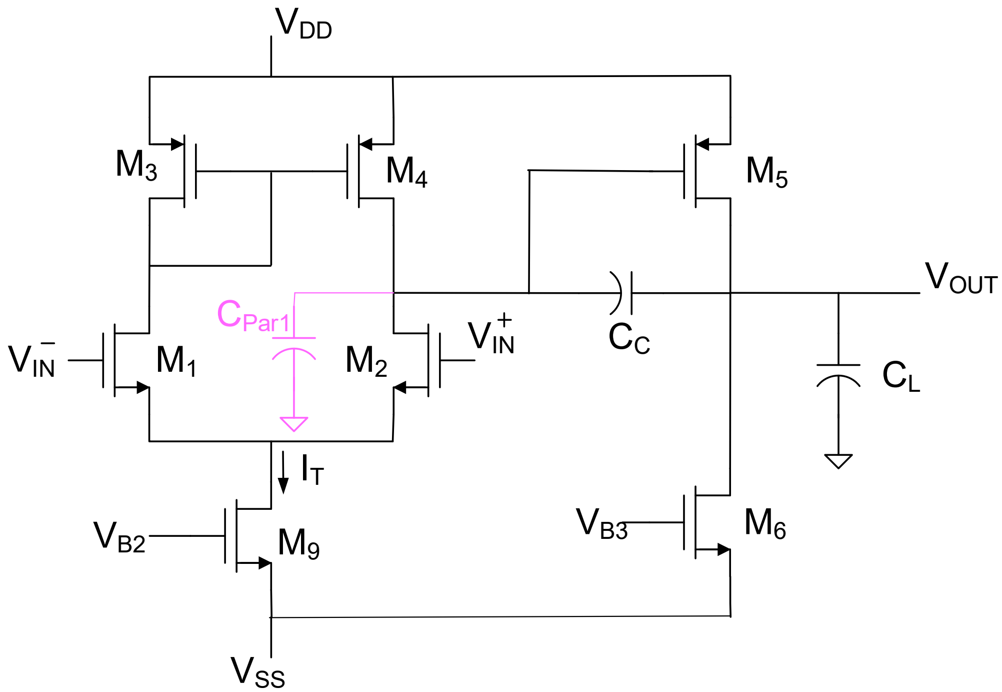
EE 435

Lecture 19

- Other methods of gain enhancement
- Linearity of Transfer Characteristics

Review from last lecture

Basic Two-Stage Op Amp



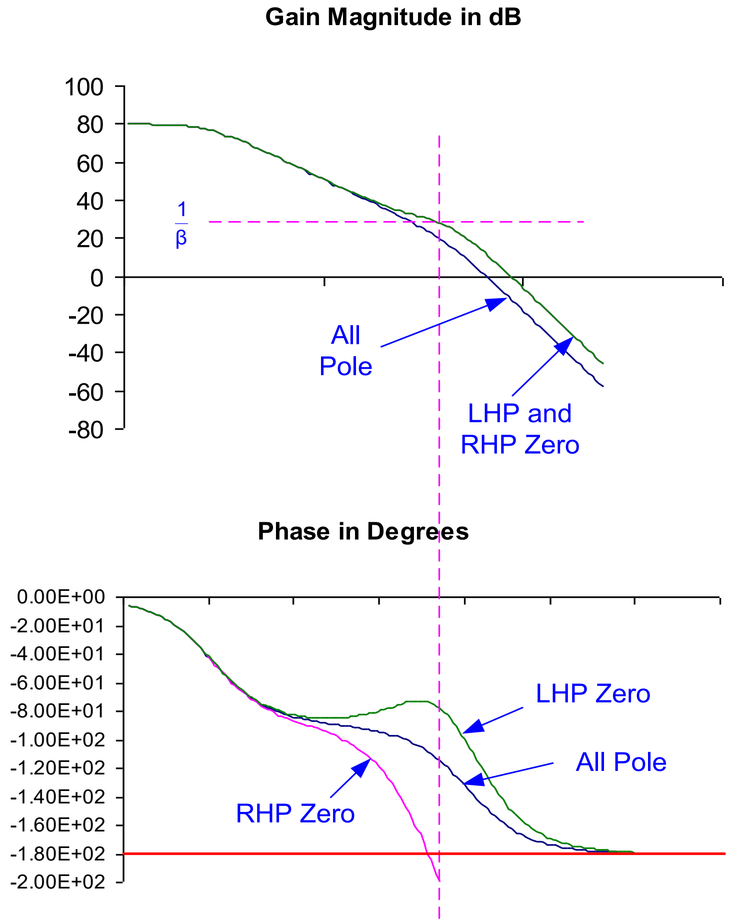
$$A_{FB}(s) \cong \frac{g_{md}\left(g_{m0} - sC_c\right)}{s^2 C_c C_L + sC_C\left(g_{mo} - \beta\, g_{md}\right) + \beta\, g_{md} g_{mo}}$$

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 ?



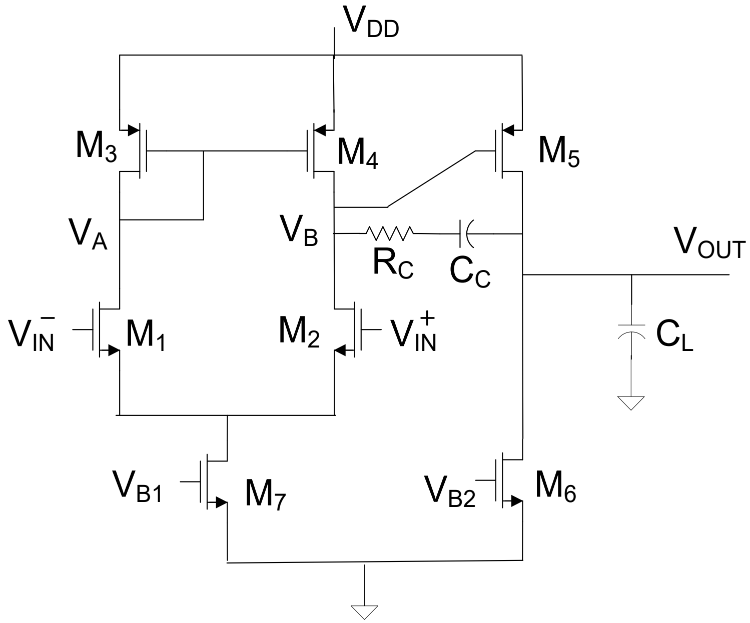
p_1=1, p_2=1000, z_x={none,250,-250}

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

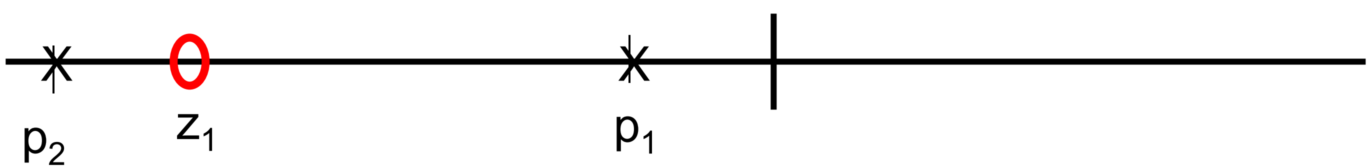
Two-stage amplifier with LHP Zero Compensation

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

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

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

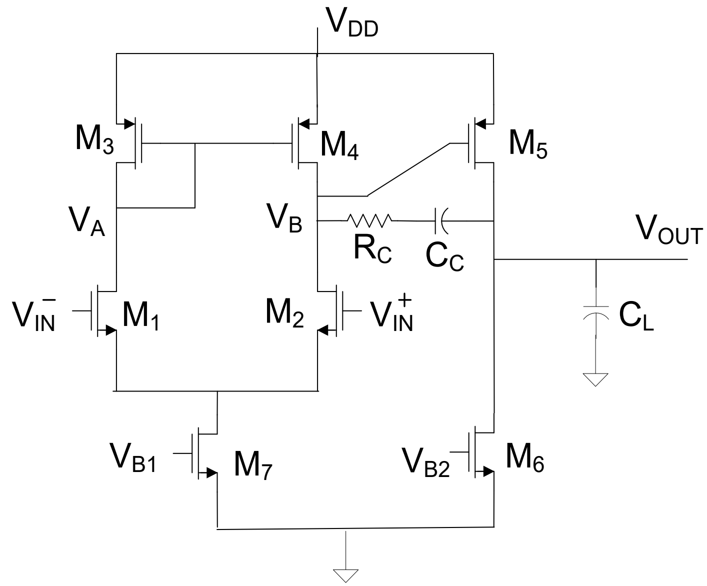
$$p_2=-\frac{g_{m5}}{C_L}$$



where should z_1 be placed?

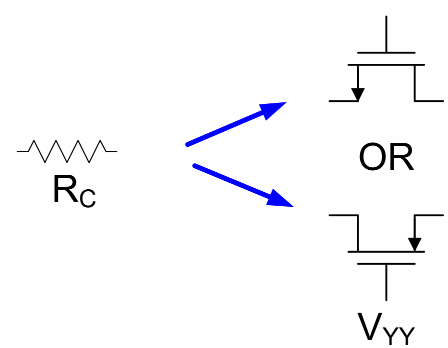
Review from last lecture

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)

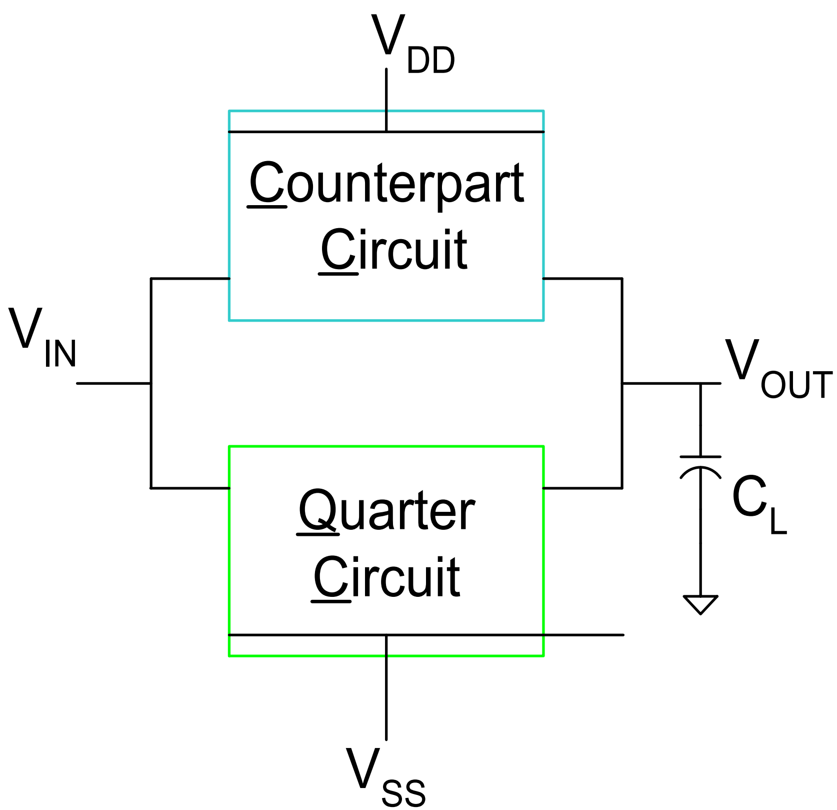
V_{DD} or GND often used for V_{XX} or V_{YY}

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

Other Methods of Gain Enhancement



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

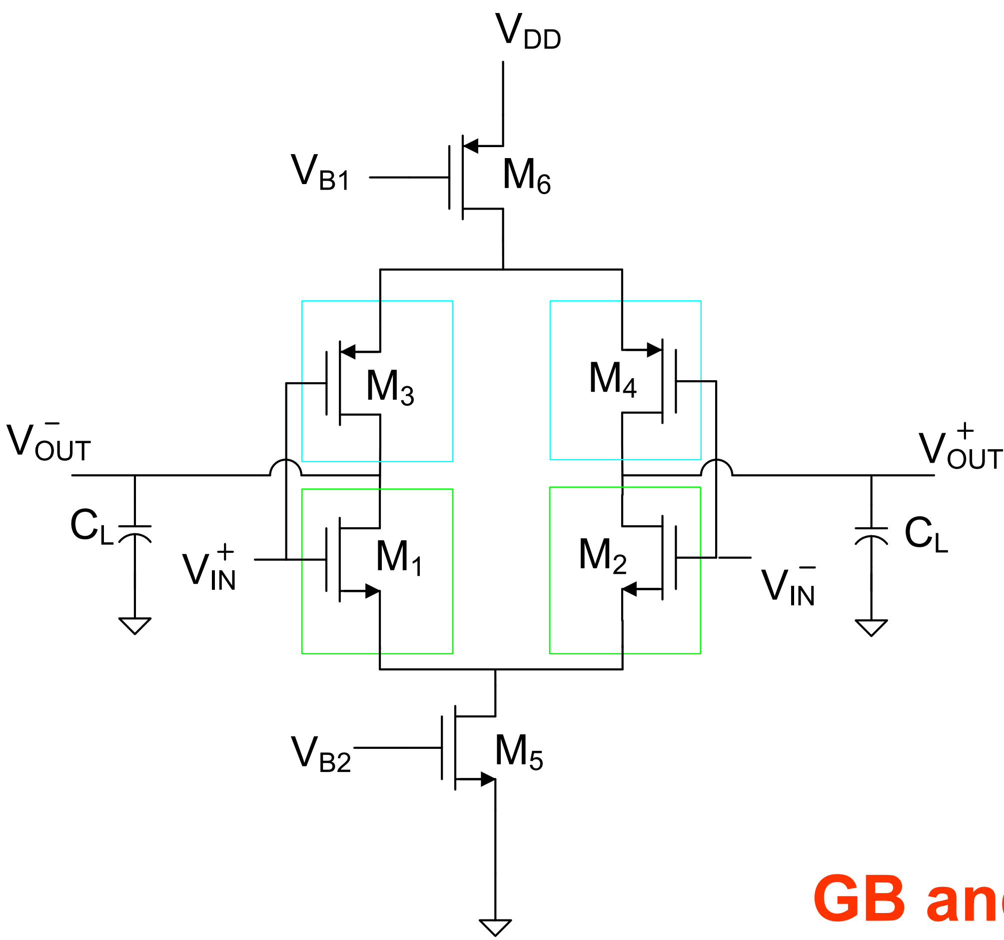
$$GB = \frac{g_{mQC} + g_{mCC}}{C_L}$$

Consider now increasing numerator by changing the excitation

Review from last lecture

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

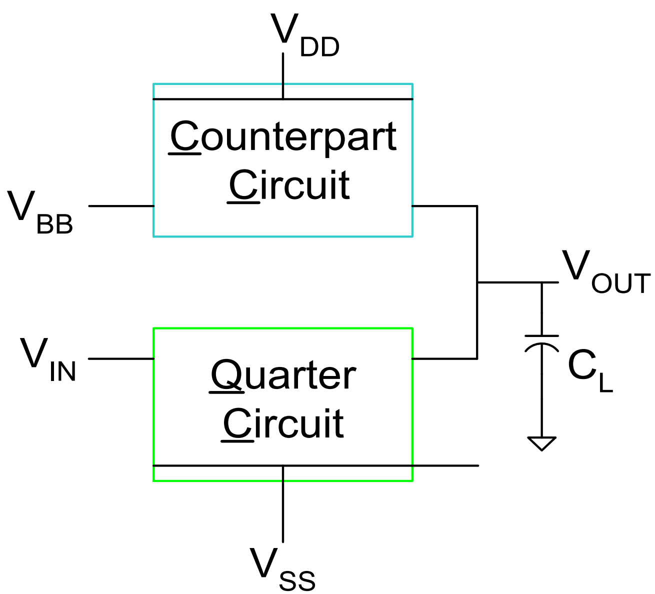
Increasing the transconductance
(current mirror op amp) but it didn't really help because
the output conductance increased proportionally

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:

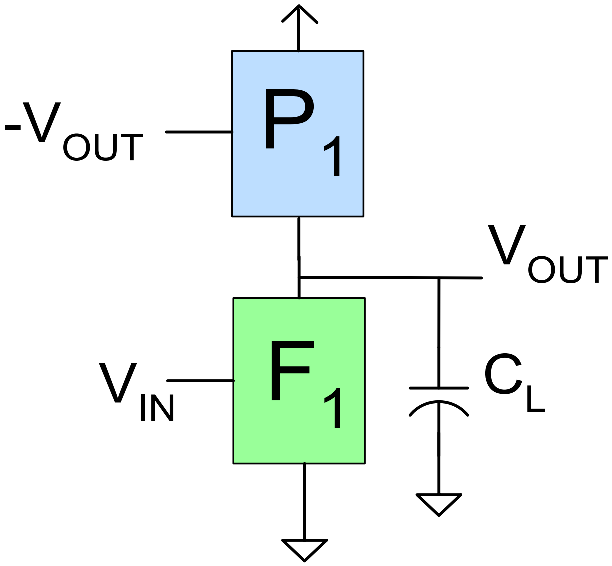
1. Decrease denominator of A_{V0}
2. Increase numerator of A_{V0}

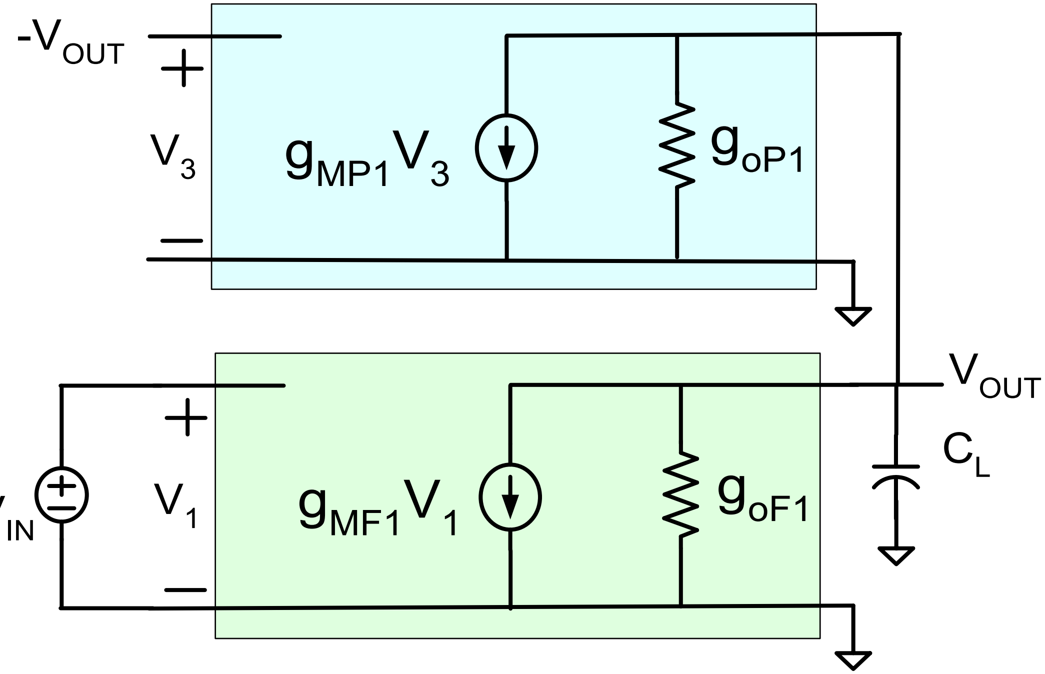
Consider again decreasing the denominator

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

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

Other Methods of Gain Enhancement



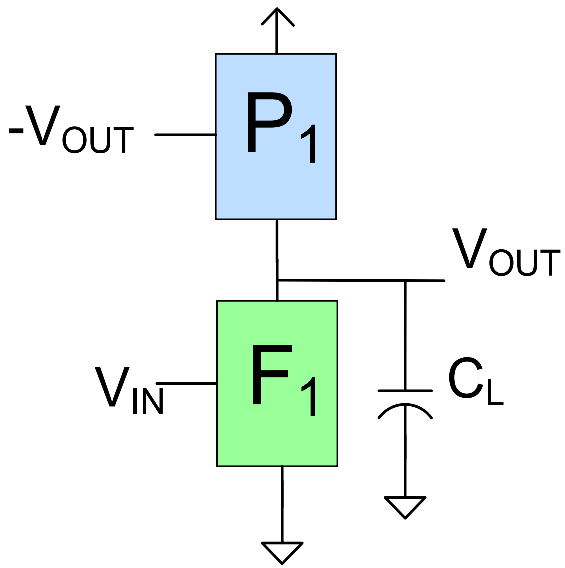


$$\left.\begin{aligned} &V_{OUT}\left(sC_L + g_{oP1} + g_{oF1}\right) + g_{mF1}V_{IN} + g_{mP1}V_3 = 0 \\ &V_3 = -V_{OUT} \end{aligned}\right\}$$

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

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

Gain Enhancement with Regenerative Feedback



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

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

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

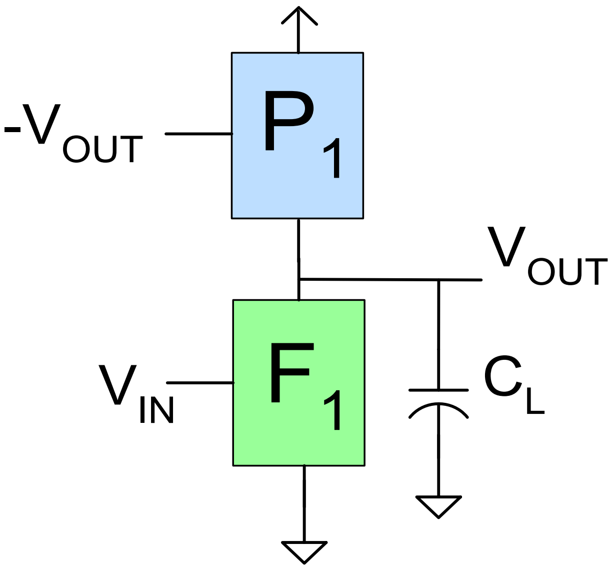
$$GB = \frac{g_{mF1}}{C_L}$$

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



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

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

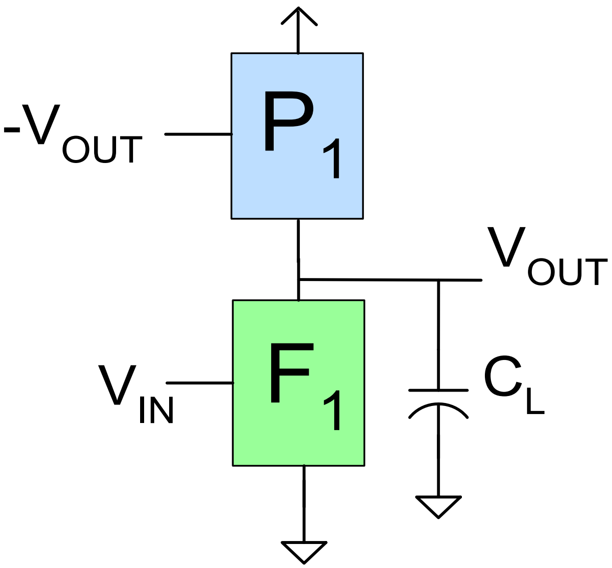
The GB does not degrade !

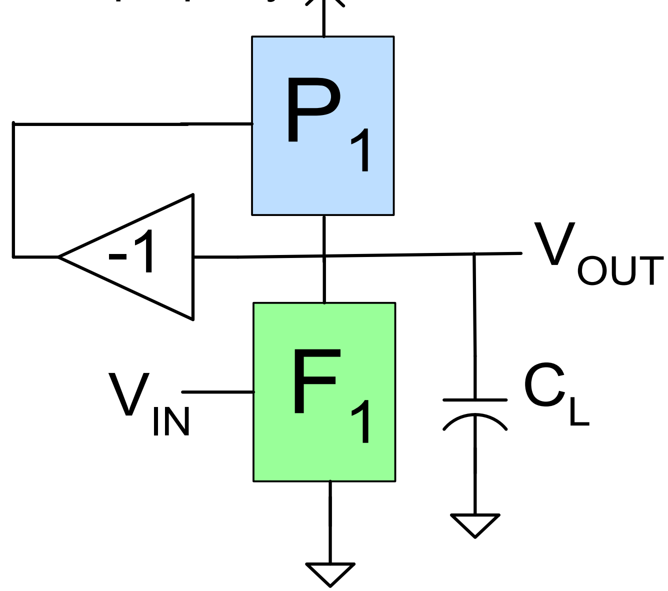
This circuit has a positive feedback loop (V_{INP1}:V_{OUT}:-V_{OUT})

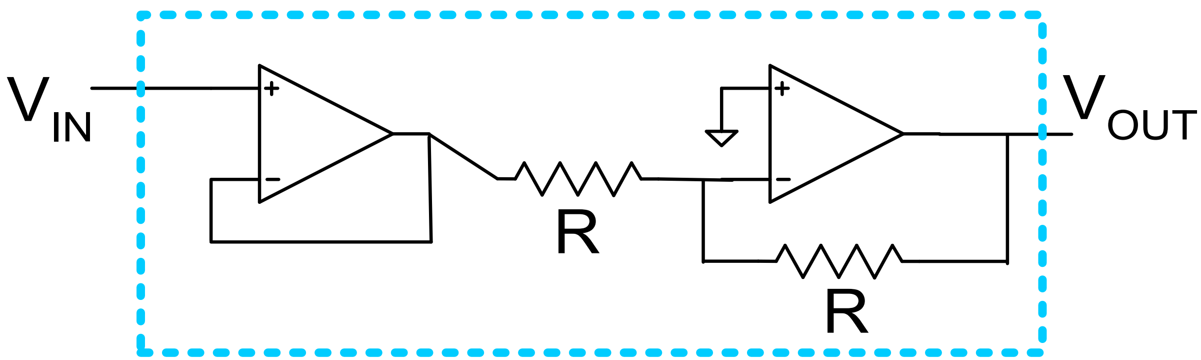
But - can we easily build circuits with this property?

Gain Enhancement with Regenerative Feedback

But - can we easily build circuits with this property?





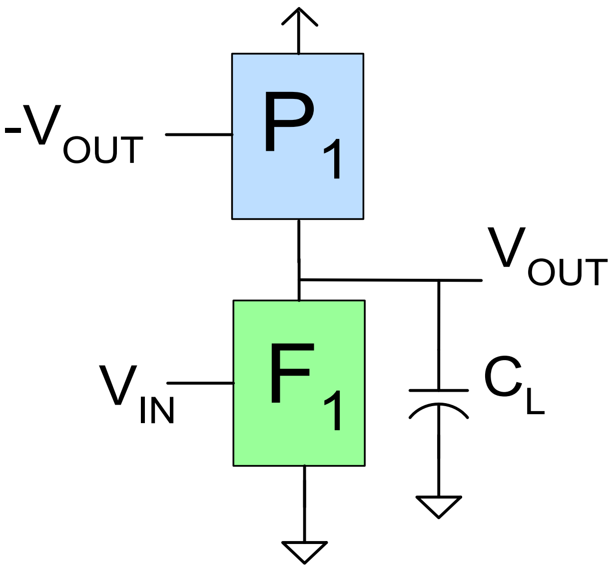


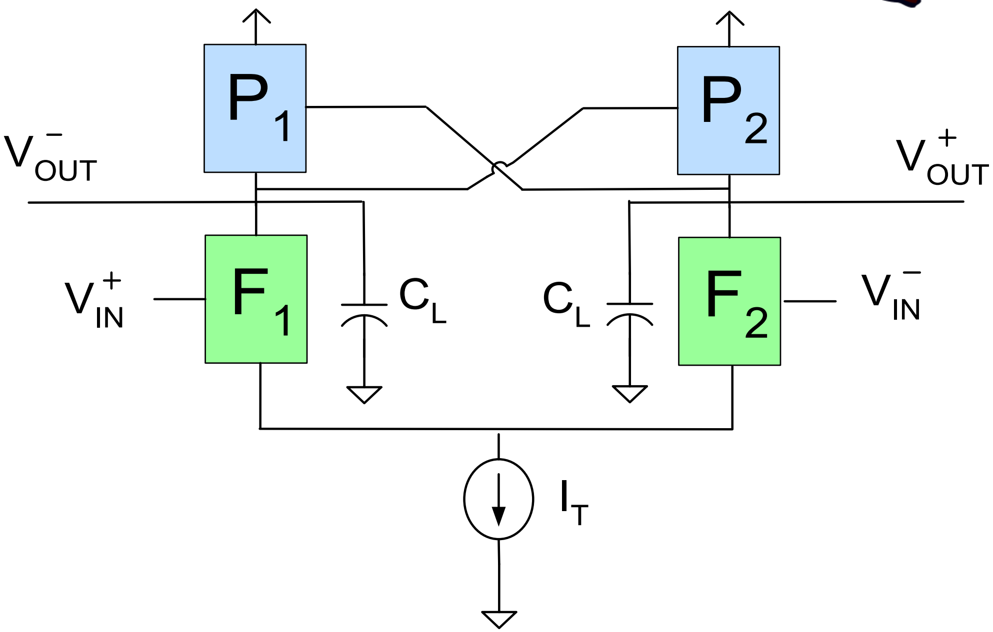
But – the inverting amplifier may be more difficult to build than the op amp itself!

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?

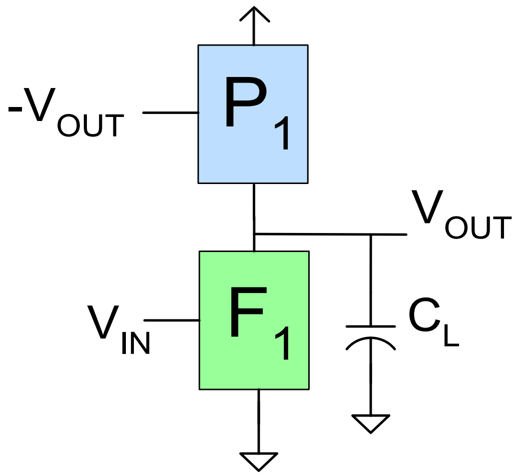




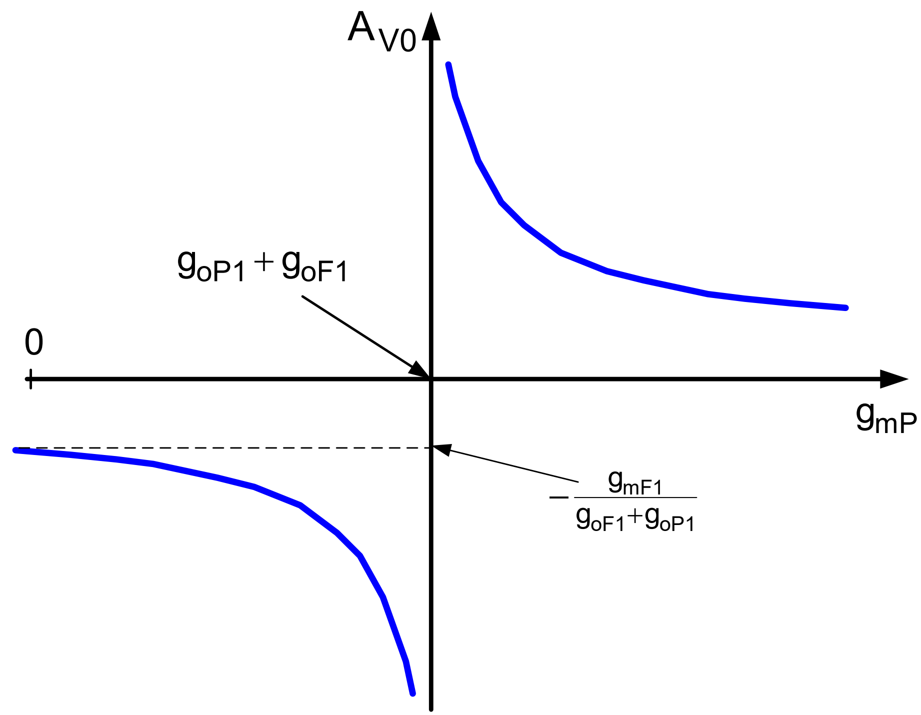
But – the inverting amplifier may be more difficult to build than the op amp itself!

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

Gain Enhancement with Regenerative Feedback

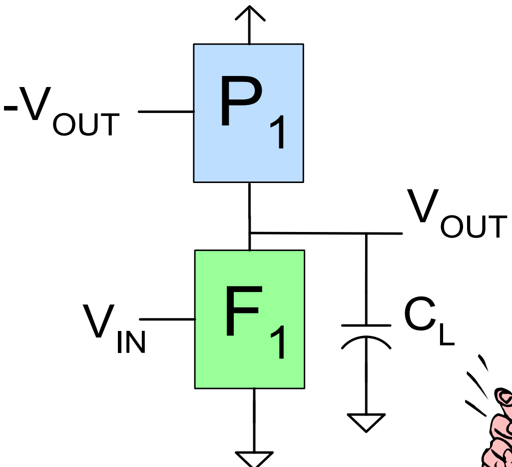


$$A_{V0}(s) = \frac{-g_{mF1}}{sC_L + g_{oF1} + g_{oP1} - g_{mP1}}$$



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

Gain Enhancement with Regenerative Feedback



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

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

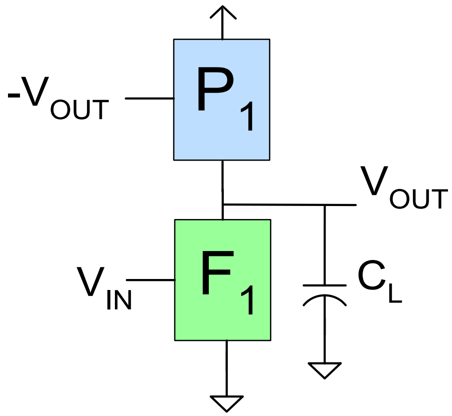
If $g_{mP1} > g_{oF1}+g_{oP1}$, the pole will be in the RHP !!

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

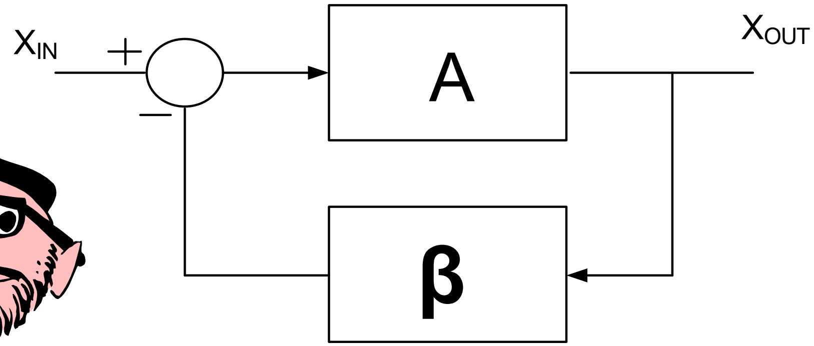


This will make the op amp unstable

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

But is Positive Feedback really bad?

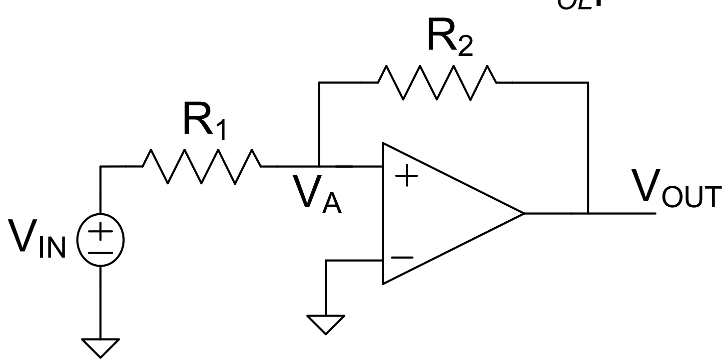
Remember – Why do we want a large Op Amp Gain Anyway?



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

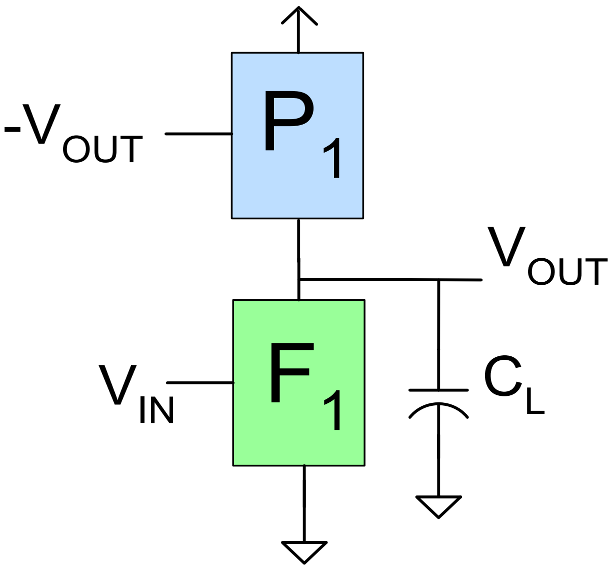
To make A_{FB} <u>very</u> close to $1/\beta$

Even when standard $A_{VFB} = \dfrac{A_{OL}}{1 + A_{OL}\beta}$ 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



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

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

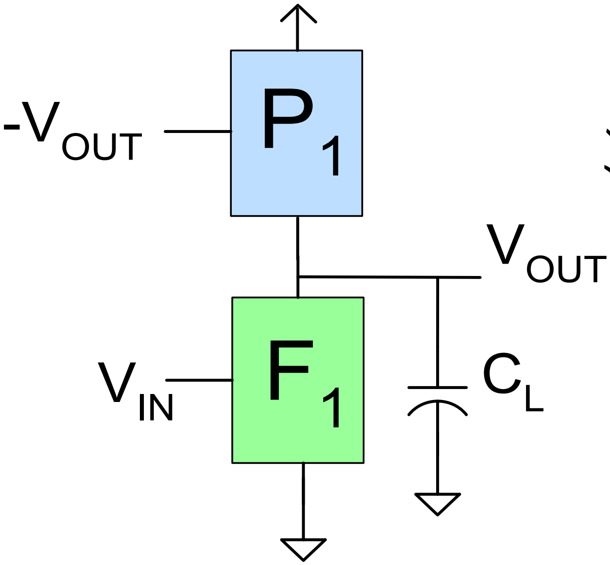
If $g_{mP1} > g_{oF1} + g_{oP1}$, the pole will be in the RHP !!

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



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

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

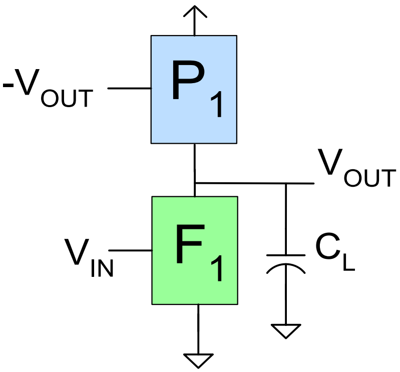
If $g_{mP1} > g_{oF1}+g_{oP1}$, the pole will be in the RHP !!

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

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

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

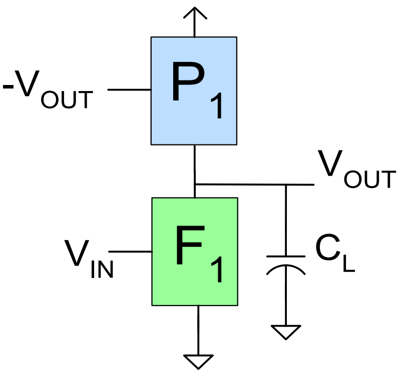
How?

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

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

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

Gain Enhancement with Regenerative Feedback

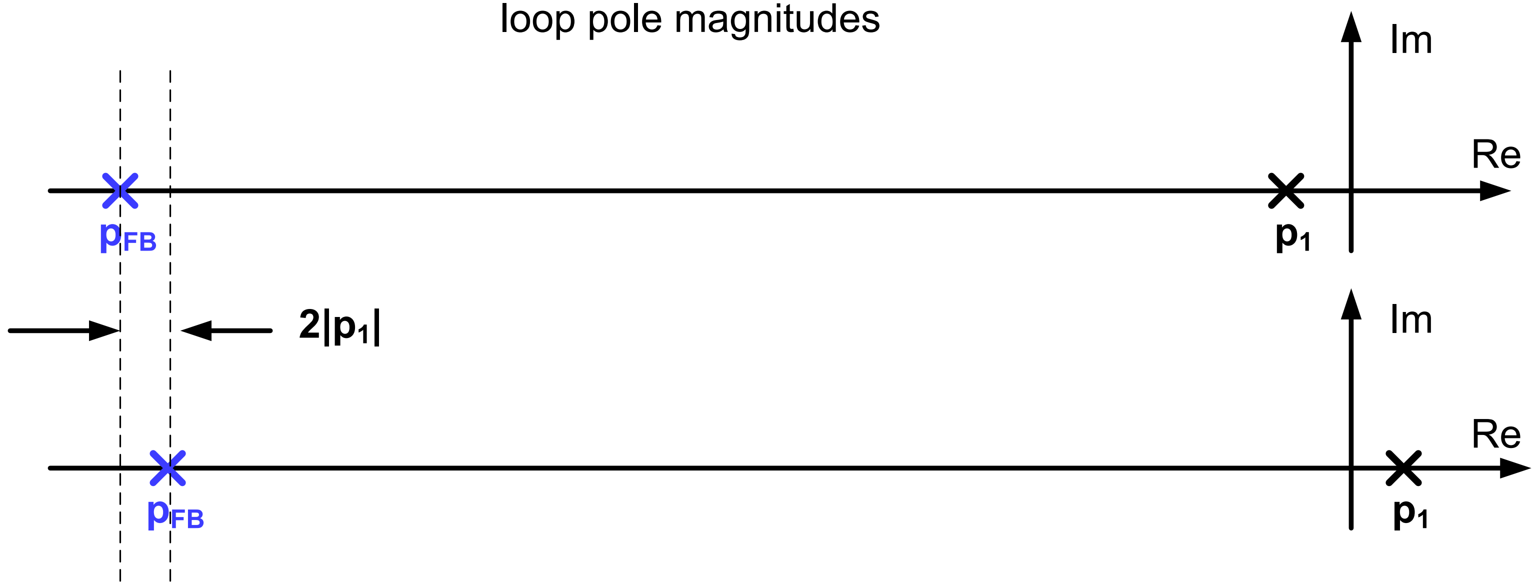


It can be shown that the feedback amplifier is usually stable even if the open-loop Op amp is unstable

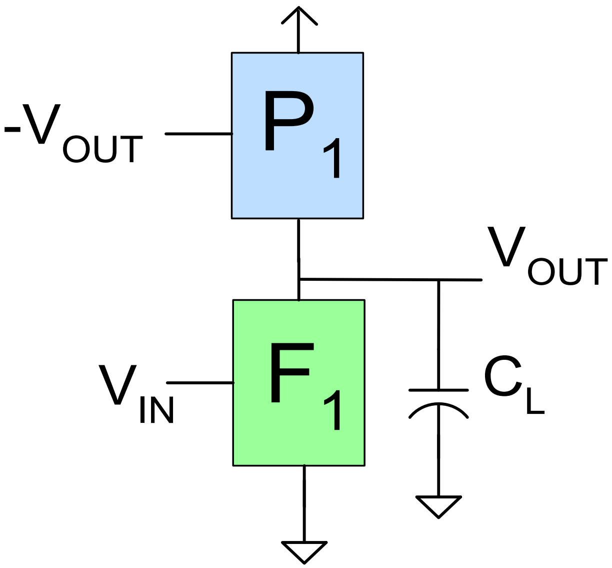
How?

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

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

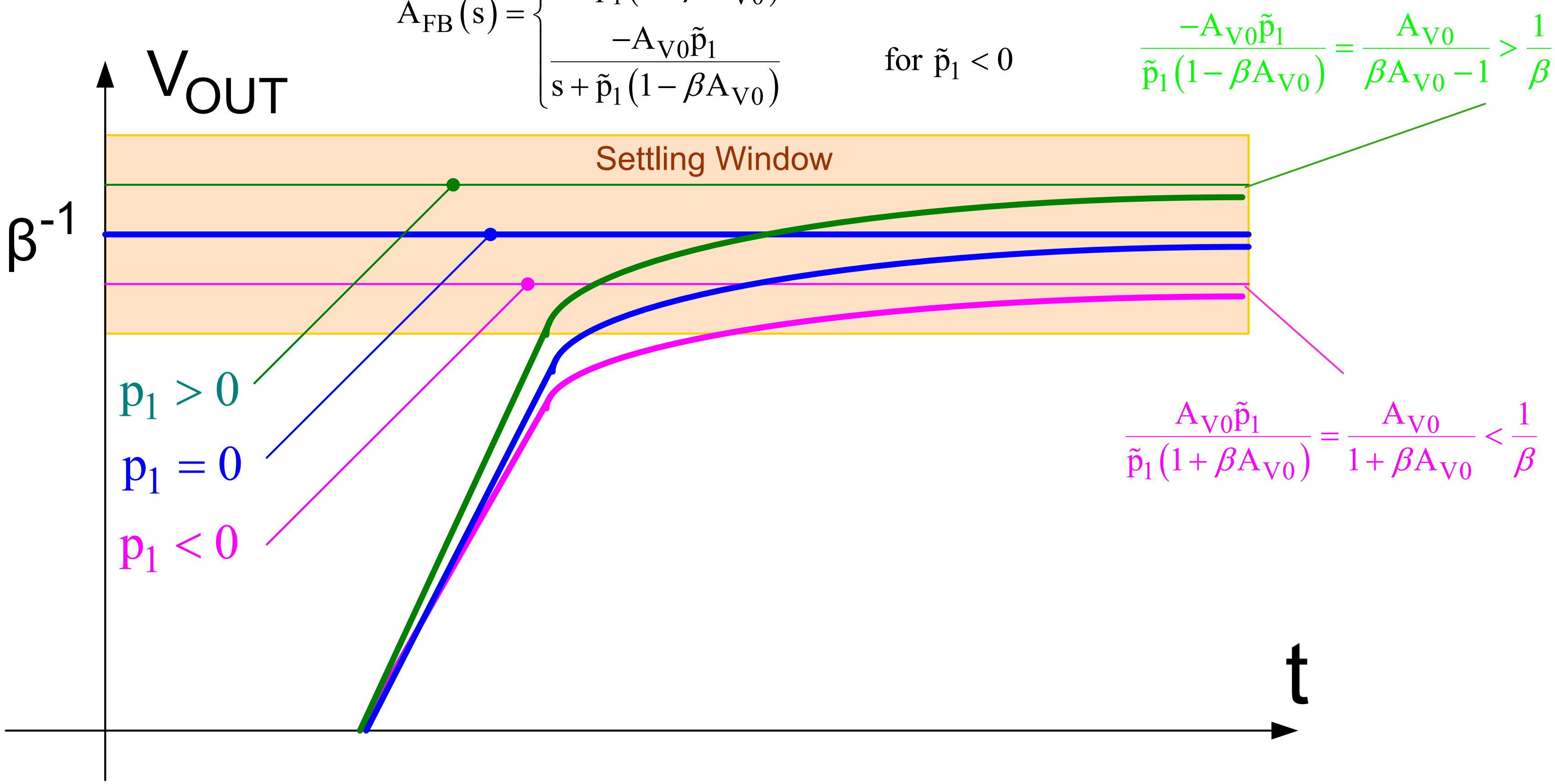
Why?

Gain Enhancement with Regenerative Feedback

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

Why?

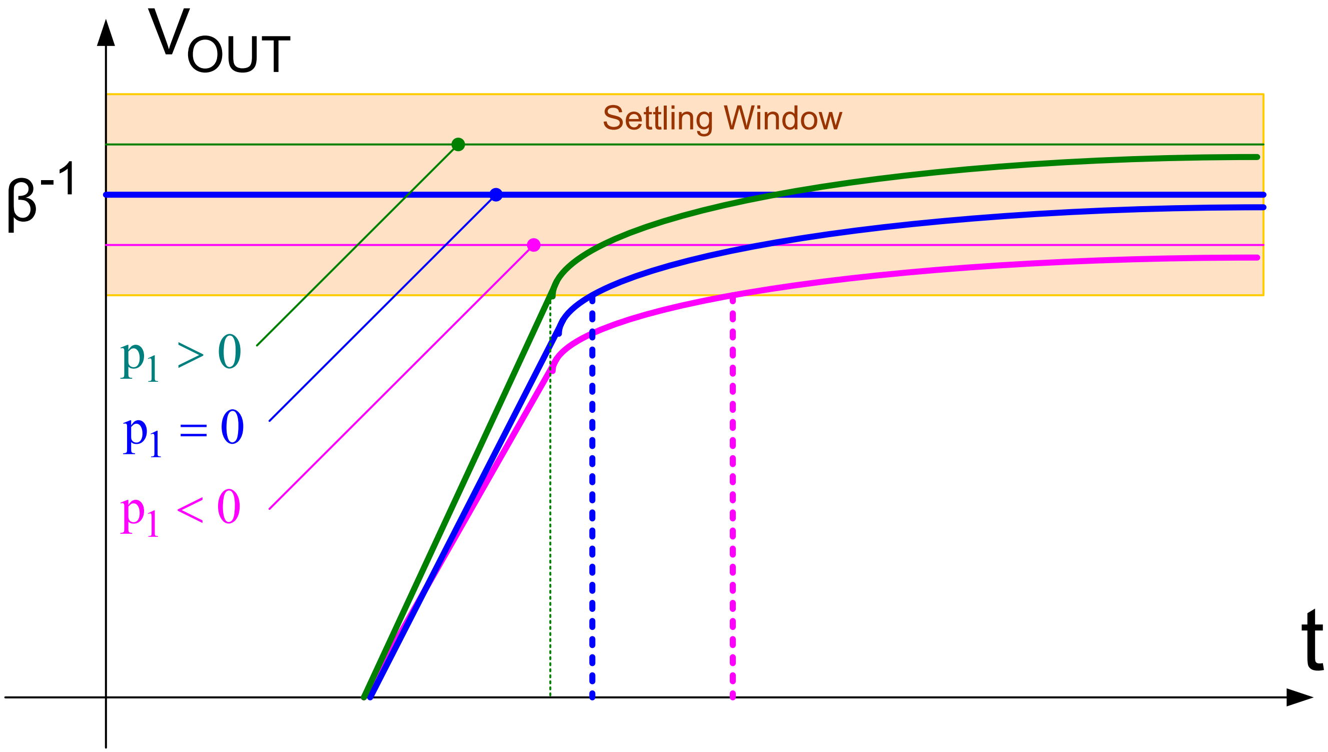
$$A_{FB}(s) = \begin{cases} \dfrac{A_{V0}\tilde{p}_1}{s + \tilde{p}_1\left(1 + \beta A_{V0}\right)} & \text{for } \tilde{p}_1 > 0 \\[2ex] \dfrac{-A_{V0}\tilde{p}_1}{s + \tilde{p}_1\left(1 - \beta A_{V0}\right)} & \text{for } \tilde{p}_1 < 0 \end{cases}$$



Gain Enhancement with Regenerative Feedback

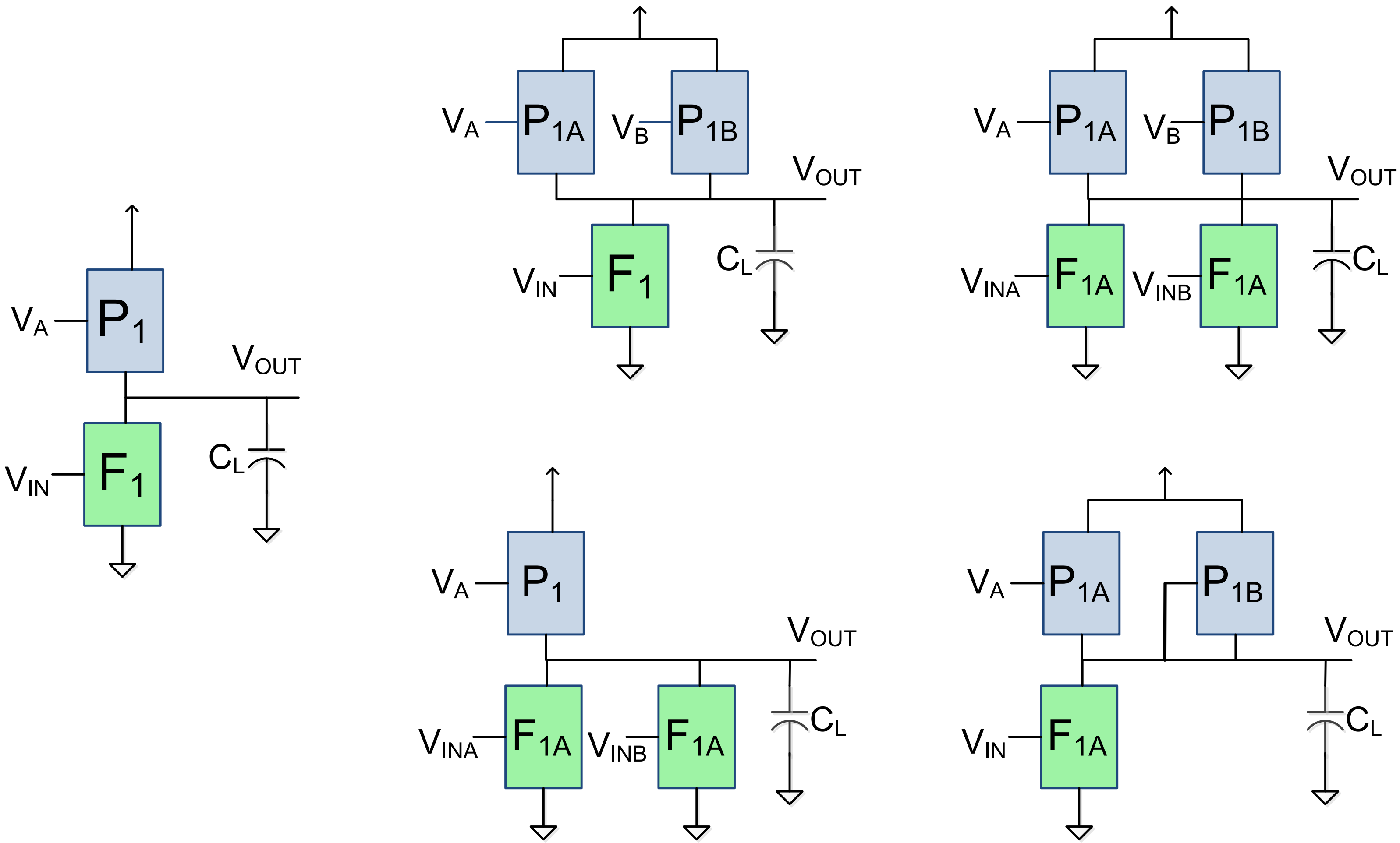
The feedback performance can actually be enhanced if the open-loop amplifier is unstable

Why?

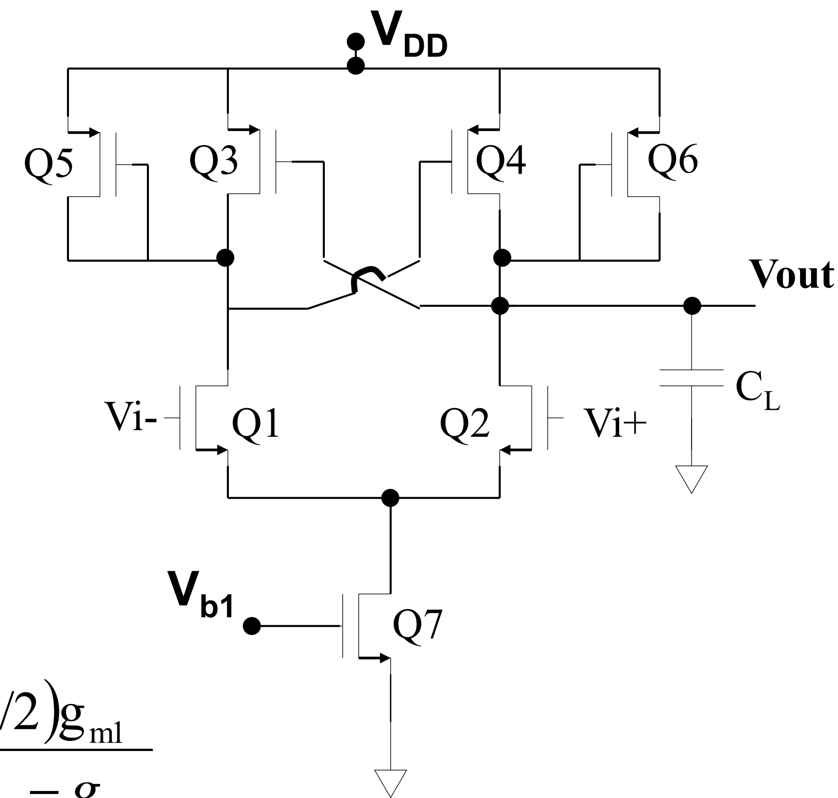


- Time required to get in settling window can be reduced with RHP pole
- But, if pole is too far in RHP, response will exit top of window

Some Half-Circuits with Interesting Potential



Existing Positive Feedback Amplifier



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

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

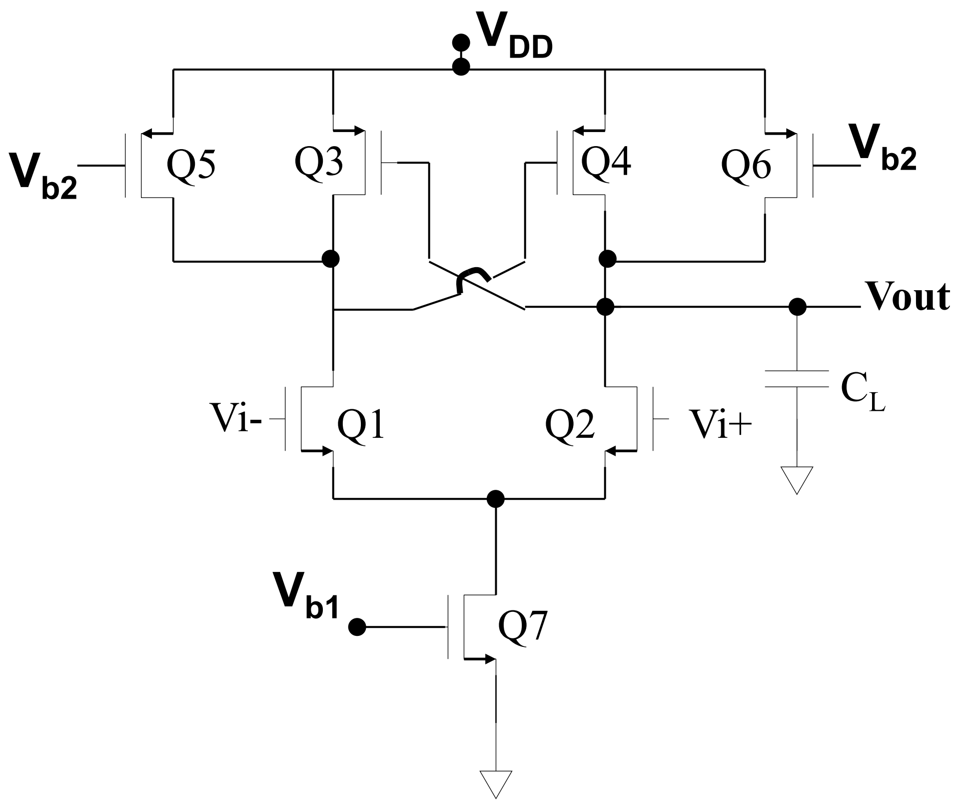
Existing Positive Feedback Amplifier

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

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

- 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
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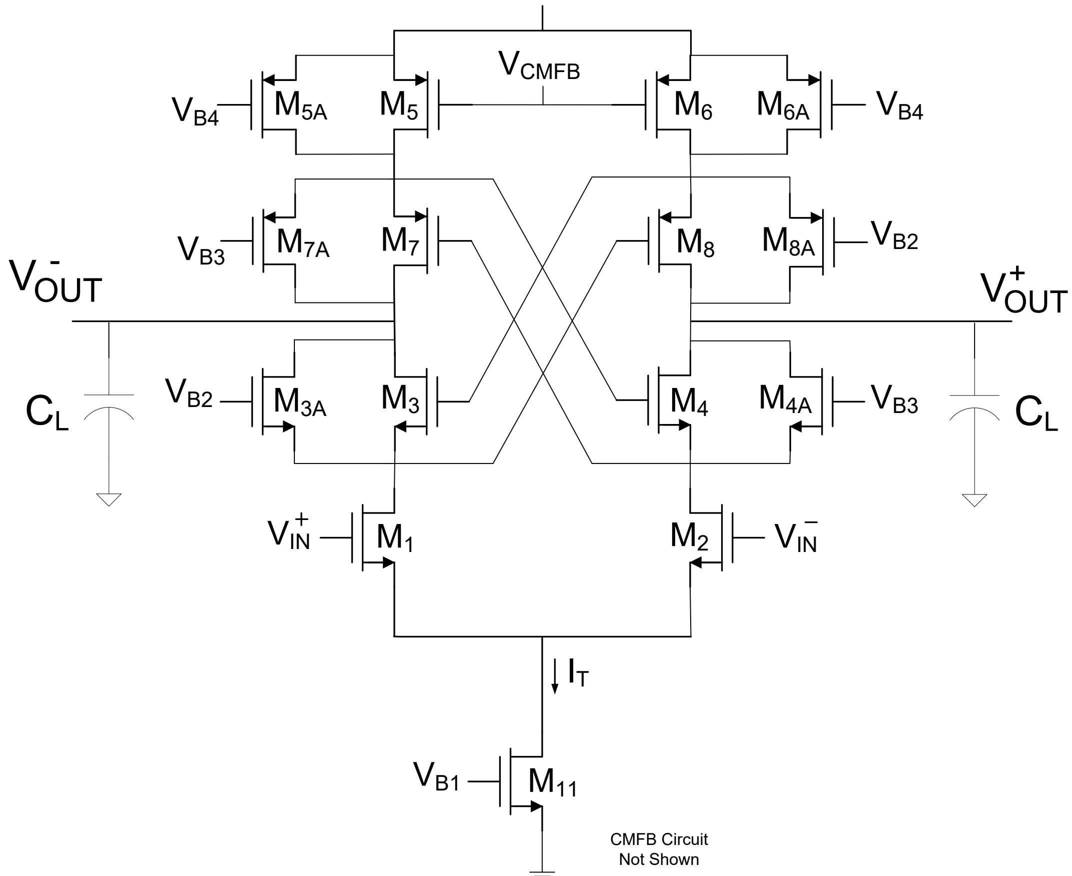
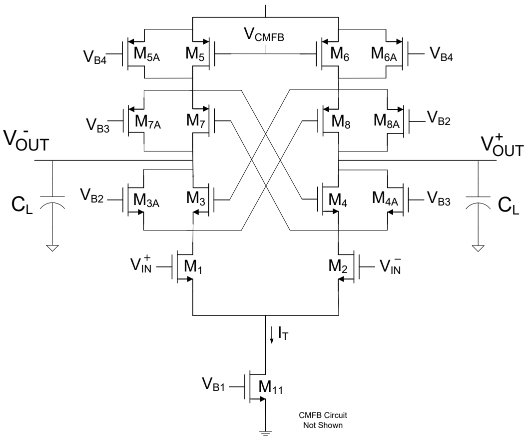
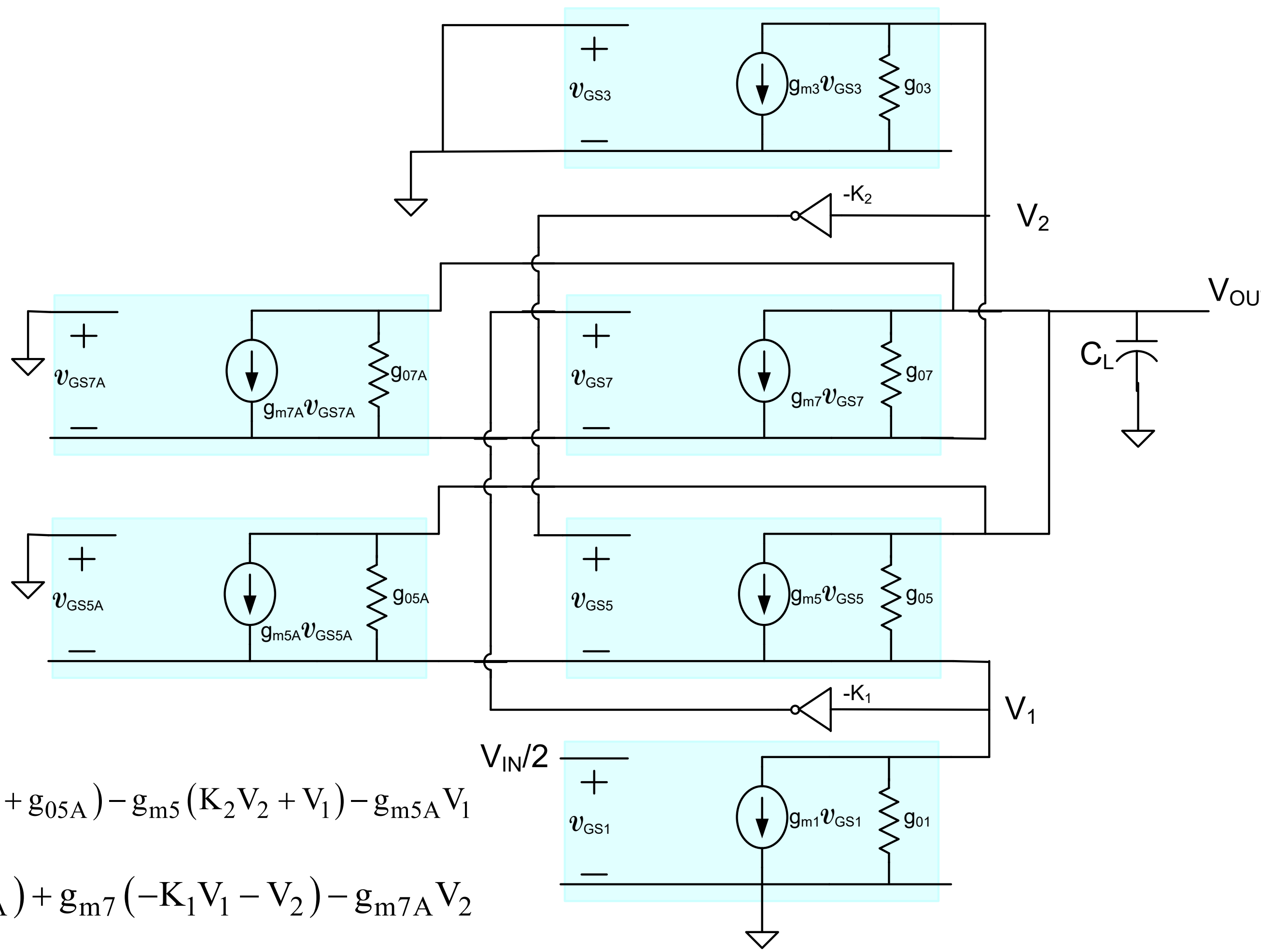
Another Positive Feedback Amplifier



- 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

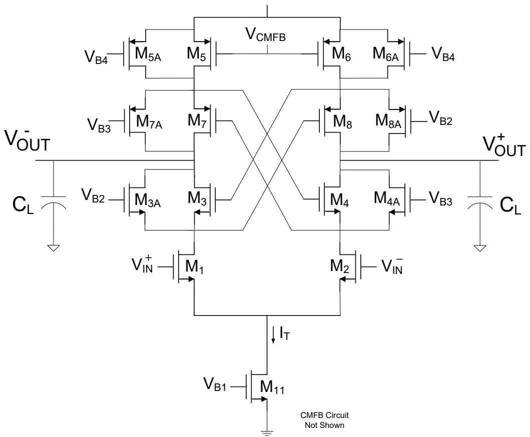
$$V_1(g_{01}+g_{05}+g_{05A})+g_{m1}V_{IN}/2=V_0(g_{05}+g_{05A})-g_{m5}(K_2V_2+V_1)-g_{m5A}V_1$$

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

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

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

Another Positive Feedback Amplifier



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

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

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

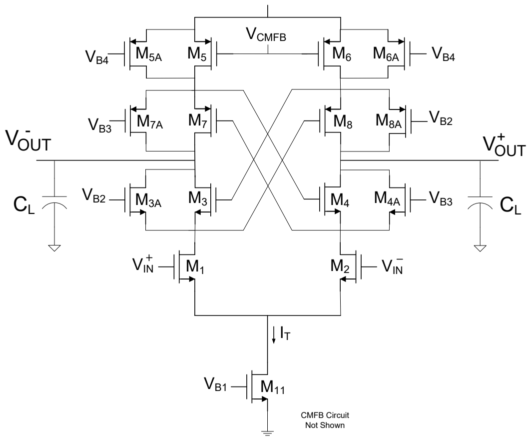
Transfer function solution with MAPLE T(s)=N(s)/S(s)

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



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

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

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

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

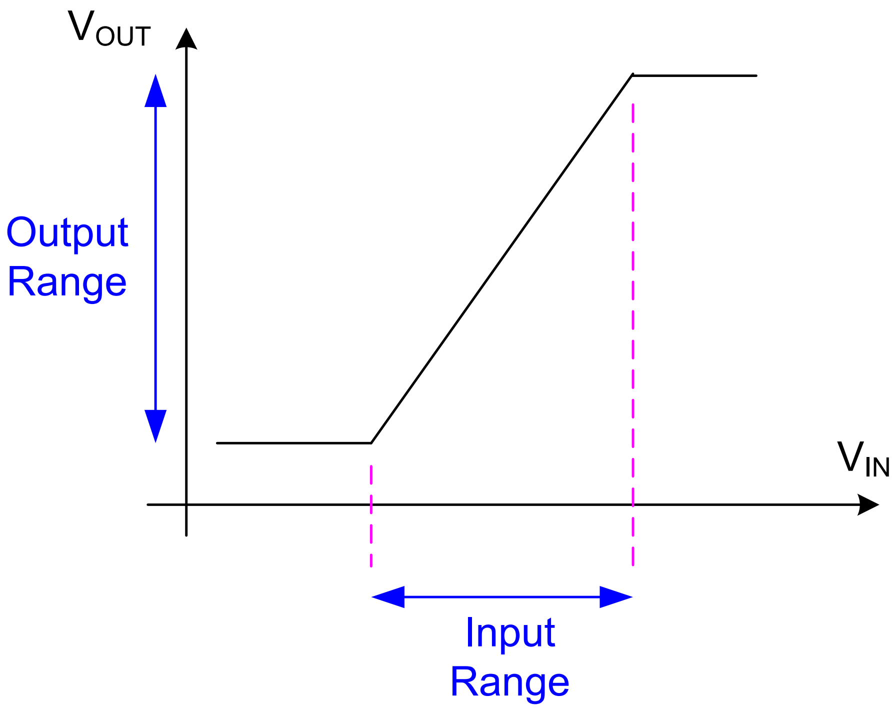
Signal Swing and Linearity

Signal swing identifies range over which signals can be applied and still maintain operation of devices in desired region of operation

Some subset of the signal swing range will be quite linear

Often that subset is close to the entire signal swing range

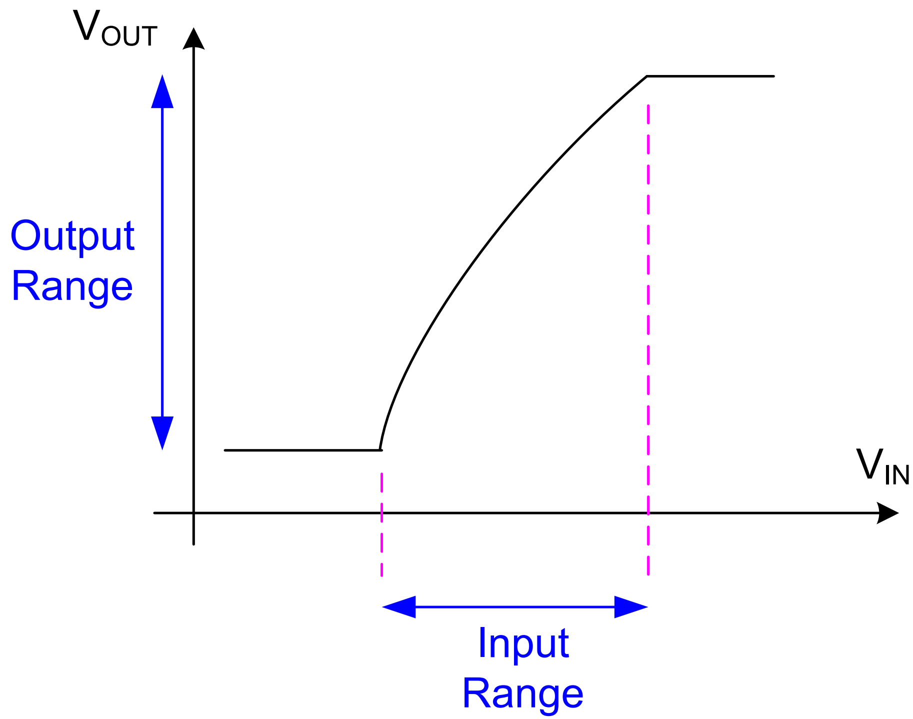
Signal Swing and Linearity



Ideal Scenario:

Completely Linear over Input and Output Range

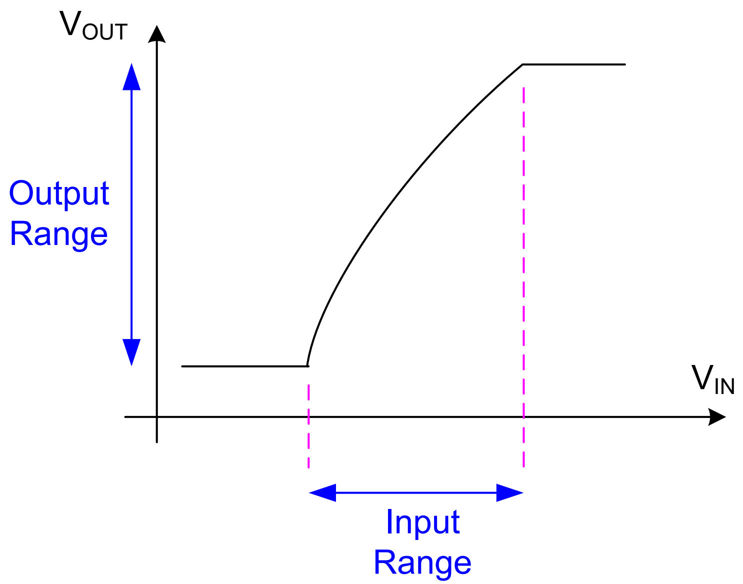
Signal Swing and Linearity

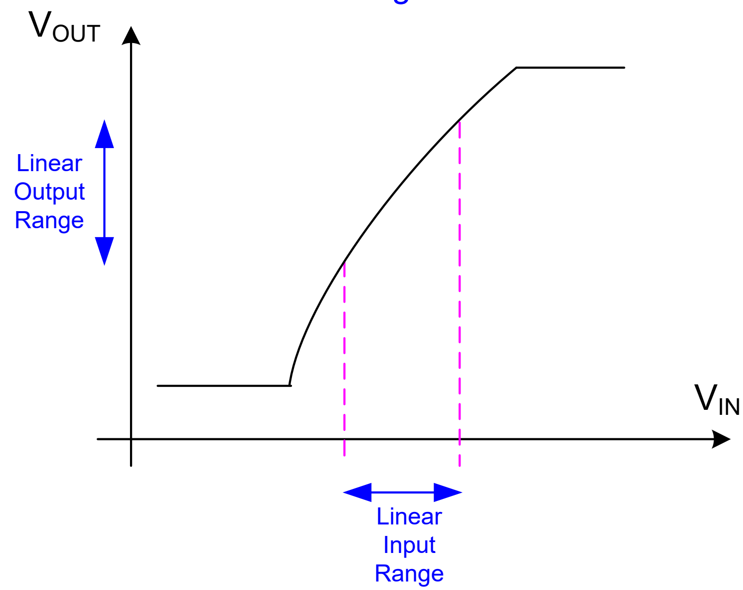


Realistic Scenario:

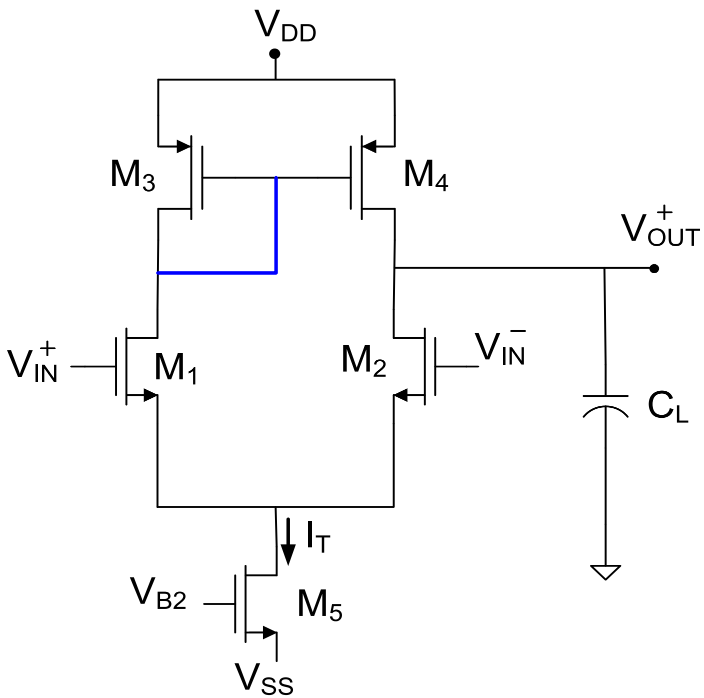
- Modest Nonlinearity throughout Input Range
- But operation will be quite linear over subset of this range

Signal Swing and Linearity

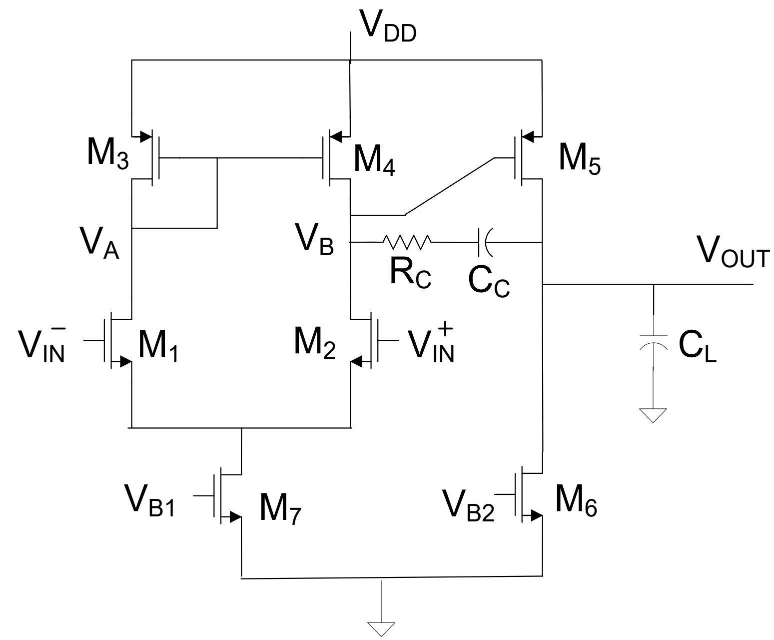




Linearity of Amplifiers



Single-Stage

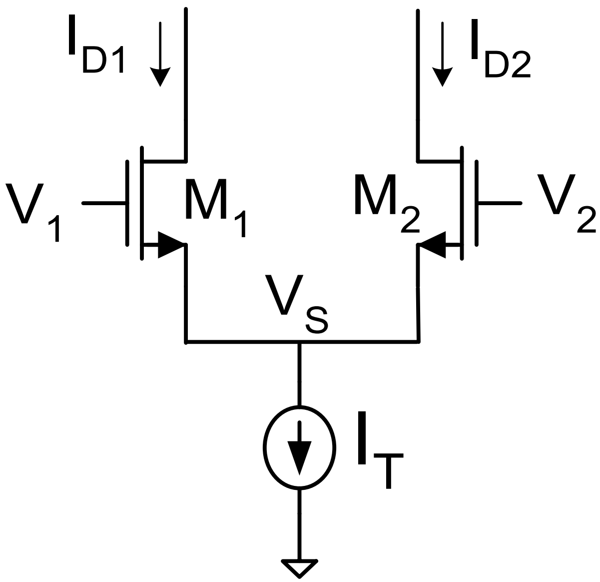


Two-Stage

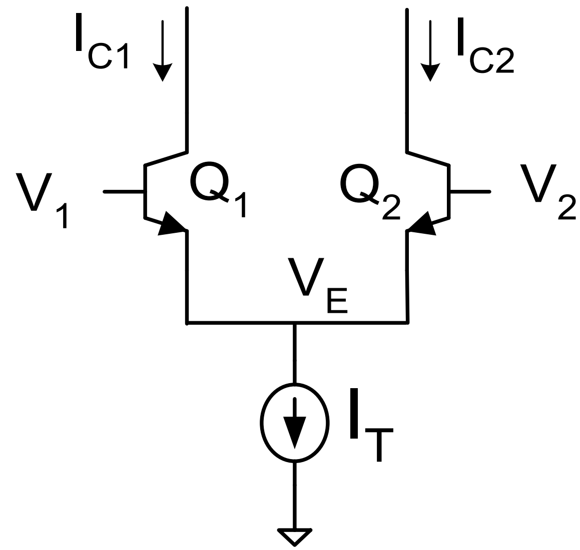
Linearity of differential pair of major concern

Linearity of common-source amplifier is of major concern (since signals so small at output of differential pair)

Differential Input Pairs

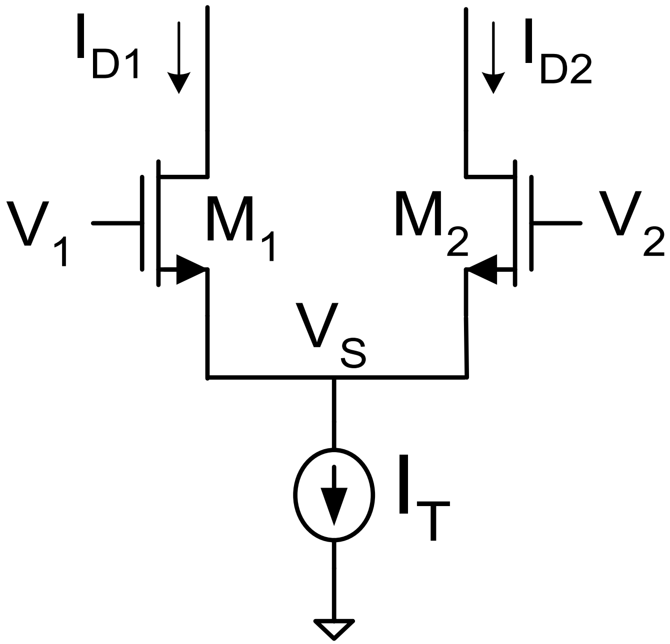


MOS Differential Pair



Bipolar Differential Pair

MOS Differential Pair



$$I_{D1} = \frac{\mu C_{OX} W}{2L}\left(V_1 - V_S - V_T\right)^2$$

$$I_{D2} = \frac{\mu C_{OX} W}{2L}\left(V_2 - V_S - V_T\right)^2$$

$$I_{D1} + I_{D2} = I_T$$

$$\sqrt{I_{D1}}\sqrt{\frac{2L}{\mu C_{OX} W}} = V_1 - V_S - V_T$$

$$\sqrt{I_{D2}}\sqrt{\frac{2L}{\mu C_{OX} W}} = V_2 - V_S - V_T$$

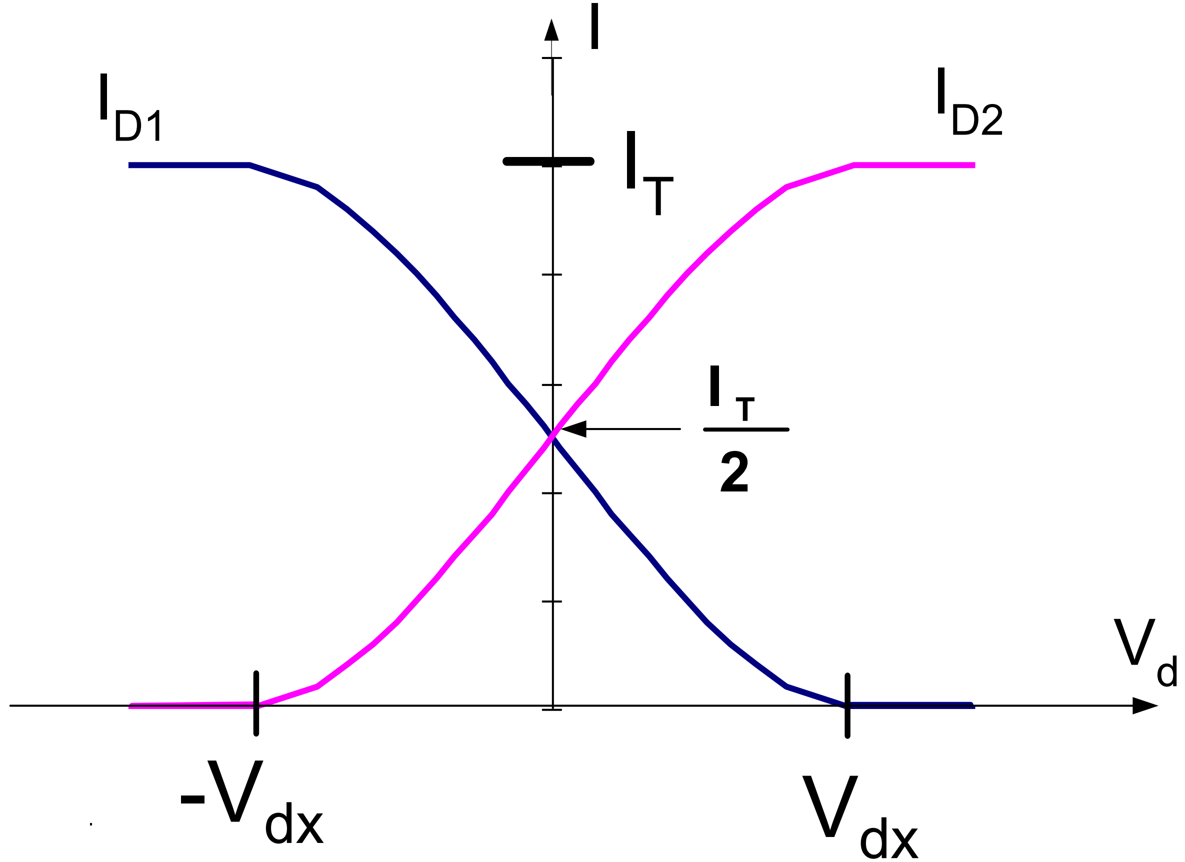
$$V_d = V_2 - V_1$$

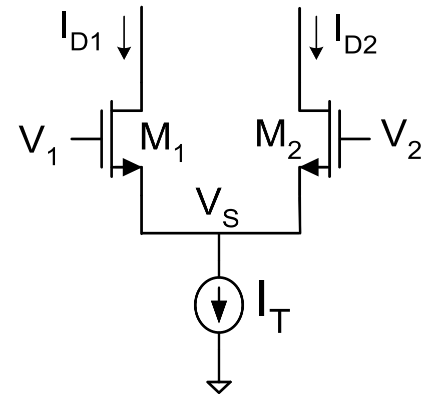
$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_T - I_{D1}} - \sqrt{I_{D1}}\right)$$

$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_{D2}} - \sqrt{I_T - I_{D2}}\right)$$

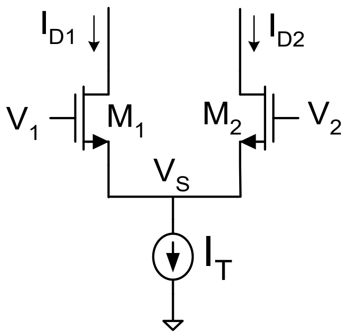
Transfer Characteristics of MOS Differential Pair

$$V_d = \sqrt{\frac{2L}{\mu C_{ox} W}}\left(\sqrt{I_{D2}} - \sqrt{I_T - I_{D2}}\right)$$





MOS Differential Pair



$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_T - I_{D1}} - \sqrt{I_{D1}}\right)$$

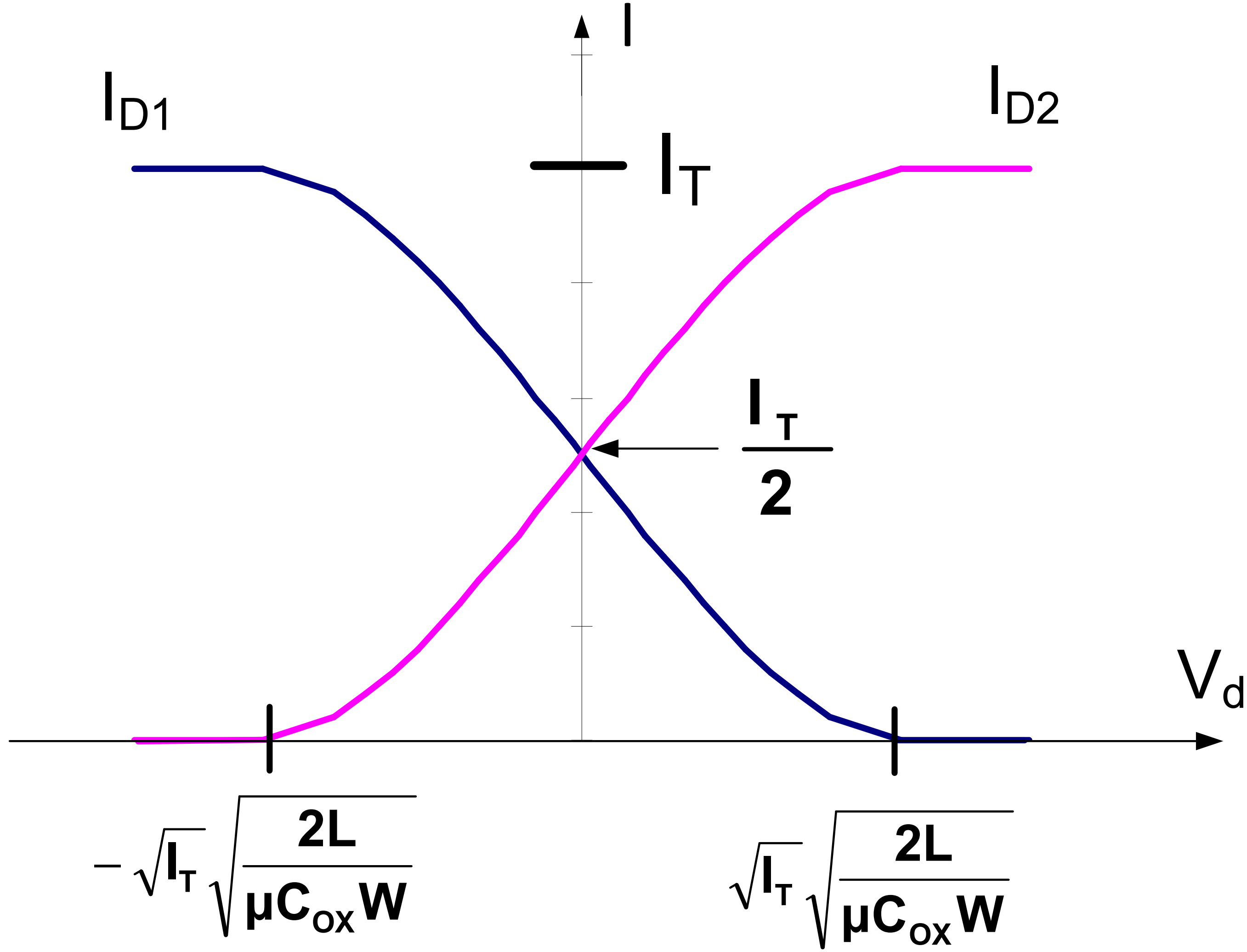
$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_{D2}} - \sqrt{I_T - I_{D2}}\right)$$

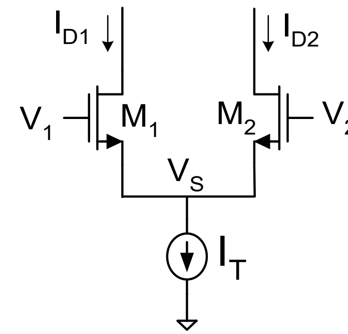
What values of V_d will cause all of the current to be steered to the left or the right ?

$$V_{dx} = \pm\sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_T}\right)$$

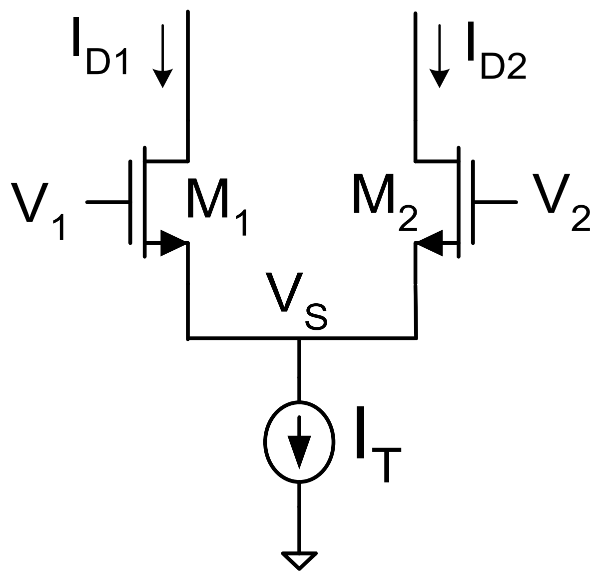
Transfer Characteristics of MOS Differential Pair

$$V_d = \sqrt{\frac{2L}{\mu C_{ox} W}}\left(\sqrt{I_{D2}} - \sqrt{I_T - I_{D2}}\right)$$





Q-point Calculations



$$\frac{I_T}{2} = \frac{\mu C_{OX} W}{2L}(V_{EB})^2$$

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

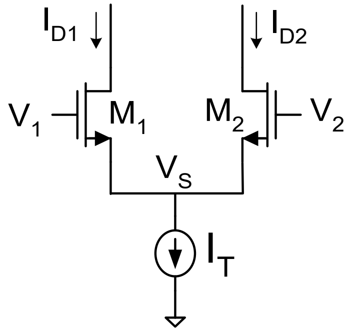
$$V_{dx} = \pm\sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_T}\right)$$

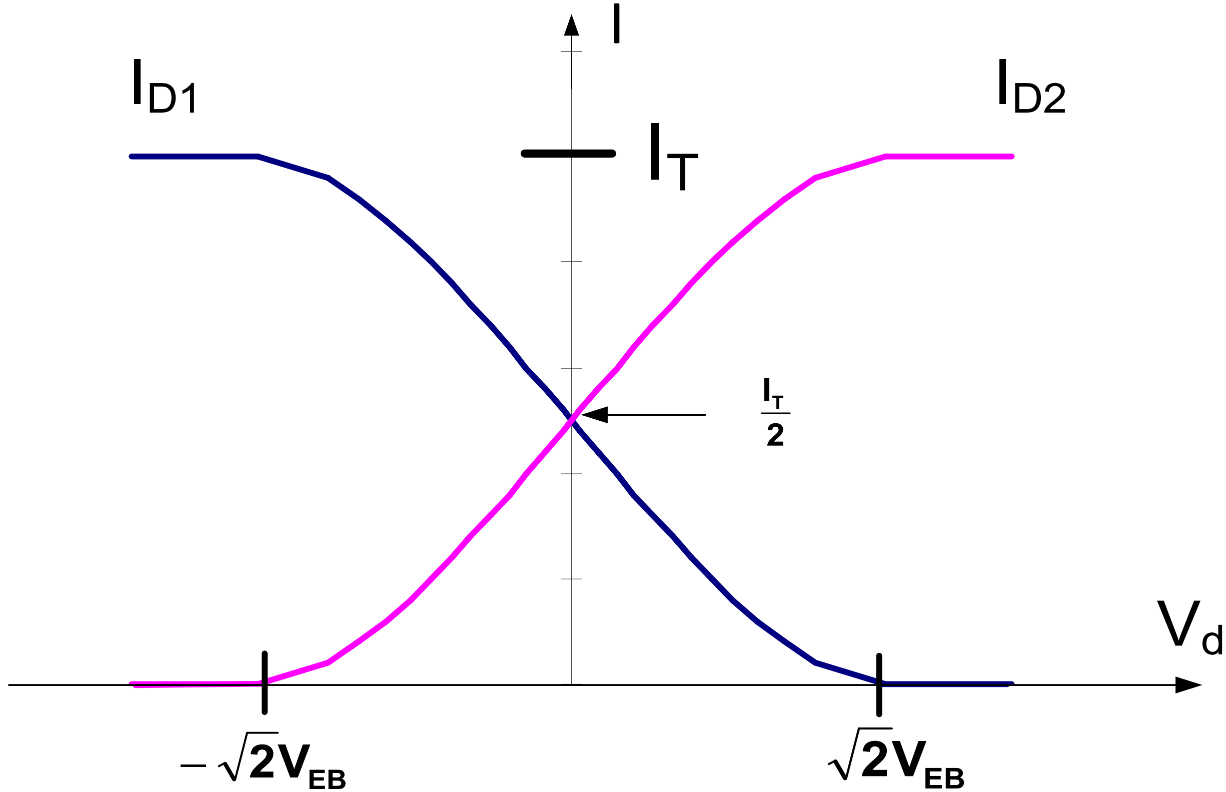
Observe !!

$$V_{dx} = \pm\sqrt{2}V_{EB}$$

Transfer Characteristics of MOS Differential Pair

$$V_d = \sqrt{\frac{2L}{\mu C_{ox} W}}\left(\sqrt{I_{D2}} - \sqrt{I_T - I_{D2}}\right)$$

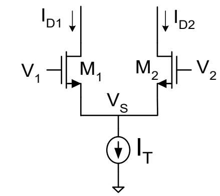




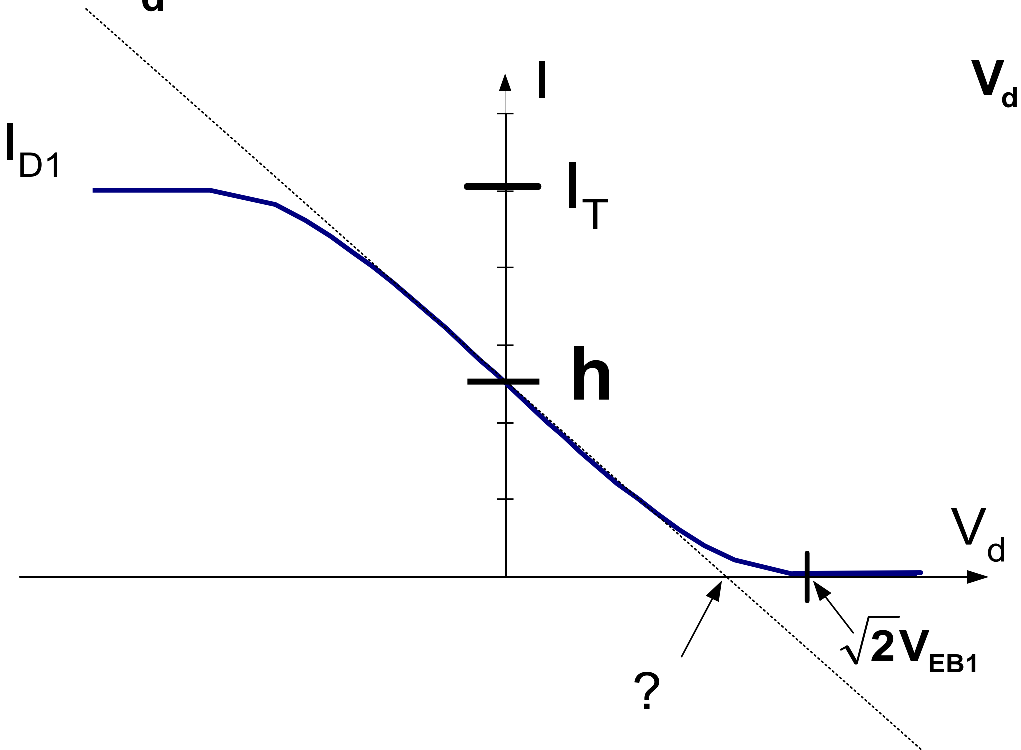
V_{EB} affects linearity

How linear is the amplifier ?

How linear is the amplifier ?



$$\mathbf{I = mV_d + h}$$



$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_T - I_{D1}} - \sqrt{I_{D1}}\right)$$

Consider the fit line:

$$\mathbf{I = mV_d + h}$$

When V_d=0, I=I_T/2, thus

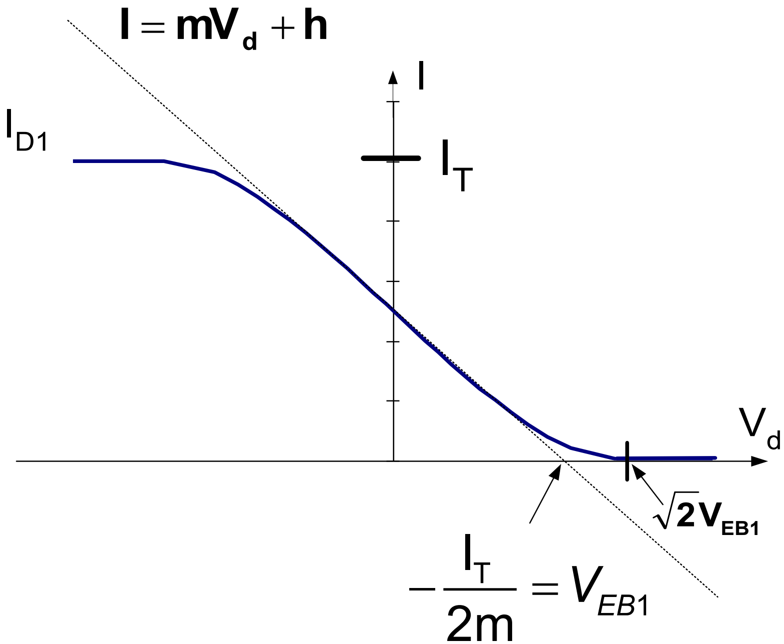
$$\mathbf{h = \frac{I_T}{2}}$$

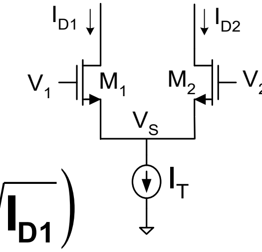
$$\mathbf{V_{dint} = -\frac{h}{m} = -\frac{I_T}{2m}}$$

$$\mathbf{m = \left.\frac{\partial I_{D1}}{\partial V_d}\right|_{Q-pt}}$$

Q-pt = (0,h)

How linear is the amplifier ?





$$V_d = \sqrt{\frac{2L}{\mu C_{ox} W}}\left(\sqrt{I_T - I_{D1}} - \sqrt{I_{D1}}\right)$$

$$m = \left.\frac{\partial I_{D1}}{\partial V_d}\right|_{Q-pt}$$

$$\frac{\partial V_d}{\partial I_{D1}} = \sqrt{\frac{2L}{\mu C_{ox} W}}\left.\left(\frac{1}{2}\left(I_T - I_{D1}\right)^{-1/2}(-1) - \frac{1}{2}\left(I_{D1}\right)^{-1/2}\right)\right|_{Q-point}$$

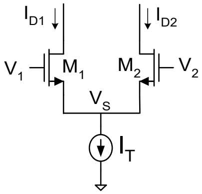
$$\frac{\partial V_d}{\partial I_{D1}} = -2\sqrt{\frac{L}{\mu C_{ox} W}}\sqrt{\frac{1}{I_T}}$$

$$\sqrt{\frac{L}{\mu C_{ox} W}} = \frac{V_{EB1}}{\sqrt{I_T}}$$

$$\frac{\partial V_d}{\partial I_{D1}} = -2\frac{V_{EB1}}{I_T}$$

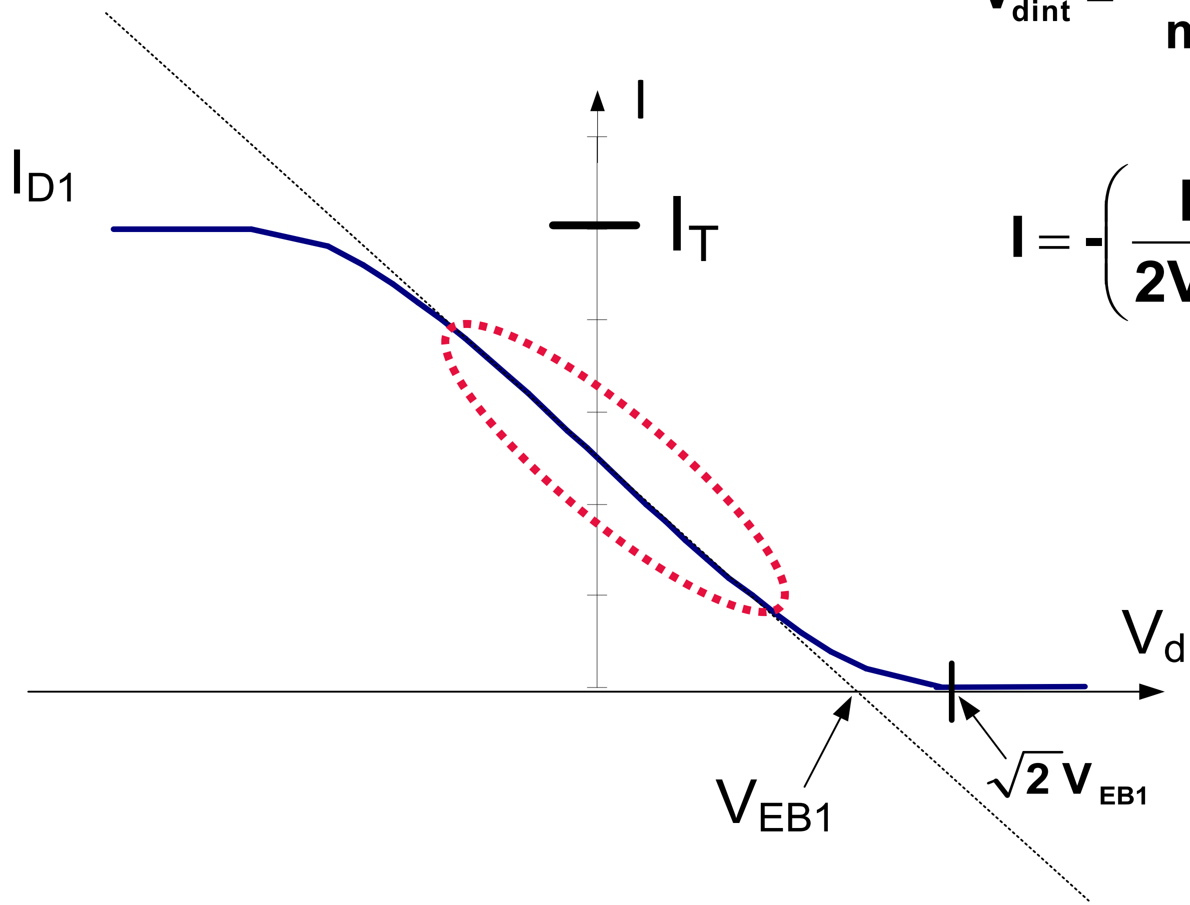
$$m = \left.\frac{\partial I_{D1}}{\partial V_d}\right|_{Q-pt} = -\frac{I_T}{2V_{EB1}}$$

How linear is the amplifier ?

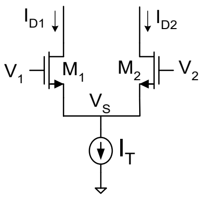


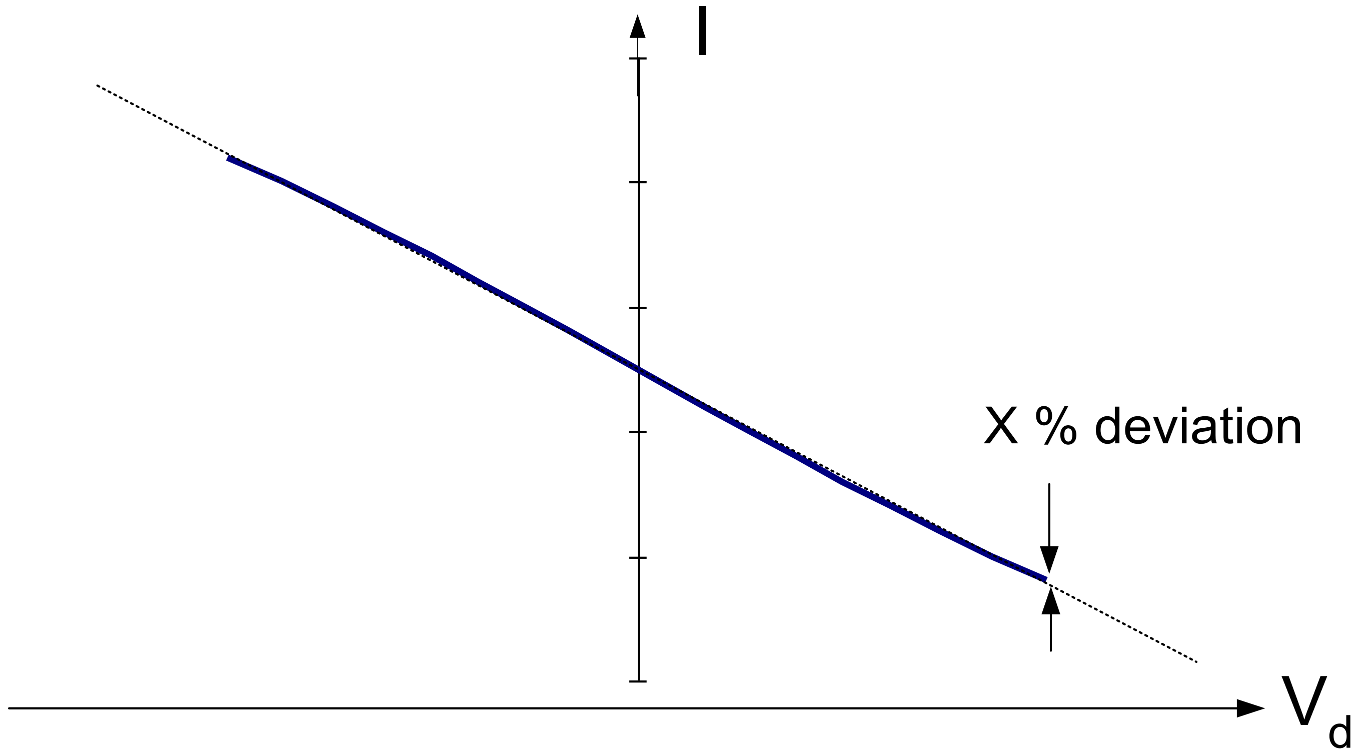
$$V_{dint} = -\frac{h}{m} = -\frac{I_T}{2m} = V_{EB1}$$

$$I = -\left(\frac{I_T}{2V_{EB1}}\right)V_d + \frac{I_T}{2}$$



How linear is the amplifier ?

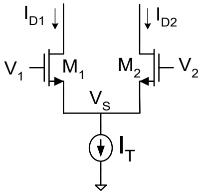


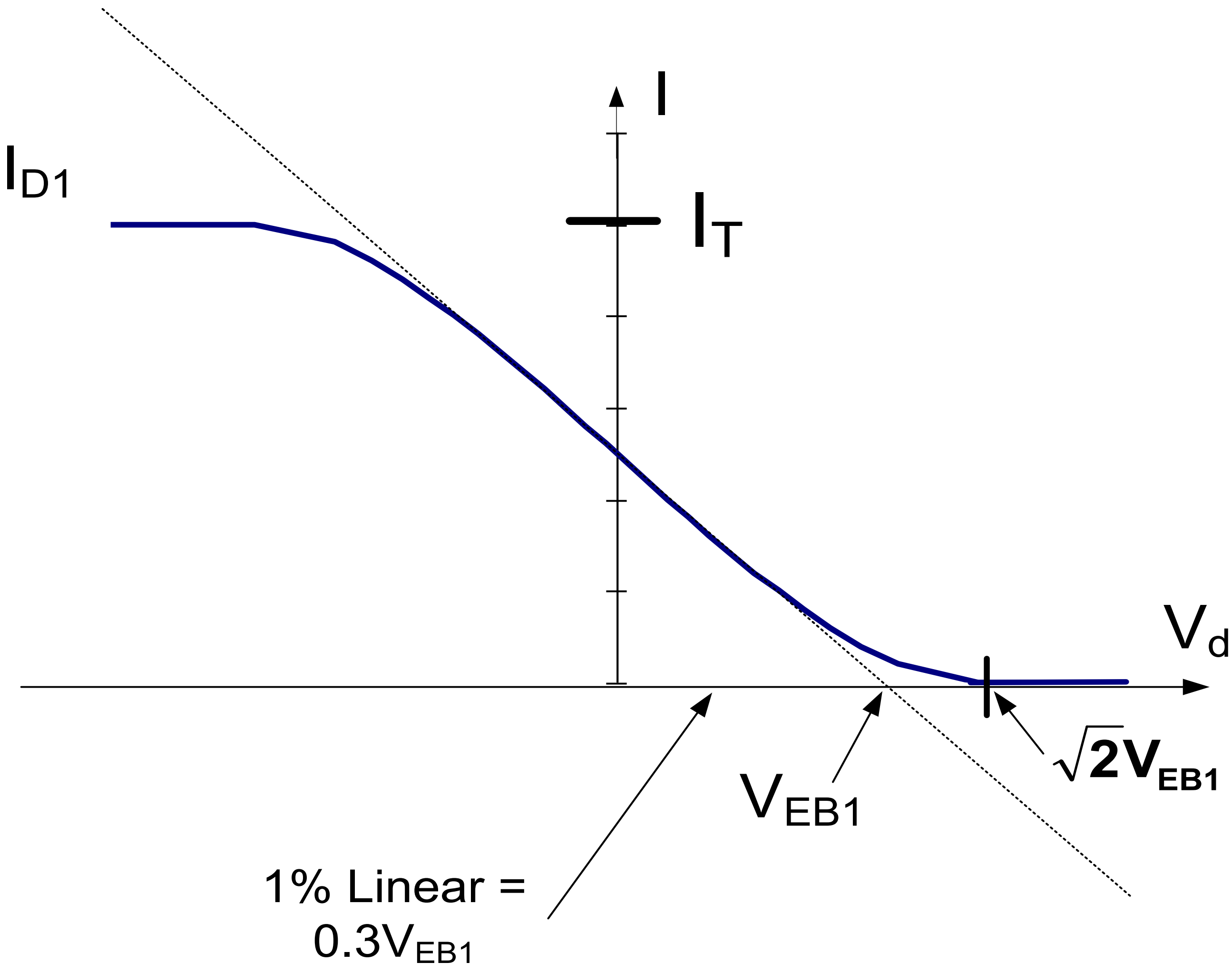


It can be shown that a 1% deviation from the straight line occurs at

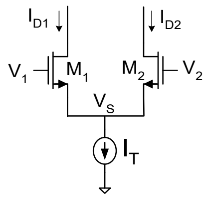
$V_d \cong \dfrac{V_{EB}}{3}$ and a 0.1% variation occurs at $V_d \cong \dfrac{V_{EB}}{10}$

How linear is the amplifier ?

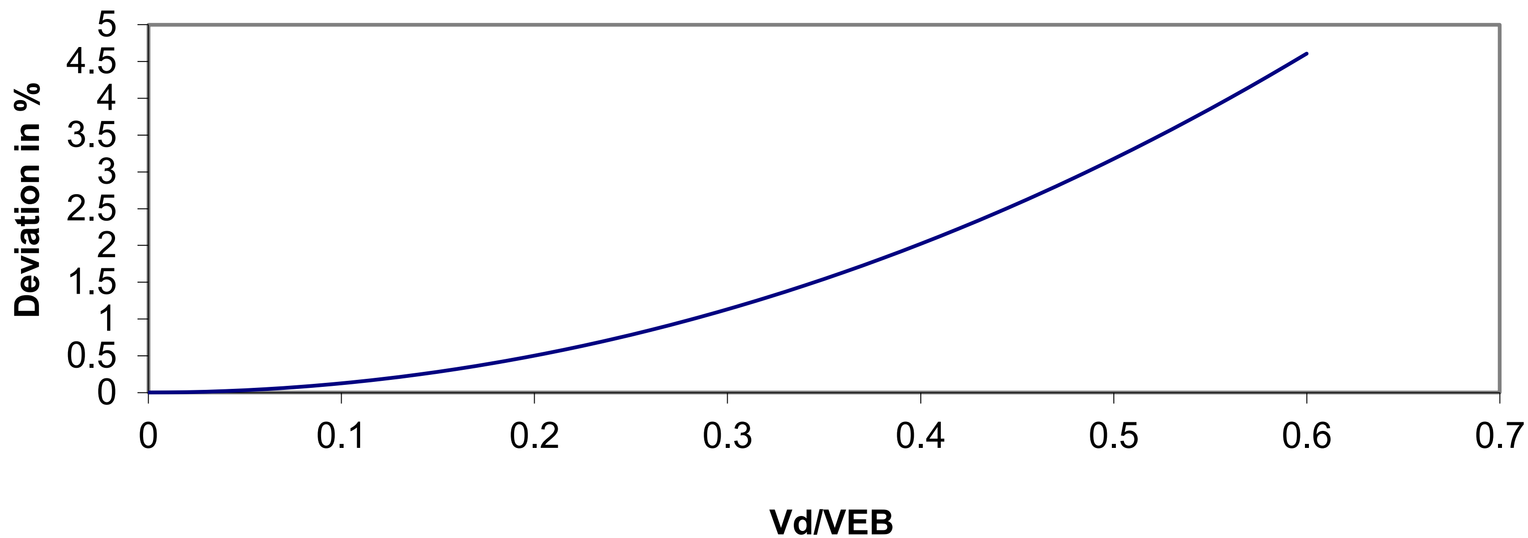




How linear is the amplifier ?



Deviation from Linear



Vd/VEB	θ	Vd/VEB	θ	Vd/VEB	θ
0.02	0.005	0.22	0.607	0.42	2.23
0.04	0.020	0.24	0.723	0.44	2.45
0.06	0.045	0.26	0.849	0.46	2.68
0.08	0.080	0.28	0.985	0.48	2.92
0.1	0.125	0.3	1.13	0.5	3.18
0.12	0.180	0.32	1.29	0.52	3.44
0.14	0.245	0.34	1.46	0.54	3.71
0.16	0.321	0.36	1.63	0.56	4.00
0.18	0.406	0.38	1.82	0.58	4.30
0.2	0.501	0.4	2.02	0.6	4.61

Stay Safe and Stay Healthy !

End of Lecture 19