EE 435

Lecture 9:

Folded-Cascode Amplifiers
Current Mirror Op Amps

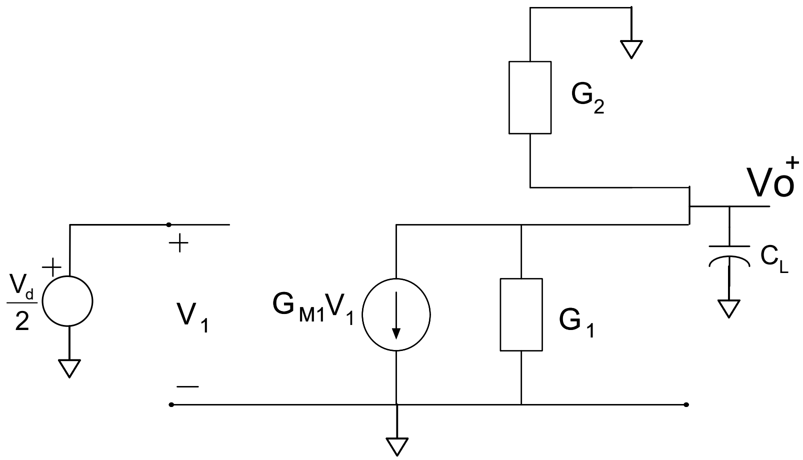
Where we are at:

Basic Op Amp Design

- Fundamental Amplifier Design Issues
- Single-Stage Low Gain Op Amps
- Single-Stage High Gain Op Amps
- Other Basic Gain Enhancement Approaches
- Two-Stage Op Amp

Review from Last Lecture

Are there other useful high output impedance circuits that can be used for the quarter circuit?



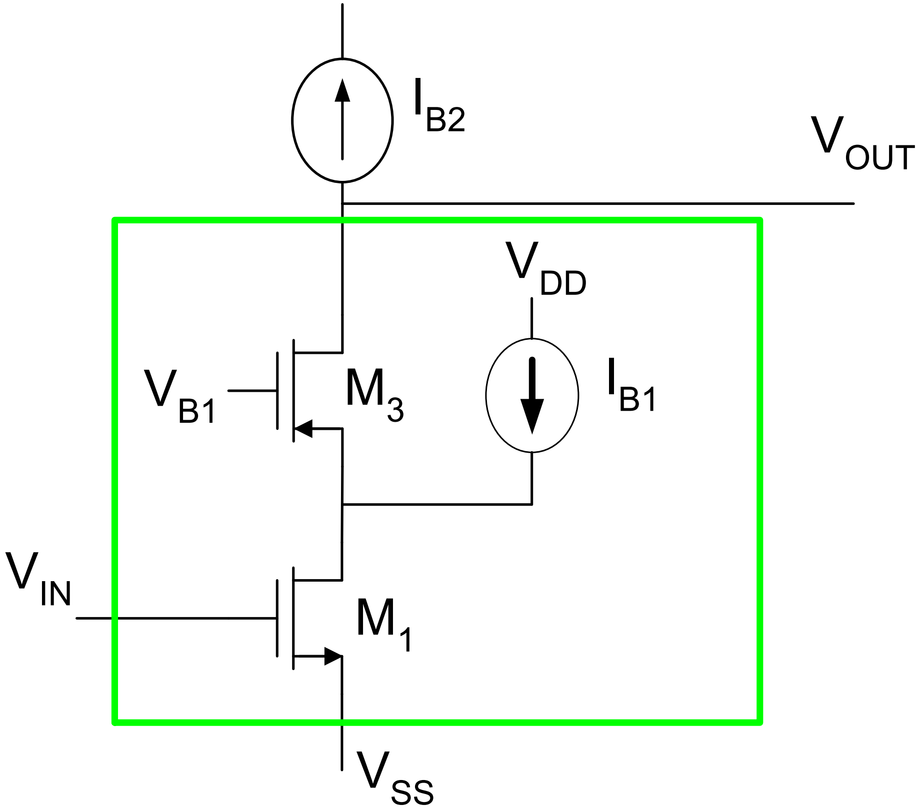
$$\boxed{A_{V0} = \frac{-G_{M1}}{2(G_1 + G_2)}}$$

$$BW = \frac{G_1 + G_2}{C_L}$$

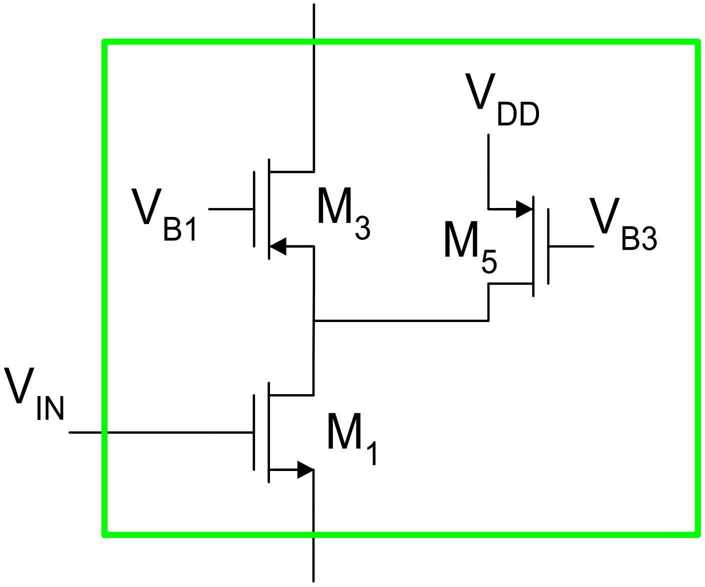
$$GB = \frac{G_{M1}}{2C_L}$$

Review from Last Lecture

Implementation of Biased Folded Cascode Amplifier?



Biased Folded Cascode



Implementation of Biased Folded Cascode

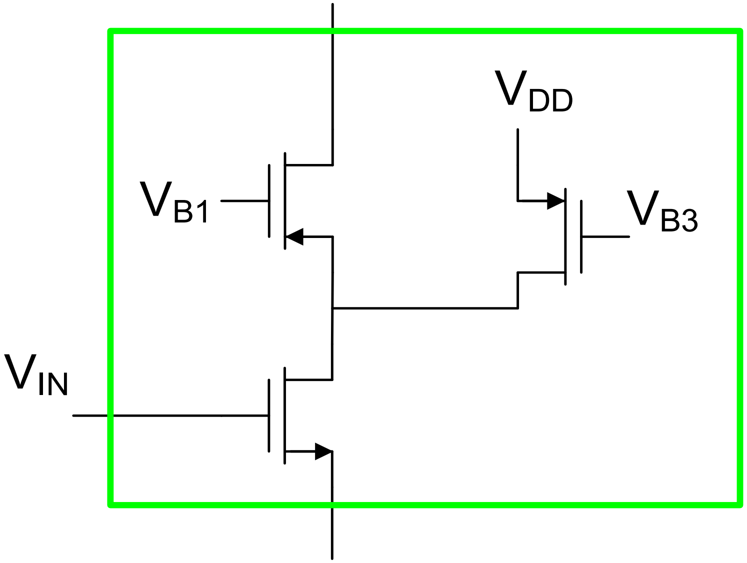
Review from Last Lecture

Basic Amplifier Structure Comparisons

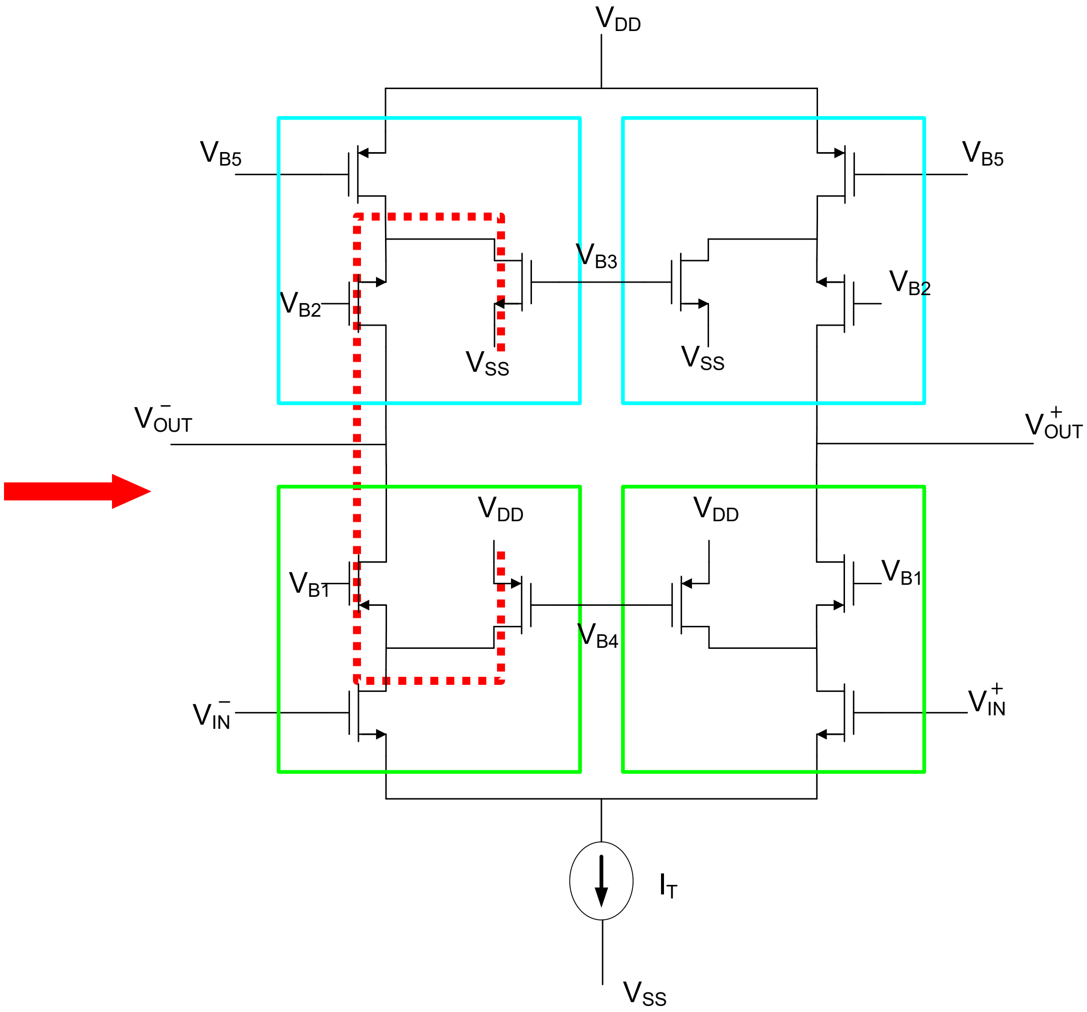
Practical Parameter Domain		
Common Source	$A_{VO}=\left(\frac{2}{\lambda}\right)\left(\frac{1}{V_{EB}}\right)$	$GB=\left(\frac{2P}{V_{DD}C_L}\right)\left(\frac{1}{V_{EB}}\right)$
Cascode	$A_{VO}=\left(\frac{4}{\lambda_1\lambda_3}\right)\left(\frac{1}{V_{EB1}V_{EB3}}\right)$	$GB=\left(\frac{2P}{V_{DD}C_L}\right)\left(\frac{1}{V_{EB1}}\right)$
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	$A_{VO}\approx\left(\frac{4\theta}{(\theta\lambda_1+\lambda_5)\lambda_3V_{EB1}V_{EB3}}\right)$	$GB=\left(\frac{2P}{V_{DD}C_L}\right)\left[\frac{\theta}{V_{EB1}}\right]$

Review from Last Lecture

Folded-Cascode Operational Amplifier



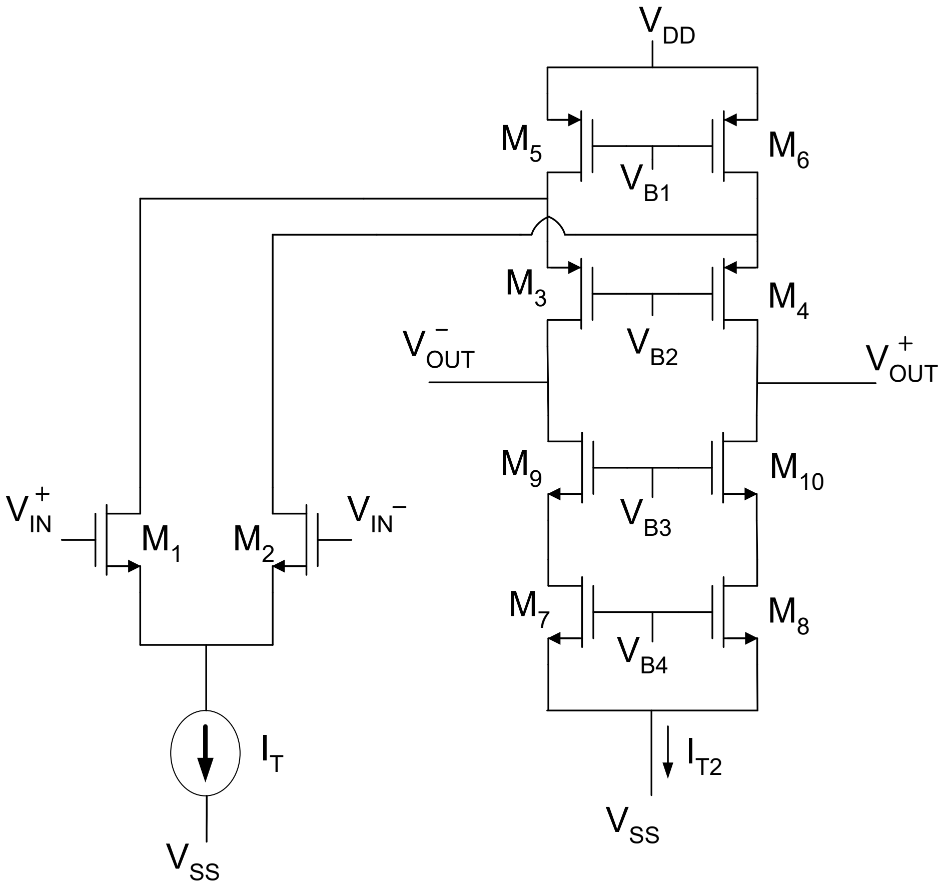
QUARTER CIRCUIT



Op Amp

Review from Last Lecture

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**

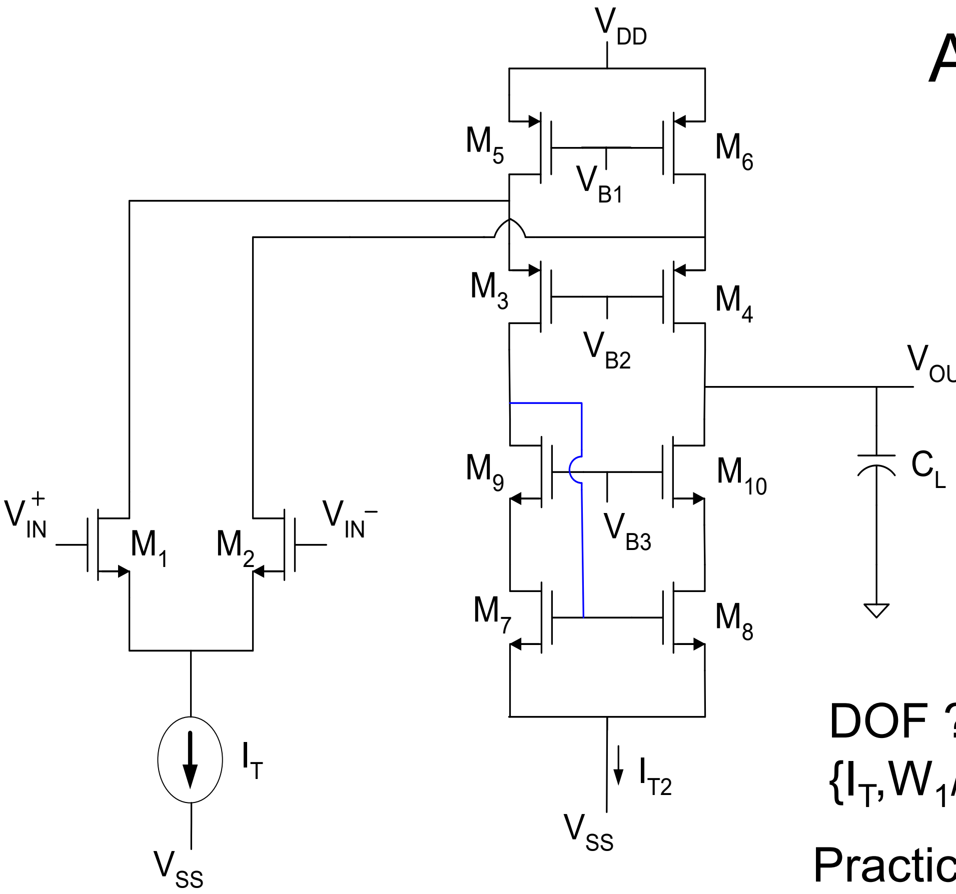
Review from Last Lecture

Operational Amplifier Structure Comparison

Practical Parameter Domain – Single-ended output exressions: Need CMFB			
Reference Op Amp	$A_{V0}=\left[\frac{1}{\lambda_1+\lambda_3}\right]\left(\frac{1}{V_{EB1}}\right)$	$GB=\left(\frac{P}{2V_{DD}C_L}\right)\bullet\left[\frac{1}{V_{EB1}}\right]$	$SR=\frac{P}{2V_{DD}C_L}$
Telescopic Cascode	$A_{V0}=\frac{2}{V_{EB1}\left(\lambda_1\lambda_3V_{EB3}+\lambda_5\lambda_7V_{EB5}\right)}$	$GB=\left(\frac{P}{2V_{DD}C_L}\right)\bullet\left[\frac{1}{V_{EB1}}\right]$	$SR=\frac{P}{2V_{DD}C_L}$
Regulated Cascode Θ=pct power in A	$A_{V0}\approx\frac{2}{V_{EB1}\left(\frac{\lambda_1\lambda_3V_{EB3}}{A_1}+\frac{\lambda_5\lambda_7V_{EB7}}{A_3}\right)}$	$GB=\left(\frac{P(1-\theta)}{2V_{DD}C_L}\right)\bullet\left[\frac{1}{V_{EB1}}\right]$	$SR=\frac{P(1-\theta)}{2V_{DD}C_L}$
Folded Cascode Θ=fraction of current of M_5 that is in M_1	$A_{V0}=\frac{2\theta}{V_{EB1}\left(\left(\theta\lambda_1+\lambda_5\right)\lambda_3V_{EB3}+\left(1-\theta\right)\lambda_9\lambda_7V_{EB9}\right)}$	$GB=\left(\frac{P}{2V_{DD}C_L}\right)\bullet\left[\frac{\theta}{V_{EB1}}\right]$	$SR=\frac{\theta\, P}{2V_{DD}C_L}$

Review from Last Lecture

Folded Cascode Op Amp (Single-ended Output)



$$A_{V0} \approx \frac{g_{m1}}{(g_{O1}+g_{O5})\frac{g_{O3}}{g_{m3}}+(g_{O7})\frac{g_{O9}}{g_{m9}}}$$

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

How many degrees of freedom are there?

What is a practical design parameter set?

DOF ? 9 DOF

$\{I_T, W_1/L_1, W_5/L_5, W_3/L_3, W_9/L_9, W_7/L_7, V_{B1}, V_{B2}, V_{B3}\}$

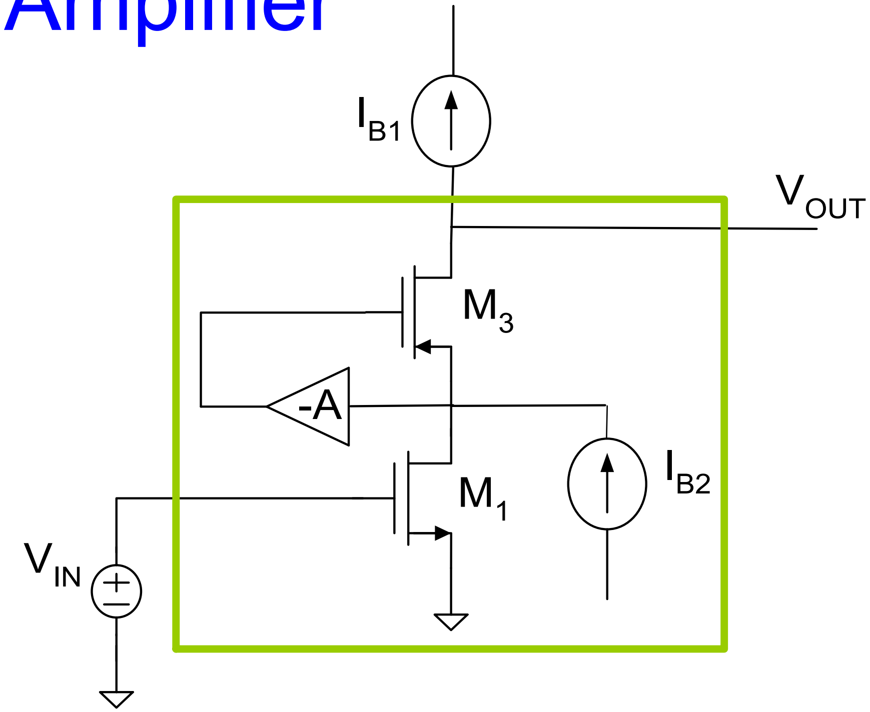
Practical Design Parameters

$\{P, \theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB7}, V_{EB9}, V_{B2}, V_{B3}\}$
where $\theta = I_T/(I_T+I_{T2})$

Folded Gain-boosted Cascode Amplifier

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

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



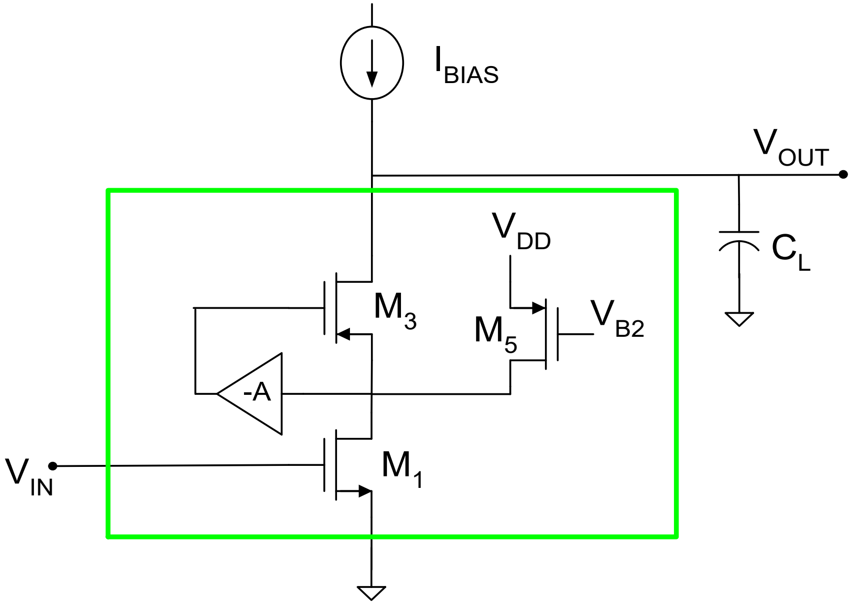
- **with ideal current source bias**
- **modest improvement in output swing**

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	$A_{VO} = \frac{g_{m1}}{\left(g_{O1} + g_{O5}\right)} \frac{g_{m3}}{g_{o3}} A$	$GB = \frac{g_{m1}}{C_L}$

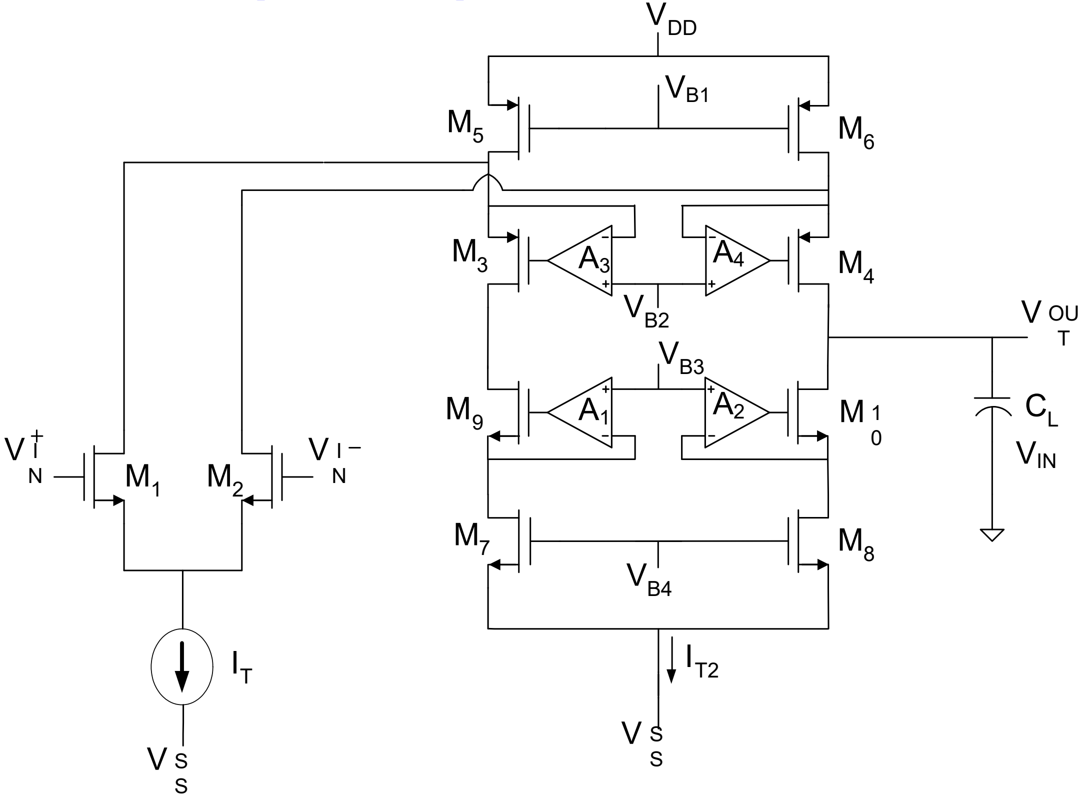
Basic Amplifier Structure Comparisons

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}**
- **Either single-ended or differential outputs**
- **Can connect counterpart as current mirror to eliminate CMFB**
- **Folding caused modest deterioration in GB efficiency and gain**
- **Modest improvement in output swing**

Operational Amplifier Structure Comparison

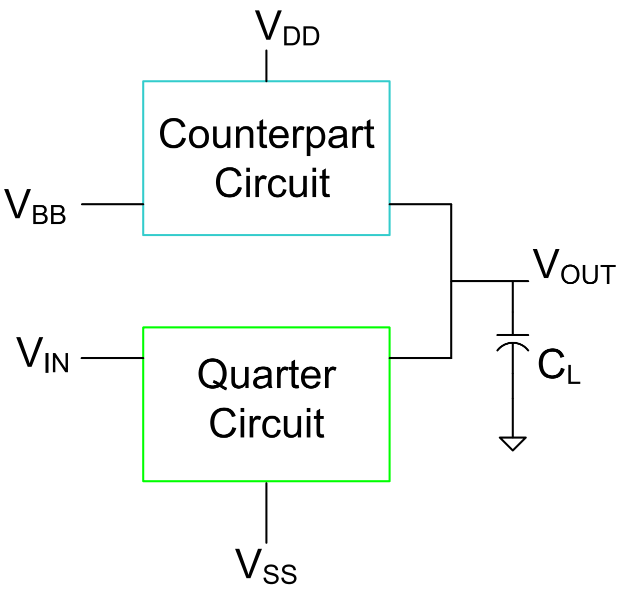
Small Signal Parameter Domain: Single-ended Output, Need CMFB			
Reference Op Amp	$A_{VO} = \frac{1}{2}\frac{g_{m1}}{g_{O1}+g_{O3}}$	$GB = \frac{g_{m1}}{2C_L}$	$SR = \frac{I_T}{2C_L}$
Telescopic Cascode	$A_o = \frac{\frac{g_{m1}}{2}}{g_{o1}\frac{g_{o3}}{g_{m3}} + g_{o7}\frac{g_{o5}}{g_{m5}}}$	$GB = \frac{g_{m1}}{2C_L}$	$SR = \frac{I_T}{2C_L}$
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	$A_o = \frac{\frac{g_{m1}}{2}}{(g_{o1}+g_{o5})\frac{g_{o3}}{g_{m3}A_3} + g_{o7}\frac{g_{o9}}{g_{m9}A_9}}$	$GB = \frac{g_{m1}}{2C_L}$	$SR = \frac{I_T}{2C_L}$

Summary of Folded Amplifier Performance

- \+ Modest improvement in output signal swing (from 5 $V_{DS\ SAT}$ to 4$V_{DS\ SAT}$)
- \+ Can directly feed output back to input to create buffer
- \- Deterioration in A_{V0} (maybe 30% or more)
- \- Deterioration in GB power efficiency (can be significant)
- \- 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:

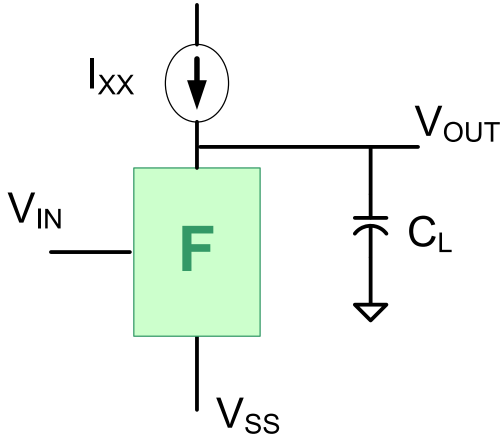
1. Decrease denominator of A_{V0}
2. Increase numerator of A_{V0}

Previous approaches focused on decreasing denominator

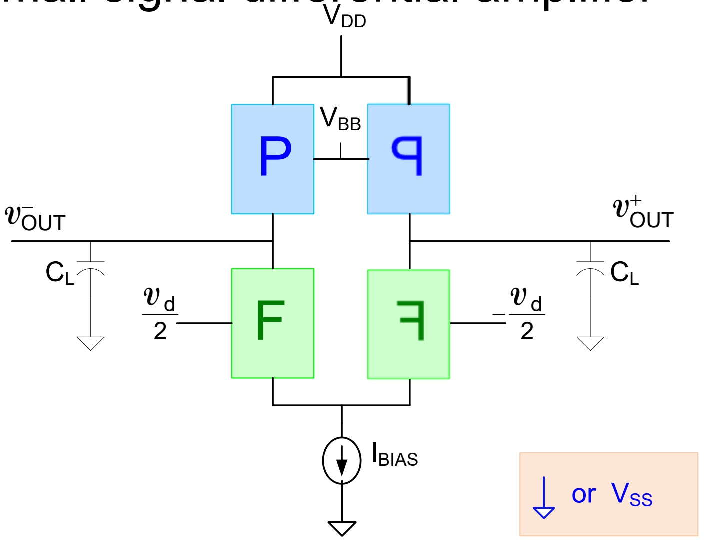
Consider now increasing numerator

Determination of op amp characteristics from quarter circuit characteristics

Small signal Quarter Circuit



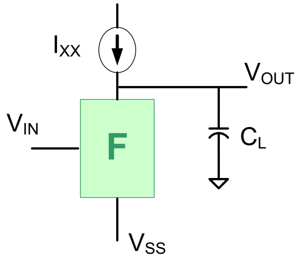
Small signal differential amplifier



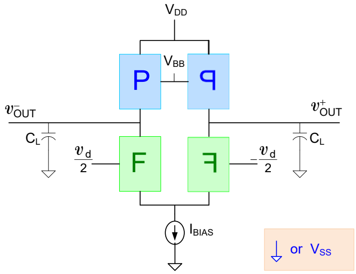
$$A_{VQC}(s)=\frac{-G_M}{sC_L+G} \quad \Longleftrightarrow \quad A_V=\frac{V_O^-}{V_d}=\frac{-\frac{G_{M1}}{2}}{sC_L+G_1+G_2}$$

- Note that the counterpart circuit is simply serving as the biasing current source
- Could use counterpart circuits (or other circuits) from other quarter circuits for “P”
- Counterpart circuits connected as one-port
- Can think of making differential op amp directly from quarter circuit

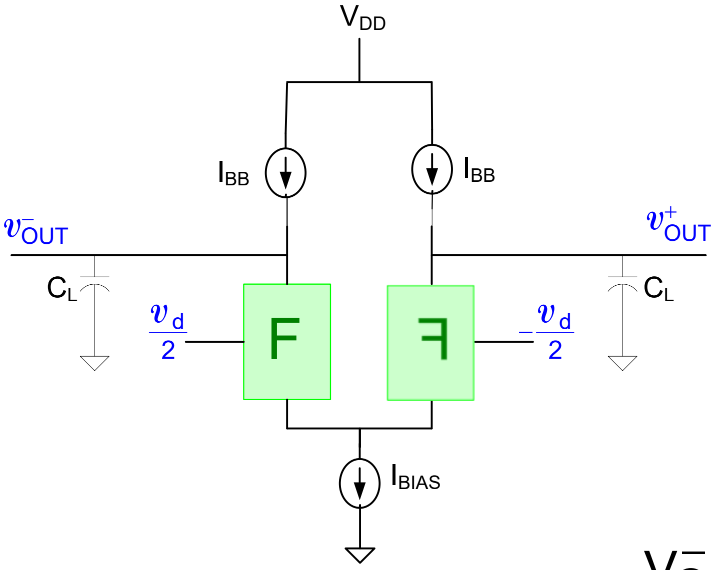
Differential input op amp directly from quarter circuit

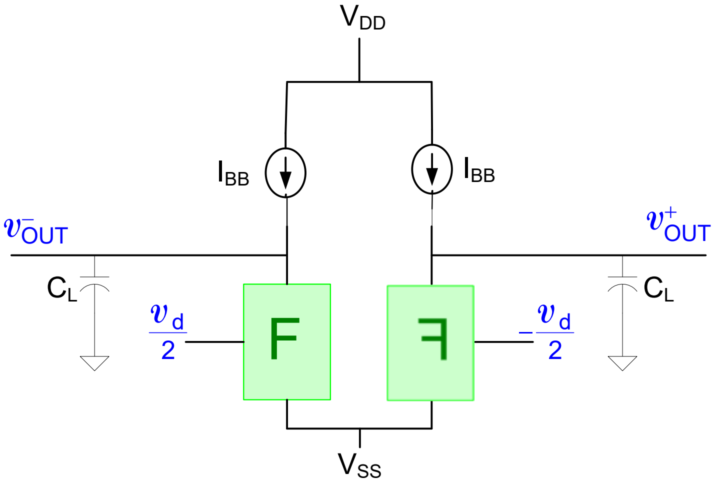


$$A_{VQC}(s) = \frac{-G_M}{sC_L + G}$$



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





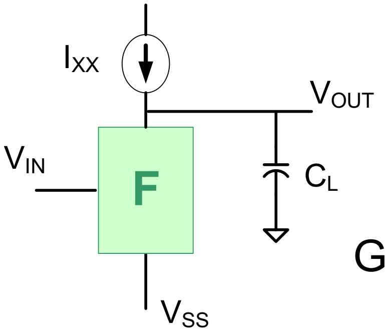
$$A_V = \frac{V_O^-}{V_d} = \frac{-\frac{G_{M1}}{2}}{sC_L + G_1 + G_{I_{BB}}}$$

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

Alternative insight into what is happening

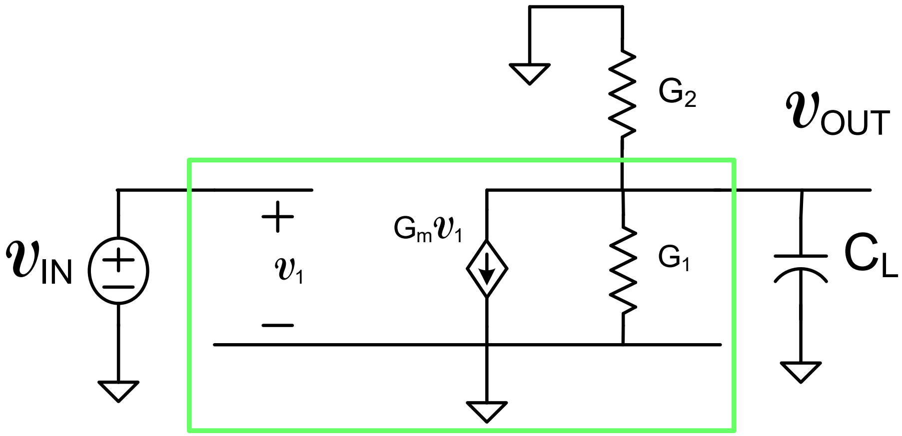
Can think of this as “steering” signal-dependent current to the output node which drives the total output conductance on the output node to obtain a signal-dependent output voltage

Consider general half-circuit:



$$G_2 = G_{I_{XX}}$$

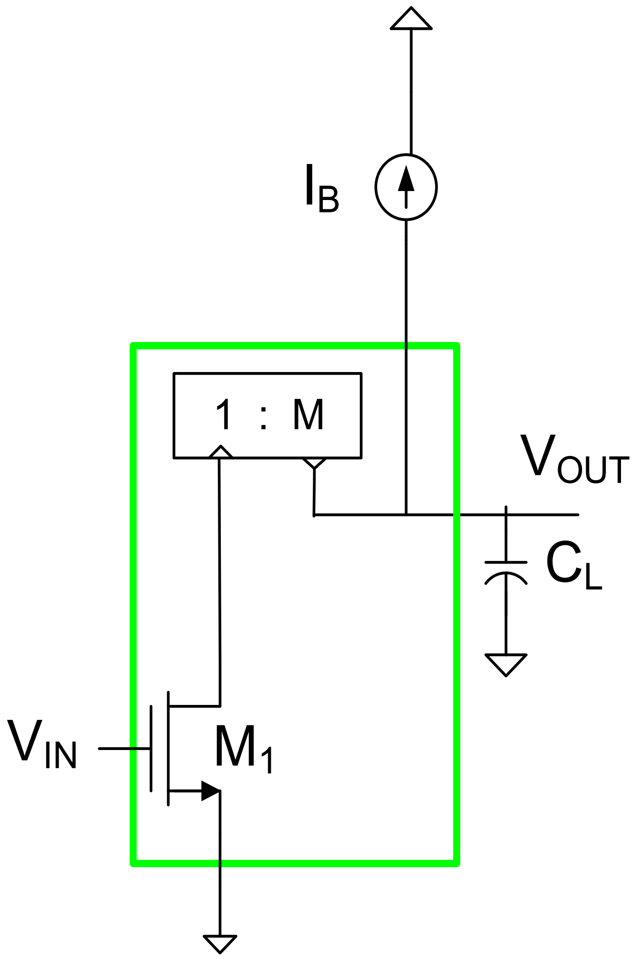
$$A_V(s) = \frac{-G_M}{sC_L + G_1 + G_2}$$



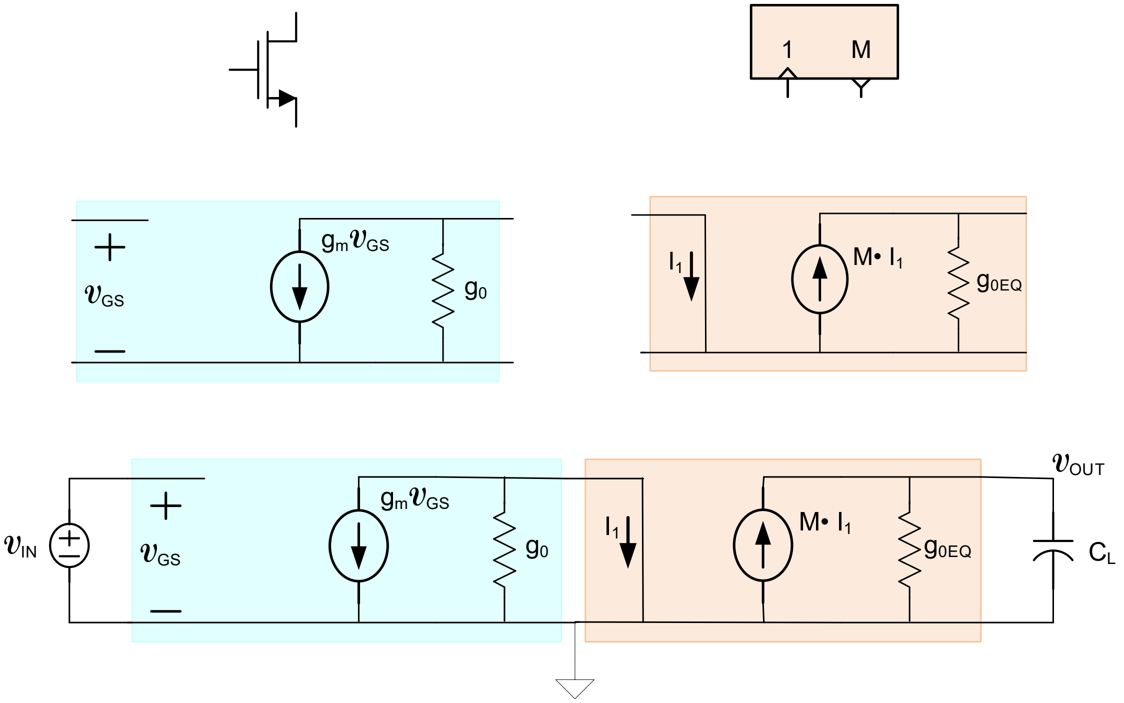
$$v_{OUT}\left(G_1 + G_2 + sC_L\right) + G_M v_{IN} = 0$$

Can G_M be increased by steering more current to the output?

g_{mEQ} Gain Enhancement Strategy



Consider this quarter circuit

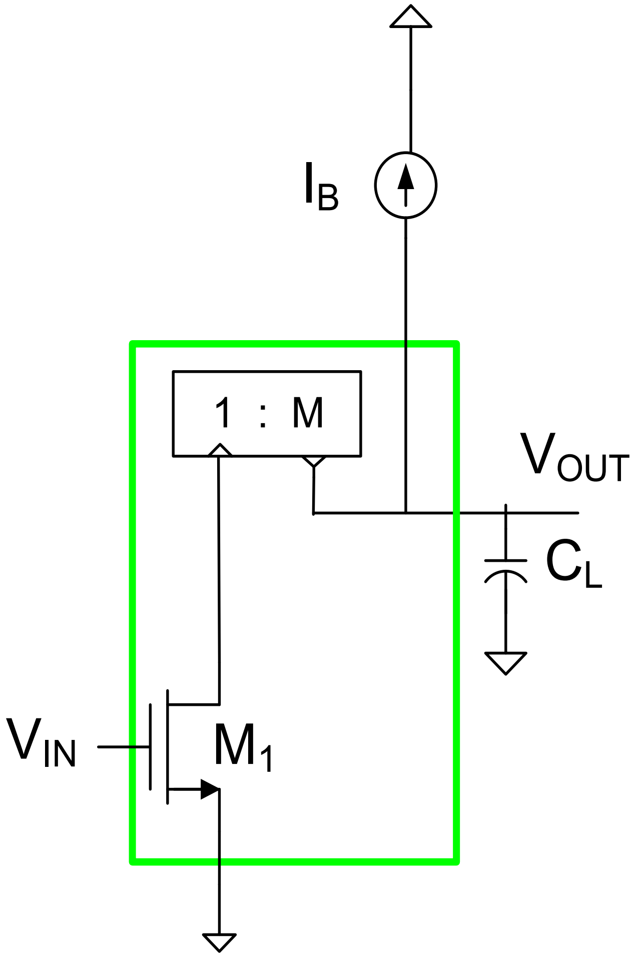


$$\left.\begin{aligned} v_{OUT}\left(sC_L + g_{OEQ}\right) &= MI_1 \\ I_1 &= -g_m v_{IN} \end{aligned}\right\} \Longrightarrow \frac{v_{OUT}}{v_{IN}} = -\frac{Mg_m}{sC_L + g_{OEQ}}$$

$$g_{mEQ} = Mg_m$$

Have increased effective g_m by M !!

g_{mEQ} Gain Enhancement Strategy



Consider this quarter circuit

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

g_m is increased by the mirror gain !

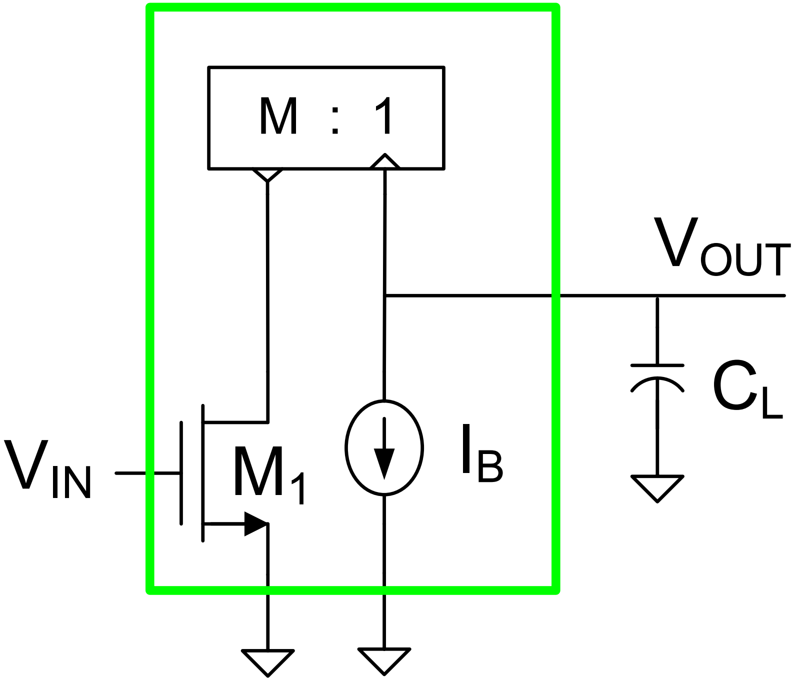
Folding is required to establish the correct bias current direction

Consider using the quarter circuit itself to form the op amp

Could have done this (or can do) for other quarter circuits as well

Output conductance of QC: g_{OQC}

g_{mEQ} Gain Enhancement Strategy



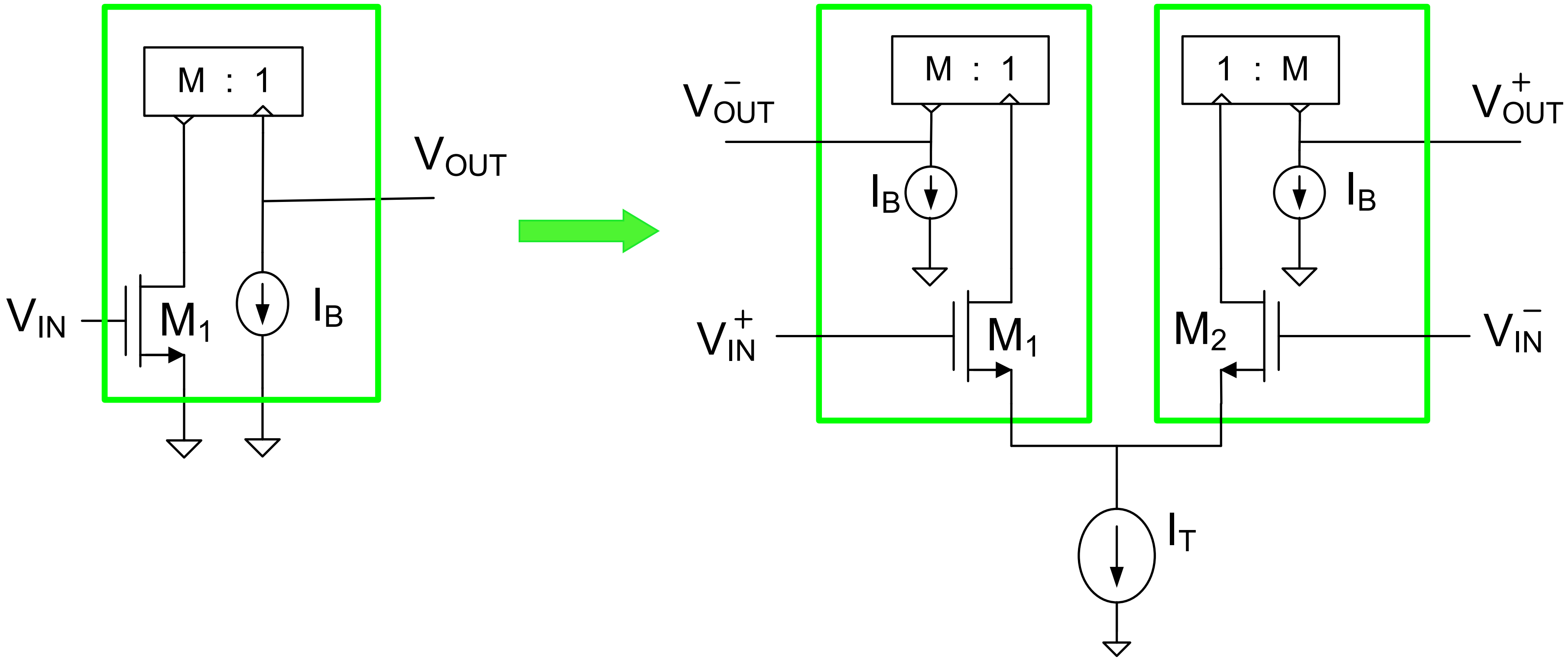
$$g_{MQC} = g_{M1}M$$

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

$$A_V = \frac{-g_{m1}M}{sC_L + g_{0EQ}}$$

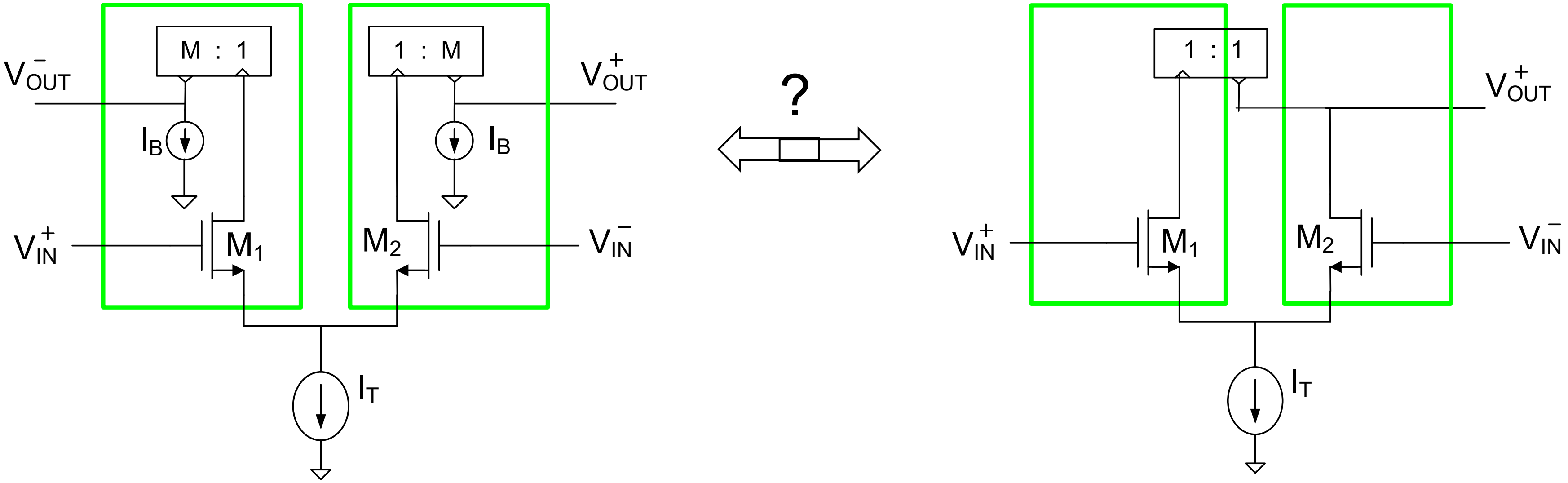
Redraw to absorb I_B in the quarter circuit

g_{mEQ} Gain Enhancement Strategy



g_{mEQ} Gain Enhancement Strategy

Have we seen something very similar to this before?



increases effective g_m by a factor of M

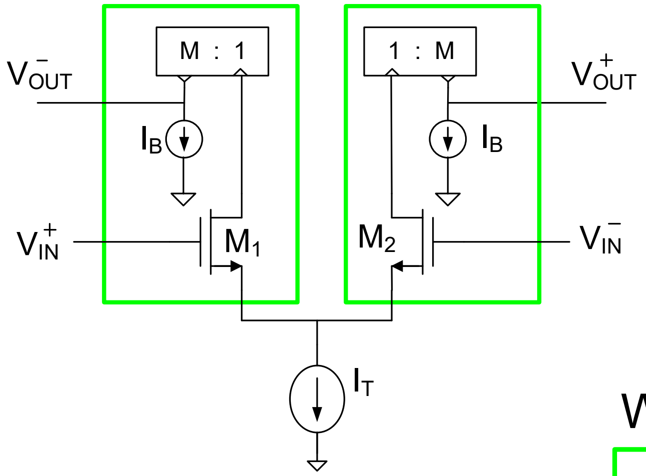
does not sacrifice an output

doubled effective g_m (factor of 1+M)

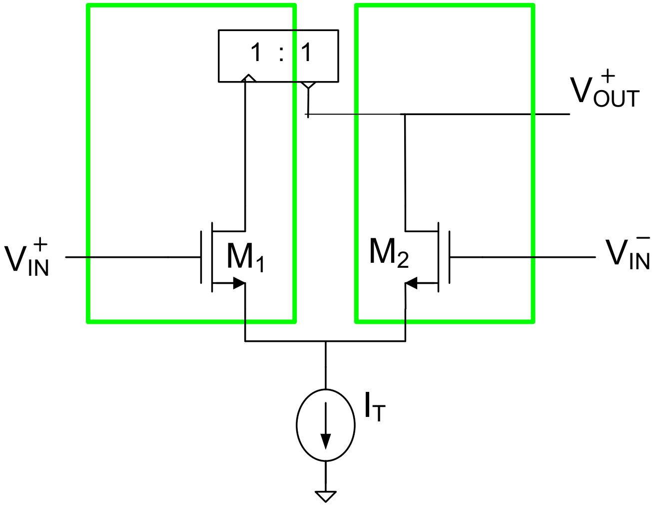
sacrificed one output

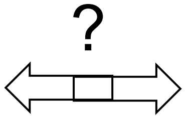
eliminates need for CMFB

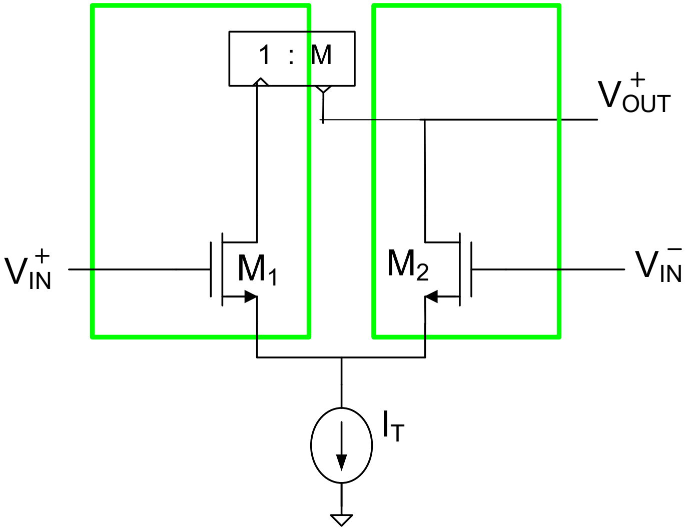
What about this?



What about this circuit?



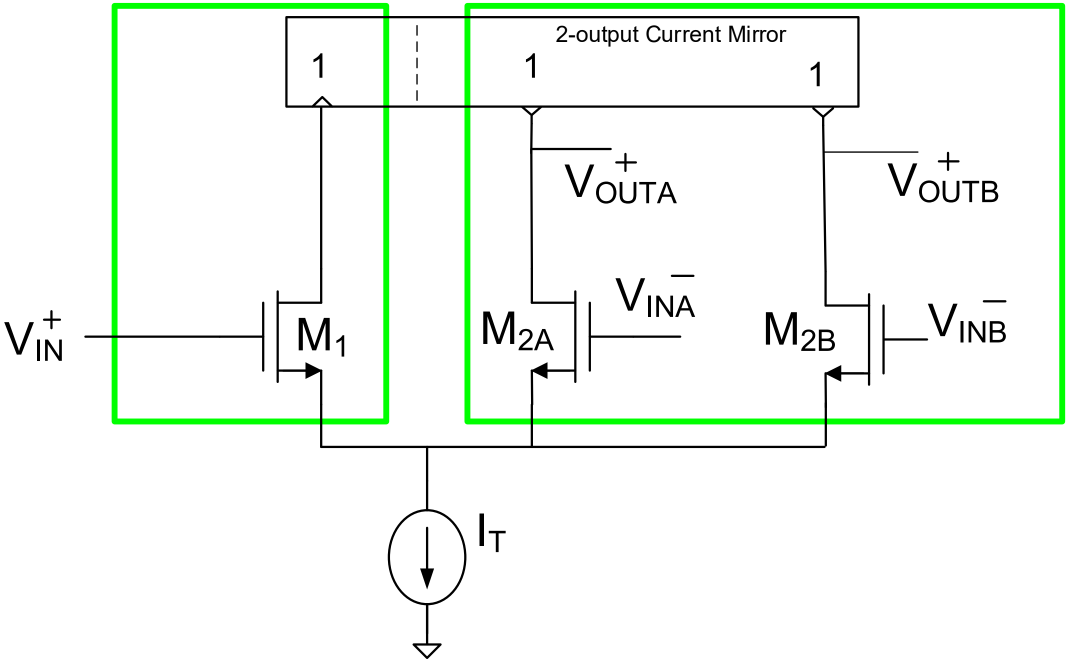


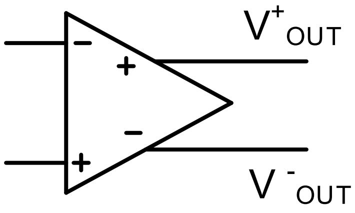


Increases effective g_m by 1+M

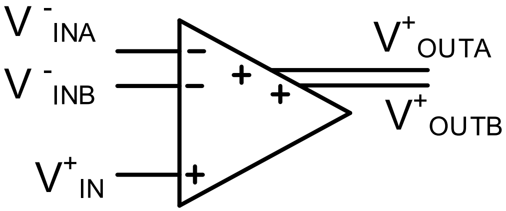
Leave this circuit to HW problem

What about this?





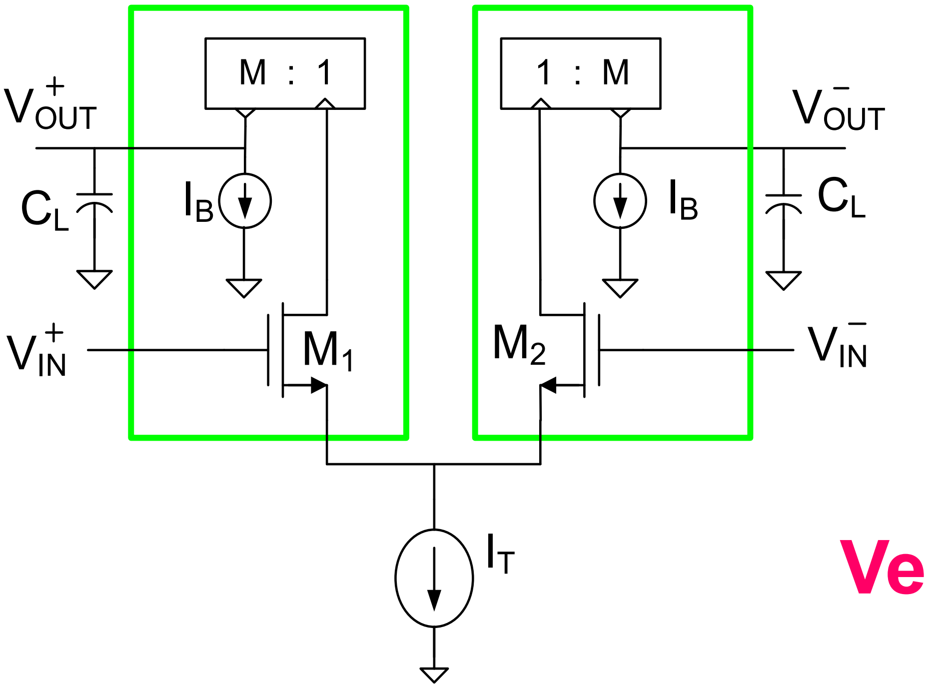
Not Quite



New Device

Interesting properties – is it useful?

Current Mirror Op Amps



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

$$A_{Vd}=\frac{-\frac{g_{m1}}{2}M}{sC_L+g_{0EQ}}$$

Very Simple Structure!

Premise: Transconductance gain increased by mirror gain M

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

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

$$g_{OEQ}=g_{O-mirror}+g_{OI_{BB}}$$

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

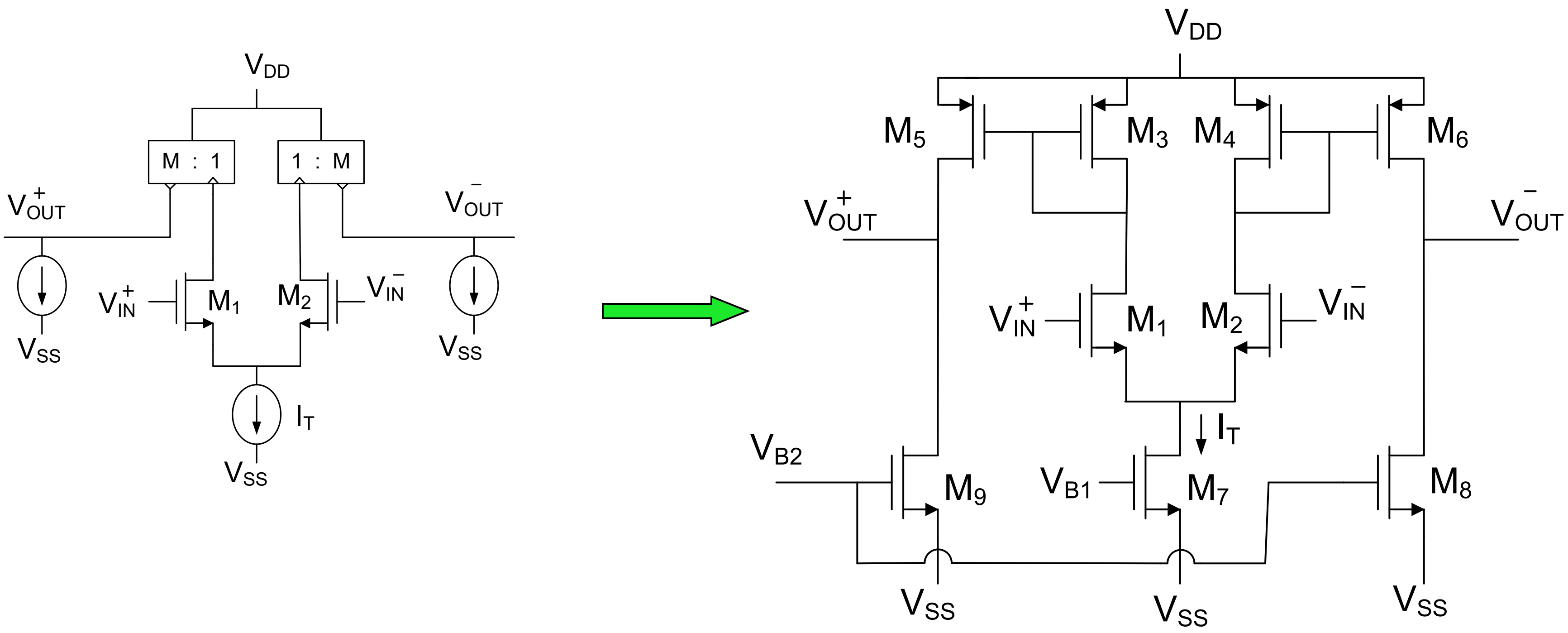
$$A_{V0}=-\frac{g_{mEQ}}{g_{OEQ}}$$

Premise: GB very good as well

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

Still need to generate the bias current I_B

Current Mirror Op Amps



Need CMFB to establish V_{B2}

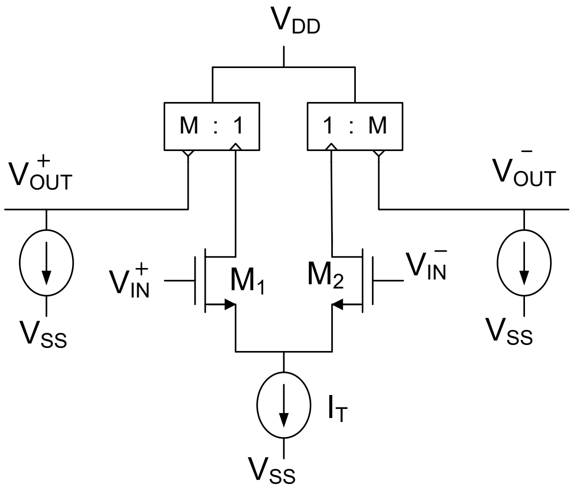
Basic Current Mirror Op Amp

Can use higher output impedance current mirrors

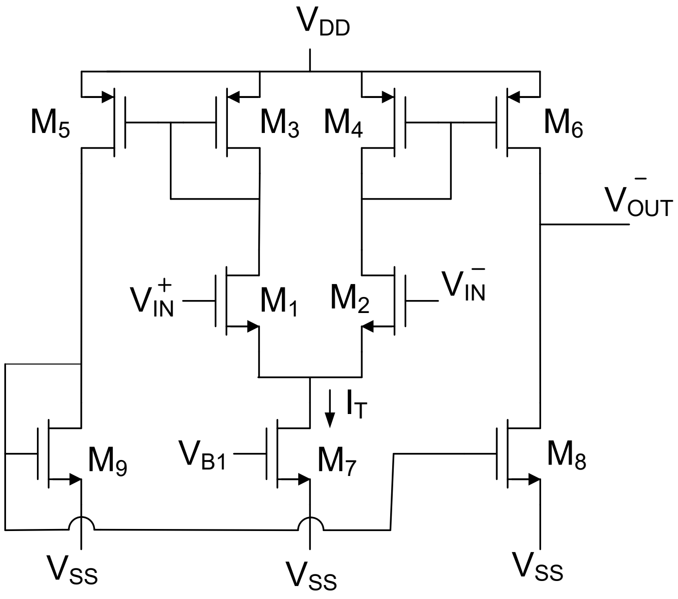
Can use current mirror bias to eliminate CMFB but loose one output

Current Mirror Op Amps

Elimination of CMFB



$$A_{Vd} = \frac{V_{OUT}^{-}}{V_d} = \frac{-\frac{g_{m1}}{2}M}{sC_L + g_{0EQ}}$$



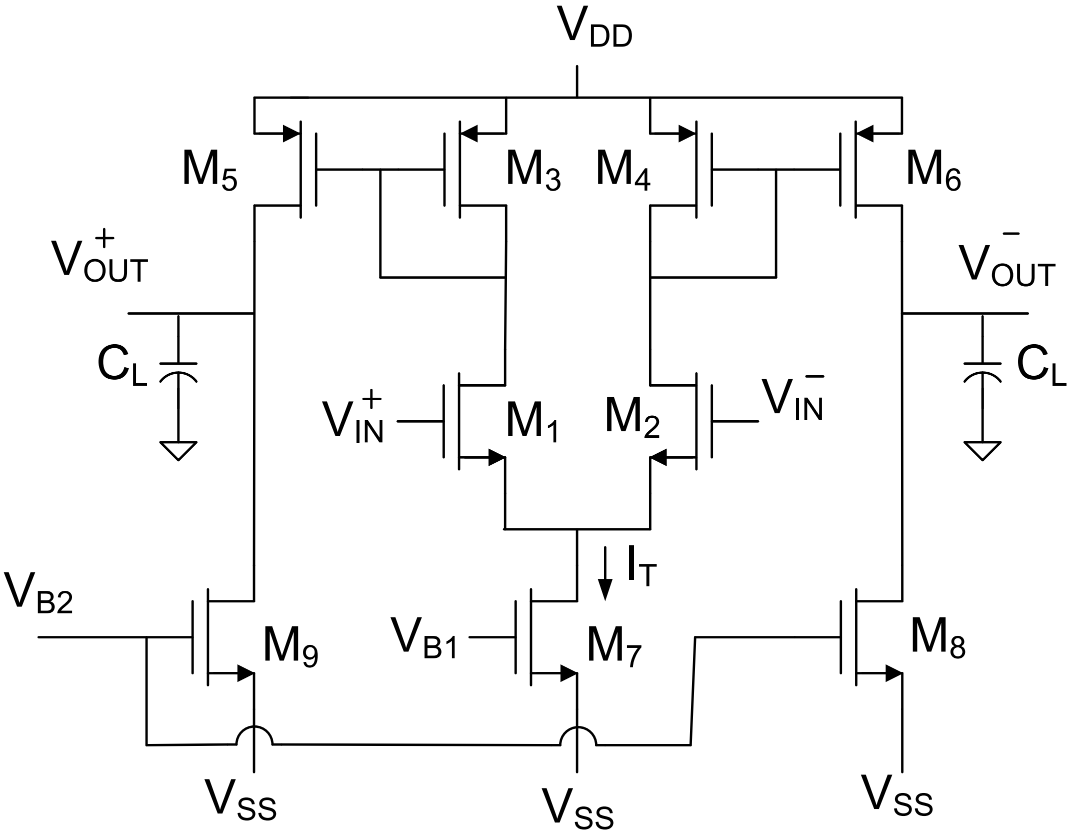
Alternative Basic Current Mirror Op Amp

$$A_{Vd} = \frac{-g_{m1}M}{sC_L + g_{0EQ}}$$

- Eliminated CMFB
- Doubled g_{meq}
- Sacrificed one output
- Good Signal Swing at input and outpu
- Only 9 transistors
- Very simple circuit

Is this a real clever solution?

Basic Current Mirror Op Amp



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

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

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

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

CMFB not shown

$$A_{Vd} = \frac{-g_{mEQ}}{sC_L + g_{0EQ}} = \frac{-\frac{g_{m1}}{2}M}{sC_L + g_{0EQ}}$$

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

Still need to verify improvements by factor of M in practical parameter domain !

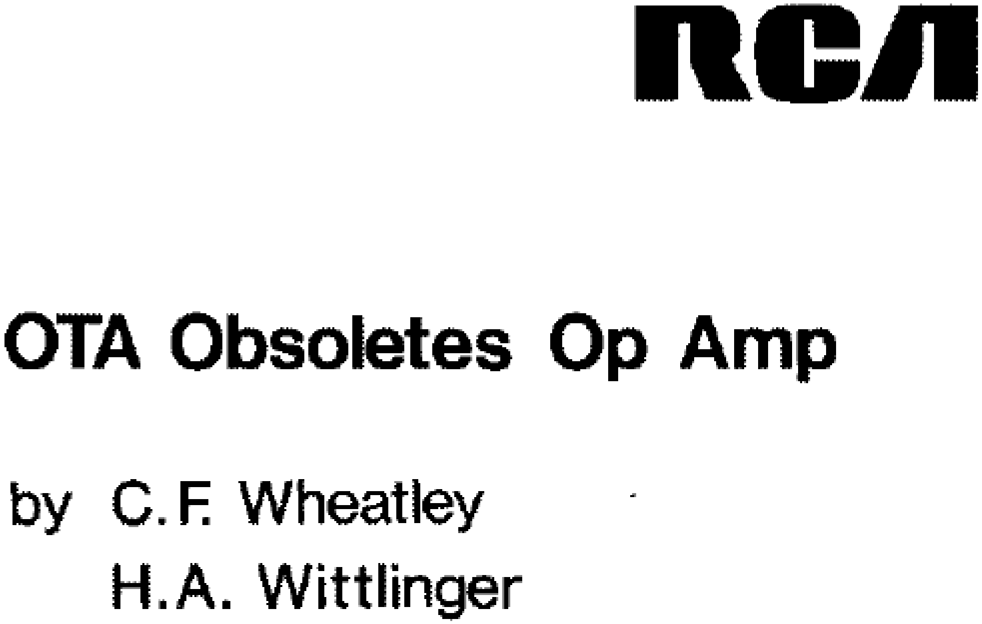
Basic Current Mirror Op Amp

- 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?

Before answering this question will investigate some OTA applications

Seminal Work on the OTA



RCA

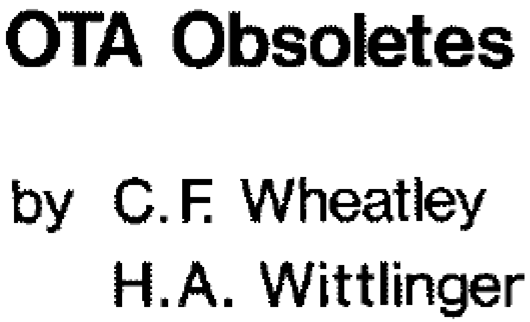
OTA Obsoletes Op Amp

by C.F. Wheatley
H.A. Wittlinger

From:

N.E.C. PROCEEDINGS

Seminal Work on the OTA



OTA Obsoletes Op Amp

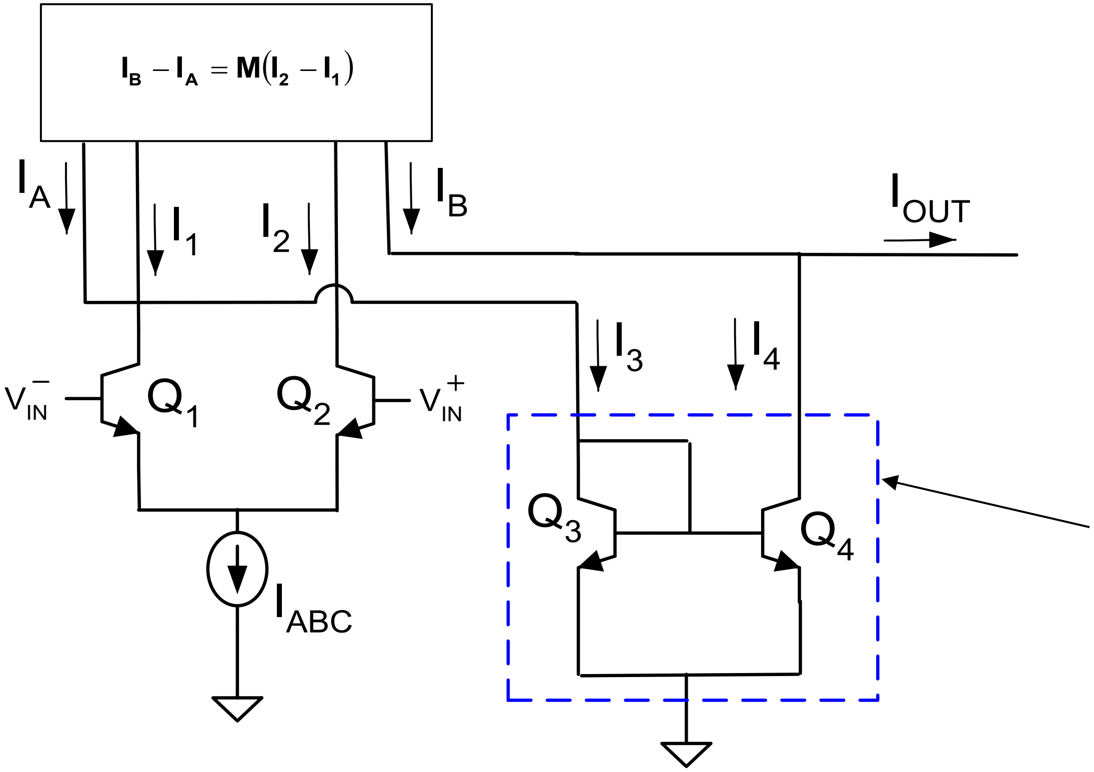
by C.F. Wheatley
H.A. Wittlinger

From:

1969 N.E.C. PROCEEDINGS
December 1969

First integrated circuit Op Amp designed by Bob Widlar of Fairchild in 1963 at age of 26 with selling price of $300

Original OTA



Current Mirror

$$I_A = I_3$$

$$I_B = I_{OUT} + I_4$$

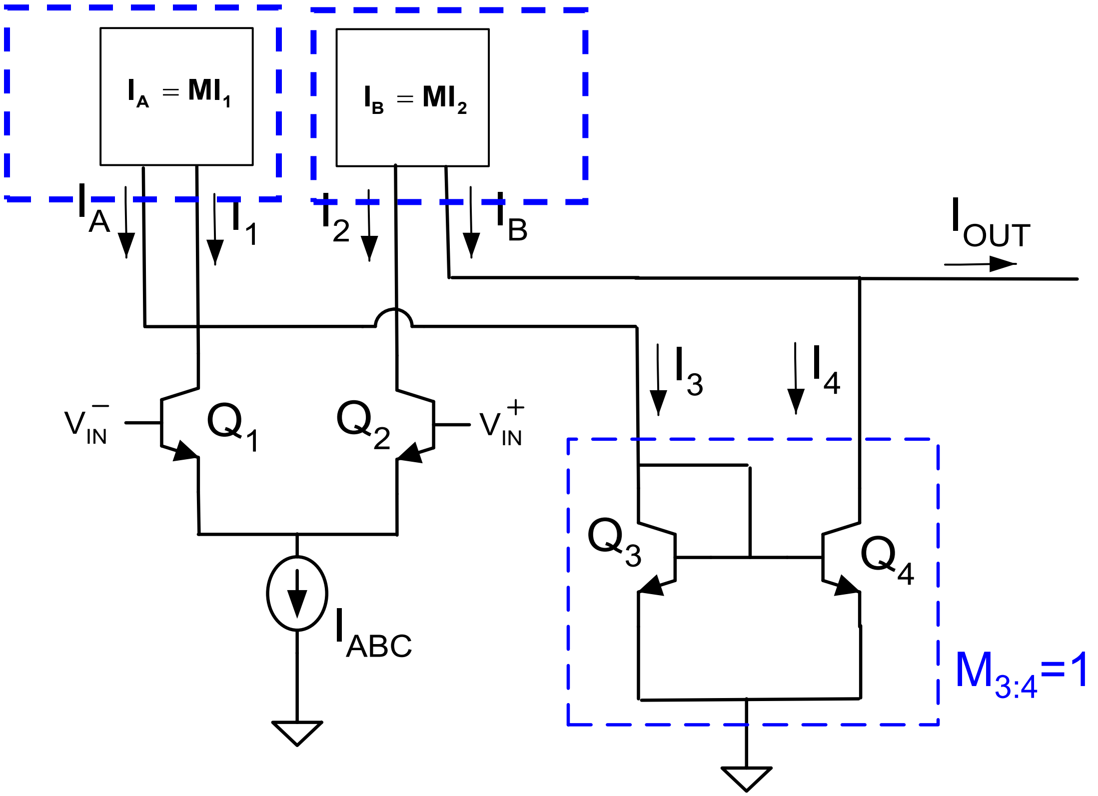
$$I_4 = I_3$$

$$I_A = MI_1$$

$$I_B = MI_2$$

$$\Longrightarrow \quad I_{OUT} = M(I_2 - I_1)$$

Original OTA



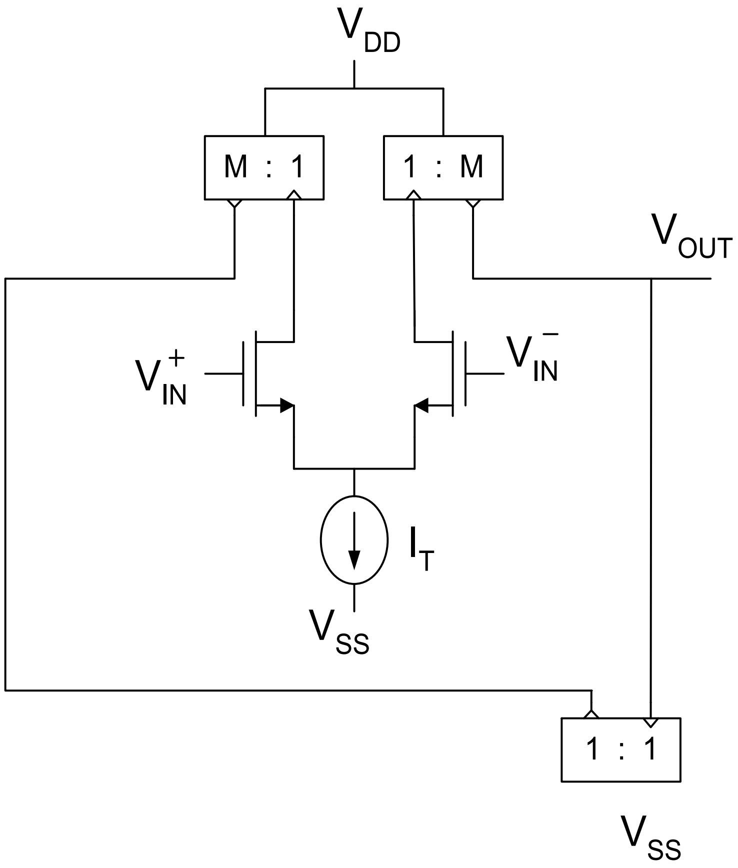
3-mirror OTA

$$V_{IN} = V_{IN}^+ - V_{IN}^-$$

$$\left.\begin{aligned} I_{OUT} &= M(I_2 - I_1) \\ I_2 - I_1 &= g_{m1} V_{IN} \end{aligned}\right\} \Longrightarrow \begin{aligned} I_{OUT} &= M g_{m1} V_{IN} \\ g_{meq} &= M g_{m1} \\ I_{OUT} &= g_{mEQ} V_{IN} \end{aligned}$$

Small-signal expressions same for MOS and Bipolar Structures

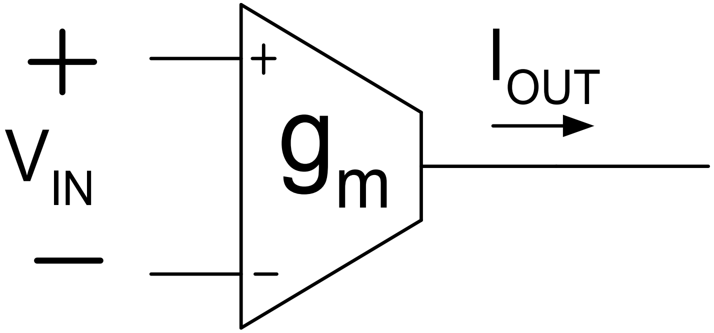
Current Mirror Op Amp W/O CMFB



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

For convenience, drop g_{mEQ} notation

Often termed an OTA

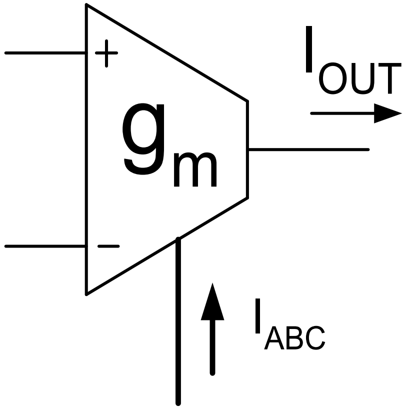


Introduced by Wheatley and Whitlinger in 1969

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

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



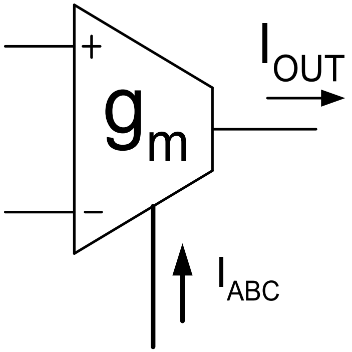
$$g_m = \begin{cases} K \bullet I_{ABC} & \text{for BJT circuits} \\ K\sqrt{I_{ABC}} & \text{for MOS circuits} \end{cases}$$

2 to 3 decades of adjustment for MOS

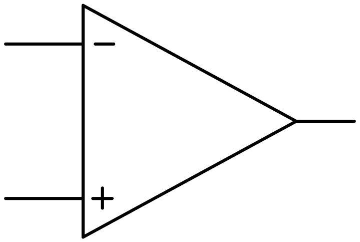
5 to 6 decades of adjustment for BJT

OTA Circuits

OTA often used open loop



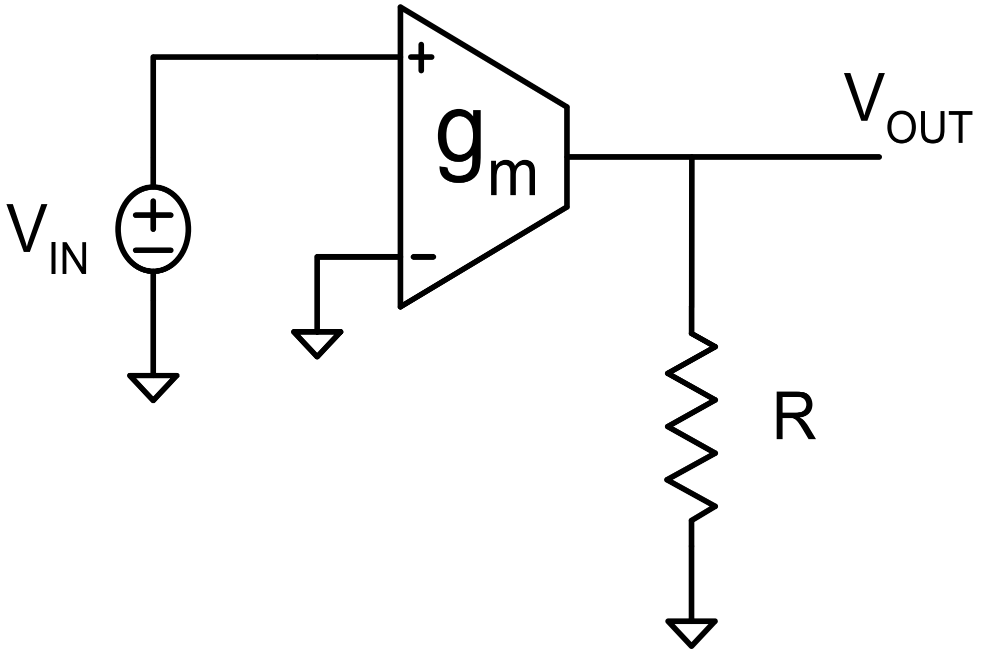
Recall: Op Amp almost never used open loop



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.

OTA Applications



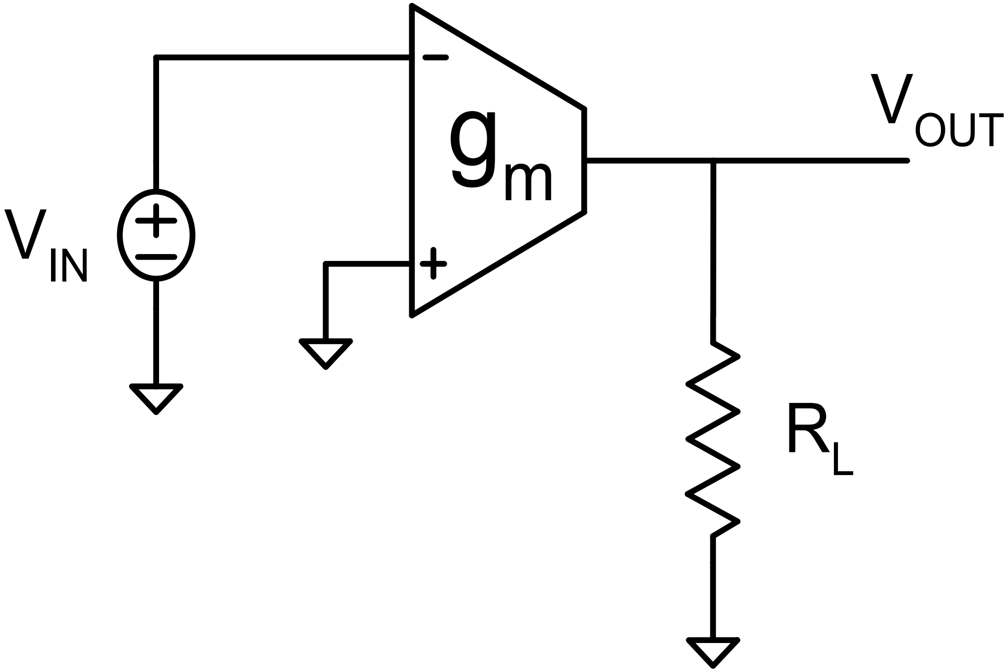
$$V_{OUT} = g_m R \bullet V_{IN}$$

g_m is controllable with I_{ABC}

Voltage Controlled Amplifier

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

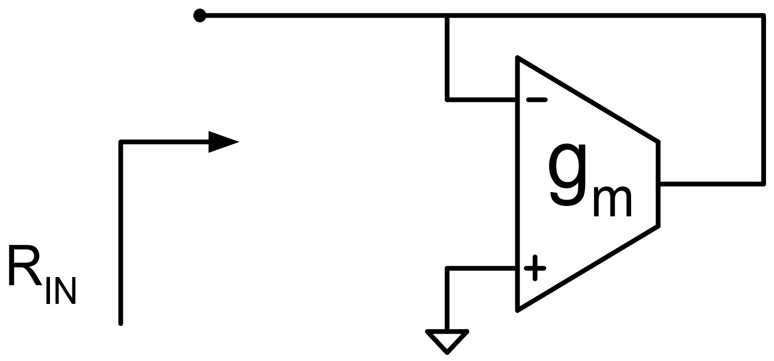
OTA Applications

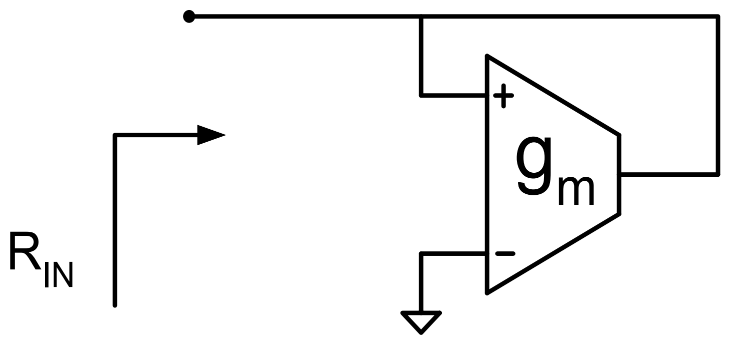


$$V_{OUT} = -g_m R \bullet V_{IN}$$

Voltage Controlled Inverting Amplifier

OTA Applications





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

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

Voltage Controlled Resistances

Guest Speaker:

Jonathan Crandall
Skyworks
Cedar Rapids Iowa

Stay Safe and Stay Healthy !

End of Lecture 9