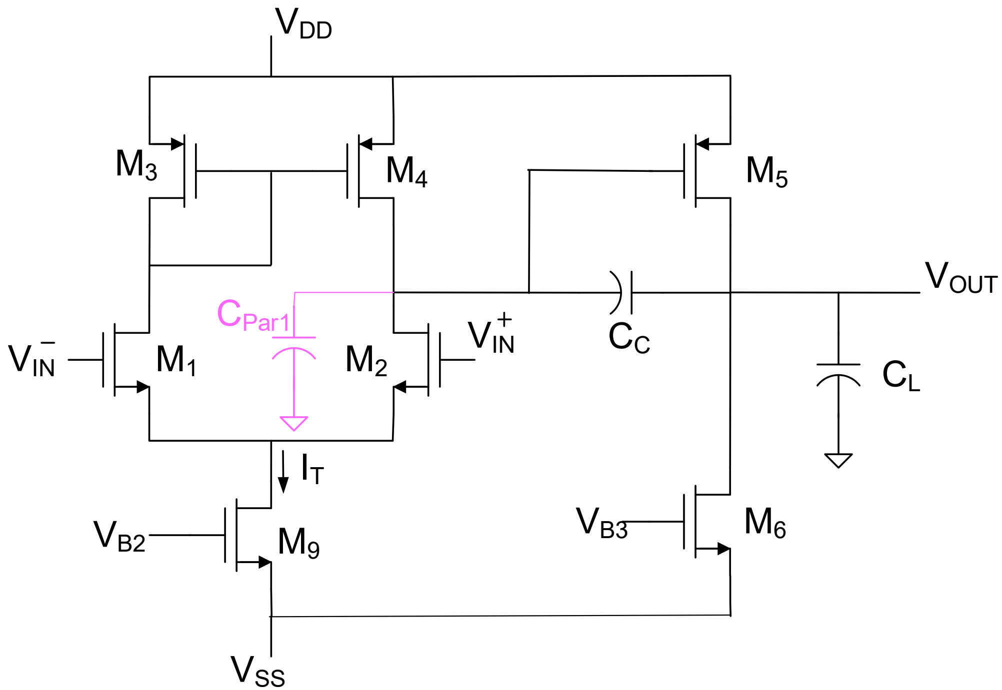
# EE 435

## Lecture 19

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

# Basic Two-Stage Op Amp



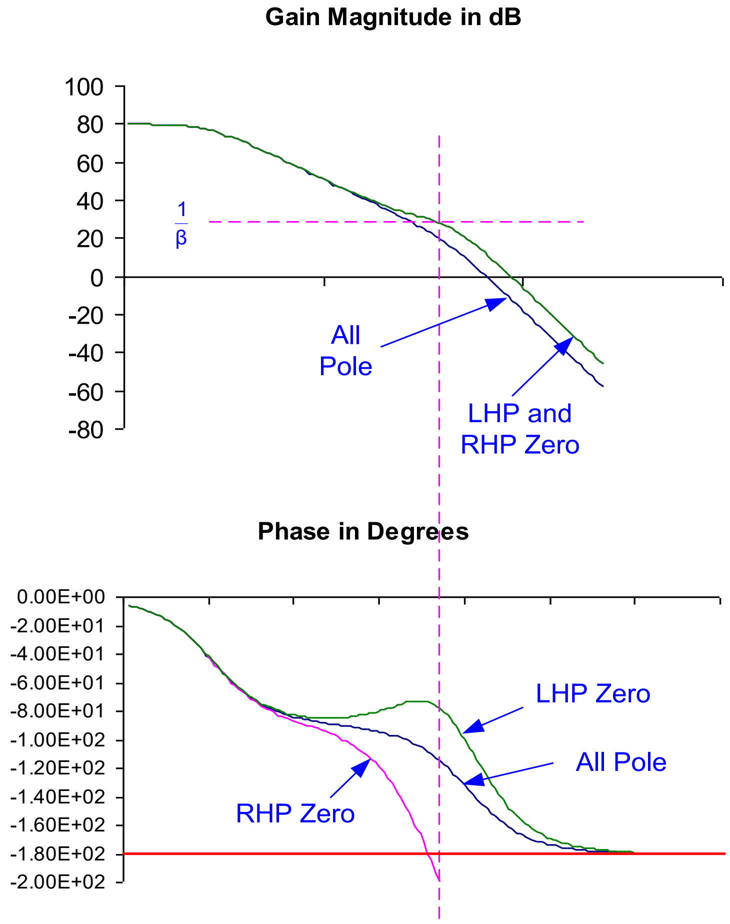

$$A_{FB}(s) \cong \frac{g_{md}(g_{m0} - sC_c)}{s^2 C_c C_L + sC_C(g_{mo} - \beta\, g_{md}) + \beta\, g_{md} g_{mo}}$$

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 ?



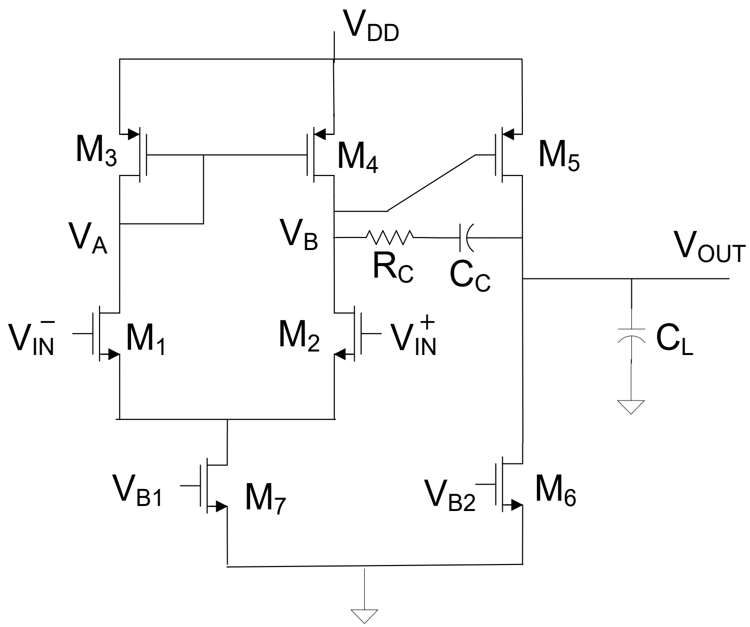

$p_1=1$, $p_2=1000$, $z_x=\{none,250,-250\}$

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

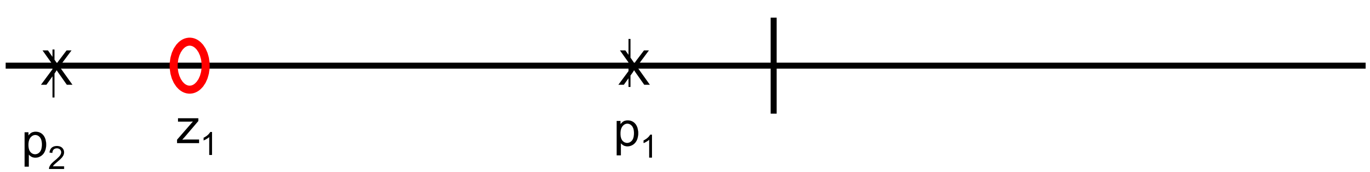
# Two-stage amplifier with LHP Zero Compensation

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

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

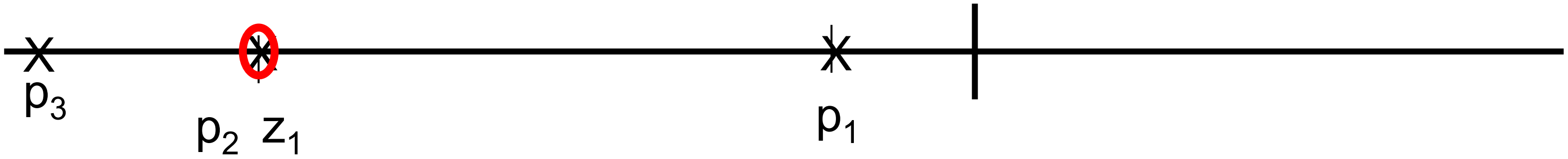
$$p_1=-\frac{g_{o1}+g_{o5}}{C_C\left(\frac{g_{m5}}{g_{05}+g_{o6}}\right)}$$

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




where should $z_1$ be placed?

# Two-stage amplifier with LHP Zero Compensation

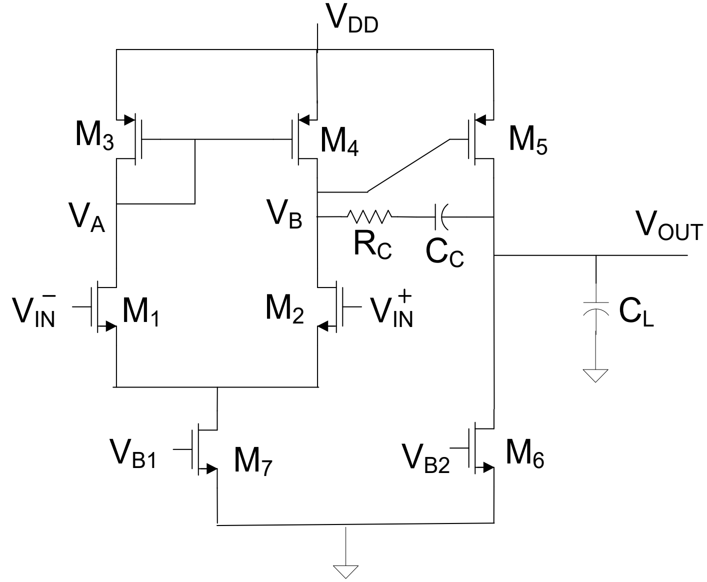



$$z_1 = \frac{-g_{m5}}{C_C\left[\frac{g_{m5}}{g_C} - 1\right]}$$

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)

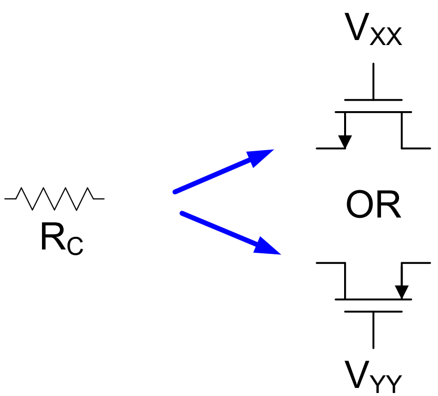
$C_C$ often chosen to meet phase margin (or settling/overshoot) requirements after all other degrees of freedom used with computer simulation from magnitude and phase plots

# Basic Two-Stage Op Amp with LHP zero




## 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)

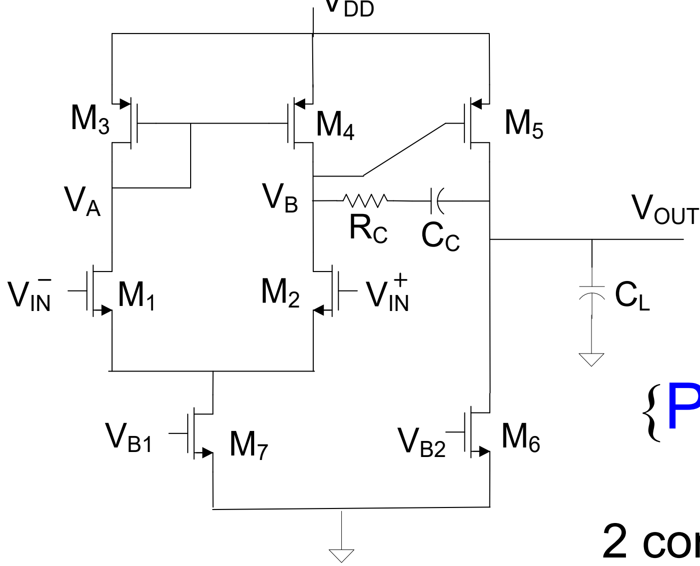
$V_{DD}$ or GND often used for $V_{XX}$ or $V_{YY}$

$V_{BQ}$ 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), $z_1 = p_2 = \dfrac{-g_{m5}}{C_C\left[\dfrac{g_{m5}}{g_C}-1\right]}$

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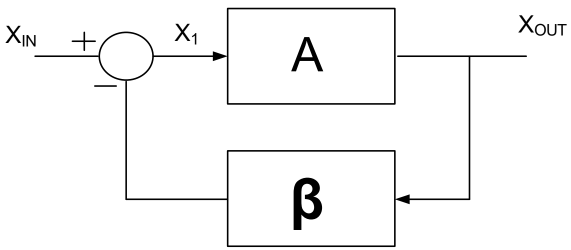
## Design Flow:

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

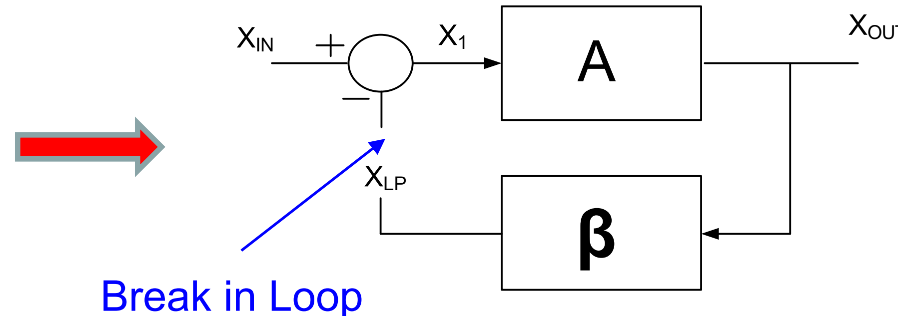
   (or preferably desired closed-loop performance for desired $\beta$)

# Two-Stage Amplifiers

## 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

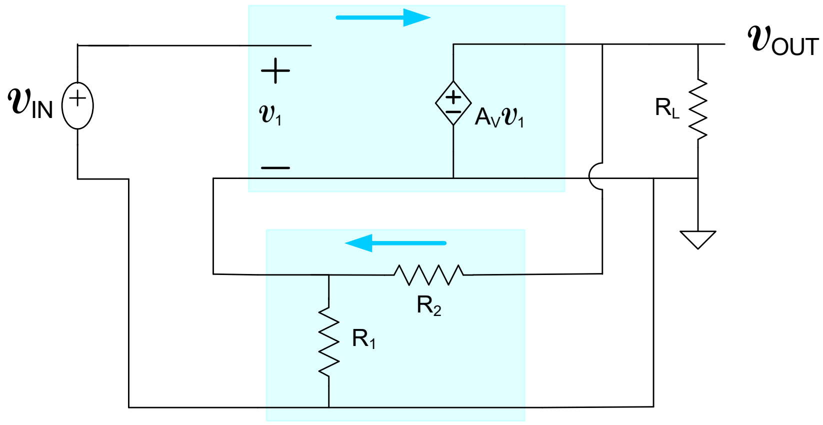
# Loop Gain - Aβ

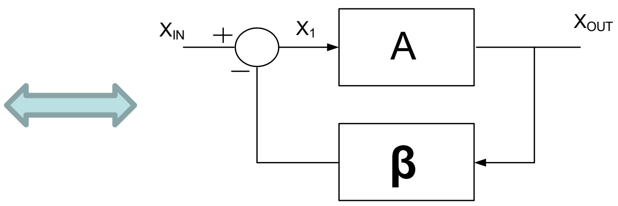
Loop Gain is a Critical Concept for Compensation of Feedback Amplifiers when Using Phase Margin Criteria (If you must!)

- 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

# Loop Gain - Aβ

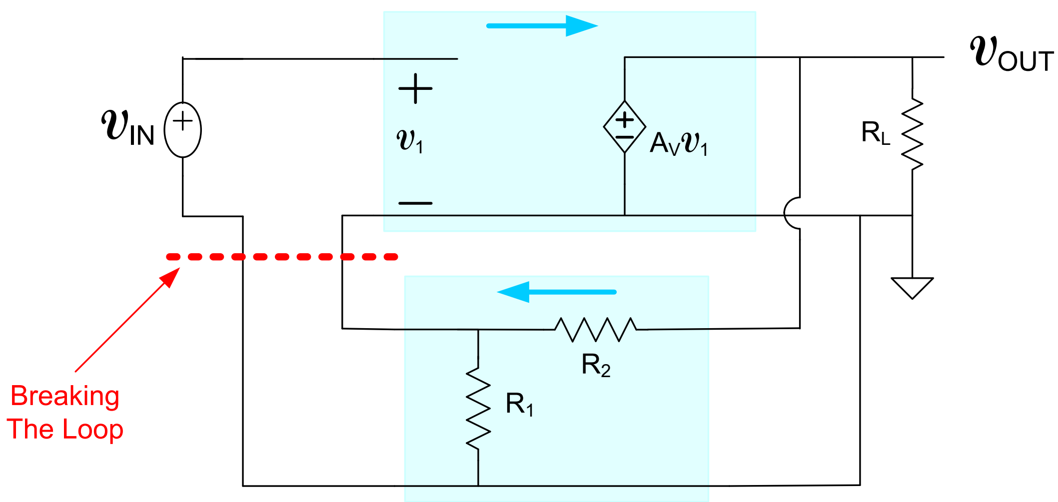
(for voltage-series feedback configuration)



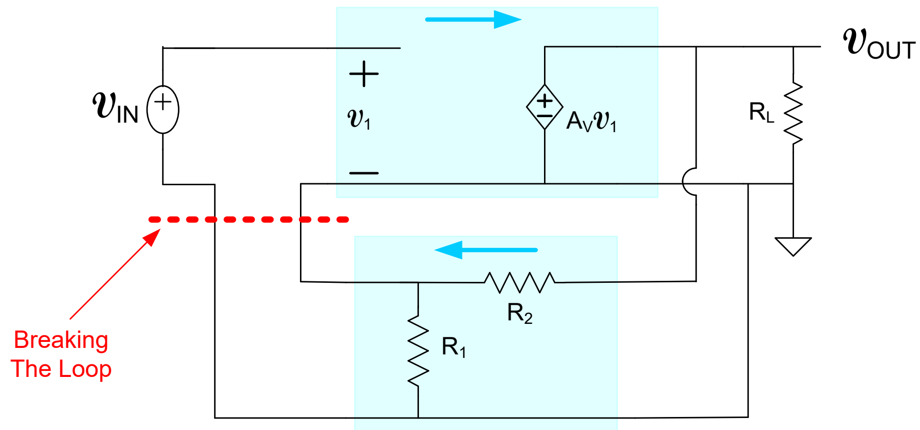

Block diagram represents small-signal feedback model

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



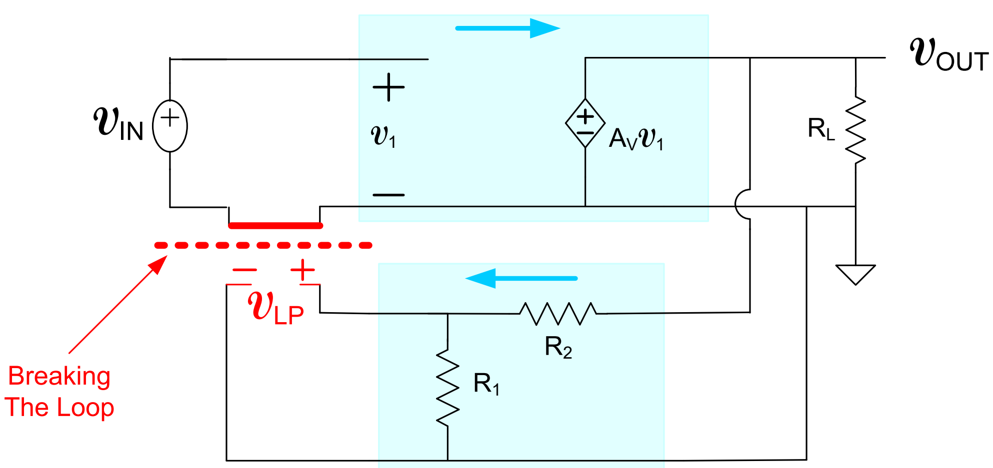
# Loop Gain - Aβ

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



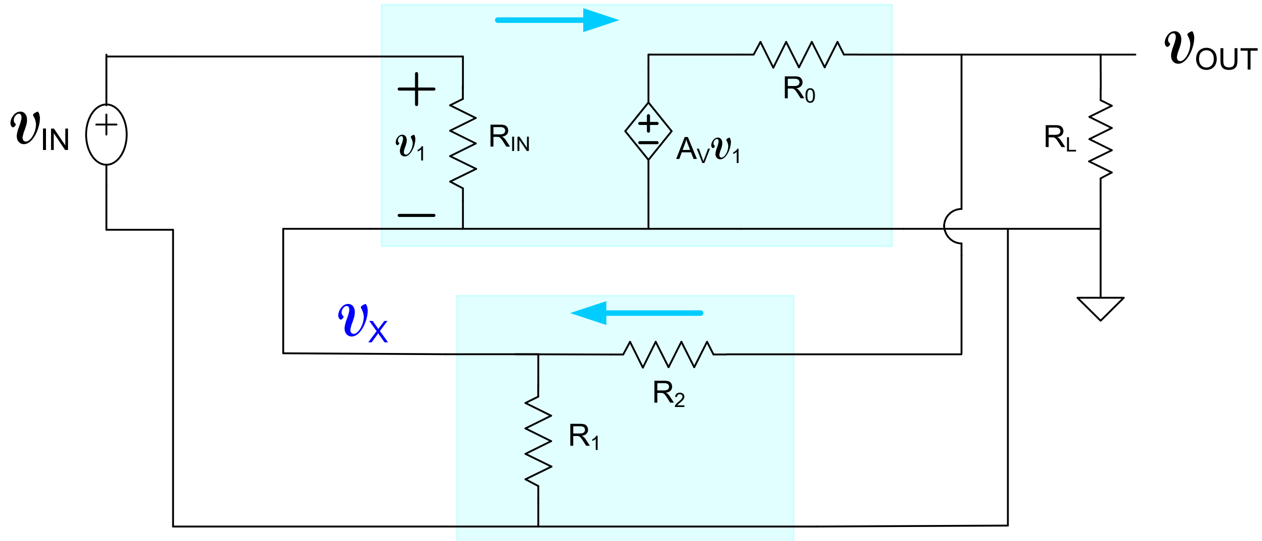

$$v_{LP} = v_{IN} A_V \frac{R_1}{R_1+R_2}$$

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

Block diagram represents small-signal feedback model

# Loop Gain - Aβ

But what if the amplifier is not ideal?




For the feedback amplifier:

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

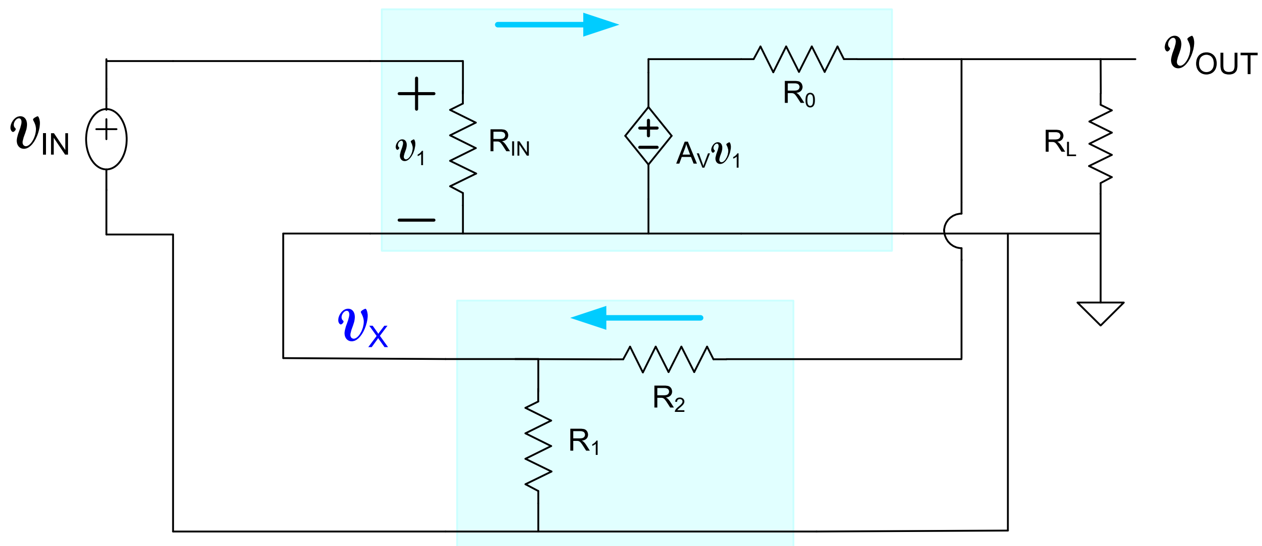
Solving, we obtain

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

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 !

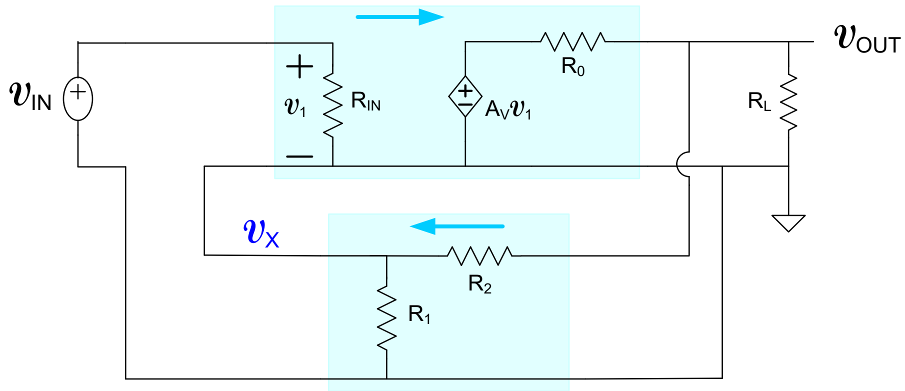
Remember: $A_{FB} = \frac{F_1(s)}{1+A\beta}$   Characteristic Polynomial Determined by

$$D(s) = 1 + A\beta$$

Whatever is added to "1" in the denominator is the loop gain

# Loop Gain - Aβ

But what if the amplifier is not ideal?




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

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

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

Can be rewritten as

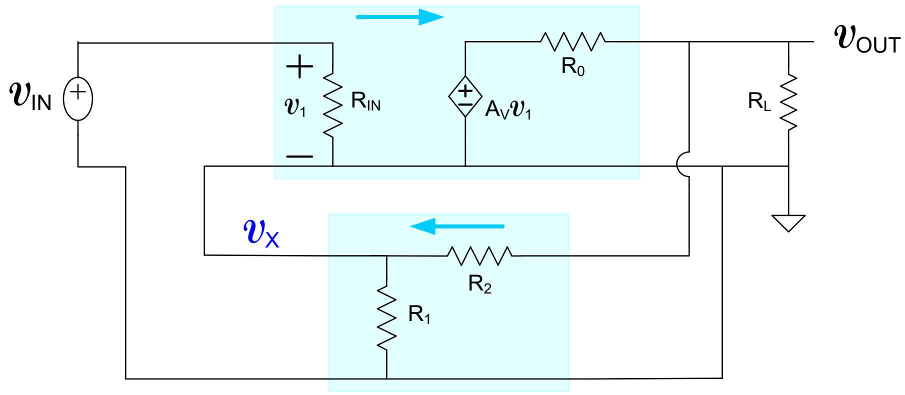
$$A_{FB} = \frac{\dfrac{G_{IN}G_2}{\left(G_O+G_L\right)\left[G_1+G_2+G_{IN}\right]+G_2\left(G_1+G_{IN}\right)} + A_V\left(\dfrac{G_O\left[G_1+G_2\right]}{\left(G_O+G_L\right)\left[G_1+G_2+G_{IN}\right]+G_2\left(G_1+G_{IN}\right)}\right)}{1+A_V\left[\dfrac{G_2 G_O}{\left(G_O+G_L\right)\left[G_1+G_2+G_{IN}\right]+G_2\left(G_1+G_{IN}\right)}\right]}$$

The Loop Gain is

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

# 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

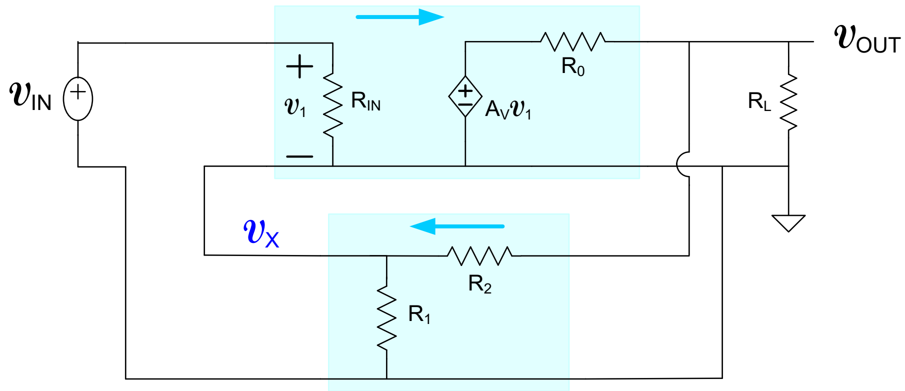
$$A_{LOOP} = (A_{VL})\left[\frac{G_2}{G_1+G_2}\right]$$

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

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

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

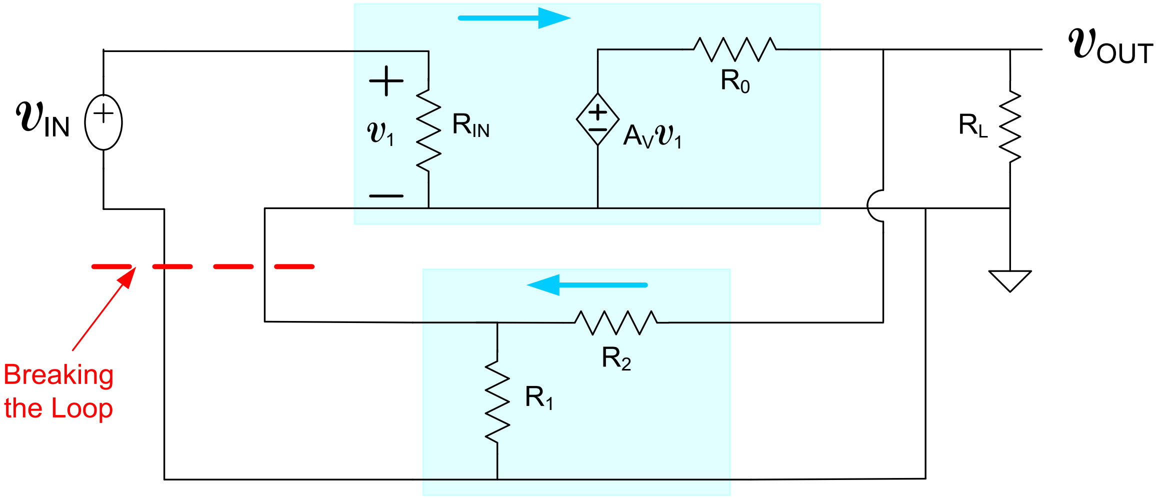
This is a really “messy” expression

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?

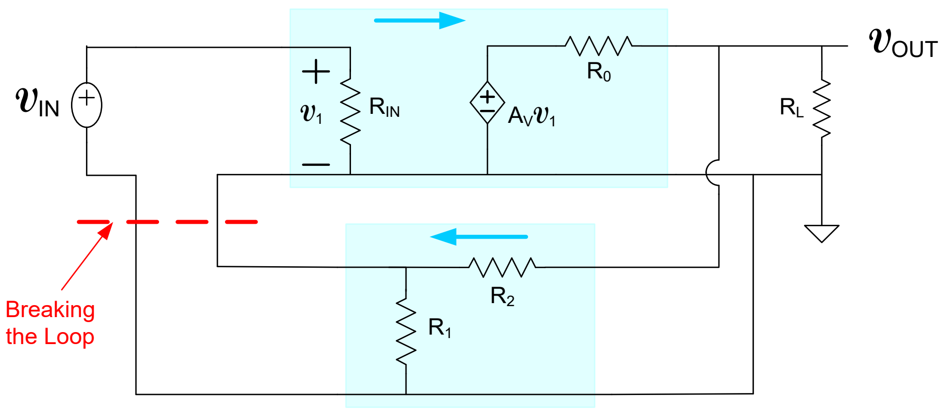


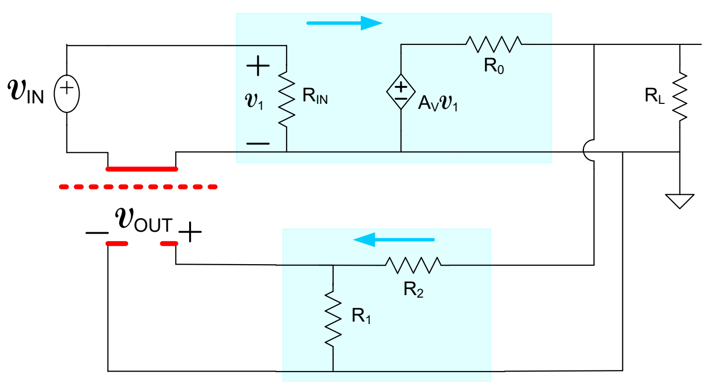

- Most authors talk about breaking the loop to determine the loop gain Aβ
- In many if not most applications, breaking the loop will alter the loading of either the A amplifier or the β amplifier or both
- Should break the loop in such a way that the loading effects of A and β are approximately included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

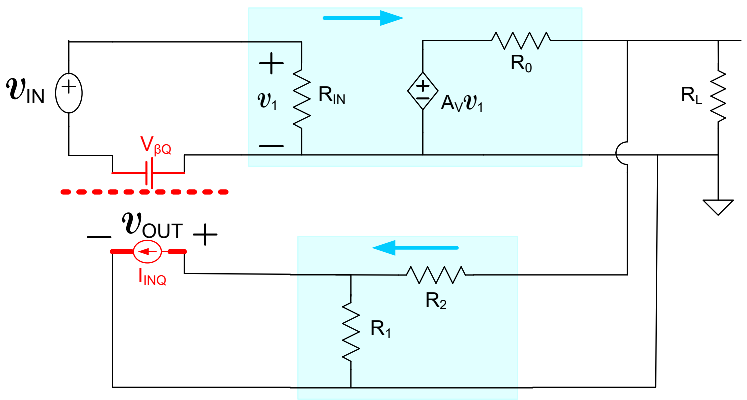
(for voltage-series feedback configuration)

But what if the amplifier is not ideal?




Standard Small-Signal Loop Gain Circuit



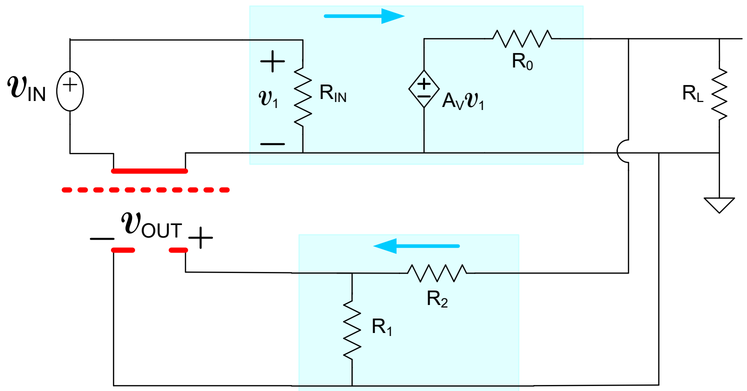

Standard Loop Gain Circuit including Biasing

(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?




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

Loop Gain from Terminated Loop

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

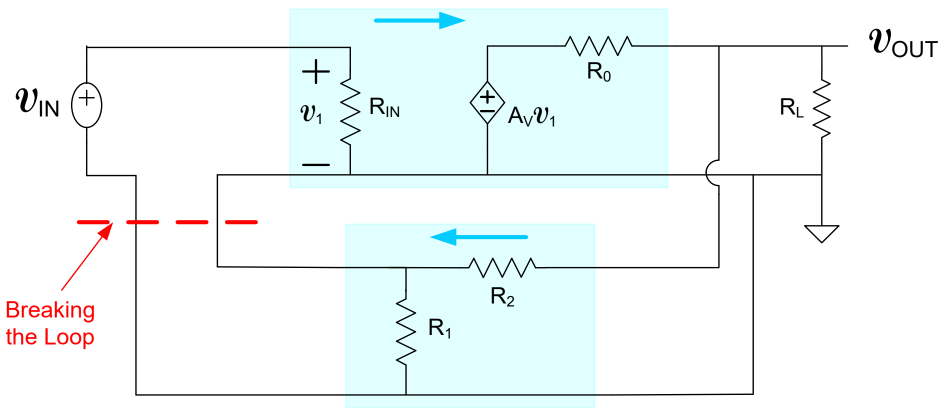
Real Loop Gain

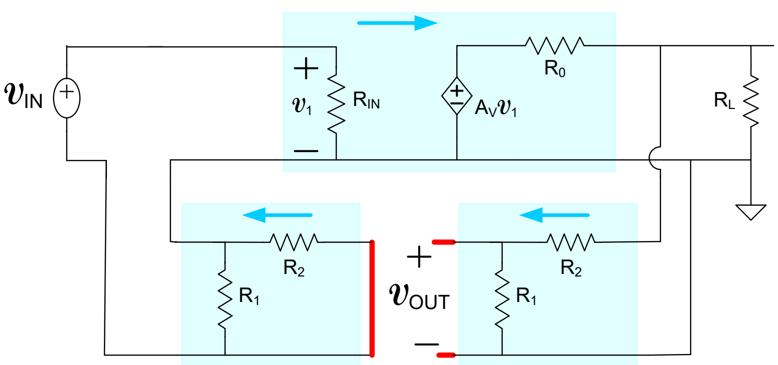
Breaking loop even with this termination will result in some error in $A_{LOOP}$

# Loop Gain - Aβ

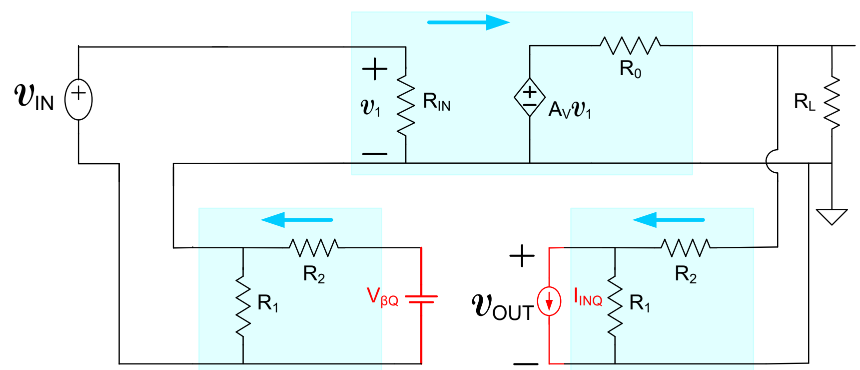
(for voltage-series feedback configuration)

But what if the amplifier is not ideal?




Better Standard Small-Signal Loop Gain Circuit



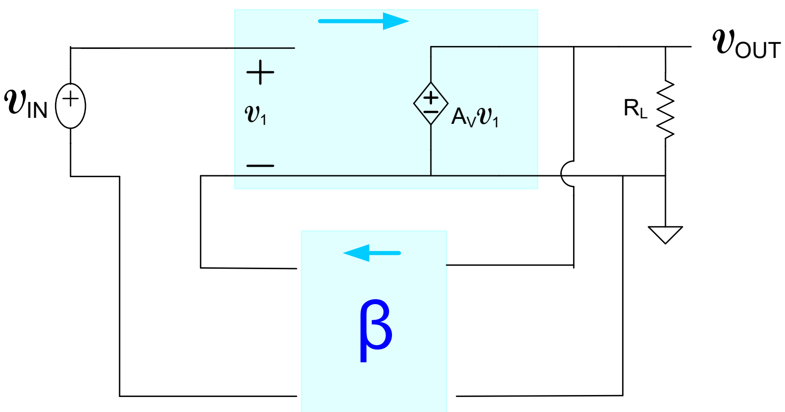

Better Loop Gain Circuit including Biasing

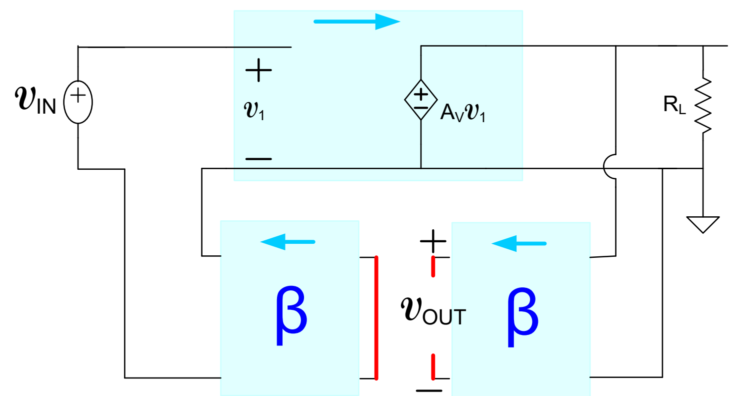
(terminations shown in ss circuit are what is needed in the actual amplifier)

# Loop Gain - Aβ

## for four basic amplifier types

voltage-series feedback

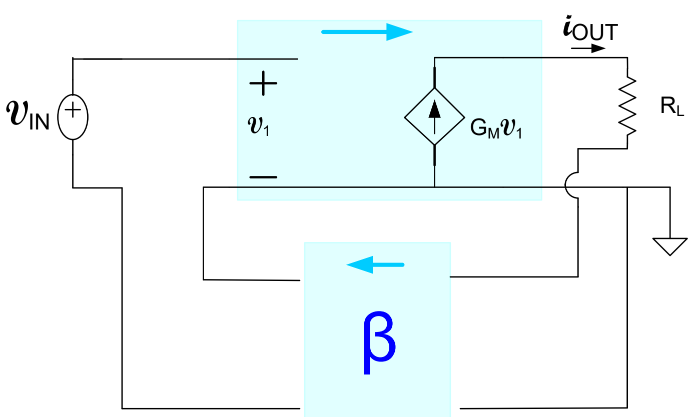


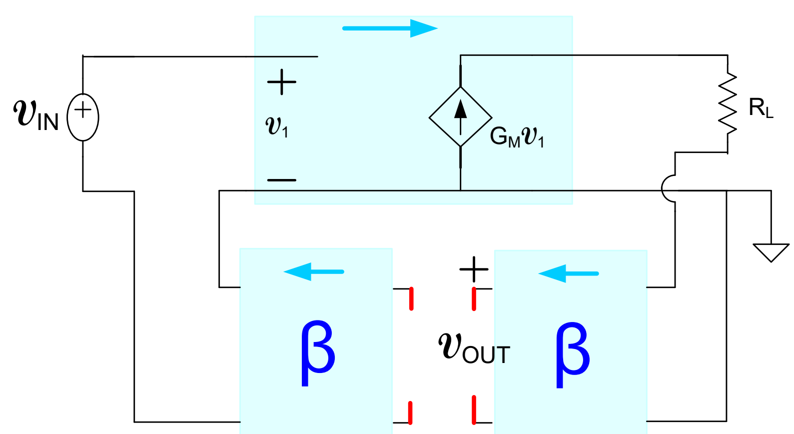




Feedback Amplifier

Loop Gain Amplifier

current-series feedback

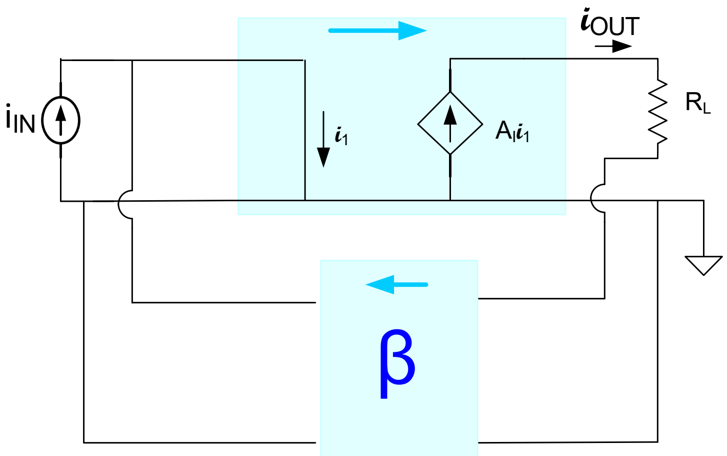


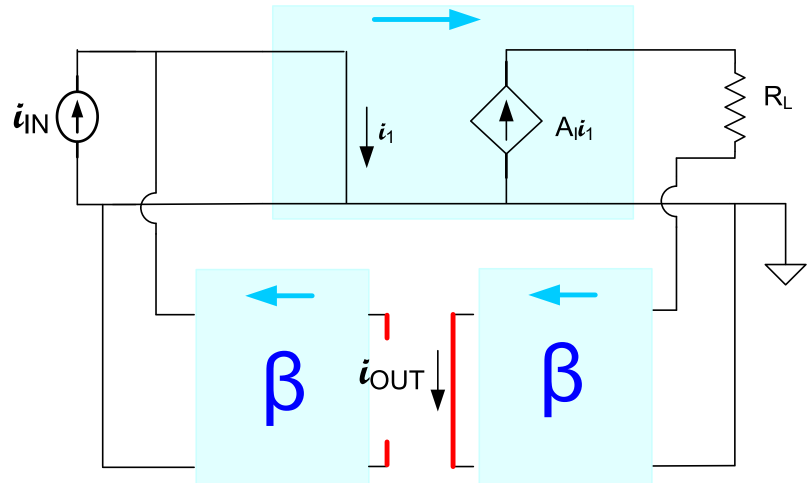



# Loop Gain - Aβ

## for four basic amplifier types

current-shunt feedback

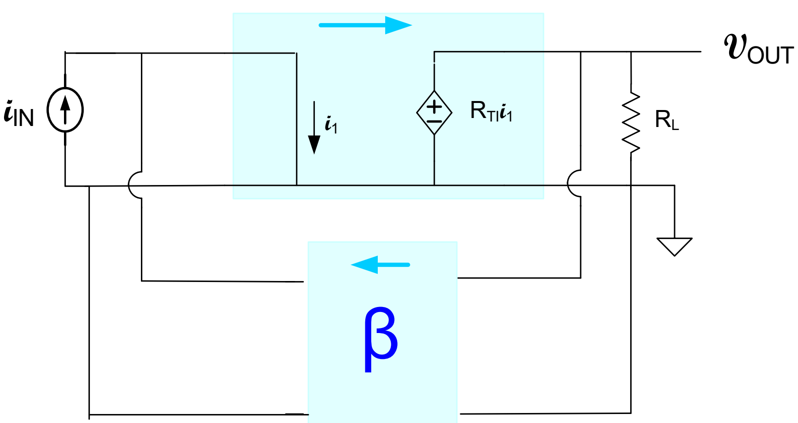


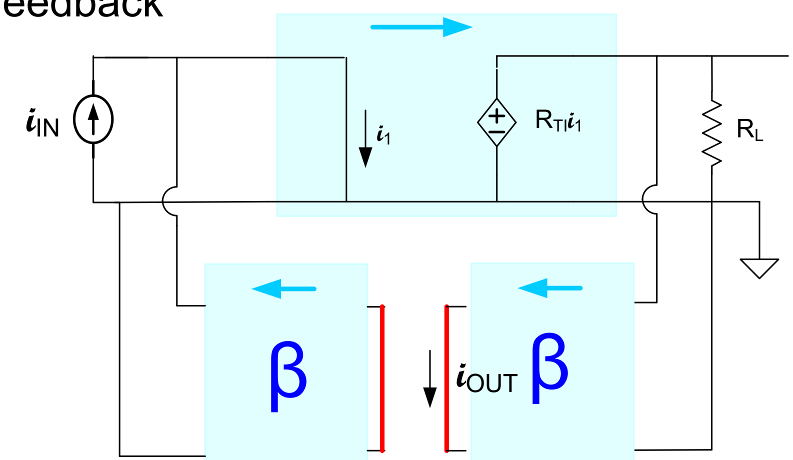




Feedback Amplifier

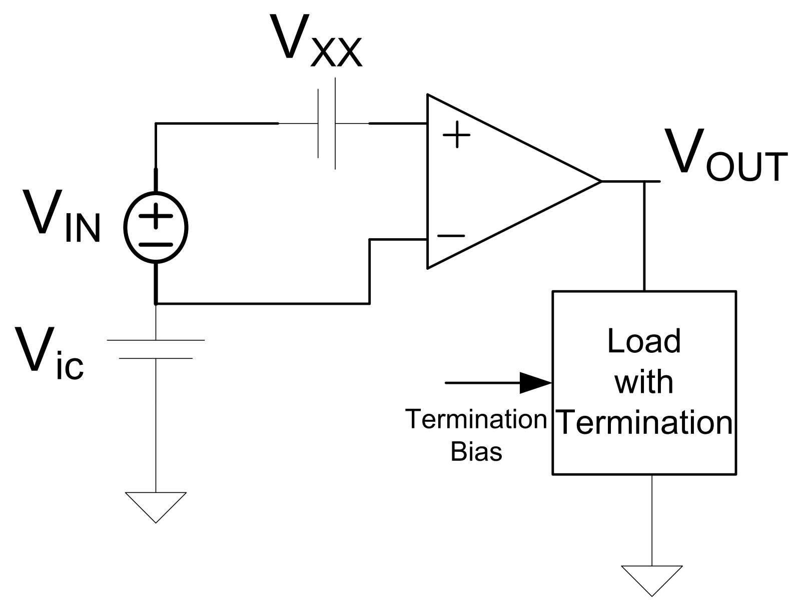
Loop Gain Amplifier

voltage-shunt feedback



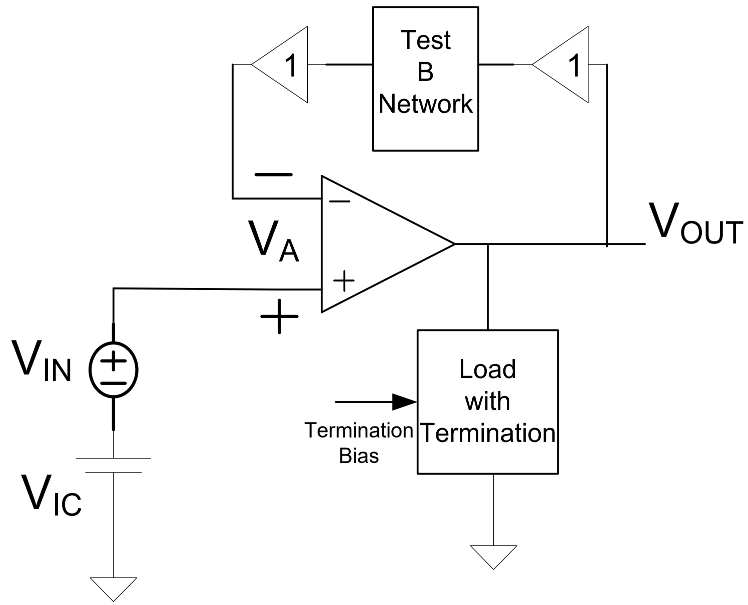
# Open-loop gain simulations




- 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)



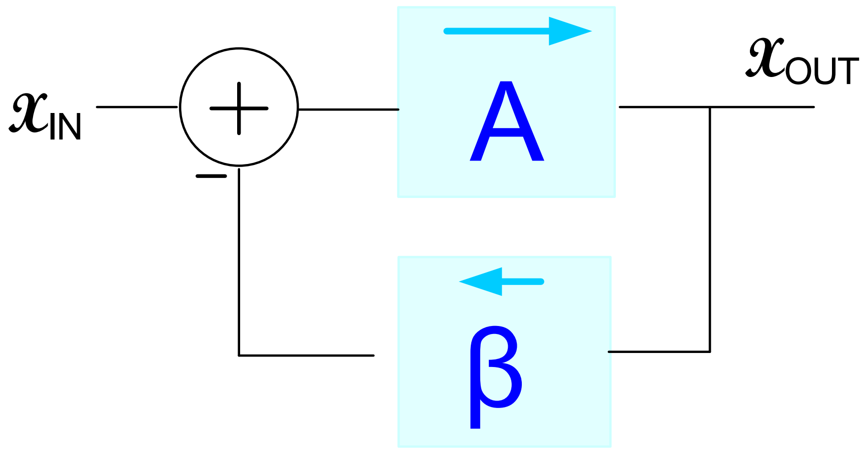

$$A_{VL} = \frac{V_{OUT}}{V_A}$$

- 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

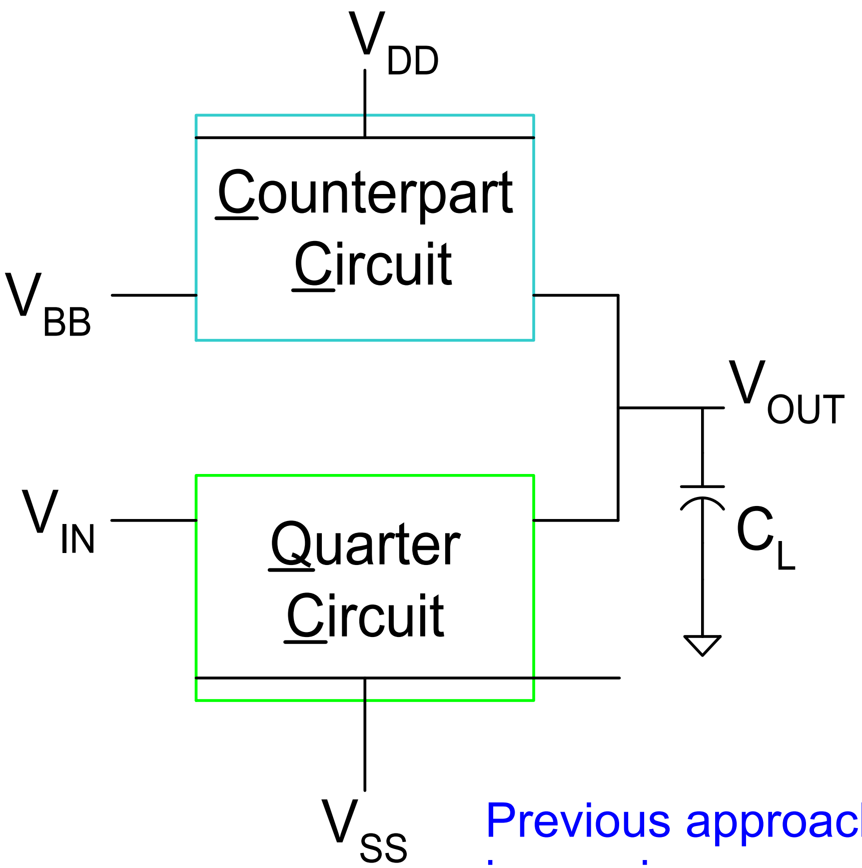
Increasing the transconductance
(current mirror op amp) but it didn't really help because
the output conductance increased proportionally

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:




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

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

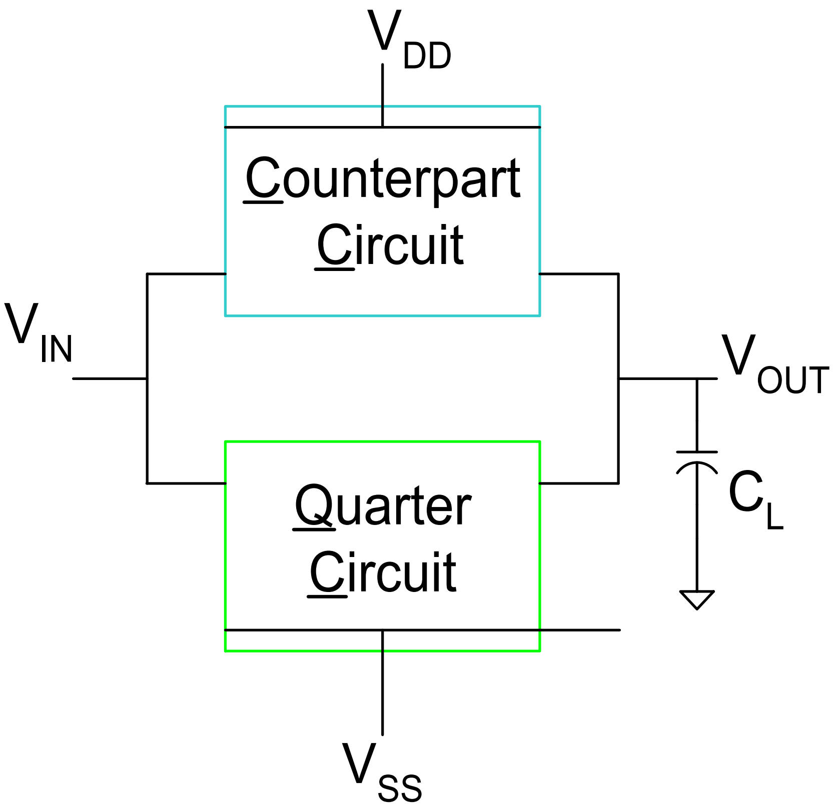
Two Strategies:

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



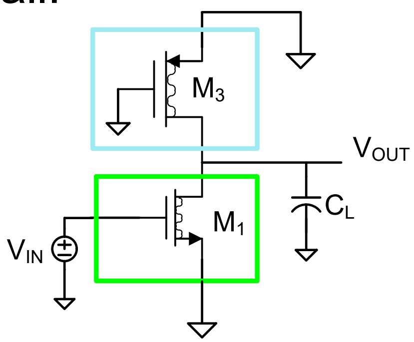

$$A_{V0} = \frac{-(g_{mQC} + g_{mCC})}{g_{oQC} + g_{oCC}}$$

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

**Consider now increasing numerator by changing the excitation**

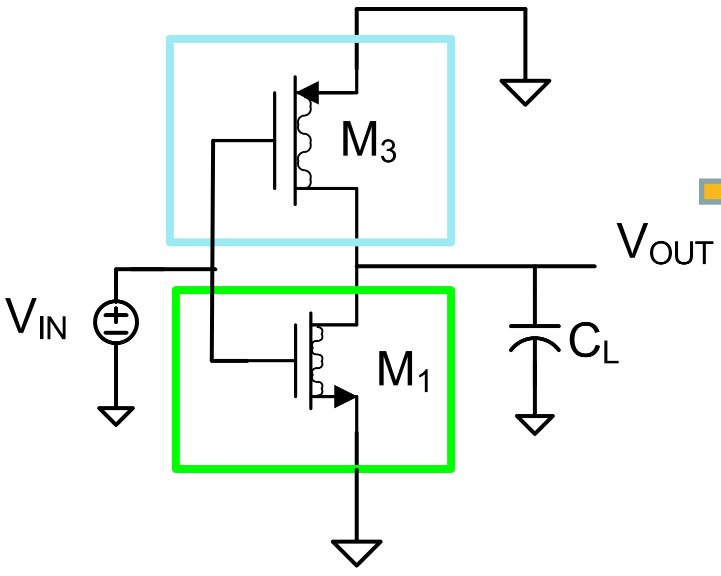
# $g_{meq}$ Enhancement with Driven Counterpart Circuit

Recall:




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

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

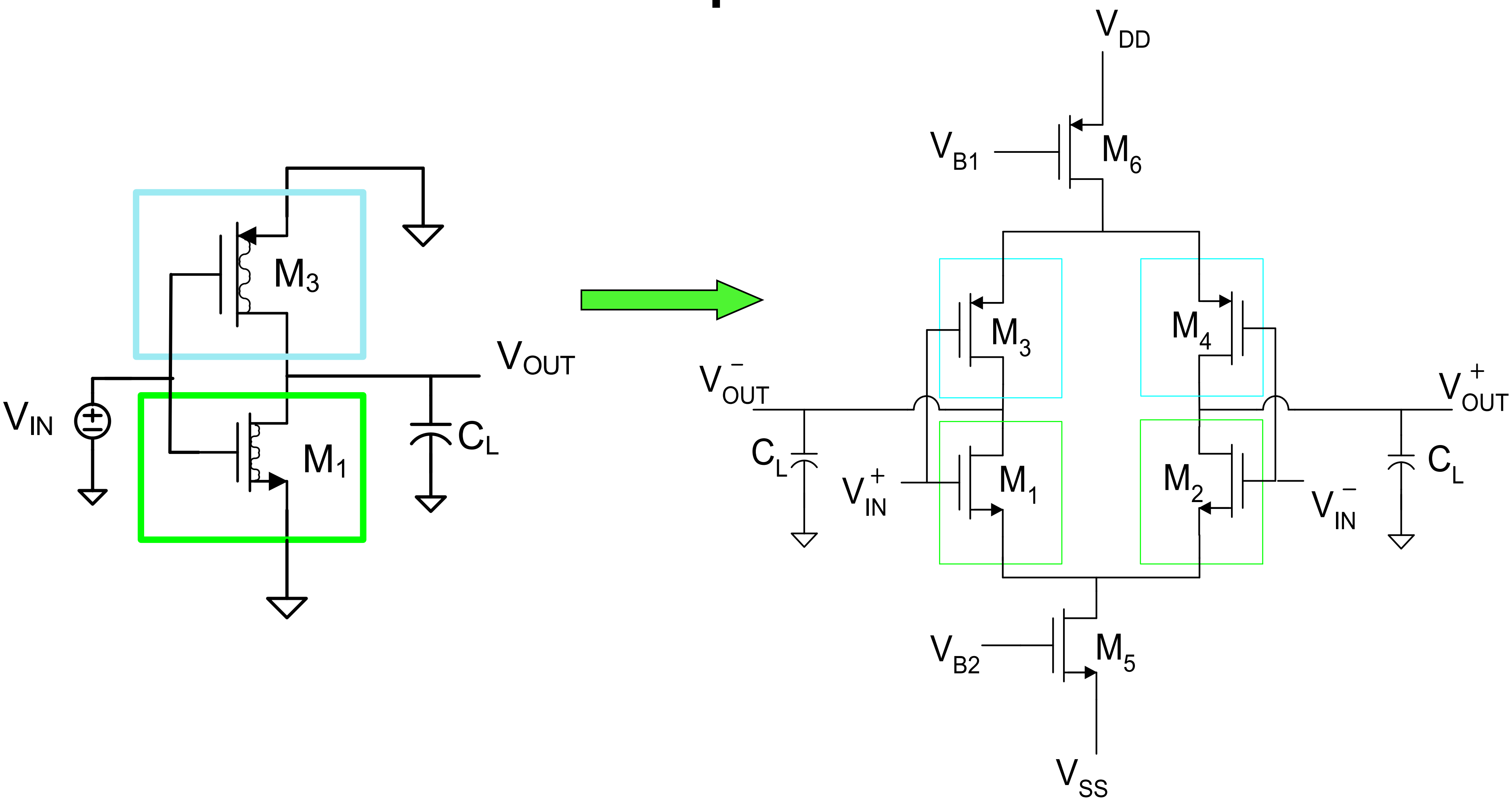



$$A_{V0} = \frac{g_{m1} + g_{m3}}{g_{o1} + g_{o3}}$$

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

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

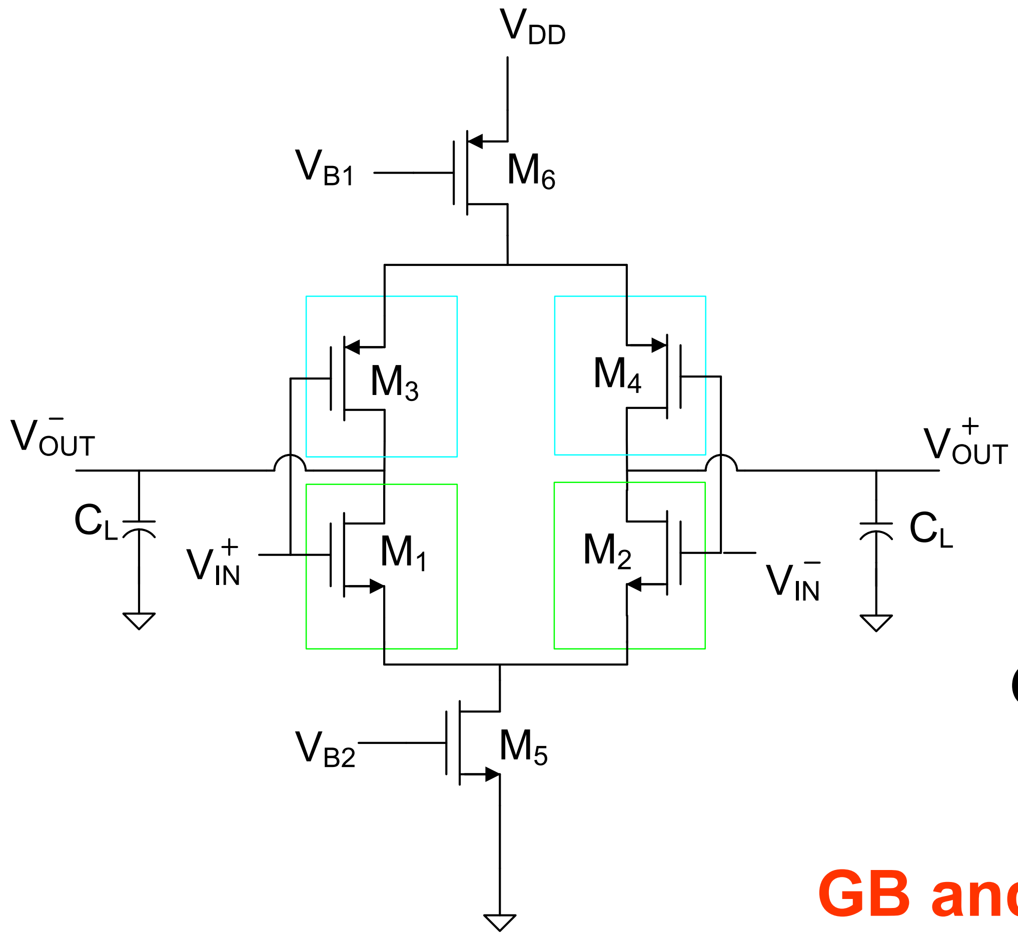
# $g_{meq}$ Enhancement with Driven Counterpart Circuit




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

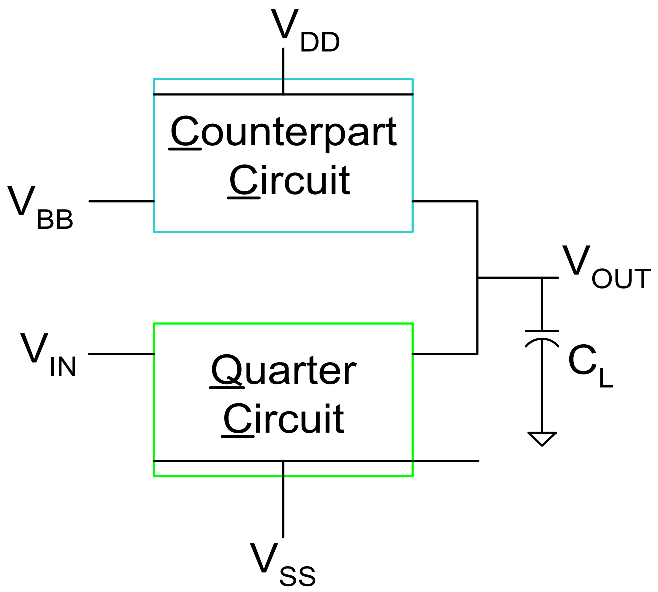
Increasing the transconductance
(current mirror op amp) but it didn't really help because
the output conductance increased proportionally

→ 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:

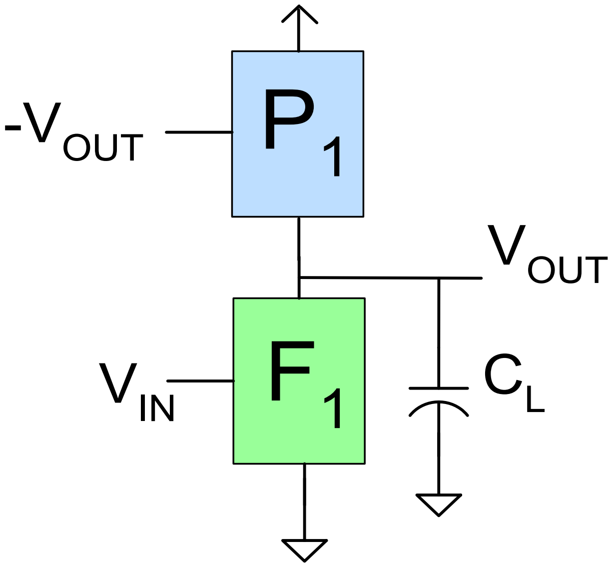
1. Decrease denominator of $A_{V0}$
2. Increase numerator of $A_{V0}$

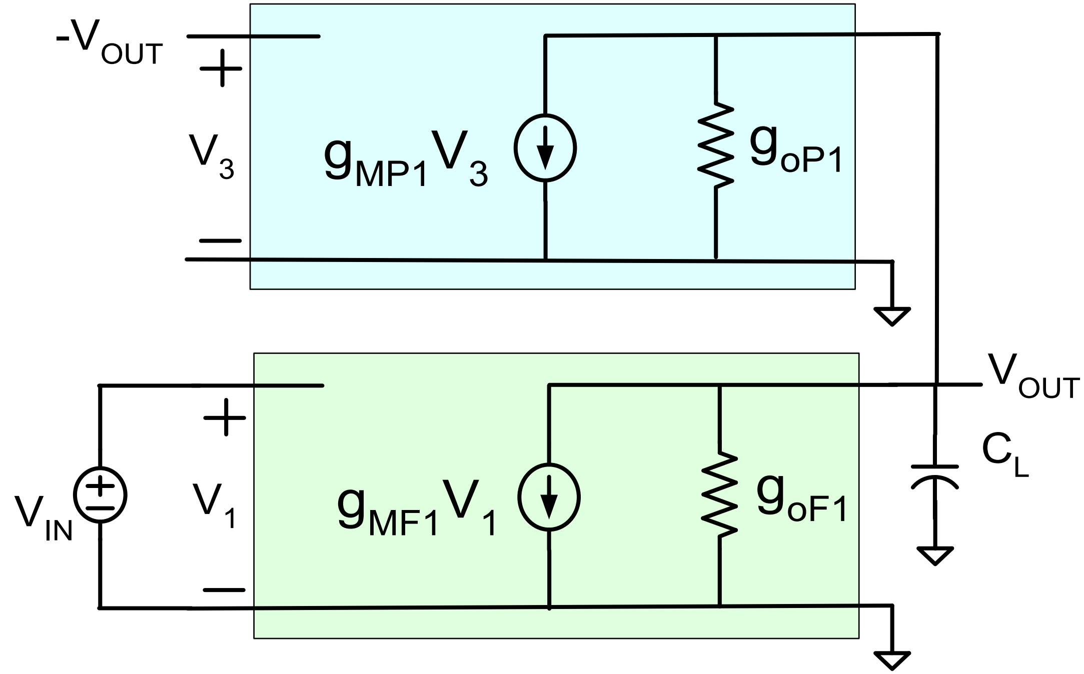
**Consider again decreasing the denominator**

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

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

# Other Methods of Gain Enhancement



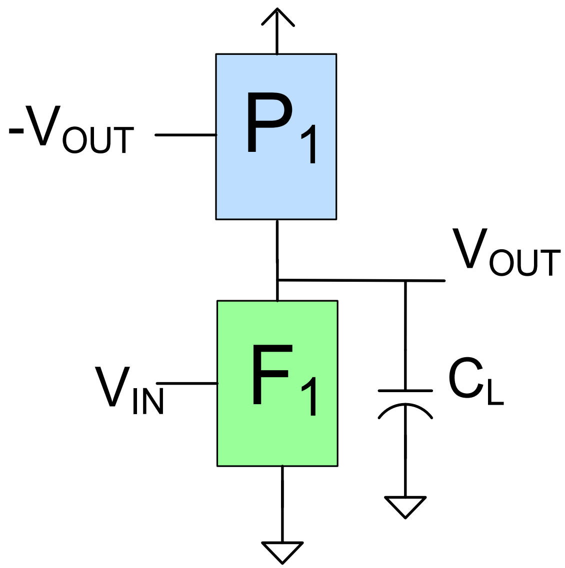




$$\left.\begin{array}{l} V_{OUT}\left(sC_L + g_{oP1} + g_{oF1}\right) + g_{mF1}V_{IN} + g_{mP1}V_3 = 0 \\ V_3 = -V_{OUT} \end{array}\right\}$$

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

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

# Gain Enhancement with Regenerative Feedback




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

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

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

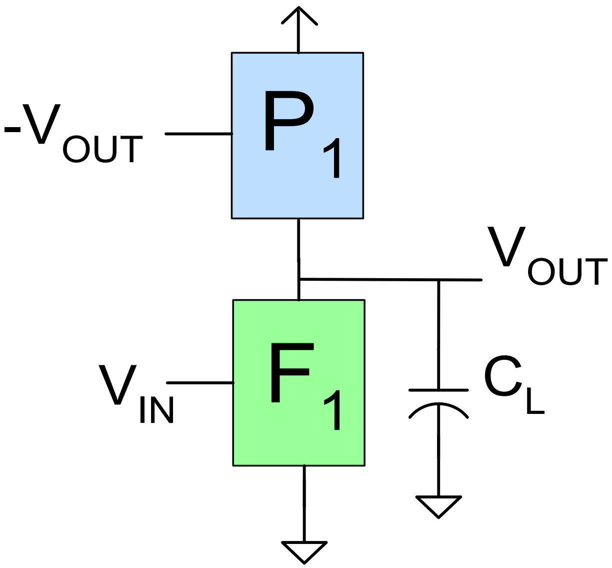
$$GB = \frac{g_{mF1}}{C_L}$$

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

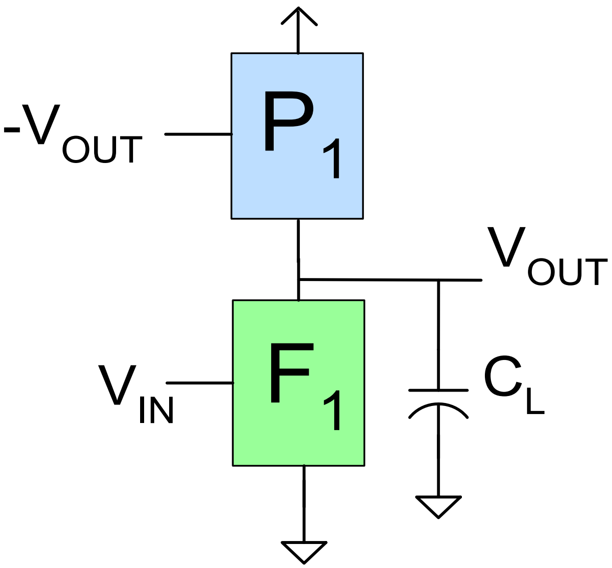
The GB does not degrade !

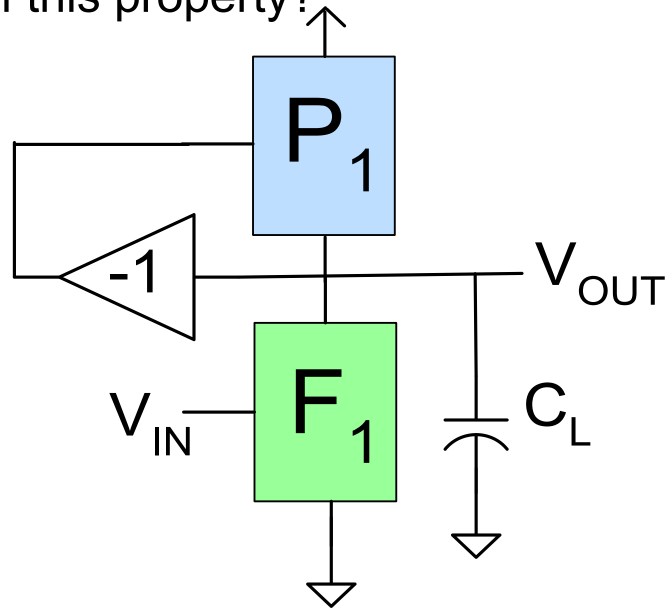
This circuit has a positive feedback loop ($V_{INP1}$:$V_{OUT}$:-$V_{OUT}$)

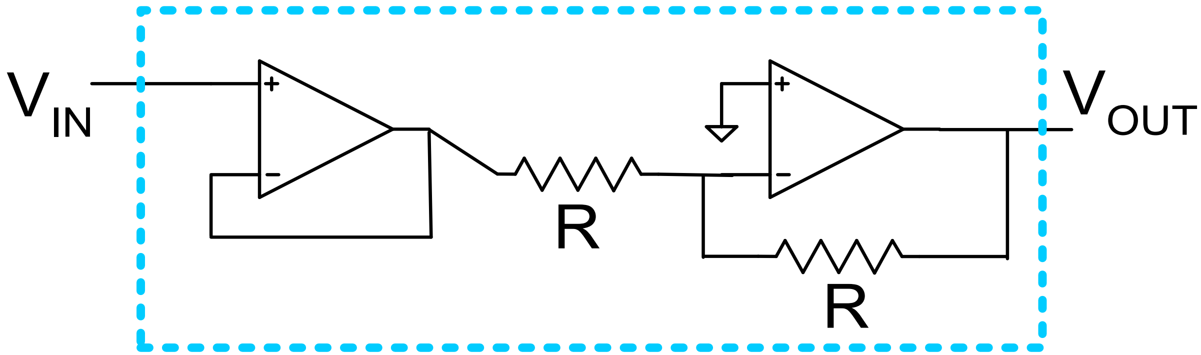
But - can we easily build circuits with this property?

# Gain Enhancement with Regenerative Feedback

But - can we easily build circuits with this property?



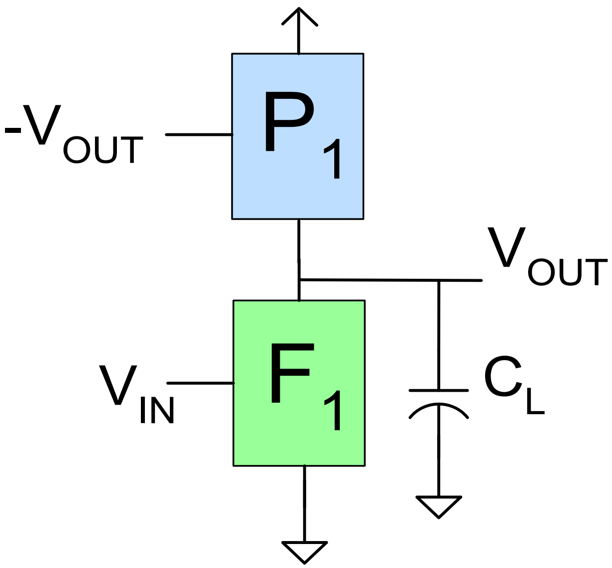



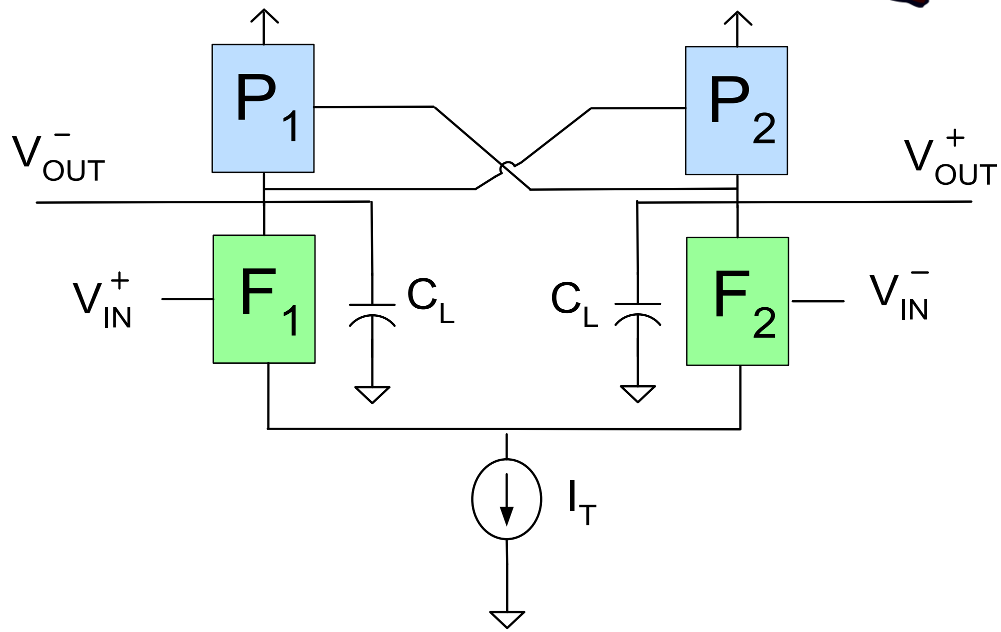

But – the inverting amplifier may be more difficult to build than the op amp itself!

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?

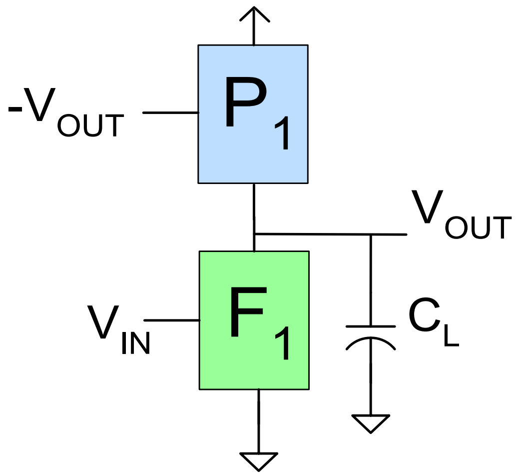


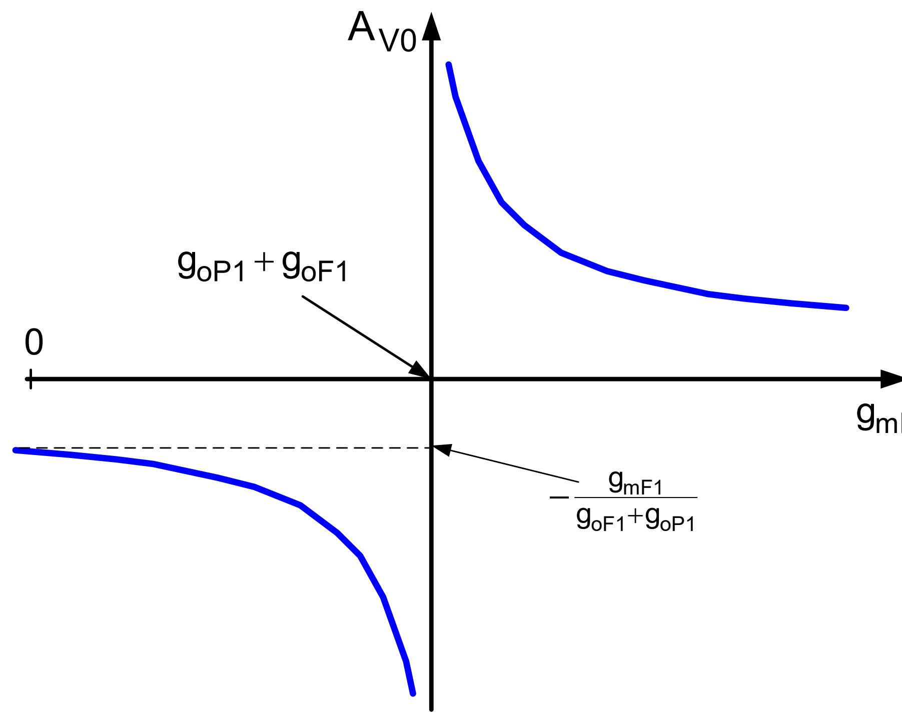

But – the inverting amplifier may be more difficult to build than the op amp itself!

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

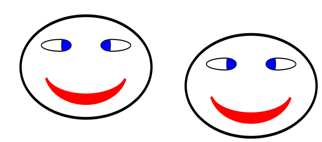
# Gain Enhancement with Regenerative Feedback




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




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

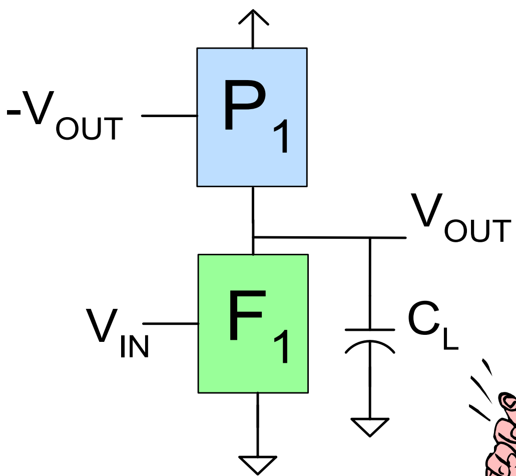


Term this “gain reversing” when dc gain changes sign with pole

Stay Safe and Stay Healthy !

End of Lecture 19

# Gain Enhancement with Regenerative Feedback




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

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

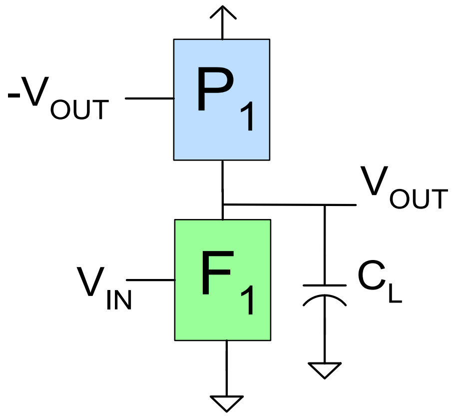
If $g_{mP1} > g_{oF1} + g_{oP1}$, the pole will be in the RHP !!

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

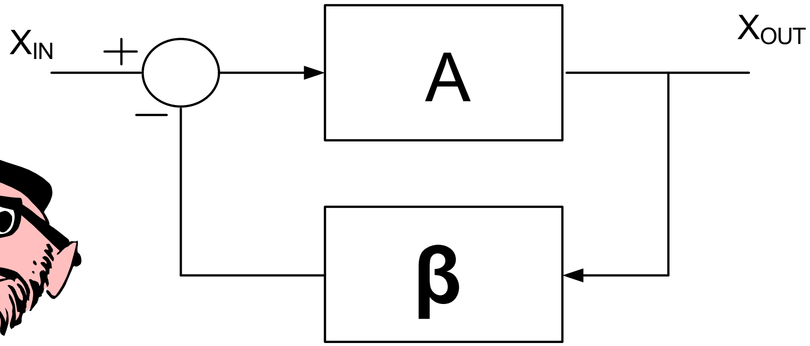



This will make the op amp unstable


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

But is Positive Feedback really bad?

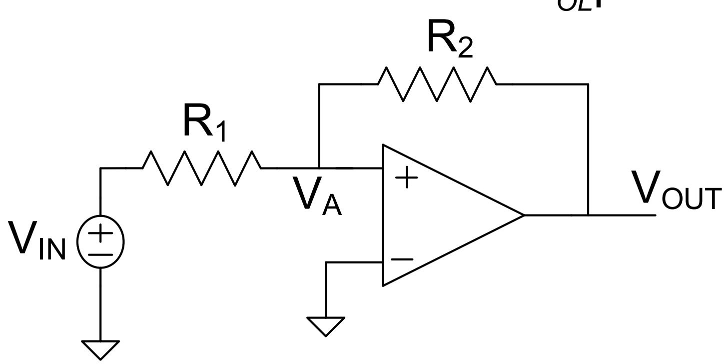
# Remember – Why do we want a large Op Amp Gain Anyway?




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

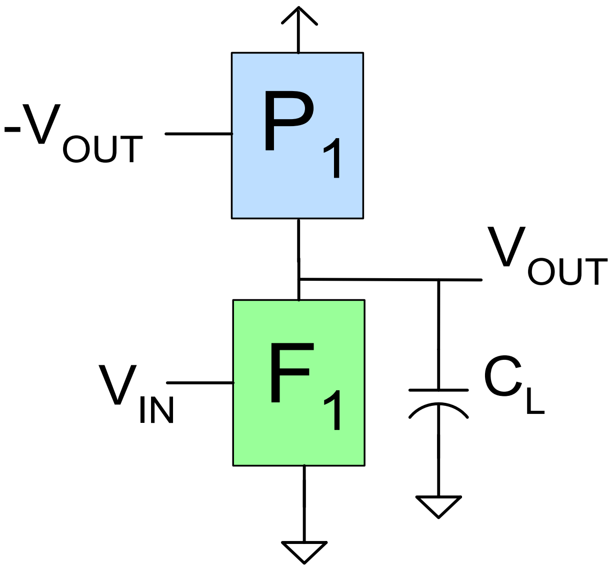
To make $A_{FB}$ very close to $1/\beta$

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 $A_{VFB}$ very close to $-R_2/R_1$

# Gain Enhancement with Regenerative Feedback




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

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

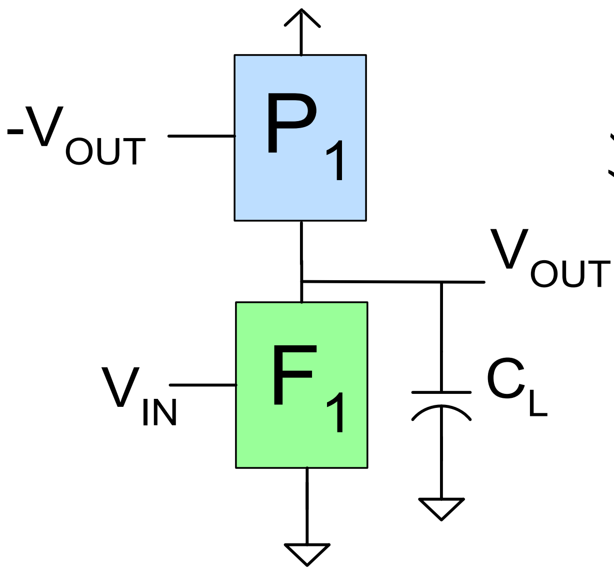
If $g_{mP1} > g_{oF1}+g_{oP1}$, the pole will be in the RHP !!

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

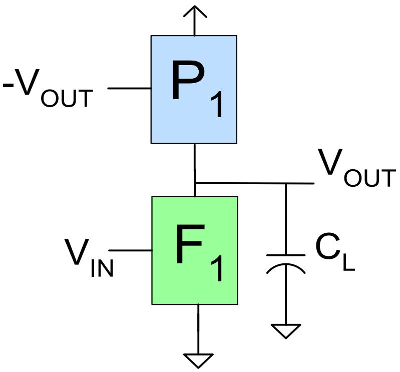
For Op Amp

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

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

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 $A_{V0}>0$

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

Stay Safe and Stay Healthy !

End of Lecture 19