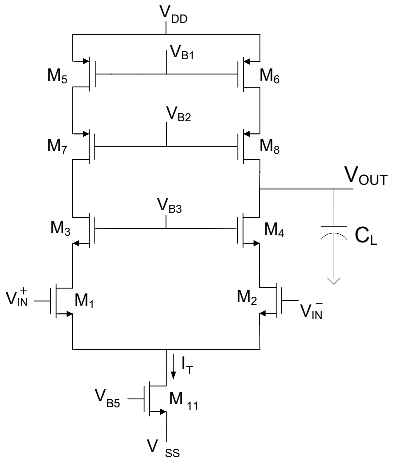
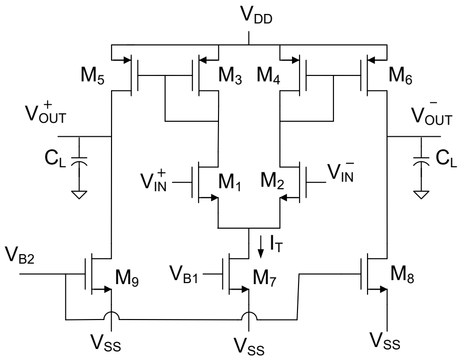
EE 435
Lecture 11

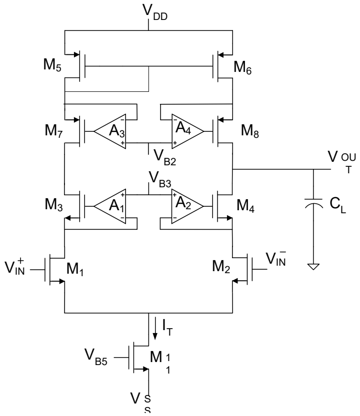
Current Mirror Op Amps
Cascaded Amplifiers
-- Stability Issues
Basic Concepts of Frequency-Dependent Feedback Systems

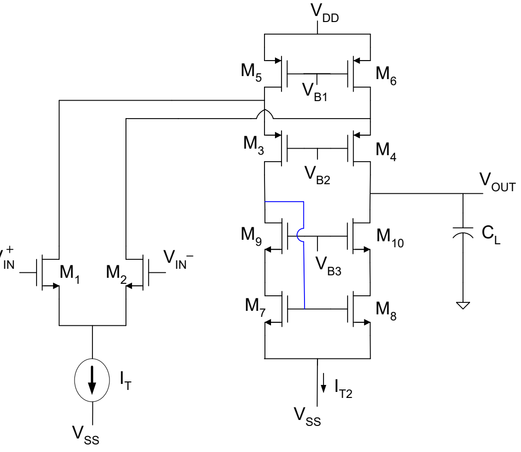
Review from last lecture:

Are these "high gain" amplifiers really high gain amplifiers?









Are these high gain voltage amplifiers?

Yes : if loading ignored - but not good voltage amplifiers because output impedance is high

Are these high gain transconductance amplifiers?

No!

Are these high gain current amplifiers?

No input current but if modified with low impedance shunt at input, have low current gain

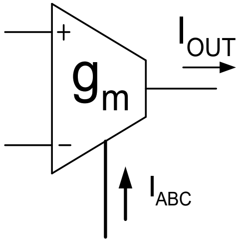
Are these high gain transresistance amplifiers?

No input current but if modified with low impedance shunt at input, transresistance gain would not be high even if loading of output neglected

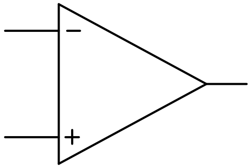
Review from last lecture:

Returning to Challenge Slide:
OTA Circuits

OTA often used open loop



Recall: Op Amp almost never used as an open amplifie

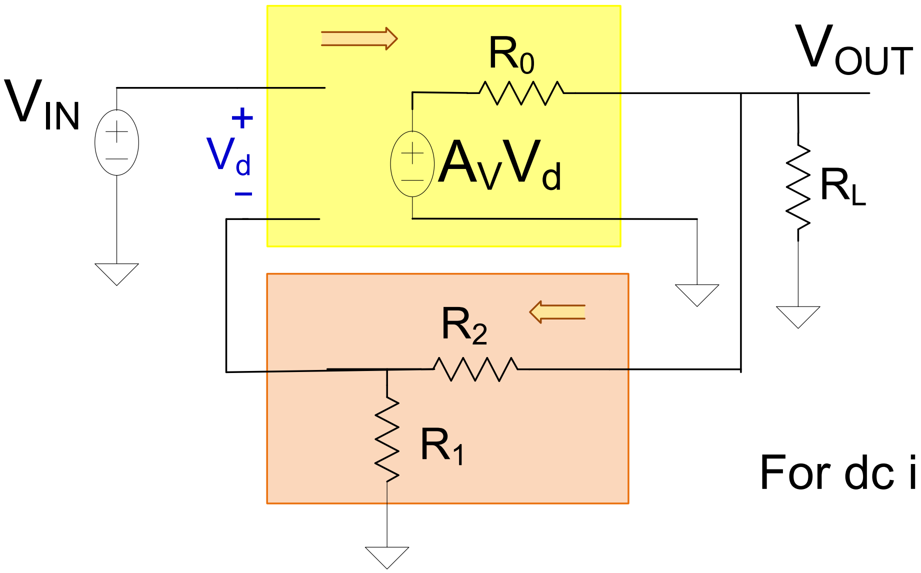


Since we just showed that the OTA is also a good high-gain op amp it seems there are conflicting statements

➡ Challenge to students: Resolve what may appear to be conflicting statements. But not a high gain transconductance amplifier and not a low output impedance voltage amplifier !!

Review from last lecture:

Effective Gain of Operational Amplifiers



For dc input, $A_V = A_{V0}$

$$A_{VF} = \frac{A_{V0}}{1+\beta A_{V0}} \Longrightarrow A_{VF} = \frac{A_{VEFF}}{1+\beta A_{VEFF}}$$

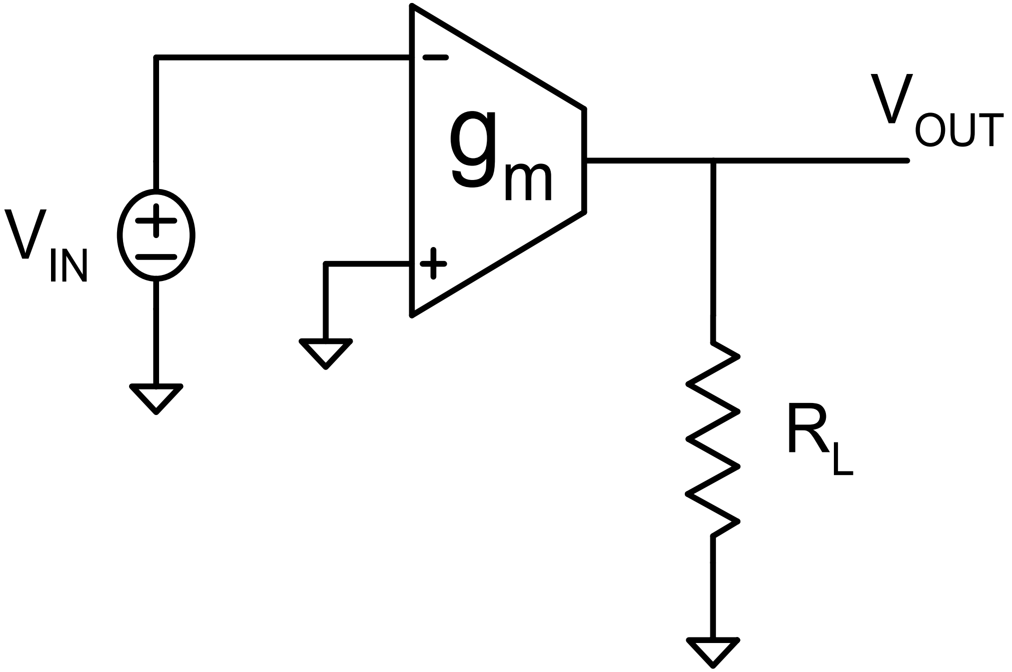
The open loop gain of an operational amplifier used in a FB configuration must include the loading of the feedback network and load resistor

Some FB networks cause little or no loading and others can be significant

Often a buffer stage is added to the output of the op amp when used in FB applications driving “heavy” loads

Review from last lecture:

OTA Applications



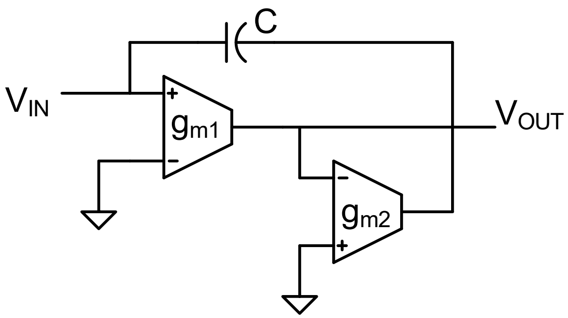
$$V_{OUT} = -g_m R \bullet V_{IN}$$

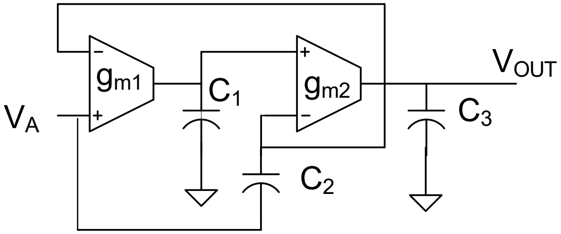
Voltage Controlled Inverting Amplifier

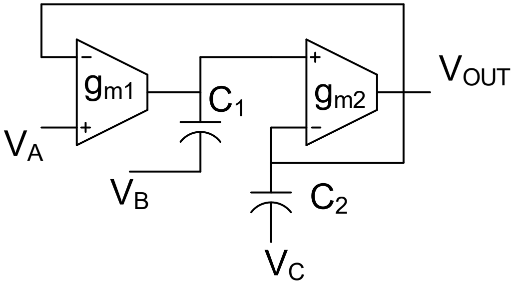
Review from last lecture:

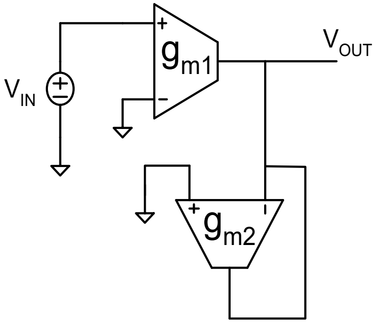
OTA Applications

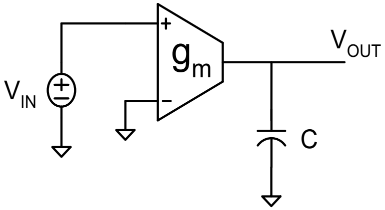
- OTA Applications are Extensive
- Programmable Features Are Attractive
- Can be Readily Integrated (often without resistors)
- Excellent high frequency performance

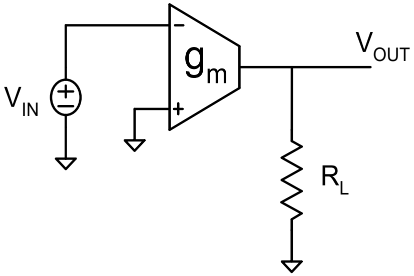


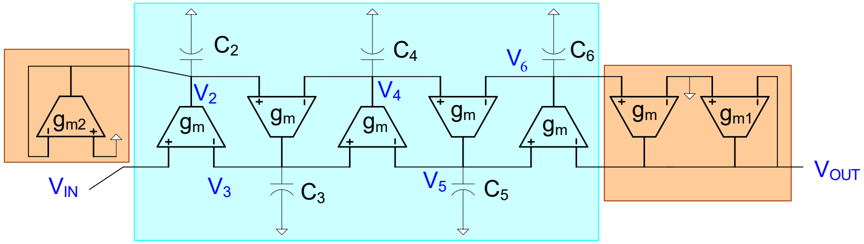












Review from last lecture:

Properties of OTA-Based Circuits

- Can realize arbitrarily complex functions
- Circuits are often simpler than what can be obtained with Op Amp counterparts
- Inherently offer excellent high frequency performance
- Can be controlled with a dc voltage or current
- Often used open-loop rather than in a feedback configuration (circuit properties depend directly on g_m)
- Other high output impedance op amps can also serve as OTA
- Linearity is limited
- Signal swing may be limited but can be good too
- Circuit properties process and temperature dependent

Consider Again Current Mirror Op Amp

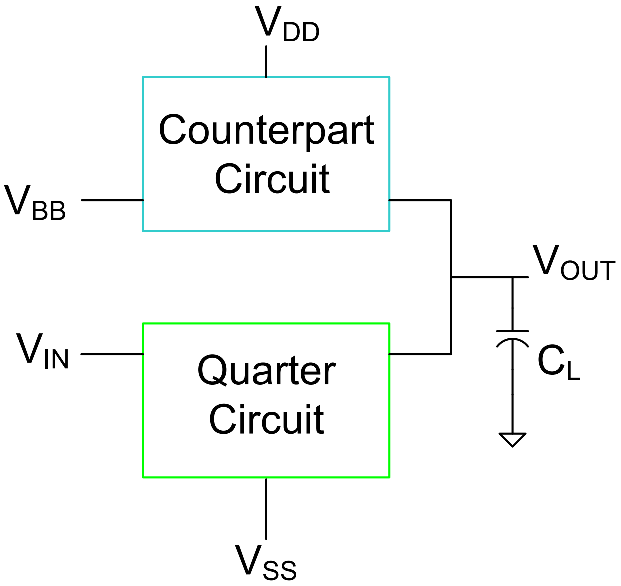
- Current-Mirror Op Amp offers strategy for g_m enhancement
- Very Simple Structure
- Has applications as an OTA
- But – how good are the properties of the CMOA?

Is this a real clever solution?

Recall:

Other Methods of Gain Enhancement

Recall:



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

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

Two Strategies:

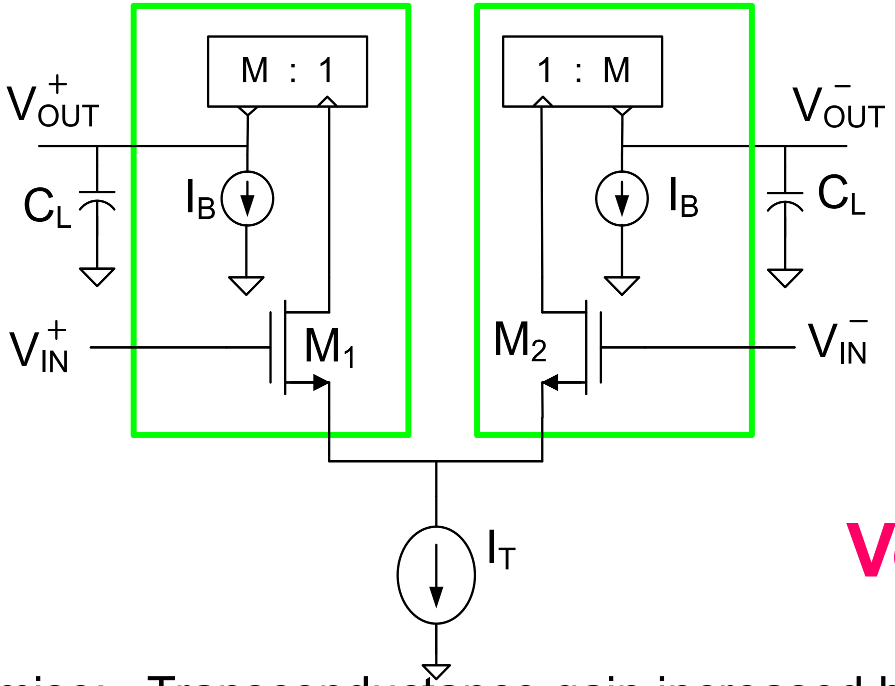
1. Decrease denominator of A_{V0}
2. Increase numerator of A_{V0}

Previous approaches focused on decreasing denominator

Consider now increasing numerator

Recall:

Current Mirror Op Amps



$$A_{V0} = \frac{V_{OUT}^{-}}{V_{IN}^{+} - V_{IN}^{+}}$$

Very Simple Structure!

Premise: Transconductance gain increased by mirror gain M

$$g_{mEQ} = M\frac{g_{m1}}{2}$$

(for $V_{IN}+=V_d/2$)

$$g_{OEQ} = g_{OQC} + g_{OI_{BB}}$$

Premise: If output conductance is small, gain can be very high

$$A_{V0} = -\frac{g_{mEQ}}{g_{OEQ}}$$

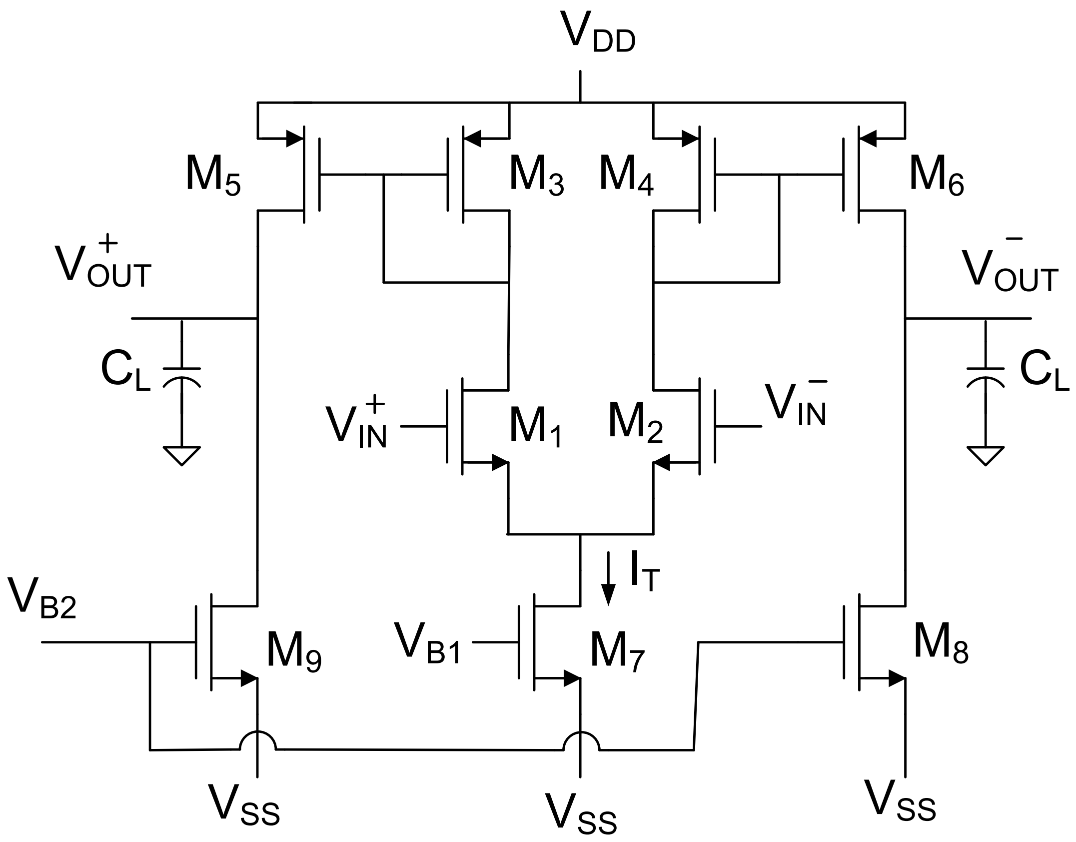
Premise: GB very good as well

Still need to generate the bias current I_B

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

Recall:

Basic Current Mirror Op Amp



CMFB not shown

$$g_{mEQ} = M\frac{g_{m1}}{2}$$

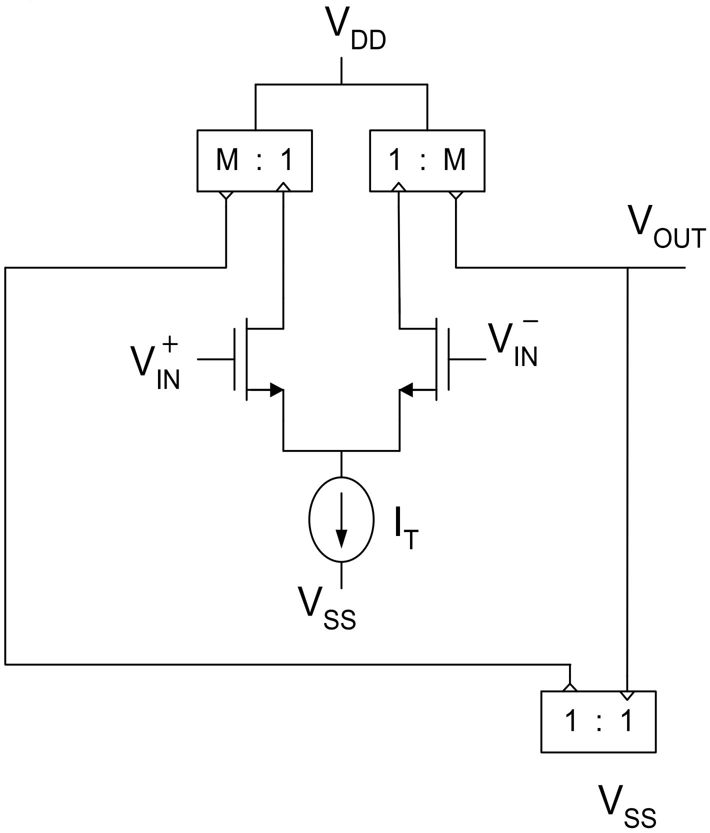
$$g_{OEQ} = g_{O6} + g_{O8}$$

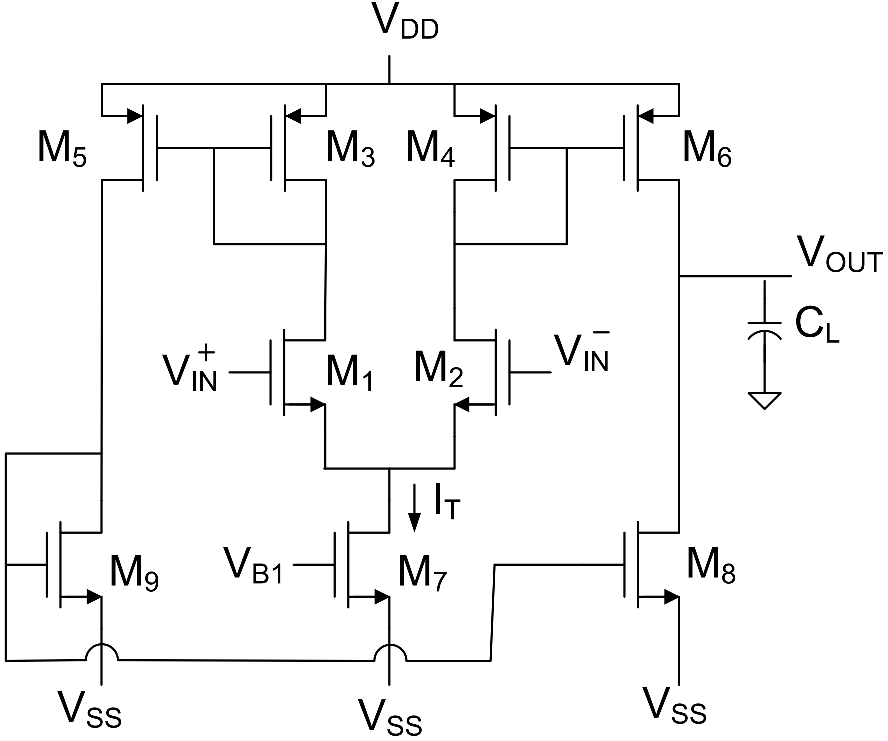
$$GB = M\frac{g_{m1}}{2C_L}$$

$$A_{VO} = \frac{M\bullet\frac{g_{m1}}{2}}{g_{O6} + g_{O8}}$$

$$SR = \frac{M\bullet I_T}{2C_L}$$

Current Mirror Op Amp W/O CMFB





Current Mirror op Amp with Basic Current Mirrors

All 3 current mirrors can be cascoded or regulated cascoded to dramatically decrease output conductance and thus voltage gain !

$$A_{VO} = -\frac{M \bullet g_{m1}}{g_{OEQ}} \qquad GB = M\frac{g_{m1}}{2C_L}$$

$$g_{OEQ} = g_{O6} + g_{O8} \qquad GB = M\frac{g_{m1}}{2C_L}$$

$$g_{mEQ} = Mg_{m1}$$

$$\mathbf{SR} = \frac{\mathbf{MI_T}}{\mathbf{C_L}}$$

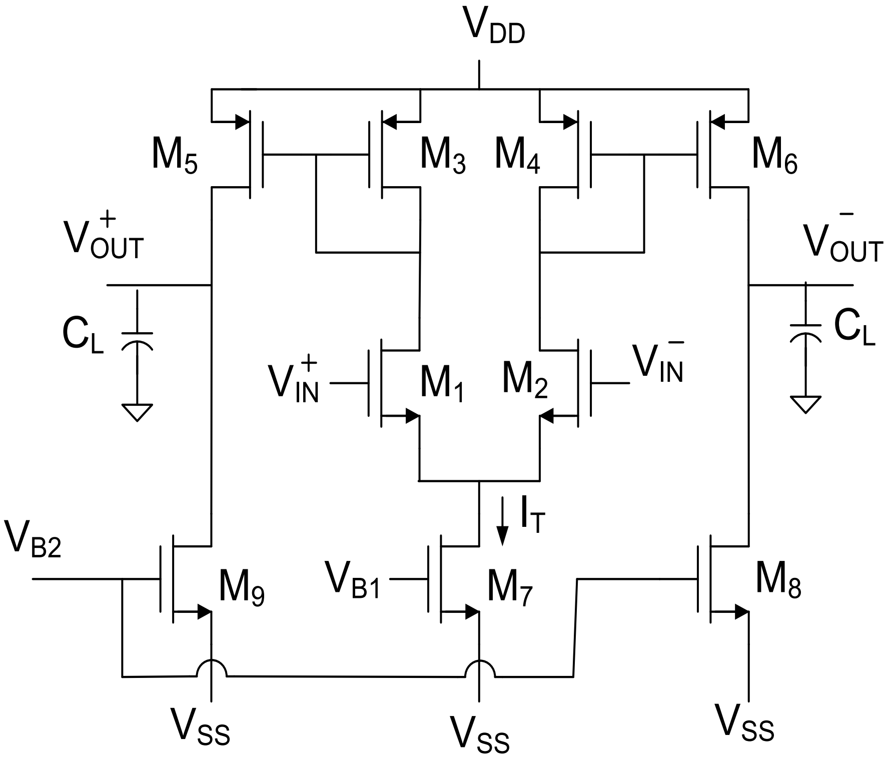
$$A_{VO} = -\frac{M \bullet g_{m1}}{g_{O6} + g_{O8}}$$

Recall:

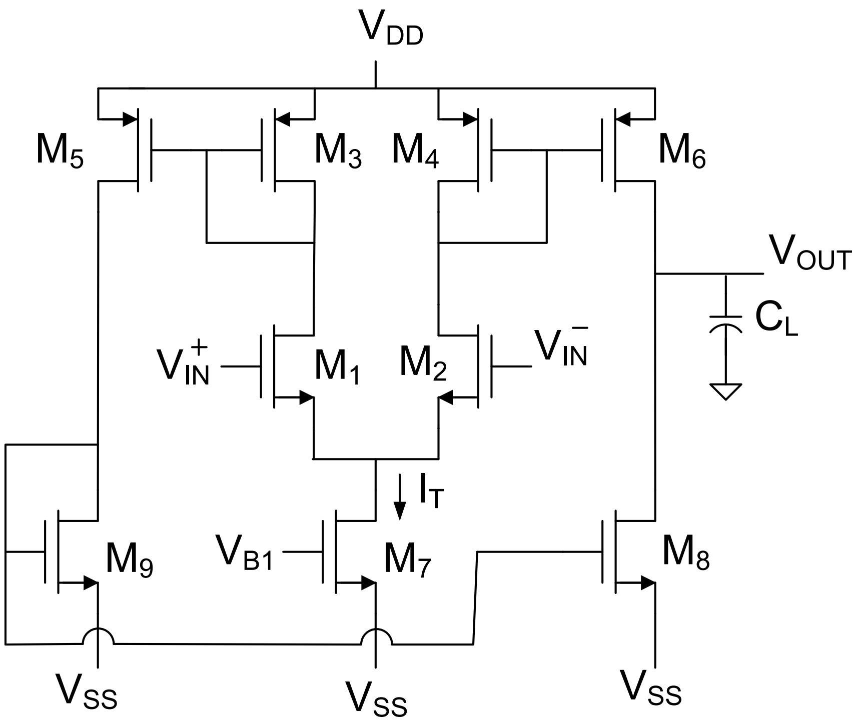
- Current-Mirror Op Amp offers strategy for g_m enhancement
- Very Simple Structure
- Has applications as an OTA
- Based upon small signal analysis, performance appears to be very good !
- But – how good are the properties of the CMOA?

Is this a real clever solution?

SR of Current Mirror Op Amp



(CMFB Circuit not Shown)



$$SR = \frac{MI_T}{2C_L}$$

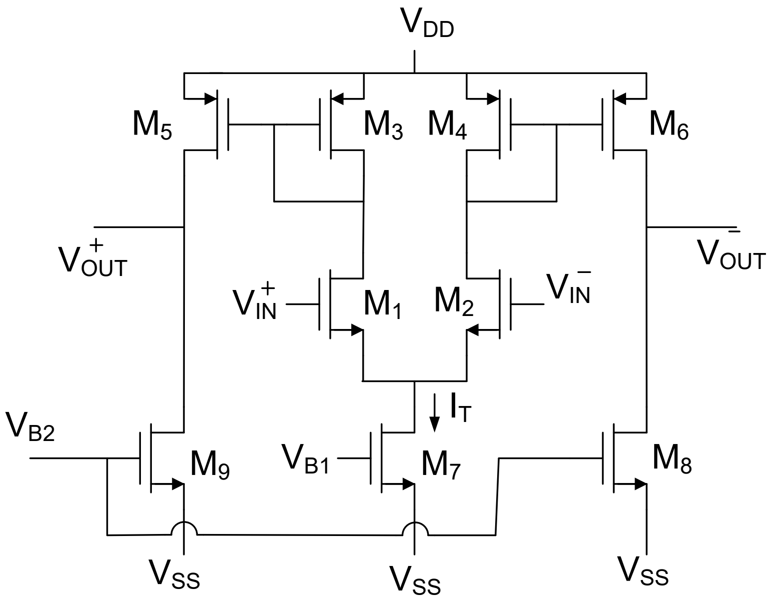
$$\mathbf{SR} = \frac{\mathbf{MI_T}}{\mathbf{C_L}}$$

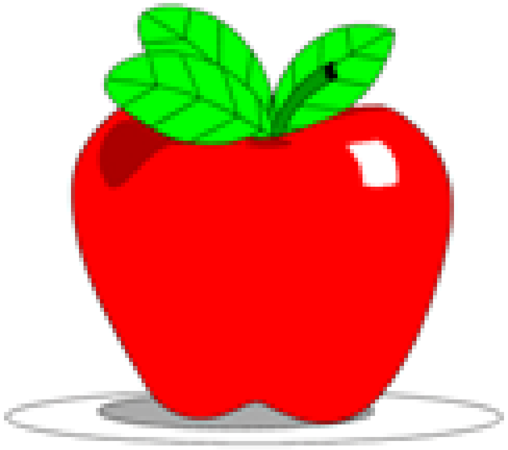
Comparison of Current-Mirror Op Amps with Previous Structures

Does the simple mirror gain really provide an “almost free” gain enhancement ?

$$A_{VO} = -\frac{M \bullet \frac{g_{m1}}{2}}{g_{o6} + g_{o8}}$$

$$= \frac{W_6 L_4}{W_4 L_6}$$





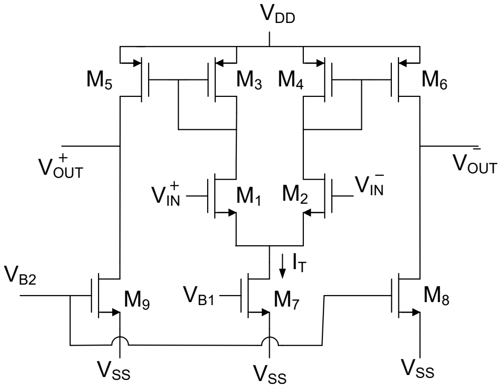
Ask the apple comparison question !

What parameter domain is used for A_{V0} expression?

Mixed parameters : some small signal and some practical parameters ??

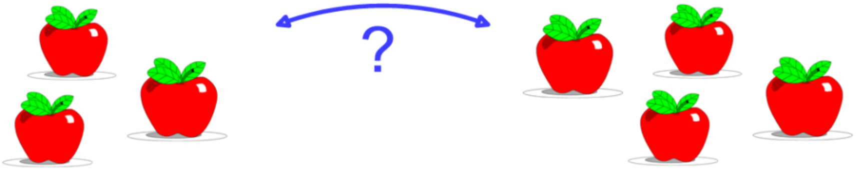
Comparison of Current-Mirror Op Amps with Previous Structures

Does the simple mirror gain really provide an “almost free” really large gain enhancement ?



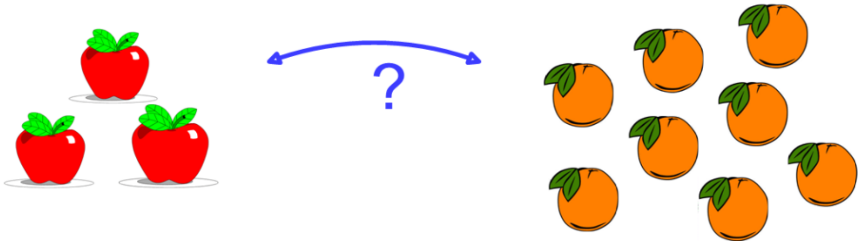
$$A_{VO} = -\frac{M \bullet \frac{g_{m1}}{2}}{g_{o6} + g_{o8}}$$

$$M = \frac{W_6 L_4}{W_4 L_6}$$



Are we comparing Apples with Apples?

- In the small-signal parameter domain?
- In the practical parameter domain?
- Does it matter if we are making a comparison?



Reference Op Amp

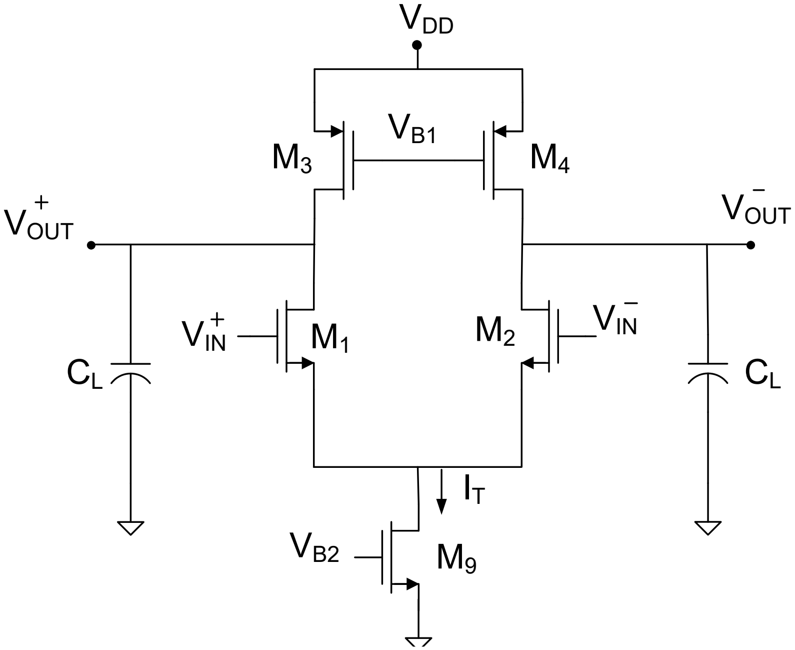
Recall single-ended output performance :

$$A(s) = \frac{\frac{g_{m1}}{2}}{sC_L + g_{O1} + g_{O3}}$$

$$A_{VO} = \frac{1}{2}\frac{g_{m1}}{g_{O1} + g_{O3}} \qquad A_{V0} = \left[\frac{1}{\lambda_1 + \lambda_3}\right]\left(\frac{1}{V_{EB1}}\right)$$

$$GB = \frac{g_{m1}}{2C_L} \qquad GB = \left(\frac{P}{2V_{DD}C_L}\right)\bullet\left[\frac{1}{V_{EB1}}\right]$$

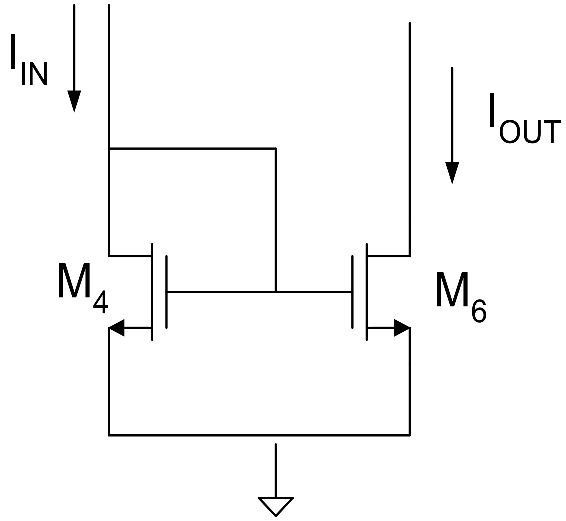
$$SR = \frac{I_T}{2C_L} \qquad SR = \frac{P}{2V_{DD}C_L}$$



Comparison of Current-Mirror Op Amps with Previous Structures

Does the simple mirror gain really provide an “almost free” gain enhancement ?

$$A_{VO} = -\frac{M \bullet \frac{g_{m1}}{2}}{g_{O6} + g_{O8}}$$



$$M = \frac{W_6 L_4}{W_4 L_6}$$

Can be easily shown that:

$$M = \frac{g_{m6}}{g_{m4}}$$

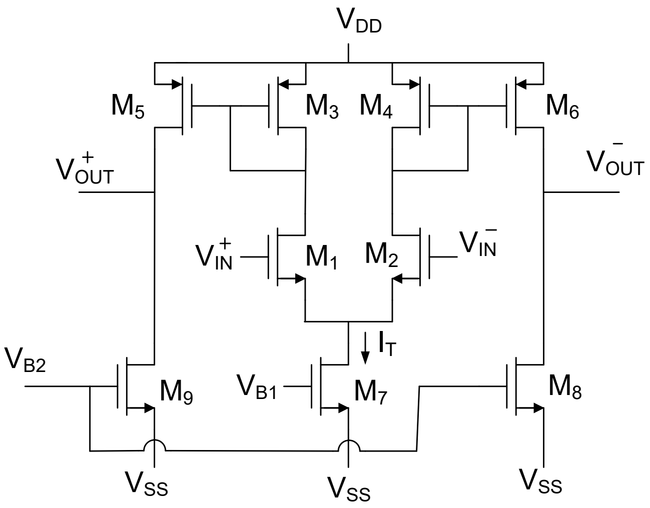
$$A_{VO} = -\frac{\frac{g_{m6}}{g_{m4}} \bullet \frac{g_{m1}}{2}}{g_{O6} + g_{O8}}$$

Gain Enhancement Potential Less Apparent but still Improved by g_{m6}/g_{m4} ratio

Comparison of Current-Mirror Op Amps with Previous Structures

Does the simple mirror gain really provide an "almost free" gain enhancement ?

$$A_{VO} = -\frac{M \bullet \frac{g_{m1}}{2}}{g_{O6} + g_{O8}}$$



Consider how the gain appears in the practical parameter domain

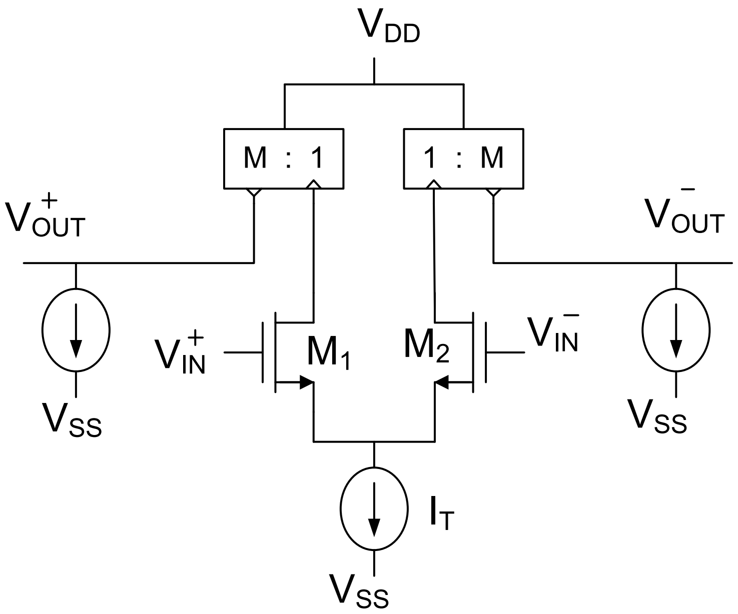
$$A_{V0} = \frac{\frac{1}{2}\left(2\frac{I_T}{2}M\right)}{V_{EB1}\left(\lambda_{M6} + \lambda_{M8}\right)I_{D8Q}} = \frac{\frac{I_T}{2}M}{V_{EB1}\left(\lambda_{M6} + \lambda_{M8}\right)M\frac{I_T}{2}} = \frac{1}{V_{EB1}\left(\lambda_{M6} + \lambda_{M8}\right)} \cong \frac{1}{2\lambda V_{EB1}}$$

This is exactly the same as was obtained for the simple differential amplifier!

For a given V_{EB1}, there is NO gain enhancement !

Comparison of Current-Mirror Op Amps with Previous Structures

How does the GB power efficiency compare with previous amplifiers ?



$$GB=\frac{g_{mEQ}}{C_L}=\frac{M\frac{g_{m1}}{2}}{C_L}=\frac{MI_T}{2V_{EB1}C_L}$$

$$P=\left(V_{DD}-V_{SS}\right)I_T\left(1+M\right)$$

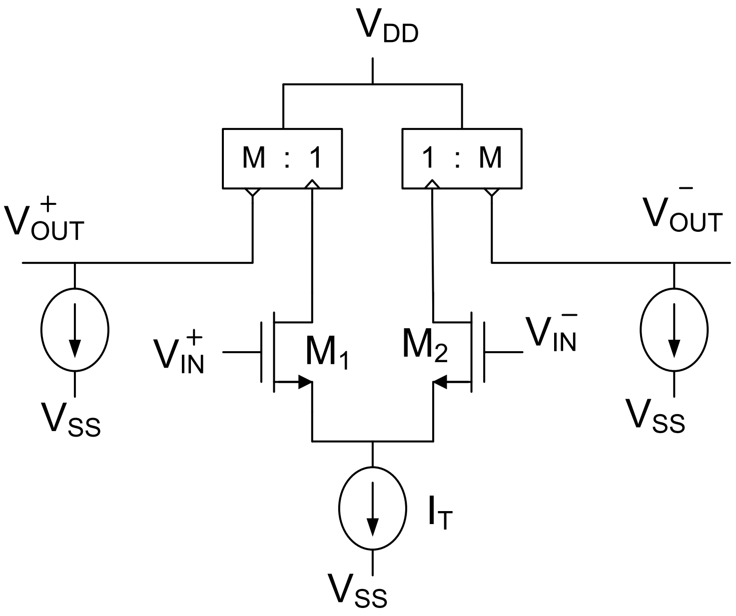
$$GB=\frac{MI_T}{2V_{EB1}C_L}=\boxed{\left(\frac{P}{2V_{EB1}\left(V_{DD}-V_{SS}\right)C_L}\right)}\left[\frac{M}{1+M}\right]$$

GB for Telescopic Cascode and Ref Op Amp !

- GB efficiency decreased for all M !
- GB efficiency decreased significantly for small M !!

Comparison of Current-Mirror Op Amps with Previous Structures

How does the SR compare with previous amplifiers ?



$$SR_{\text{Ref Op Amp}} = \frac{I_T}{2C_L}$$

$$SR = \frac{M \bullet I_T}{2C_L}$$

SR Improved by factor of M !

but …

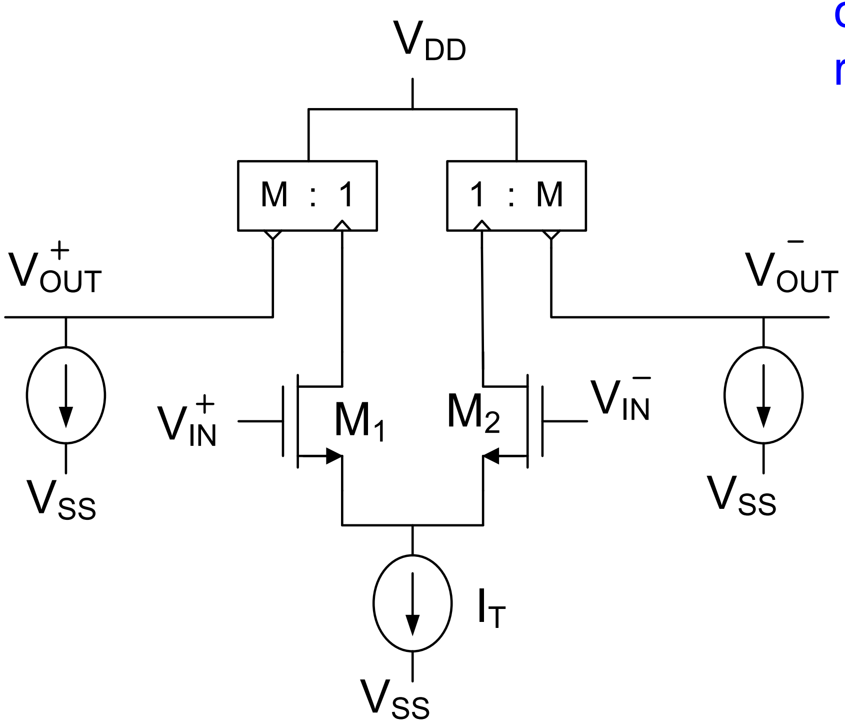
$$P = (V_{DD} - V_{SS}) I_T (1 + M)$$

$$SR = \frac{P}{2(V_{DD} - V_{SS})C_L}\left[\frac{M}{1+M}\right]$$

$$SR_{\text{Ref OpAmp}} = \frac{P}{2(V_{DD}\text{-}V_{SS})C_L}$$

SR Really Less than for Ref Op Amp !!

Comparison of Current-Mirror Op Amps with Previous Structures



How does the Current Mirror Op Amp really compare with previous amplifiers or with reference amplifier?

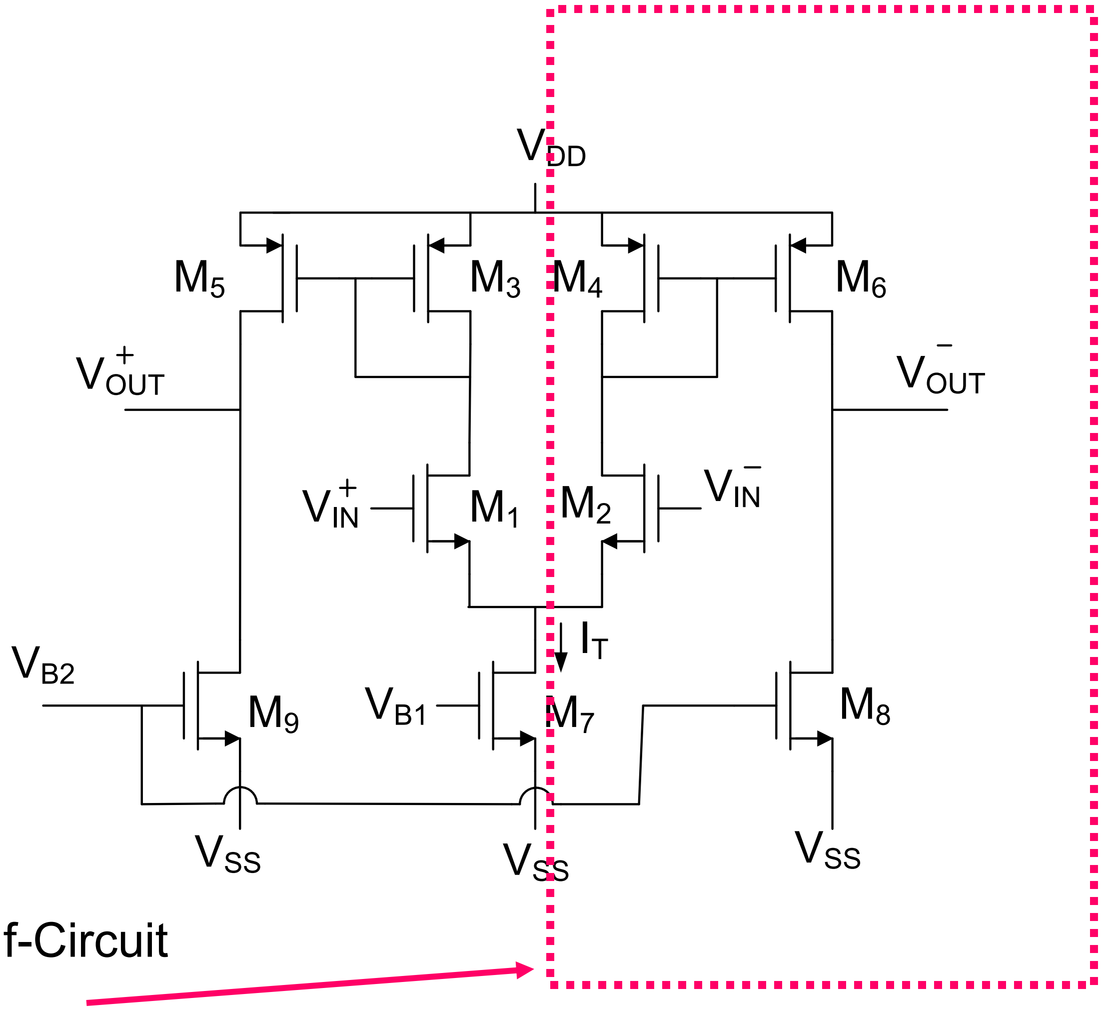
Perceived improvements may appear to be very significant

Actual performance is not as good in almost every respect !

But performance is comparable to other circuits and the circuit structure is really simple

Widely used architecture as well but maybe more for OTA applications

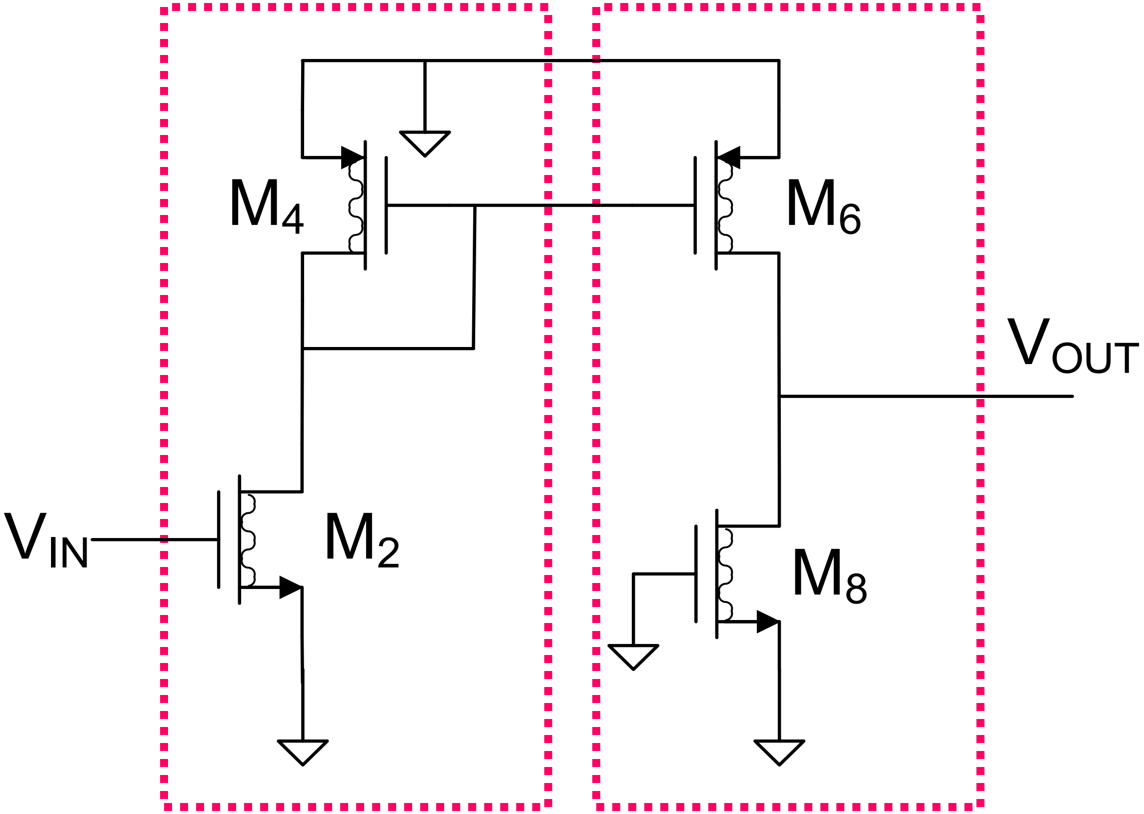
Current-Mirror Op Amps – Another Perspective !



Differential Half-Circuit

Note: Source node of M_1 and M_2 at ac ground with differential excitations

Current-Mirror Op Amps – Another Perspective !



$$V_{IN} = \frac{V_d}{2}$$

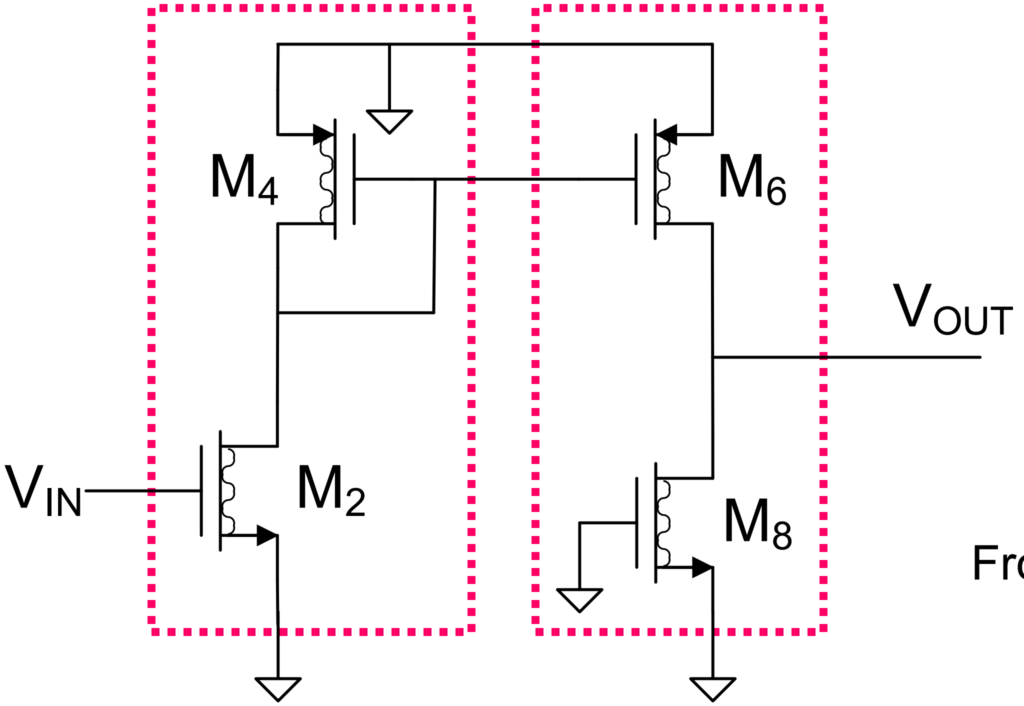
Differential Half-Circuit

Cascade of n-channel common source amplifier
with p-channel common-source amplifier !

Differential Half-Circuit is comprised of two stages and is not symmetric !

Current-Mirror Op Amps – Another Perspective !

Differential Half-Circuit



$$V_{IN} = \frac{V_d}{2}$$

$$A_{Vd} = -\frac{1}{2}\left(\boxed{\frac{g_{m2}}{g_{m4}}}\right)\left(\frac{g_{m6}}{g_{O6}+g_{O8}}\right)$$

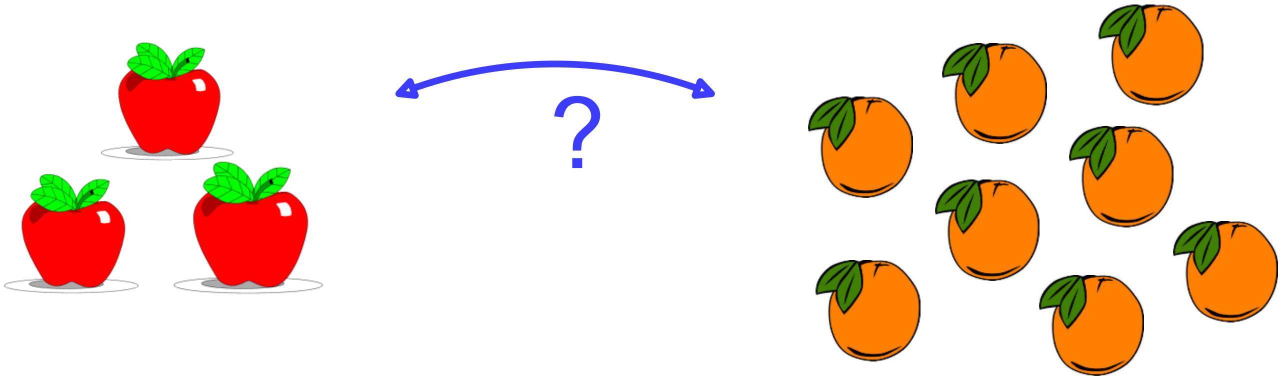
From Current Mirror Analysis :

$$A_{VdO} = -\frac{M \bullet \frac{g_{m2}}{2}}{g_{O6}+g_{O8}} = -\frac{\boxed{\frac{g_{m6}}{g_{m4}} \bullet \frac{g_{m2}}{2}}}{g_{O6}+g_{O8}}$$

Cascade of a low-gain n-channel common source amplifier
With a high-gain p-channel common-source amplifier !

Comparison of Different Circuit Designs

- An objective comparison of different design approaches is often a critical part of the design process
- Different objective functions or different comparison approaches often lead to different conclusions
- Textbooks and the technical literature do not always identify the most appropriate objective functions
- Critical to identify metrics that capture the important characteristics of a design when making comparisons but this is often a challenging task



Current Mirror Op Amp Summary

- Current-mirror op amp offers no improvement in performance over the reference op amp

- Current-mirror op amp can be viewed as a cascade of two common-source amplifiers, one with a low gain and the other with a larger gain

- Current-mirror op amp is useful as an open-loop programmable transconductance amplifier (OTA)

- Current-mirror op amp does have reasonable performance and is a viable structure with performance comparable to that of the reference op amp!

- Current-mirror op amp will work in feedback applications as well but performance would often be better with some alternative Op Amp architectures

Stability

- Sometimes circuits that have been designed to operate as amplifiers do not amplify a signal but rather oscillate when no input signal is present (V_{in}=0V or I_{in}=0A) or “latch up”
- Circuits that are designed to operate as amplifiers but instead either oscillate or “latch up” are said to be unstable
- The stability of any circuit is determined by the location of the poles
- We will discuss stability with more rigor later
- It will be shown that if the poles of an open-loop amplifier are widely separated on the negative real axis, then a feedback amplifier built using the open-loop amplifier will be stable
- And, it will be shown that if the poles of an open-loop amplifier are not widely separated on the negative real axis, then the feedback amplifier built using the open-loop amplifier will be unstable

Poles of an Amplifier

- The poles of an amplifier are the roots of the denominator of the transfer function of the amplifier
- Each energy storage element (capacitor or inductor) introduces an additional pole (except when capacitor or inductor loops exist)
- The poles of an amplifier can often be approximated by independently considering the impedance facing each capacitor and assuming all other capacitors are either open circuits or short circuits

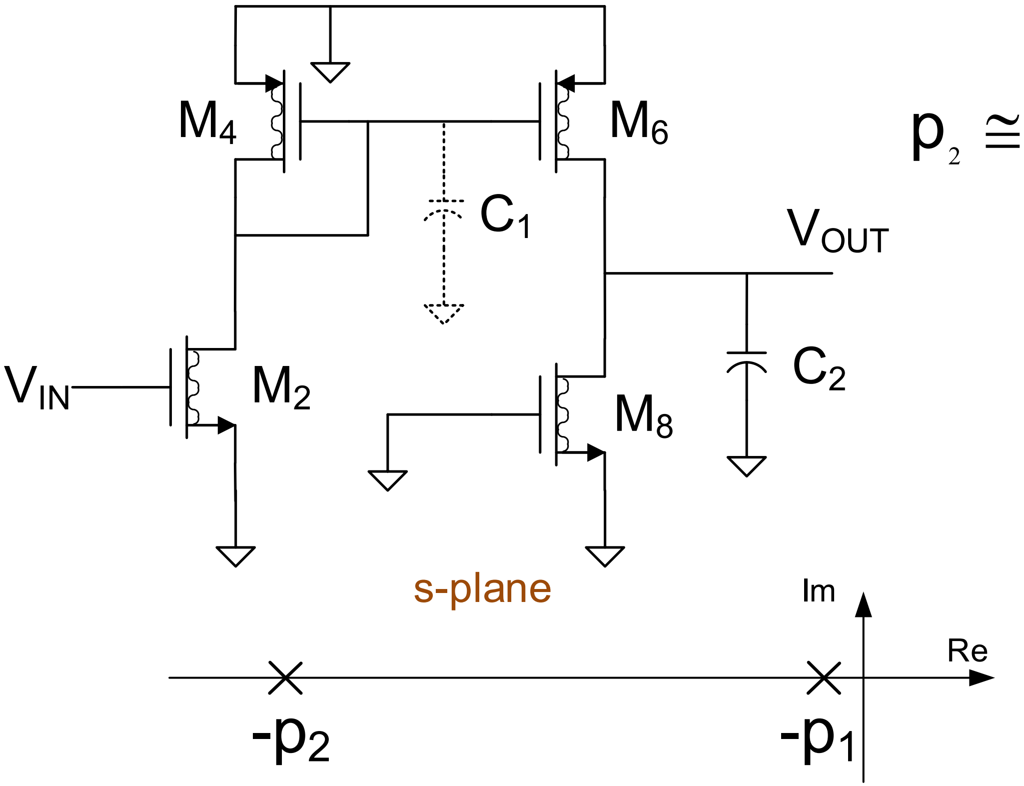
Poles of an Amplifier

- The dead network of a circuit is obtained by setting all independent sources to zero
- The poles of a circuit are absolute: That is, they are independent of where the excitation is applied or where the response is taken provided the dead networks are the same!
- Stability is absolute: That is, a circuit is either stable or unstable irrespective of where the input is applied or the response is taken provided the dead networks are the same

Current-Mirror Op Amps – Another Perspective !

Differential Half-Circuit

Are there stability issues or concerns for a FB amplifier using this Op Amp ?



Small

$$p_2 \cong -\frac{(g_{O6}+g_{O8})}{C_2}$$

Large

Large

$$p_1 \cong -\frac{g_{m4}}{C_1}$$

Small

$$|p_1| >> |p_2|$$

- It will be shown later that FB amplifiers with a large pole spread do not have stability problems
- No stability problems for current mirror op amp provided C_2 is sufficiently large !

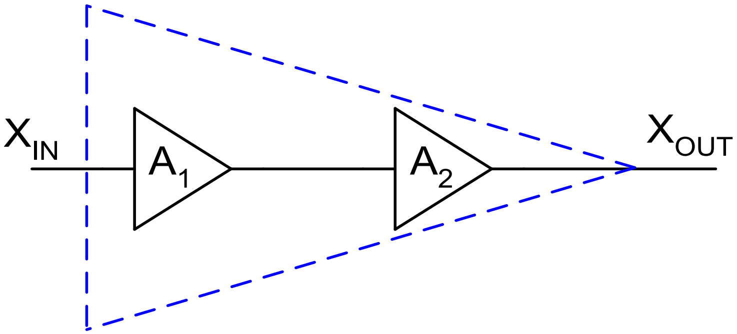
Where we are at:

Amplifier Design

- Fundamental Amplifier Design Issues
- Single-Stage Low Gain Op Amps
- Single-Stage High Gain Op Amps
- Other Basic Gain Enhancement Approaches
  - Cascaded Amplifiers
- Two-Stage Op Amp
  - Compensation
  - Breaking the Loop
- Other Issues in Amplifier Design
- Summary Remarks

Other Methods of Gain Enhancement

The current mirror op amp is actually a cascade of two amplifiers but this cascade did not give a real improvement in gain



Provided the stages are non-interacting

$$\frac{\mathbf{X_{OUT}}}{\mathbf{X_{IN}}} = \mathbf{A} = \mathbf{A_1 A_2}$$

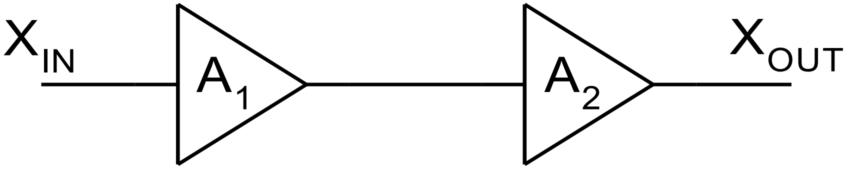
For the current mirror op amp

$$\mathbf{A_1} << \mathbf{A_2}$$

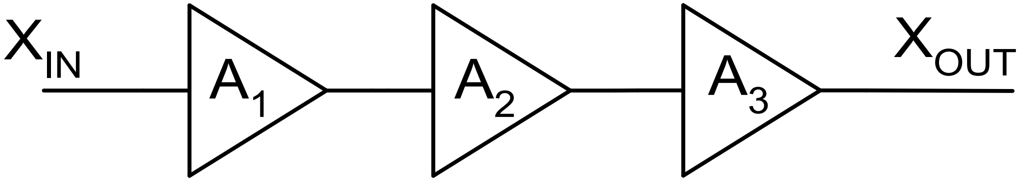
Could the gain be increased by cascading two or more amplifiers if the amplifiers had a higher gain?

Increasing Gain by Cascading

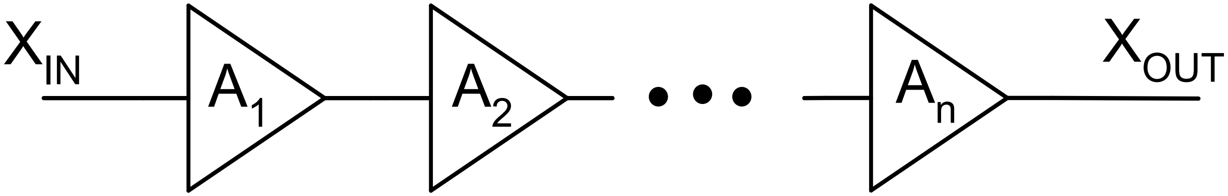
Provided the stages are non-interacting



$$\frac{X_{OUT}}{X_{IN}} = A_1 A_2$$



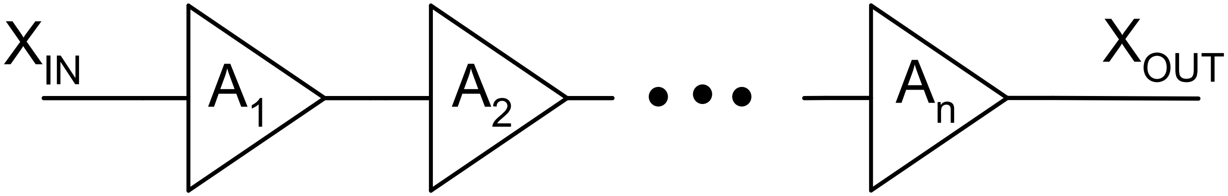
$$\frac{X_{OUT}}{X_{IN}} = A_1 A_2 A_3$$



$$\frac{X_{OUT}}{X_{IN}} = \prod_{i=1}^{n} A_i$$

Gain can be easily increased to almost any desired level !

Increasing Gain by Cascading



Provided the stages are non-interacting

$$\frac{X_{OUT}}{X_{IN}}=\prod_{i=1}^{n}A_i$$

But each of the gains will roll off with frequency so can be modeled as

$$A_k(s)=\frac{A_{0k}}{\frac{s}{\tilde{p}_k}+1}$$

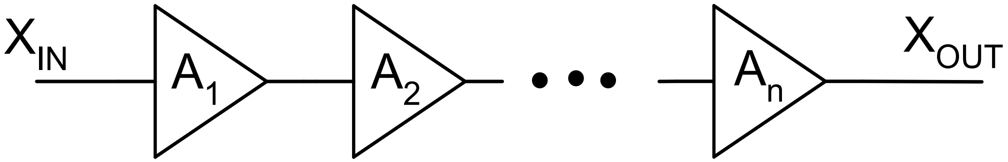
A_{0k} is the dc gain of stage k

$\tilde{p}_k$ is the negative of the pole of stage k

Thus

$$\frac{X_{OUT}}{X_{IN}}=A=\frac{\prod_{i=1}^{n}A_{0i}}{\prod_{k=1}^{n}\left(\frac{s}{\tilde{p}_k}+1\right)}$$

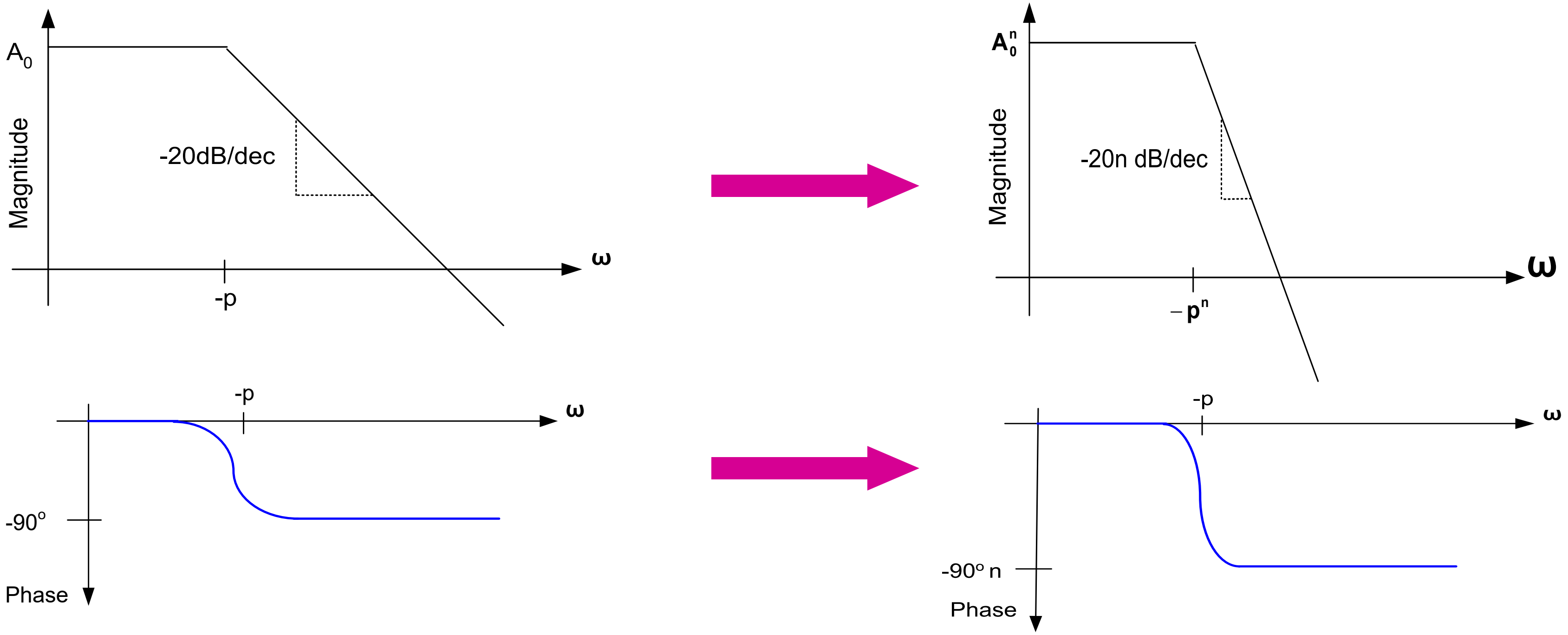
Increasing Gain by Cascading



Provided the stages are non-interacting

$$\frac{X_{OUT}}{X_{IN}} = A = \frac{\prod_{i=1}^{n} A_{0i}}{\prod_{k=1}^{n}\left(\frac{s}{\tilde{p}_k}+1\right)}$$

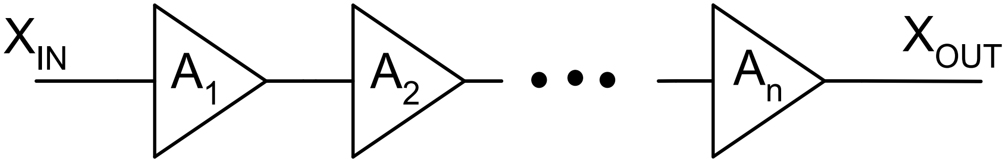
Assume for case of an example that all stages are identical with $A_{0k}=A_0$ and $\tilde{p}_k = \tilde{p} = -p$



(if inverting gain, phase will decrease from -180° to -270°)

- Much larger gain
- Much larger GB
- Much steeper gain transition
- Much more phase shift

Increasing Gain by Cascading



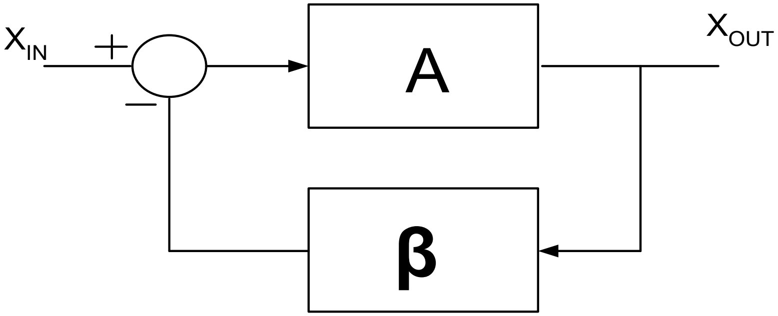
$$\frac{X_{OUT}}{X_{IN}} = A = \frac{\prod_{i=1}^{n} A_{0i}}{\prod_{k=1}^{n}\left(\frac{s}{\tilde{p}_k}+1\right)}$$

Provided the stages are non-interacting

Dramatic improvement in performance for the open-loop amplifier !!

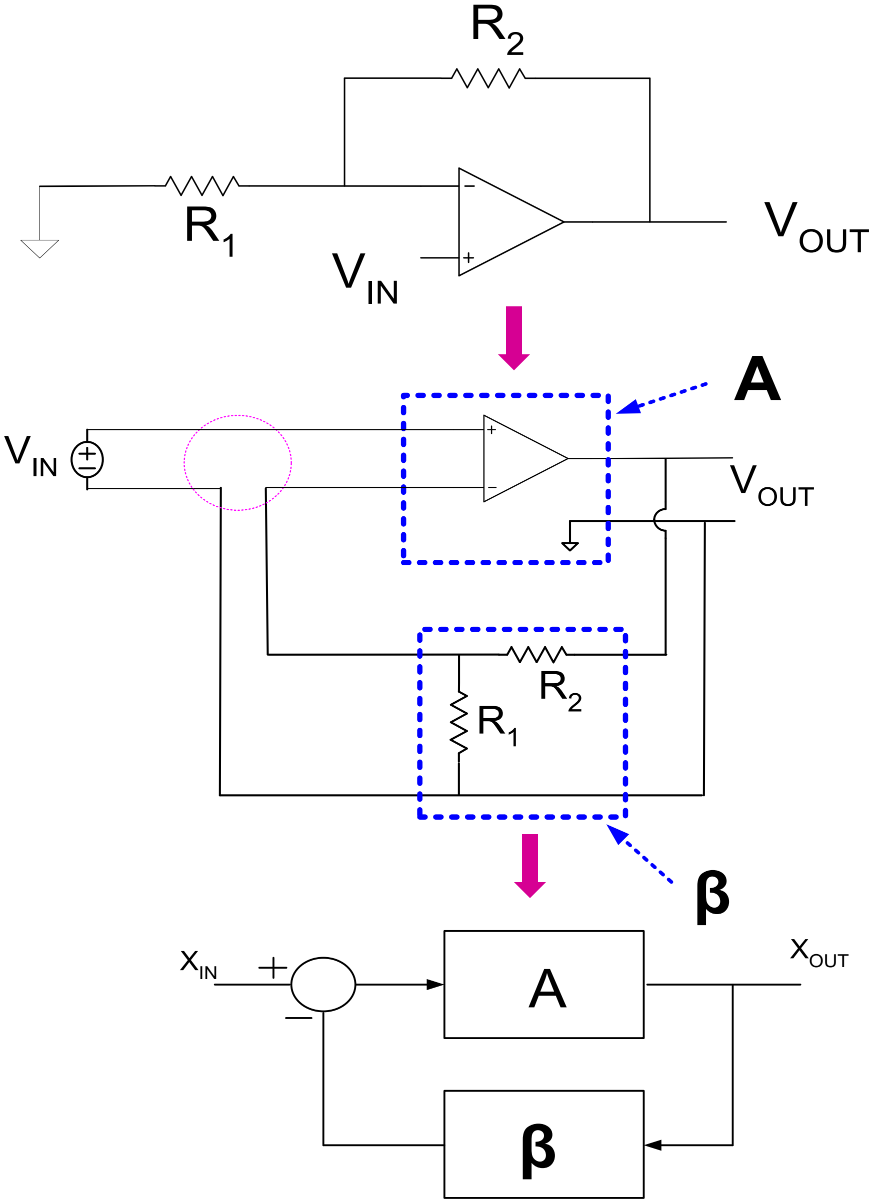
But – op amps seldom used open loop

How does the cascaded amplifier perform in a standard feedback application?



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

Feedback Amplifier Representation



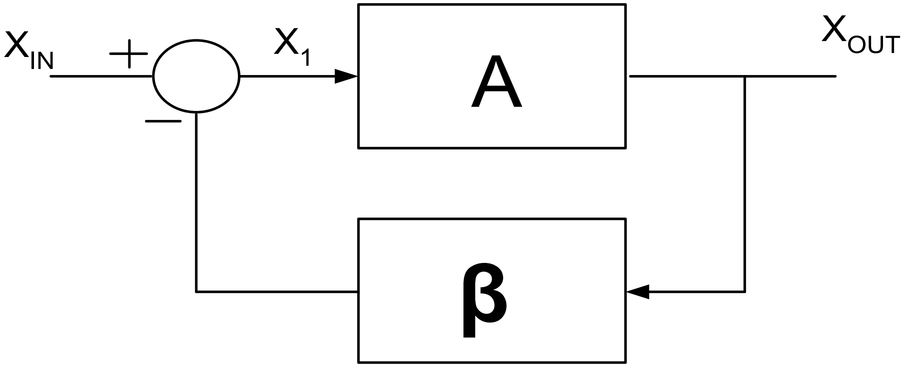
$$\frac{V_{OUT}}{V_{IN}} = \frac{1+\frac{R_2}{R_1}}{1+\frac{\left(1+\frac{R_2}{R_1}\right)}{A}}$$

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

$$A_{FB} = \frac{A}{1+A\beta} = \frac{\beta^{-1}}{1+\frac{\beta^{-1}}{A}} = \frac{1+\frac{R_2}{R_1}}{1+\frac{\left(1+\frac{R_2}{R_1}\right)}{A}}$$

Though other feedback configurations may not be so easily decomposed, concepts are similar

Frequency Response of Feedback Amplifier



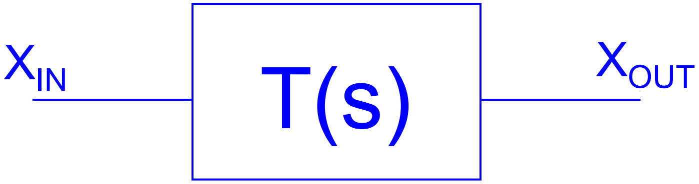
Consider the special case where A is the cascade of n identical stages

$$\frac{X_{OUT}}{X_1} = A = \frac{\prod_{k=1}^{n} A_{0k}}{\prod_{k=1}^{n}\left(\frac{s}{\tilde{p}_k}+1\right)} = \frac{A_0^n}{\left(\frac{s}{\tilde{p}}+1\right)^n}$$

$$A_{FB} = \frac{A}{1+A\beta} = \frac{A_0^n}{\left(\frac{s}{\tilde{p}}+1\right)^n + \beta A_0^n}$$

How do we determine how the amplifier is performing from A_{FB}?

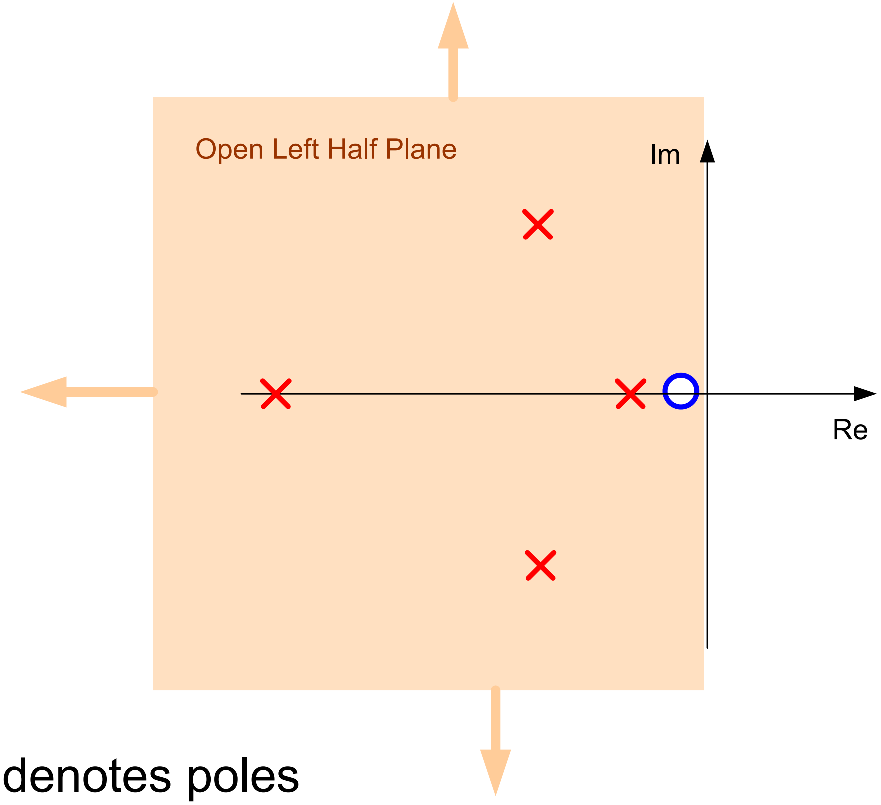
Review of Basic Concepts



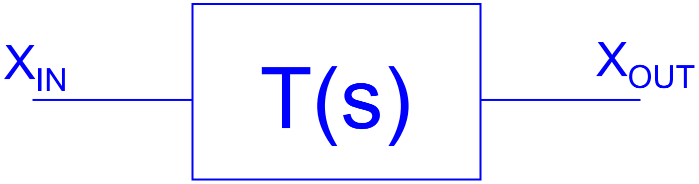
If $$T(s) = \frac{N(s)}{D(s)}$$ is the transfer function of a linear system

Roots of N(s) are termed the zeros

Roots of D(s) are termed the poles



X denotes poles
O denotes zeros



If $T(s)=\frac{N(s)}{D(s)}$ is the transfer function of a linear system

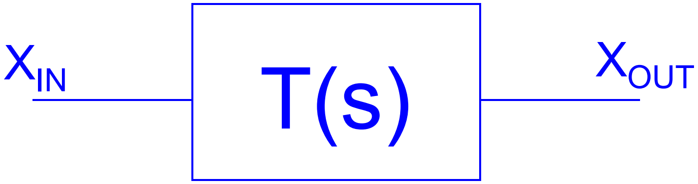
Stability

Definition: A linear system is BIBO stable if for any bounded input, the output is also bounded

BIBO: Bounded-Input Bounded-Output

- The term “stable” and the term “BIBO stable” are used interchangeably
- The amplifier community and the linear analog circuits community invariably use the term “stable”
- Slight variants of the definition of stability are common but for this course minor nuances in the definition of stability are of no concern and the concepts are identical and inherent
- **But checking for stability by considering ANY bounded input is impossible to do !**

Review of Basic Concepts



If $T(s)=\dfrac{N(s)}{D(s)}$ is the transfer function of a linear system

Roots of N(s) are termed the zeros

Roots of D(s) are termed the poles

Theorem: A linear system is stable iff all poles lie in the open left half-plane

- If a circuit is unstable, the output will either diverge to infinity or oscillate even if the input is set to 0
- A FB amplifier circuit that is not stable is not a useful “stand alone” FB amplifier
- A FB amplifier circuit that is “close” to becoming unstable is not a useful “stand alone” amplifier (close means small variations in components will cause instability)
- An amplifier circuit that exhibits excessive ringing or gain peaking is not a useful “stand alone” amplifier

Stay Safe and Stay Healthy !

End of Lecture 11