EE 435

Lecture 19

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

Lecture 18: Executive Summary

Thank You Lance

RHP zero degrades phase margin.

LHP zero improves phase margin and doesn't affect magnitude of the transfer function.

Number of Poles = Energy Storage Elements - Energy Storage Loops

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

Theta is desired to be as close to 1 as possible to maximize GB.

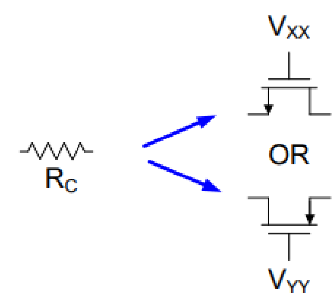
Adding a resistor Rc can help move a RHP zero.

Cancelling p2 with a zero causes an improvement in phase margin, as well as helping GB to increase due too p1 to move farther away from the imaginary axis.

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

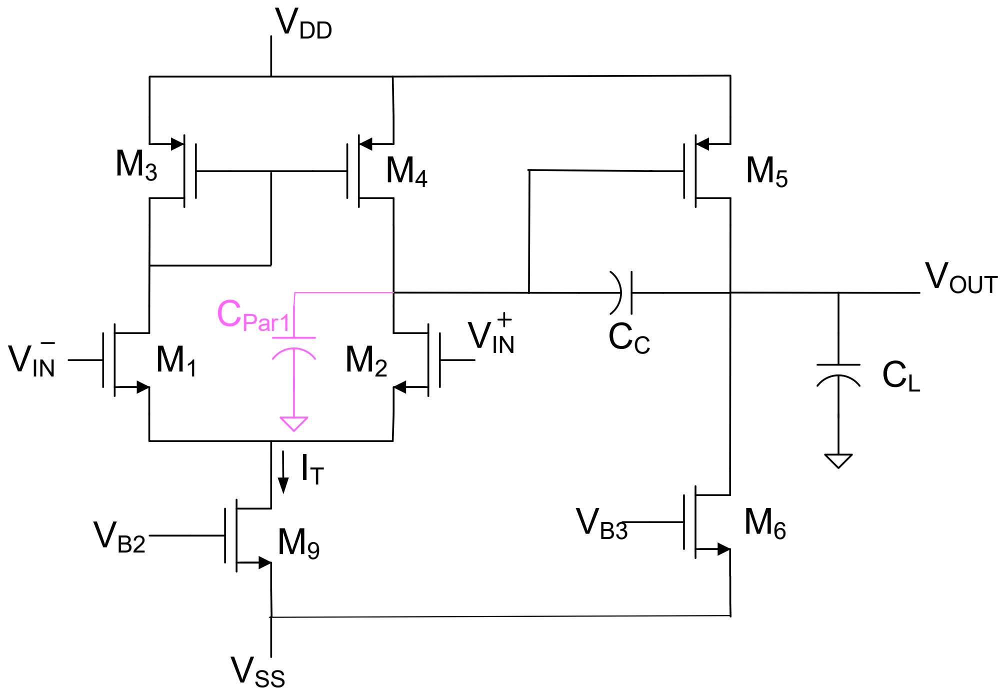
A resistor can be created using a transistor in the triode region.

VDD or GND are often used for Vxx or Vyy



Review from last lecture

Basic Two-Stage Op Amp



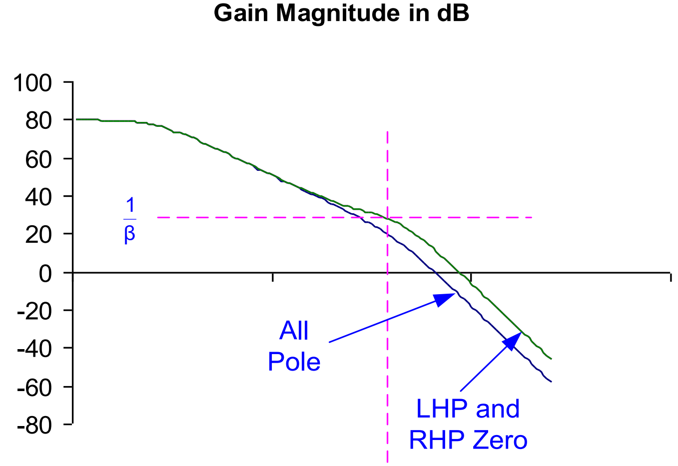
$$A_{FB}(s) \cong \frac{g_{md}(g_{m0} - sC_c)}{s^2 C_c C_L + sC_C(g_{mo} - \beta\, g_{md}) + \beta\, g_{md} g_{mo}}$$

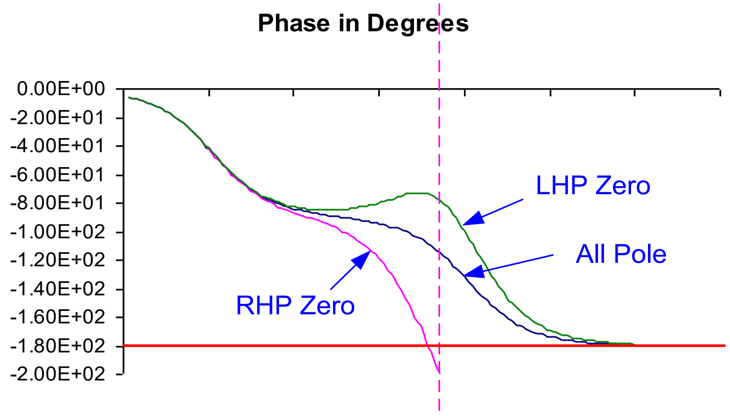
Right Half-Plane Zero Limits Performance

- 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 ?





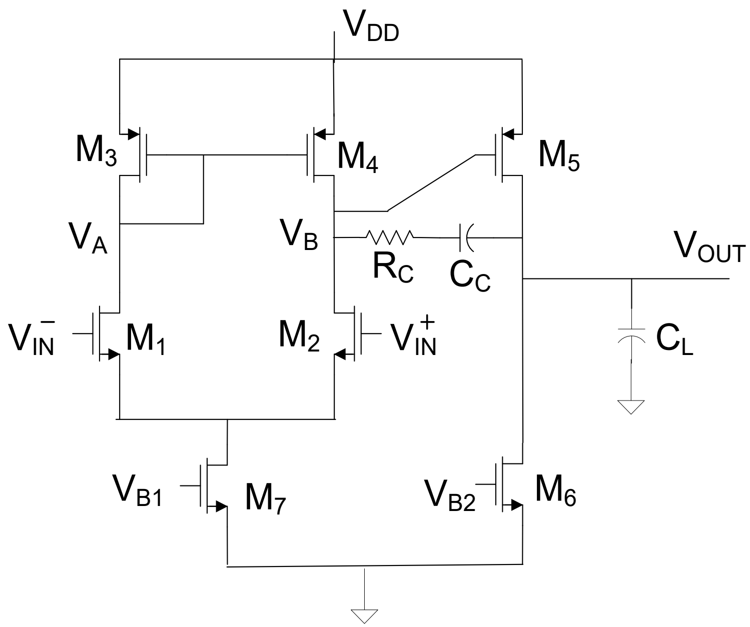
$p_1=1$, $p_2=1000$, $z_x=\{none,250,-250\}$

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

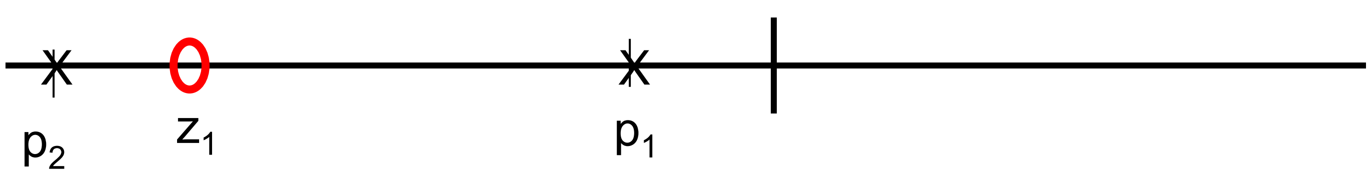
R_C has almost no effect on p_1 and p_2

Two-stage amplifier with LHP Zero Compensation

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

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

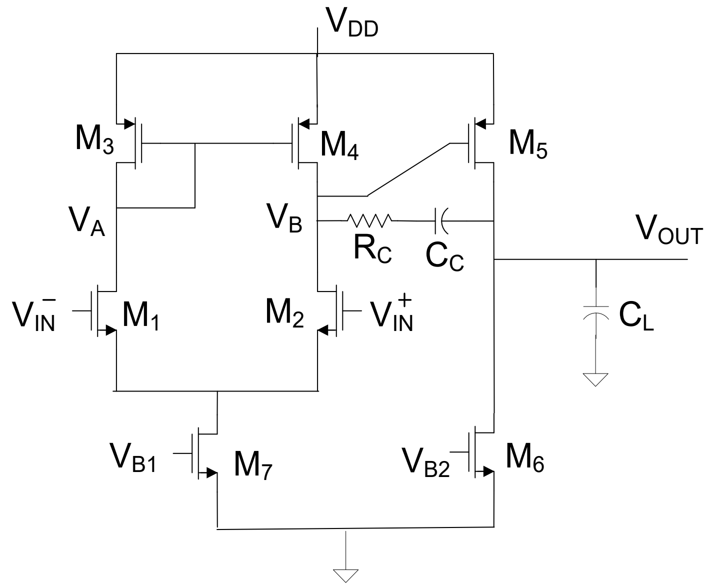
$$p_1=-\frac{g_{o1}+g_{o5}}{C_C\left(\frac{g_{m5}}{g_{05}+g_{o6}}\right)} \qquad p_2=-\frac{g_{m5}}{C_L}$$



where should z_1 be placed?

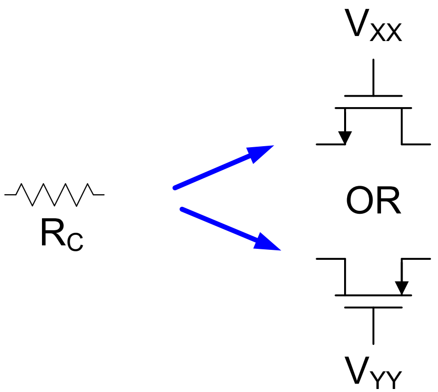
Review from last lecture

Basic Two-Stage Op Amp with LHP zero



Realization of R_C

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

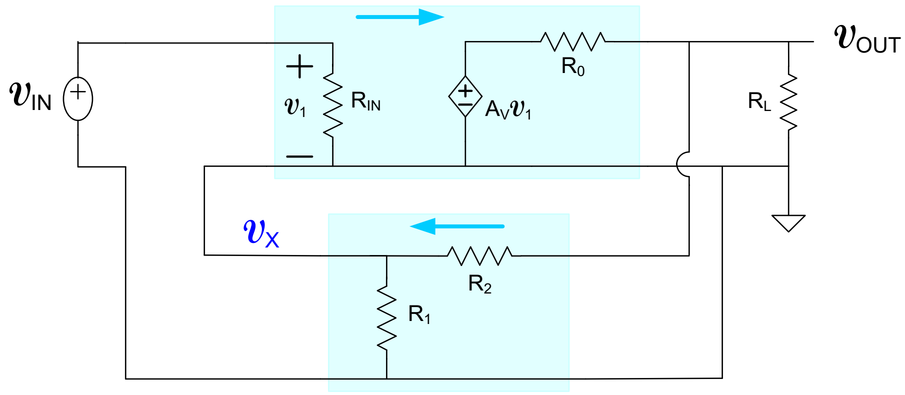


Transistors in triode region
Very little current will flow through transistors (and no dc current)
V_{DD} or GND often used for V_{XX} or V_{YY}
V_{BQ} well-established since it determines I_{Q5}
Using an actual resistor not a good idea (will not track gm5 over process and temp)

Review from last lecture

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

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

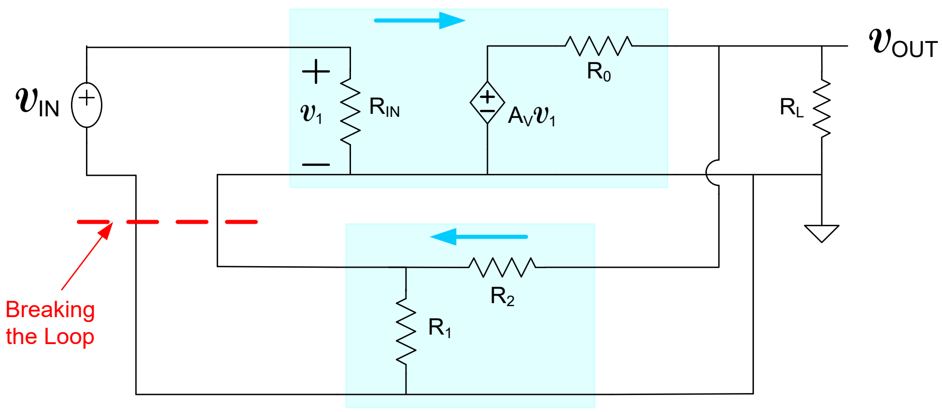
where A_{VL} is the open loop gain including loading of the load and β network !

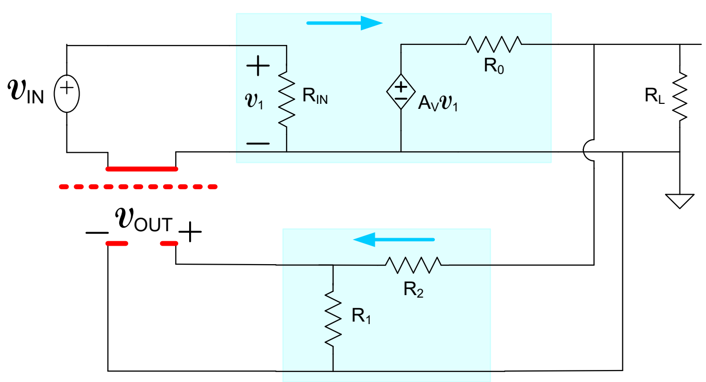
$$A_{VL} = A_V\left[\frac{G_O(G_1+G_2)}{(G_O+G_L)[G_1+G_2+G_{IN}]+G_2(G_1+G_{IN})}\right]$$

Loop Gain - Aβ

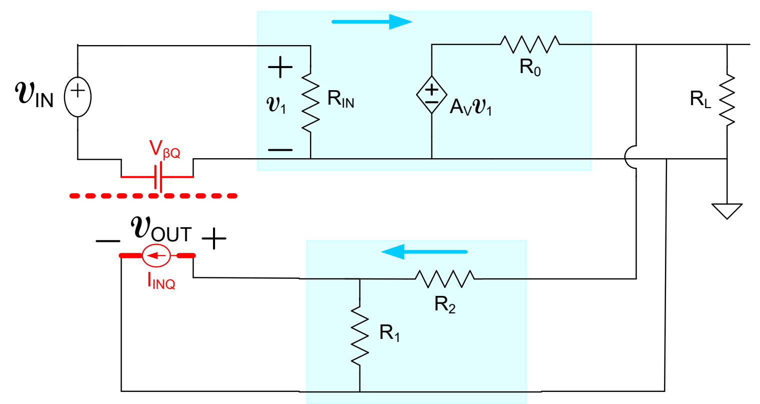
(for voltage-series feedback configuration)

But what if the amplifier is not ideal?





Standard Small-Signal Loop Gain Circuit



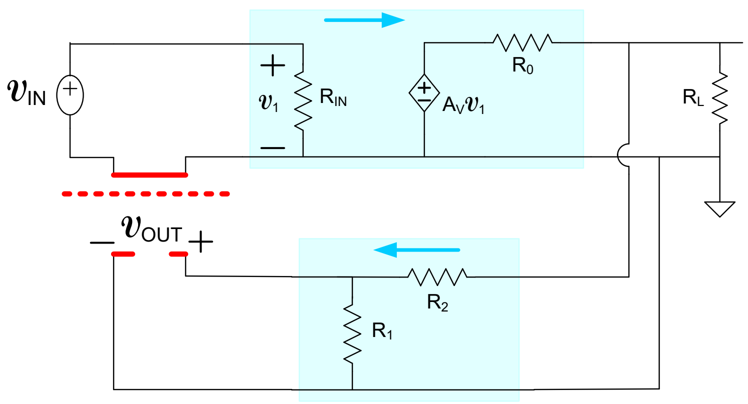
Standard Loop Gain Circuit including Biasing

(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?



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

Loop Gain from Terminated Loop

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

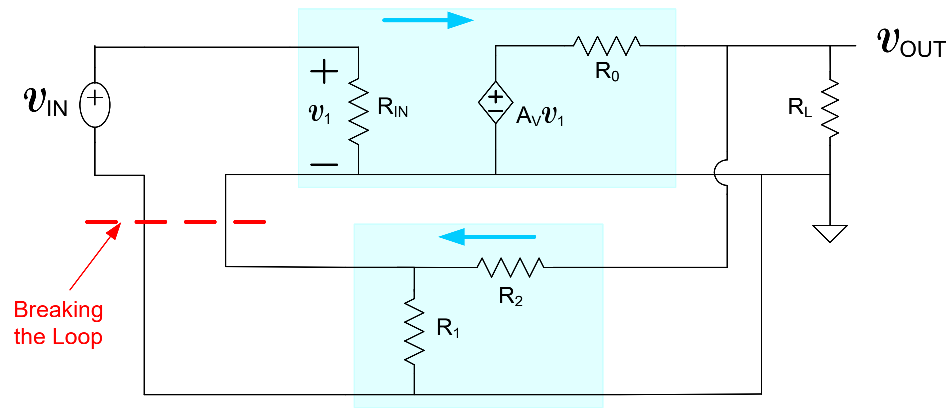
Real Loop Gain

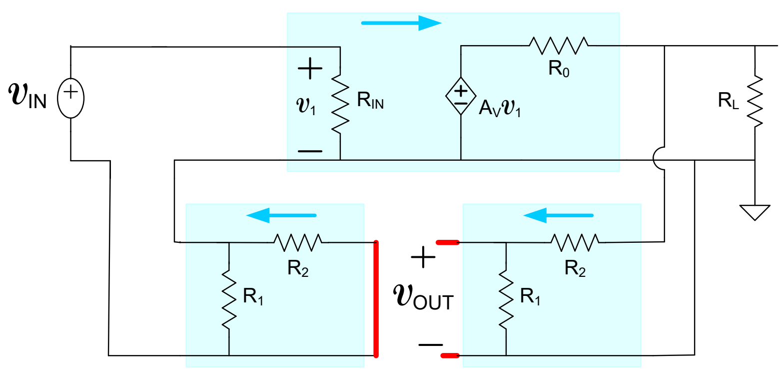
Breaking loop even with this termination will result in some error in A_{LOOP}

Loop Gain - Aβ

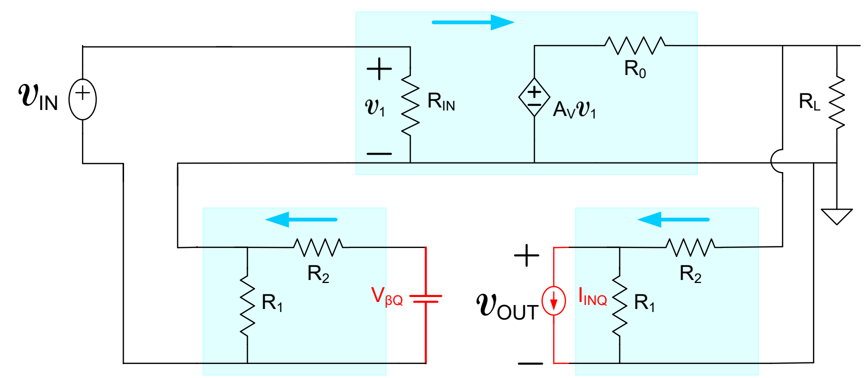
(for voltage-series feedback configuration)

But what if the amplifier is not ideal?





Better Standard Small-Signal Loop Gain Circuit



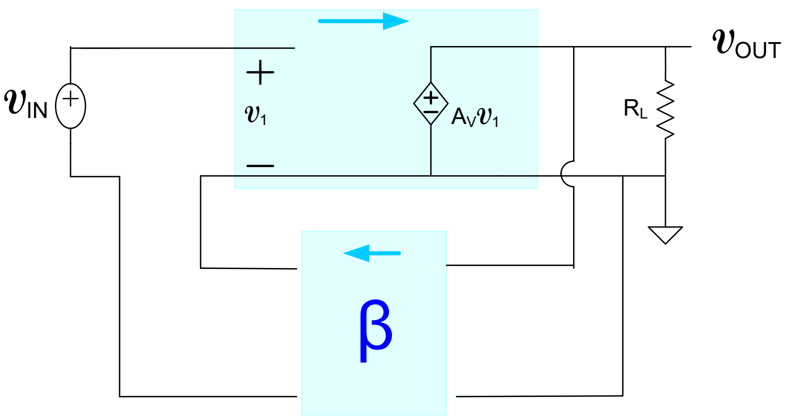
Better Loop Gain Circuit including Biasing

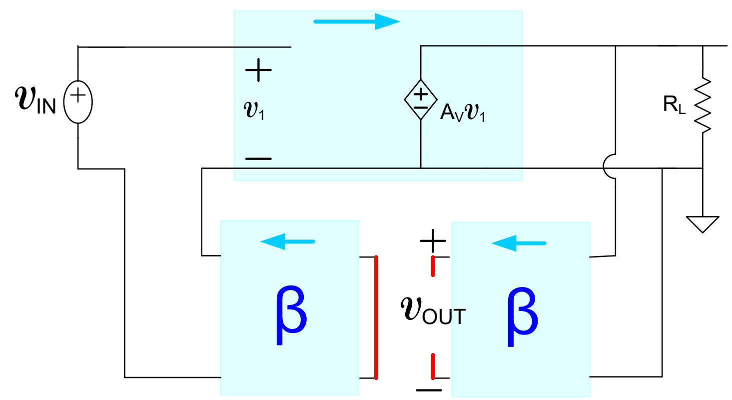
(terminations shown in ss circuit are what is needed in the actual amplifier)

Loop Gain - Aβ

for four basic amplifier types

voltage-series feedback

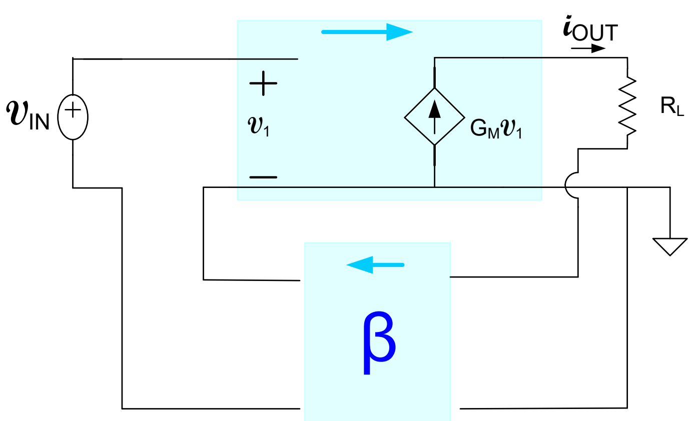


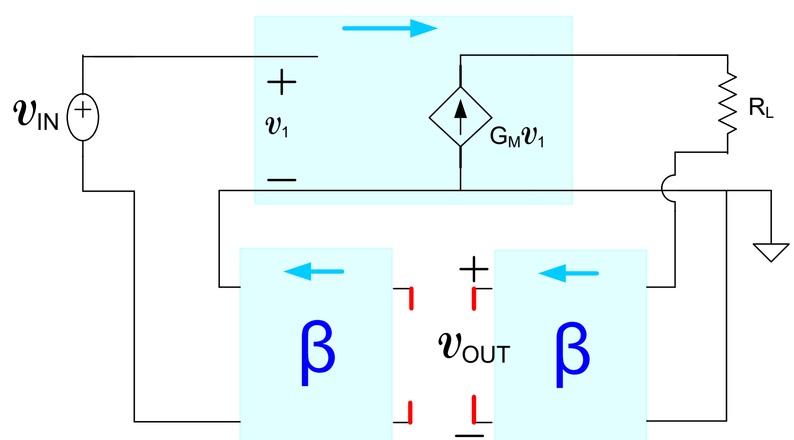


Feedback Amplifier

Loop Gain Amplifier

current-series feedback

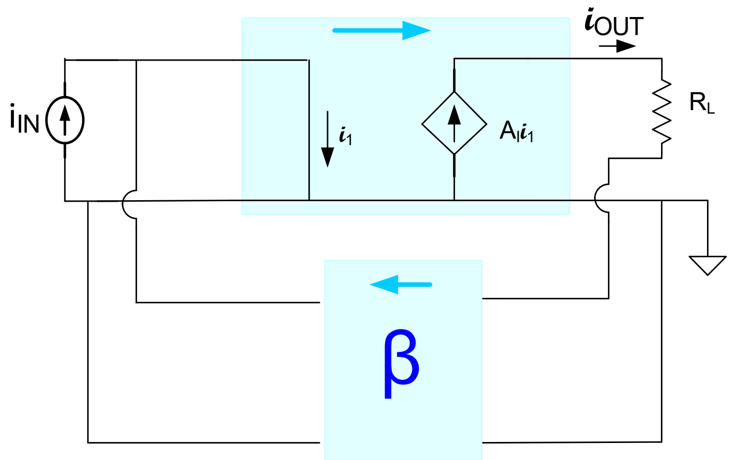


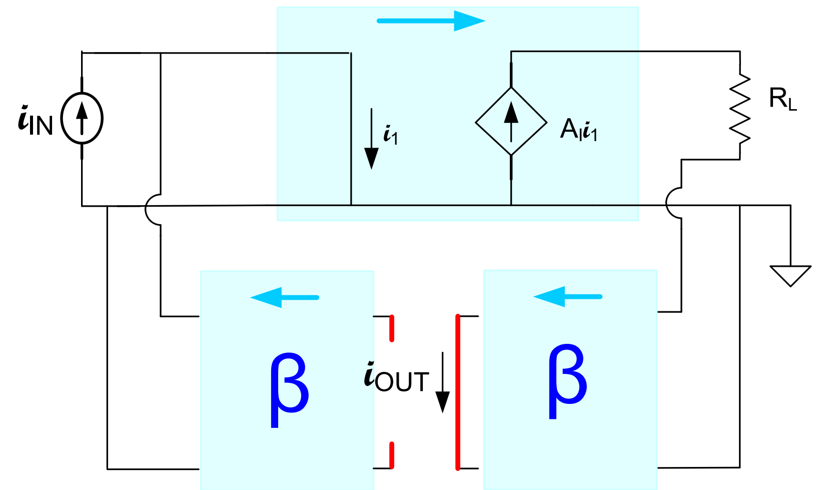


Loop Gain - Aβ

for four basic amplifier types

current-shunt feedback

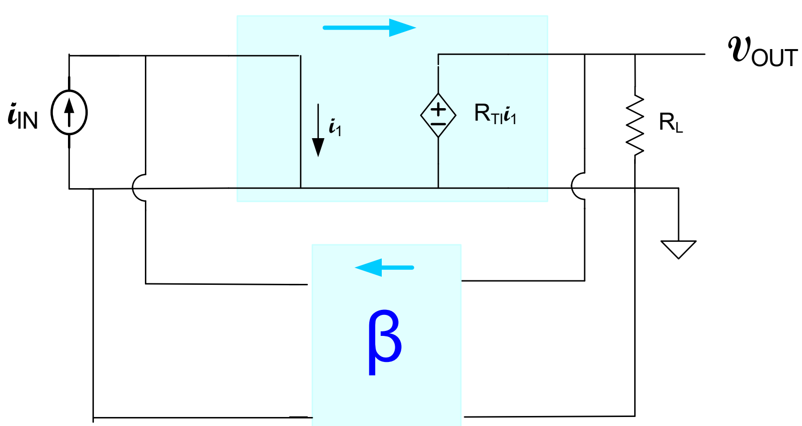


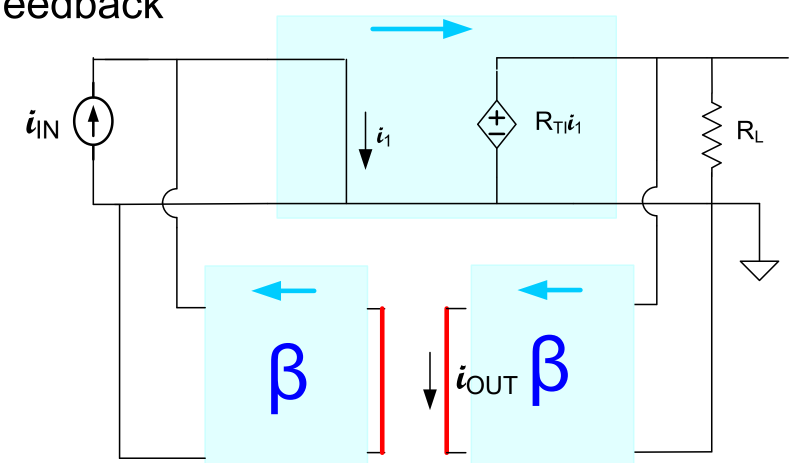


Feedback Amplifier

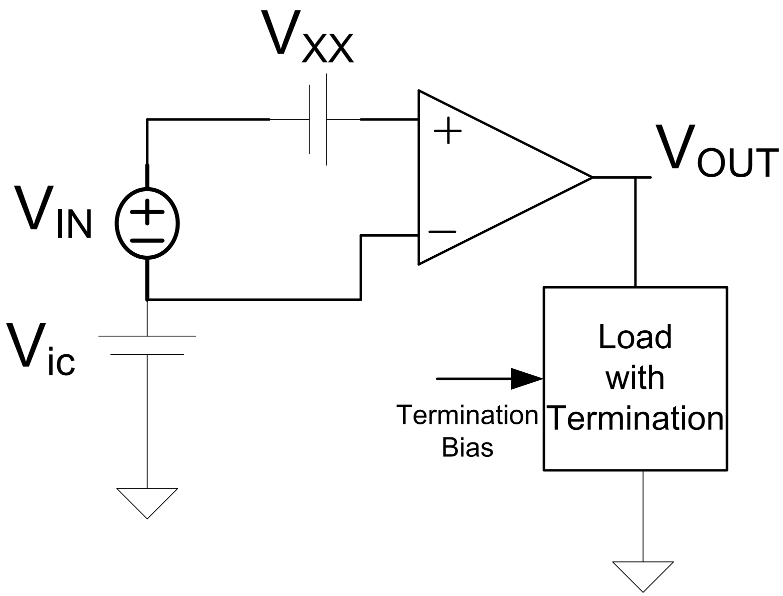
Loop Gain Amplifier

voltage-shunt feedback





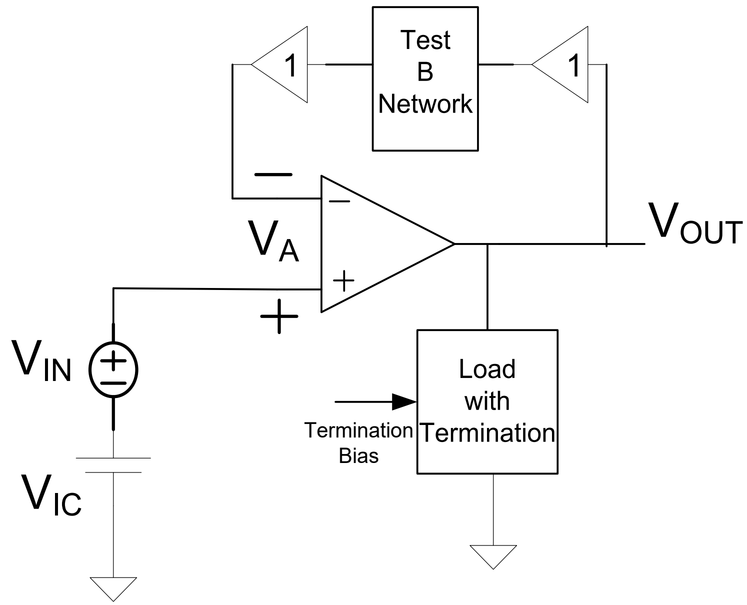
Open-loop gain simulations



- 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)



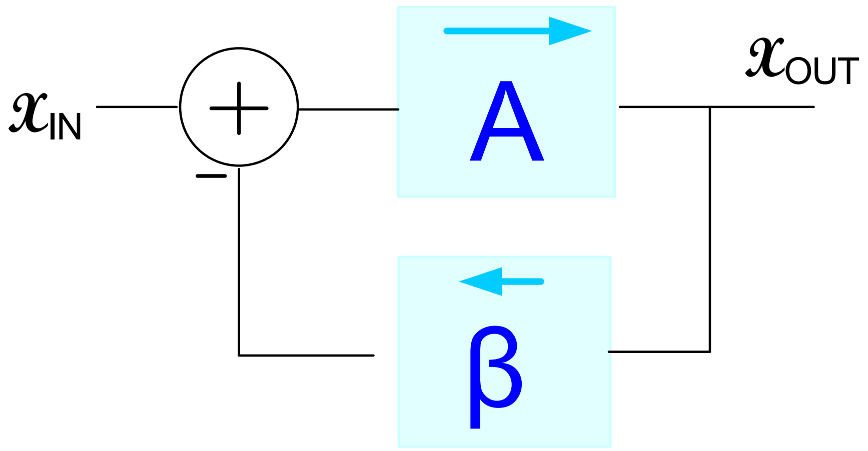
$$A_{VL} = \frac{V_{OUT}}{V_A}$$

- 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 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?

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

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

Methods used so far:

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

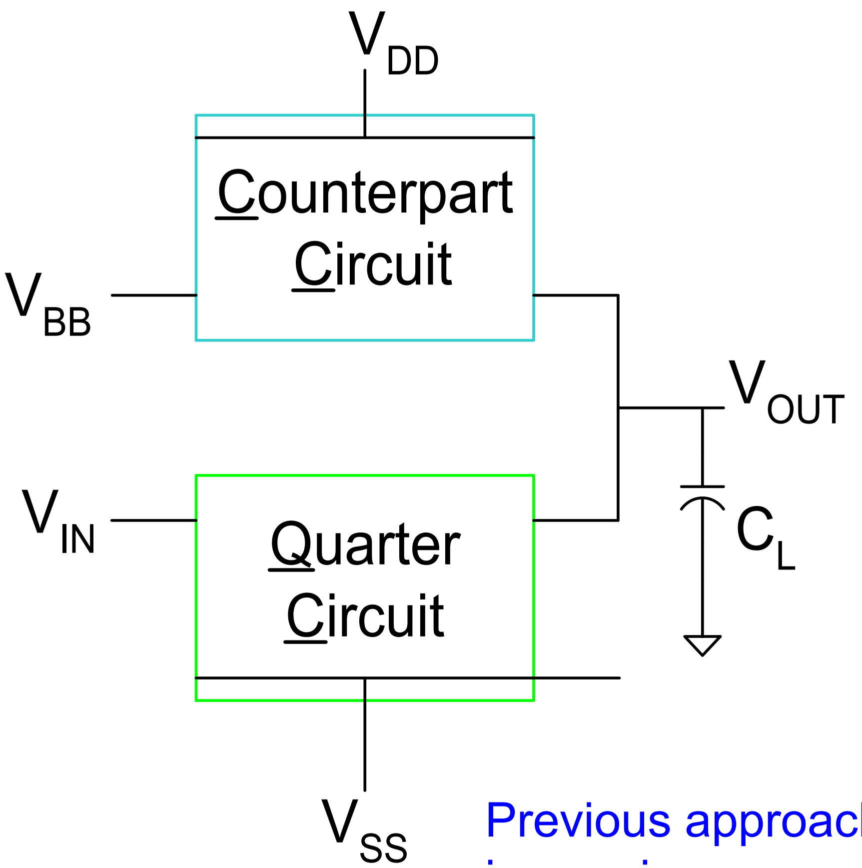
Increasing the transconductance
(current mirror op amp) but it didn’t really help because
the output conductance increased proportionally

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:



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

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

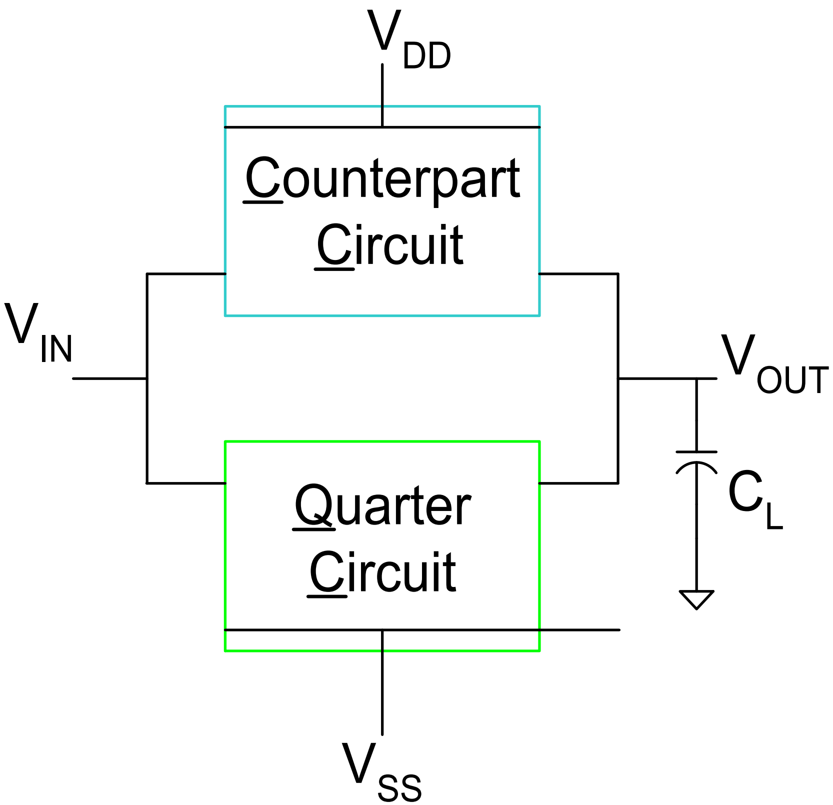
Two Strategies:

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



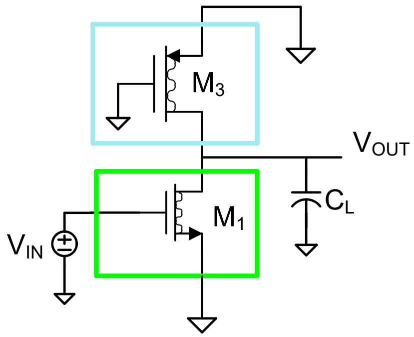
$$A_{V0} = \frac{-(g_{mQC} + g_{mCC})}{g_{oQC} + g_{oCC}}$$

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

Consider now increasing numerator by changing the excitation

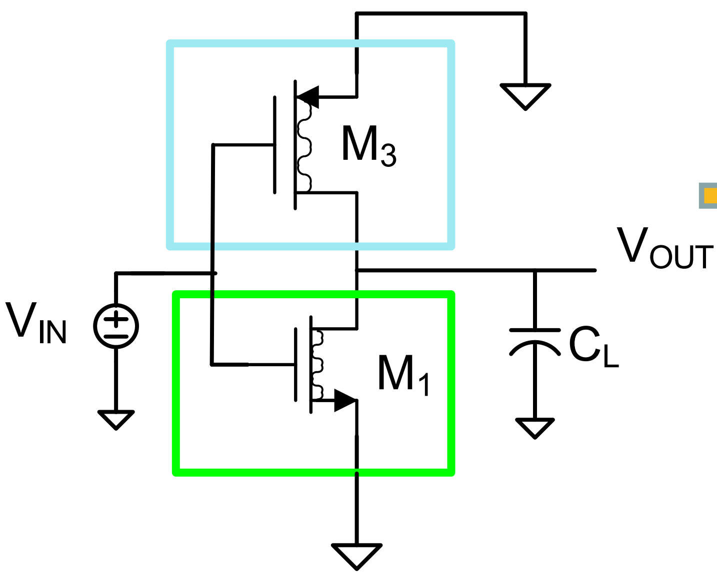
g_{meq} Enhancement with Driven Counterpart Circuit

Recall:



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

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

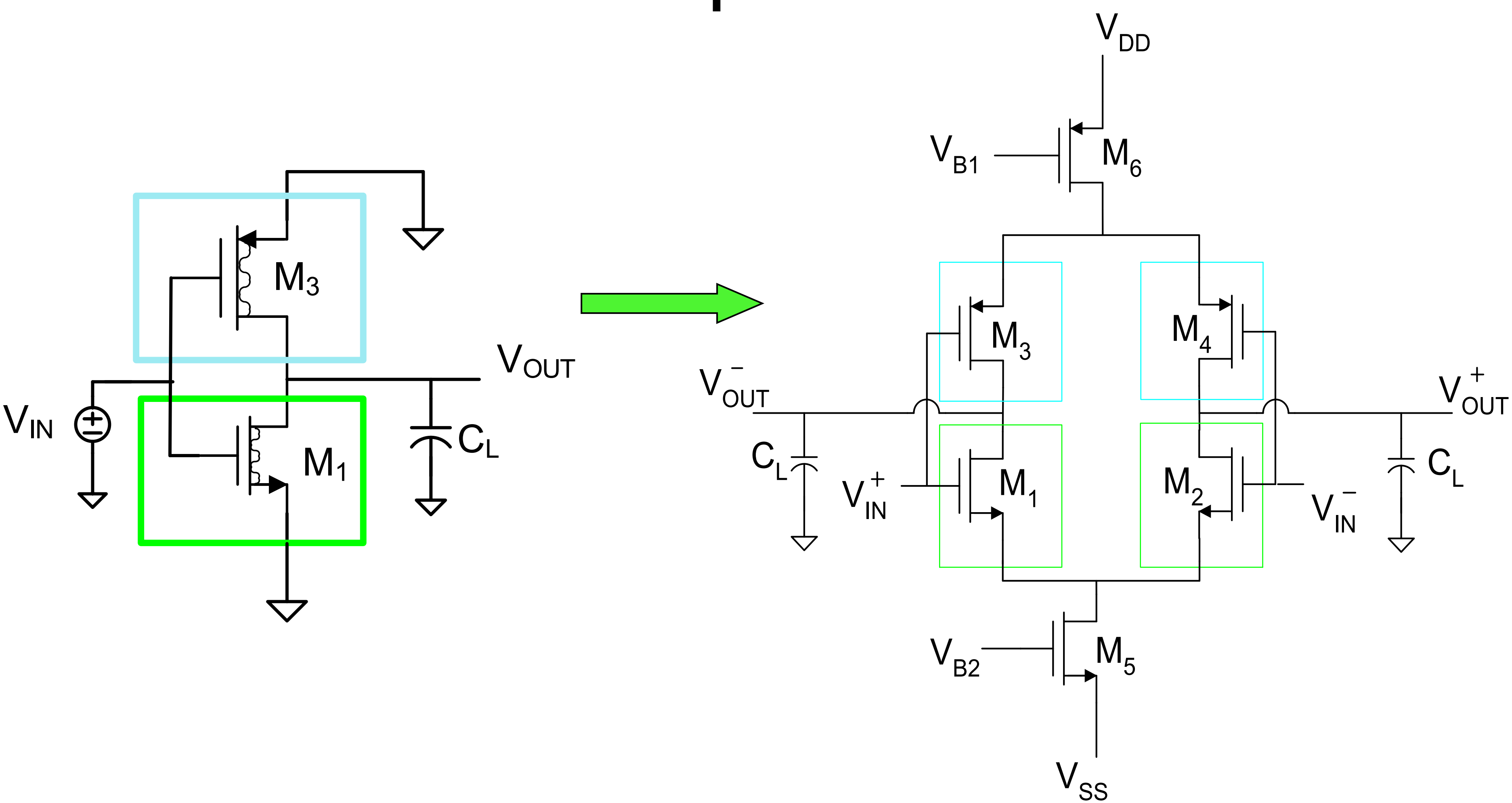


$$A_{V0} = \frac{g_{m1} + g_{m3}}{g_{o1} + g_{o3}}$$

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

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

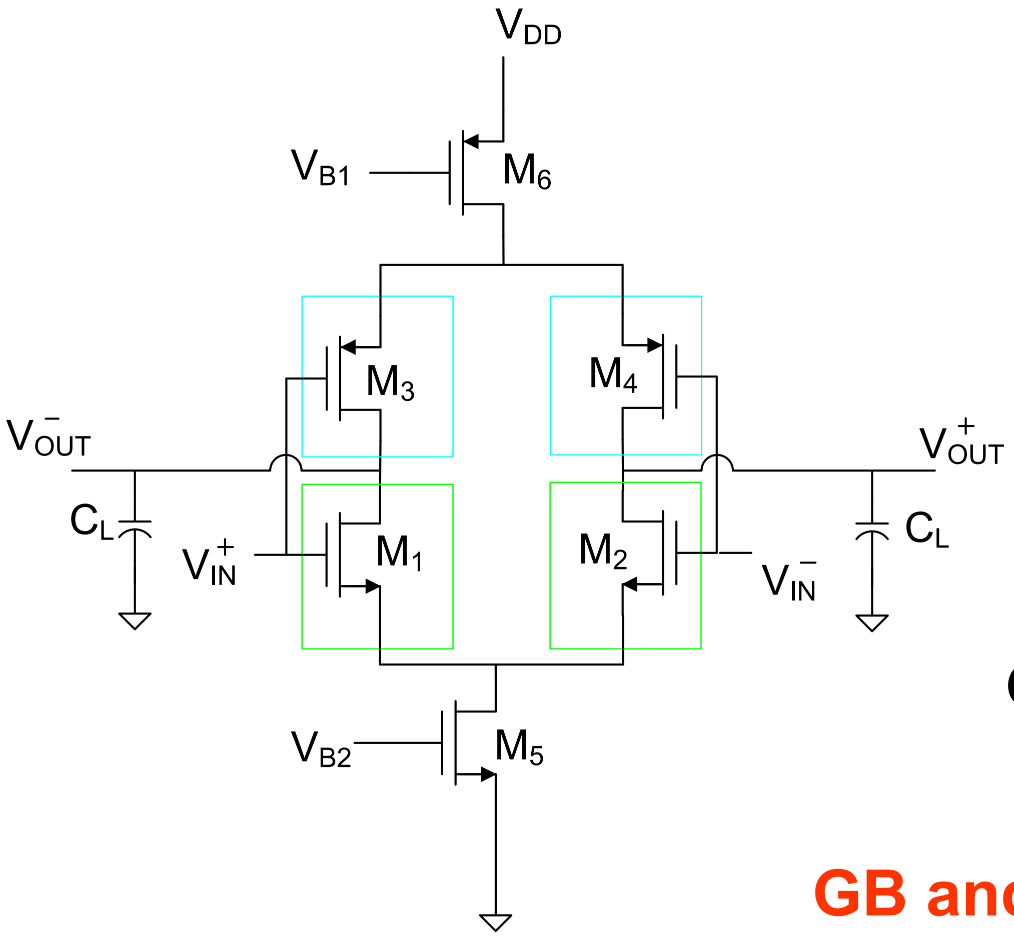
g_{meq} Enhancement with Driven Counterpart Circuit



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

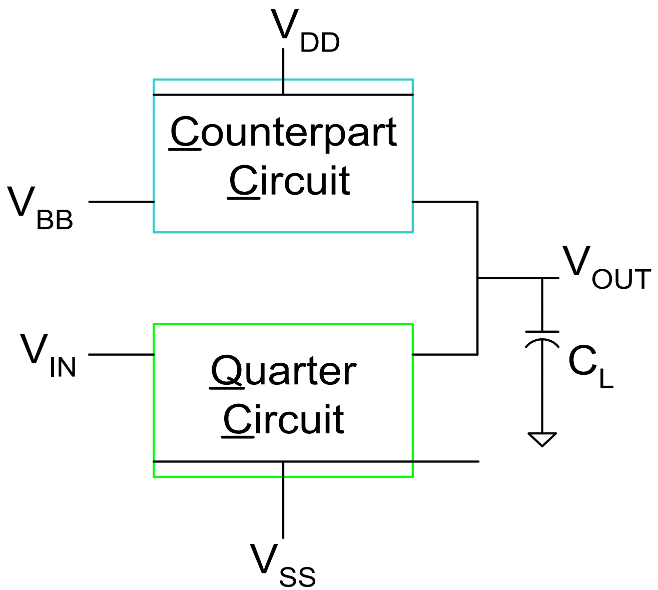
Increasing the transconductance
(current mirror op amp) but it didn't really help because
the output conductance increased proportionally

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:

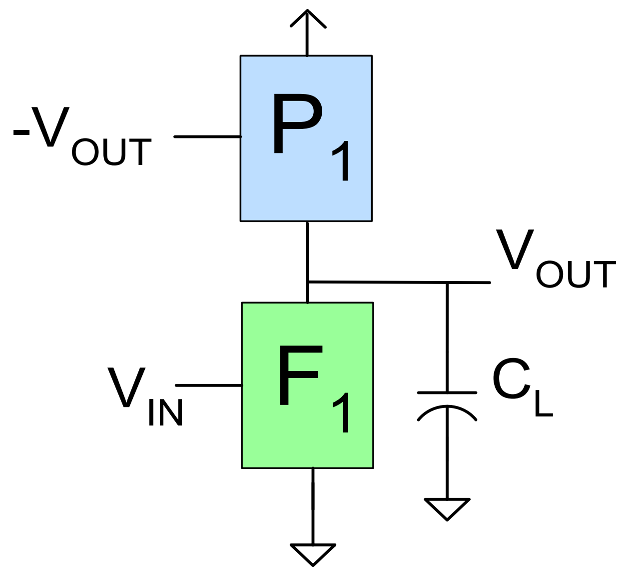
1. Decrease denominator of A_{V0}
2. Increase numerator of A_{V0}

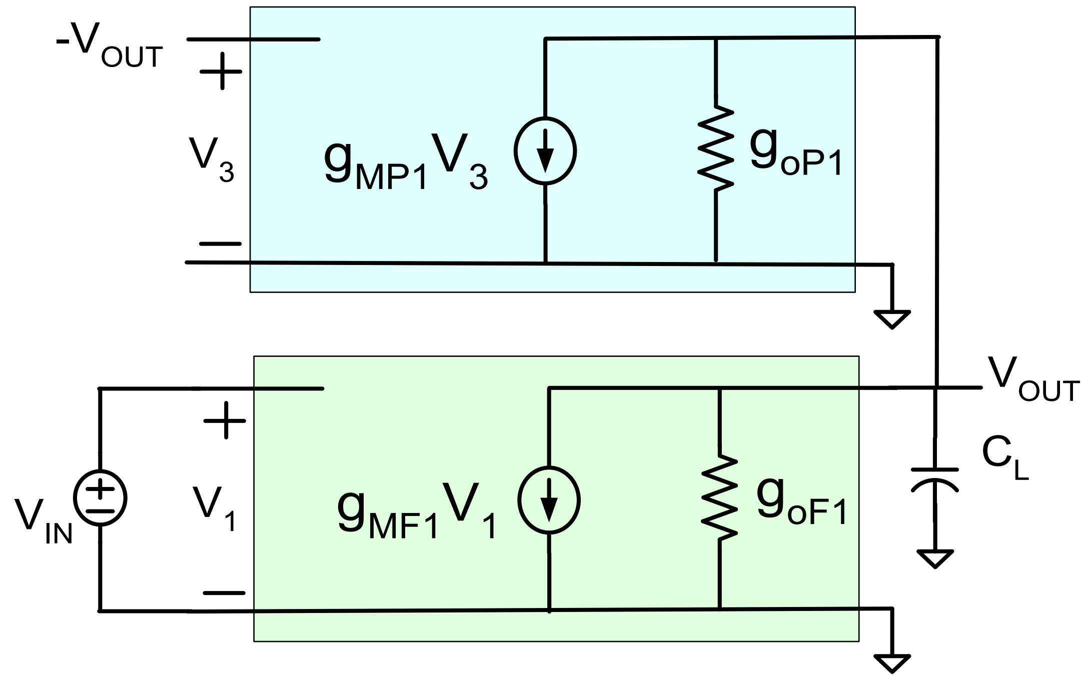
Consider again decreasing the denominator

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

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

Other Methods of Gain Enhancement



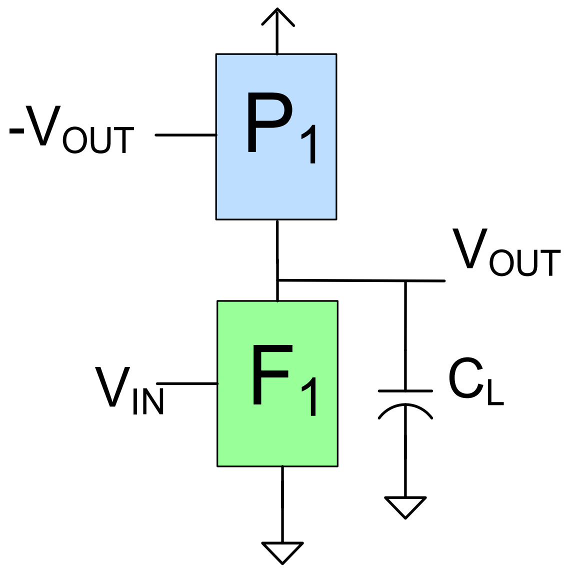


$$\left.\begin{array}{l} V_{OUT}\left(sC_L + g_{oP1} + g_{oF1}\right) + g_{mF1}V_{IN} + g_{mP1}V_3 = 0 \\ V_3 = -V_{OUT} \end{array}\right\}$$

$$A_V(s) = \frac{-g_{MQC}}{sC_L + g_{OQC} + g_{OCC} - g_{MCC}}$$

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

Gain Enhancement with Regenerative Feedback



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

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

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

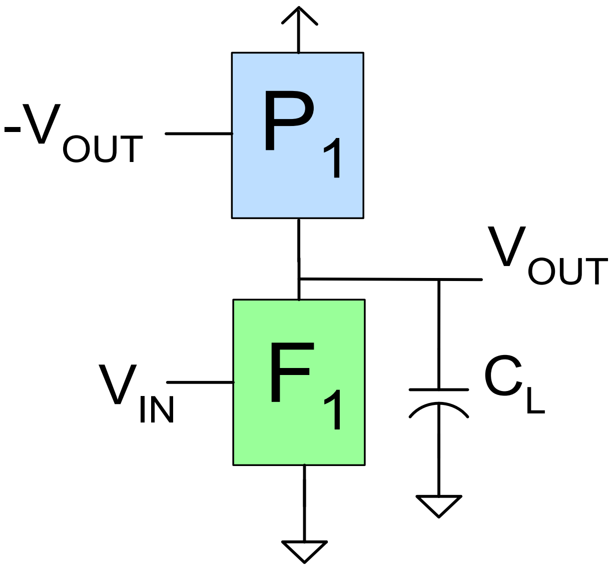
$$GB = \frac{g_{mF1}}{C_L}$$

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

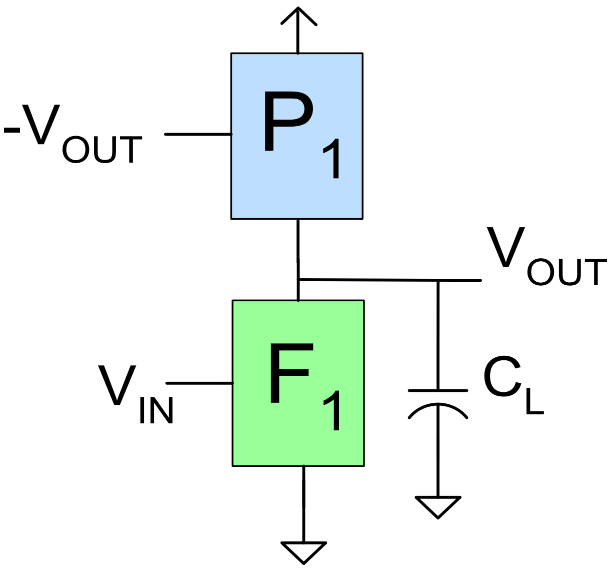
The GB does not degrade !

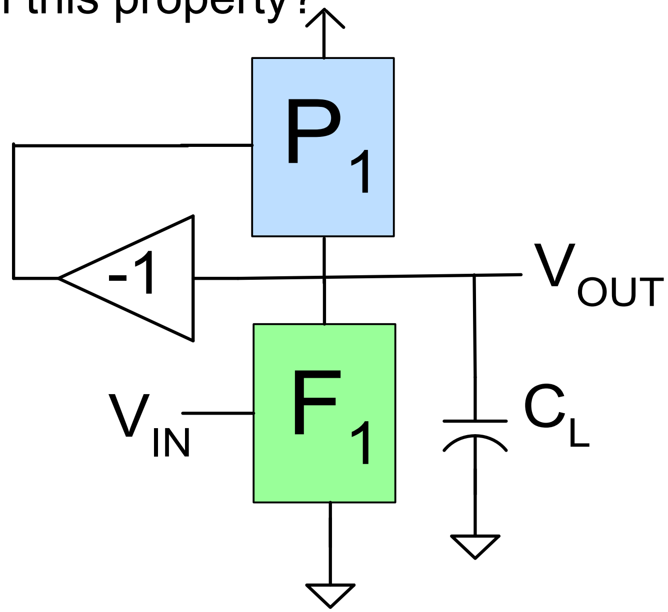
This circuit has a positive feedback loop (V_{INP1}:V_{OUT}:-V_{OUT})

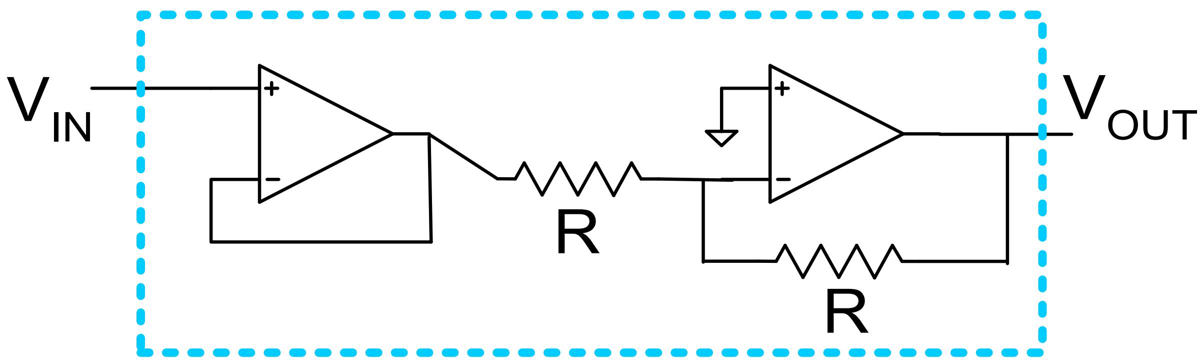
But - can we easily build circuits with this property?

Gain Enhancement with Regenerative Feedback

But - can we easily build circuits with this property?





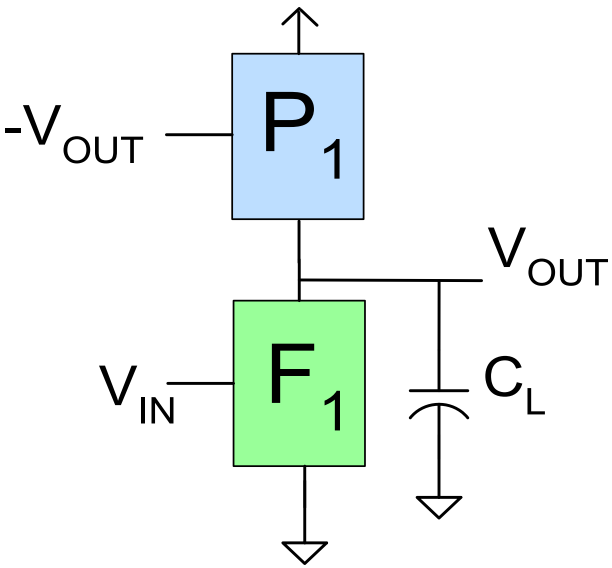


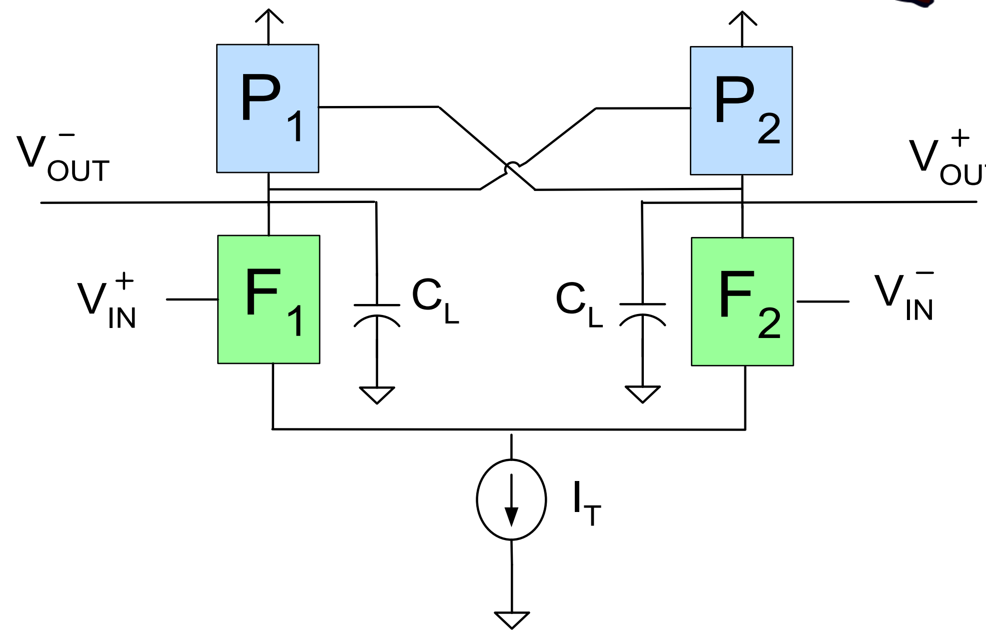
But – the inverting amplifier may be more difficult to build than the op amp itself!

Do we need 2 op amps, one with an output buffer to drive the R resistors?

Gain Enhancement with Regenerative Feedback

But - can we easily build circuits with this property?

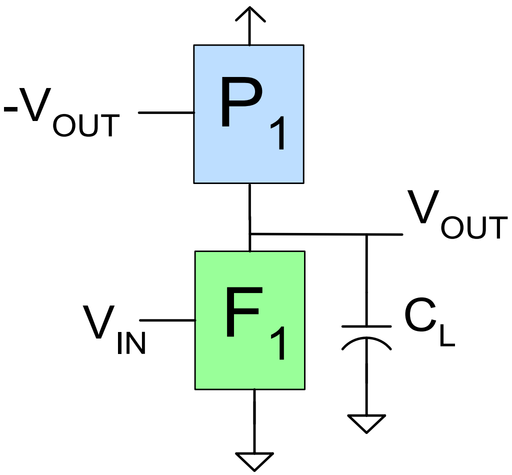




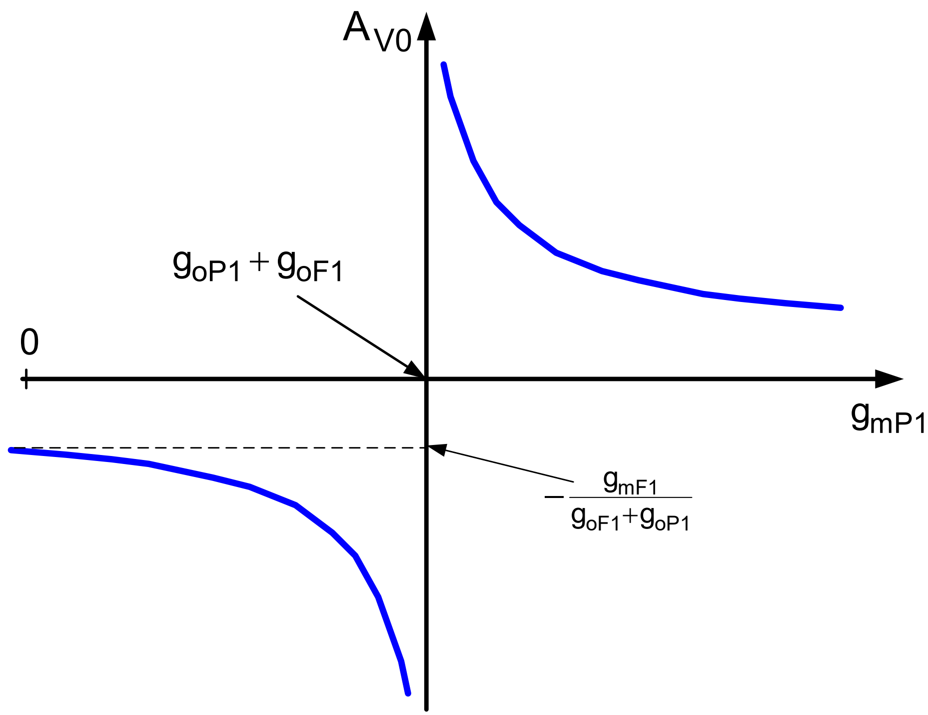
But – the inverting amplifier may be more difficult to build than the op amp itself!

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

Gain Enhancement with Regenerative Feedback

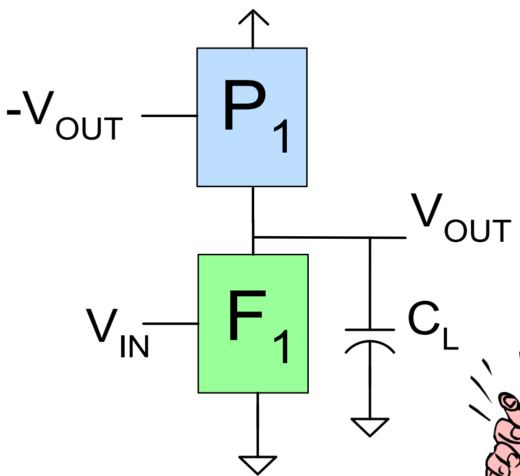


$$A_{V0}(s) = \frac{-g_{mF1}}{sC_L + g_{oF1} + g_{oP1} - g_{mP1}}$$



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

Gain Enhancement with Regenerative Feedback



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

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

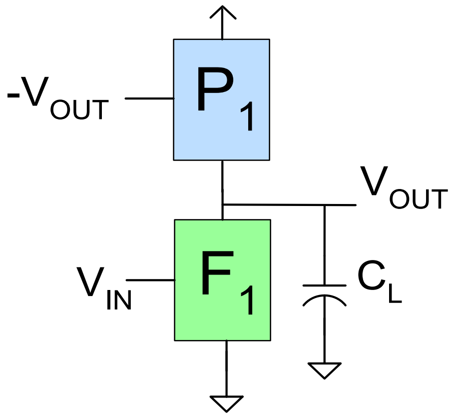
If $g_{mP1} > g_{oF1} + g_{oP1}$, the pole will be in the RHP !!

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



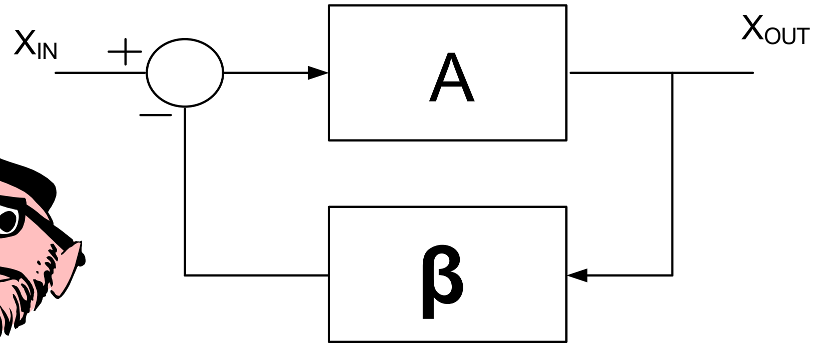
This will make the op amp unstable

Positive Feedback is BAD !!

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

But is Positive Feedback really bad?

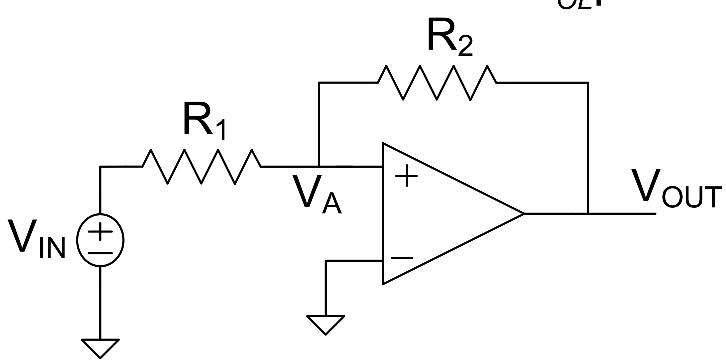
Remember – Why do we want a large Op Amp Gain Anyway?



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

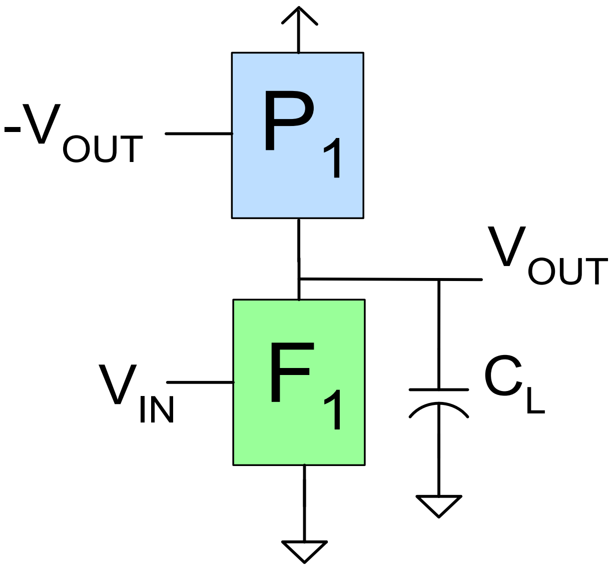
To make A_{FB} <u>very</u> close to $1/\beta$

Even when standard $A_{VFB} = \frac{A_{OL}}{1 + A_{OL}\beta}$ equation does not apply



Want A_{OL} large to make V_A very close to 0 so A_{VFB} <u>very</u> close to $-R_2/R_1$

Gain Enhancement with Regenerative Feedback



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

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

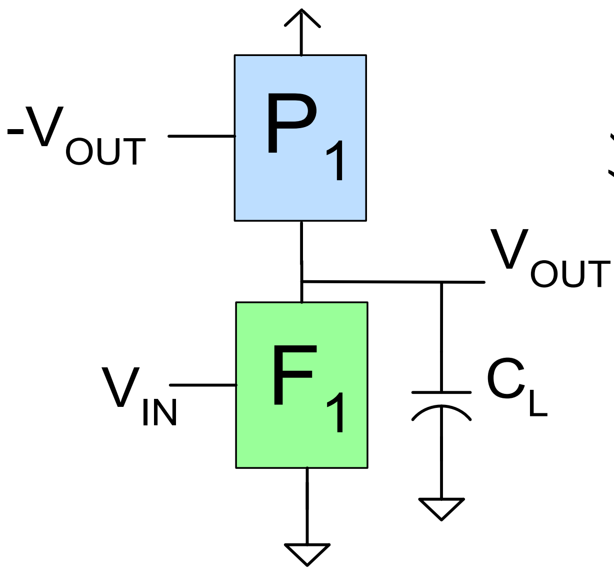
If $g_{mP1} > g_{oF1} + g_{oP1}$, the pole will be in the RHP !!

It can be shown that the feedback amplifier is usually stable even if the open-loop Op amp is unstable

The feedback performance can actually be enhanced if the open-loop amplifier is unstable

Research has been ongoing recently using this approach and it shows considerable promise for gain enhancement in low voltage processes

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 !!

It can be shown that the feedback amplifier is usually stable even if the open-loop Op amp is unstable **How?**

Recall: The numerator of A_{V0} does not change signs when the constant term in the denominator transitions from positive to negative with this approach

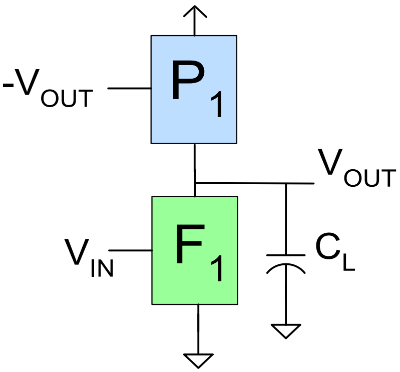
For Op Amp

$$A_{V0}(s)=\frac{V_O}{V^+-V^-}$$

$$A_{V0}(s)=\begin{cases}\dfrac{A_{V0}\tilde{p}_1}{(s+\tilde{p}_1)} & \text{for } \tilde{p}_1>0\\[2ex] \dfrac{-A_{V0}\tilde{p}_1}{(s+\tilde{p}_1)} & \text{for } \tilde{p}_1<0\end{cases}$$

where $A_{V0}>0$

Gain Enhancement with Regenerative Feedback



It can be shown that the feedback amplifier is usually stable even if the open-loop Op amp is unstable

How?

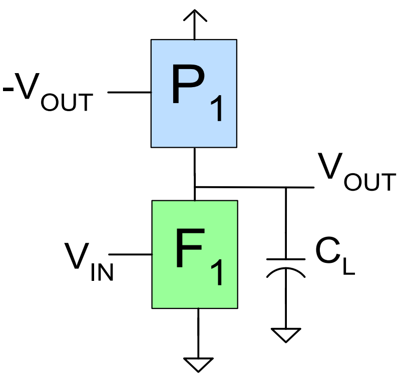
$$A_{V0}(s)=\begin{cases}\dfrac{A_{V0}\tilde{p}_1}{(s+\tilde{p}_1)} & \text{for } \tilde{p}_1>0\\[2ex] \dfrac{-A_{V0}\tilde{p}_1}{(s+\tilde{p}_1)} & \text{for } \tilde{p}_1<0\end{cases}$$

$$A_{FB}(s)=\begin{cases}\dfrac{A_{V0}\tilde{p}_1}{s+\tilde{p}_1(1+\beta A_{V0})} & \text{for } \tilde{p}_1>0\\[2ex] \dfrac{-A_{V0}\tilde{p}_1}{s+\tilde{p}_1(1-\beta A_{V0})} & \text{for } \tilde{p}_1<0\end{cases}$$

where $A_{V0}>0$

$$p_{FB}=\begin{cases}-\tilde{p}_1(1+\beta A_{V0})=p_1(1+\beta A_{V0}) & \text{for } p_1<0\\ -\tilde{p}_1(1-\beta A_{V0})=p_1(1-\beta A_{V0}) & \text{for } p_1>0\end{cases}$$

Gain Enhancement with Regenerative Feedback

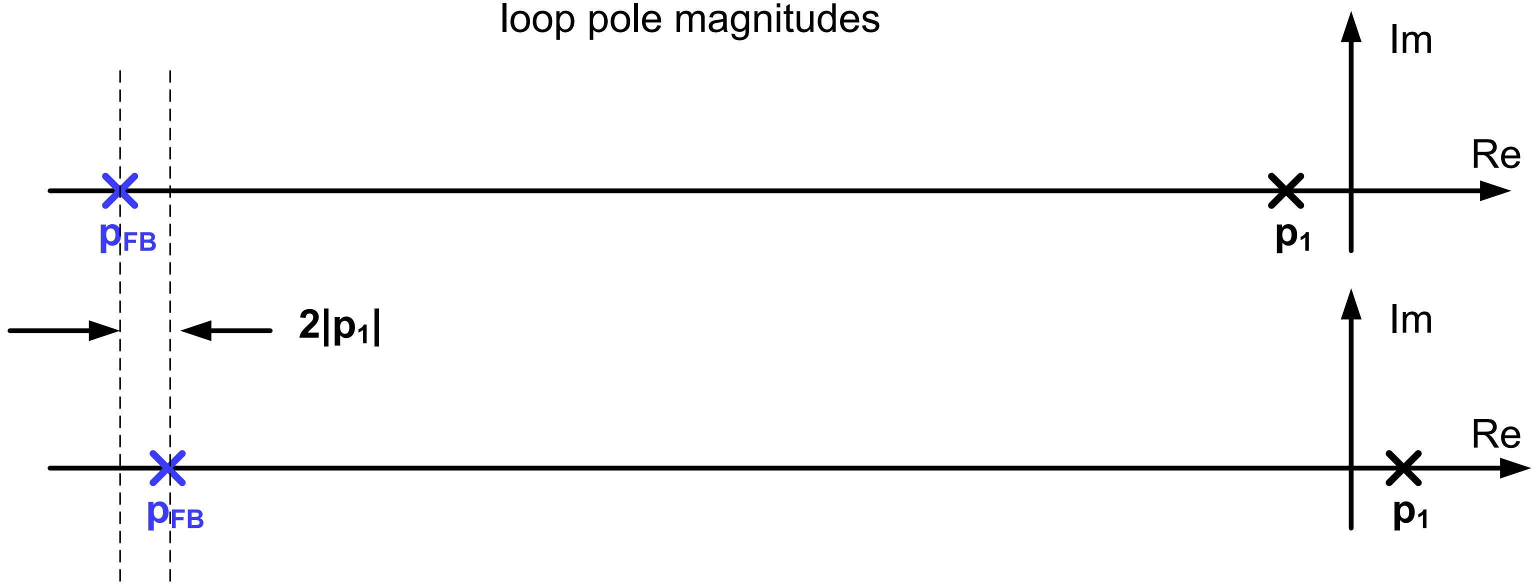


It can be shown that the feedback amplifier is usually stable even if the open-loop Op amp is unstable

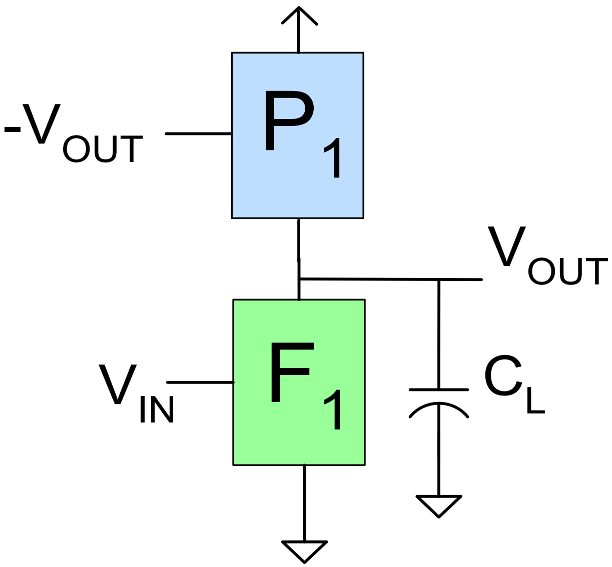
How?

$$p_{FB} = \begin{cases} -\tilde{p}_1\left(1+\beta A_{V0}\right) = p_1\left(1+\beta A_{V0}\right) & \text{for } p_1 < 0 \\ -\tilde{p}_1\left(1-\beta A_{V0}\right) = p_1\left(1-\beta A_{V0}\right) & \text{for } p_1 > 0 \end{cases}$$

Open-Loop and Closed-Loop Pole Plot for equal open-loop pole magnitudes



Gain Enhancement with Regenerative Feedback



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

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

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

The feedback performance can actually be enhanced if the open-loop amplifier is unstable

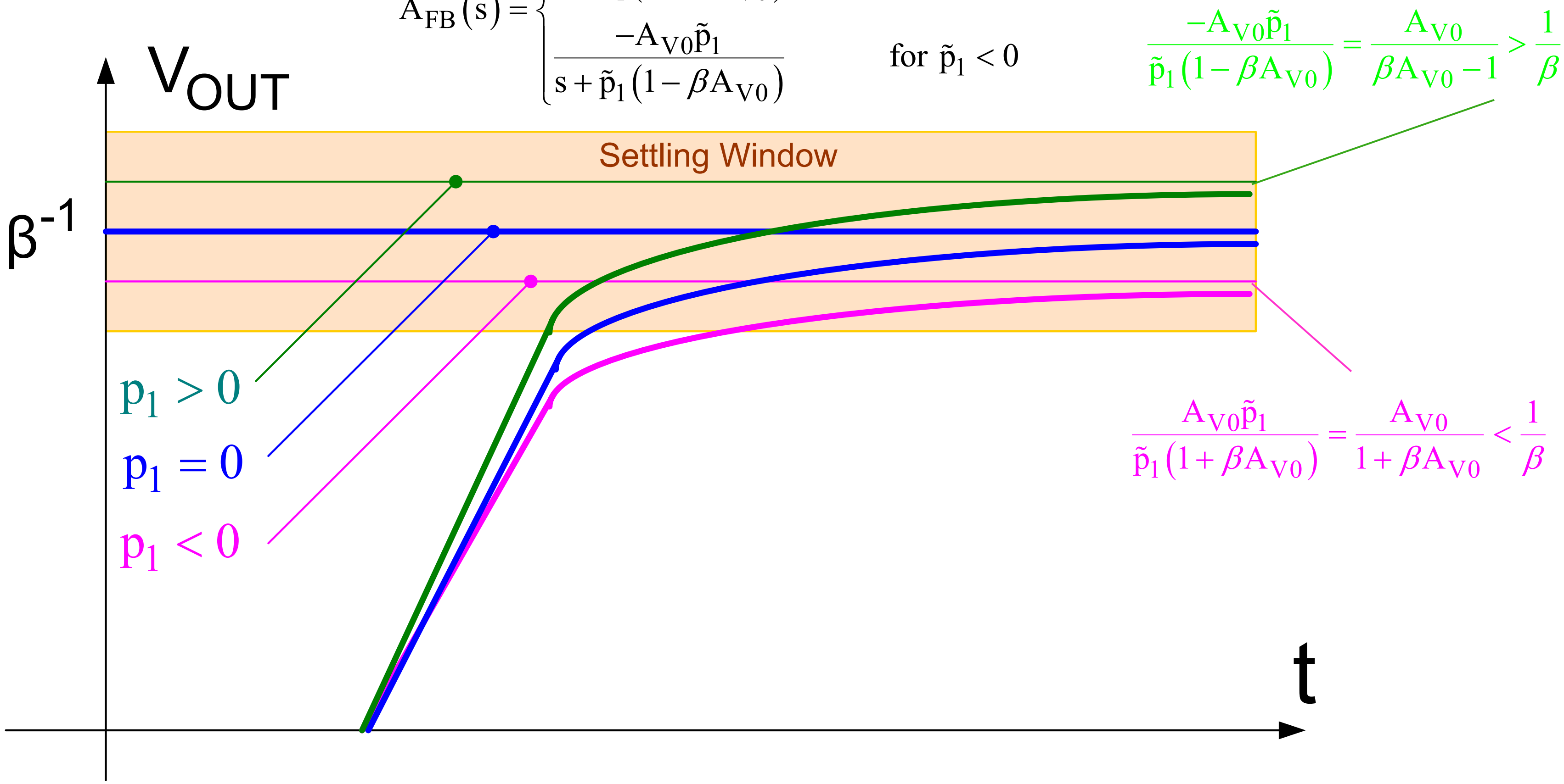
Why?

Gain Enhancement with Regenerative Feedback

The feedback performance can actually b enhanced if the open-loop amplifier is unstable

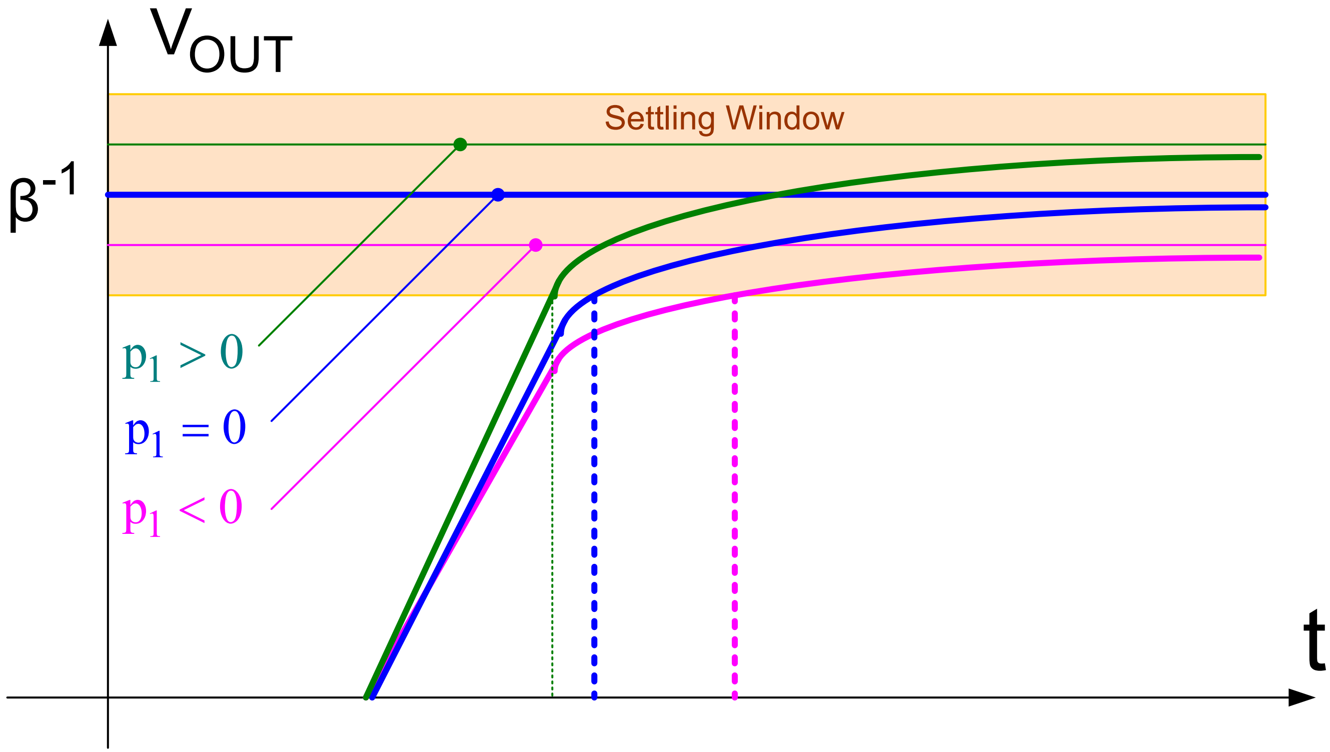
Why?

$$A_{FB}(s) = \begin{cases} \dfrac{A_{V0}\tilde{p}_1}{s + \tilde{p}_1\left(1 + \beta A_{V0}\right)} & \text{for } \tilde{p}_1 > 0 \\ \dfrac{-A_{V0}\tilde{p}_1}{s + \tilde{p}_1\left(1 - \beta A_{V0}\right)} & \text{for } \tilde{p}_1 < 0 \end{cases}$$



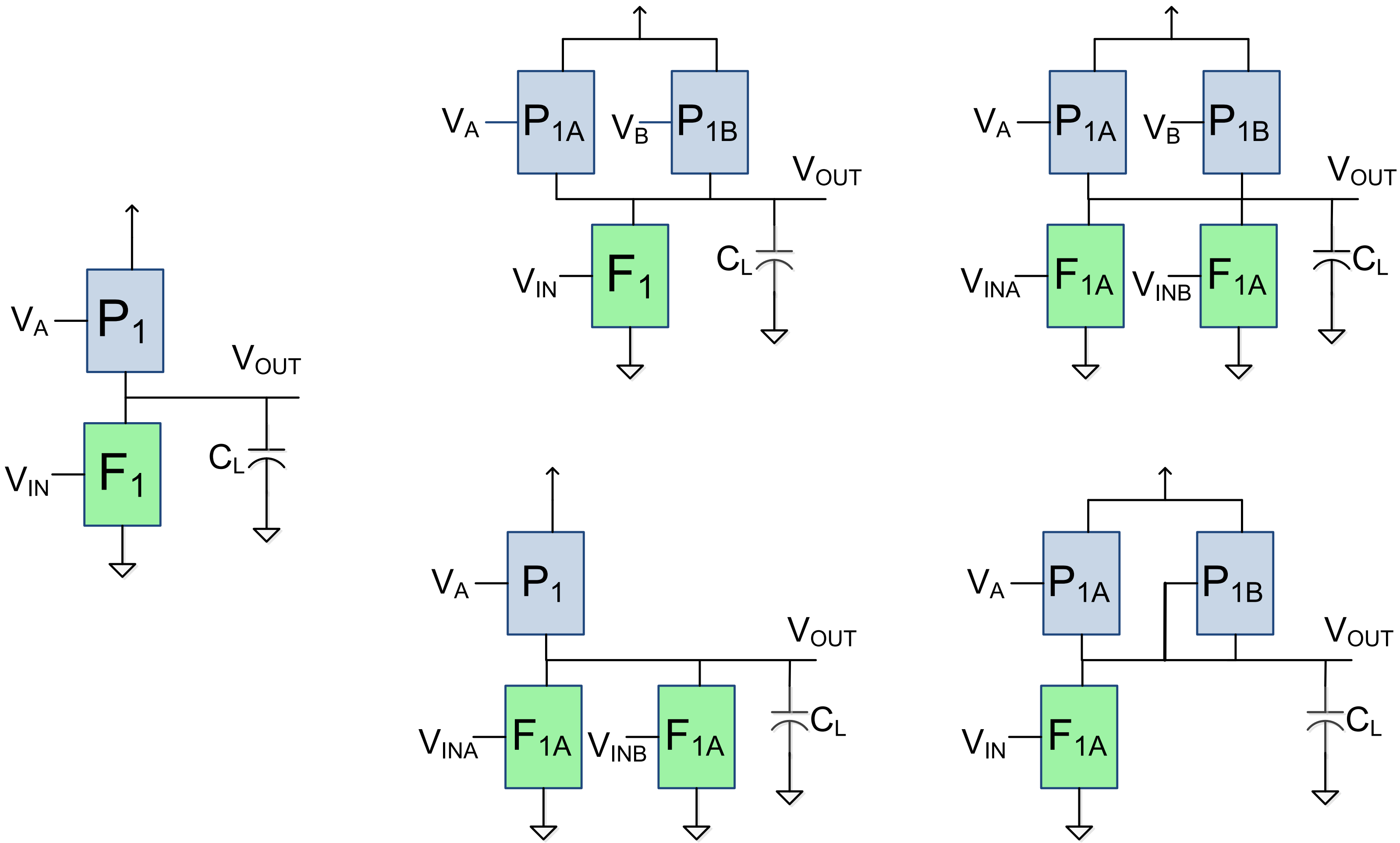
Gain Enhancement with Regenerative Feedback

The feedback performance can actually be enhanced if the open-loop amplifier is unstable   Why?

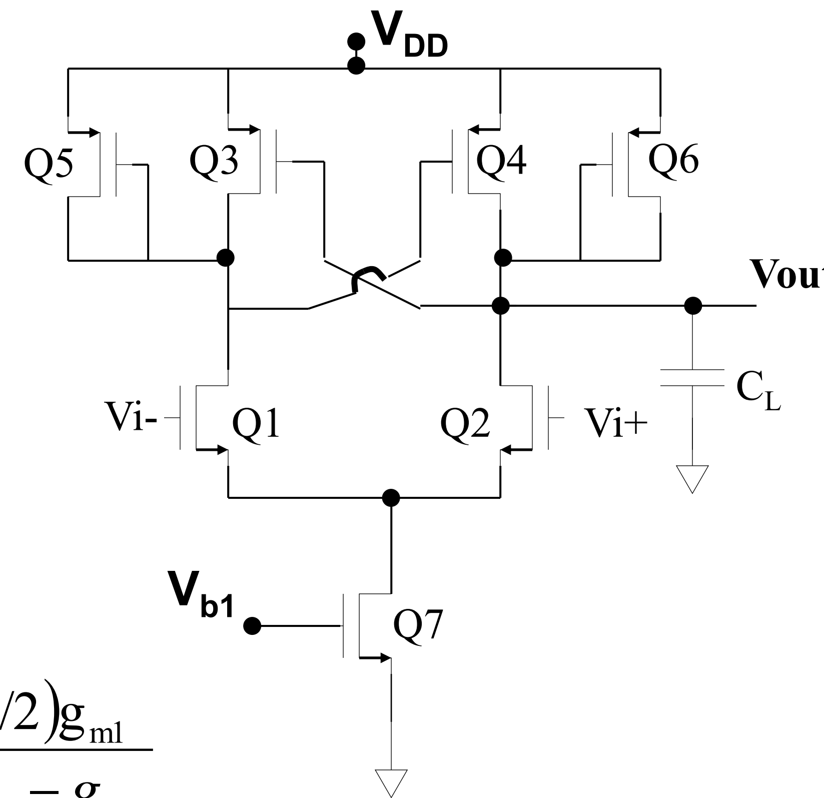


- Time required to get in settling window can be reduced with RHP pole
- But, if pole is too far in RHP, response will exit top of window

Some Half-Circuits with Interesting Potential



Existing Positive Feedback Amplifier



$$A_{VO} = \frac{(1/2)g_{m1}}{g_{o2} + g_{o4} + g_{06} + g_{m6} - g_{m4}} \approx \frac{(1/2)g_{m1}}{g_{m6} - g_{m4}}$$

$$A(s) = \frac{(1/2)g_{m1}}{sC_L + [g_{o2} + g_{o4} + g_{o6} + g_{m6} - g_{m4}]}$$

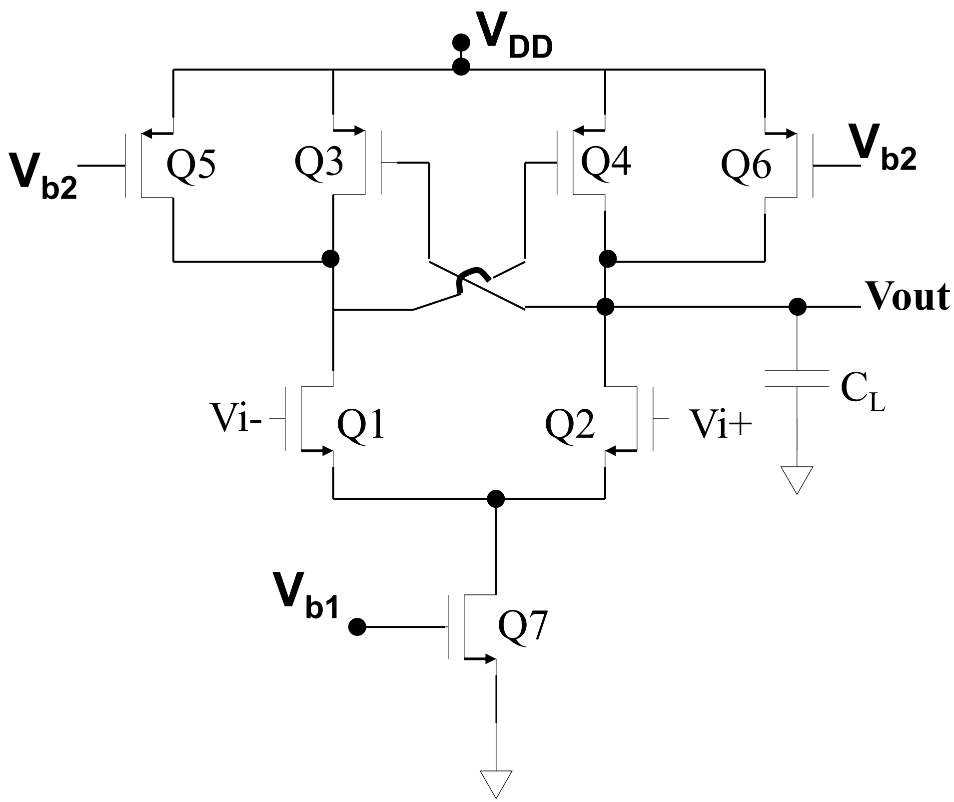
Existing Positive Feedback Amplifier

$$A_{VO} = \frac{(1/2)g_{m1}}{g_{o2} + g_{o4} + g_{o6} + g_{m6} - g_{m4}} \approx \frac{(1/2)g_{m1}}{g_{m6} - g_{m4}}$$

$$A(s) = \frac{(1/2)g_{m1}}{sC_L + [g_{o2} + g_{o4} + g_{o6} + g_{m6} - g_{m4}]}$$

- Requires precise matching of g_{m4} to $(g_{o2}+g_{o4}+g_{o6}+g_{m6})$ for good gain enhancement
- Difficult to match g_m terms to g_o-type terms

Alternate Positive Feedback Amplifier



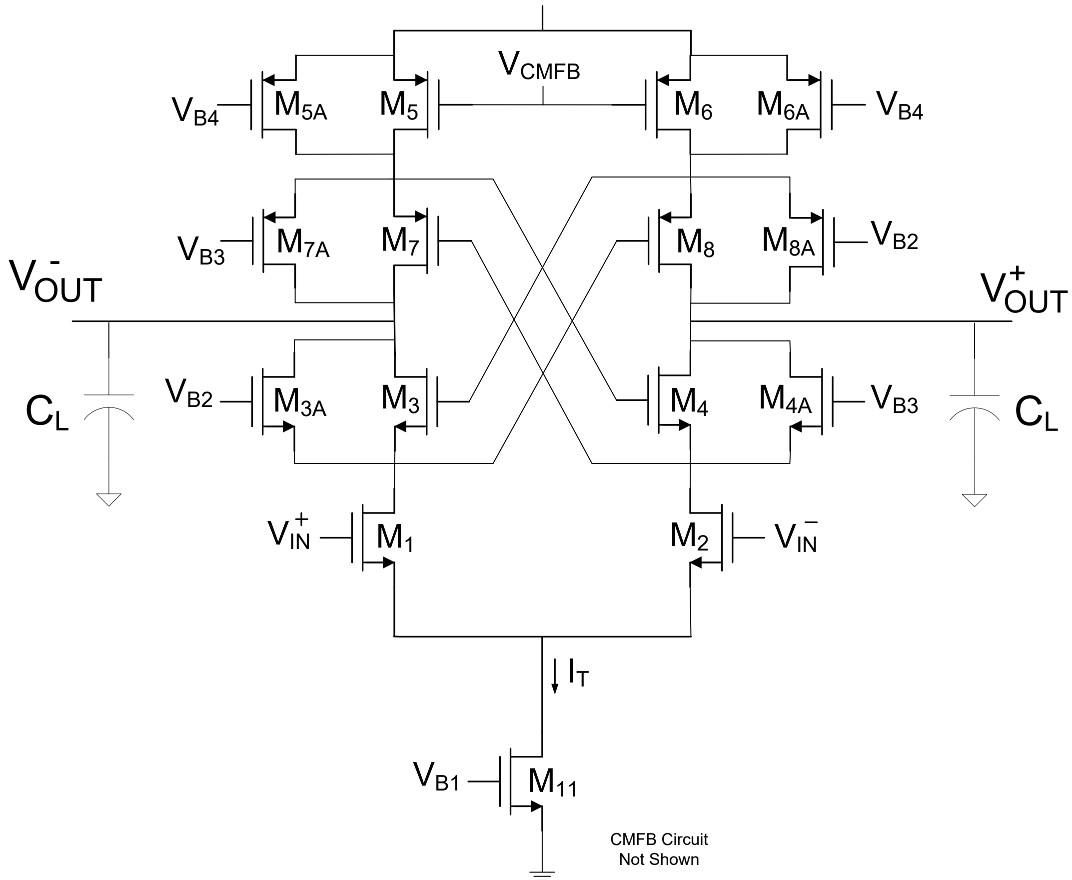
Alternate Positive Feedback Amplifier

$$A_{VO} = \frac{(1/2)g_{m1}}{g_{o2} + g_{o4} + g_{o6} - g_{m4}}$$

$$A(s) = \frac{(1/2)g_{m1}}{sC_L + [g_{o2} + g_{o4} + g_{o6} - g_{m4}]}$$

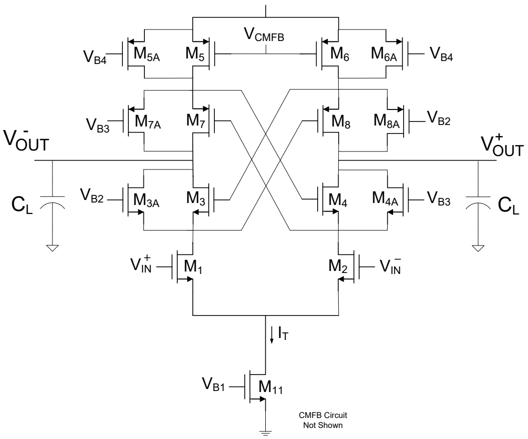
- Requires precise matching of g_{m4} to $(g_{o2}+g_{o4}+g_{o6})$ for good gain enhancement
- Difficult to match g_m terms to g_o-type terms

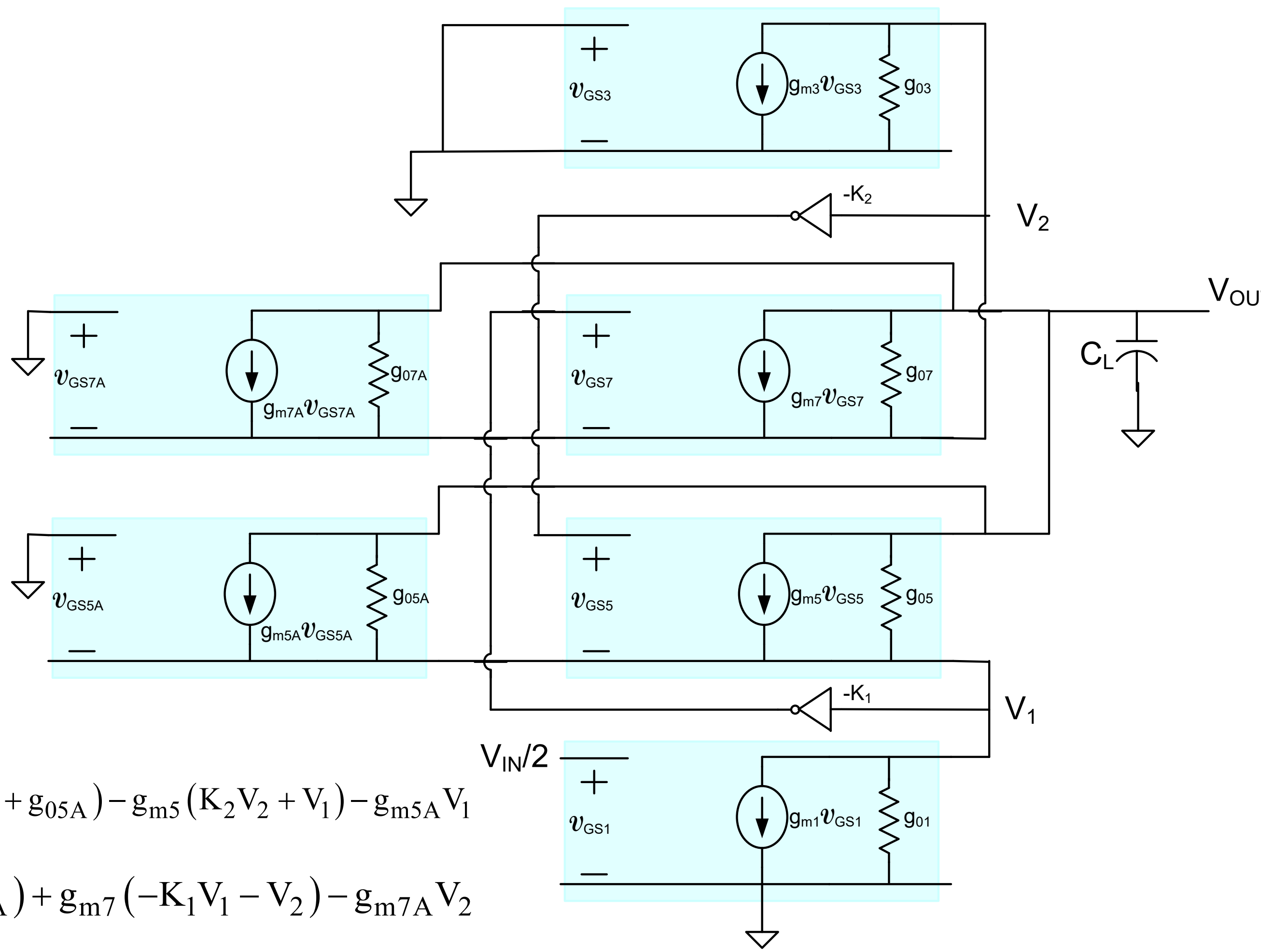
Another Positive Feedback Amplifier



- Regenerative feedback can be to either quarter circuit or counterpart circuit
- Regenerative feedback to cascode devices can significantly reduce the magnitude of the negative conductance term

Another Positive Feedback Amplifier





Small-signal half circuit

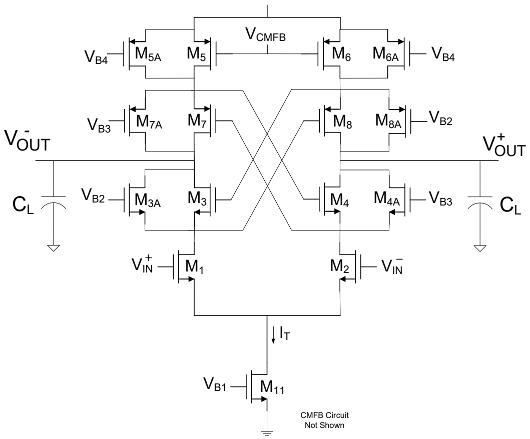
$$V_1\left(g_{01}+g_{05}+g_{05A}\right)+g_{m1}V_{IN}/2=V_0\left(g_{05}+g_{05A}\right)-g_{m5}\left(K_2V_2+V_1\right)-g_{m5A}V_1$$

$$V_2\left(g_{03}+g_{07}+g_{07A}\right)=V_0\left(g_{07}+g_{07A}\right)+g_{m7}\left(-K_1V_1-V_2\right)-g_{m7A}V_2$$

$$V_0\left(sC_L+g_{05}+g_{05A}+g_{07}+g_{07A}\right)=V_2\left(g_{07}+g_{07A}\right)+V_1\left(g_{05}+g_{05A}\right)+g_{m7}\left(K_1V_1+V_2\right)$$
$$+g_{m7A}V_2+g_{m5}\left(K_2V_2+V_1\right)+g_{m5A}V_1$$

Ki=0 if cross-coupling absent, 1 if cross-coupling present

Another Positive Feedback Amplifier



$$V_1\left(g_{01}+g_{05}+g_{05A}\right)+g_{m1}V_{IN}/2=V_0\left(g_{05}+g_{05A}\right)-g_{m5}\left(K_2V_2+V_1\right)-g_{m5A}V_1$$

$$V_2\left(g_{03}+g_{07}+g_{07A}\right)=V_0\left(g_{07}+g_{07A}\right)+g_{m7}\left(-K_1V_1-V_2\right)-g_{m7A}V_2$$

$$V_0\left(sC_L+g_{05}+g_{05A}+g_{07}+g_{07A}\right)=V_2\left(g_{07}+g_{07A}\right)+V_1\left(g_{05}+g_{05A}\right)+g_{m7}\left(K_1V_1+V_2\right)$$
$$+g_{m7A}V_2+g_{m5}\left(K_2V_2+V_1\right)+g_{m5A}V_1$$

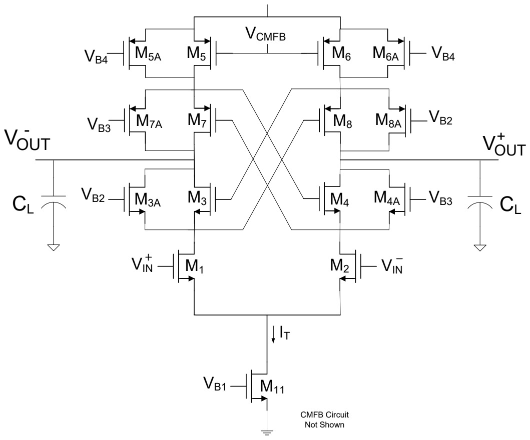
Transfer function solution with MAPLE T(s)=N(s)/S(s)

num := -(-K1 K2 gm5 gm7 + gm5 gm7 + gm7A gm5 + go7 gm5 + go3 gm5
+ go7A gm5 + K1 go3 gm7 + gm5A gm7 + go5 gm7 + go5A gm7
+ go5A go7A + go5 go7A + go5A gm7A + go5 gm7A + go5 go7
+ go5 go3 + gm5A gm7A + go5A go7 + gm5A go3 + go5A go3
+ gm5A go7A + gm5A go7) gm1

den := -go1 go7 gm5 K2 - gm7 K1 go5A go3 - gm7 K1 go5 go3
- go1 go7A gm5 K2 + (gm5A gm7A + gm7A gm5 + go5A go3
+ go5A gm7A + gm5 gm7 + go1 gm7 + go5 gm7 + go5A gm7
+ gm5A gm7 - K1 K2 gm5 gm7 + go1 go7 + gm5A go3 + go5 gm7A
+ go3 gm5 + go5 go3 + go5 go7A + go5 go7 + go1 go7A
+ go5A go7 + gm5A go7A + go5A go7A + go7 gm5 + gm5A go7
+ go7A gm5 + go1 go3 + go1 gm7A) sCL + gm7 go5 go1
+ go5A go1 go3 + gm7 go5A go1 + gm5A go7A go3 + gm5A go7 go3
+ go5A go7 go3 + go5 go7 go3 + gm5 go7 go3 + go1 go7A go3
+ go1 go7 go3 + go5A go1 go7A + go5A go1 go7 + go5 go1 go3
+ go5A go1 gm7A + go5 go1 go7 + go5 go1 gm7A + go5 go7A go3
+ go5 go1 go7A + gm5 go7A go3 + go5A go7A go3

Ki=0 if cross-coupling absent, 1 if cross-coupling present

Another Positive Feedback Amplifier



$$V_1\left(g_{01}+g_{05}+g_{05A}\right)+g_{m1}V_{IN}/2=V_0\left(g_{05}+g_{05A}\right)-g_{m5}\left(K_2V_2+V_1\right)-g_{m5A}V_1$$

$$V_2\left(g_{03}+g_{07}+g_{07A}\right)=V_0\left(g_{07}+g_{07A}\right)+g_{m7}\left(-K_1V_1-V_2\right)-g_{m7A}V_2$$

$$V_0\left(sC_L+g_{05}+g_{05A}+g_{07}+g_{07A}\right)=V_2\left(g_{07}+g_{07A}\right)+V_1\left(g_{05}+g_{05A}\right)+g_{m7}\left(K_1V_1+V_2\right)$$
$$+g_{m7A}V_2+g_{m5}\left(K_2V_2+V_1\right)+g_{m5A}V_1$$

T(s)=N(s)/D(s)

Neglecting go terms compared to gm terms, simplifies to:

num := (gm5h gm7h -K1 K2 gm5 gm7+K1 go3 gm7 +gm5h go3 + go7h gm5h
+ go5h gm7h) gm1

den := (K1 K2 gm5 gm7 - gm5h gm7h- go7h gm5h - go1 gm7h - go5h gm7h
- gm5h go3) sCL - go7h go1 go5h - go7h go1 go3 - go7h go5h go3
- go1 go5h gm7h - go1 go5h go3 - go7h gm5h go3
+ go5h gm7 K1 go3 + go7h go1 gm5 K2

Practical Comments about Positive Feedback Gain Enhancement

- Significant gain enhancement is possible but most designers avoid regenerative feedback because of unfounded concerns about closed-loop stability

- Accuracy and settling time can be improved with some regenerative feedback

- Will become more critical in emerging processes where g_m/g_o ratios degrade and where supply voltages shrink thus limiting the longstanding cascode process

- Regenerative structures can have high sensitivities

- Signal swing quite limited in some of the most basic regenerative feedback structures

- Most useful in two-stage architecture where regenerative feedback is used in first stage (effects of signal swing are reduced by gain of second stage)

Summary of Methods of Gain Enhancement

Increasing the output impedance of the amplifier

cascode, folded cascode, regulated cascode, positive feedback

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)

usually limited to a two-level cascade because of too much phase accumulation

One or more of these effects can be combined

Operational Amplifier Architectures

Most of the popular operational amplifier architectures have been introduced

Large number of different architectural choices exist with substantially different performance potential

Choice of architecture is important but judicious use of DOF is essential to obtain good performance

Few architectures offer a GB power efficiency that is better than that of the reference op amp (but some two-stage amplifiers do)

Some variants of the basic amplifier structures such as buffered output stages are commonly used in some applications

Observations about Op Amp Design

- Considerably different insight can often be obtained by viewing a circuit in multiple ways
- Various systematic procedures for designing op amps have been introduced
- It is important to understand the design space and to identify a good set of design variables
  - design spaces can be explored in many different ways but the degrees of freedom are incredibly valuable resources and should be used judiciously
- Cascaded amplifiers offer potential for gain enhancement but compensation schemes to practically work with more than two levels of cascading have not yet emerged
- Positive feedback appears to provide a promising approach for building high gain amplifiers in low voltage processes but research is ongoing into how this concept can be fully utilized

Up to this point all analysis of the op amp has focused on small-signal gain characteristics

Linearity of the amplifier does play a role in linearity and spectral performance of feedback amplifiers

Linearity is of major concern when the op amp is used open-loop such as in OTA applications

A major source of linearity is often associated with the differential input pair

Will consider linearity of the input differential pairs

Stay Safe and Stay Healthy !

End of Lecture 19