EE 435

Lecture 9:

High-Gain Single-Stage Op Amps

- Regulated Folded Cascode Op Amp
- Current-mirror op amps
- OTA Applications

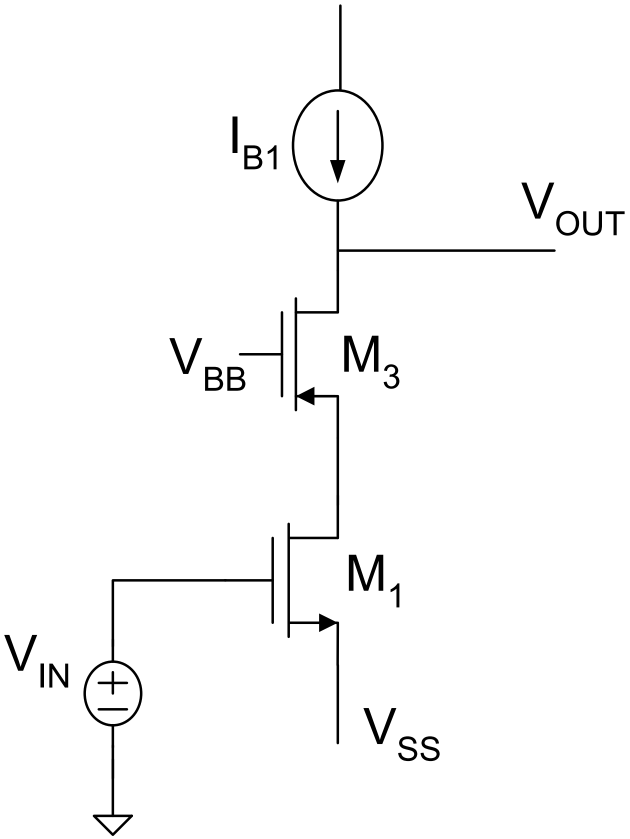
Textbook reference:

Some of the material we have been discussing appears in Chapter 3, some in Chapter 5, and some in Chapter 6 of the Martin and Johns text

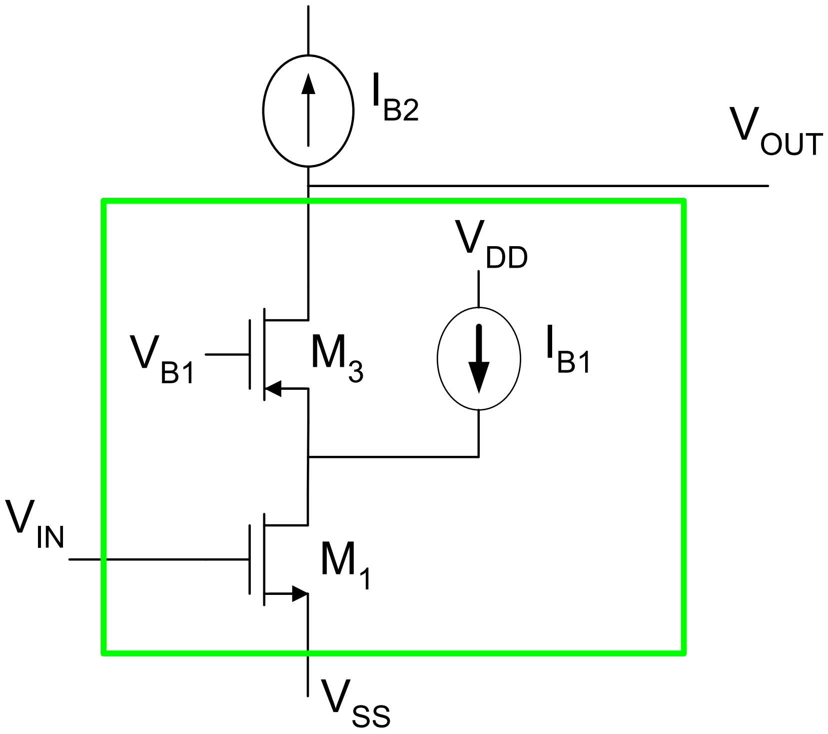
In particular, the telescopic and folded cascode structures are referred to as advanced op amps and appear in later chapters of the text

Review from Last Time

What circuit is this?



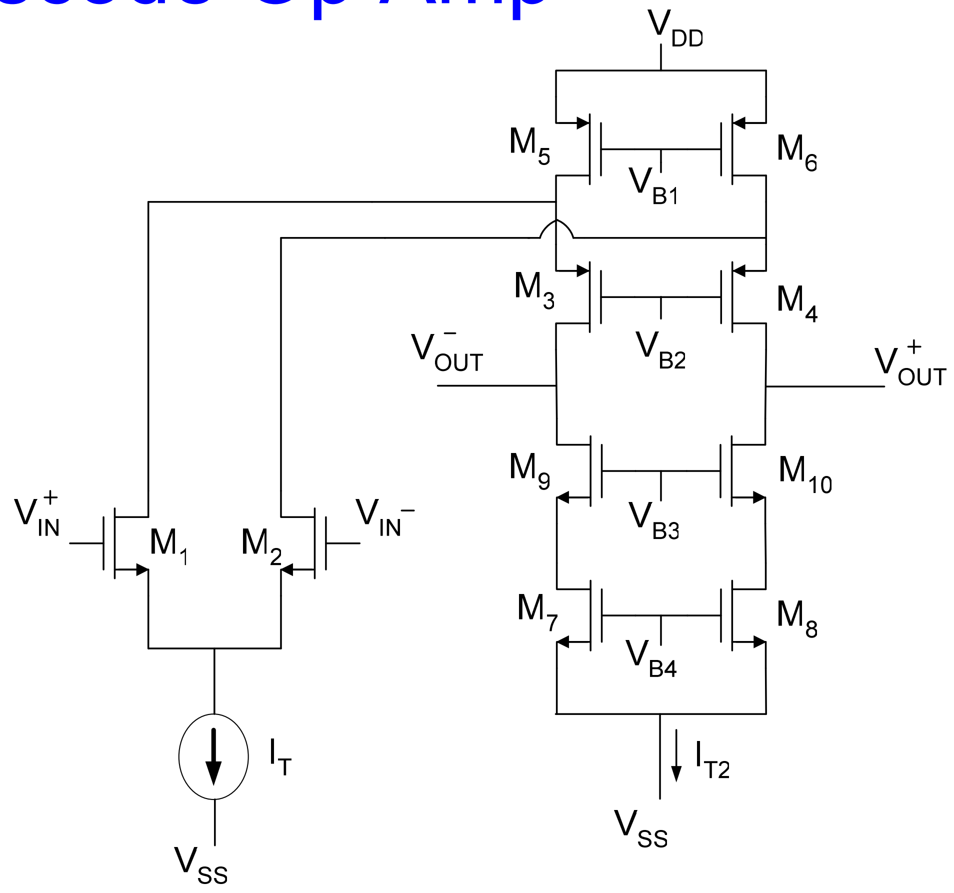
Folded Cascode Amplifier



Biased Folded Cascode

Review from Last Time

Folded Cascode Op Amp



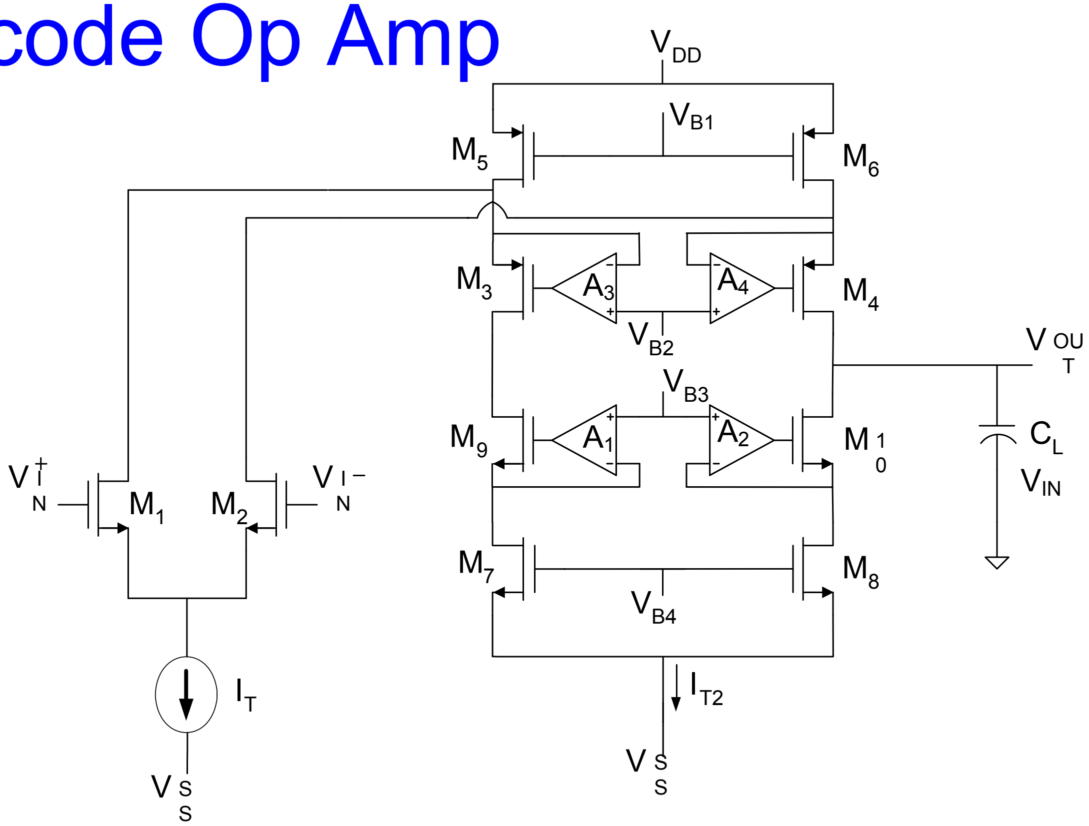
- **Needs CMFB Circuit for V_{B4}**
- **Either single-ended or differential outputs**
- **Can connect counterpart as current mirror to eliminate CMFB**
- **Folding caused modest deterioration of A_{V0} and GB energy efficiency**
- **Modest improvement in output swing**

Review from Last Time

Folded Gain-boosted Telescopic Cascode Op Amp

$$A_o \approx \frac{-\dfrac{g_{m1}}{2}}{\left(g_{O1}+g_{O5}\right)\dfrac{g_{o3}}{A_3 g_{m3}}+g_{o7}\dfrac{g_{o9}}{A_1 g_{m9}}}$$

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



- Needs CMFB Circuit for V_{B4}
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Review from Last Time

Operational Amplifier Structure Comparison

Small Signal Parameter Domain			
Reference Op Amp	$A_{VO}=\frac{1}{2}\frac{g_{m1}}{g_{O1}+g_{O3}}$	$GB=\frac{g_{m1}}{2C_L}$	$SR=\frac{I_T}{2C_L}$
Telescopic Cascode	$A_o=\frac{\frac{g_{m1}}{2}}{g_{o1}\frac{g_{o3}}{g_{m3}}+g_{o7}\frac{g_{o5}}{g_{m5}}}$	$GB=\frac{g_{m1}}{2C_L}$	$SR=\frac{I_T}{2C_L}$
Regulated Cascode	$A_o\approx\frac{\frac{g_{m1}}{2}}{g_{o1}\frac{g_{o3}}{g_{m3}A_1}+g_{o7}\frac{g_{o9}}{g_{m9}A_3}}$	$GB=\frac{g_{m1}}{2C_L}$	$SR=\frac{I_T}{2C_L}$
Folded Cascode	$A_o=\frac{\frac{g_{m1}}{2}}{(g_{o1}+g_{o5})\frac{g_{o3}}{g_{m3}}+g_{o7}\frac{g_{o9}}{g_{m9}}}$	$GB=\frac{g_{m1}}{2C_L}$	$SR=\frac{I_T}{2C_L}$
Folded Regulated Cascode	$A_o=\frac{\frac{g_{m1}}{2}}{(g_{o1}+g_{o5})\frac{g_{o3}}{g_{m3}A_3}+g_{o7}\frac{g_{o9}}{g_{m9}A_9}}$	$GB=\frac{g_{m1}}{2C_L}$	$SR=\frac{I_T}{2C_L}$

Review from Last Time

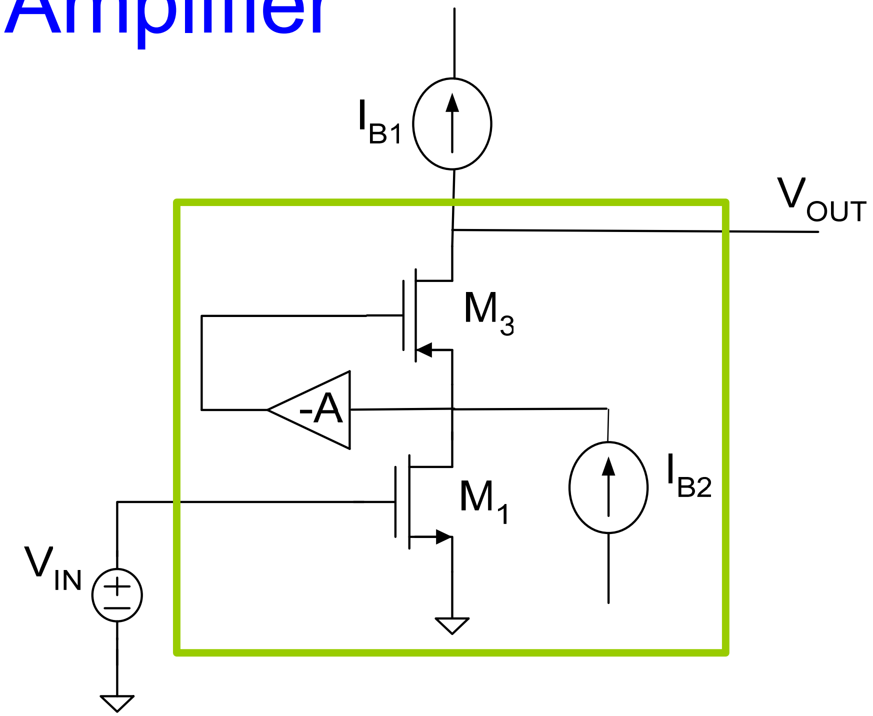
Summary of Folded Amplifier Performance

- \+ Modest improvement in output signal swing (from 5 $V_{DS\ SAT}$ to 4$V_{DS\ SAT}$)
- \- Deterioration in A_{V0} (maybe 30% or more)
- \- Deterioration in GB power efficiency (can be significant)
- \- Minor increase in circuit size

Folded Gain-boosted Cascode Amplifier

$$A_o \approx \frac{-g_{m1}}{(g_{o1})\dfrac{g_{o3}}{A\ g_{m3}}}$$

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



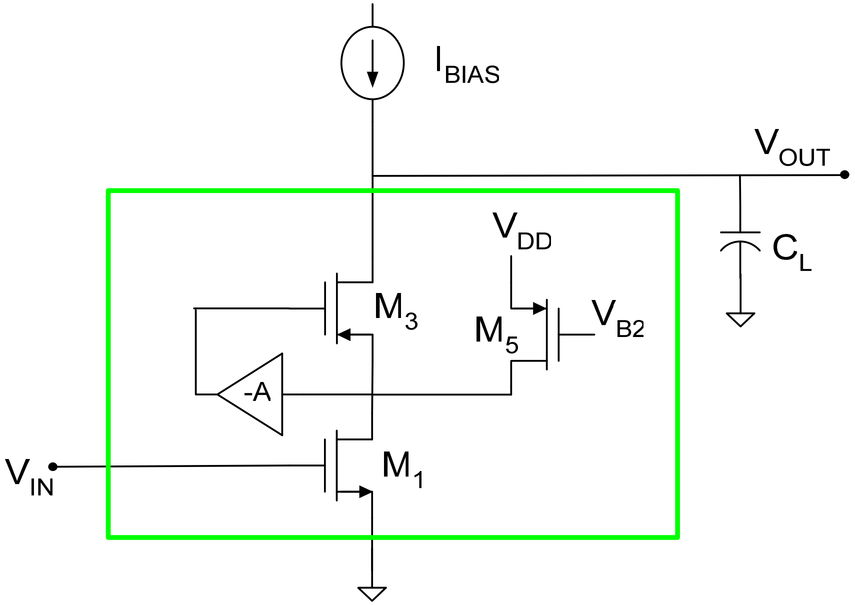
- with ideal current source bias
- modest improvement in output swing

Folded Gain-boosted Cascode Amplifier

$$\frac{V_{OUT}}{V_{IN}} \approx \frac{-g_{m1}}{sC_L + \frac{(g_{o1}+g_{o5})g_{o3}}{g_{m3}A}}$$

$$A_0 \approx \frac{-g_{m1}g_{m3}A}{(g_{o1}+g_{o5})g_{o3}}$$

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



modest improvement in output swing

Basic Amplifier Structure Comparisons

Small Signal Parameter Domain		
Common Source	$A_{VO} = \frac{g_m}{g_O}$	$GB = \frac{g_m}{C_L}$
Cascode	$A_{VO} = \frac{g_{m1}}{g_{O1}} \frac{g_{m3}}{g_{o3}}$	$GB = \frac{g_{m1}}{C_L}$
Regulated Cascode	$A_{VO} \approx \frac{g_{m1}}{g_{O1}} \frac{g_{m3}}{g_{o3}} A$	$GB = \frac{g_{m1}}{C_L}$
Folded Cascode	$A_{VO} = \frac{g_{m1}}{\left(g_{O1} + g_{O5}\right)} \frac{g_{m3}}{g_{o3}}$	$GB = \frac{g_{m1}}{C_L}$
Folded Regulated Cascode	$A_{VO} = \frac{g_{m1}}{\left(g_{O1} + g_{O5}\right)} \frac{g_{m3}}{g_{o3}} A$	$GB = \frac{g_{m1}}{C_L}$

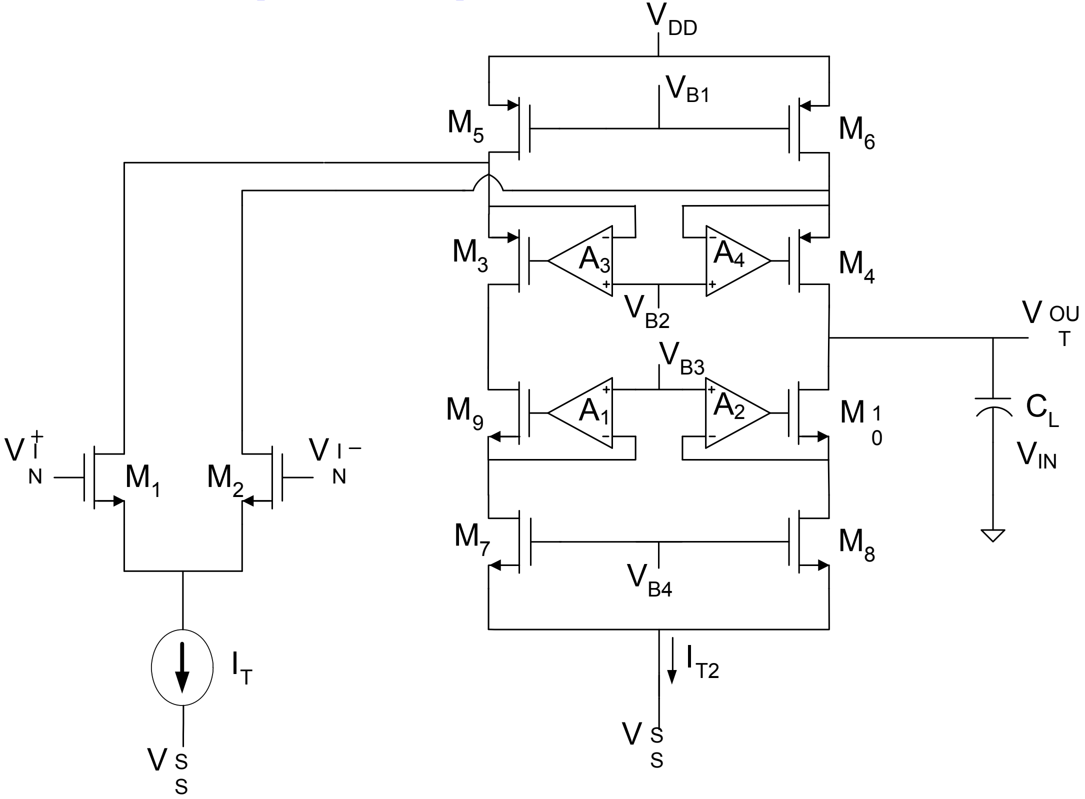
Basic Amplifier Structure Comparisons

Practical Parameter Domain		
Common Source	$A_{VO}=\left(\frac{2}{\lambda}\right)\left(\frac{1}{V_{EB}}\right)$	$GB=\left(\frac{2P}{V_{DD}C_L}\right)\left(\frac{1}{V_{EB}}\right)$
Cascode	$A_{VO}=\left(\frac{4}{\lambda_1\lambda_3}\right)\left(\frac{1}{V_{EB1}V_{EB3}}\right)$	$GB=\left(\frac{2P}{V_{DD}C_L}\right)\left(\frac{1}{V_{EB1}}\right)$
Regulated Cascode Θ=pct power in A	$A_{VO}\approx\left(\frac{4}{\lambda_1\lambda_3}\right)\left(\frac{A}{V_{EB1}V_{EB3}}\right)$	$GB=\left(\frac{2P}{V_{DD}C_L}\right)\left(\frac{(1-\theta)}{V_{EB1}}\right)$
Folded Cascode Θ=fraction of current of M_5 that is in M_1	$A_{VO}\approx\left(\frac{4\theta}{(\theta\lambda_1+\lambda_5)\lambda_3V_{EB1}V_{EB3}}\right)$	$GB=\left(\frac{2P}{V_{DD}C_L}\right)\left[\frac{\theta}{V_{EB1}}\right]$
Folded Regulated Cascode Θ_1=pct of total power in A Θ_2=fraction of current of M_5 that is in M_1	$A_{VO}\approx\left(\frac{A4\theta_2}{(\theta_2\lambda_1+\lambda_5)\lambda_3V_{EB1}V_{EB3}}\right)$	$GB=\left(\frac{2P}{V_{DD}C_L}\right)\left(\frac{\theta_2(1-\theta_1)}{V_{EB1}}\right)$

Folded Gain-boosted Telescopic Cascode Op Amp

$$A_o \approx \frac{-\dfrac{g_{m1}}{2}}{\left(g_{O1}+g_{O5}\right)\dfrac{g_{o3}}{A_3 g_{m3}} + g_{o7}\dfrac{g_{o9}}{A_1 g_{m9}}}$$

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



- **Needs CMFB Circuit for V_{B4}**
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Regulated Cascode	$A_o \approx \frac{\frac{g_{m1}}{2}}{g_{o1}\frac{g_{o3}}{g_{m3}A_1} + g_{o7}\frac{g_{o9}}{g_{m9}A_3}}$	$GB = \frac{g_{m1}}{2C_L}$	$SR = \frac{I_T}{2C_L}$
Folded Cascode	$A_o = \frac{\frac{g_{m1}}{2}}{(g_{o1} + g_{o5})\frac{g_{o3}}{g_{m3}} + g_{o7}\frac{g_{o9}}{g_{m9}}}$	$GB = \frac{g_{m1}}{2C_L}$	$SR = \frac{I_T}{2C_L}$
Folded Regulated Cascode	$A_o = \frac{\frac{g_{m1}}{2}}{(g_{o1} + g_{o5})\frac{g_{o3}}{g_{m3}A_3} + g_{o7}\frac{g_{o9}}{g_{m9}A_9}}$	$GB = \frac{g_{m1}}{2C_L}$	$SR = \frac{I_T}{2C_L}$

Summary of Folded Amplifier Performance

- \+ Modest improvement in output signal swing (from 5 $V_{DS\ SAT}$ to $4V_{DS\ SAT}$)
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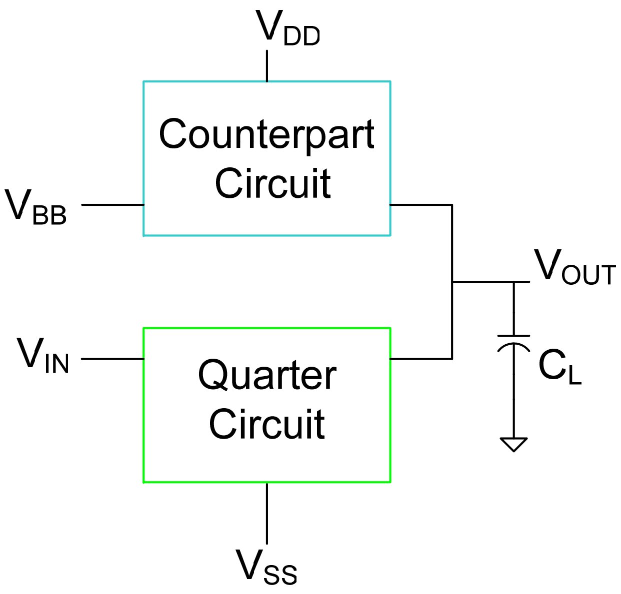
- \- Minor increase in circuit size

Other Methods of Gain Enhancement

Recall:



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

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

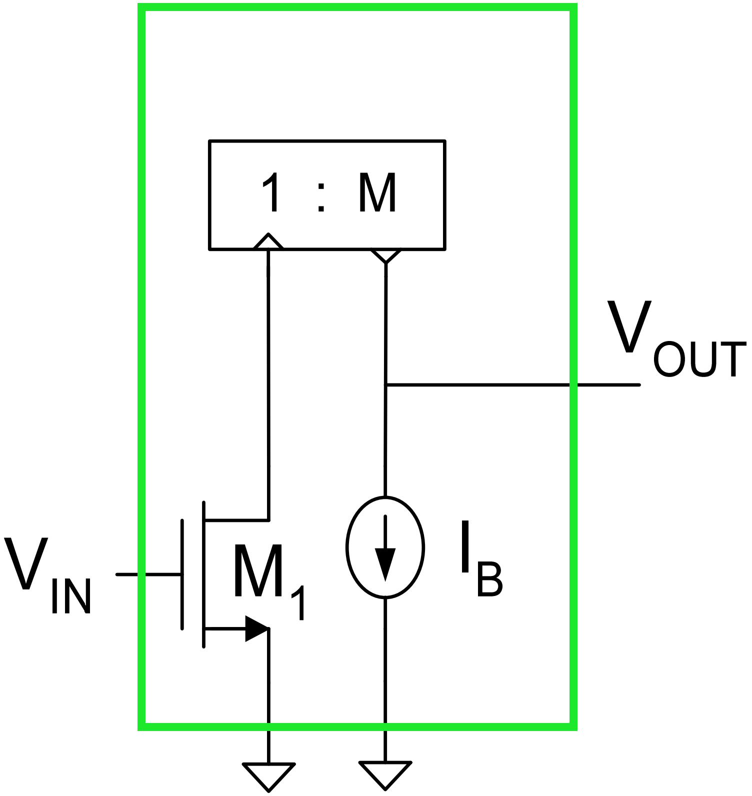
Two Strategies:

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

Previous approaches focused on decreasing denominator

Consider now increasing numerator

g_{mEQ} Gain Enhancement Strategy



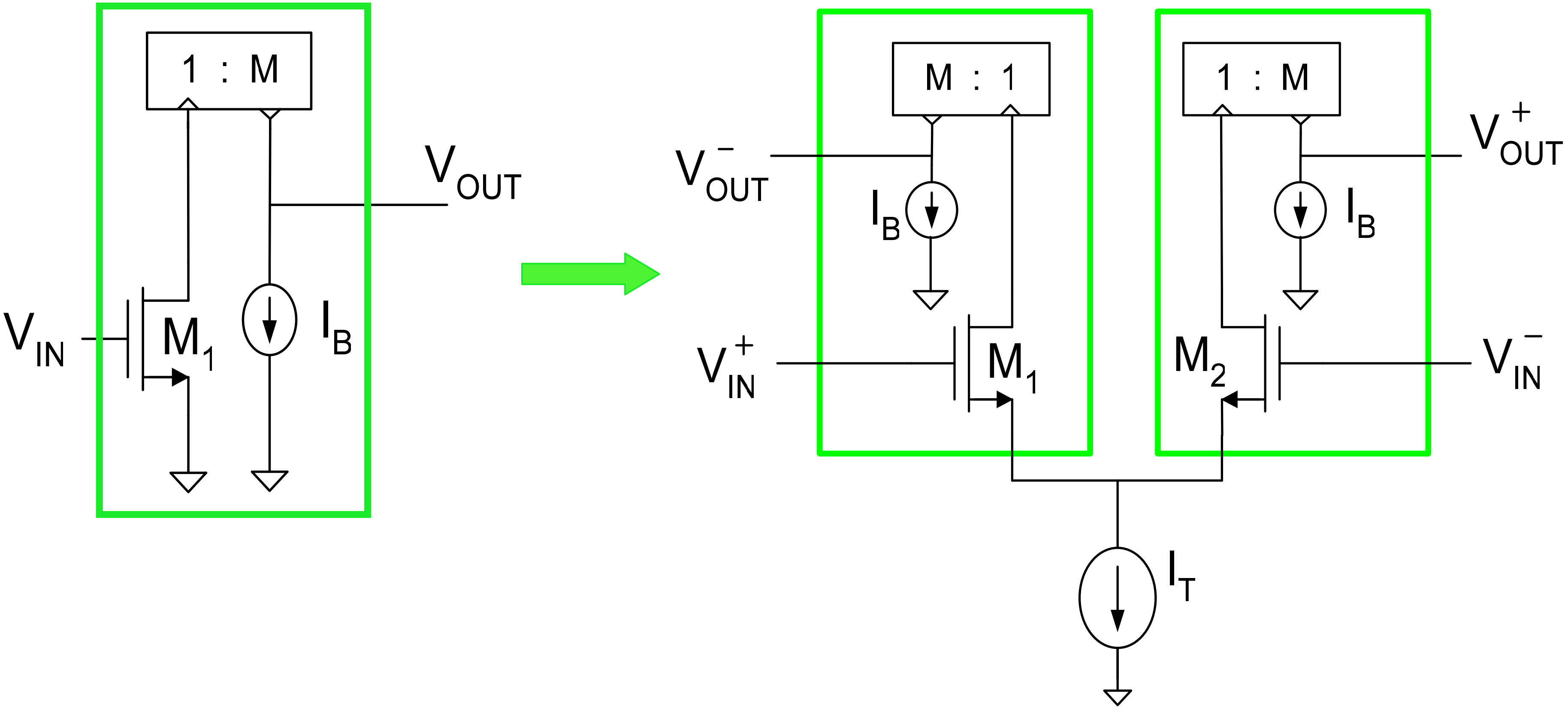
Use this as a quarter circuit

$$\mathbf{g_{MQC} = g_{m1} M}$$

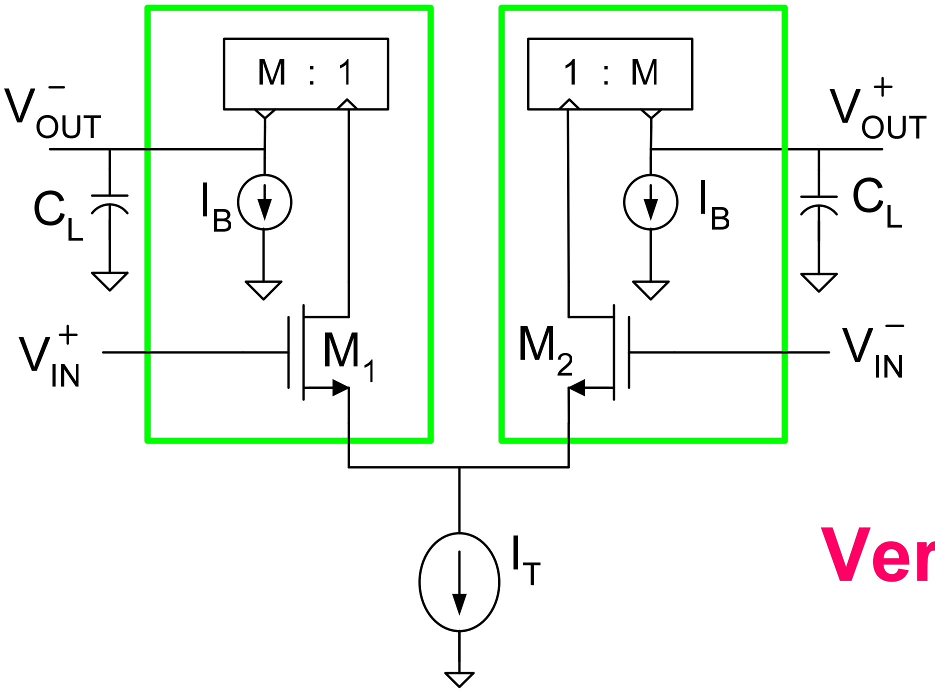
g_m is increased by the mirror gain !

use the quarter circuit itself to form the op amp

g_{mEQ} Gain Enhancement Strategy



Current Mirror Op Amps



Very Simple Structure!

Premise: Transconductance gain increased by mirror gain M

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

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

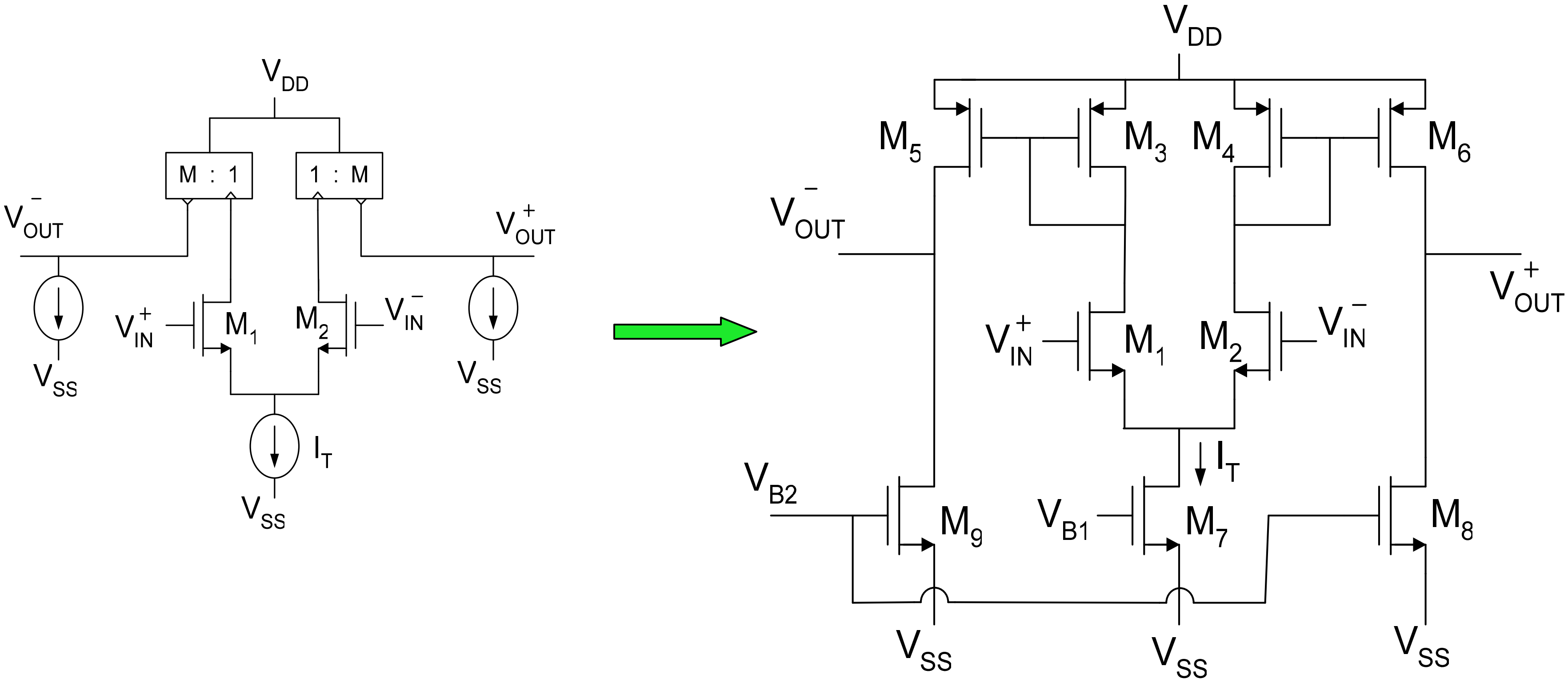
$$A_{V0} = -\frac{g_{mEQ}}{g_{OEQ}}$$

Premise: GB very good as well

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

Still need to generate the bias current I_B

Current Mirror Op Amps



Basic Current Mirror Op Amp

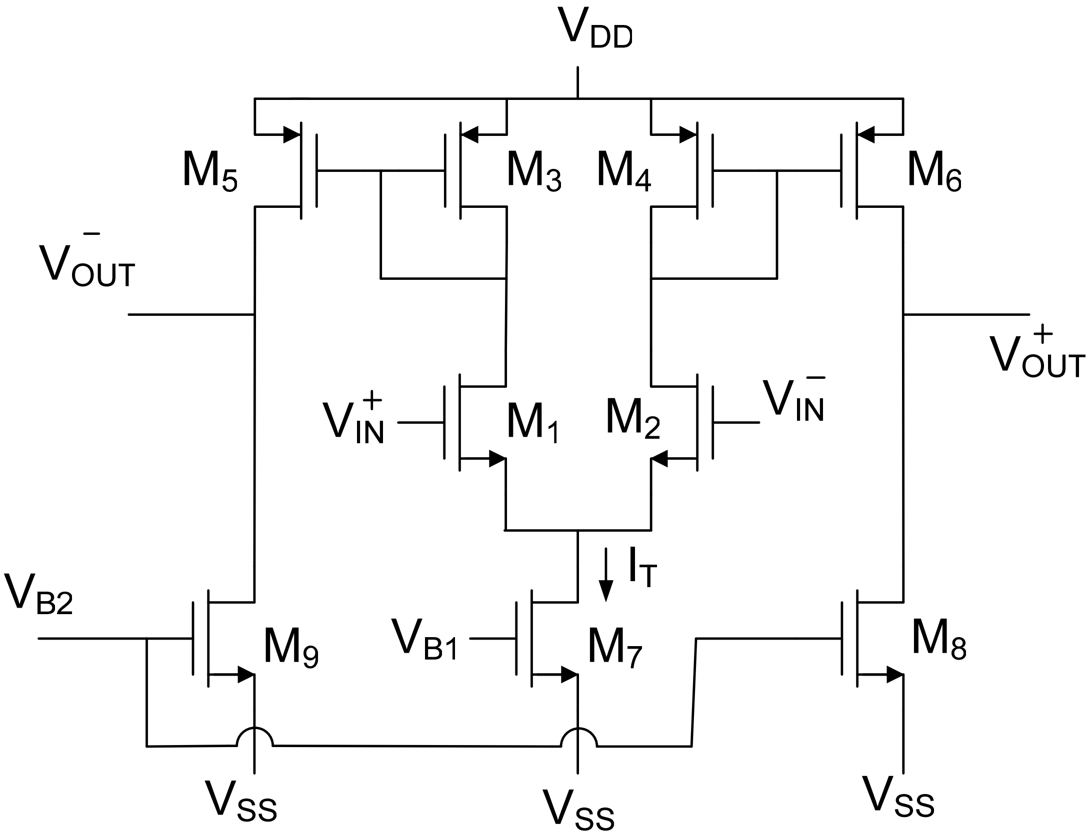
Need CMFB t0 establish V_{B2}

Can use higher output impedance current mirrors

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

Is this a real clever solution?

Basic Current Mirror Op Amp



CMFB not shown

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

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

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

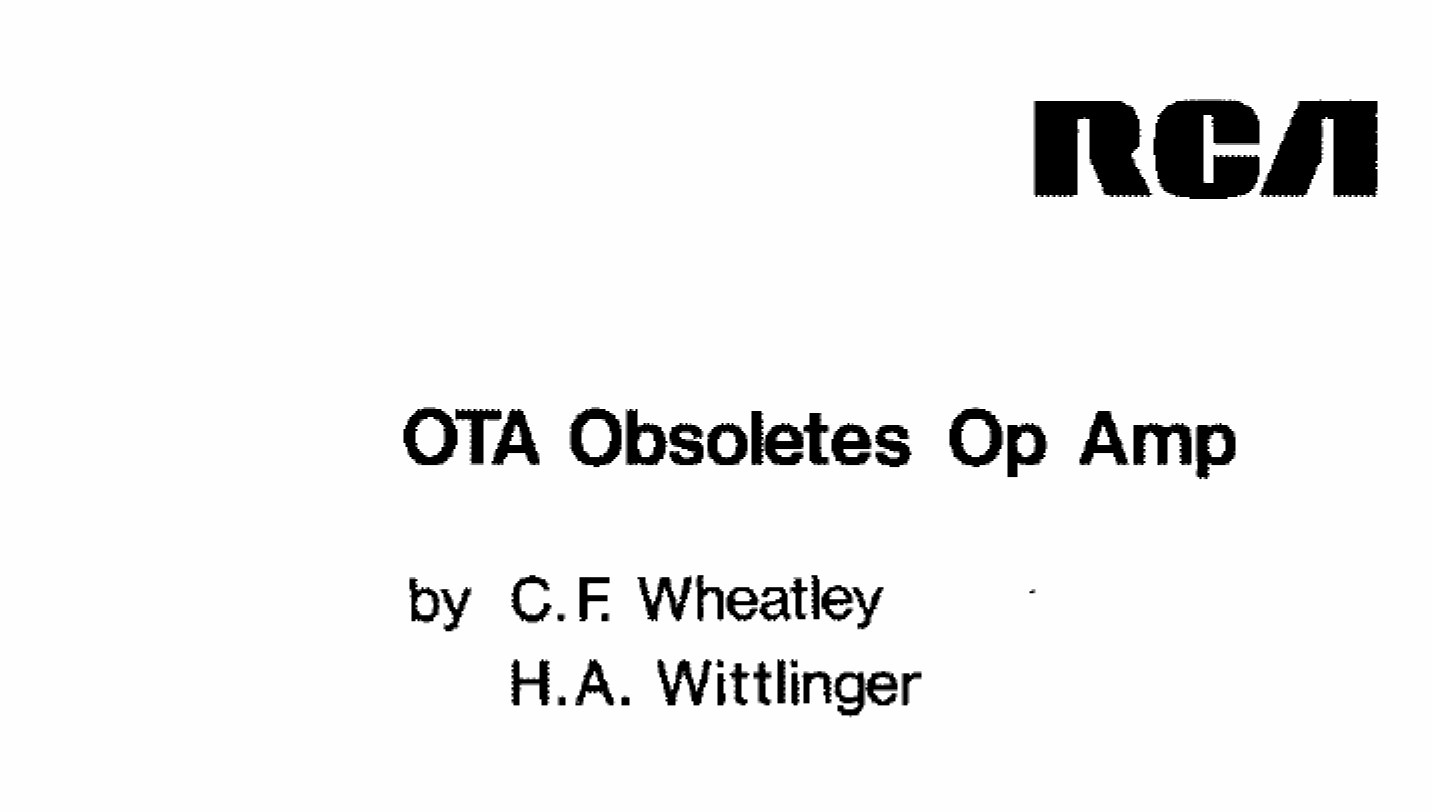
$$A_{VO} = -\frac{M \bullet \frac{g_{m1}}{2}}{g_{O6} + g_{O8}}$$

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

- Current-Mirror Op Amp 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?

Seminal Work on the OTA



RCA

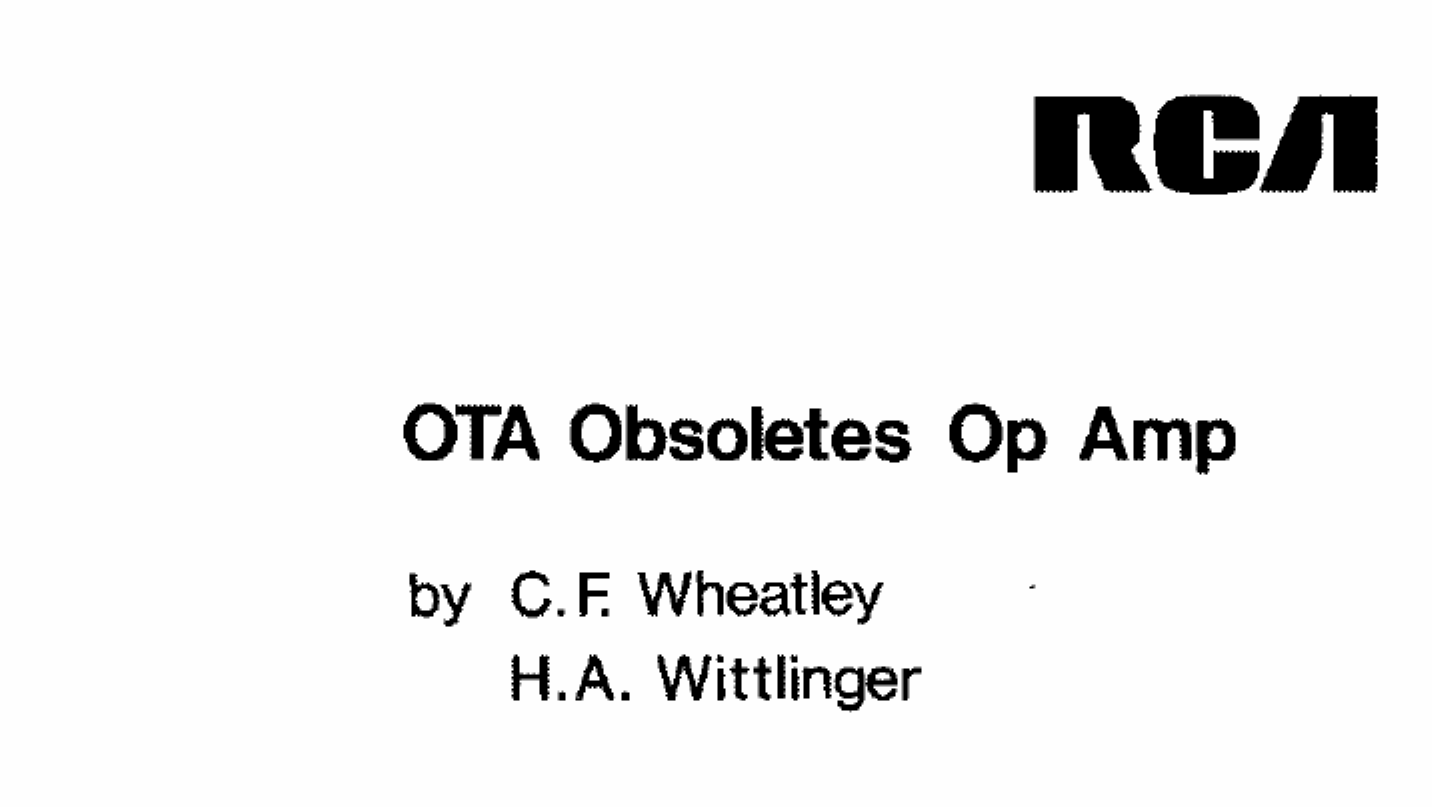
OTA Obsoletes Op Amp

by C.F. Wheatley
H.A. Wittlinger

From:

N.E.C. PROCEEDINGS

Seminal Work on the OTA



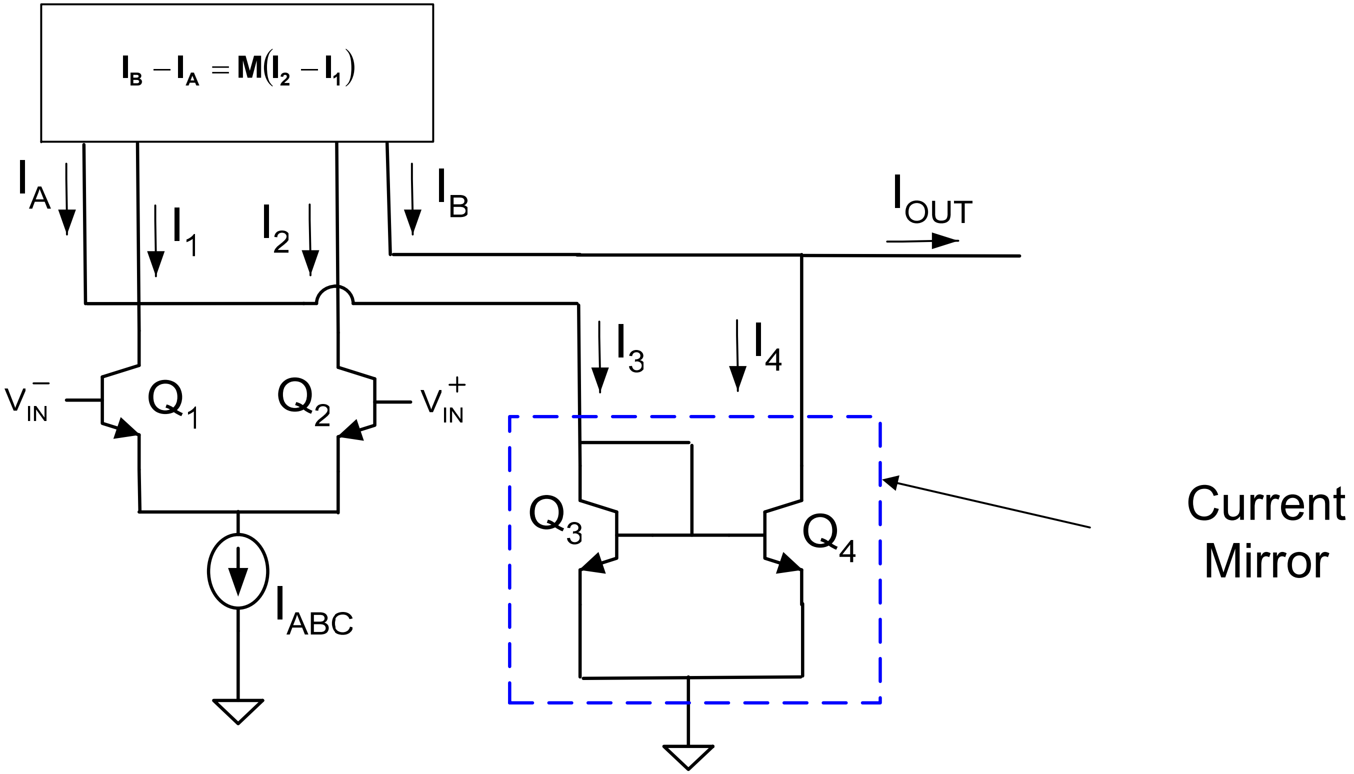
OTA Obsoletes Op Amp

by C.F. Wheatley
H.A. Wittlinger

From:

1969 N.E.C. PROCEEDINGS
December 1969

Original OTA

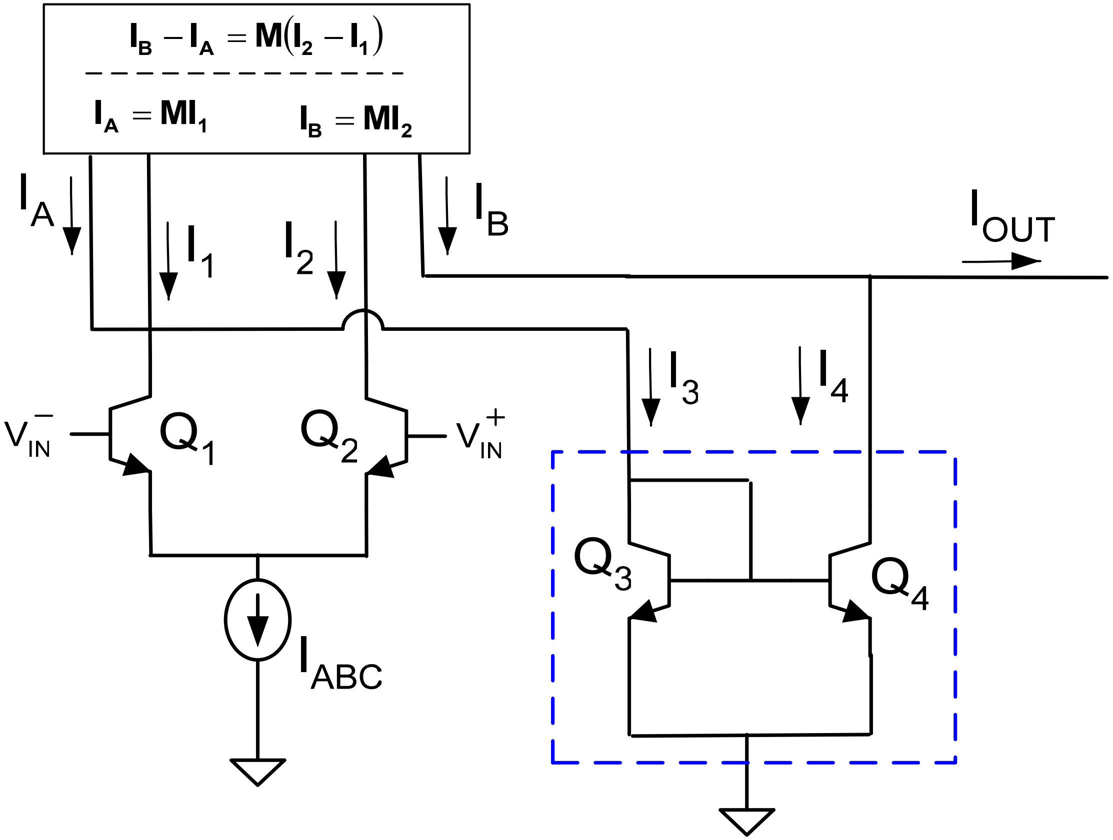


$$I_A = I_3$$

$$I_B = I_{OUT} + I_4 \quad \Longrightarrow \quad I_{OUT} = M(I_B - I_A)$$

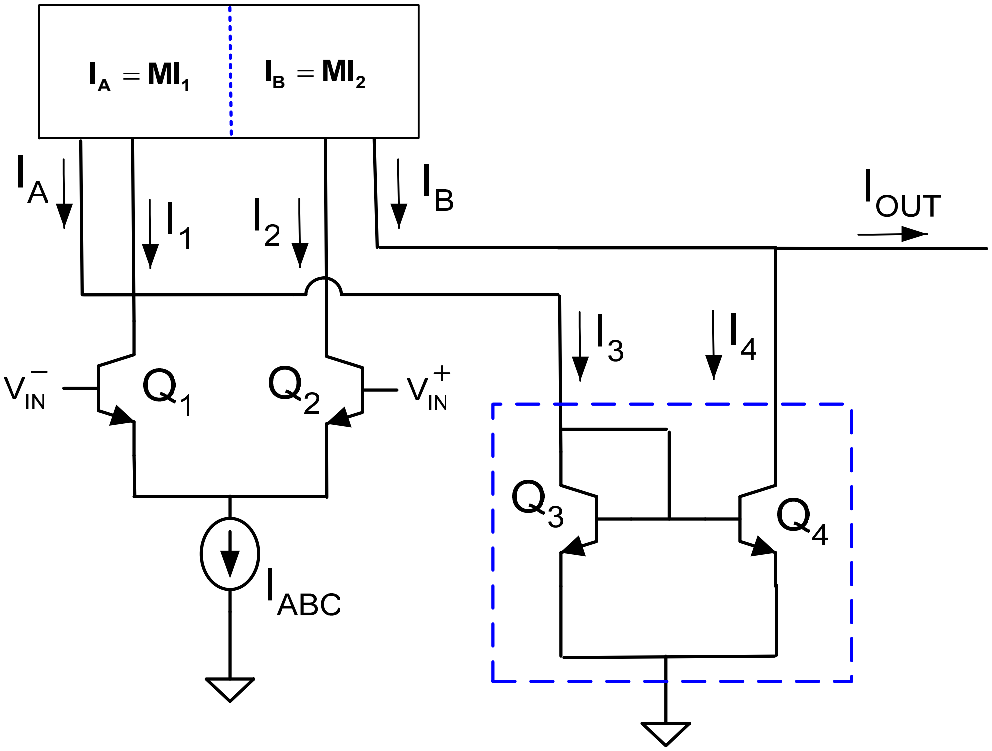
$$I_4 = I_3$$

Original OTA



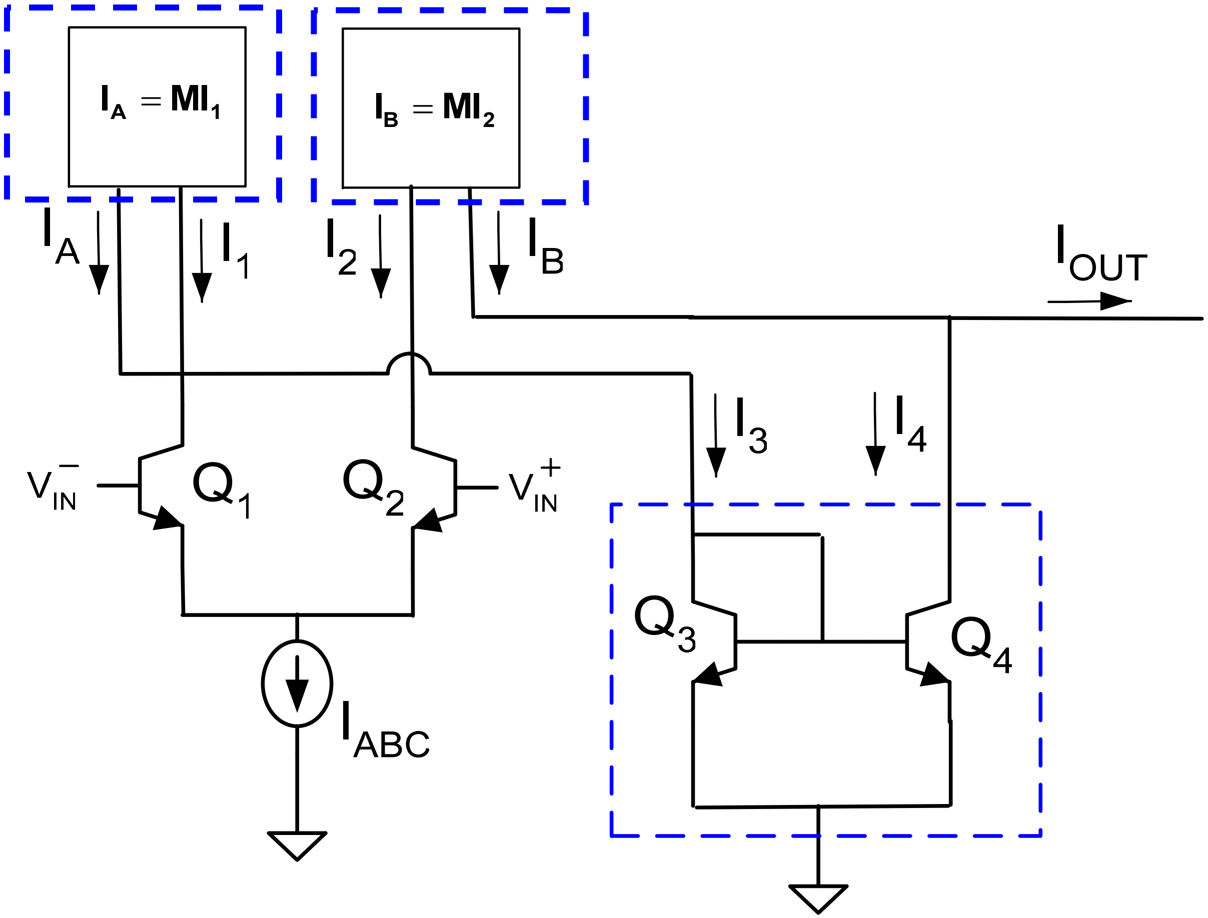
$$I_{OUT} = M(I_B - I_A)$$

Original OTA



$$I_{OUT} = M(I_B - I_A)$$

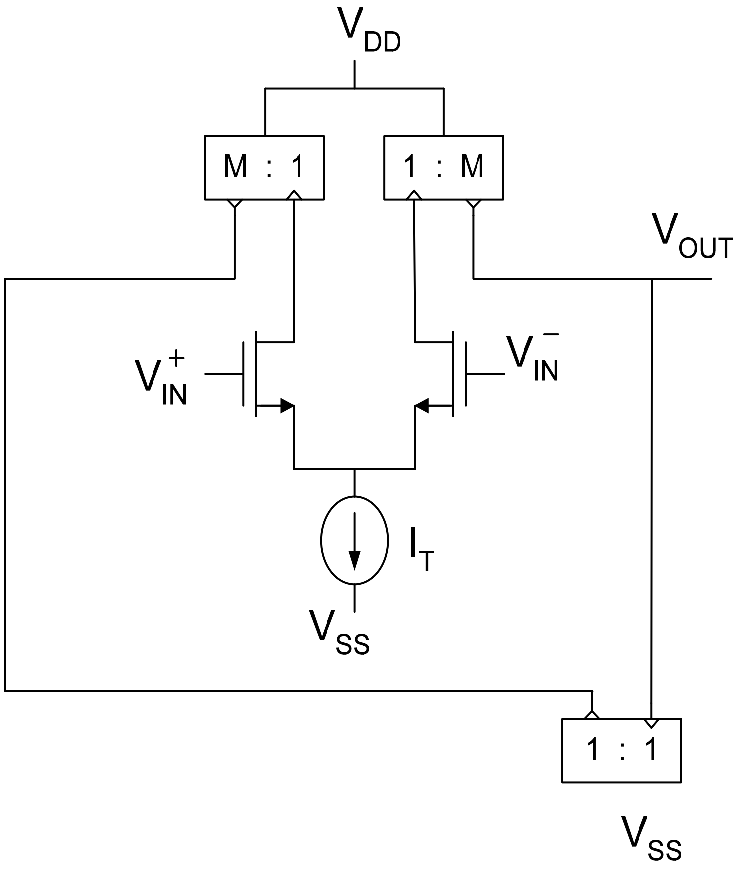
Original OTA



3-mirror OTA

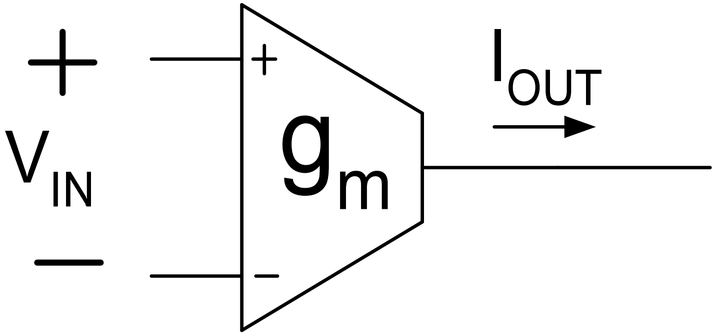
$$I_{OUT} = M(I_B - I_A)$$

Current Mirror Op Amp W/O CMFB



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

Often termed an OTA

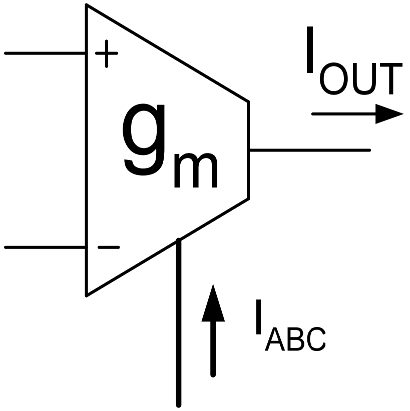


Introduced by Wheatley and Whitlinger in 1969

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

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

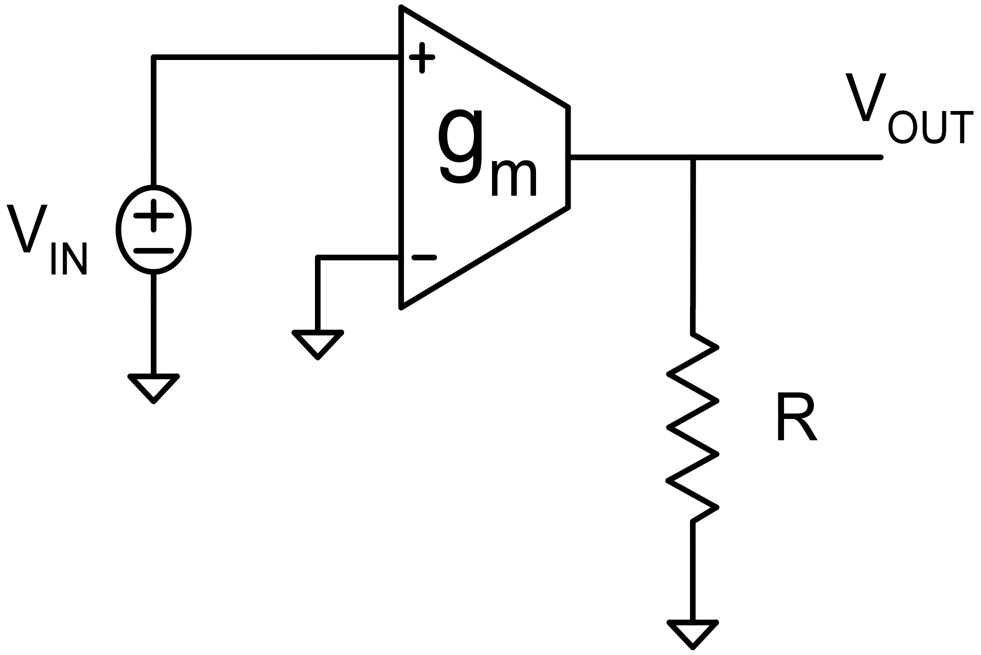


$$g_m = \begin{cases} K \bullet I_{ABC} & \text{for BJT circuits} \\ K\sqrt{I_{ABC}} & \text{for MOS circuits} \end{cases}$$

2 to 3 decades of adjustment for MOS

5 to 6 decades of adjustment for BJT

OTA Applications



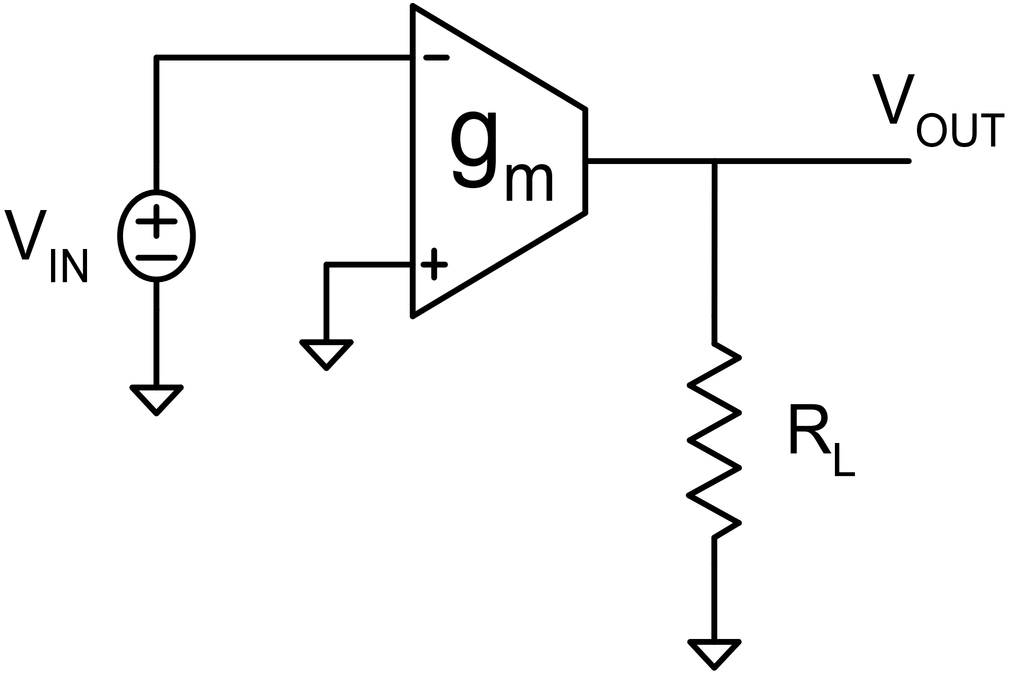
$$V_{OUT} = g_m R \bullet V_{IN}$$

g_m is controllable with I_{ABC}

Voltage Controlled Amplifier

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

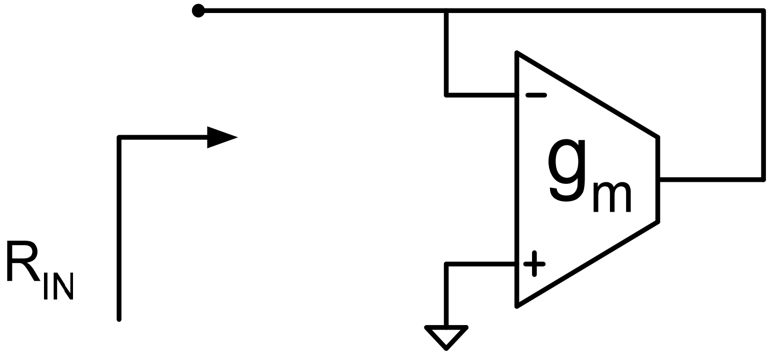
OTA Applications



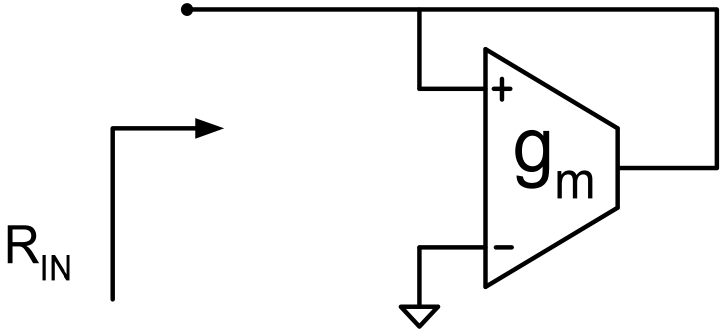
$$V_{OUT} = -g_m R \bullet V_{IN}$$

Voltage Controlled Inverting Amplifier

OTA Applications



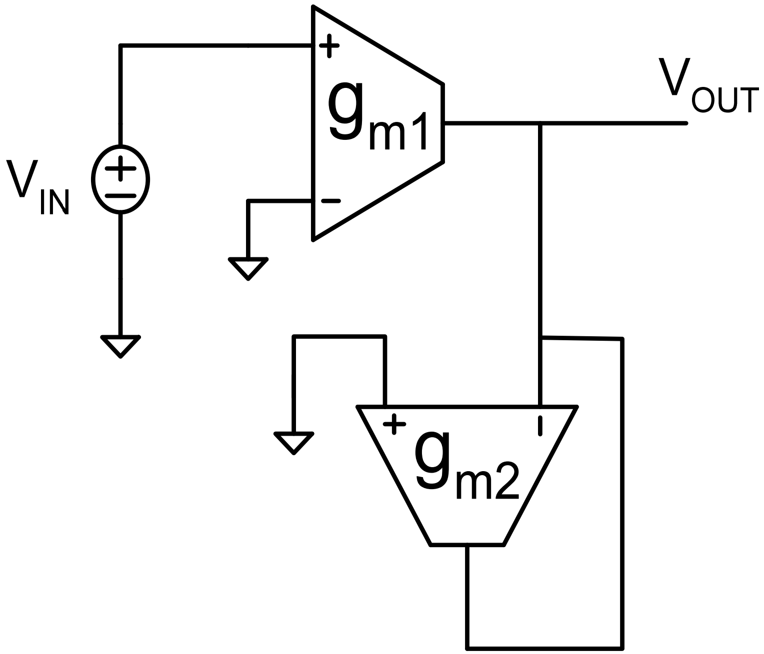
$$R_{IN} = \frac{1}{g_m}$$



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

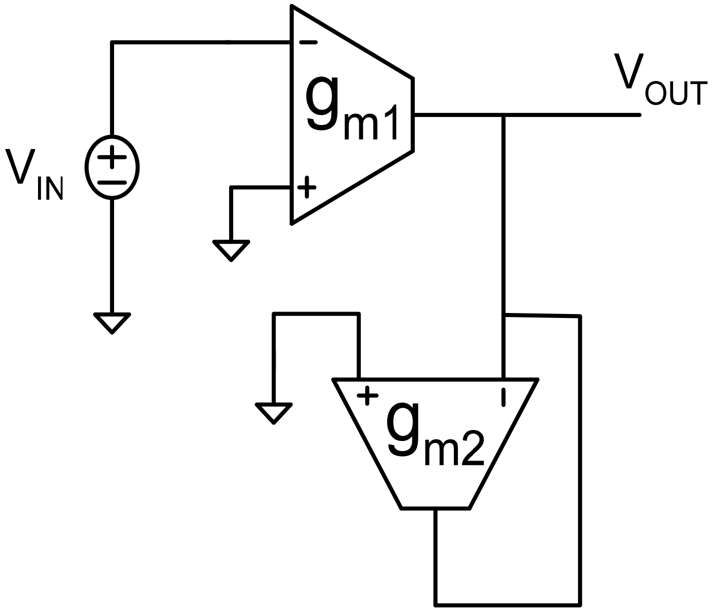
Voltage Controlled Resistances

OTA Applications



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

Noninverting Voltage Controlled Amplifier



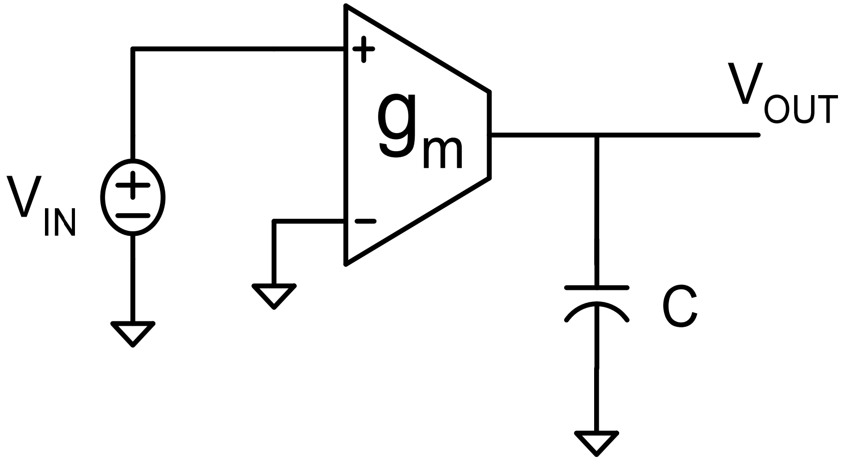
$$V_{OUT} = -\frac{g_{m1}}{g_{m2}} V_{in}$$

Inverting Voltage Controlled Amplifier

Extremely large gain adjustment is possible

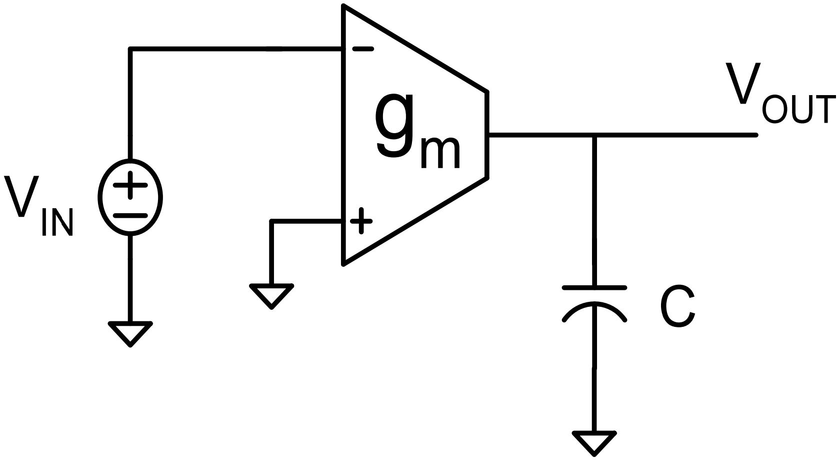
Voltage Controlled Resistorless Amplifiers

OTA Applications



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

Noninverting Voltage Controlled Integrator

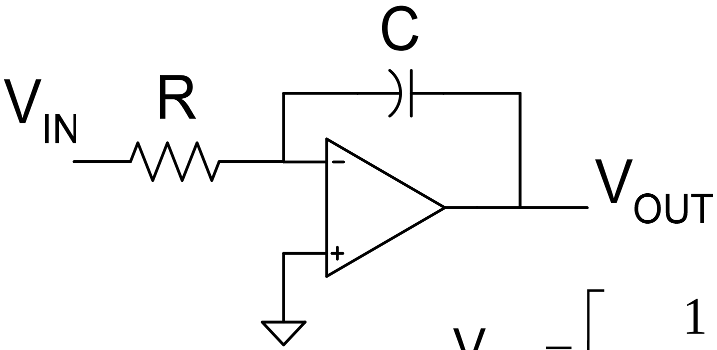


$$V_{OUT} = -\frac{g_m}{sC} V_{in}$$

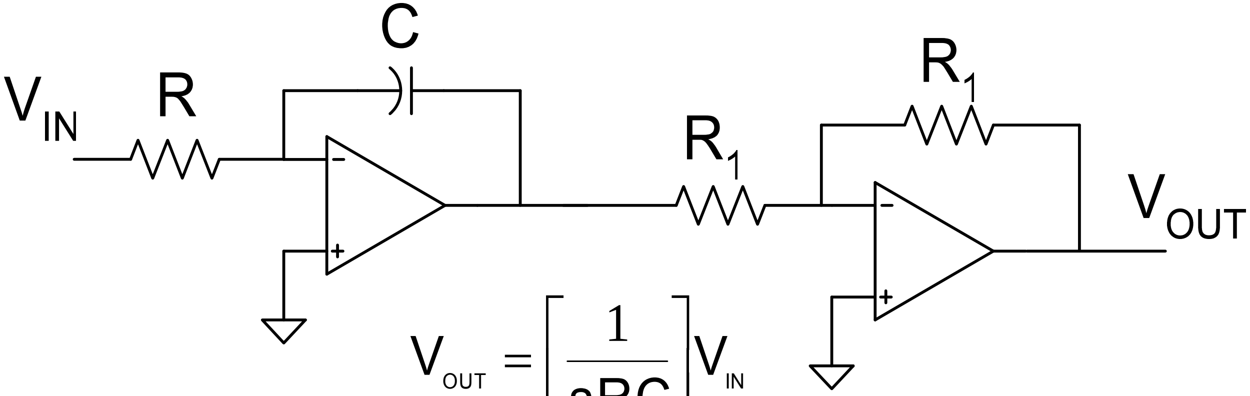
Inverting Voltage Controlled Integrator

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 !

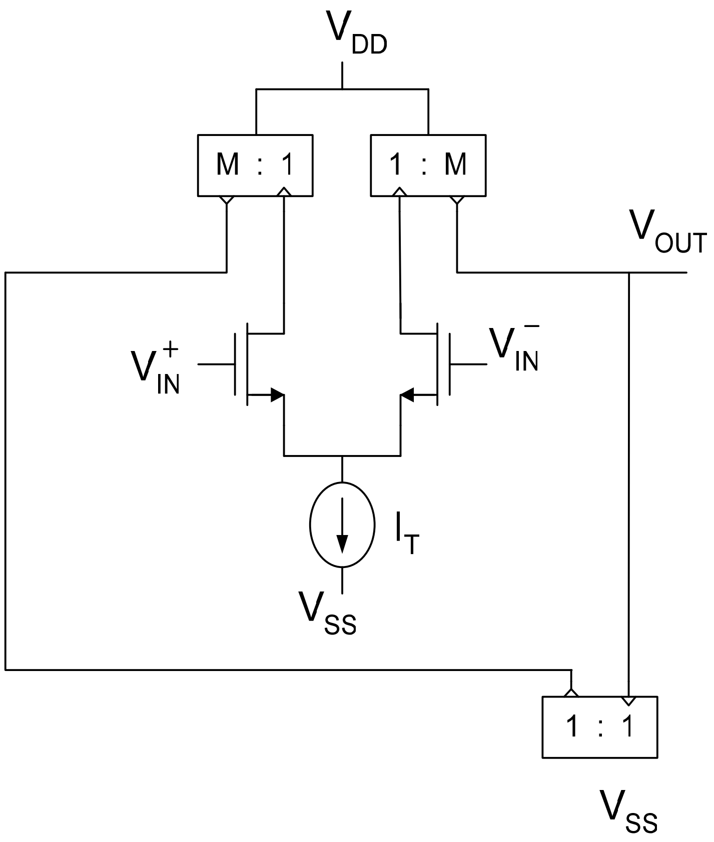
Properties of OTA-Based Circuits

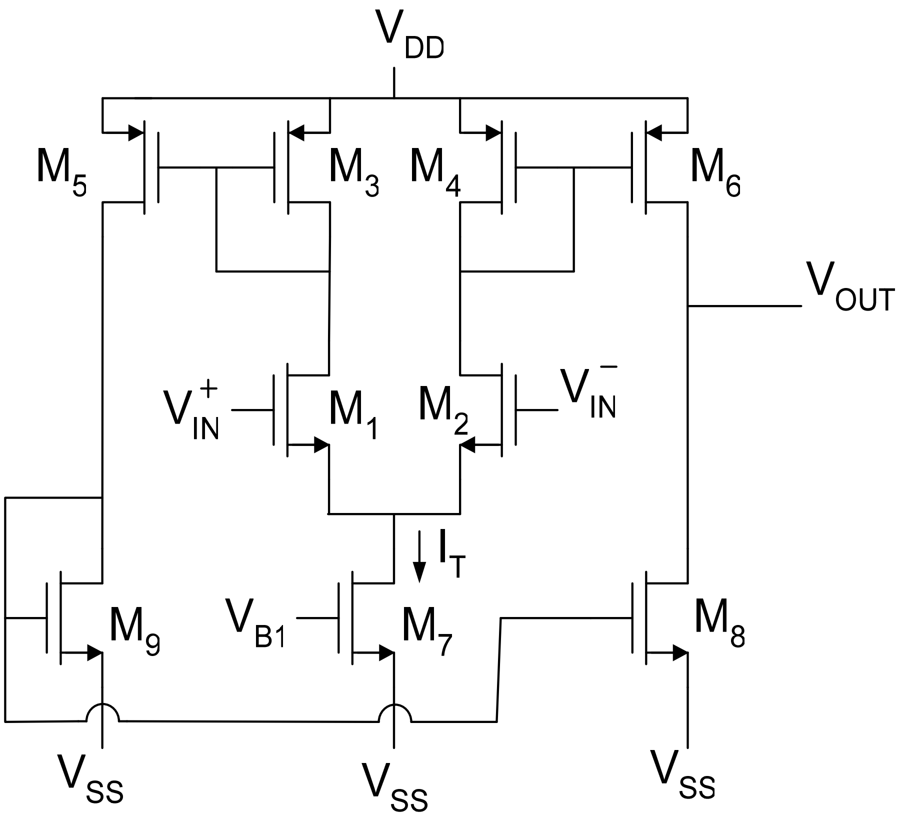
- Can realize arbitrarily complex functions
- Circuits are often simpler than what can be obtained with Op Amp counterparts
- Inherently offer excellent high frequency performance
- Can be controlled with a dc voltage or current
- Often used open-loop rather than in a feedback configuration (circuit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





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

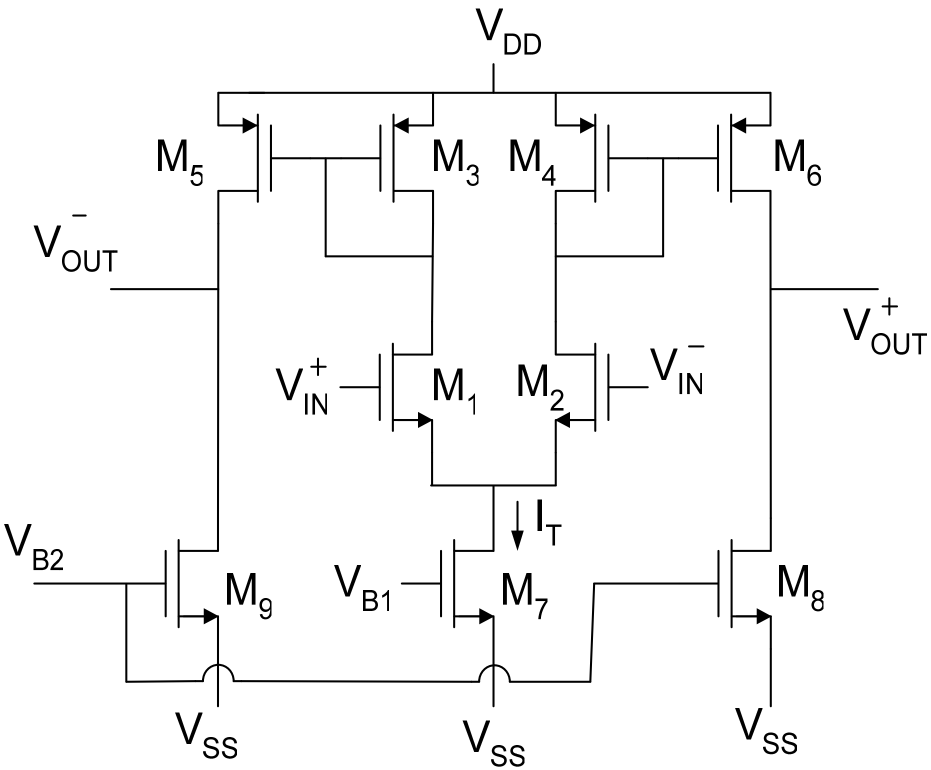
$$g_{mEQ} = M g_{m1}$$

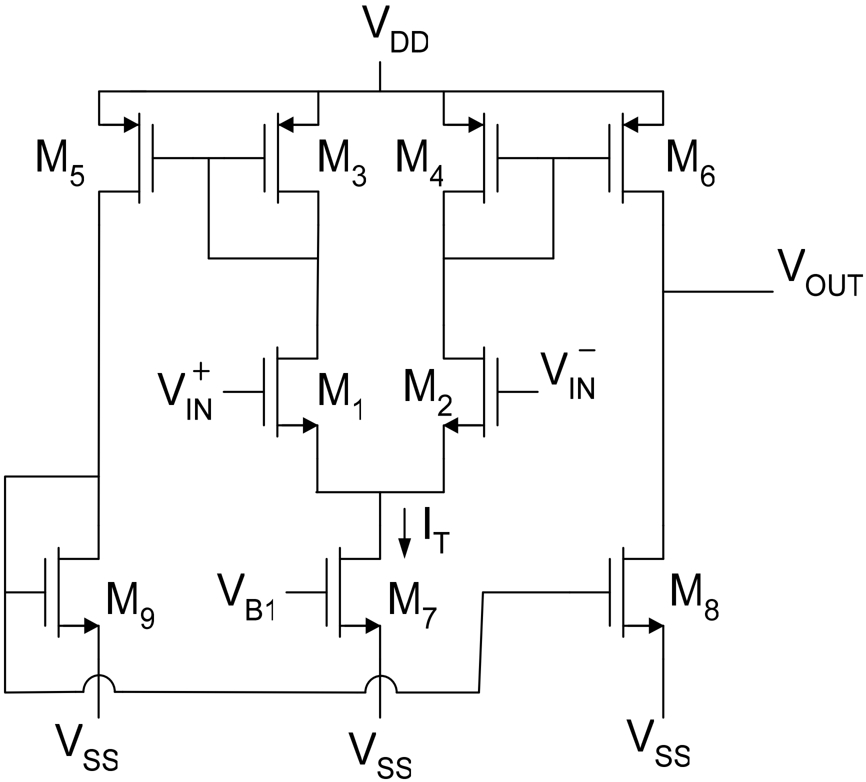
$$A_{VO} = -\frac{M \bullet g_{m1}}{g_{O6} + g_{O8}}$$

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

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

SR of Current Mirror Op Amp

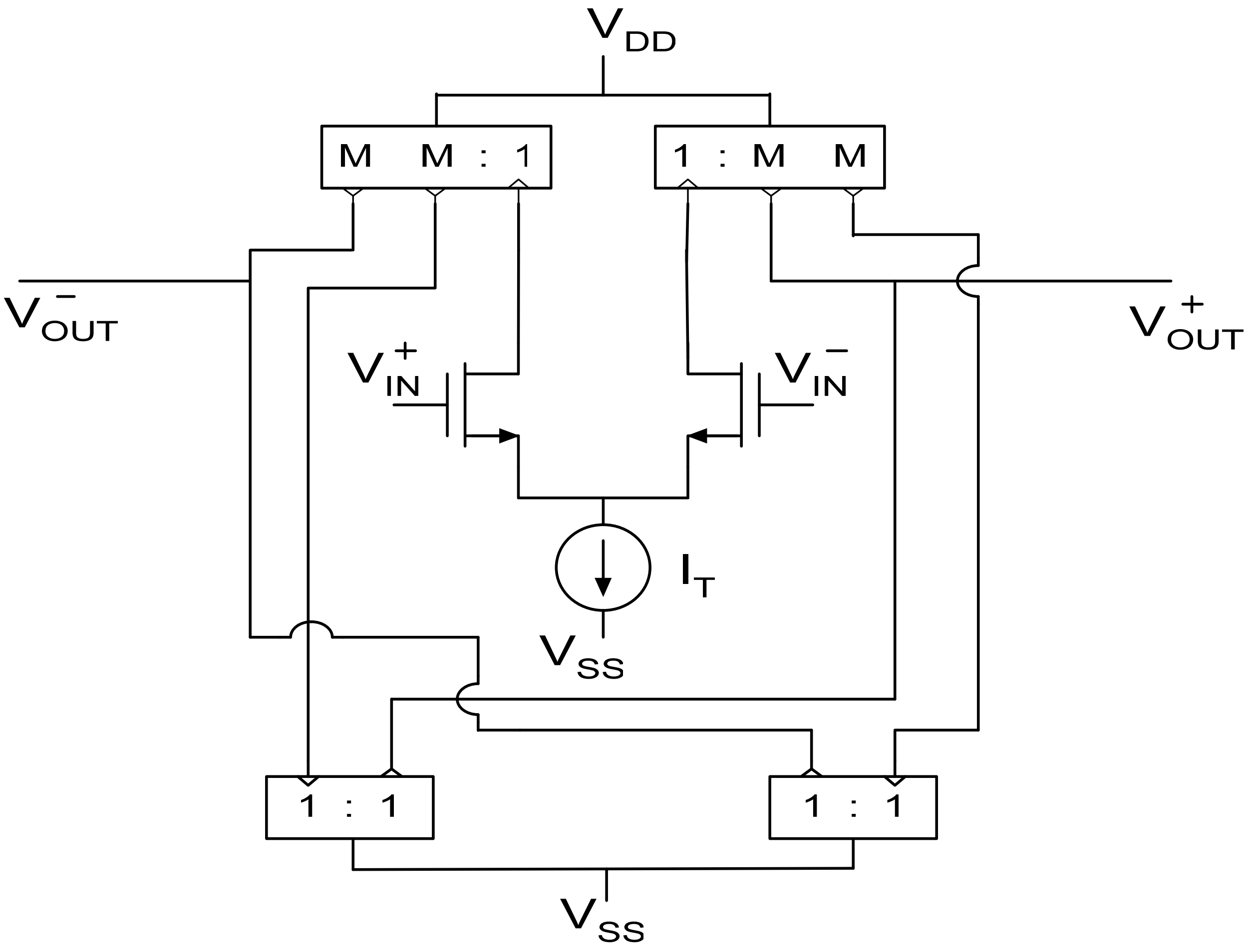




$$SR = \frac{MI_T}{2C_L}$$

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

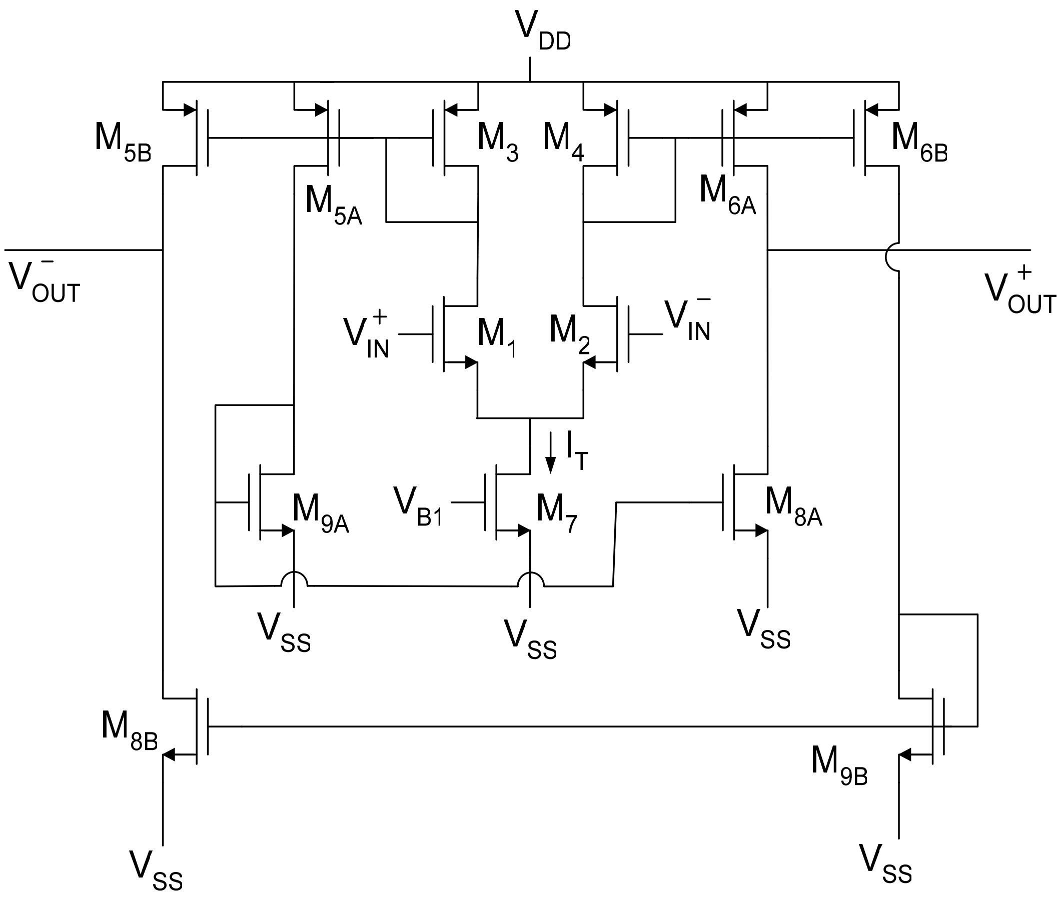
Fully Differential Current Mirror Op Amp with Improved Slew Rate



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

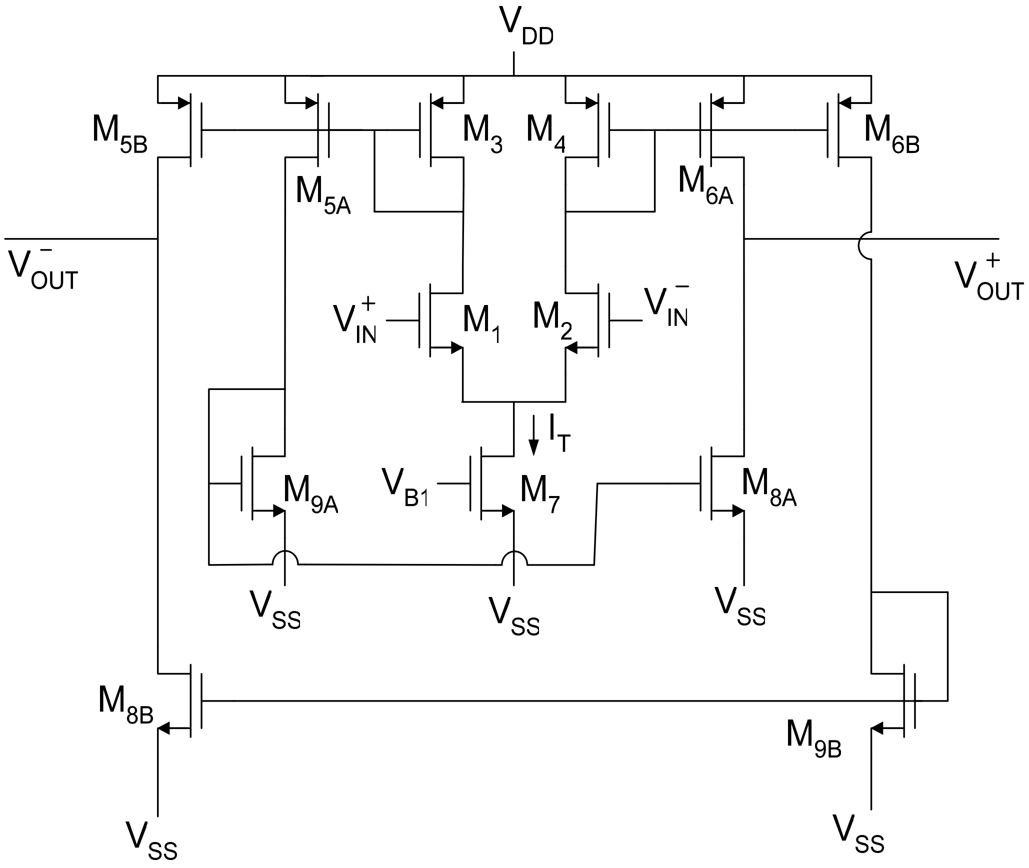
Fully Differential Current Mirror Op Amp with Improved Slew Rate

This circuit was published because of the claim for improved SR (Fig 6.15 MJ)



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

Fully Differential Current Mirror Op Amp with Improved Slew Rate



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

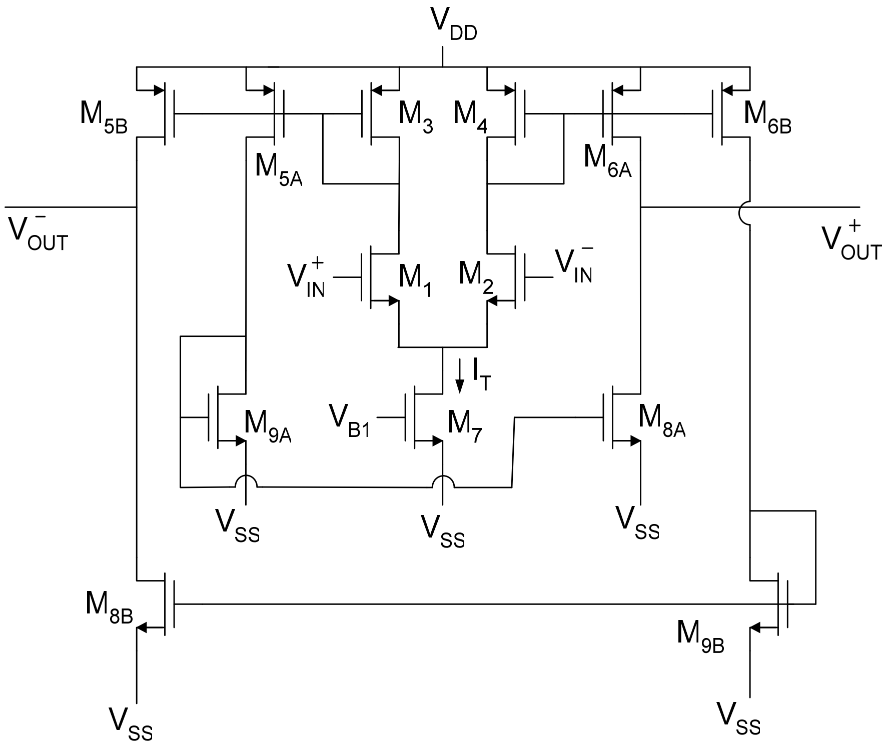
$$SR_{\text{CM Op Amp}} = \frac{M \bullet I_T}{2C_L}$$

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



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

$$SR_{CMOpAmp} = \frac{M \bullet I_T}{2C_L}$$

Improved a factor of 2 !

but …

$$P_{CM\,Op\,Amp} = V_{DD} I_T (1+M)$$

$$P = V_{DD} I_T (1+2M)$$

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

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

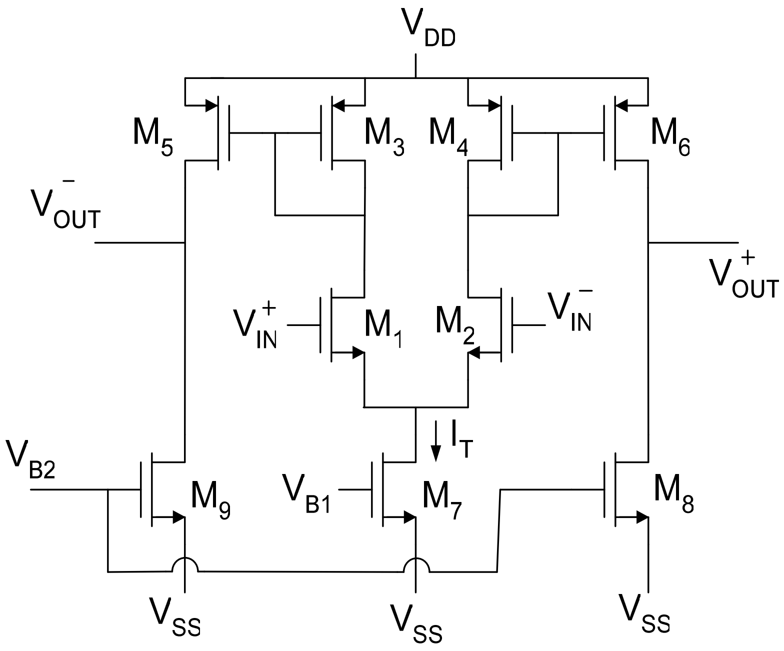
SR actually about the same for “improved SR circuit” and basic OTA

Comparison of Current-Mirror Op Amps with Previous Structures

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

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

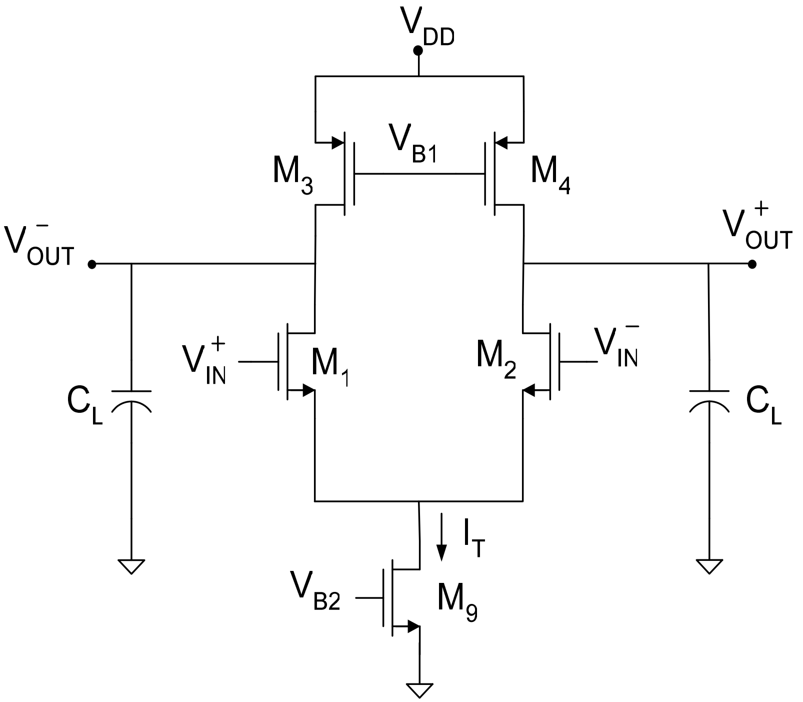
$$M = \frac{W_6 L_4}{W_4 L_6}$$



Reference Op Amp

Consider single-ended output performance :

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



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

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

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

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

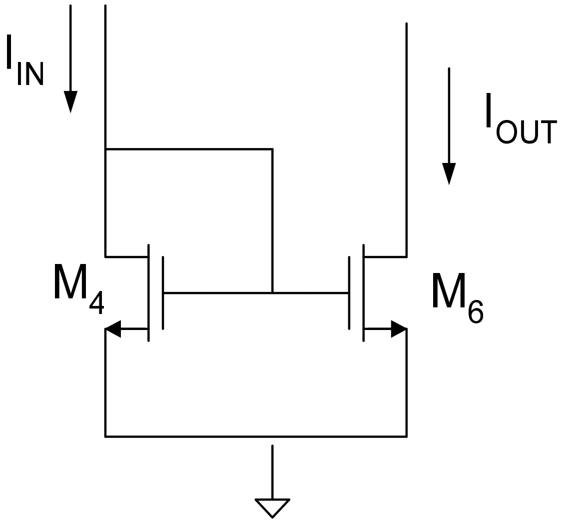
$$SR=\frac{I_T}{2C_L}$$

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

Comparison of Current-Mirror Op Amps with Previous Structures

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

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



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

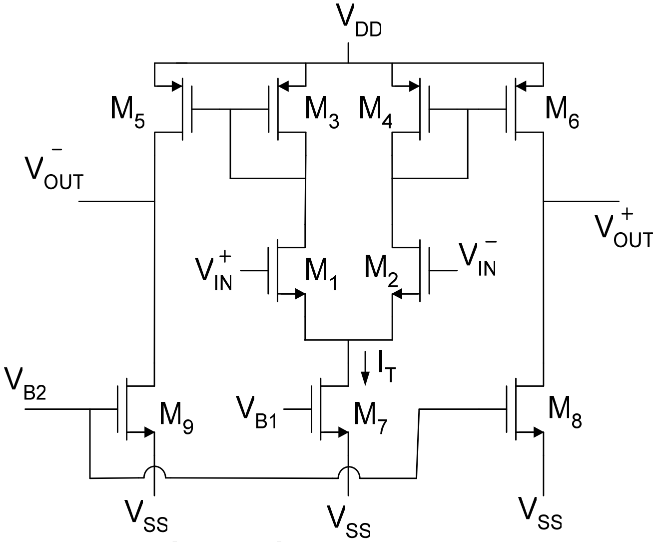
$$M = \frac{g_{m6}}{g_{m4}}$$

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

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 ?



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

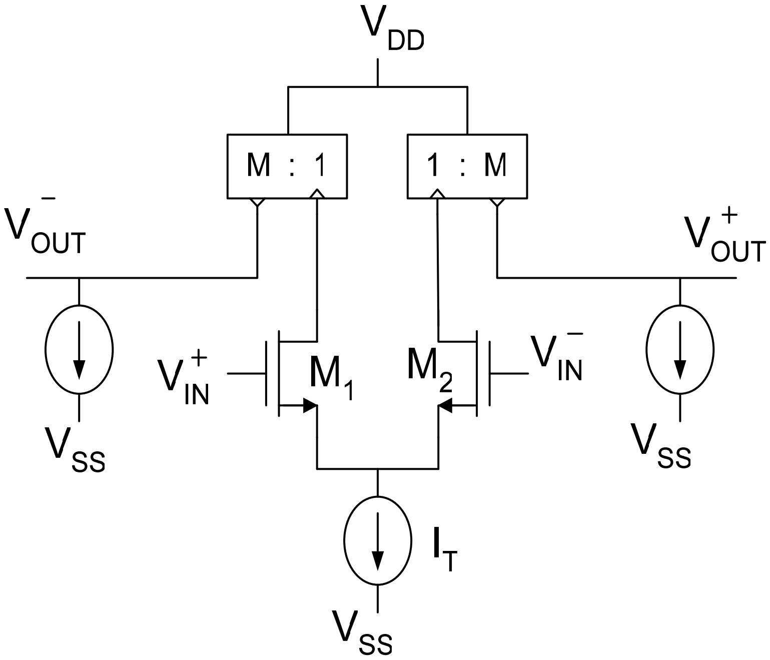
Consider how the gain appears in the practical parameter domain

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

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 ?



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

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

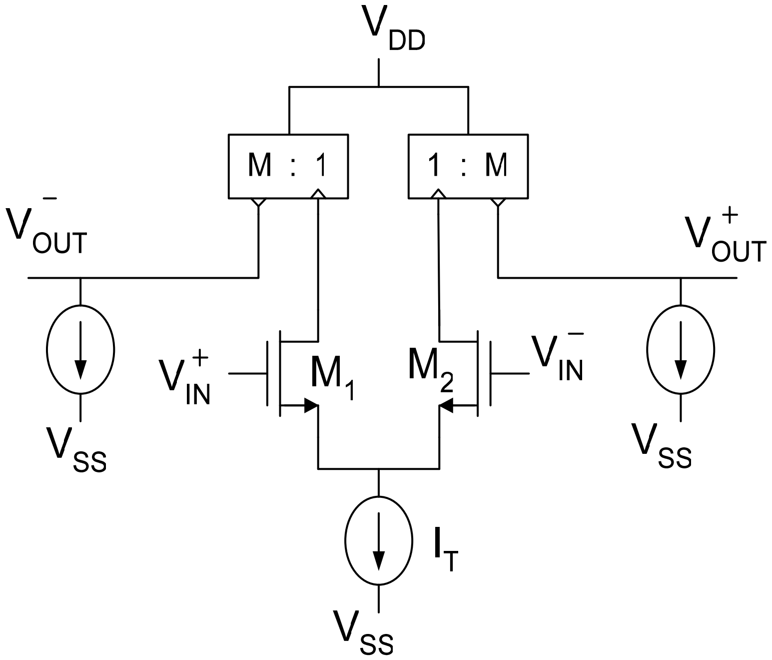
$$GB = \frac{MI_T}{2V_{EB1}C_L} = \boxed{\left(\frac{P}{2V_{EB1}V_{DD}C_L}\right)}\left[\frac{M}{1+M}\right]$$

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 ?



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

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

SR Improved by factor of M !

but …

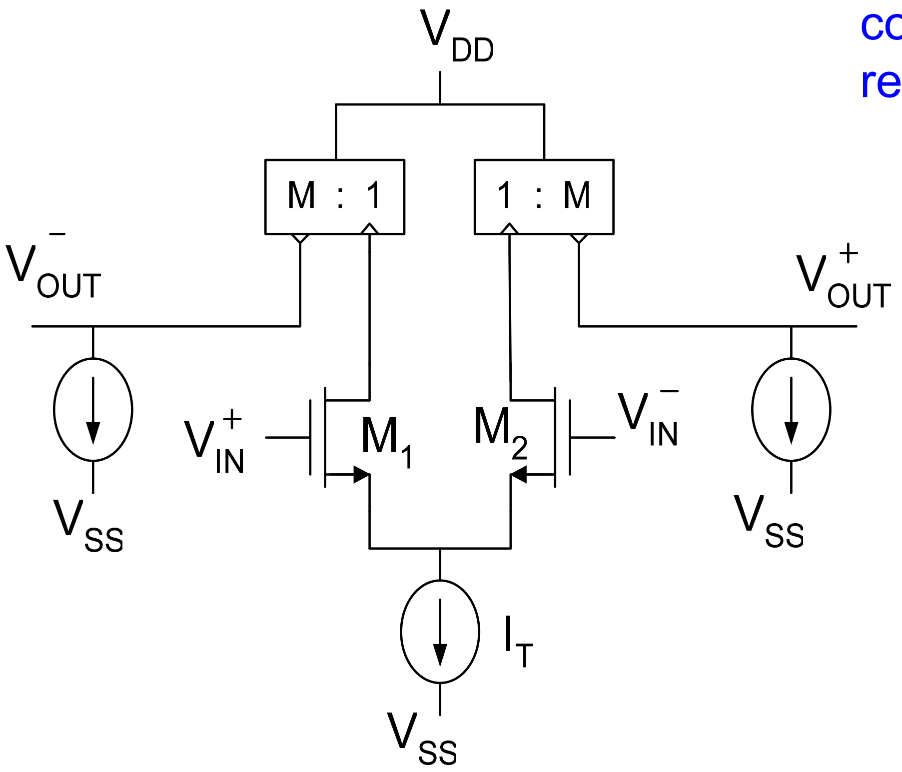
$$P = V_{DD} I_T (1+M)$$

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

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

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 !

End of Lecture 9