EE 435
Lecture 11

OTA Circuits

Current Mirror Op Amps

Cascaded Amplifiers

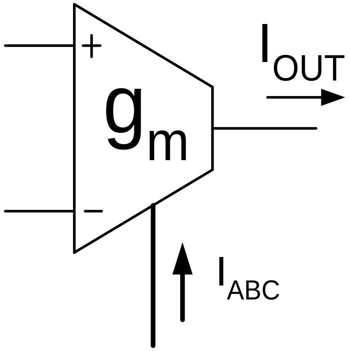
-- Stability Issues

Basic Concepts of Frequency-Dependent Feedback Systems

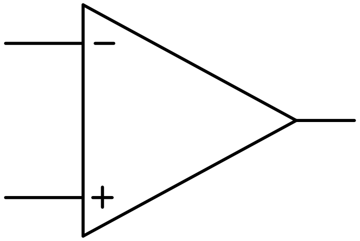
Review from last lecture:

OTA Circuits

OTA often used open loop



Recall: Op Amp almost never used open loop

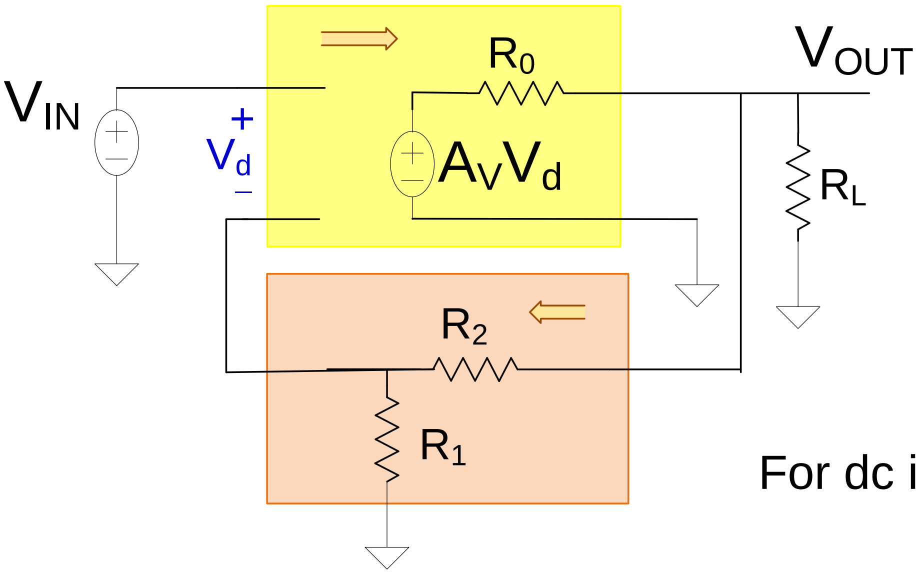


Since we just showed that the OTA is also a good high-gain op amp it seems there are conflicting statements

Challenge to students: Resolve what may appear to be conflicting statements. Will discuss this issue during the next lecture.

Review from last lecture:

Effective Gain of Operational Amplifiers



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

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

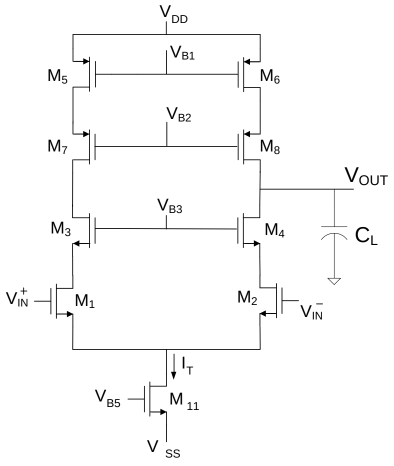
The open loop gain of an operational amplifier used in a FB configuration must include the loading of the feedback network and load resistor

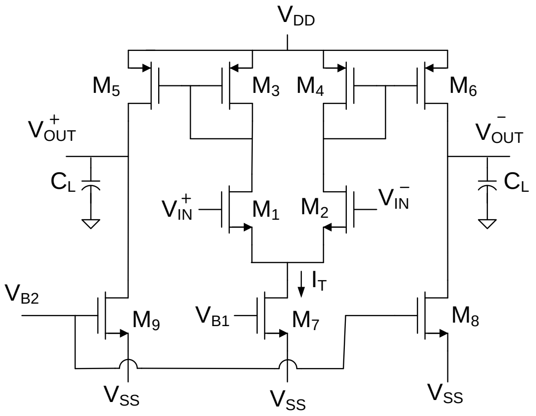
Some FB networks cause little or no loading and others can be significant

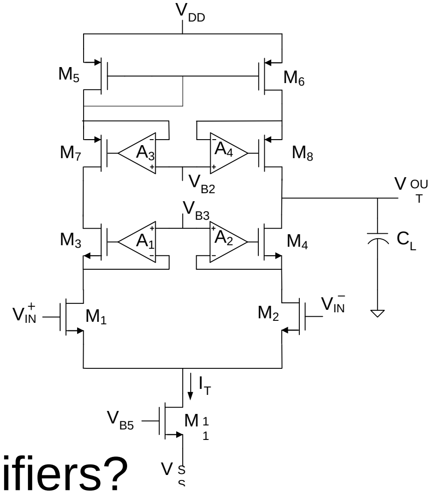
Often a buffer stage is added to the output of the op amp when used in FB applications driving “heavy” loads

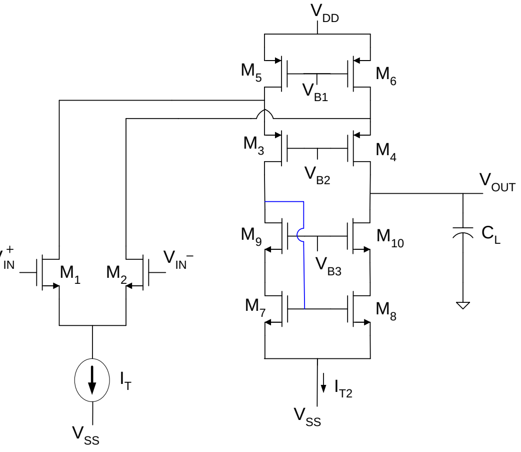
Review from last lecture:

Are these “high gain” amplifiers really high gain amplifiers?









Are these high gain voltage amplifiers?

Yes if loading ignored

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

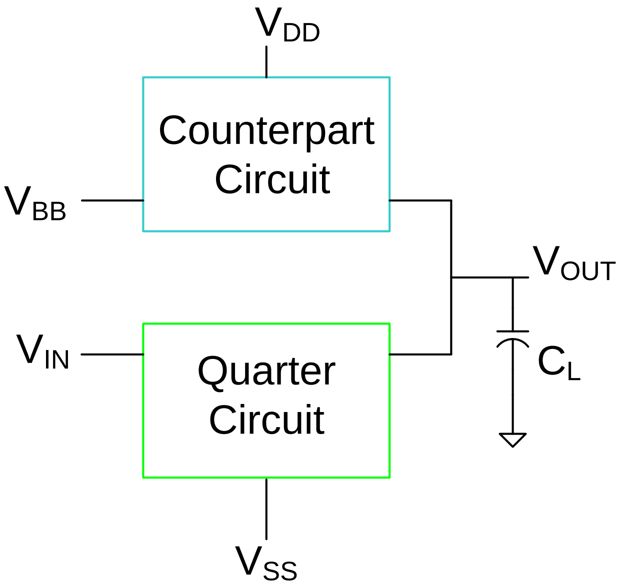
Are these high gain transresistance amplifiers?

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:

Other Methods of Gain Enhancement

Recall:



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

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

Two Strategies:

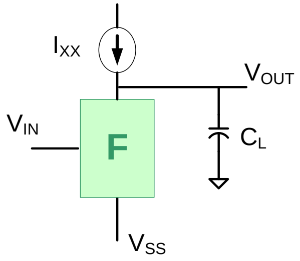
1. Decrease denominator of A_{V0}
2. Increase numerator of A_{V0}

Previous approaches focused on decreasing denominator

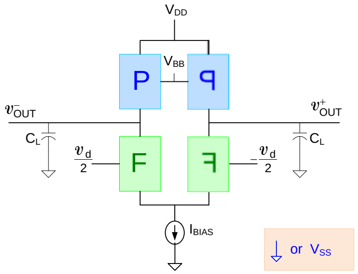
Consider now increasing numerator

Review from last lecture:

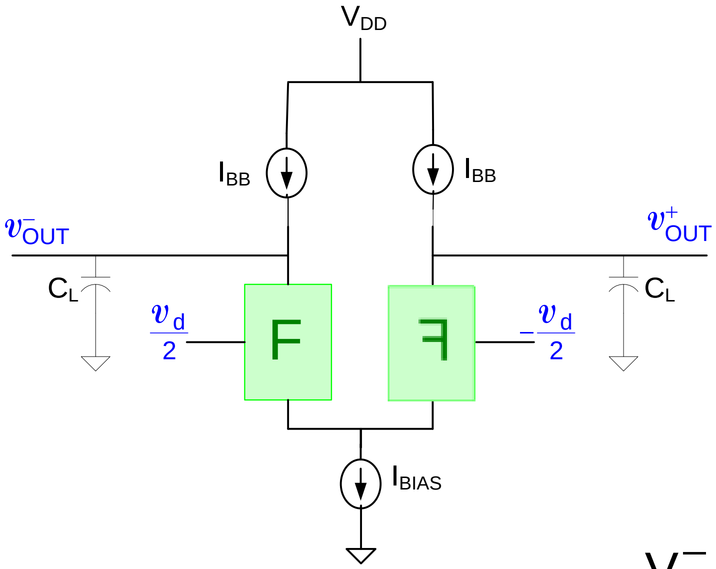
Differential input op amp directly from quarter circuit

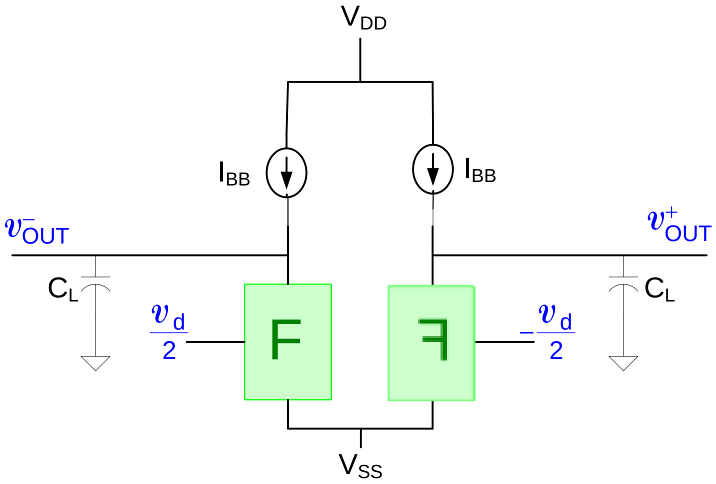


$$A_{VQC}(s) = \frac{-G_M}{sC_L + G}$$



$$A_V = \frac{V_O^-}{V_d} = \frac{-\frac{G_{M1}}{2}}{sC_L + G_1 + G_2}$$



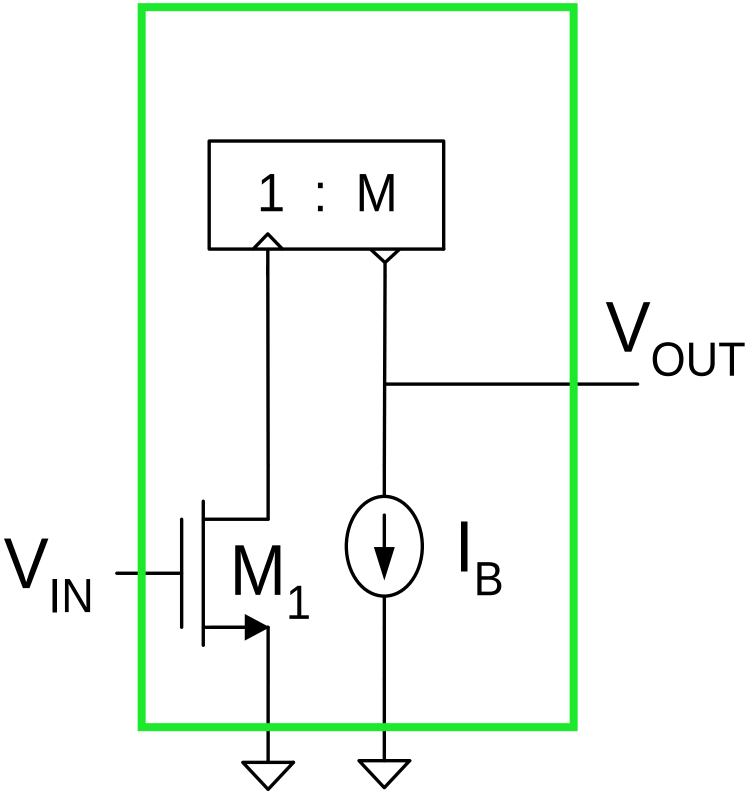


$$A_V = \frac{V_O^-}{V_d} = \frac{-\frac{G_{M1}}{2}}{sC_L + G_1 + G_{I_{BB}}}$$

$G_{I_{BB}}$ is the output conductance of I_{BB}

Review from last lecture:

g_{mEQ} Gain Enhancement Strategy



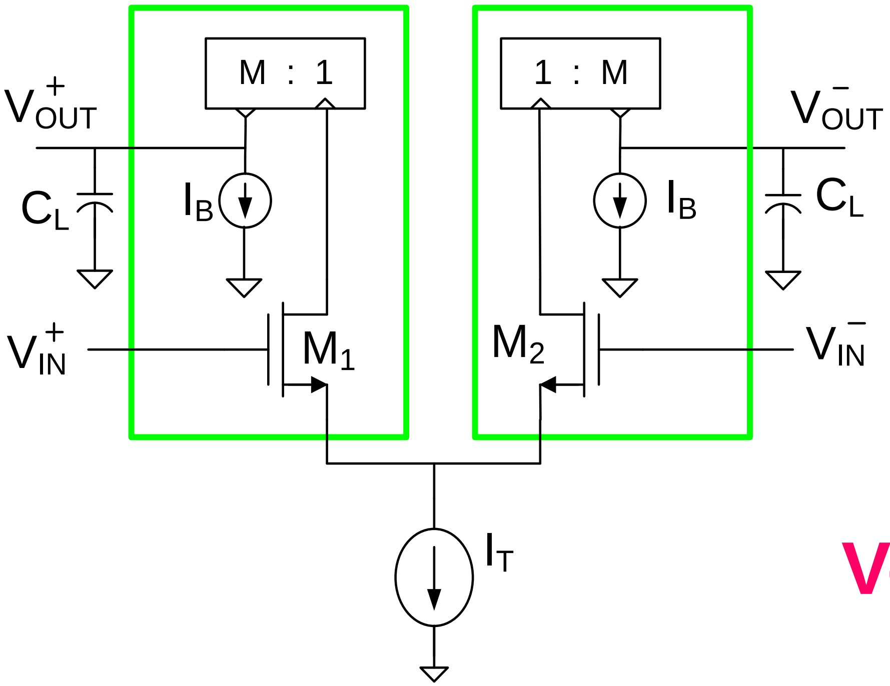
$$g_{MQC} = g_{M1}M$$

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

Redraw to absorb I_B in the quarter circuit

Review from last lecture:

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

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

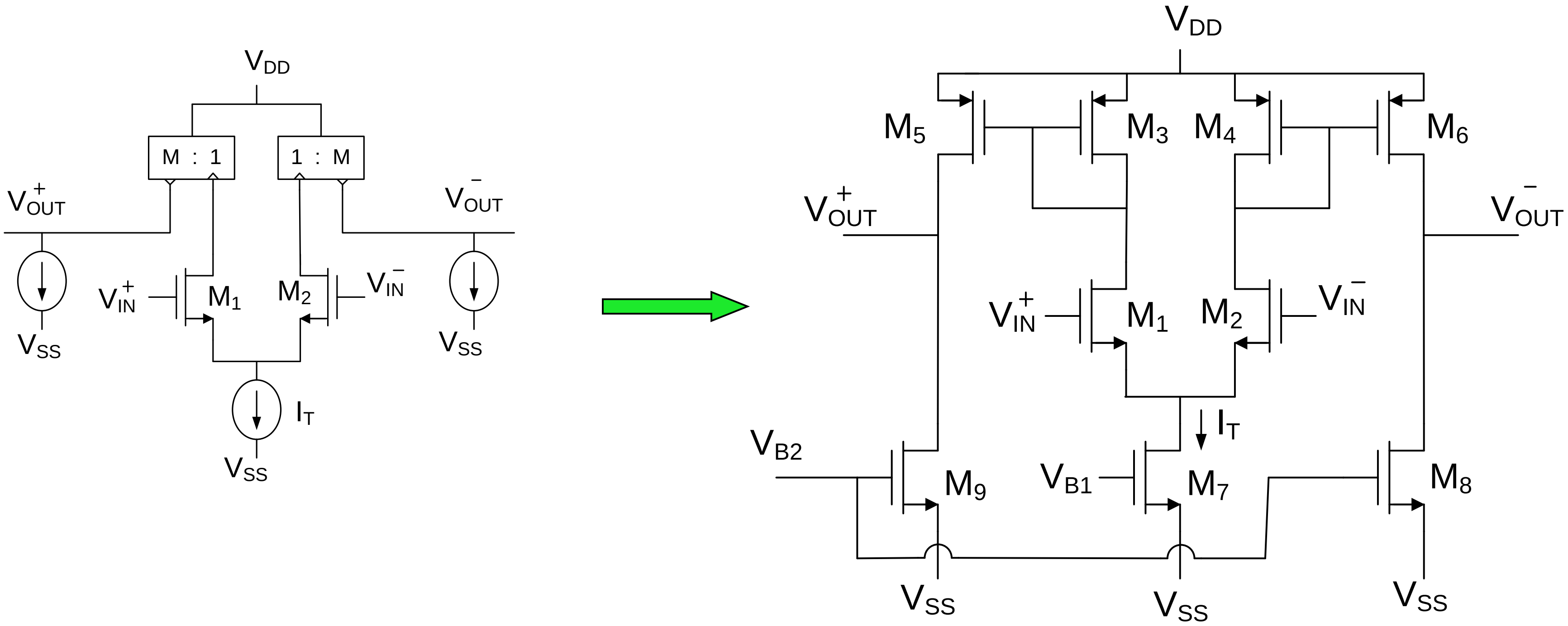
Premise: GB very good as well

Still need to generate the bias current I_B

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

Review from last lecture:

Current Mirror Op Amps



Need CMFB to establish V_{B2}

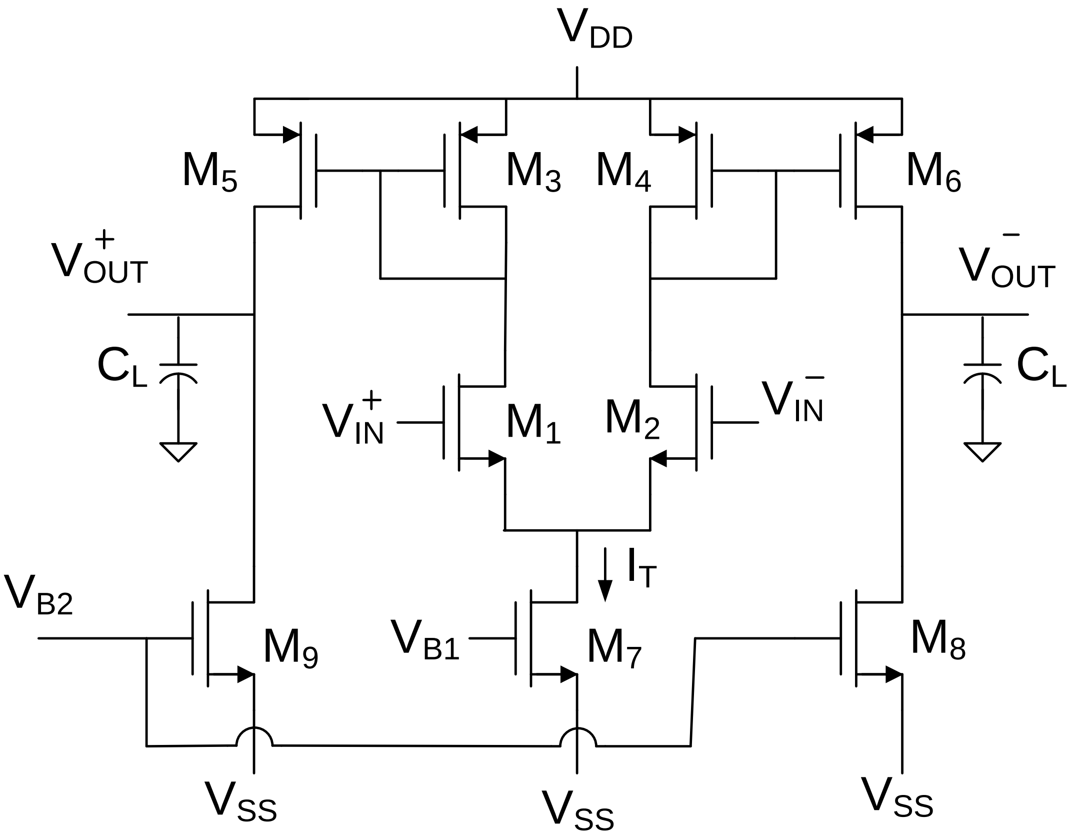
Basic Current Mirror Op Amp

Can use higher output impedance current mirrors

Can use current mirror bias to eliminate CMFB but loose one output

Review from last lecture:

Basic Current Mirror Op Amp



CMFB not shown

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

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

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

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

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

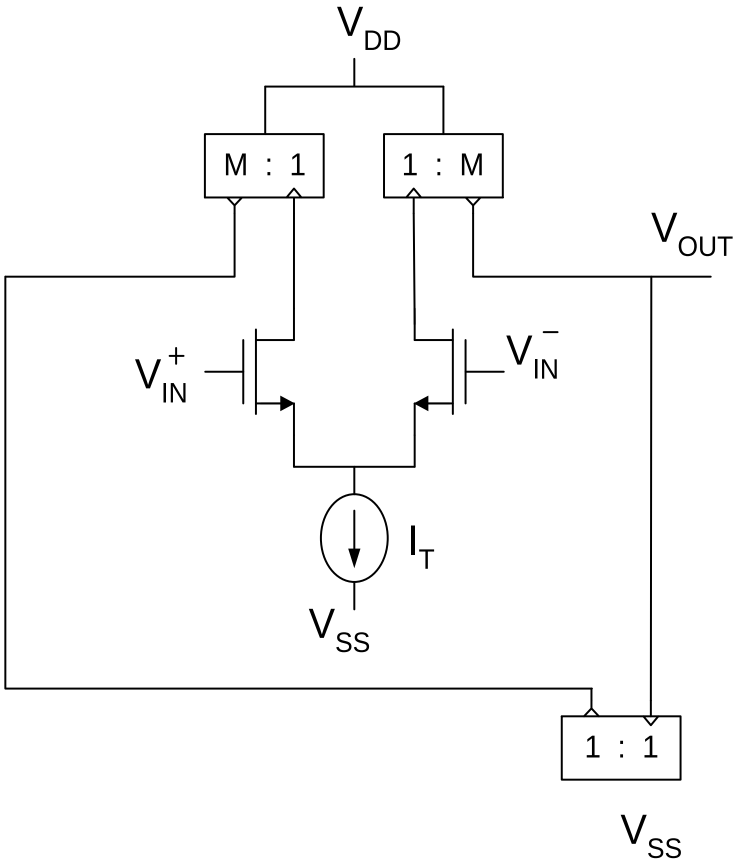
Review from last lecture:

- 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?

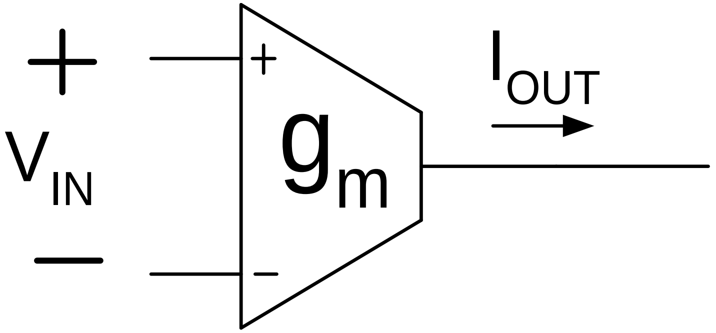
Review from last lecture:

Current Mirror Op Amp W/O CMFB



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

Often termed an OTA



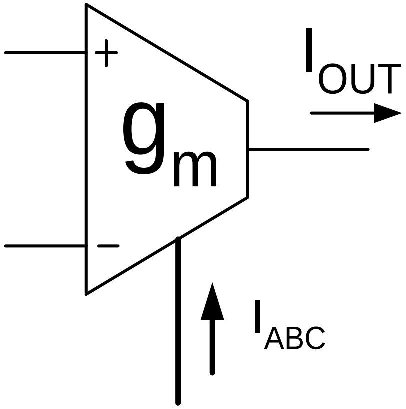
Introduced by Wheatley and Whitlinger in 1969

$$I_{OUT} = g_m V_{IN}$$

Review from last lecture:

OTA Circuits

- OTA often used open loop
- Excellent High Frequency Performance
- Gain can be made programmable with dc current
- Large or very large adjustment ranges possible



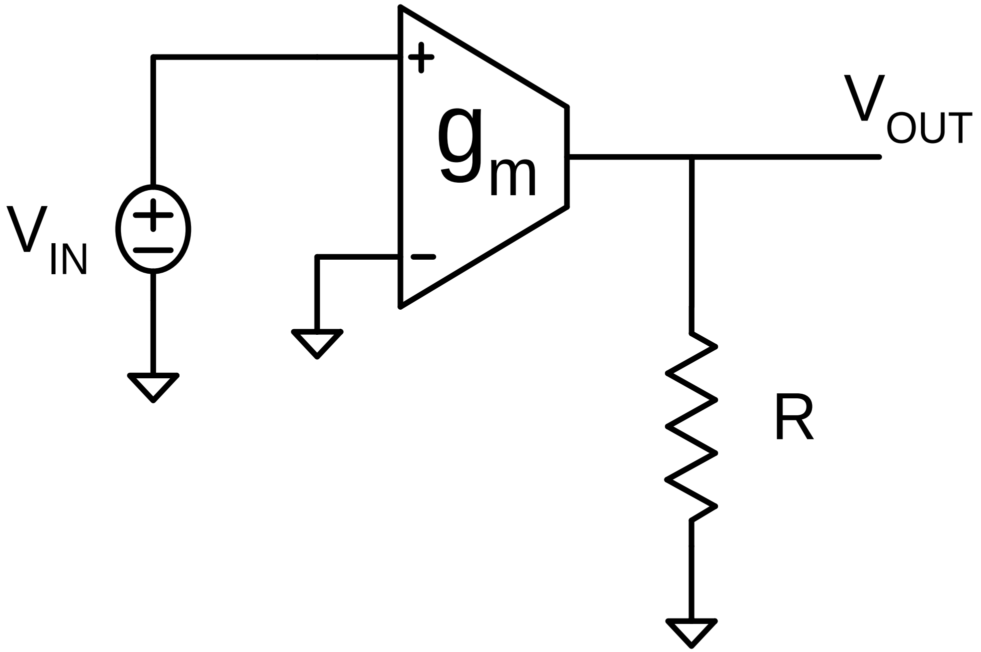
$$g_m = \begin{cases} K \bullet I_{ABC} & \text{for BJT circuits} \\ K\sqrt{I_{ABC}} & \text{for MOS circuits} \end{cases}$$

2 to 3 decades of adjustment for MOS

5 to 6 decades of adjustment for BJT

Review from last lecture:

OTA Applications



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

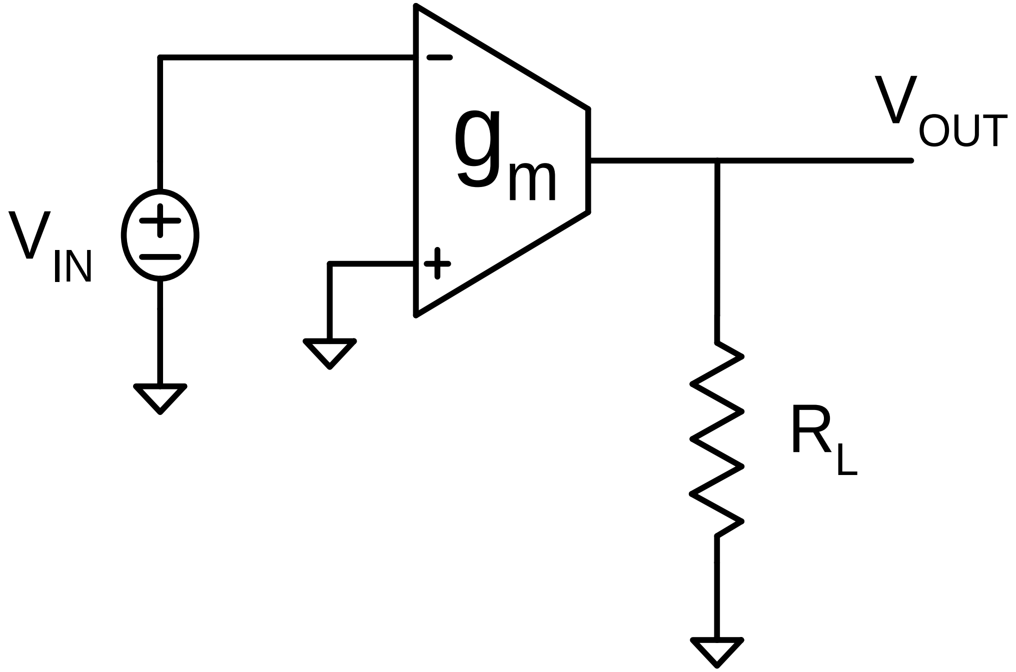
g_m is controllable with I_{ABC}

Voltage Controlled Amplifier

Note: Technically current-controlled, control variable not shown here and on following slides

Review from last lecture:

OTA Applications

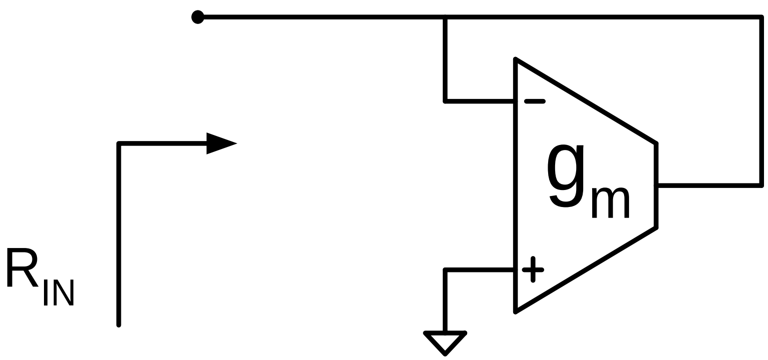


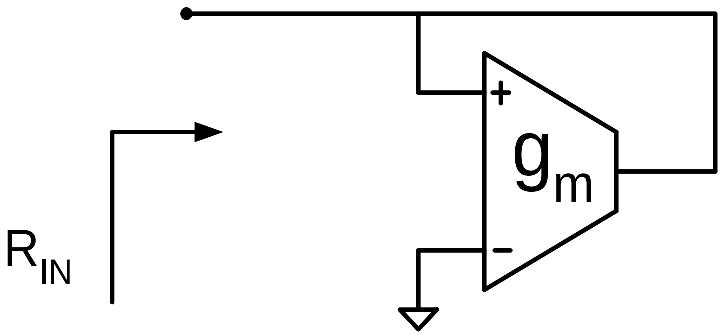
$$V_{OUT} = -g_m R \bullet V_{IN}$$

Voltage Controlled Inverting Amplifier

Review from last lecture:

OTA Applications



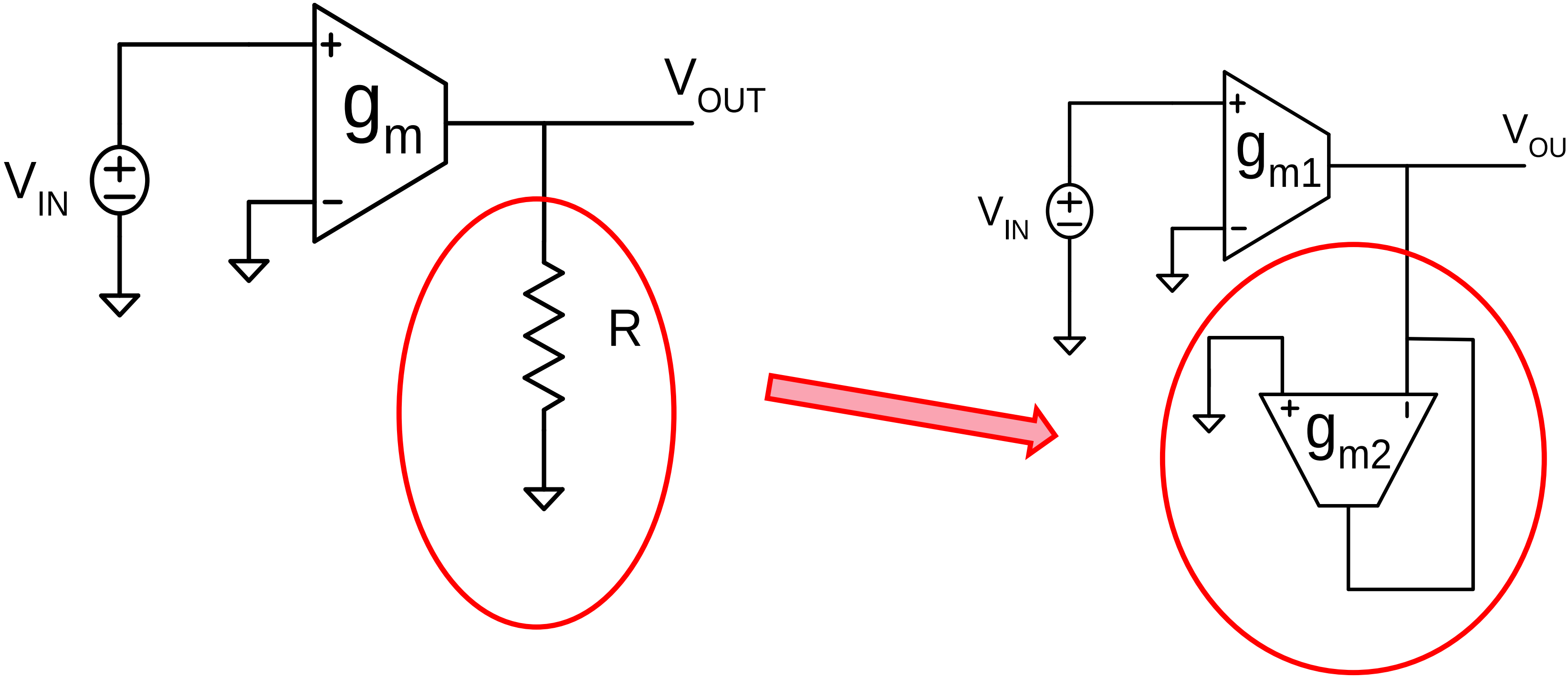


$$R_{IN} = \frac{1}{g_m}$$

$$R_{IN} = -\frac{1}{g_m}$$

Voltage Controlled Resistances

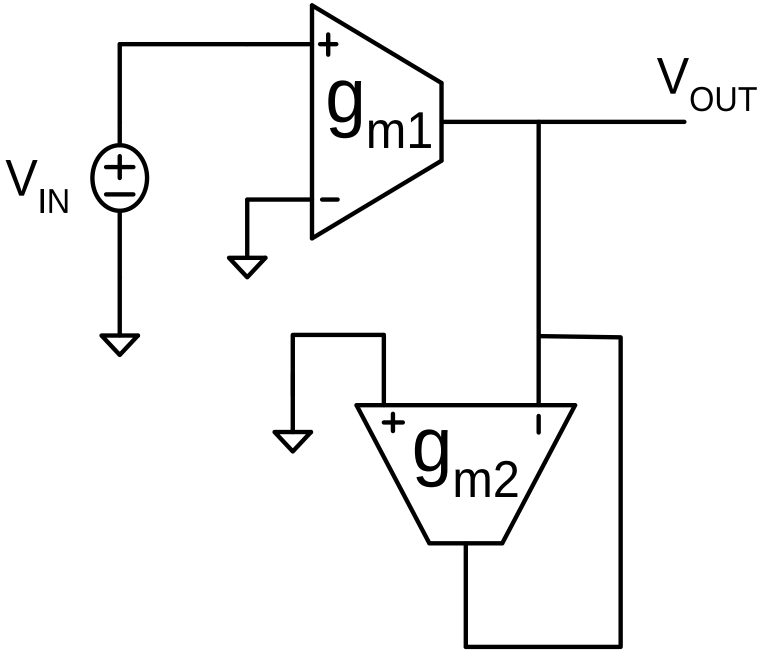
OTA Applications



Resistorless Amplifiers

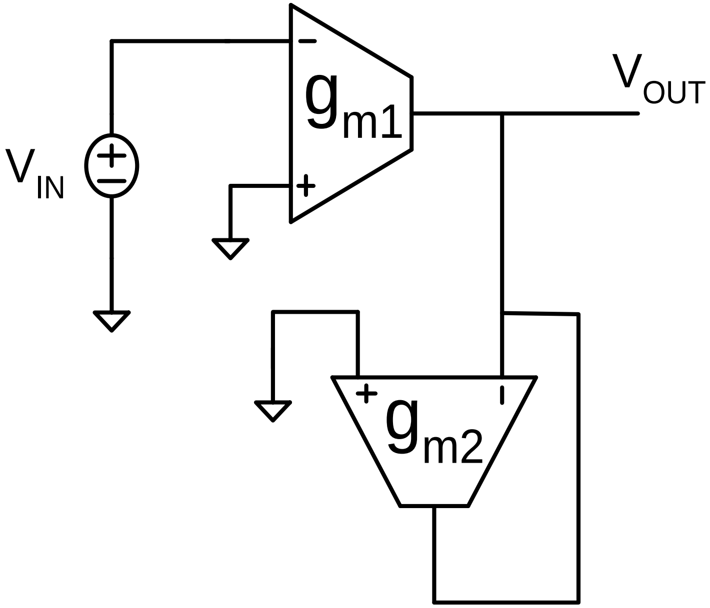
Would anyone ever do something like this ?

OTA Applications



$$V_{OUT} = \frac{g_{m1}}{g_{m2}} V_{in}$$

Noninverting Voltage Controlled Amplifier



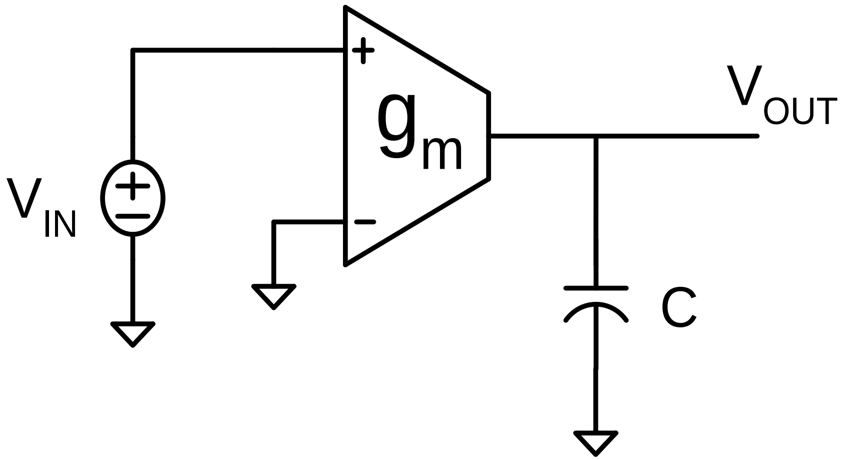
$$V_{OUT} = -\frac{g_{m1}}{g_{m2}} V_{in}$$

Inverting Voltage Controlled Amplifier

Extremely large gain adjustment is possible

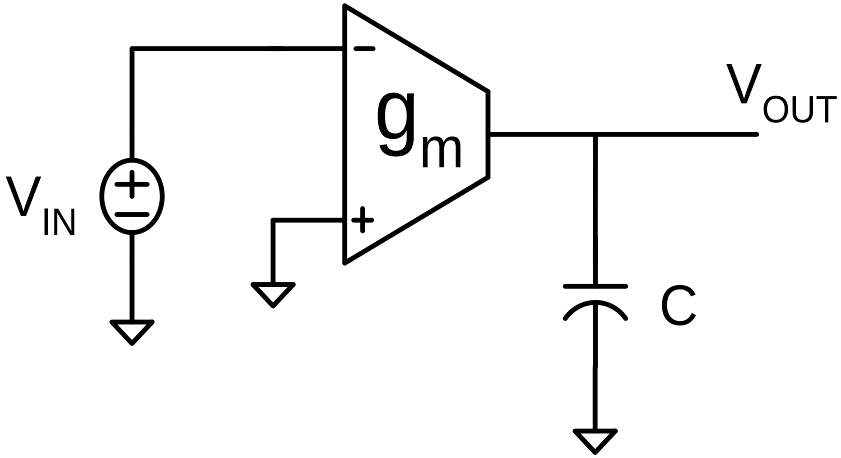
Voltage Controlled Resistorless Amplifiers

OTA Applications



$$V_{OUT} = \frac{g_m}{sC} V_{in}$$

Noninverting Voltage Controlled Integrator

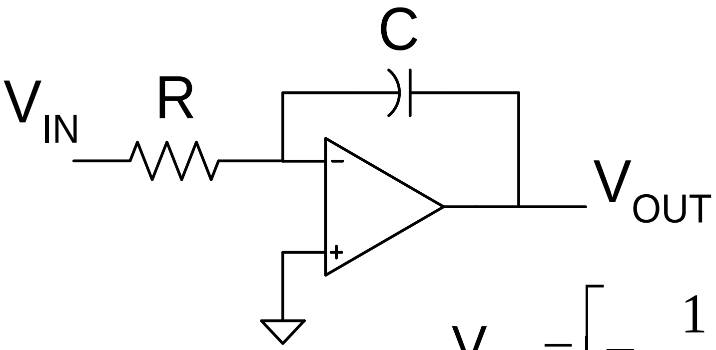


$$V_{OUT} = -\frac{g_m}{sC} V_{in}$$

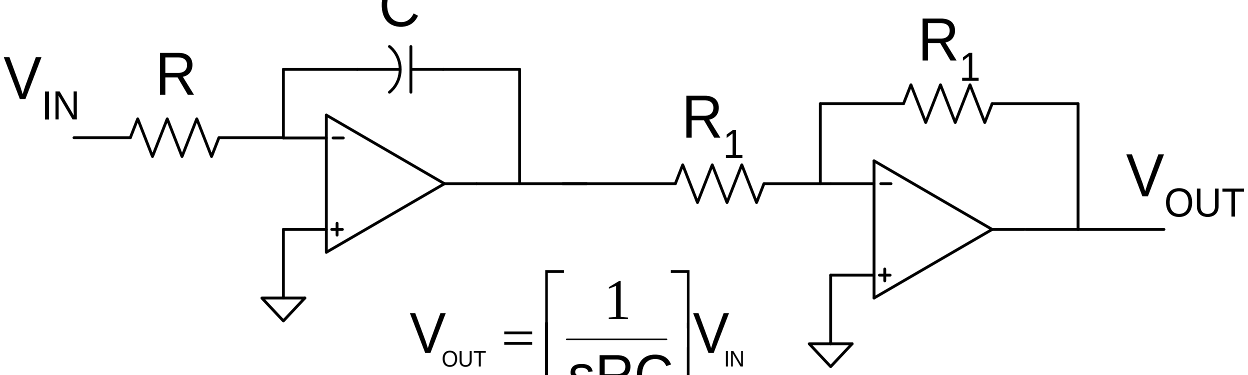
Inverting Voltage Controlled Integrator

Voltage Controlled Integrators

Comparison with Op Amp Based Integrators



$$V_{OUT} = \left[-\frac{1}{sRC} \right] V_{IN}$$



$$V_{OUT} = \left[\frac{1}{sRC} \right] V_{IN}$$

OTA-based integrators require less components and significantly less for realizing the noninverting integration function !

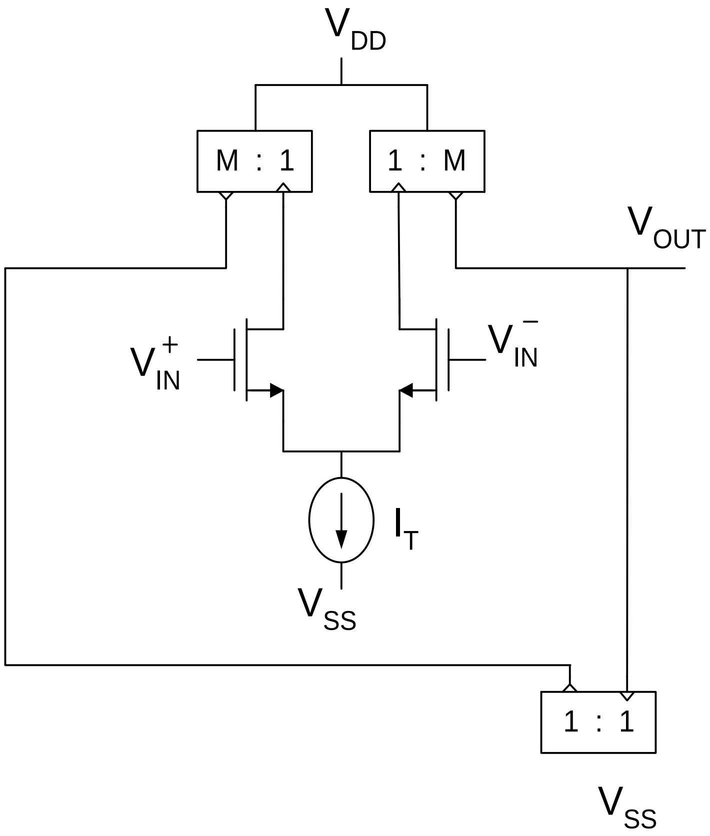
Properties of OTA-Based Circuits

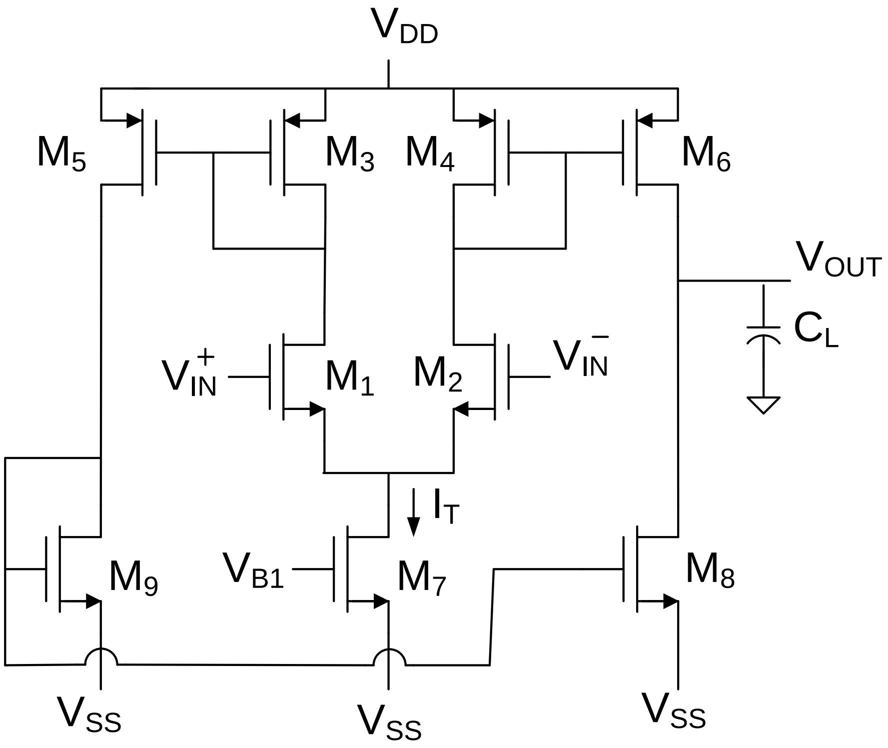
- Can realize arbitrarily complex functions
- Circuits are often simpler than what can be obtained with Op Amp counterparts
- Inherently offer excellent high frequency performance
- Can be controlled with a dc voltage or current
- Often used open-loop rather than in a feedback configuration (circuit 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

- 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?

Current Mirror Op Amp W/O CMFB





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

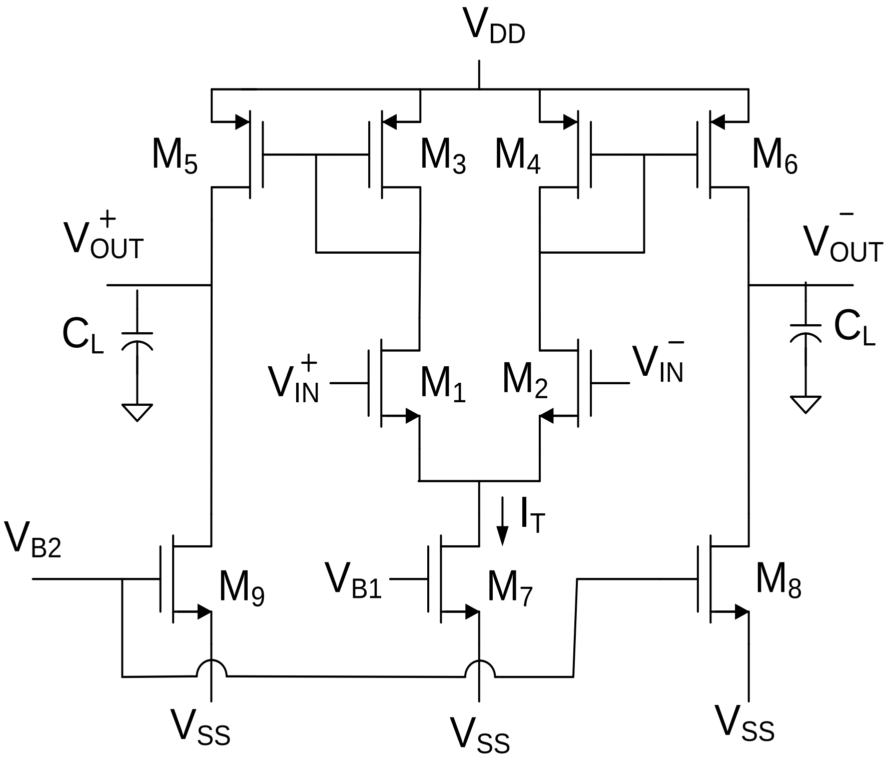
$$g_{mEQ} = Mg_{m1}$$

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

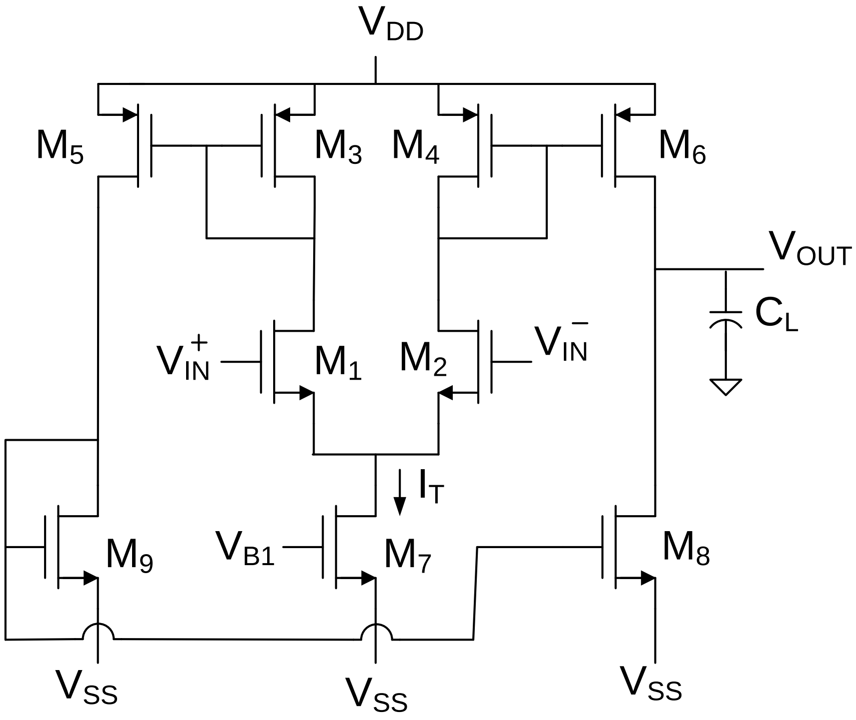
$$A_{VO} = -\frac{M \bullet g_{m1}}{g_{O6} + g_{O8}}$$

And can use higher output impedance current mirrors to decrease g_{OEQ}

SR of Current Mirror Op Amp

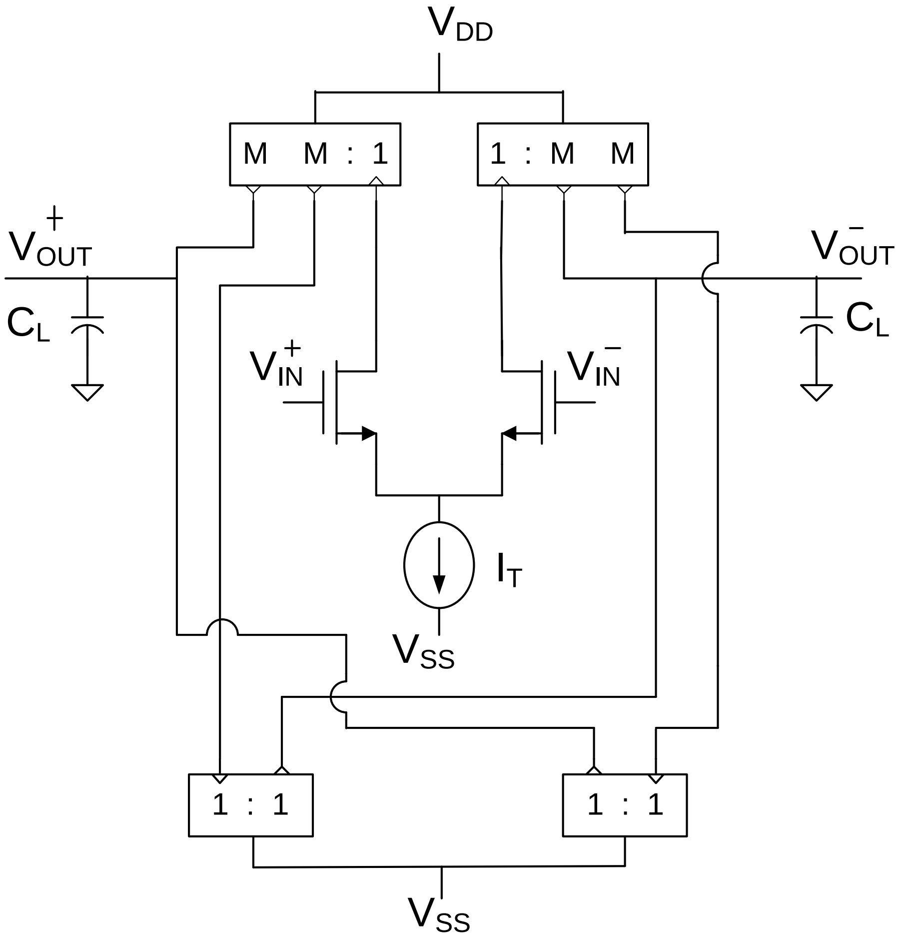


$$SR = \frac{MI_T}{2C_L}$$



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

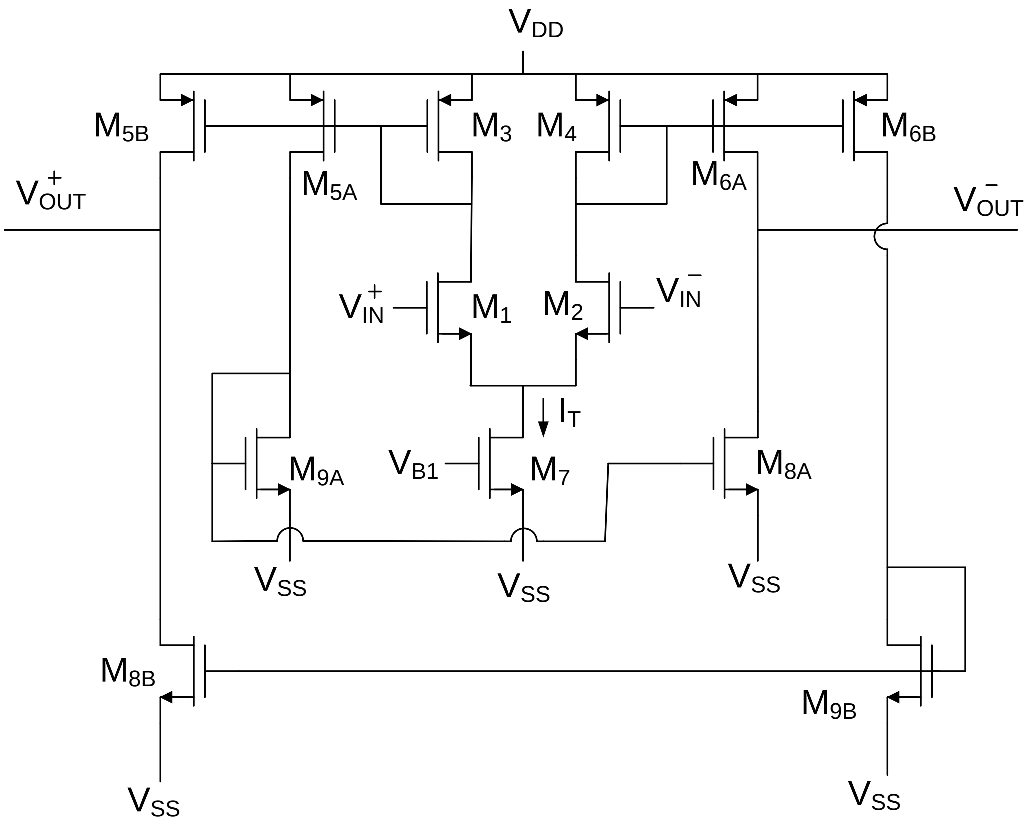
Fully Differential Current Mirror Op Amp with Improved Slew Rate



Need CMFB circuit and requires modest circuit modification to provide CMFB insertion point

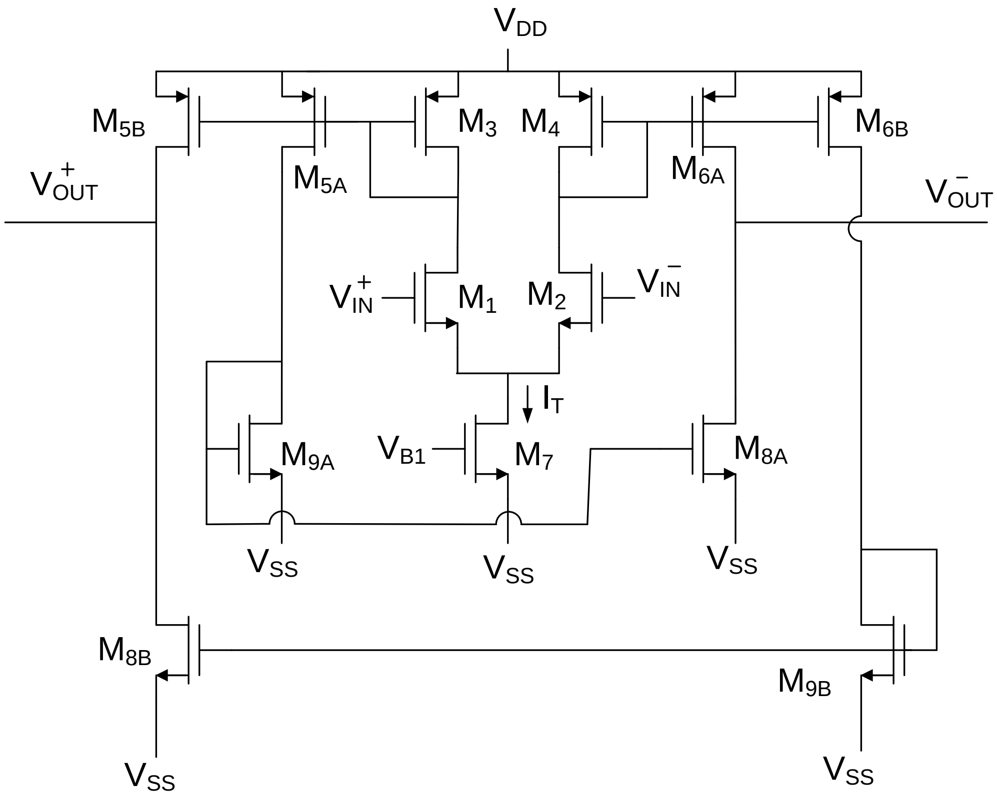
Fully Differential Current Mirror Op Amp with Improved Slew Rate

This circuit was published because of the claim for improved SR



Need CMFB circuit and requires modest circuit modification to provide CMFB insertion point

Fully Differential Current Mirror Op Amp with Improved Slew Rate



$$SR_{\text{CMOp Amp}} = \frac{M \bullet I_T}{2C_L}$$

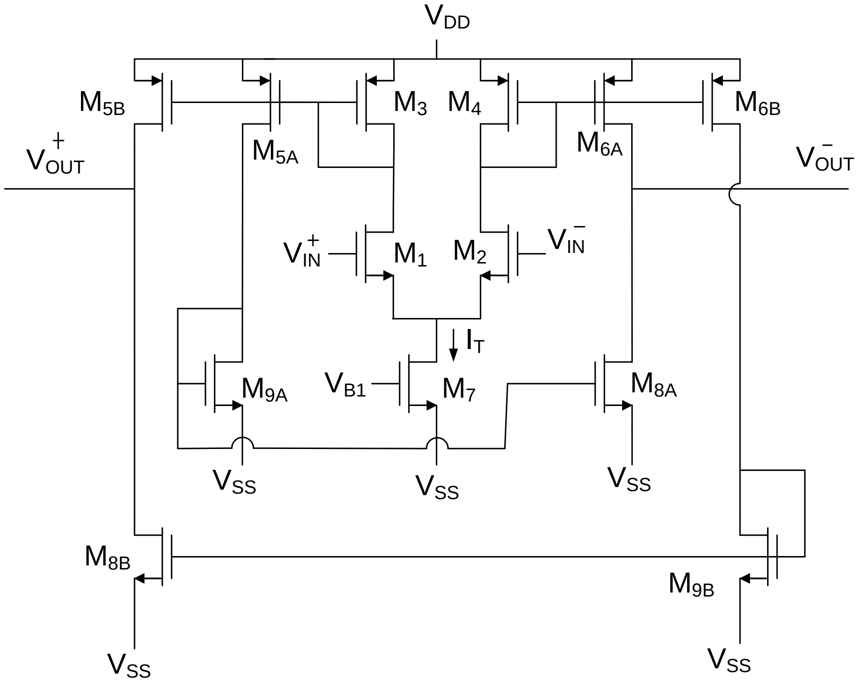
$$SR_{IMP} = \frac{MI_T}{C_L}$$

Improved a factor of 2 !

but …

Need CMFB circuit and requires modest circuit modification to provide CMFB insertion point

Fully Differential Current Mirror Op Amp with Improved Slew Rate



$$SR_{\text{CMOp Amp}} = \frac{M \bullet I_T}{2C_L}$$

$$SR_{\text{IMP}} = \frac{MI_T}{C_L}$$

Improved a factor of 2 !

but …

$$P_{\text{CMOp Amp}} = V_{DD} I_T (1+M)$$

$$P_{\text{IMP}} = V_{DD} I_T (1+2M)$$

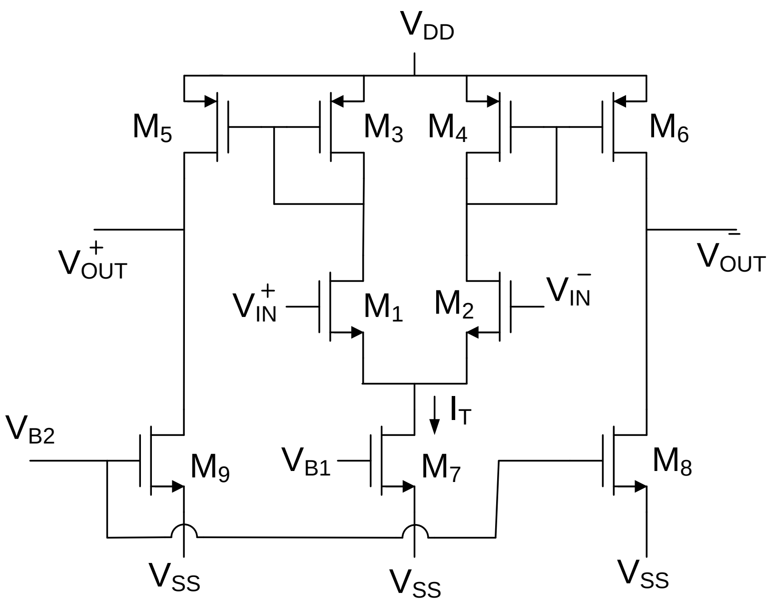
$$SR_{\text{CMOp Amp}} = \left(\frac{P}{V_{DD}C_L}\right)\left[\frac{M}{2[1+M]}\right]$$

$$SR_{\text{IMP}} = \left(\frac{P}{V_{DD}C_L}\right)\left[\frac{M}{1+2M}\right]$$

SR actually about the same for “improved SR circuit” and basic OTA

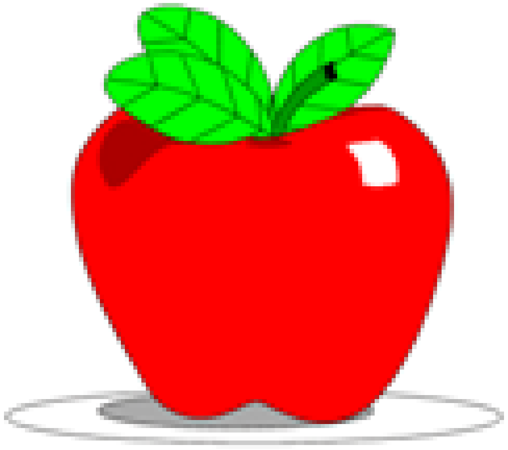
Comparison of Current-Mirror Op Amps with Previous Structures

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



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

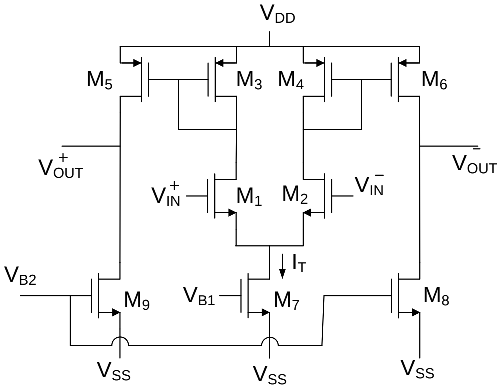
$$M = \frac{W_6 L_4}{W_4 L_6}$$



Ask the apple comparison question !

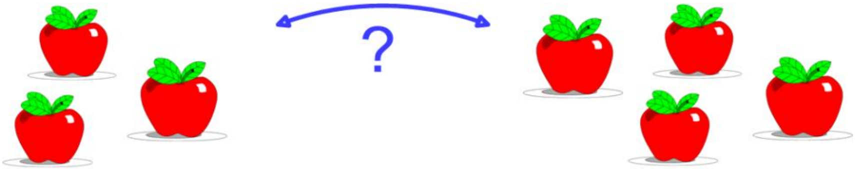
Comparison of Current-Mirror Op Amps with Previous Structures

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



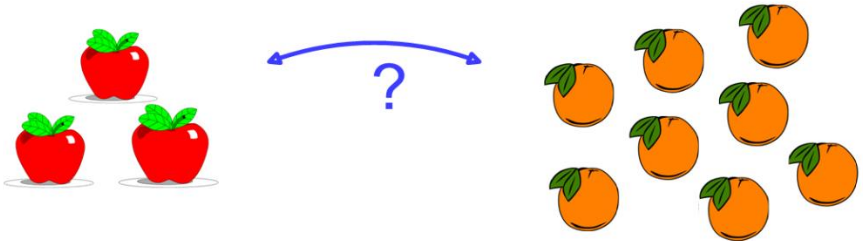
$$A_{VO} = -\frac{M \bullet \frac{g_{m1}}{2}}{g_{O6} + g_{O8}}$$

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



Are we comparing Apples with Apples?

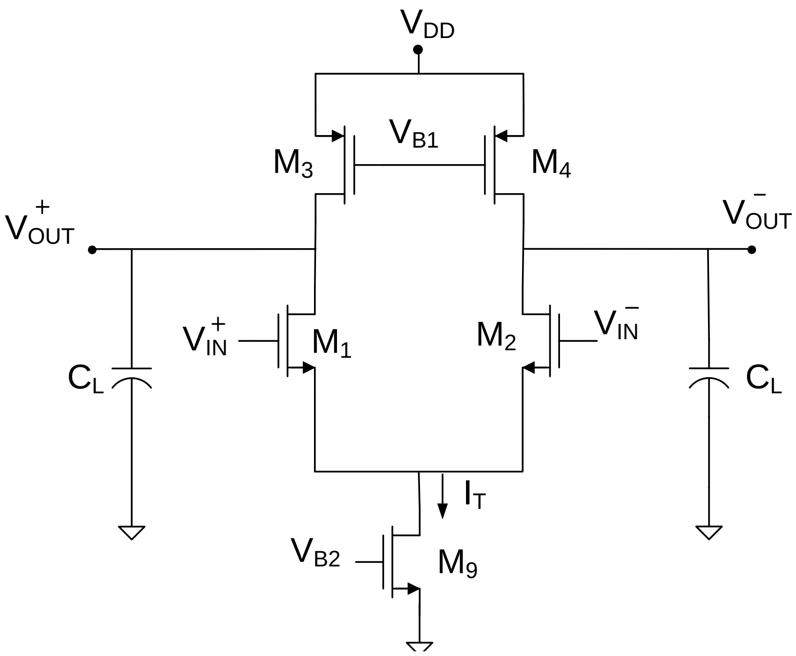
- In the small-signal parameter domain?
- In the practical parameter domain?
- Does it matter if we are making a comparison?



Reference Op Amp

Consider single-ended output performance :

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



$$A_{VO} = \frac{1}{2}\frac{g_{m1}}{g_{O1} + g_{O3}}$$

$$A_{V0} = \left[\frac{1}{\lambda_1 + \lambda_3}\right]\left(\frac{1}{V_{EB1}}\right)$$

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

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

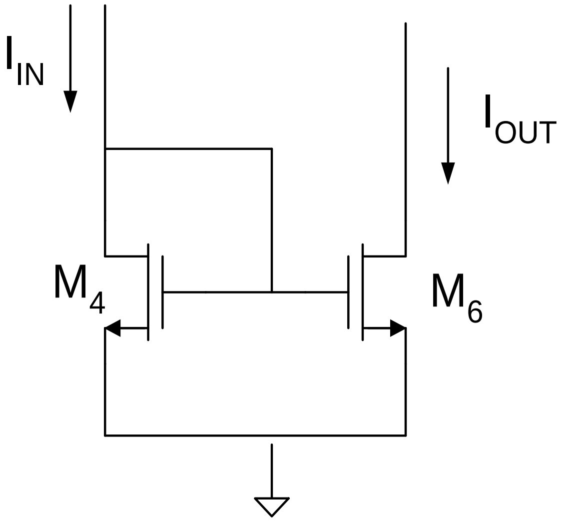
$$SR = \frac{I_T}{2C_L}$$

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

Comparison of Current-Mirror Op Amps with Previous Structures

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

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



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

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

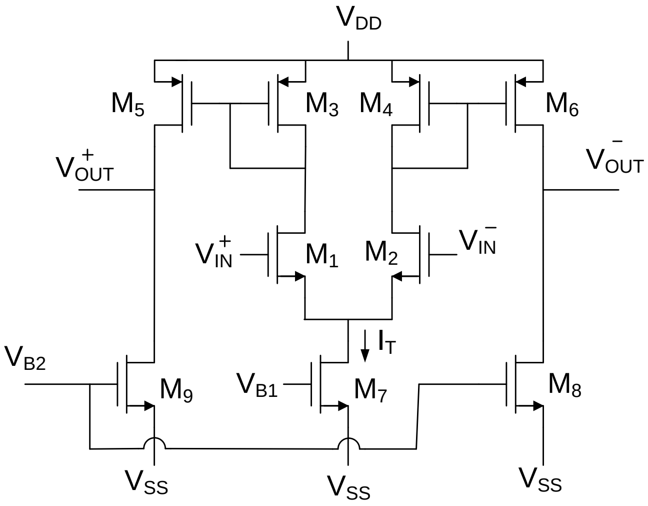
$$A_{VO} = -\frac{\frac{g_{m6}}{g_{m4}} \bullet \frac{g_{m1}}{2}}{g_{O6} + g_{O8}}$$

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 ?

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



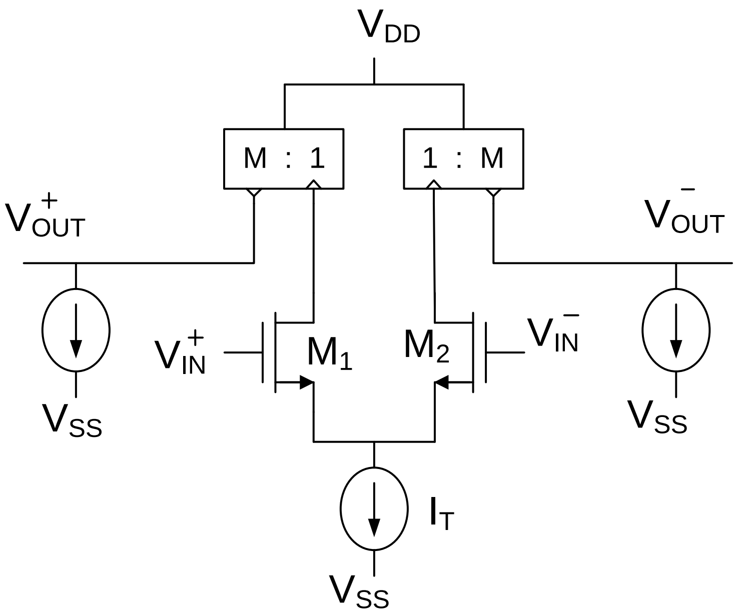
Consider how the gain appears in the practical parameter domain

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

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 ?



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

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

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

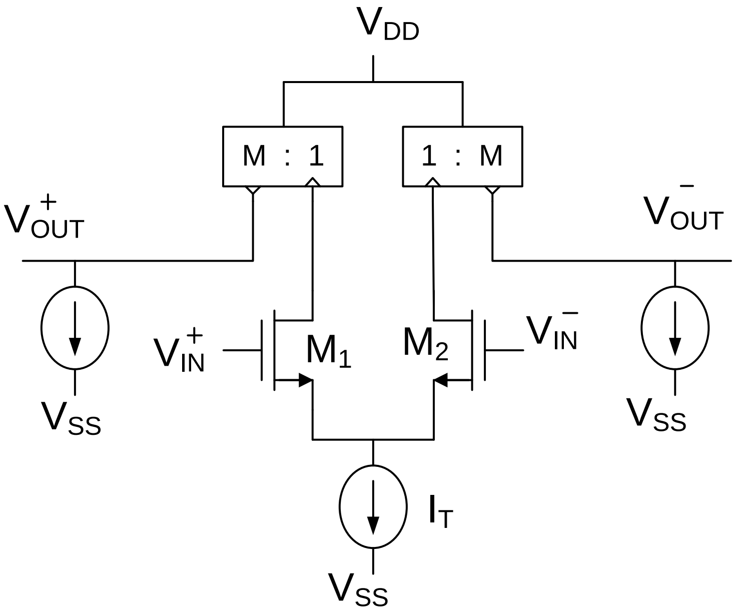
GB for Telescopic Cascode and Ref Op Amp !

GB efficiency decreased 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 …

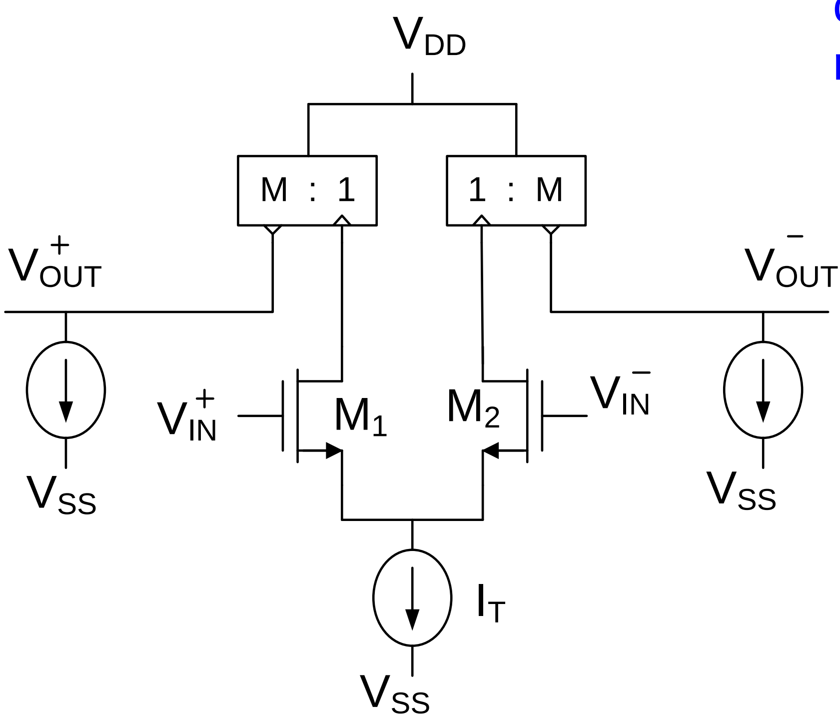
$$P = V_{DD} I_T (1+M)$$

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

$$SR_{\text{Ref OpAmp}} = \frac{P}{2V_{DD}C_L}$$

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?

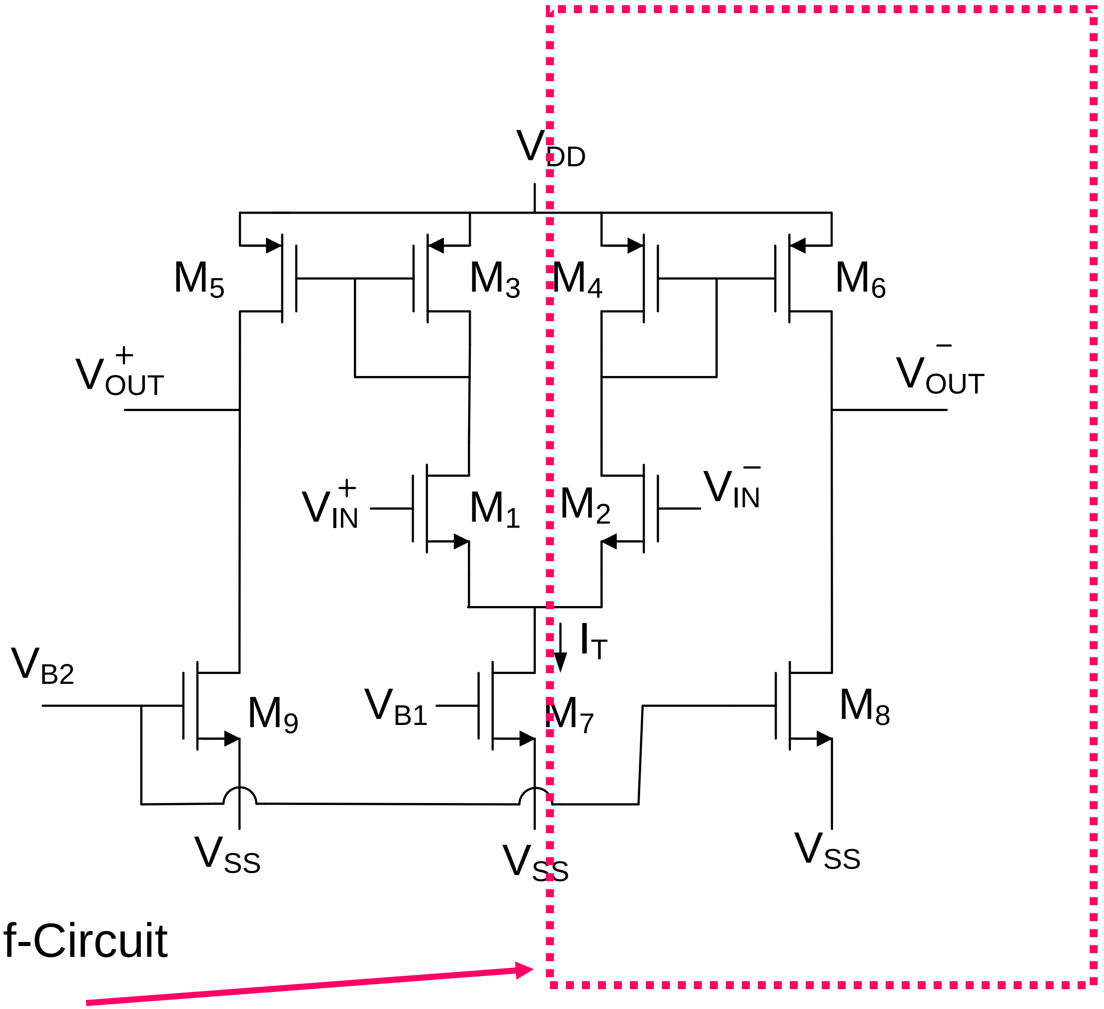
Perceived improvements may appear to be very significant

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

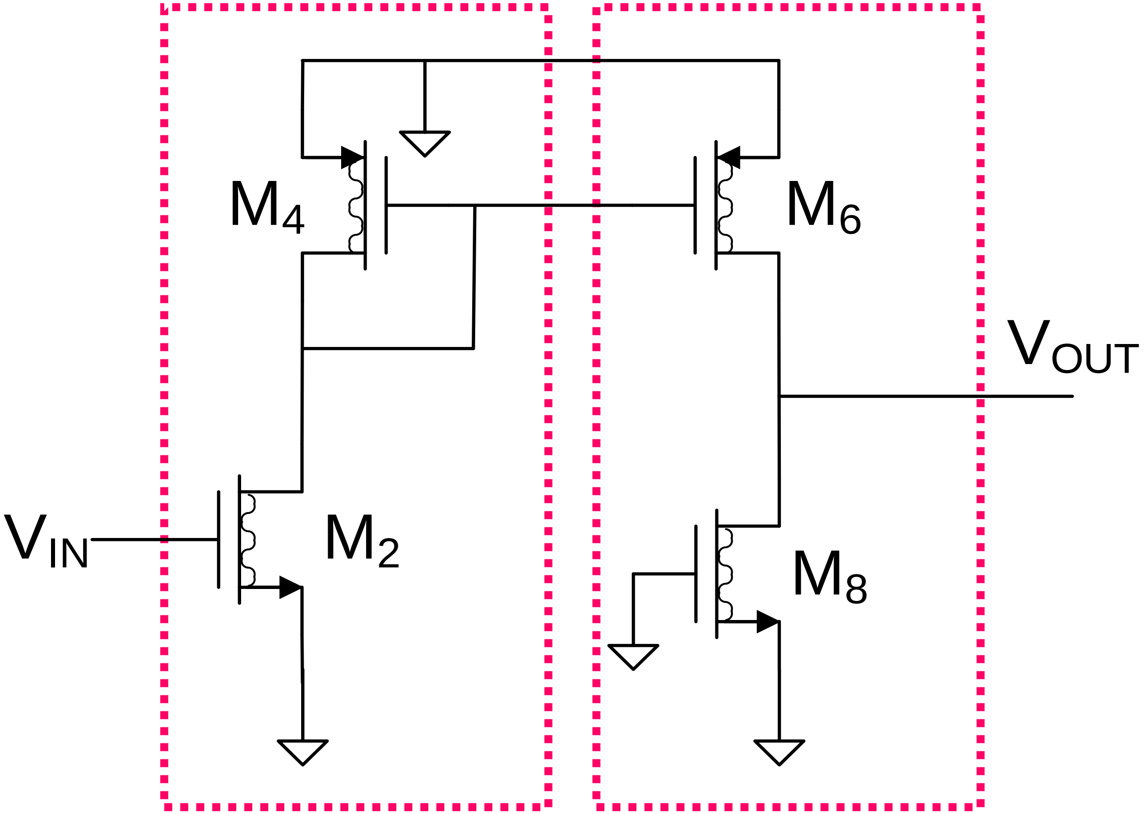
Current-Mirror Op Amps – Another Perspective !



Differential Half-Circuit

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

Current-Mirror Op Amps – Another Perspective !



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

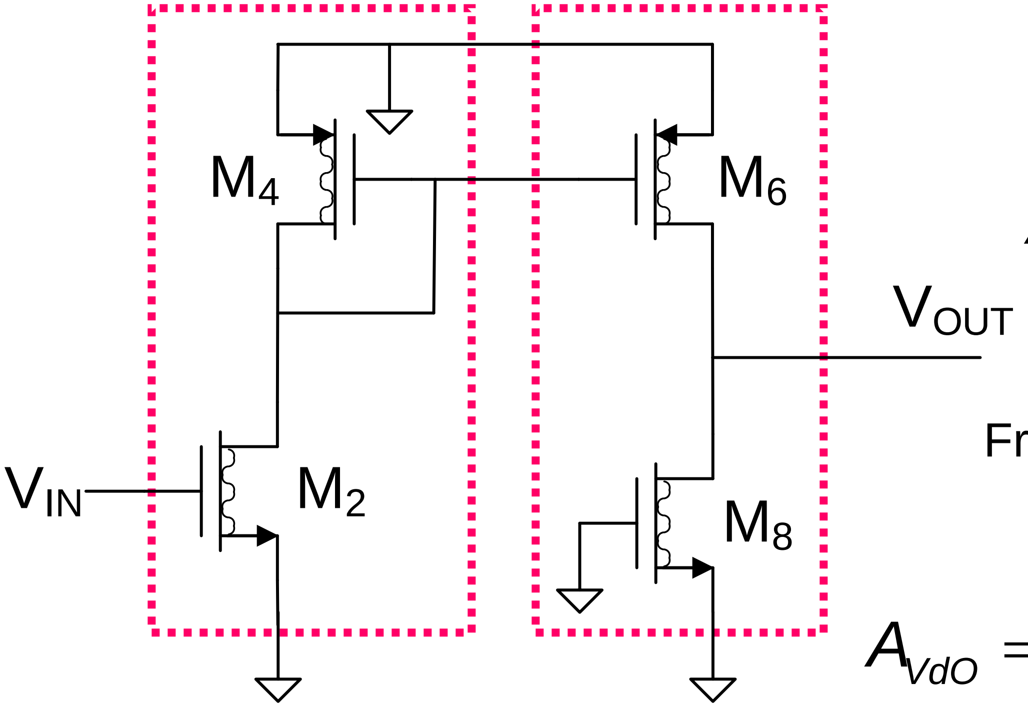
Differential Half-Circuit

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



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

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

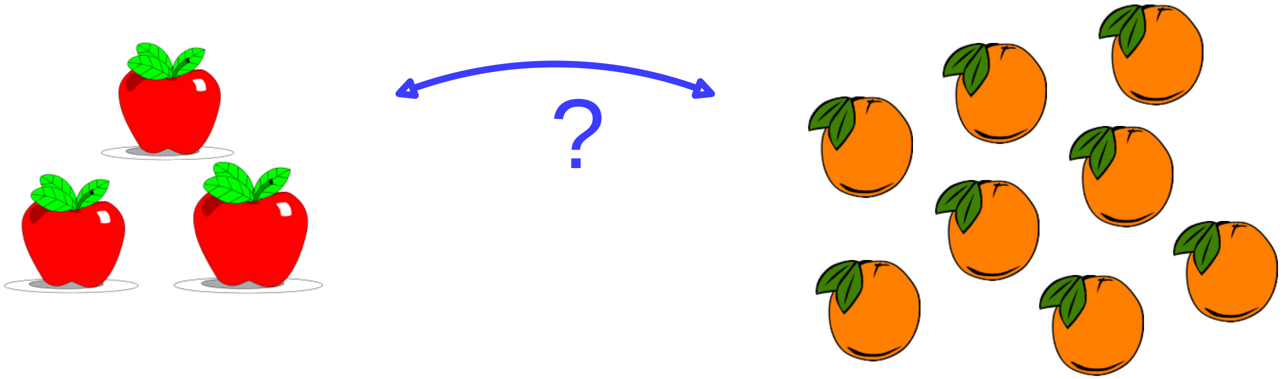
From Current Mirror Analysis :

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

Cascade of n-channel common source amplifier
with 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

- Current-mirror op amp will work in feedback applications as well but performance would often be better with 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

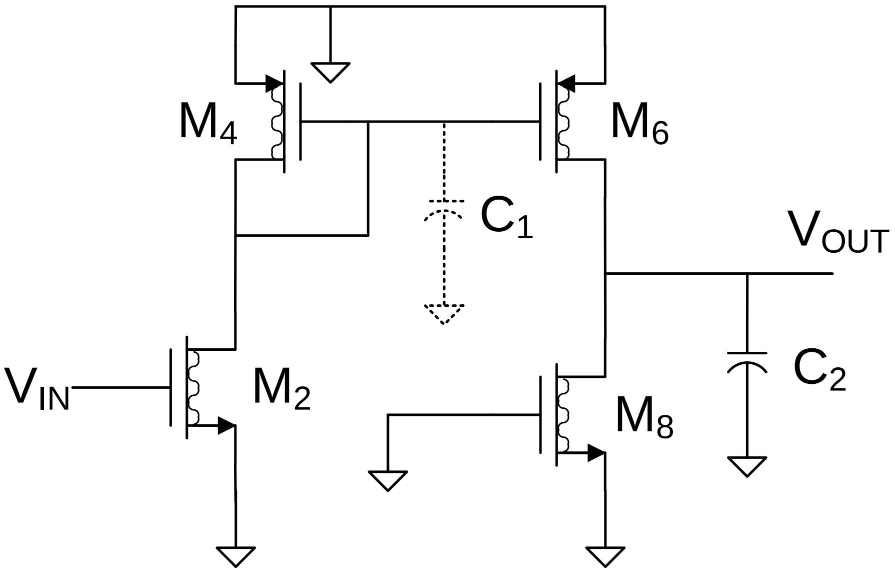
- The poles of a circuit are absolute: That is, they are independent of where the excitation is applied or where the response is taken provided the dead networks are the same!

- 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 !

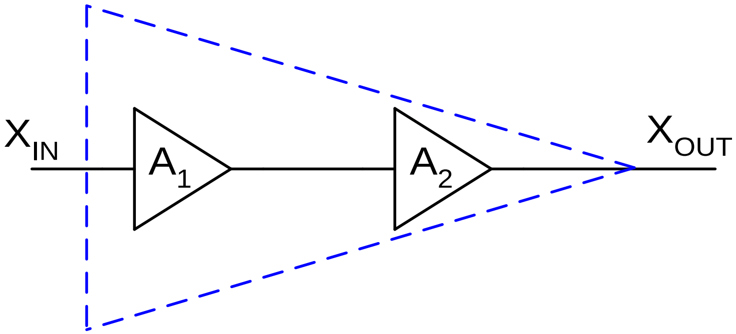
Where we are at:

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

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

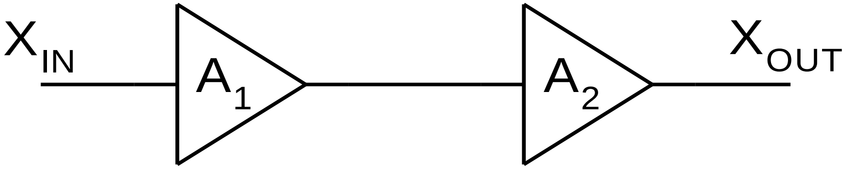
For the current mirror op amp

$$A_1 << A_2$$

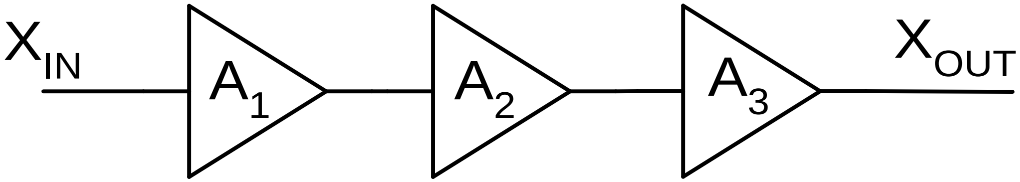
Could the gain be increased by cascading two or more amplifiers if the amplifiers had a higher gain?

Increasing Gain by Cascading

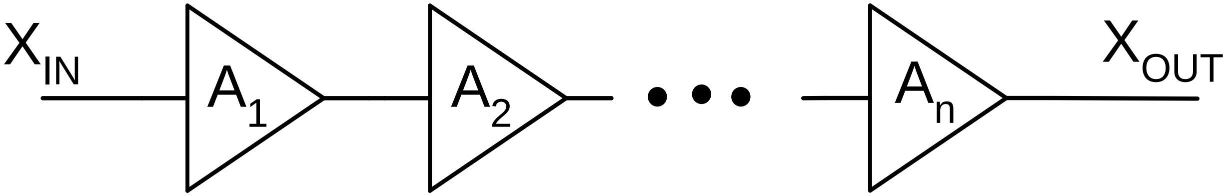
Provided the stages are non-interacting



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



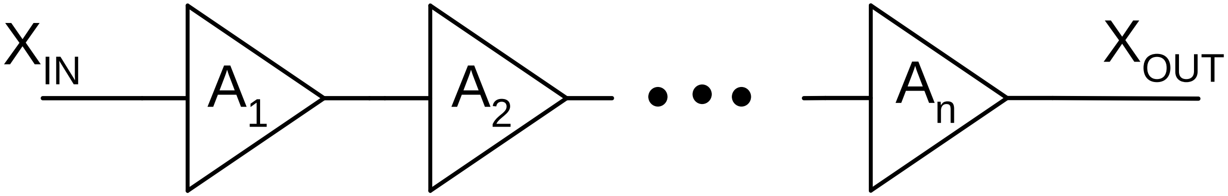
$$\frac{X_{OUT}}{X_{IN}} = A_1 A_2 A_3$$



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

Gain can be easily increased to almost any desired level !

Increasing Gain by Cascading



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

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

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

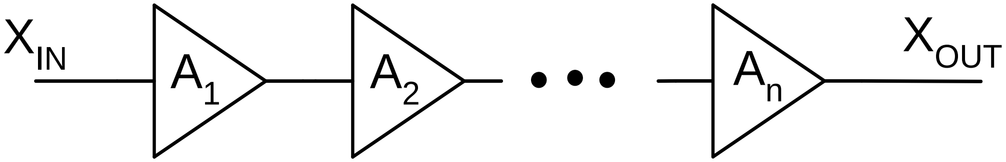
A_{0k} is the dc gain of stage k

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

Thus

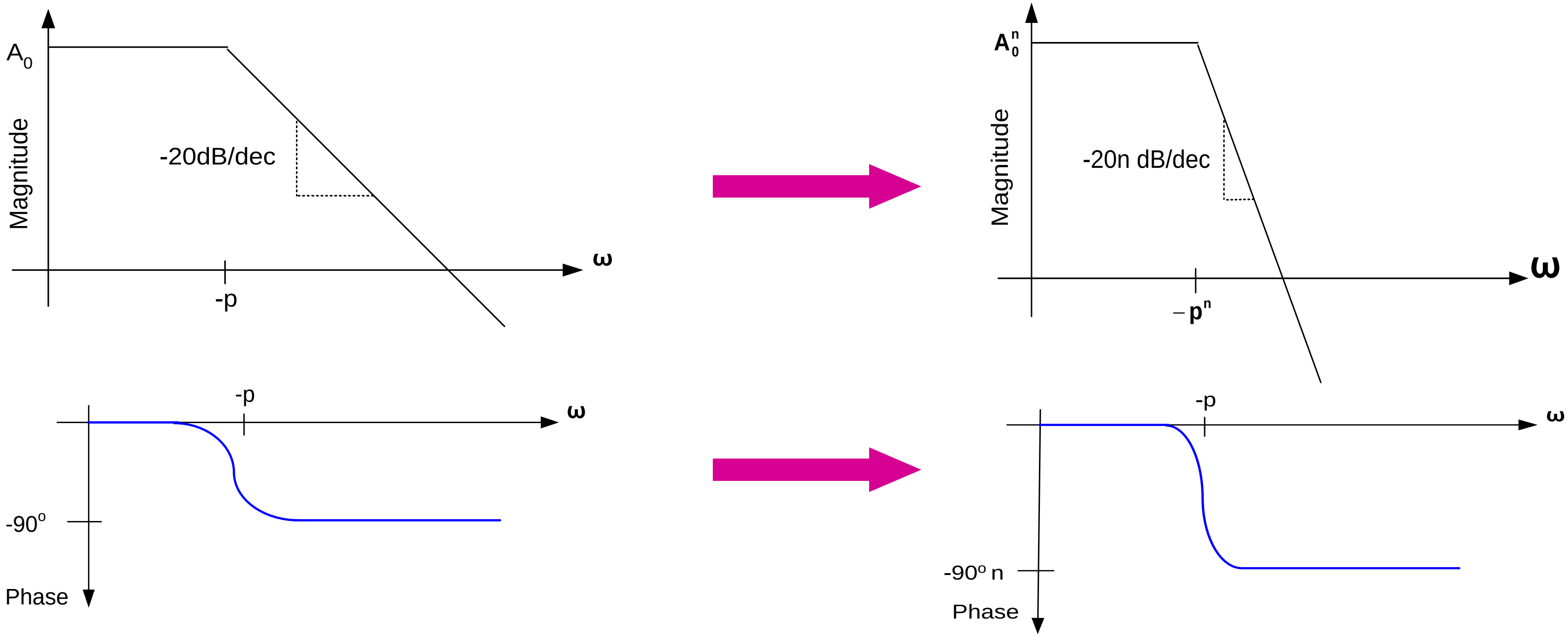
$$\frac{X_{OUT}}{X_{IN}} = A = \frac{\prod_{i=1}^{n} A_{0i}}{\prod_{k=1}^{n}\left(\frac{s}{\tilde{p}_k} + 1\right)}$$

Increasing Gain by Cascading



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

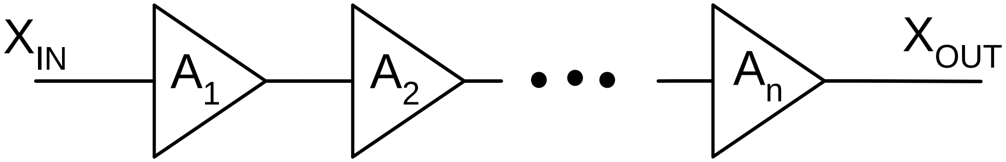
Assume for case of an example that all stages are identical with $A_{0k}=A_0$ and $\tilde{p}_k = \tilde{p} = -p$



(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

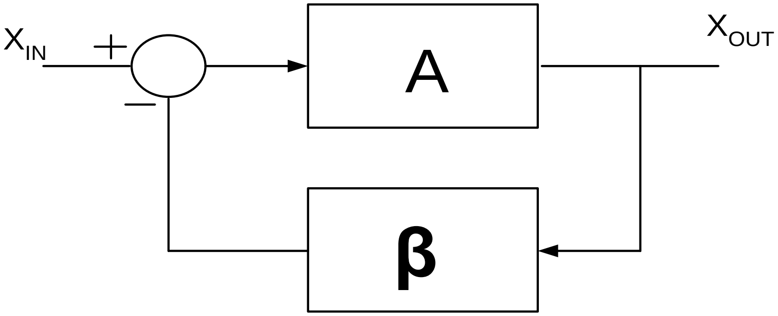


$$\frac{X_{OUT}}{X_{IN}} = A = \frac{\prod_{i=1}^{n} A_{0i}}{\prod_{k=1}^{n}\left(\frac{s}{\tilde{p}_k}+1\right)}$$

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?



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

Stay Safe and Stay Healthy !

End of Lecture 11