# EE 435
# Lecture 10

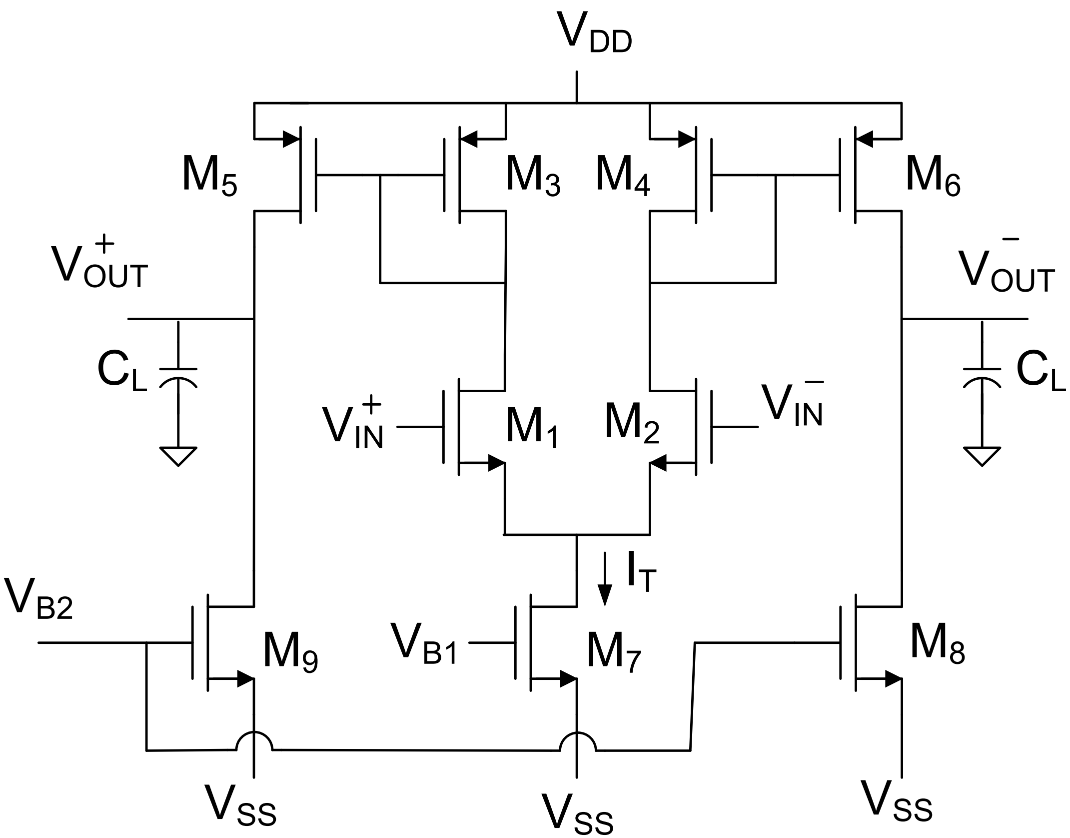
Laboratory Support
Transconductance vs Voltage Gain
OTA Applications

# 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<br>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<br>Θ=fraction of current of $M_5$ that is in $M_1$ | $A_{VO}\approx\left(\frac{4\theta}{(\theta\lambda_1+\lambda_5)\lambda_3 V_{EB1}V_{EB3}}\right)$ | $GB=\left(\frac{2P}{V_{DD}C_L}\right)\left[\frac{\theta}{V_{EB1}}\right]$ |
| Folded Regulated Cascode<br>$\Theta_1$=pct of total power in A<br>$\Theta_2$=fraction of current of $M_5$ that is in $M_1$ | $A_{VO}\approx\left(\frac{A4\theta_2}{(\theta_2\lambda_1+\lambda_5)\lambda_3 V_{EB1}V_{EB3}}\right)$ | $GB=\left(\frac{2P}{V_{DD}C_L}\right)\left(\frac{\theta_2(1-\theta_1)}{V_{EB1}}\right)$ |

Review from Last Lecture

# Basic Current Mirror Op Amp




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

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

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

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

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

CMFB not shown

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



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

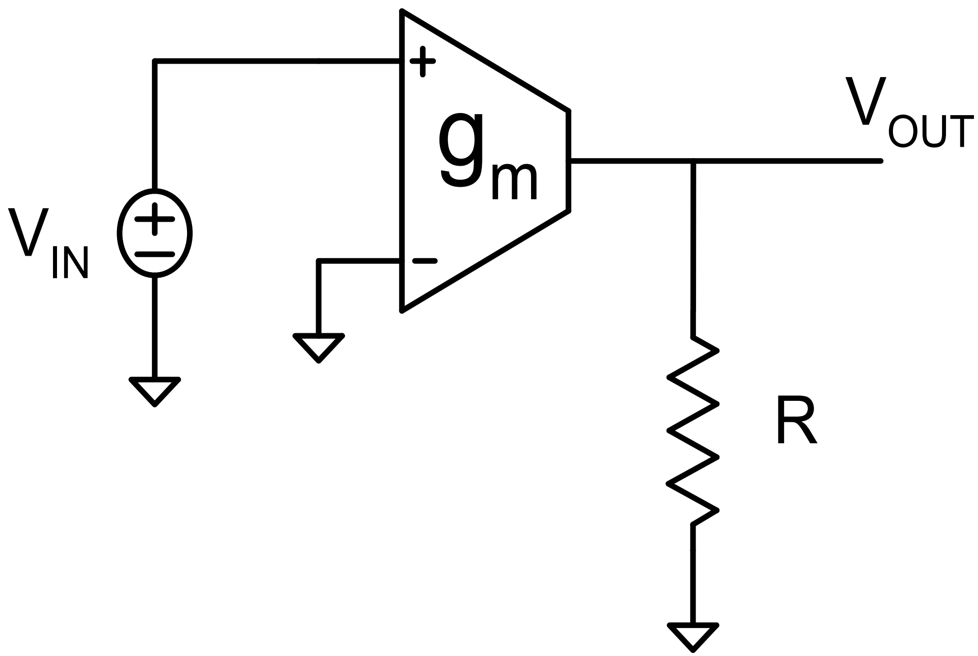
# Basic Current Mirror Op Amp

- 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?

**Review from Last Lecture**

# OTA Applications




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

$g_m$ is controllable with $I_{ABC}$

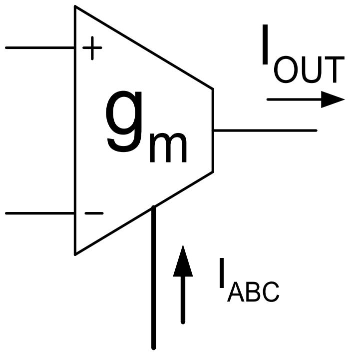
**Voltage Controlled Amplifier**

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

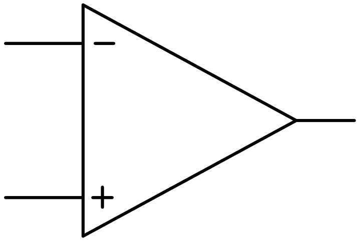
**Review from Last Lecture**

# OTA Circuits

OTA often used open loop



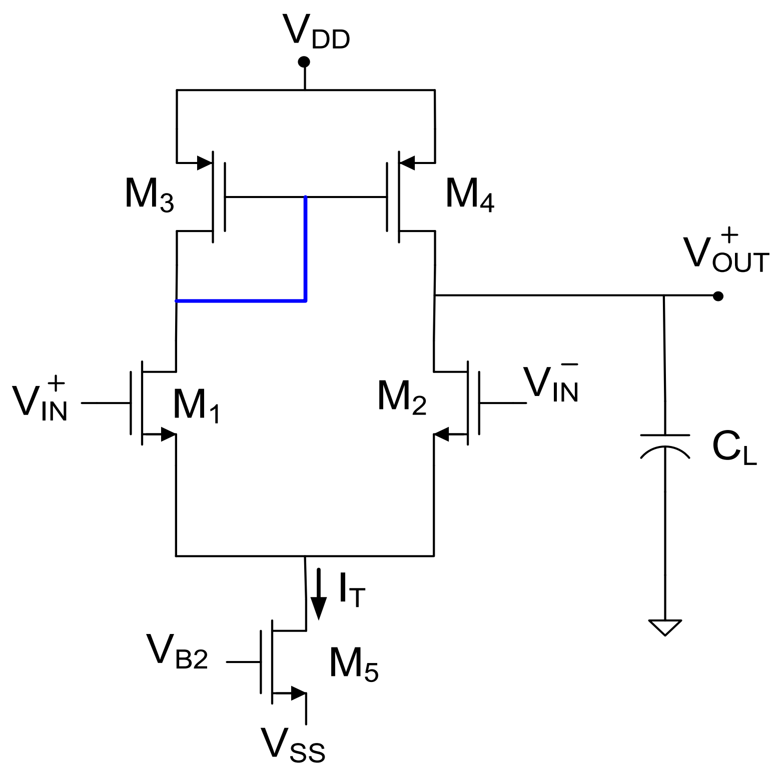

Recall: Op Amp almost never used open loop




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

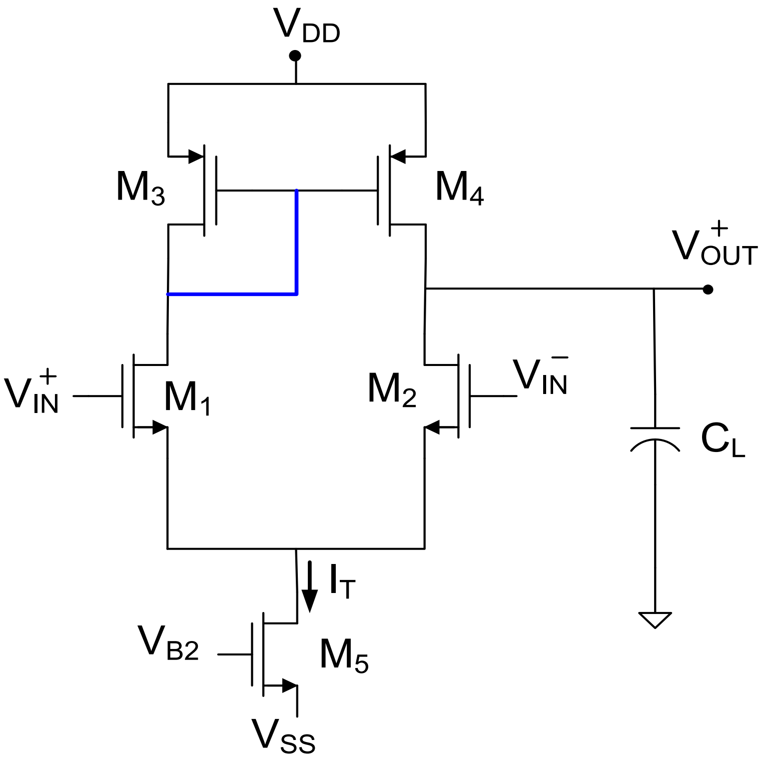
Challenge to students: Resolve what may appear to be conflicting statements. Will discuss this issue during the next lecture.

# Laboratory Support:



Recall from Lecture 6

# Design space for single-stage op amp




Performance Parameters in Practical Parameter Domain $\{V_{EB1}\ V_{EB3}\ V_{EB5}\ P\}$:

$$A_0 = \left[\frac{1}{\lambda_1 + \lambda_3}\right]\left(\frac{2}{V_{EB1}}\right)$$

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

$$SR = \frac{P}{(V_{DD} - V_{SS})C_L}$$

$$V_{OUT} < V_{DD} - |V_{EB3}|$$

$$V_{OUT} > V_{ic} - V_{T2}$$

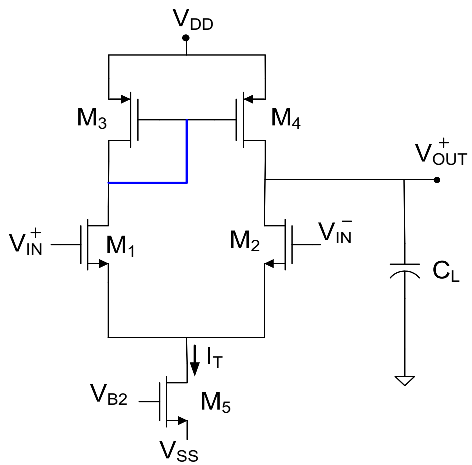
$$V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$$

$$V_{ic} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}$$

**Simple Expressions (7) in Practical Parameter Domain**

Recall from Lecture 6

# Design example for single-stage op amp




Performance Parameters in Practical Parameter Domain $\{V_{EB1}\ V_{EB3}\ V_{EB5}\ P\}$:

$$A_0 = \left[\frac{1}{\lambda_1+\lambda_3}\right]\left(\frac{2}{V_{EB1}}\right)$$

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

$$SR = \frac{P}{(V_{DD}-V_{SS})C_L}$$

$$V_{OUT} < V_{DD} - |V_{EB3}|$$

$$V_{OUT} > V_{ic} - V_{T2}$$

$$V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$$

$$V_{ic} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}$$

Assume design to meet $A_0$, GB and signal swing specs.

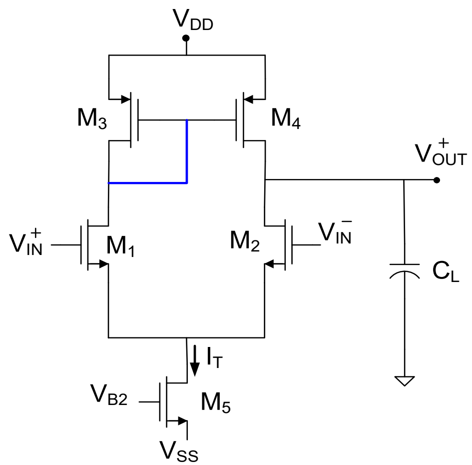
1. Select Parameter Domain (will use practical parameter domain) $\{V_{EB1}\ V_{EB3}\ V_{EB5}\ P\}$
2. Pick $V_{EB1}$ to meet gain requirement ) $\{\cancel{V_{EB1}}\ V_{EB3}\ V_{EB5}\ P\}$

$$V_{EB1} = \left[\frac{1}{\lambda_1+\lambda_3}\right]\left(\frac{2}{A_0}\right)$$

3. Pick P to meet GB requirement $\{\cancel{V_{EB1}}\ V_{EB3}\ V_{EB5}\ \cancel{P}\}$
4. Pick $V_{EB3}$ and $V_{EB5}$ to meet signal swing requirements
5. Map back from the Practical Parameter Domain to the Natural Parameter domain (next page)

Recall from Lecture 6

# Design example for single-stage op amp




Performance Parameters in Practical Parameter Domain $\{ V_{EB1}\ V_{EB3}\ V_{EB5}\ \ P\}$:

Mapping from Practical Parameter Domain $\{ V_{EB1}\ V_{EB3}\ V_{EB5}\ \ P\}$ to Natural Parameter Domain $\{ W_1/L_1\ \ W_3/L_3\ \ W_5/L_5\ \ I_T\}$

From expression $I_{Dk} = \dfrac{\mu_k C_{ox} W_k}{2L_k} V_{EBk}^2$ it follows that

$$\frac{W_1}{L_1} = \frac{1}{\mu_n C_{OX} V_{EB1}^2} \frac{P}{V_{DD} - V_{SS}}$$

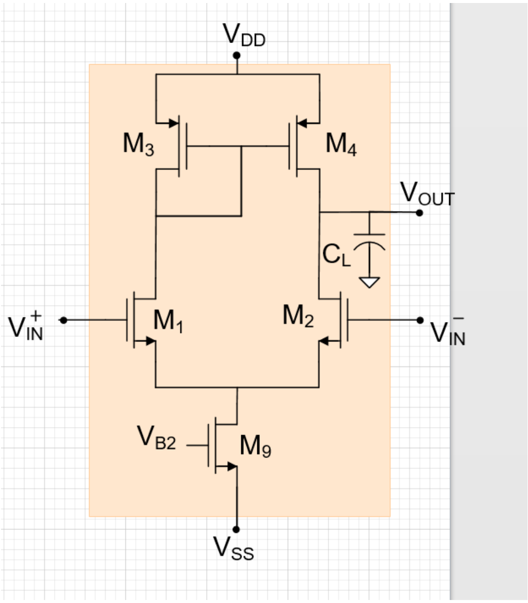
$$\frac{W_3}{L_3} = \frac{1}{\mu_p C_{OX} V_{EB3}^2} \frac{P}{V_{DD} - V_{SS}}$$

$$\frac{W_5}{L_5} = \frac{2}{\mu_n C_{OX} V_{EB5}^2} \frac{P}{V_{DD} - V_{SS}}$$

$$I_T = \frac{P}{V_{DD} - V_{SS}} \quad \text{or} \quad V_{B2} = V_{EB5} + V_{ss} + V_{THn}$$

# Design Space Exploration

## Consider the 5T Op Amp with CM Biasing




### 5T Op Amp Design

**Process Paramaters**

| | | |
|---|---|---|
| **μnCOX** | 350 | uAV^2 |
| **μpCOX** | 75 | uAV^2 |
| **VTHn** | 0.4 | V |
| **VTHp** | -0.4 | V |
| **λ** | 0.01 | V^-1 |

**Fixed Contraints**

| | | |
|---|---|---|
| **VDD** | 2 | V |
| **VSS** | -2 | V |
| **CL** | 10 | pf |
| **L1=L2=...=L k** | 0.5 | um |
| **VB2** | 0.6 | V |

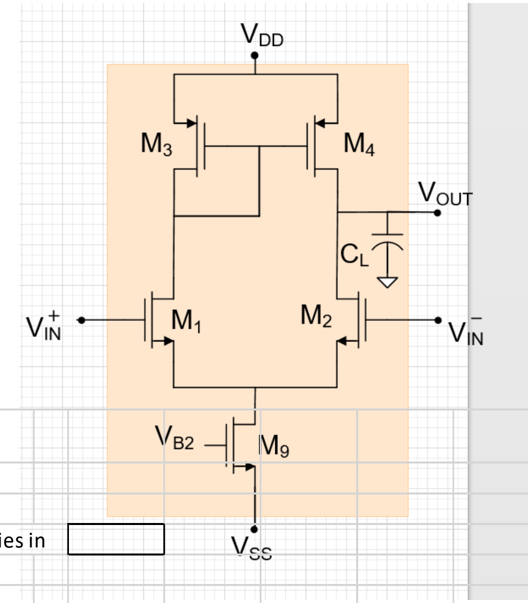
Input Quantities in

| **Op Amp** | **Design Variables** | | | | **Performance Characteristics** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No** | **VEB1** | **VEB3** | **VEB9** | **P (mw)** | **A0** | **BW (MHz)** | **GB (MHz)** | **SR (V/uS)** | **Vomax** | **Vomin** | **VCM** | **IT (mA)** |
| 1 | 0.1 | -0.1 | 0.1 | 5 | 1000 | 0.20 | 199.04 | 0.125 | 1.9 | 0 | 0.1 | 1.25 |
| 2 | 0.2 | -0.2 | 0.1 | 5 | 500 | 0.20 | 99.52 | 0.125 | 1.8 | -0.1 | 0.1 | 1.25 |
| 3 | 0.4 | -0.1 | 0.1 | 5 | 250 | 0.20 | 49.76 | 0.125 | 1.9 | -0.3 | 0.1 | 1.25 |
| 4 | 0.05 | -0.1 | 0.1 | 5 | 2000 | 0.20 | 398.09 | 0.125 | 1.9 | 0.05 | 0.1 | 1.25 |
| 5 | 0.1 | -0.1 | 0.1 | 1 | 1000 | 0.04 | 39.81 | 0.025 | 1.9 | 0 | 0.1 | 0.25 |
| 6 | 0.1 | -0.1 | 0.1 | 10 | 1000 | 0.40 | 398.09 | 0.25 | 1.9 | 0 | 0.1 | 2.5 |
| 7 | 0.1 | -0.1 | 0.1 | 0.1 | 1000 | 0.00 | 3.98 | 0.0025 | 1.9 | 0 | 0.1 | 0.025 |
| 8 | 0.1 | -0.1 | 0.1 | 20 | 1000 | 0.80 | 796.18 | 0.5 | 1.9 | 0 | 0.1 | 5 |
| 9 | 0.1 | -0.1 | 0.2 | 1 | 1000 | 0.04 | 39.81 | 0.025 | 1.9 | 0 | 0.1 | 0.25 |
| 10 | 0.1 | -0.2 | 0.1 | 0.1 | 1000 | 0.00 | 3.98 | 0.0025 | 1.8 | 0 | 0.1 | 0.025 |

| **No** | **Practical Design Values in um** | | | | | **Small Signal Parameters (if desired)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **W1** | **W2** | **W3** | **W4** | **W9** | **gm1** | **gm3** | **gm9** | **go1** | **go3** | **go9** |
| 1 | 357.1 | 357.1 | 1666.7 | 1666.7 | 714.3 | 0.0125 | 0.0125 | 0.025 | 6.25E-06 | 6.25E-06 | 1.3E-05 |
| 2 | 89.3 | 89.3 | 416.7 | 416.7 | 714.3 | 0.00625 | 0.00625 | 0.025 | 6.25E-06 | 6.25E-06 | 1.3E-05 |
| 3 | 22.3 | 22.3 | 1666.7 | 1666.7 | 714.3 | 0.003125 | 0.0125 | 0.025 | 6.25E-06 | 6.25E-06 | 1.3E-05 |
| 4 | 1428.6 | 1428.6 | 1666.7 | 1666.7 | 714.3 | 0.025 | 0.0125 | 0.025 | 6.25E-06 | 6.25E-06 | 1.3E-05 |
| 5 | 71.4 | 71.4 | 333.3 | 333.3 | 142.9 | 0.0025 | 0.0025 | 0.005 | 1.25E-06 | 1.25E-06 | 2.5E-06 |
| 6 | 714.3 | 714.3 | 3333.3 | 3333.3 | 1428.6 | 0.025 | 0.025 | 0.05 | 1.25E-05 | 1.25E-05 | 2.5E-05 |
| 7 | 7.1 | 7.1 | 33.3 | 33.3 | 14.3 | 0.00025 | 0.00025 | 0.0005 | 1.25E-07 | 1.25E-07 | 2.5E-07 |
| 8 | 1428.6 | 1428.6 | 6666.7 | 6666.7 | 2857.1 | 0.05 | 0.05 | 0.1 | 0.000025 | 0.000025 | 0.00005 |
| 9 | 71.4 | 71.4 | 333.3 | 333.3 | 35.7 | 0.0025 | 0.0025 | 0.0025 | 1.25E-06 | 1.25E-06 | 2.5E-06 |
| 10 | 7.1 | 7.1 | 8.3 | 8.3 | 14.3 | 0.00025 | 0.000125 | 0.0005 | 1.25E-07 | 1.25E-07 | 2.5E-07 |

# Design Space Exploration

## Embedded Spreadsheet




### 5T Op Amp Design

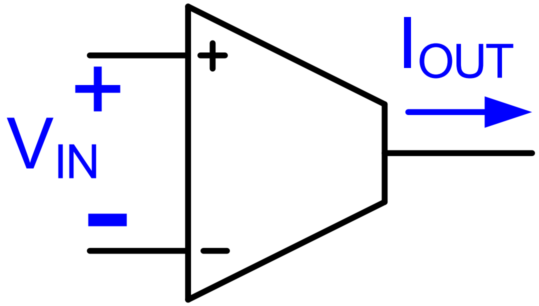
| Process Paramaters | | |
|---|---|---|
| **µnCOX** | 350 | uAV^2 |
| **µpCOX** | 75 | uAV^2 |
| **VTHn** | 0.4 | V |
| **VTHp** | -0.4 | V |
| **λ** | 0.01 | V^-1 |

| Fixed Contraints | | |
|---|---|---|
| **VDD** | 2 | V |
| **VSS** | -2 | V |
| **CL** | 10 | pf |
| **L1=L2=...=Lk** | 0.5 | um |
| **VB2** | 0.6 | V |

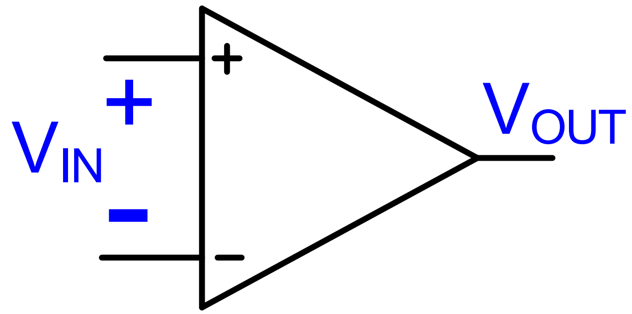
Input Quantities in

| Op Amp | Design Variables | | | | Performance Characteristics | | | | | | | | Practical Design Values in um | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No | VEB1 | VEB3 | VEB9 | P (mw) | A0 | BW (MHz) | GB (MHz) | SR (V/uS) | Vomax | Vomin | VCM | IT (mA) | W1 | W2 | W3 | W4 | W9 |
| 1 | 0.1 | -0.1 | 0.1 | 5 | 1000 | 0.20 | 199.04 | 0.125 | 1.9 | 0 | 0.1 | 1.25 | 357.1 | 357.1 | 1666.7 | 1666.7 | 714.3 |
| 2 | 0.2 | -0.2 | 0.1 | 5 | 500 | 0.20 | 99.52 | 0.125 | 1.8 | -0.1 | 0.1 | 1.25 | 89.3 | 89.3 | 416.7 | 416.7 | 714.3 |
| 3 | 0.4 | -0.1 | 0.1 | 5 | 250 | 0.20 | 49.76 | 0.125 | 1.9 | -0.3 | 0.1 | 1.25 | 22.3 | 22.3 | 1666.7 | 1666.7 | 714.3 |
| 4 | 0.05 | -0.1 | 0.1 | 5 | 2000 | 0.20 | 398.09 | 0.125 | 1.9 | 0.05 | 0.1 | 1.25 | 1428.6 | 1428.6 | 1666.7 | 1666.7 | 714.3 |
| 5 | 0.1 | -0.1 | 0.1 | 1 | 1000 | 0.04 | 39.81 | 0.025 | 1.9 | 0 | 0.1 | 0.25 | 71.4 | 71.4 | 333.3 | 333.3 | 142.9 |
| 6 | 0.1 | -0.1 | 0.1 | 10 | 1000 | 0.40 | 398.09 | 0.25 | 1.9 | 0 | 0.1 | 2.5 | 714.3 | 714.3 | 3333.3 | 3333.3 | 1428.6 |
| 7 | 0.1 | -0.1 | 0.1 | 0.1 | 1000 | 0.00 | 3.98 | 0.0025 | 1.9 | 0 | 0.1 | 0.025 | 7.1 | 7.1 | 33.3 | 33.3 | 14.3 |
| 8 | 0.1 | -0.1 | 0.1 | 20 | 1000 | 0.80 | 796.18 | 0.5 | 1.9 | 0 | 0.1 | 5 | 1428.6 | 1428.6 | 6666.7 | 6666.7 | 2857.1 |
| 9 | 0.1 | -0.1 | 0.2 | 1 | 1000 | 0.04 | 39.81 | 0.025 | 1.9 | 0 | 0.1 | 0.25 | 71.4 | 71.4 | 333.3 | 333.3 | 35.7 |
| 10 | 0.1 | -0.2 | 0.1 | 0.1 | 1000 | 0.00 | 3.98 | 0.0025 | 1.8 | 0 | 0.1 | 0.025 | 7.1 | 7.1 | 8.3 | 8.3 | 14.3 |

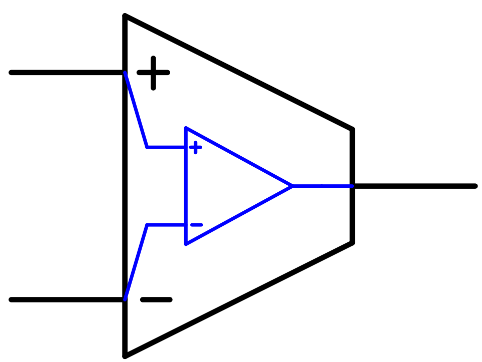
# Transconductance vs Voltage Gain




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




$$V_{OUT} = A_V V_{IN}$$

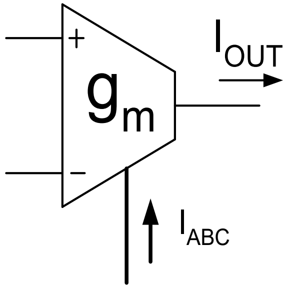


Same Circuit – Two Perspectives

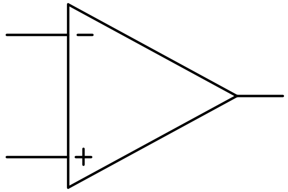
# Returning to Challenge Slide:

# OTA Circuits

OTA often used open loop



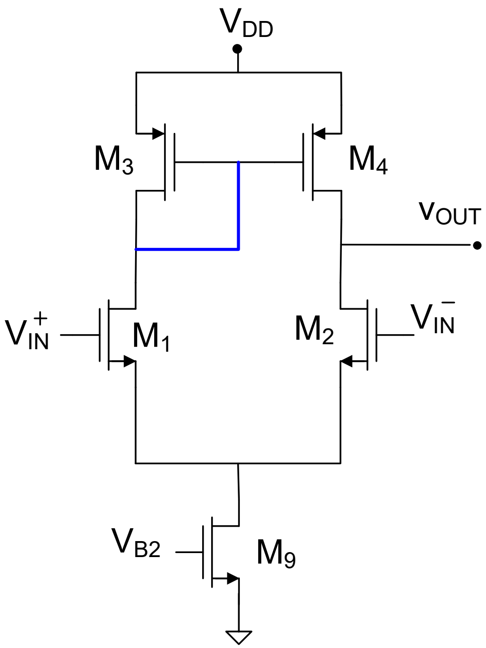

Recall:  Op Amp almost never used open loop

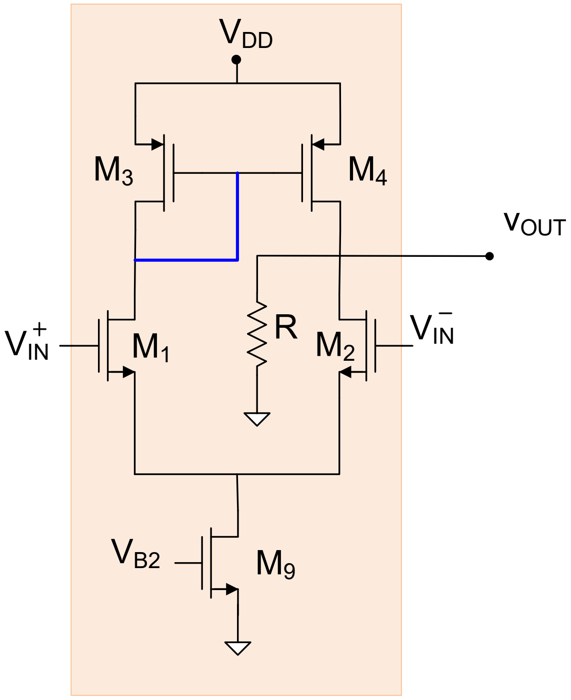



Since we just showed that the OTA is also a good high-gain op amp it seems there are conflicting statements

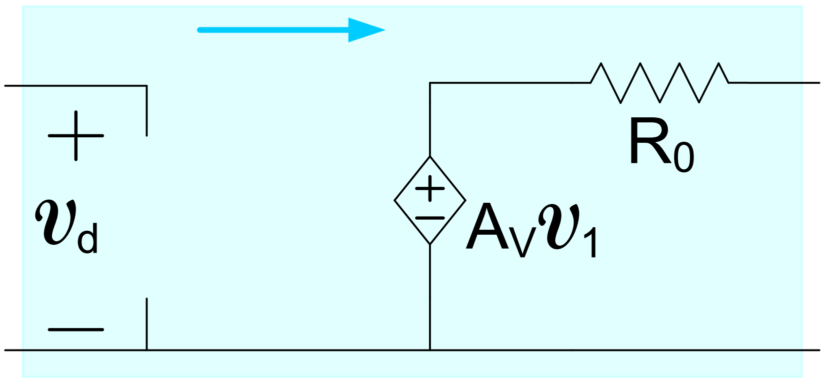
➡ Challenge to students:   Resolve what may appear to be conflicting statements.

# Compare the Gain and Output Impedance of These 2 Amplifiers

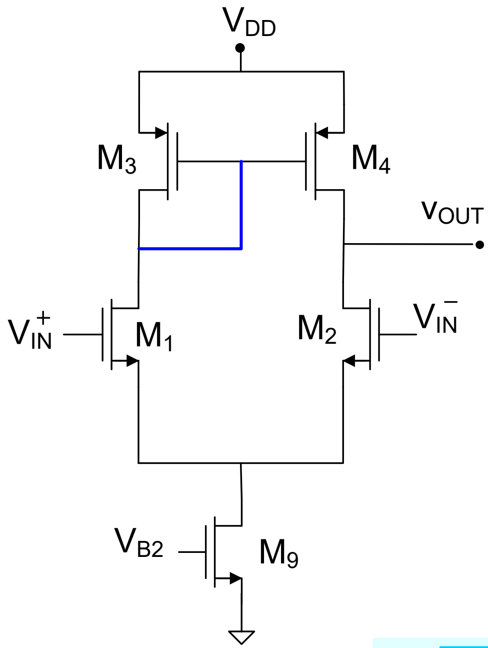


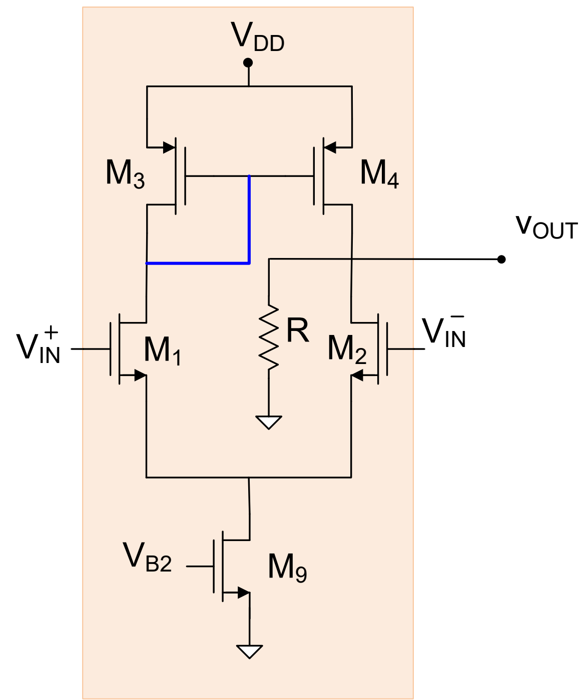



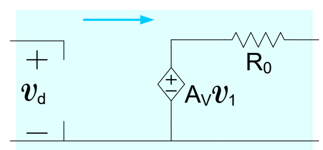

Both can be modeled as a two-port:



# Compare the Gain and Output Impedance of These 2 Amplifiers




$$A_V = -\frac{g_{m1}}{2g_{01}} = \frac{1}{\lambda V_{EB1}}$$

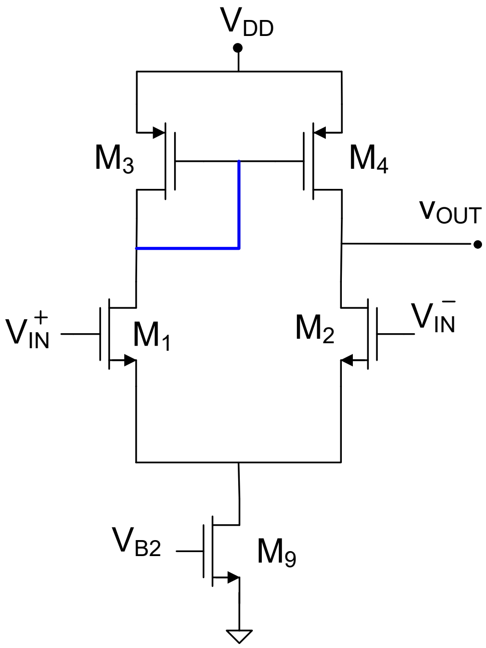
$$g_O = 2g_{01} = \lambda I_{TAIL}$$

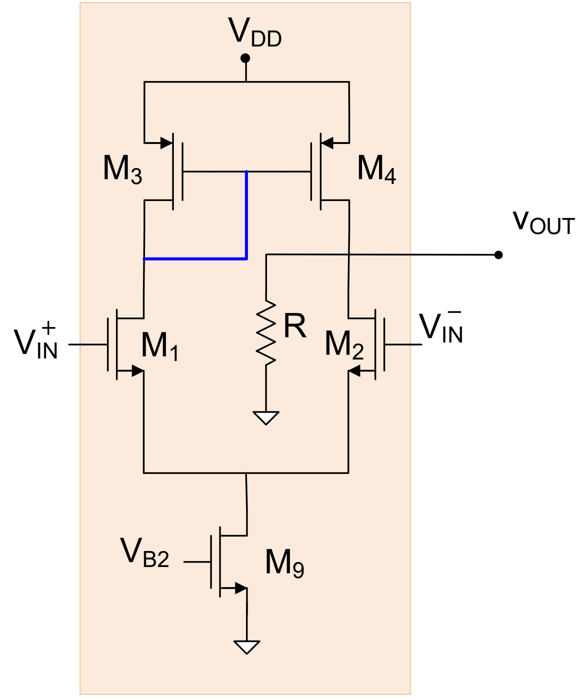
$$A_V = -g_{m1}\frac{R}{1+2Rg_{01}}$$

$$g_O = 2g_{01} + \frac{1}{R}$$

# Compare the Gain and Output Impedance of These 2 Amplifiers

How do they compare if $V_{EB1}$=0.2V, R=1K, $\lambda$=0.01$V^{-1}$ ,$I_{TAIL}$=1mA




$$A_V = -\frac{g_{m1}}{2g_{01}} = \frac{1}{\lambda V_{EB1}}$$

$$g_O = 2g_{01} = \lambda I_{TAIL}$$

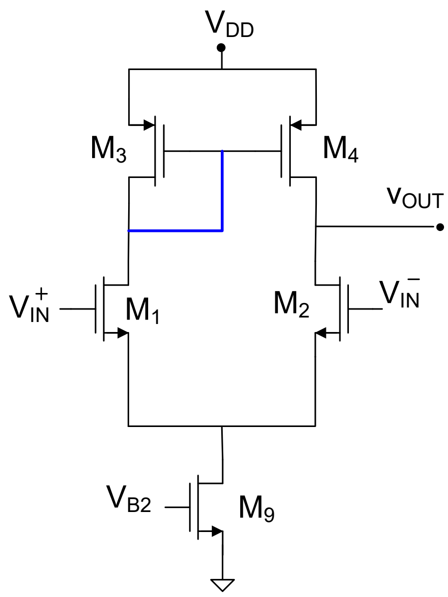
$$A_V = -g_{m1}\frac{R}{1+2Rg_{01}} = -\frac{I_{TAIL}}{V_{EB1}}\frac{R}{1+2Rg_{01}}$$

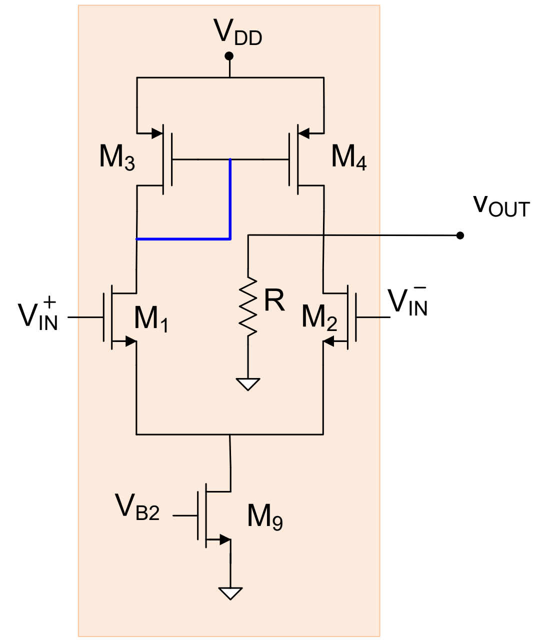
$$g_O = 2g_{01} + \frac{1}{R}$$

# Compare the Gain and Output Impedance of These 2 Amplifiers

How do they compare if $V_{EB1}$=0.2V, R=1K, $\lambda$=0.01$V^{-1}$ ,$I_{TAIL}$=1mA

- Is the open-loop op amp gain high?
- Is the output impedance low?




$$A_V = -\frac{1}{\lambda V_{EB1}} = -500$$

$$A_V = -\frac{I_{TAIL}}{V_{EB1}} \frac{R}{1+2Rg_{01}} = -4.95$$

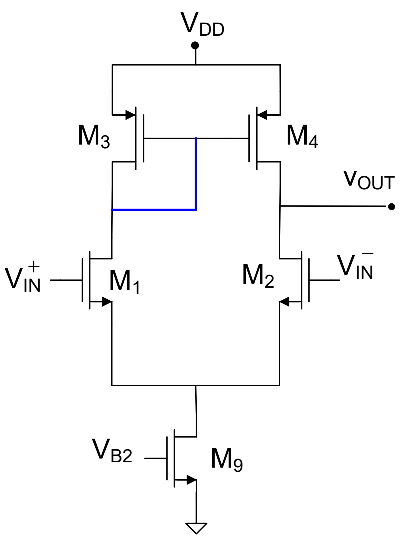
$$g_O = \lambda I_{TAIL} = 10^{-5}\Omega^{-1}$$

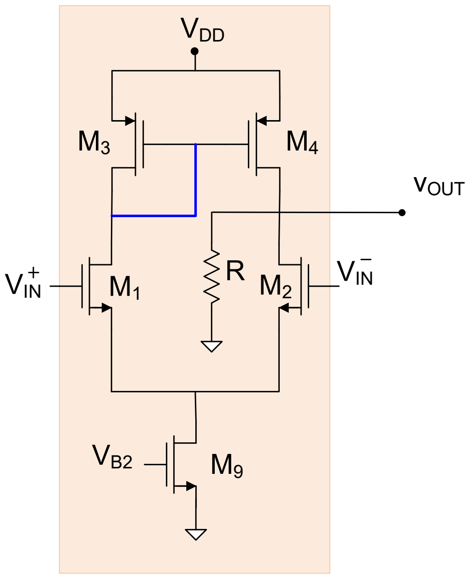
$$g_O = 2g_{01} + \frac{1}{R} = 1.02x10^{-3}\Omega^{-1}$$

# Compare the Gain and Output Impedance of These 2 Amplifiers

## Is the open-loop op amp gain high?

This effect will be much more dramatic for the other high gain op amps, including the Current Mirror Op Amp, that  we have considered thus far!

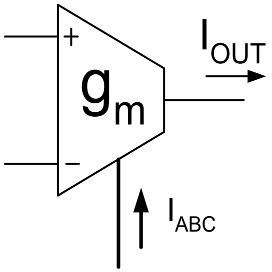


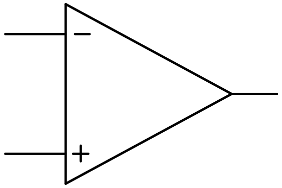
# Returning to Challenge Slide:

# OTA Circuits

OTA often used open loop




Recall:  Op Amp almost never used open loop

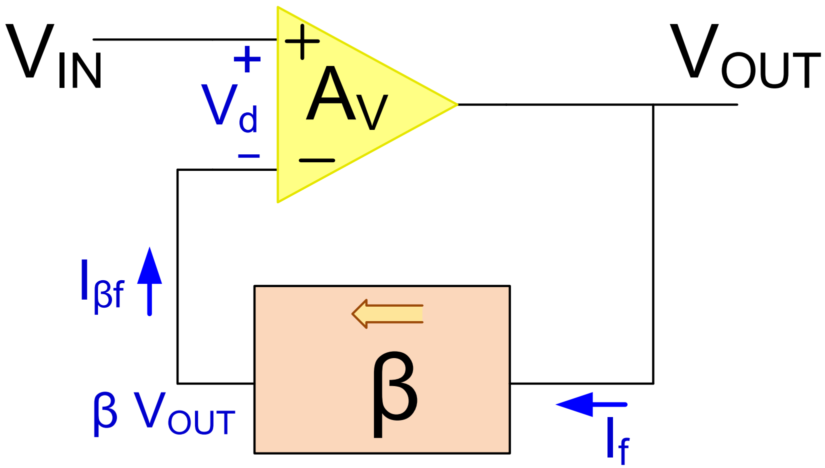



Since we just showed that the OTA is also a good high-gain op amp it seems there are conflicting statements

➡ Challenge to students:   Resolve what may appear to be conflicting statements.

# One Standard Feedback Configuration

Voltage-Series Feedback (one of the 4 most basic types)



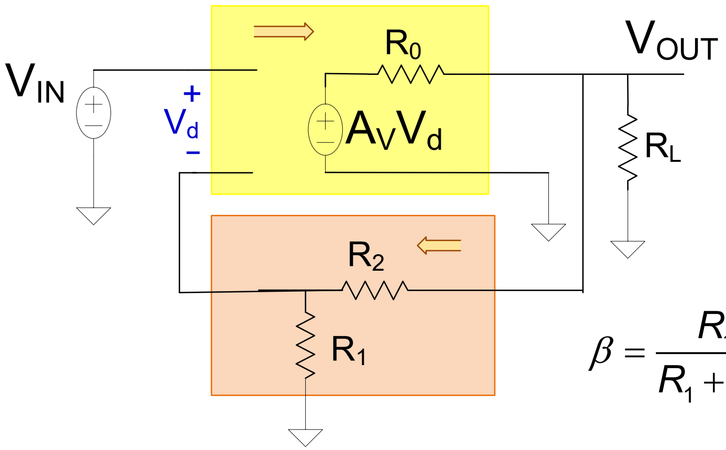

Assume ideal input and output impedance on $A_V$ and β

$$\left.\begin{aligned} V_d &= V_{IN} - \beta V_{OUT} \\ V_{OUT} &= A_V V_d \end{aligned}\right\} \Rightarrow \quad A_{VF} = \frac{A_V}{1+\beta A_V} \underset{A_V \to \infty}{\simeq} \frac{1}{\beta}$$

$$V_d \underset{A_V \to \infty}{\simeq} 0$$

# One Standard Feedback Configuration

## Voltage-Series Feedback (one of the 4 most basic types)




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

Define:

$$\theta = \frac{[R_1 + R_2]//R_L}{R_0 + [R_1 + R_2]//R_L}$$

## Include Loading of nonideal A amplifier with β network

$$A_{VEFF} = \frac{V_{OUT}}{V_d}$$

$$V_d = V_{IN} - \beta V_{OUT}$$

$$V_{OUT} = A_{VEFF}\left(V_{IN} - \beta V_{OUT}\right)$$

$$V_d = V_{IN}\frac{1}{1+\beta A_{VEFF}}$$

$$A_{VF} = \frac{V_{OUT}}{V_{IN}} = \frac{A_{VEFF}}{1+\beta A_{VEFF}} \underset{A_{VEFF}\to\infty}{\simeq} \frac{1}{\beta}$$

$$V_d \underset{A_{VEFF}\to\infty}{\simeq} 0$$

$$V_{OUT} = A_V V_d\left(\frac{[R_1 + R_2]//R_L}{R_0 + [R_1 + R_2]//R_L}\right) = \theta A_V V_d$$

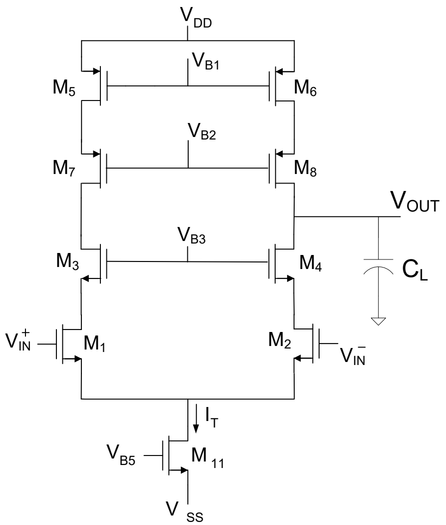
$$A_{VEFF} = \theta A_V$$

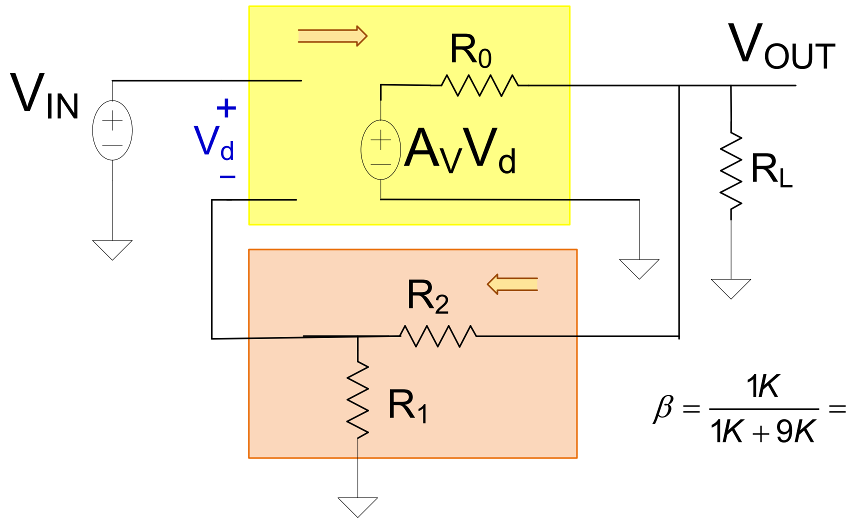
$$A_{VF} = \frac{A_{VEFF}}{1+\beta A_{VEFF}}$$

# Example: Effects of Loading

Consider telescopic cascode op amp with $V_{EB1}=V_{EB3}=V_{EB5}=200mV$, $I_T=100uA$, $\lambda=.01V^{-1}$

Assume $R_1=1K$, $R_2=9K$, $R_L=10K$




$$\theta = \frac{[R_1+R_2]//R_L}{R_0+[R_1+R_2]//R_L}$$

$$\beta = \frac{1K}{1K+9K} = 0.1$$

Without considering loading, it follows that for dc input:

$$A_{V0} = \frac{2}{V_{EB1}\left(\lambda_1\lambda_3V_{EB3}+\lambda_5\lambda_7V_{EB5}\right)}$$

$$g_{OUT} = g_{02}\frac{g_{04}}{g_{m4}} + g_{06}\frac{g_{08}}{g_{m8}}$$

$$A_{VF} = \frac{A_{V0}}{1+\beta A_{V0}} = \frac{2.5x10^6}{1+2.5x10^6x0.1} = 9.999960$$

$A_{VF}$ very close to the ideal value of $\frac{1}{\beta} = 10.000$

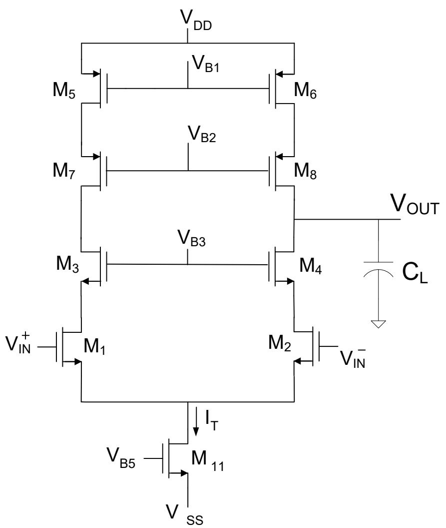
$$A_{V0} = \frac{1}{V_{EB1}^2\lambda^2} = 2.5x10^6$$

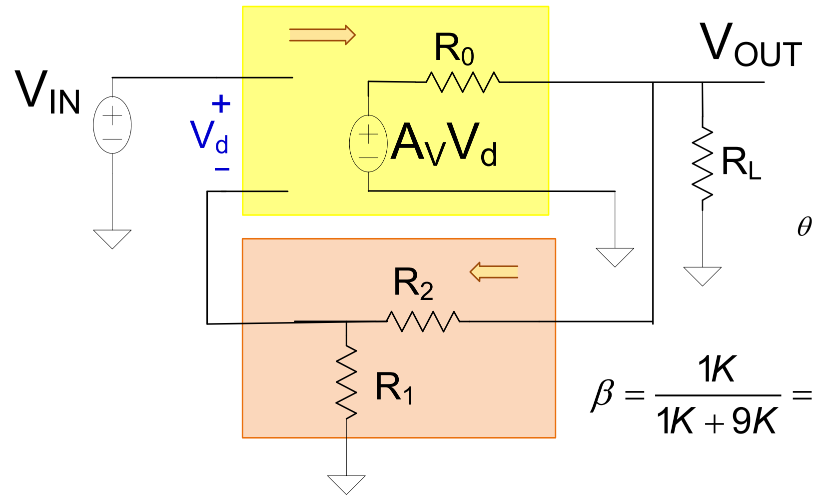
$$g_{OUT} = 2\lambda I_{D2Q}\frac{\lambda I_{D4Q}}{2\frac{I_{D4Q}}{V_{EB4}}} = \lambda^2 I_{D2Q}V_{EB4} = \lambda^2\frac{I_T}{2}V_{EB4} = 10^{-9}$$

# Example: Effects of Loading

Consider telescopic cascode op amp with $V_{EB1}=V_{EB3}=V_{EB5}=200mV$, $I_T=100uA$, $\lambda=.01V^{-1}$

Assume $R_1=1K$, $R_2=9K$, $R_L=10K$




$$\theta = \frac{[R_1+R_2]//R_L}{R_0+[R_1+R_2]//R_L}$$

$$\beta = \frac{1K}{1K+9K} = 0.1$$

$$A_{V0} = \frac{2}{V_{EB1}\left(\lambda_1\lambda_3 V_{EB3} + \lambda_5\lambda_7 V_{EB5}\right)}$$

$$g_{OUT} = g_{02}\frac{g_{04}}{g_{m4}} + g_{06}\frac{g_{08}}{g_{m8}}$$

$$A_{V0} = \frac{1}{V_{EB1}^2\lambda^2} = 2.5x10^6$$

$$g_{OUT} = 2\lambda I_{D2Q}\frac{\lambda I_{D4Q}}{2\frac{I_{D4Q}}{V_{EB4}}} = \lambda^2 I_{D2Q}V_{EB4} = \lambda^2\frac{I_T}{2}V_{EB4} = 10^{-9}$$

With Loading for dc input:

$$R_0 = 10^9\Omega$$

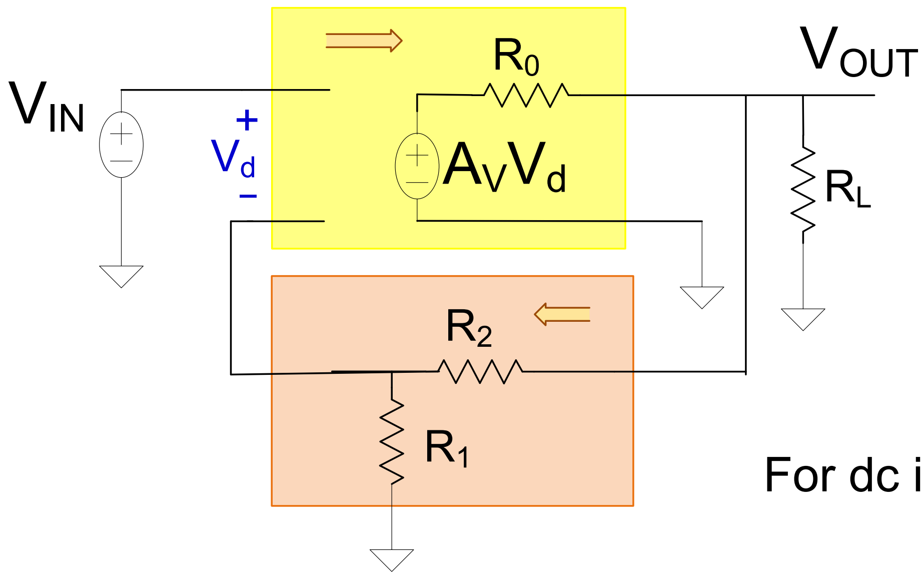
$$\theta = \frac{[R_1+R_2]//R_L}{R_0+[R_1+R_2]//R_L} = \frac{5K}{10^9+5K} \cong 5x10^{-6}$$

$$A_{VEFF} = \theta A_V = 5x10^{-6}x2.5x10^6 = 12.5$$

$$A_{VF} = \frac{A_{VEFF}}{1+\beta A_{VEFF}} = \frac{12.5}{1+1.25} = 5.\tilde{5}$$

Almost useless as a FB amplifier in this application !

# Effective Gain of Operational Amplifiers




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

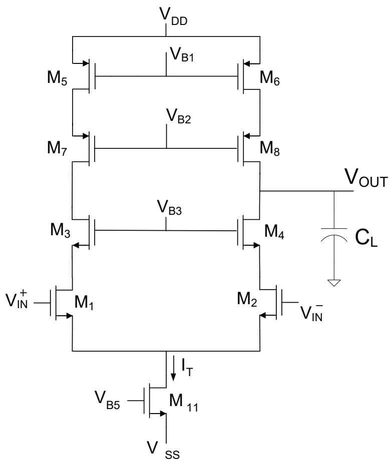
$$A_{VF} = \frac{A_{V0}}{1+\beta A_{V0}} \Rightarrow A_{VF} = \frac{A_{VEFF}}{1+\beta A_{VEFF}}$$

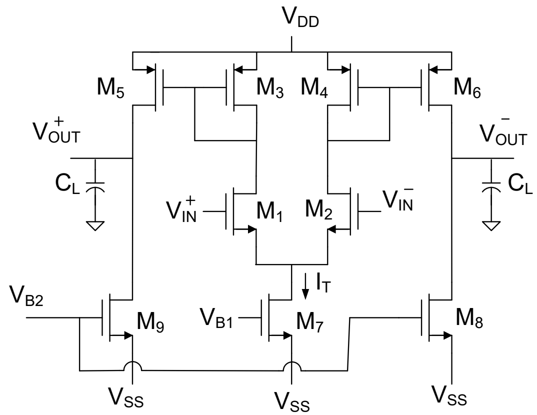
The open loop gain of an operational amplifier used in a FB configuration must include the loading of the feedback network and load resistor

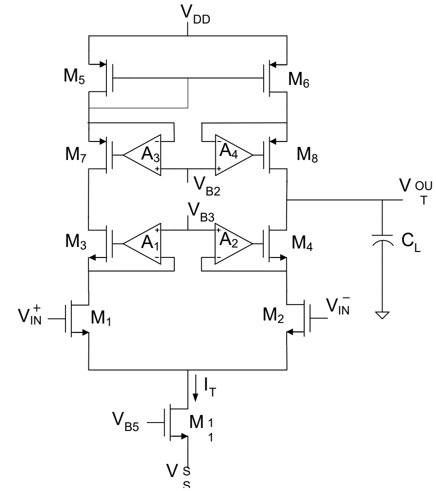
Some FB networks cause little or no loading and others can be significant

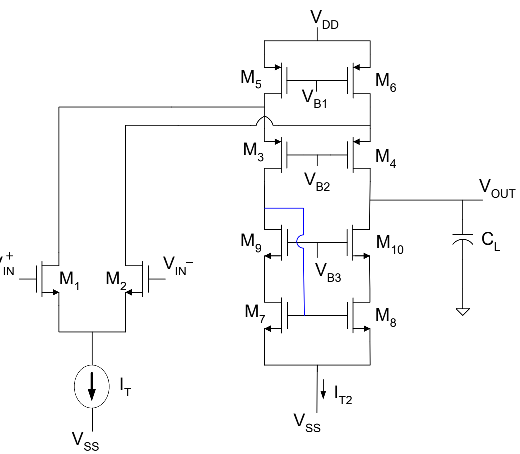
Often a buffer stage is added to the output of the op amp when used in FB applications driving “heavy” loads

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



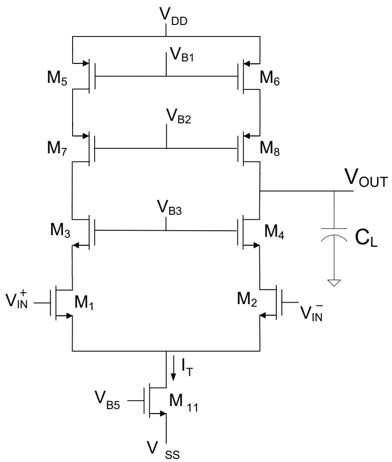



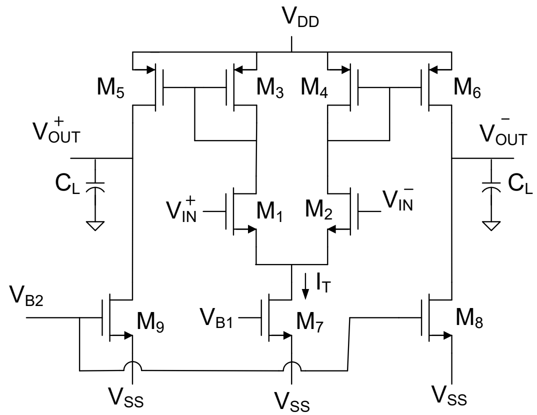



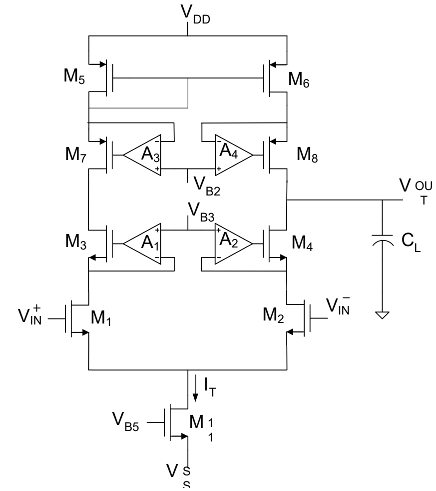



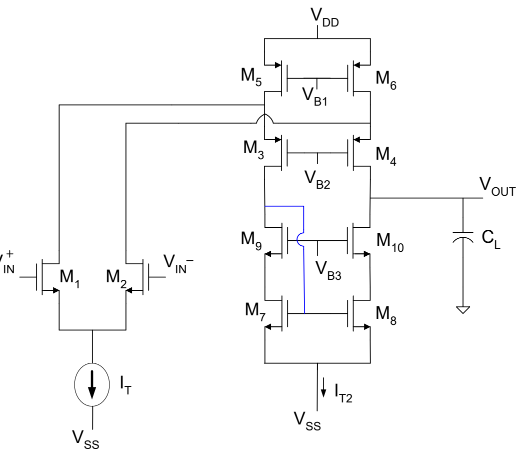

- All have high voltage gain if not driving heavy loads !
- Output buffer stage can be added to all to drive heavy loads and maintain high effective voltage gain
- All have very high output impedance so are inherently transconductance amplifiers
- None have large transconductance gain so are not good for feedback applications as transconductance amplifiers

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



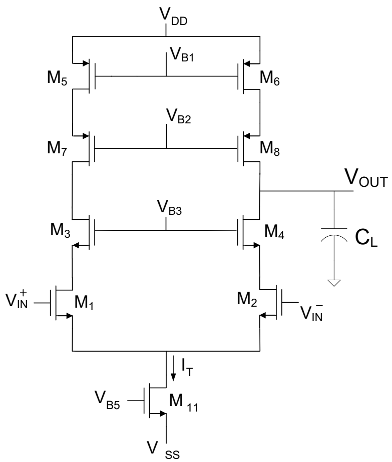



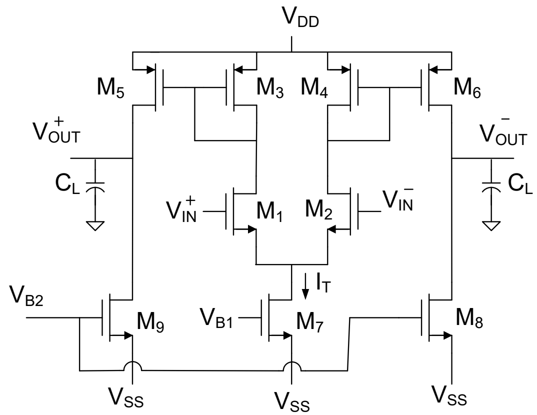



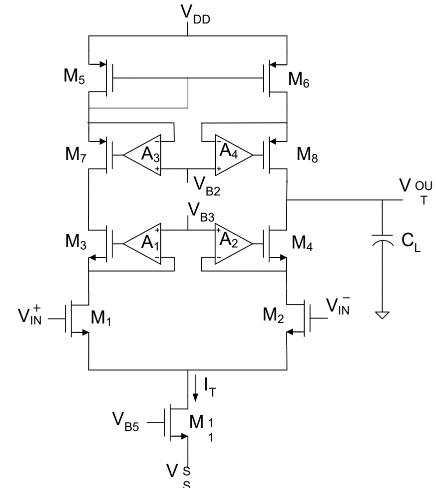



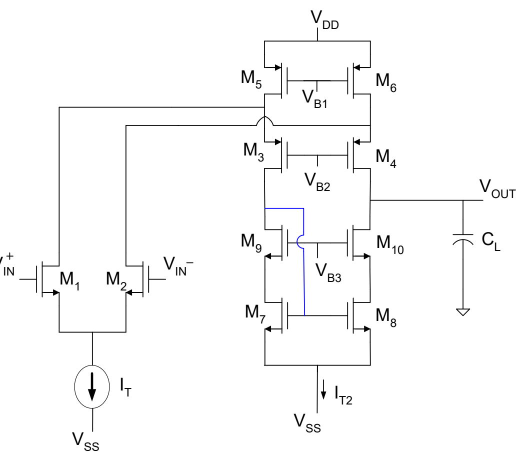

- High voltage gain op amps are seldom used open loop to build voltage amplifiers
- Since all have low transconductance gains, can be used open-loop in transconductance applications
- When used in transconductance applications, often termed Operational Transconductance Amplifiers (OTAs)
- When intended to be used as OTAs, voltage or current control input often added to electrically control the gain.

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



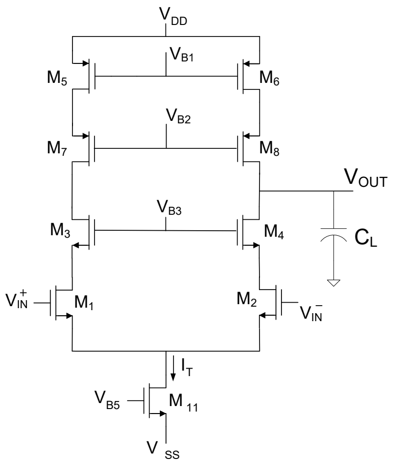

Are these high gain voltage amplifiers?

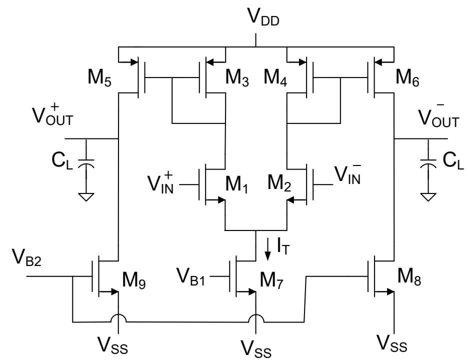
Are these high gain transconductance amplifiers?

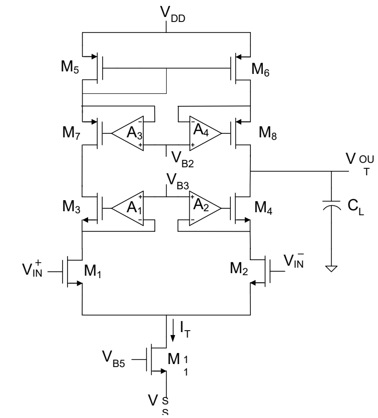
Are these high gain current amplifiers?

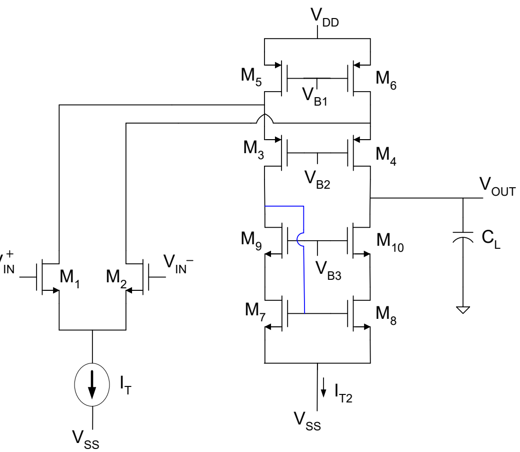
Are these high gain transresistance amplifiers?

# 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

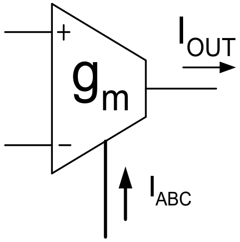
Are these high gain transresistance amplifiers?

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

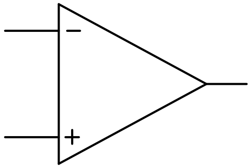
# Returning to Challenge Slide:

# OTA Circuits

OTA often used open loop




Recall: Op Amp almost never used as an open amplifie



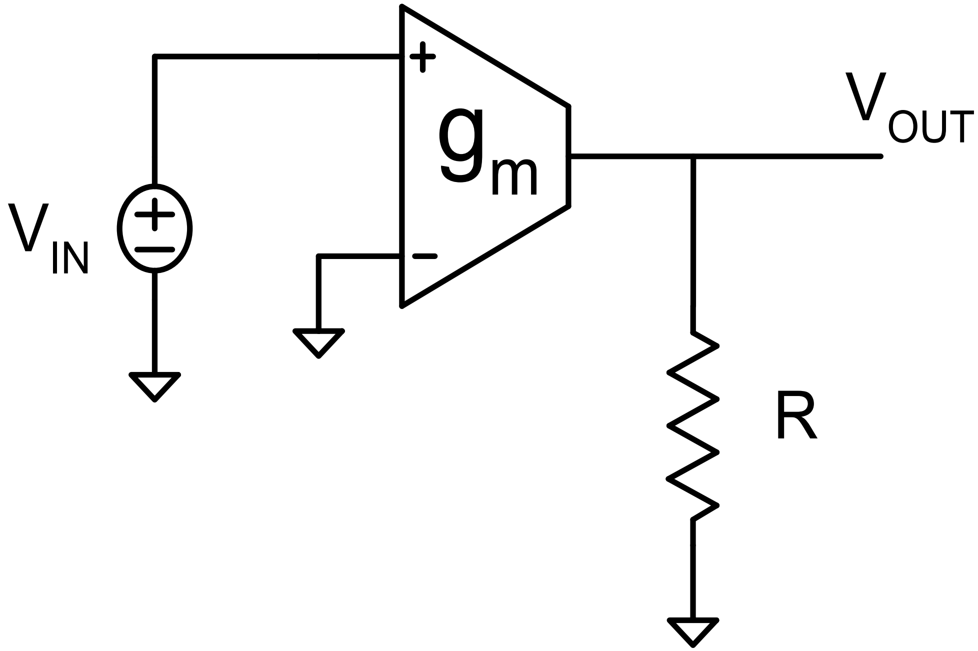

Since we just showed that the OTA is also a good high-gain op amp it seems there are conflicting statements

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 !!

# OTA Applications

(Some were discussed earlier but will be repeated here)

# OTA Applications



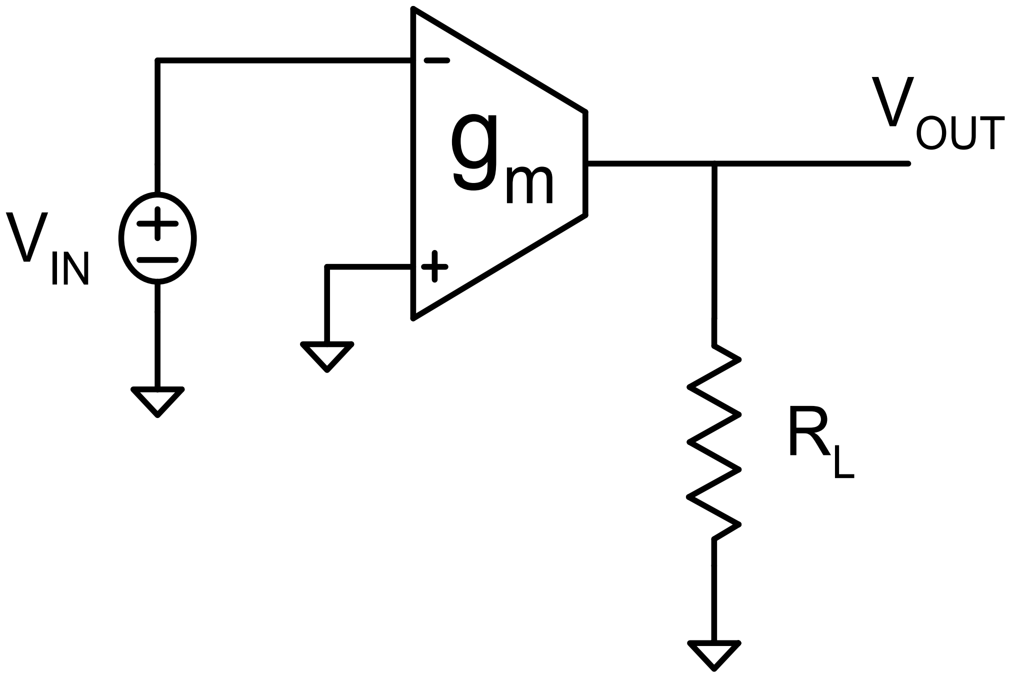

$$V_{OUT} = g_m R \bullet V_{IN}$$

$g_m$ is controllable with $I_{ABC}$

**Voltage Controlled Amplifier**

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

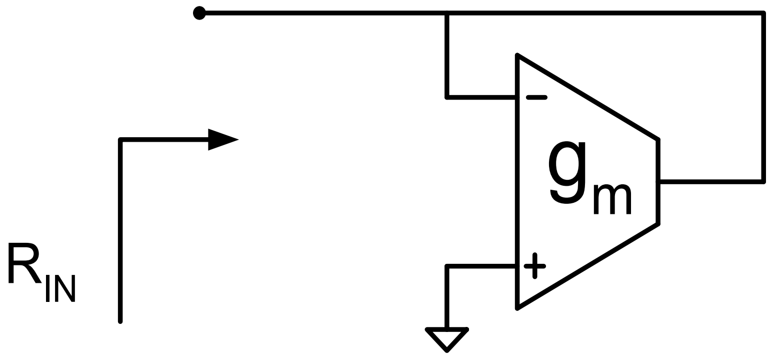
# OTA Applications

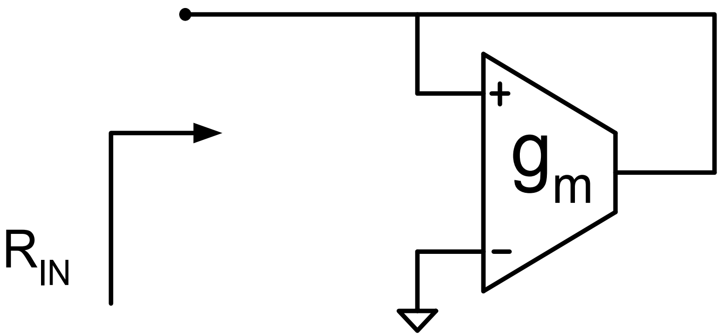



$$V_{OUT} = -g_m R \bullet V_{IN}$$

Voltage Controlled Inverting Amplifier

# OTA Applications



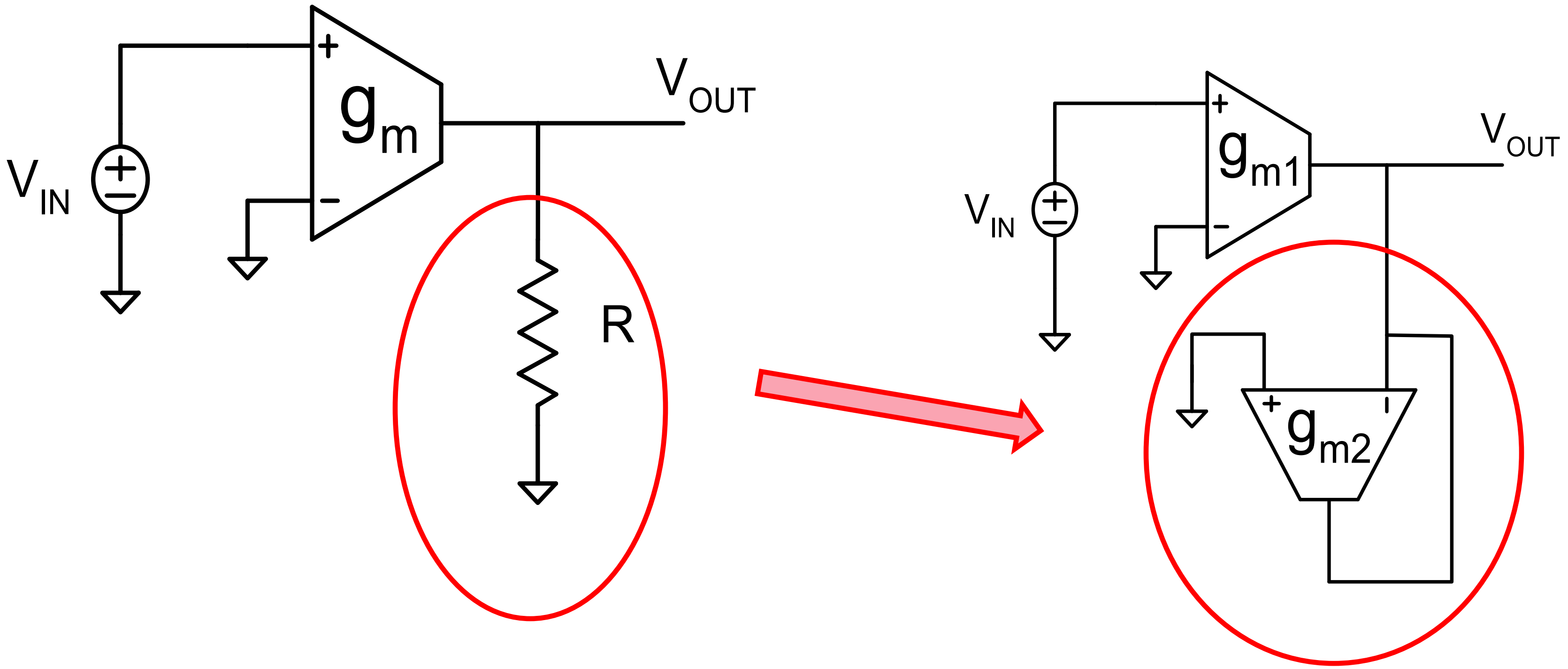




$$R_{IN} = \frac{1}{g_m}$$

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

Voltage Controlled Resistances

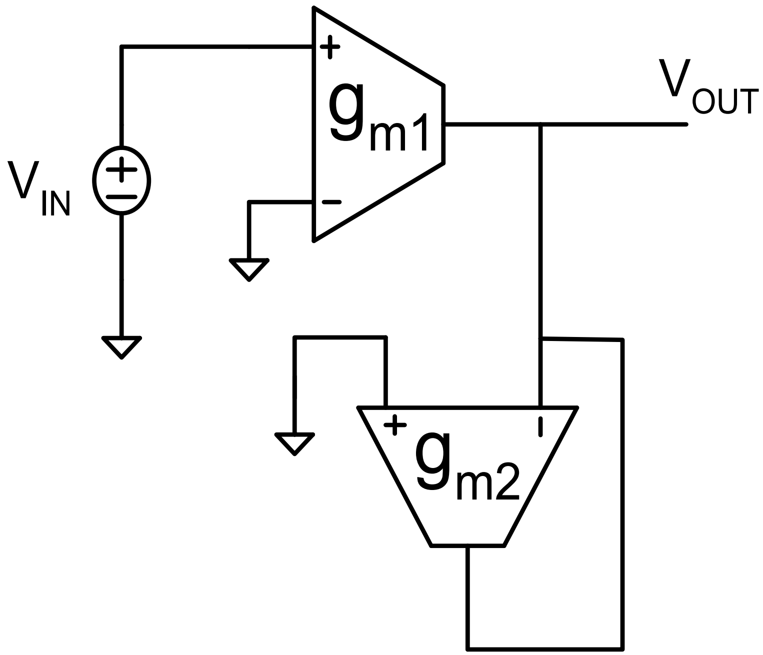
# OTA Applications




Resistorless Amplifiers

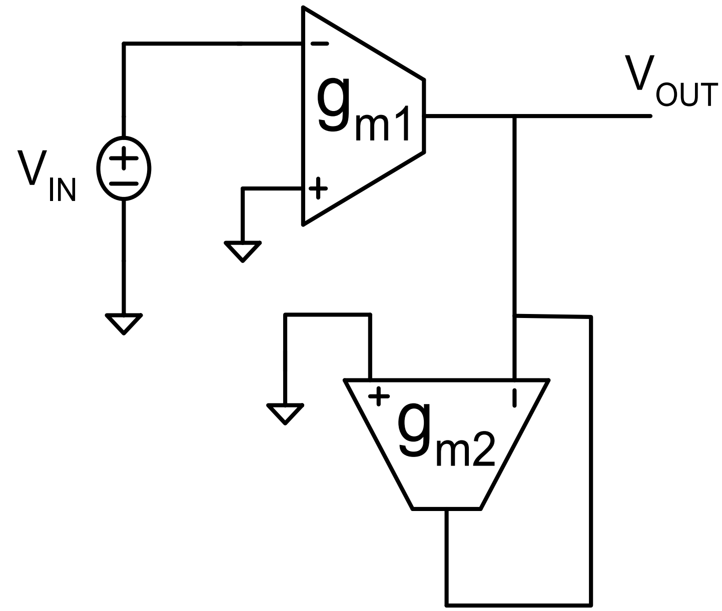
Would anyone ever do something like this ?

# OTA Applications




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

Noninverting Voltage Controlled Amplifier



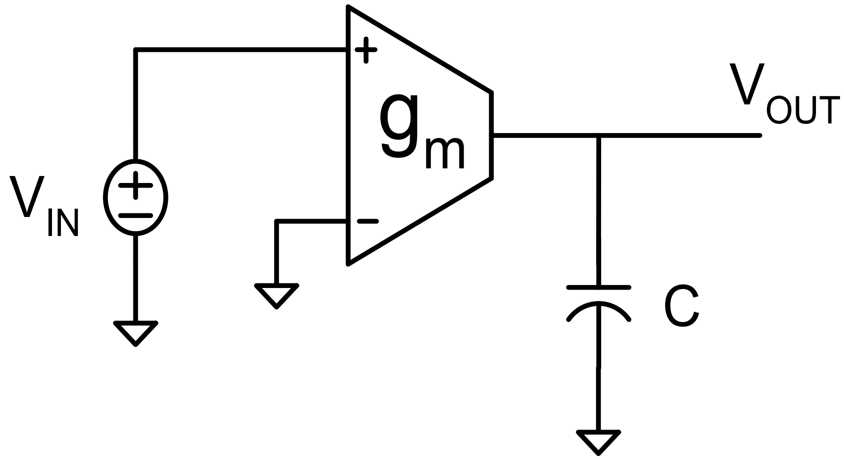

$$V_{OUT} = -\frac{g_{m1}}{g_{m2}} V_{in}$$

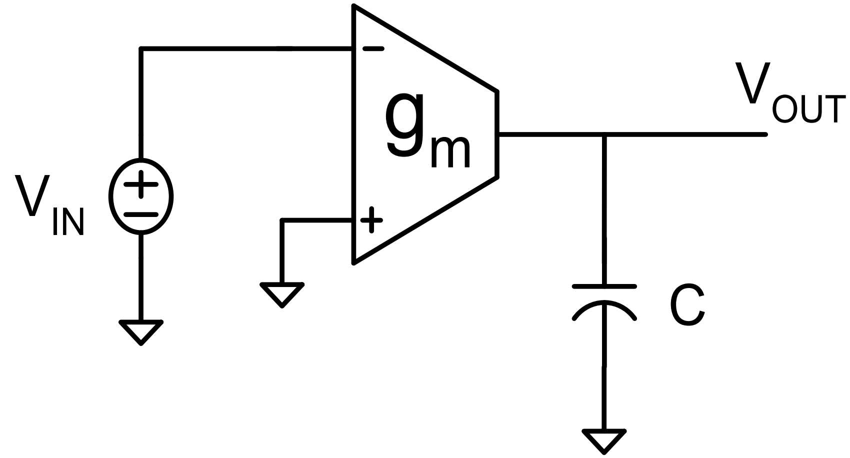
Inverting Voltage Controlled Amplifier

*Extremely large gain adjustment is possible*

Voltage Controlled Resistorless Amplifiers

# OTA Applications




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

Noninverting Voltage Controlled Integrator

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

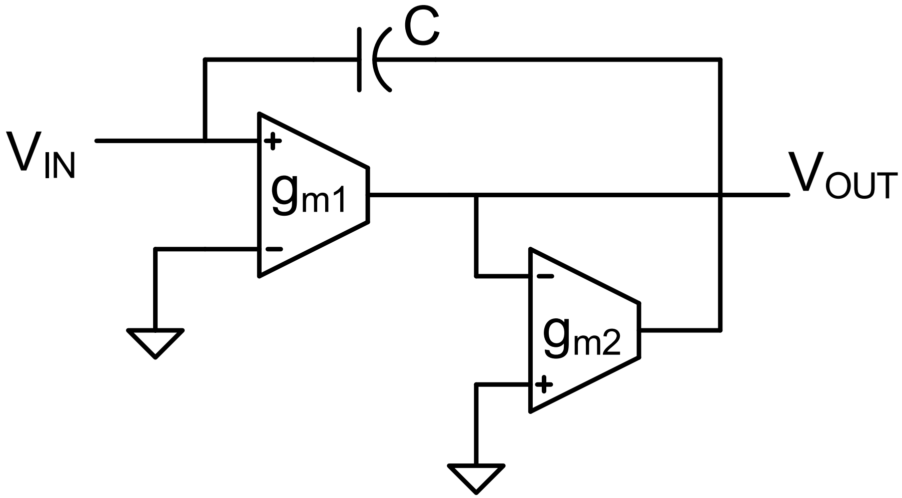
Inverting Voltage Controlled Integrator

Voltage Controlled Integrators

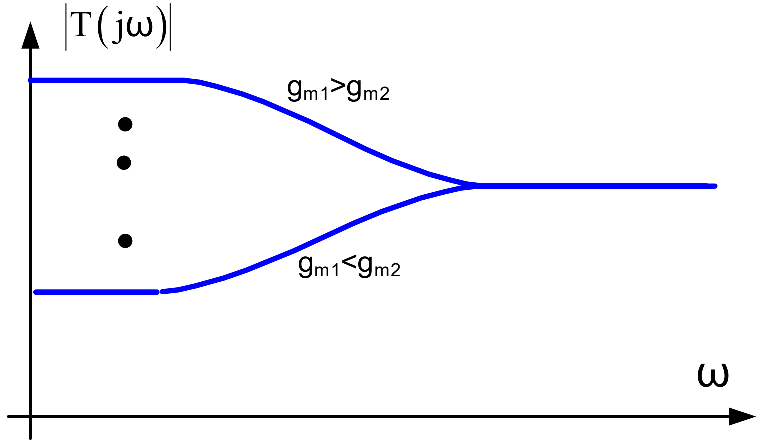
# OTA Applications

## Shelving Equalizer (First-order filter)

Programmable with $g_{m1}$ or $g_{m2}$




$$T(s) = \frac{sC + g_{m1}}{sC + g_{m2}}$$

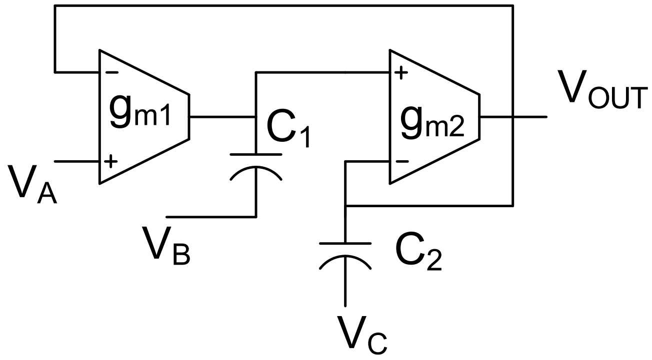


# OTA Applications

## Biquadratic Filter

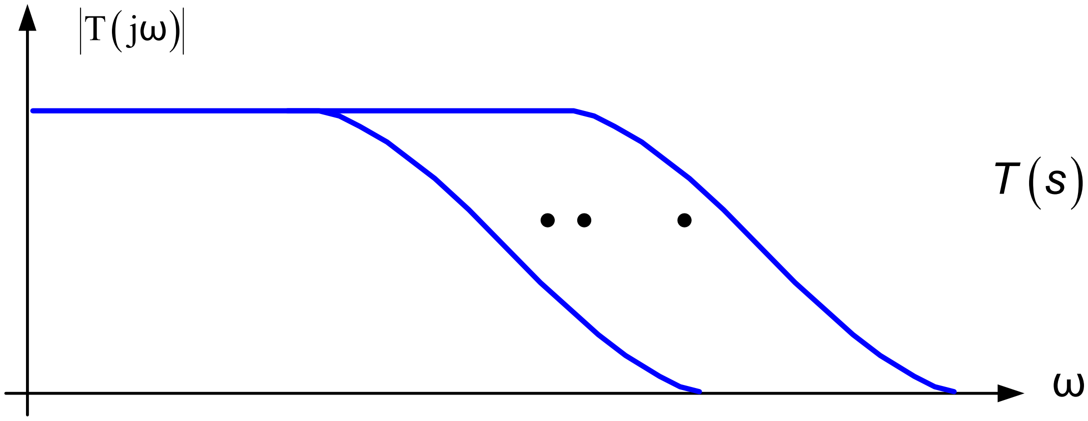
Programmable with $g_{m1}$ or $g_{m2}$

Individual or Combined Inputs Can Be Used (Lowpass, Bandpass,Highpass, Notch,…)



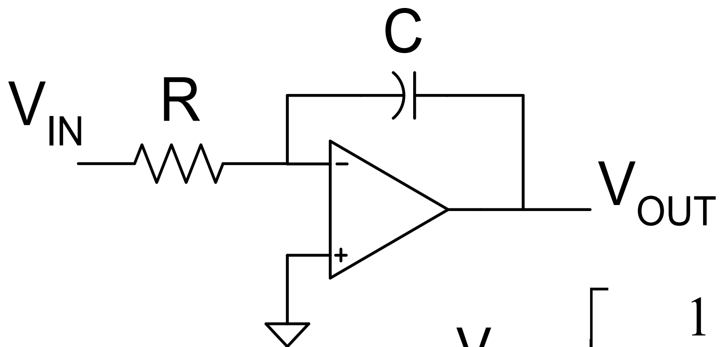

$$V_{OUT}(s) = \frac{V_C s^2 + V_B s \frac{g_{m2}}{C_2} + V_A \frac{g_{m1} g_{m2}}{C_1 C_2}}{s^2 + s \frac{g_{m2}}{C_2} + \frac{g_{m1} g_{m2}}{C_1 C_2}}$$

Lowpass response only shown ($V_C$=0, $V_B$=0, $V_{IN}$=$V_A$)

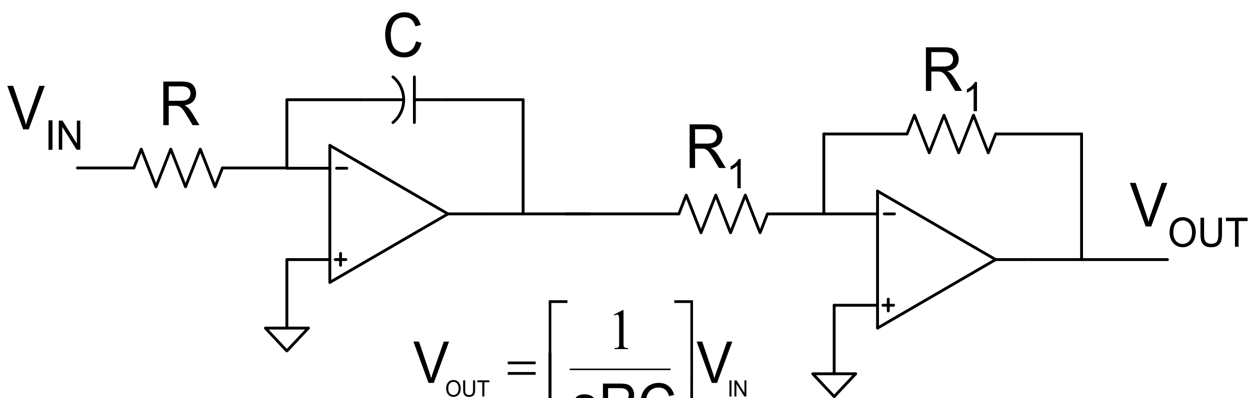



$$T(s) = \frac{V_{OUT}}{V_{IN}} = \frac{\frac{g_{m1} g_{m2}}{C_1 C_2}}{s^2 + s \frac{g_{m2}}{C_2} + \frac{g_{m1} g_{m2}}{C_1 C_2}}$$

# Comparison with Op Amp Based Integrators




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

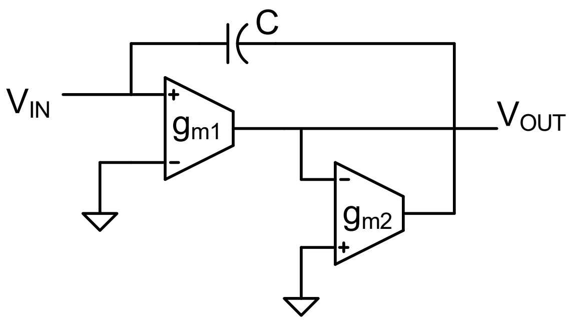


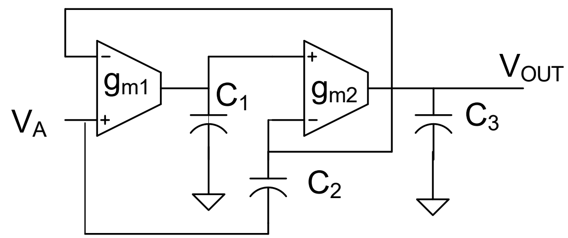

$$V_{OUT} = \left[ \frac{1}{sRC} \right] V_{IN}$$

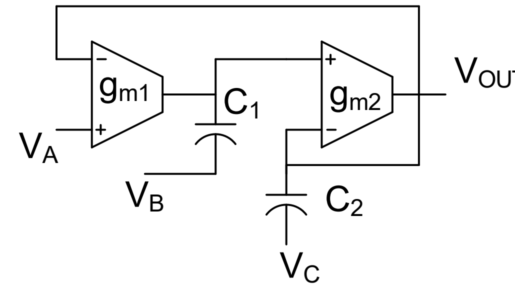
OTA-based integrators require less components and significantly less for realizing the noninverting integration function !

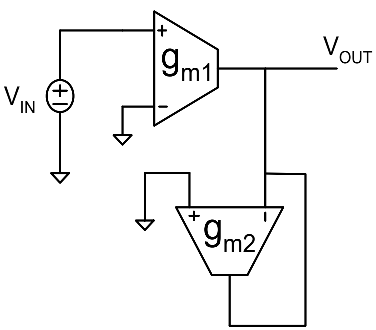
# OTA Applications

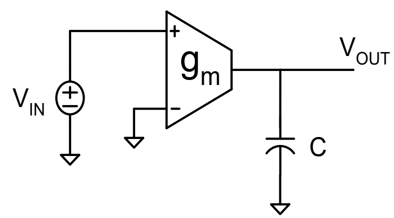
- OTA Applications are Extensive
- Programmable Features Are Attractive
- Can be Readily Integrated (often without resistors)
- Excellent high frequency performance

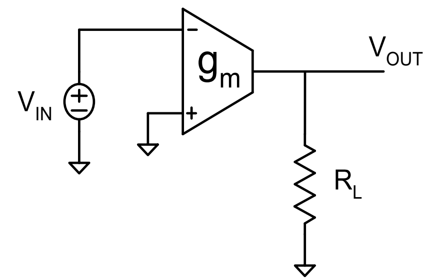


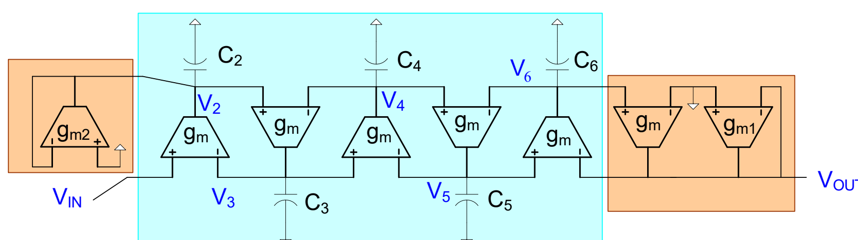



# Summary of Properties of OTA-Based Circuits

- 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

Stay Safe and Stay Healthy !

End of Lecture 10