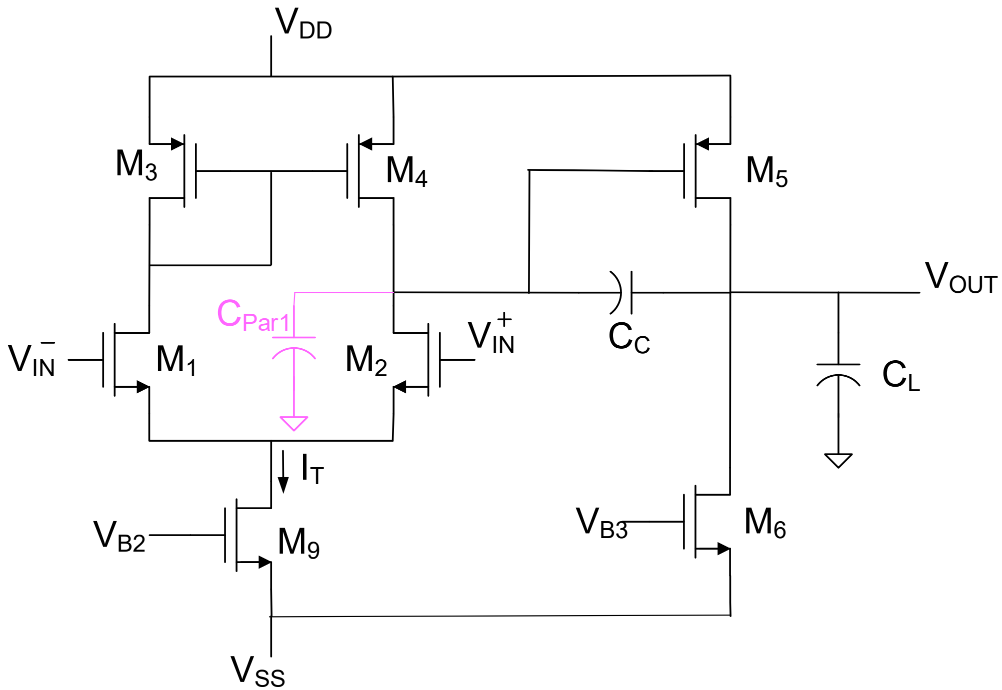
EE 435

Lecture 19

- Determination of Loop Gain
- Other methods of gain enhancement
- Linearity of Transfer Characteristics

Review from last lecture

Basic Two-Stage Op Amp



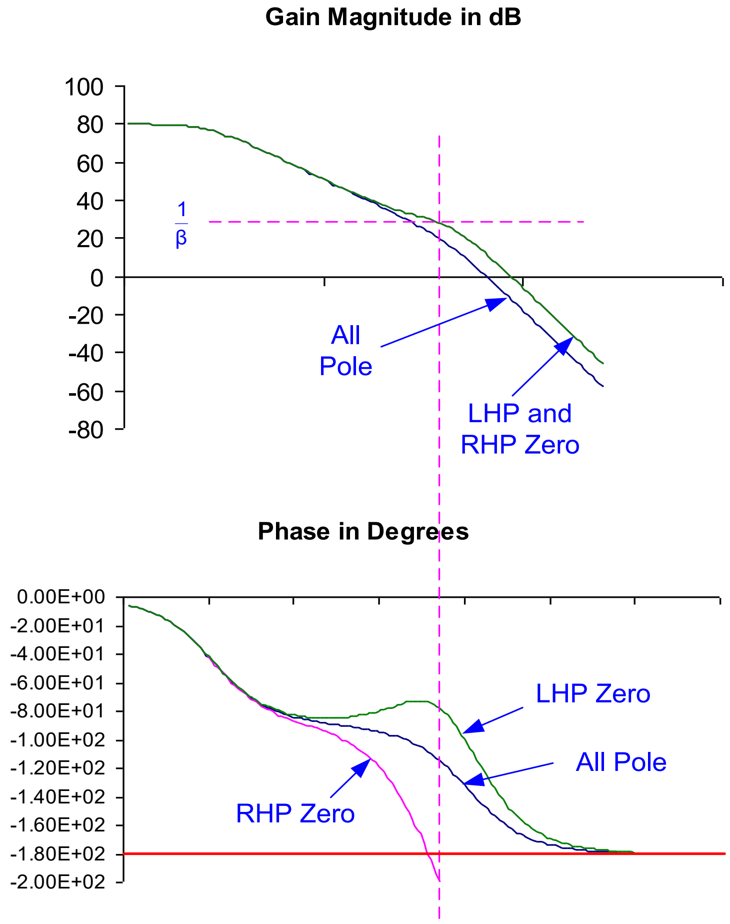
$$A_{FB}(s) \cong \frac{g_{md}(g_{m0} - sC_c)}{s^2 C_C C_L + sC_C(g_{mo} - \beta\, g_{md}) + \beta\, g_{md} g_{mo}}$$

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 ?

Review from last lecture

Why does the RHP zero limit performance ?



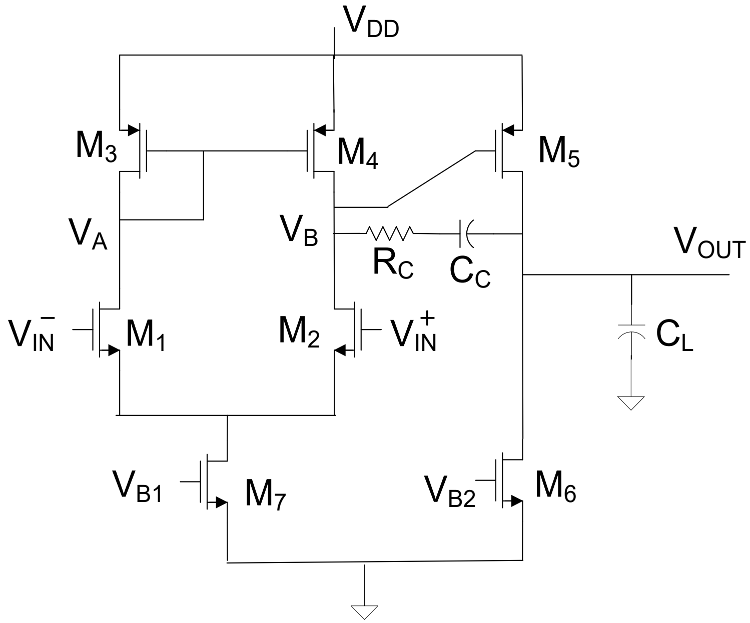
$p_1=1$, $p_2=1000$, $z_x=\{none,250,-250\}$

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

Review from last lecture

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

Review from last lecture

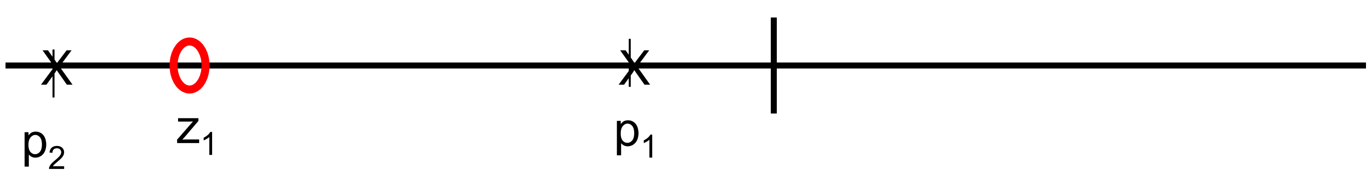
Two-stage amplifier with LHP Zero Compensation

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

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

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

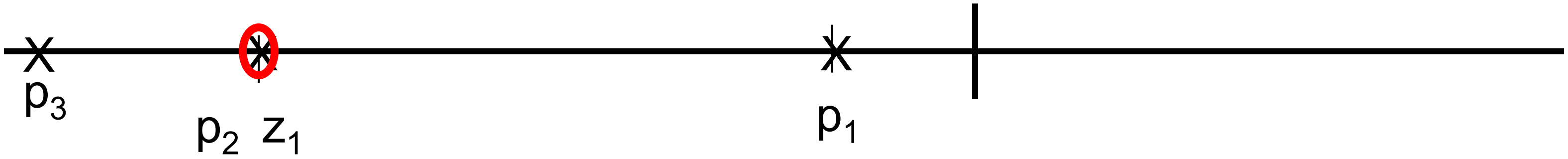
$$p_2=-\frac{g_{m5}}{C_L}$$



where should z_1 be placed?

Review from last lecture

Two-stage amplifier with LHP Zero Compensation



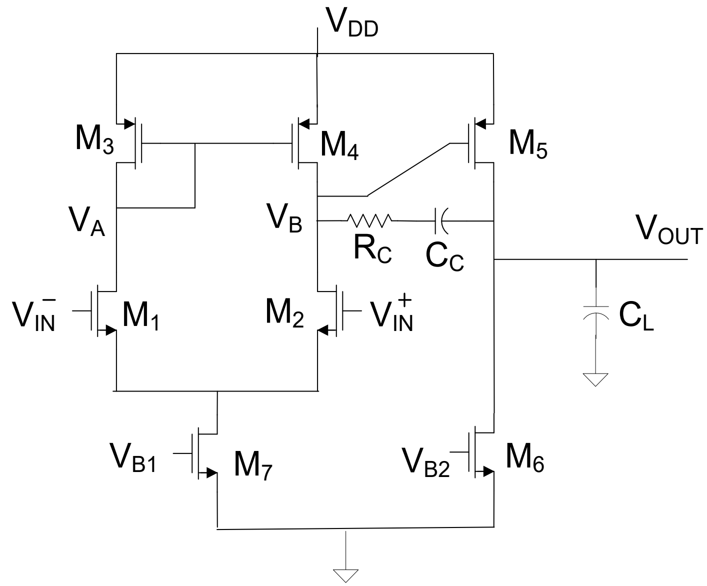
$$z_1 = \frac{-g_{m5}}{C_C\left[\frac{g_{m5}}{g_C}-1\right]}$$

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

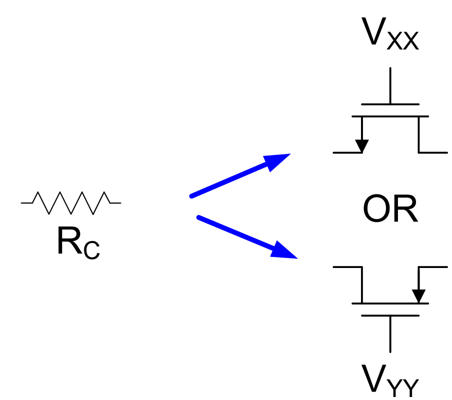
Review from last lecture

Basic Two-Stage Op Amp with LHP zero



Realization of R_C

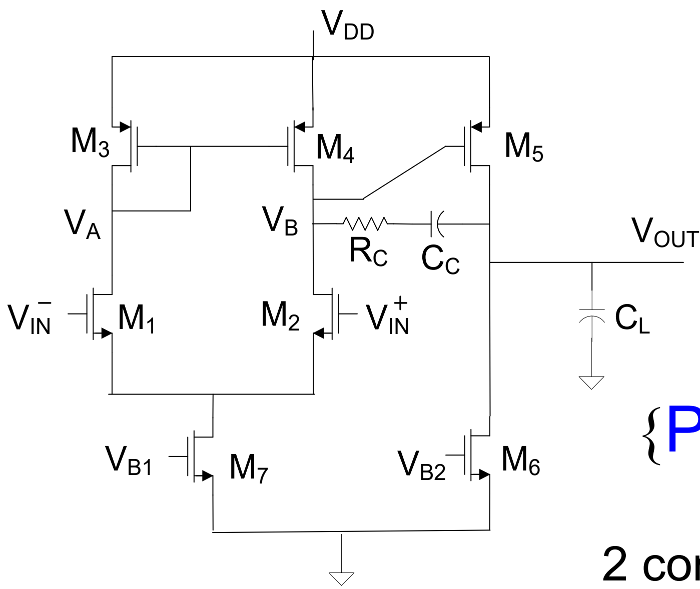
$$R_C = \frac{L}{\mu C_{OX} W V_{EB}}$$



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 gm5 over process and temp)

Review from last lecture

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:

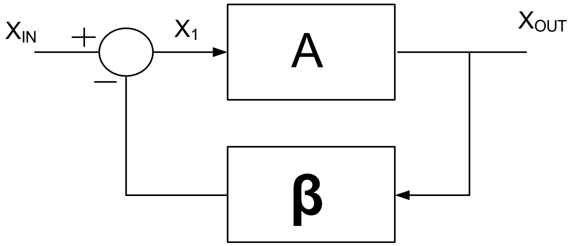
1. Ignore R_C and design as if RHP zero is present
2. Pick R_C to cancel p_2
3. Adjust p_1 (i.e. change/reduce C_C) to achieve desired phase margin

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

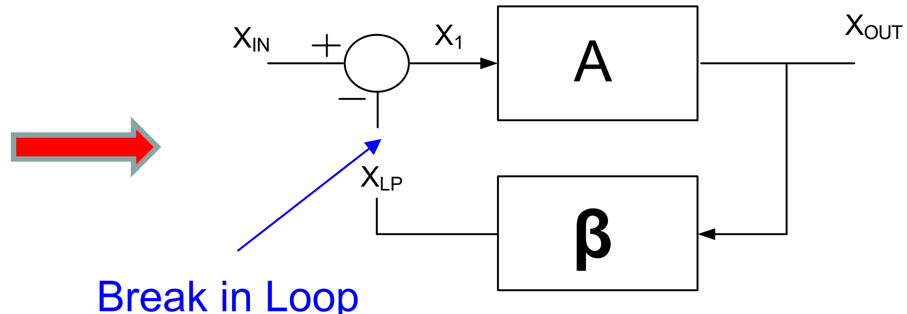
Review from last lecture

Two-Stage Amplifiers

Classical Loop Gain Analysis



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



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

- 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

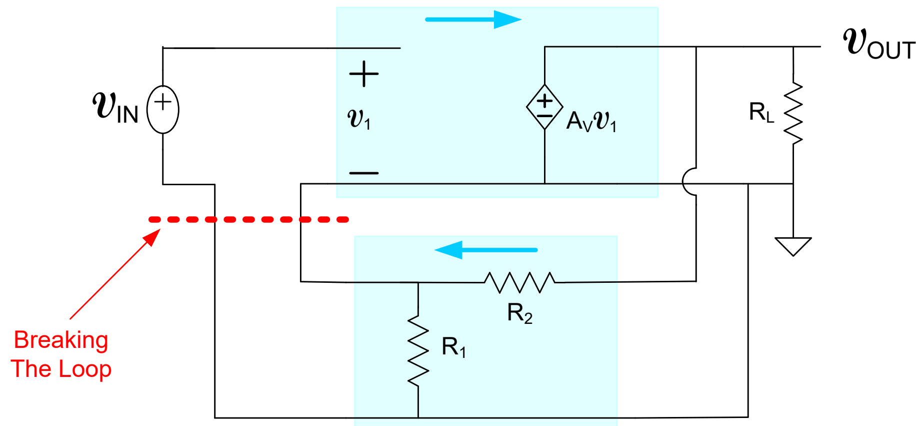
Loop Gain is a Critical Concept for Compensation of Feedback Amplifiers when Using Phase Margin Criteria (If you must!)

- 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

Review from last lecture

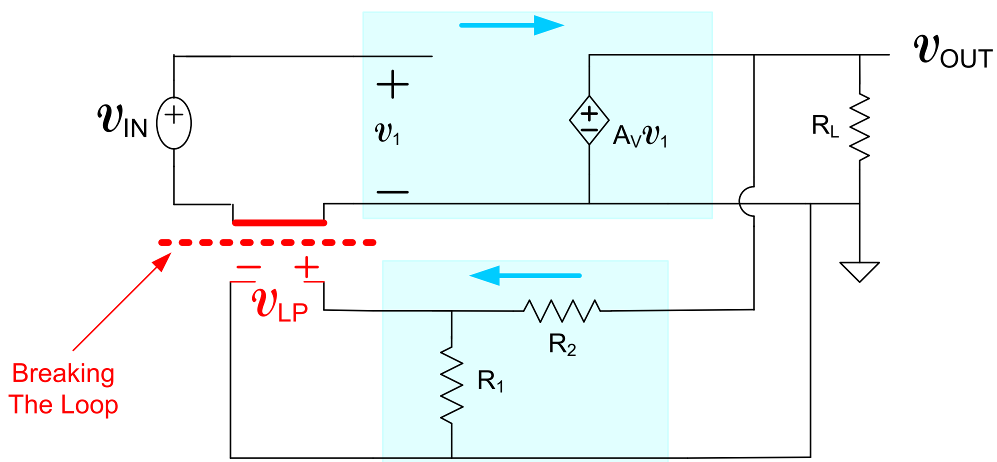
Loop Gain - Aβ

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



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

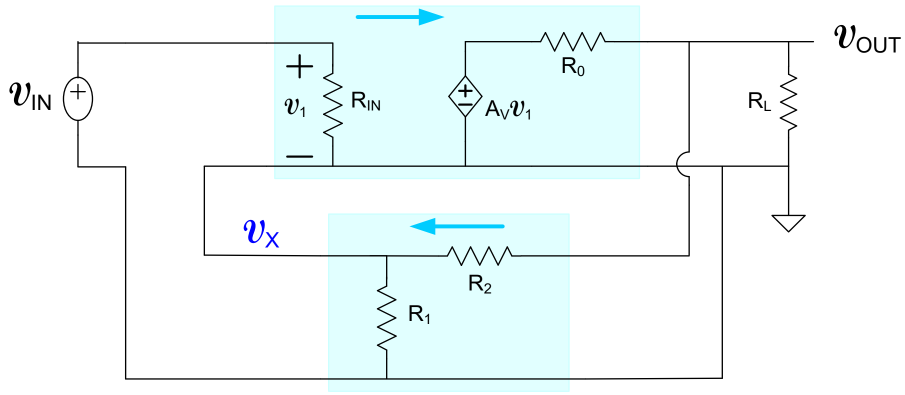
$$\frac{v_{LP}}{v_{IN}} = A_{LOOP} = A\beta$$

Block diagram represents small-signal feedback model

Review from last lecture

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

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

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

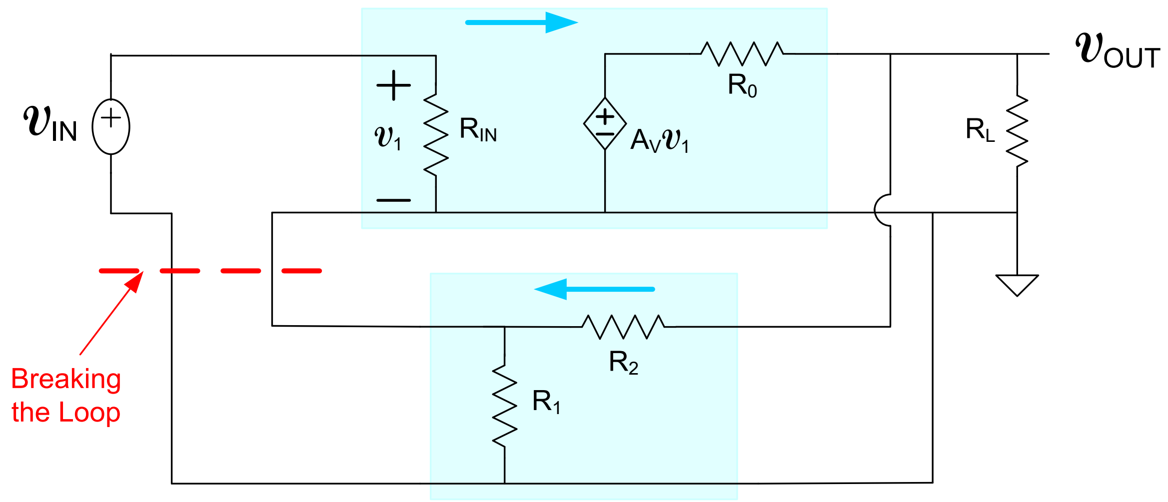
This is a really “messy” expression

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?

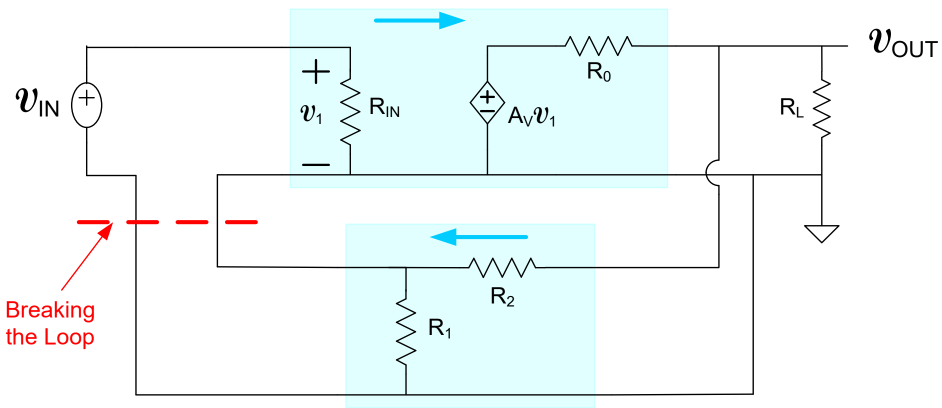


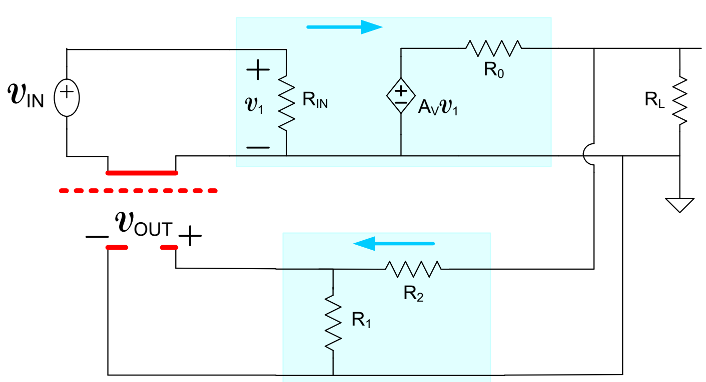
- Most authors talk about breaking the loop to determine the loop gain Aβ
- In many if not most applications, breaking the loop will alter the loading of either the A amplifier or the β amplifier or both
- Should break the loop in such a way that the loading effects of A and β are approximately included
- 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

Loop Gain - Aβ

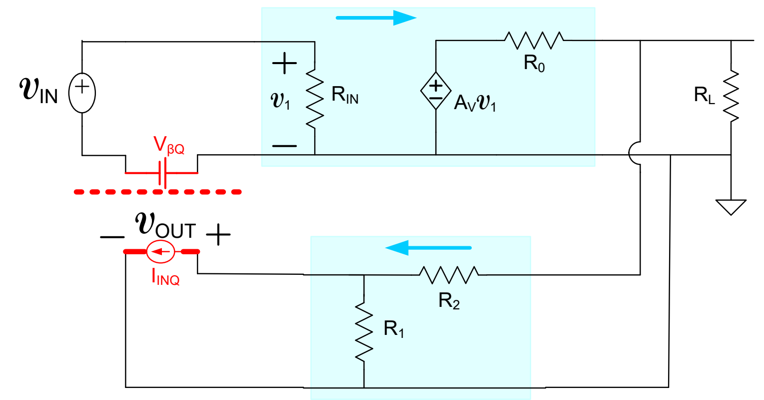
(for voltage-series feedback configuration)

But what if the amplifier is not ideal?





Standard Small-Signal Loop Gain Circuit



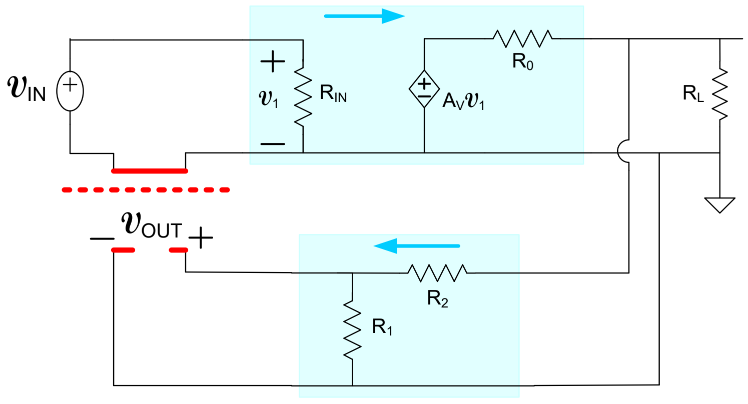
Standard Loop Gain Circuit including Biasing

(terminations shown in ss circuit are what is needed in the actual amplifier)

Loop Gain - Aβ

(for voltage-series feedback configuration)

But what if the amplifier is not ideal?



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

Loop Gain from Terminated Loop

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

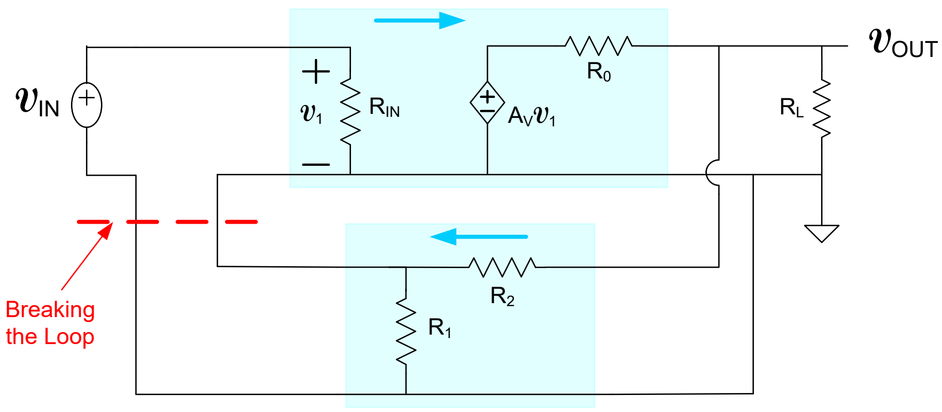
Real Loop Gain

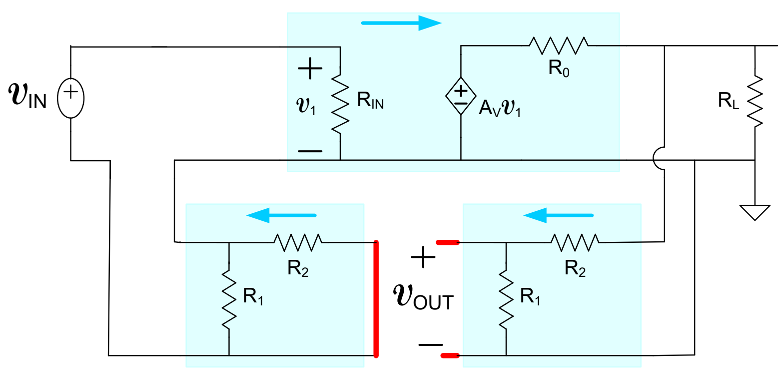
Breaking loop even with this termination will result in some error in A_{LOOP}

Loop Gain - Aβ

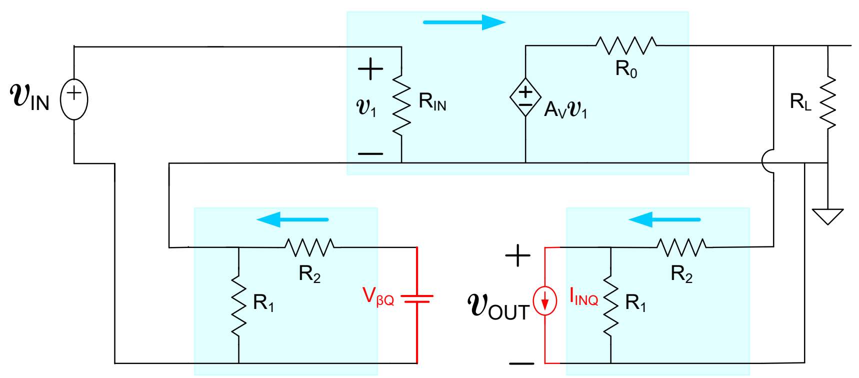
(for voltage-series feedback configuration)

But what if the amplifier is not ideal?





Better Standard Small-Signal Loop Gain Circuit



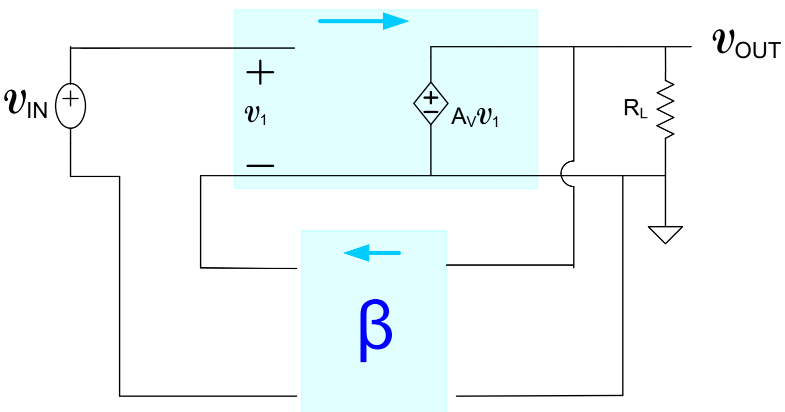
Better Loop Gain Circuit including Biasing

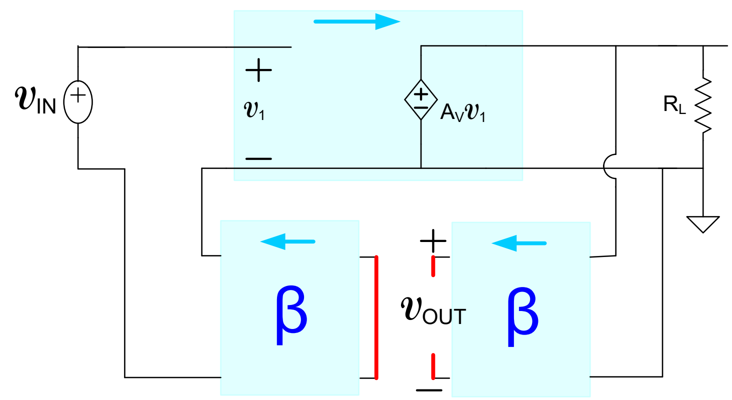
(terminations shown in ss circuit are what is needed in the actual amplifier)

Loop Gain - Aβ

for four basic amplifier types

voltage-series feedback

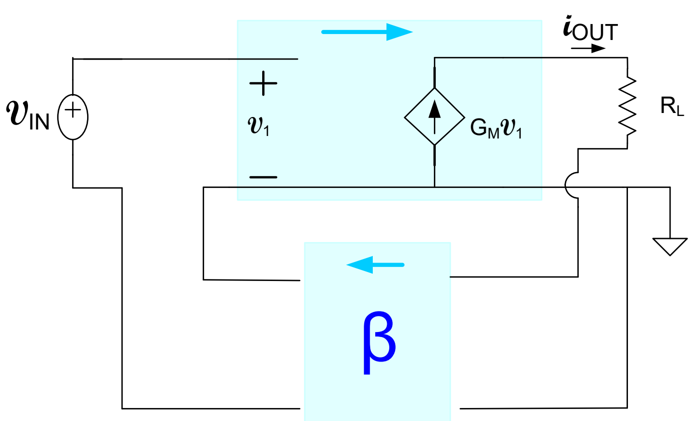


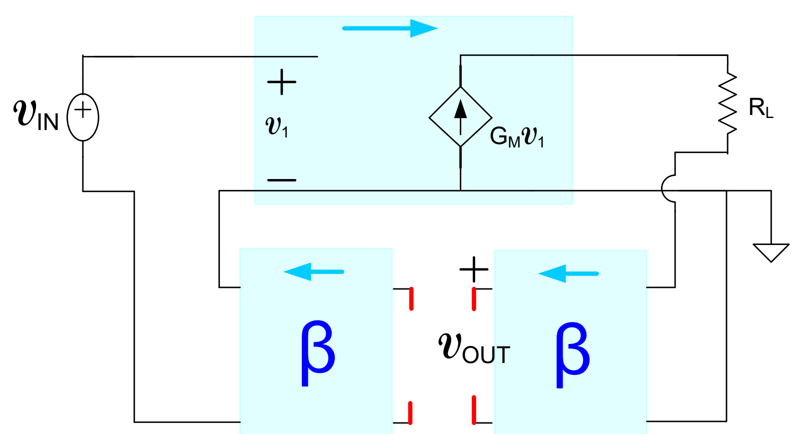


Feedback Amplifier

Loop Gain Amplifier

current-series feedback

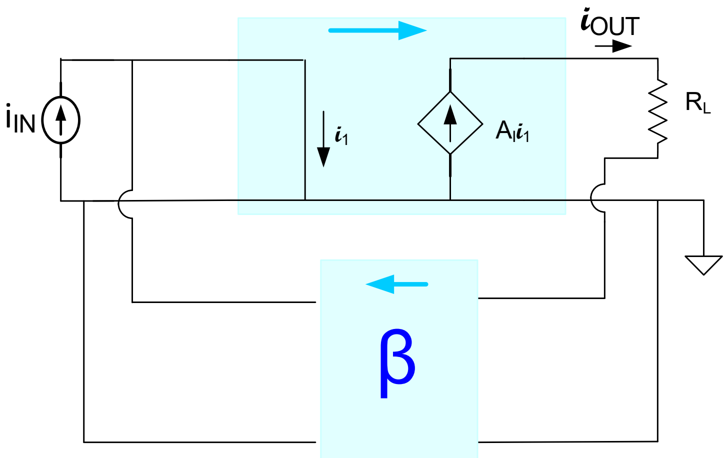


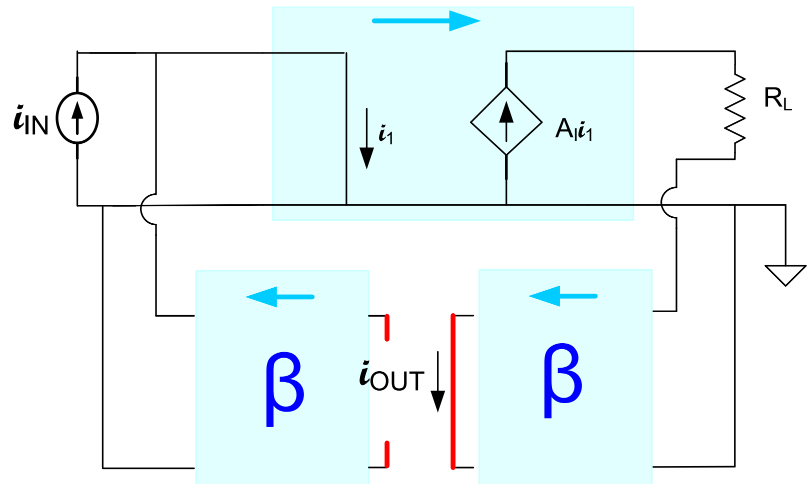


Loop Gain - Aβ

for four basic amplifier types

current-shunt feedback

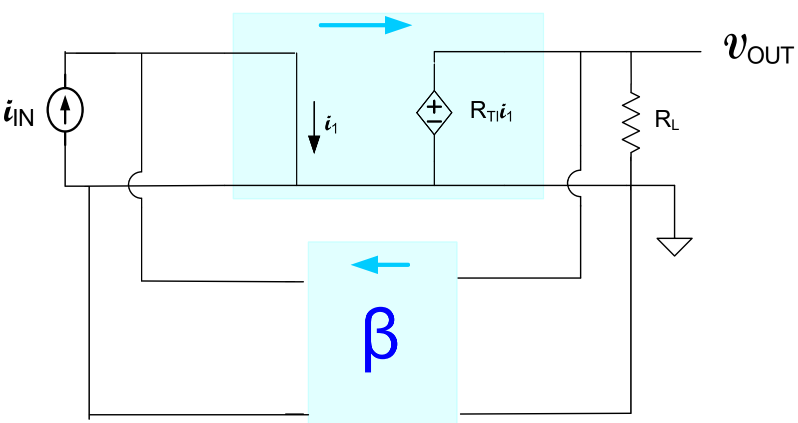


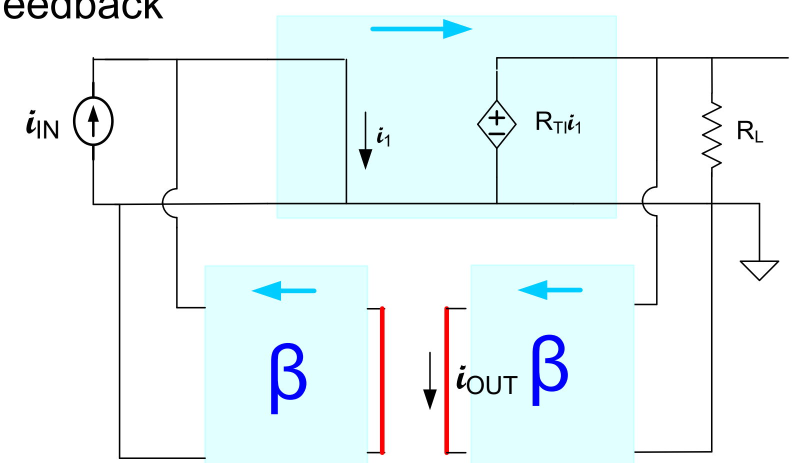


Feedback Amplifier

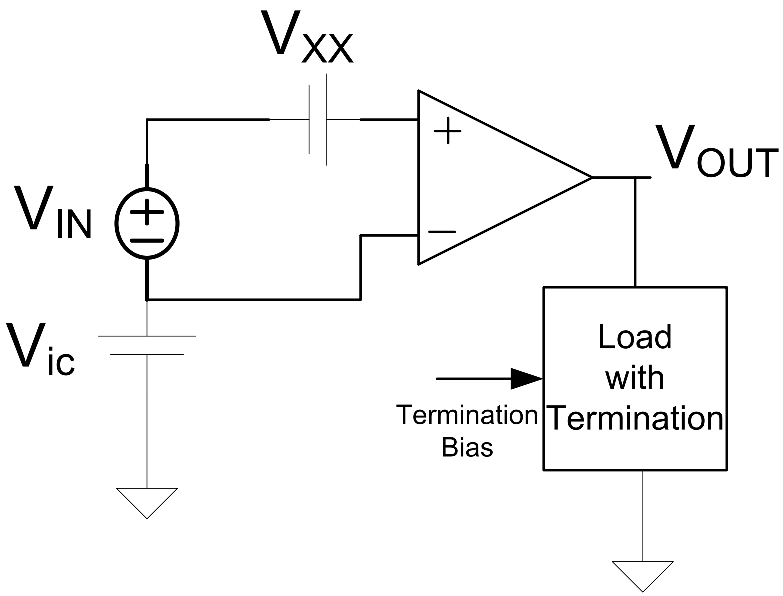
Loop Gain Amplifier

voltage-shunt feedback





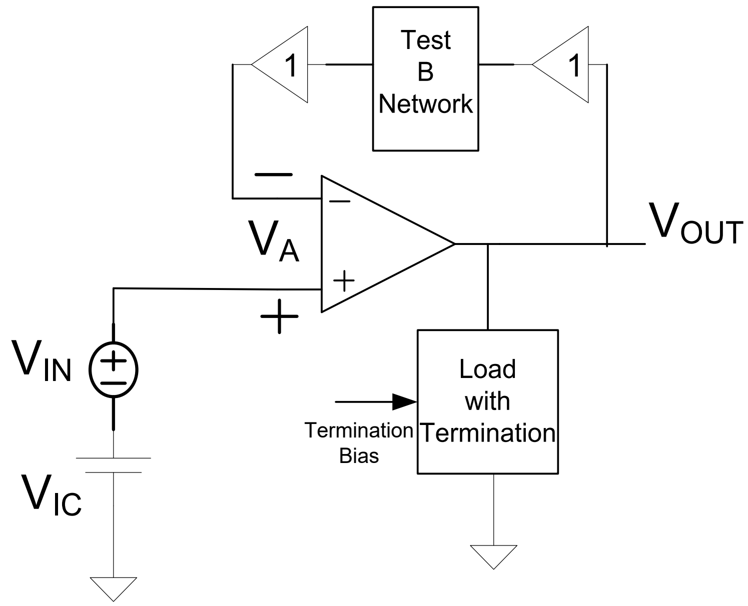
Open-loop gain simulations



- Must first adjust V_{XX} to trim out any systematic offset
- Always verify all devices are operating in the desired region of operation
- If an ac input is applied to V_{IN}, no information about linearity or signal swing will be obtained
- If any changes in amplifier circuit are made, V_{XX} must be trimmed again
- Include any loading including loading of beta network (with proper termination)

Open-loop gain simulations

(with a closed-loop test bench)



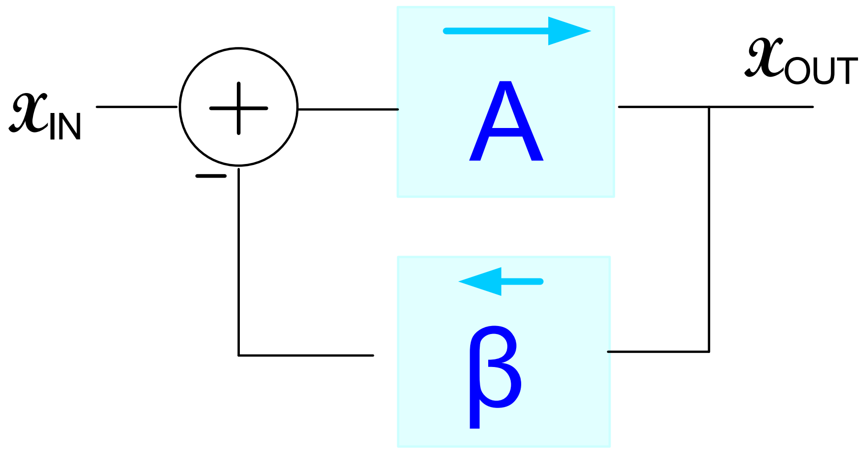
$$A_{VL} = \frac{V_{OUT}}{V_A}$$

- Stabilizes the effect of the systematic offset voltage
- Test β network may not be related to actual β at all
- Loading of actual β network included in "Load with Termination"
- Input and output buffers eliminate any loading effects of the test β network
- A_V must be calculated from measurements (simulations) of V_{OUT} and V_A
- Test β network must be chosen so overall network is stable

Why not just use actual β network for test β network?

Feedback circuit with actual β network may even be unstable before compensation is complete

Feedback simulations



Why not just simulate the frequency response of the actual feedback amplifier and look at the magnitude of the gain to see if that is what we want ?

Isn't that what we really want anyway?

If the amplifier is overly underdamped or oscillatory, won't that show up anyway?

Remember, the small-signal analysis will have the same magnitude response for minimum-phase and non-minimum phase systems !

Tools for Helping with Amplifier Compensation

Numerous tools but generally require analytical models

Based upon testbenches using actual circuit schematics (though behavioral descriptions can be included)

STB (in Spectre)

The Spectre STB analysis provides a way to simulate continuous time loop gain, phase margin and gain margin without breaking the feedback loop.

In the stability analysis you are required to choose a probe from which the loop gain measurements are taken. The probes, described below, can be found in the analogLib library.

Many sources on line discussing STB analysis.
(One youtube video is listed below (without assessment of either validity or quality)

https://youtu.be/L8wJhENPZNc

Other Methods of Gain Enhancement

$$A_{V0} = \frac{-g_{MQC}}{g_{OQC} + g_{OCC}} \Rightarrow A_{V0} = \frac{-g_{MQC1}}{g_{OQC1} + g_{OCC1}} \bullet \frac{-g_{MQC2}}{g_{OQC2} + g_{OCC2}}$$

Methods used so far:

Increasing the output impedance of the amplifier
cascode, folded cascode, regulated cascode

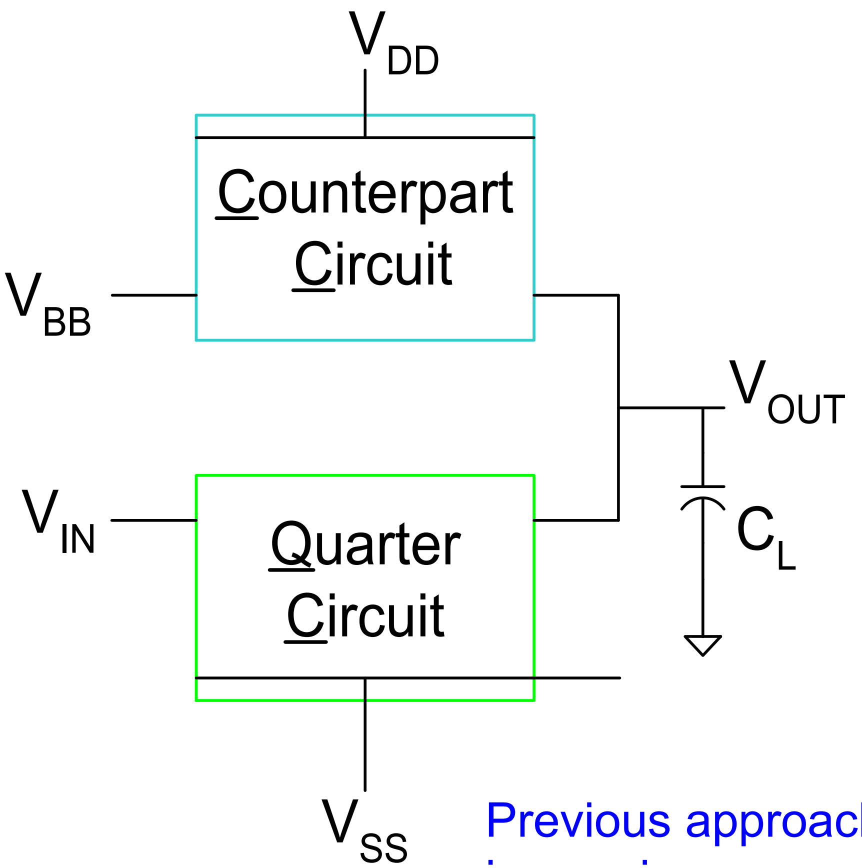
Increasing the transconductance
(current mirror op amp) but it didn't really help because
the output conductance increased proportionally

Cascading gives a multiplicative gain effect
(thousands of architectures but compensation is essential)
practically limited to a two-level cascade because of too much phase accumulation

Recall:

Other Methods of Gain Enhancement

Recall:



$$A_{V0} = \frac{-g_{MQC}}{g_{OQC} + g_{OCC}}$$

$$GB = \frac{g_{mQC}}{C_L}$$

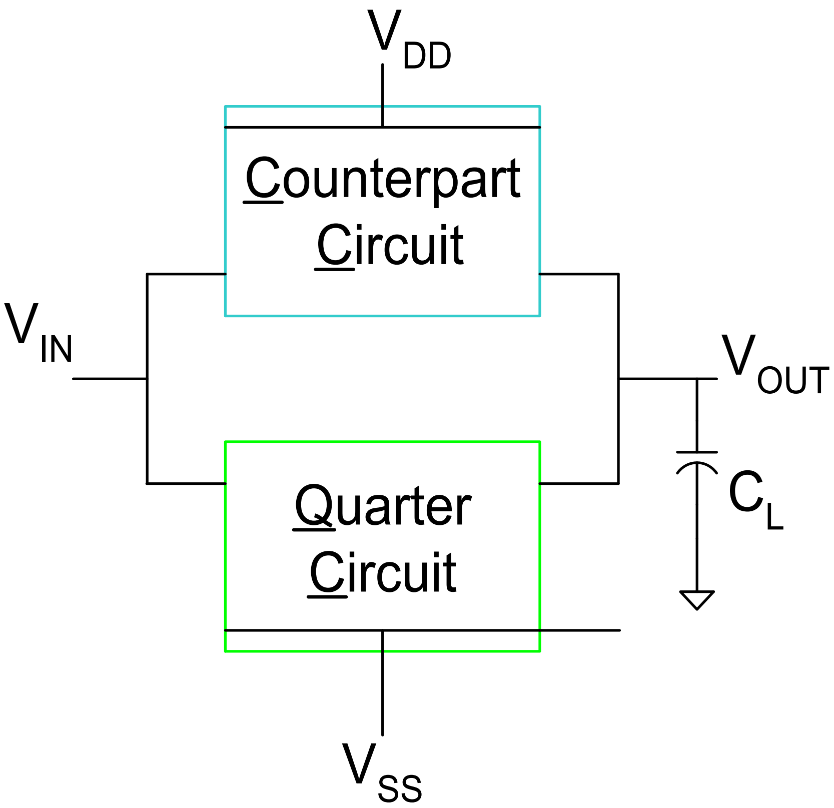
Two Strategies:

1. Decrease denominator of A_{V0}
2. Increase numerator of A_{V0}

Previous approaches focused on decreasing denominator or increasing numerator with current mirror

Consider now increasing numerator with excitation

Other Methods of Gain Enhancement



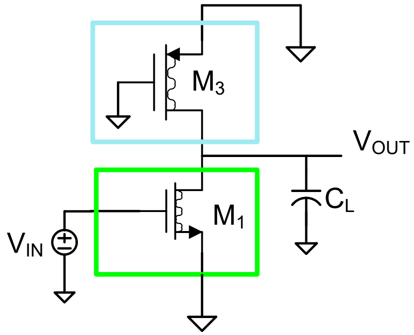
$$A_{V0} = \frac{-(g_{mQC} + g_{mCC})}{g_{oQC} + g_{oCC}}$$

$$GB = \frac{g_{mQC} + g_{mCC}}{C_L}$$

Consider now increasing numerator by changing the excitation

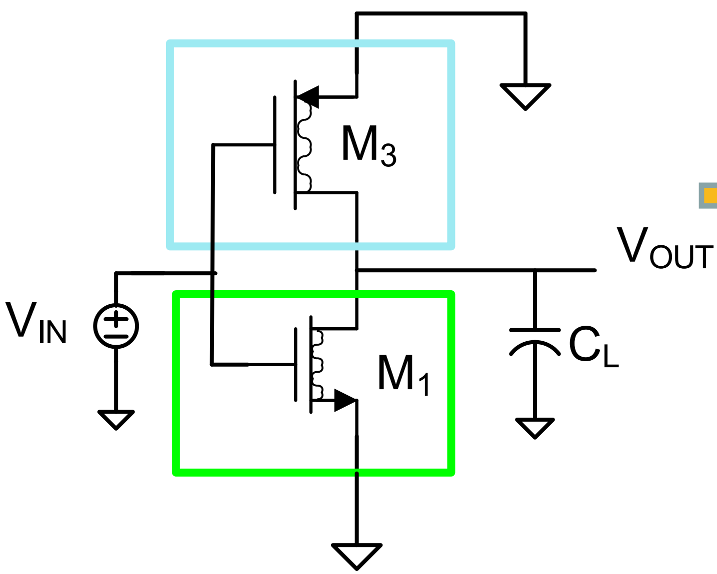
g_{meq} Enhancement with Driven Counterpart Circuit

Recall:



$$A_{V0} = \frac{g_{m1}}{g_{o1} + g_{o3}}$$

$$GB = \frac{g_{m1}}{C_L}$$

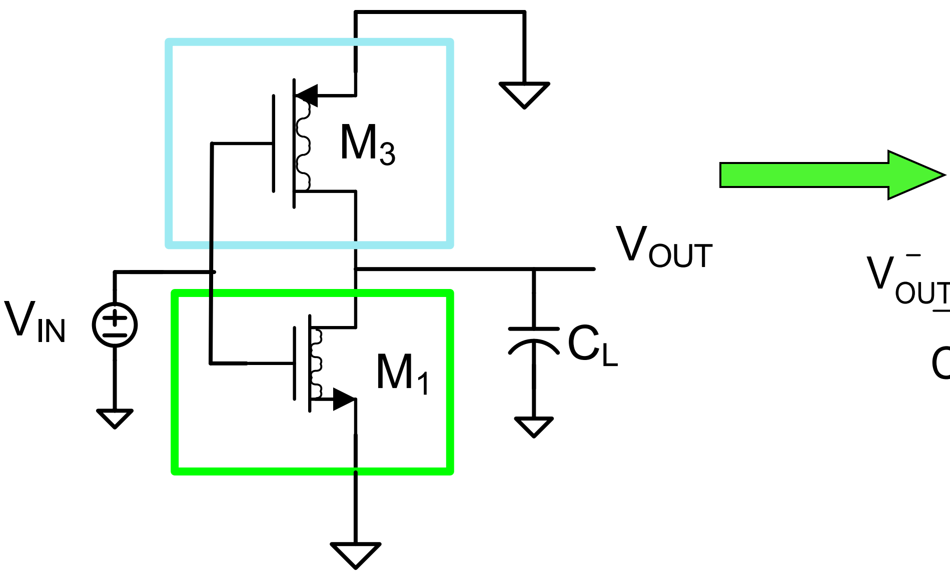


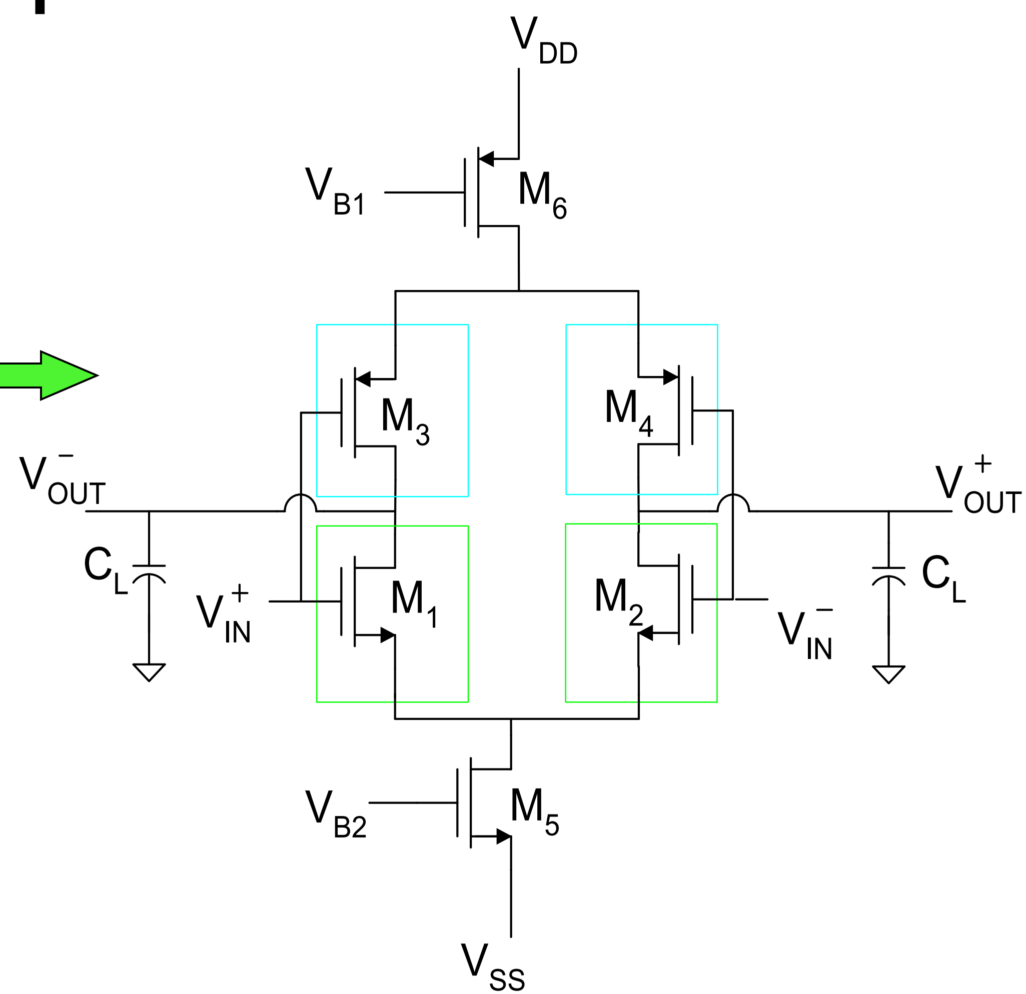
$$A_{V0} = \frac{g_{m1} + g_{m3}}{g_{o1} + g_{o3}}$$

$$GB = \frac{g_{m1} + g_{m3}}{C_L}$$

- In the small-signal parameter domain, both gain and GB appear to be enhancement
- Is this real?

g_{meq} Enhancement with Driven Counterpart Circuit

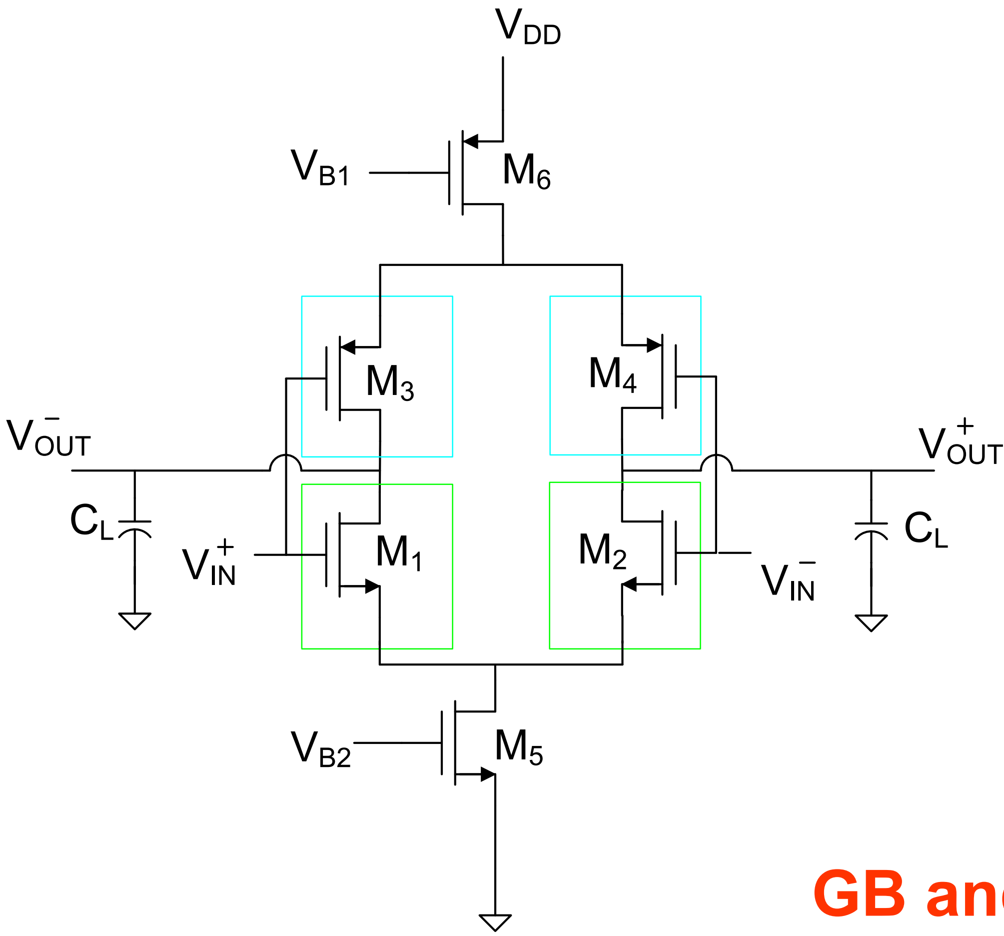




Needs CMFB Circuit to V_{B1} or V_{B2}

g_{meq} Enhancement with Driven Counterpart Circuit

Is this real?



$$A_{V0} = \frac{1}{2}\frac{g_{m1} + g_{m3}}{g_{o1} + g_{o3}}$$

$$GB = \frac{1}{2}\frac{g_{m1} + g_{m3}}{C_L}$$

$$A_{V0} = \frac{\frac{1}{V_{EB1}} + \frac{1}{V_{EB3}}}{\lambda_1 + \lambda_2}$$

$$GB = \left[\frac{P}{2V_{DD}C_L}\right]\left(\frac{1}{V_{EB1}} + \frac{1}{V_{EB3}}\right)$$

GB and A_{V0} improved !

Other Methods of Gain Enhancement

Increasing the output impedance of the amplifier
cascode, folded cascode, regulated cascode

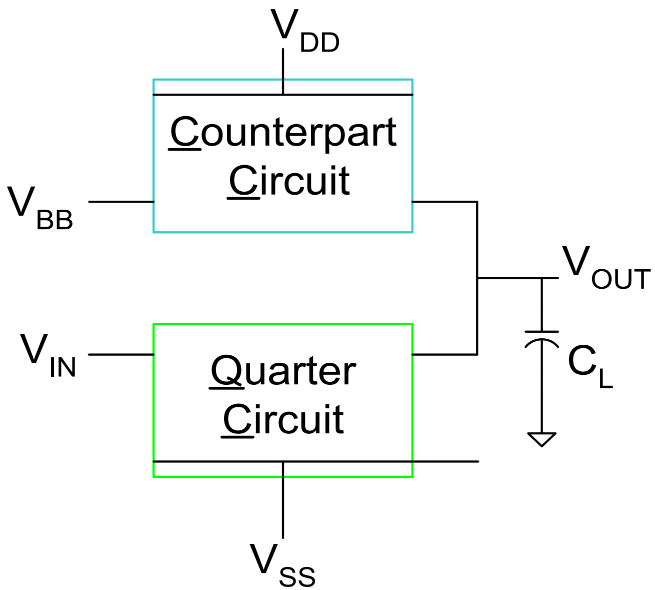
Increasing the transconductance
(current mirror op amp) but it didn't really help because
the output conductance increased proportionally

Driving the counterpart circuit does offer some improvements in gain

Cascading gives a multiplicative gain effect
(thousands of architectures but compensation is essential)
practically limited to a two-level cascade because of too much phase accumulation

Recall:

Other Methods of Gain Enhancement



$$A_{V0} = \frac{-g_{MQC}}{g_{OQC} + g_{OCC}}$$

Two Strategies:

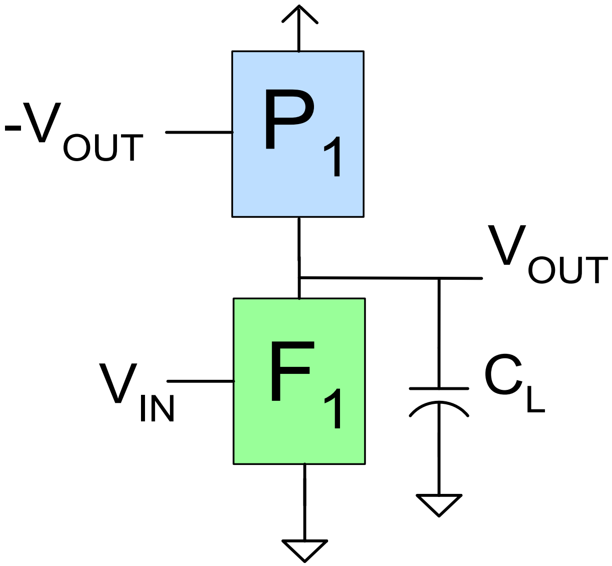
1. Decrease denominator of A_{V0}
2. Increase numerator of A_{V0}

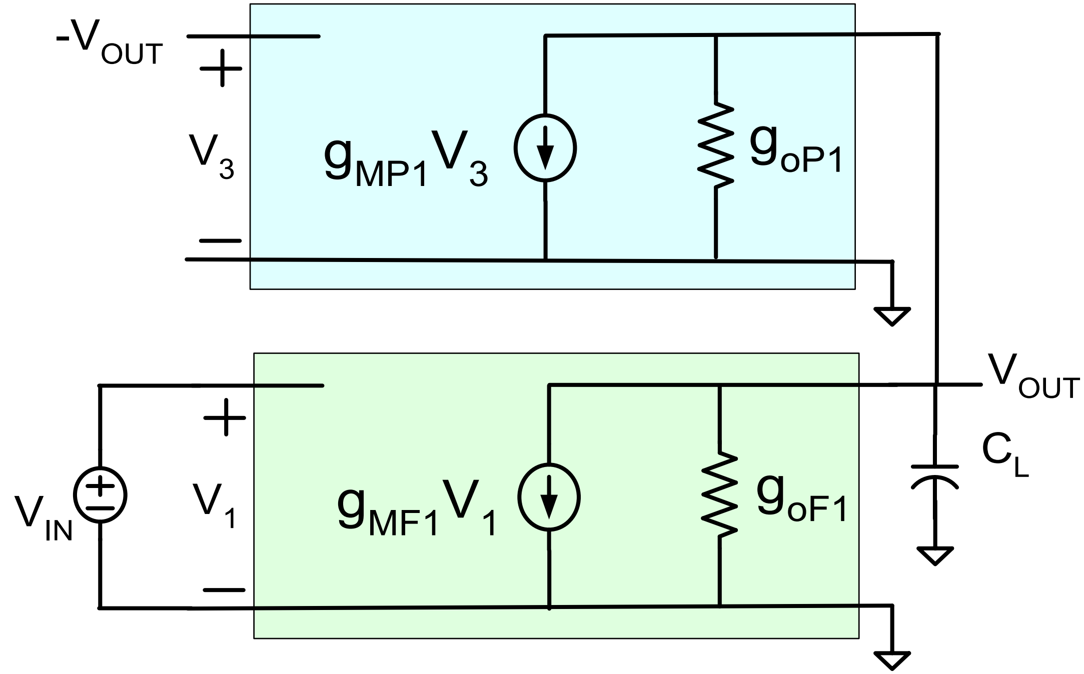
Consider again decreasing the denominator

$$A_{V0} = \frac{-g_{MQC}}{g_{OQC} + g_{OCC} - g_{OX}}$$

Is it possible to come up with circuits that will provide a subtraction of conductance in the denominator ?

Other Methods of Gain Enhancement

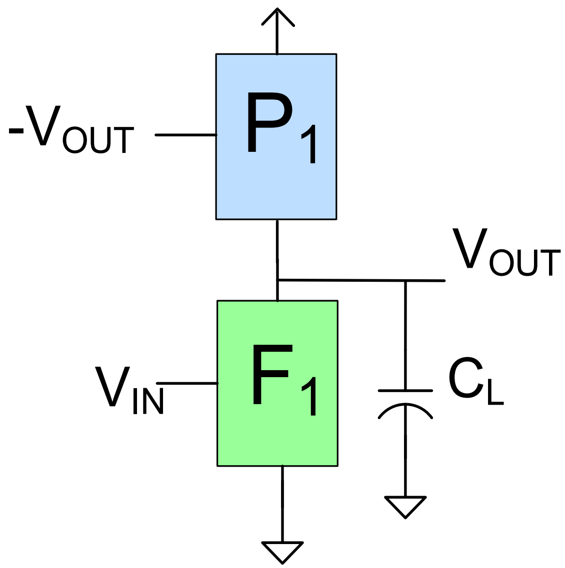




$$\left.\begin{aligned} &V_{OUT}\left(sC_L + g_{oP1} + g_{oF1}\right) + g_{mF1}V_{IN} + g_{mP1}V_3 = 0 \\ &V_3 = -V_{OUT} \end{aligned}\right\}$$

$$A_V(s) = \frac{-g_{MQC}}{sC_L + g_{OQC} + g_{OCC} - g_{MCC}} \qquad A_V(s) = \frac{-g_{mF1}}{sC_L + g_{oF1} + g_{oP1} - g_{mP1}}$$

Gain Enhancement with Regenerative Feedback



$$A_{V0} = \frac{-g_{mF1}}{sC_L + g_{oF1} + g_{oP1} - g_{mP1}}$$

$$A_{V0} = \frac{g_{mF1}}{g_{oF1} + g_{oP1} - g_{mP1}}$$

$$BW = \frac{g_{oF1} + g_{oP1} - g_{mP1}}{C_L}$$

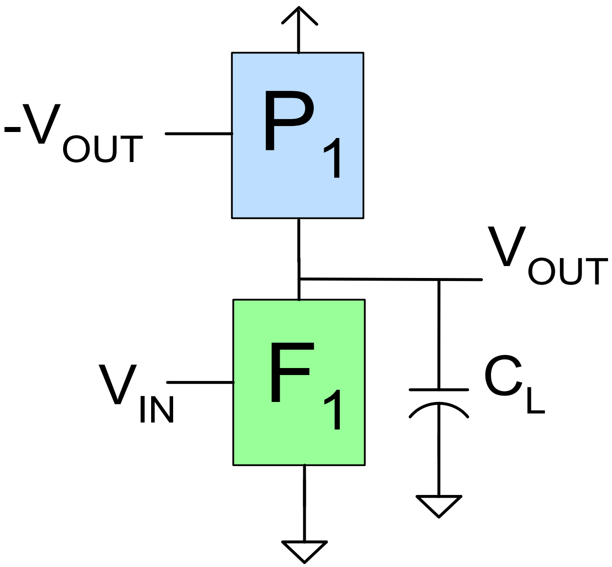
$$GB = \frac{g_{mF1}}{C_L}$$

The gain can be made arbitrarily large by selecting g_{mP1} appropriately

The GB does not degrade !

But if not careful, maybe g_{mP1} will get too large!

Gain Enhancement with Regenerative Feedback



$$A_{V0} = \frac{-g_{mF1}}{sC_L + g_{oF1} + g_{oP1} - g_{mP1}}$$

$$A_{V0} = \frac{g_{mF1}}{g_{oF1} + g_{oP1} - g_{mP1}}$$

$$BW = \frac{g_{oF1} + g_{oP1} - g_{mP1}}{C_L}$$

$$GB = \frac{g_{mF1}}{C_L}$$

The gain can be made arbitrarily large by selecting g_{mP1} appropriately

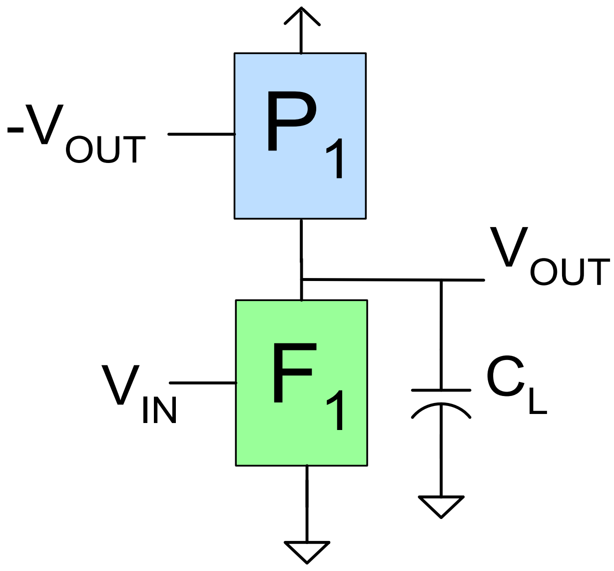
The GB does not degrade !

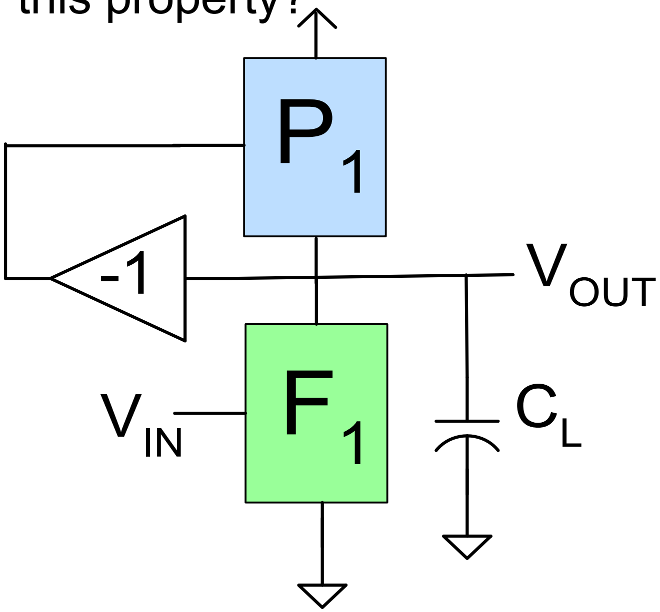
This circuit has a positive feedback loop (V_{INP1}:V_{OUT}:-V_{OUT})

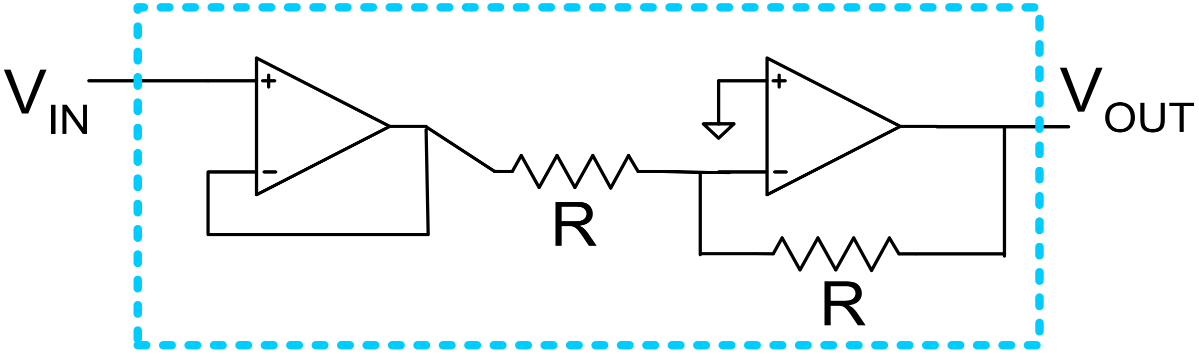
But - can we easily build circuits with this property?

Gain Enhancement with Regenerative Feedback

But - can we easily build circuits with this property?





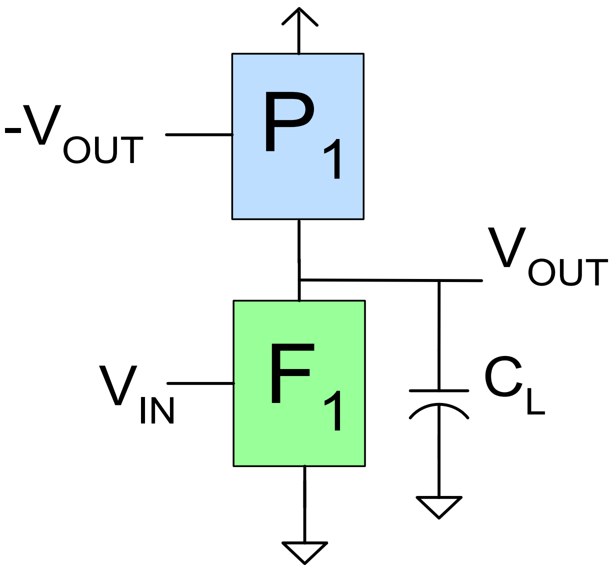


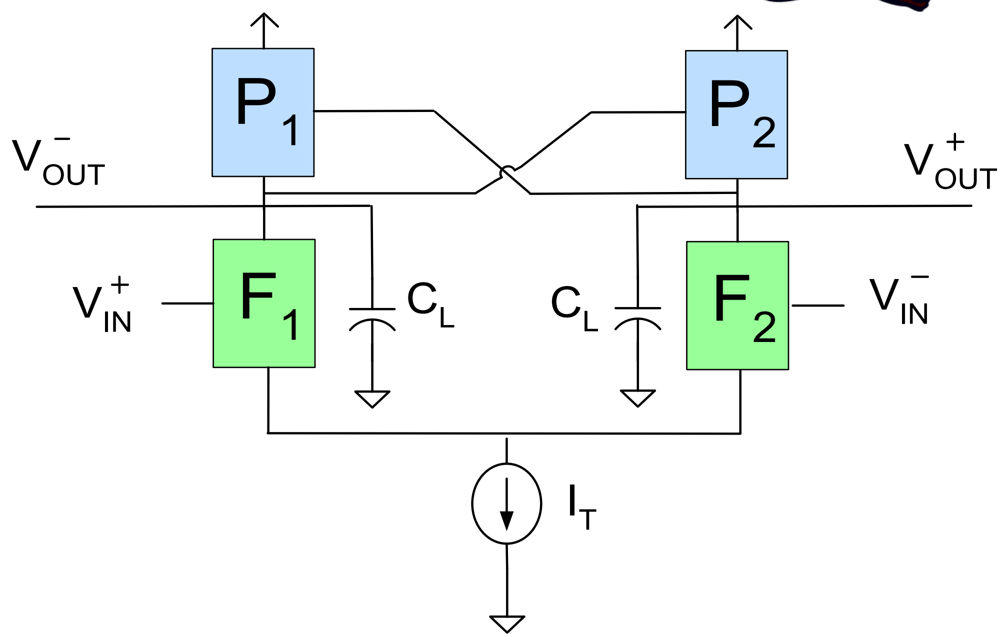
But – the inverting amplifier may be more difficult to build than the op amp itself!

Do we need 2 op amps, one serving as a buffer to drive the R resistors?

Gain Enhancement with Regenerative Feedback

But - can we easily build circuits with this property?

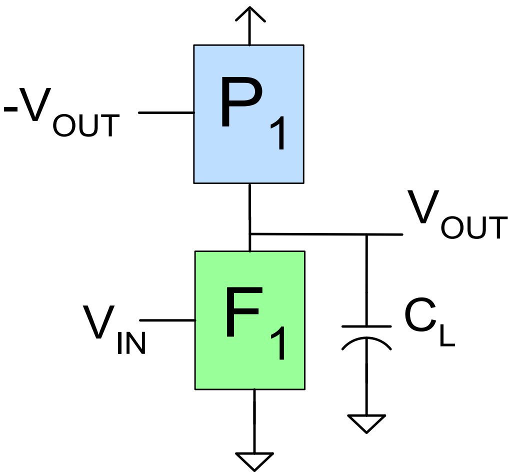




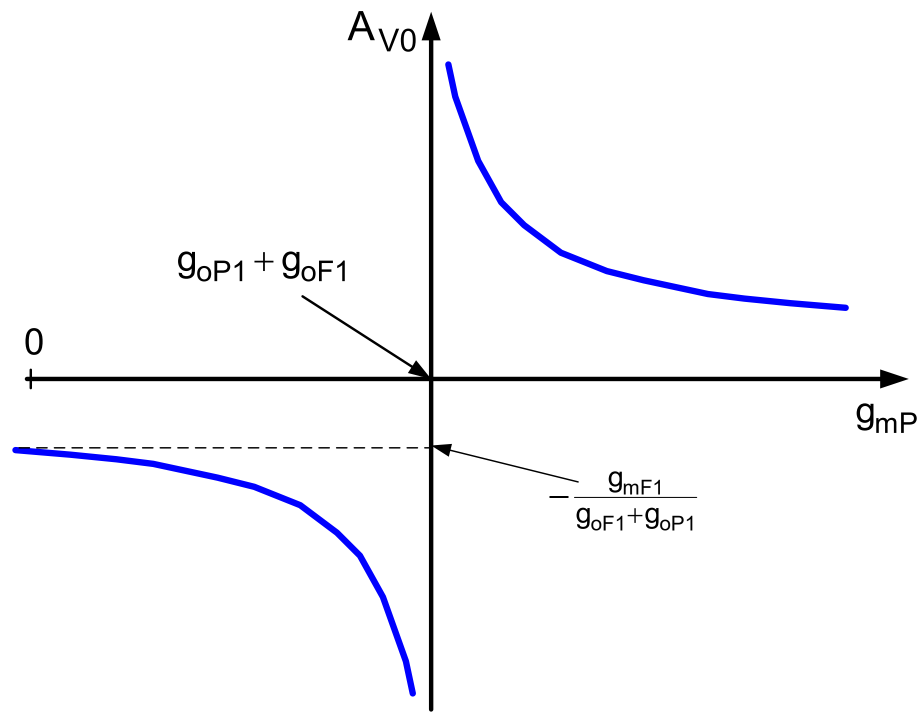
But – the inverting amplifier may be more difficult to build than the op amp itself!

YES – simply by cross-coupling the outputs in a fully differential structure

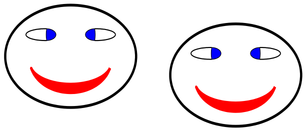
Gain Enhancement with Regenerative Feedback



$$A_{V0}(s) = \frac{-g_{mF1}}{sC_L + g_{oF1} + g_{oP1} - g_{mP1}}$$

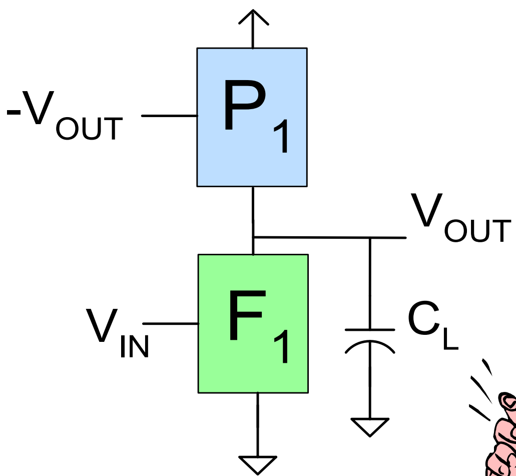


If $g_{mP1} = g_{oF1}+g_{oP1}$, the dc gain will become infinite !!



Term this “gain reversing” when dc gain changes sign with pole

Gain Enhancement with Regenerative Feedback



$$A_{V0}(s) = \frac{-g_{mF1}}{sC_L + g_{oF1} + g_{oP1} - g_{mP1}}$$

$$p = \frac{-g_{oF1} - g_{oP1} + g_{mP1}}{C_L}$$

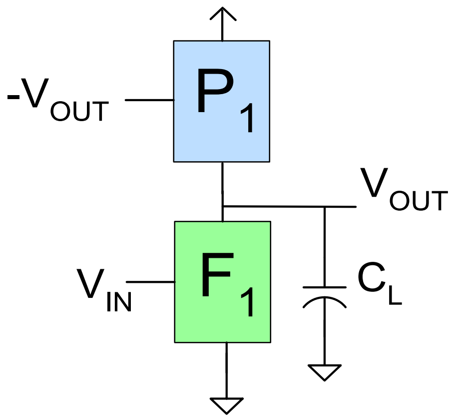
If $g_{mP1} > g_{oF1} + g_{oP1}$, the pole will be in the RHP !!

This will make the op amp unstable

Positive Feedback is BAD !!

This is the major reason most have avoided using the structure !

Gain Enhancement with Regenerative Feedback



This will make the op amp unstable

Positive Feedback is BAD !!

This is the major reason most have avoided using the structure !

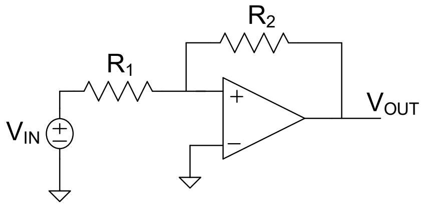
But is Positive Feedback really bad?

Is an unstable operational amplifier really bad?

Is positive feedback bad?

Is an unstable operational amplifier really bad?

From Problem 7 HW 1



Why is this circuit is seldom discussed?

Support your answer with sound analytical principles or concepts.

Stay Safe and Stay Healthy !

End of Lecture 19