaking" of the loop that does not result in this expression for A_{VL} will result in some errors though they may be small

Loop Gain - Aβ

(for voltage-series feedback configuration)

But what if the amplifier is not ideal?



- Most authors talk about breaking the loop to determine the loop gain Aβ
- In many if not most applications, breaking the loop will alter the loading of either the A amplifier or the β amplifier or both
- Should break the loop in such a way that the loading effects of A and β are approximately included
- Consequently, breaking the loop will often alter the actual loop gain a little
- Q-point must not be altered when breaking the loop (for analysis with simulator)
- In most structures, broken loop only gives an approximation to actual loop gain
- Sometimes challenging to break loop in appropriate way

Stay Safe and Stay Healthy !

End of Lecture 18