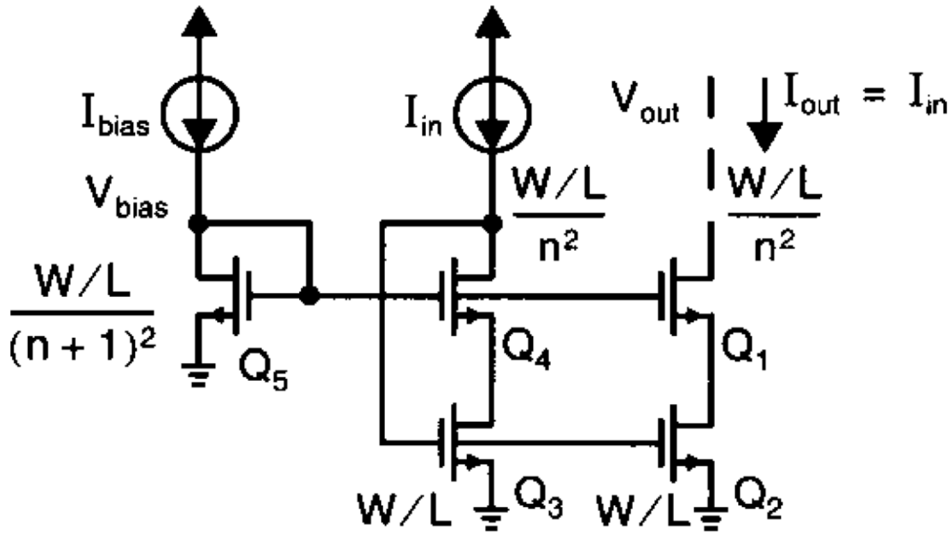
# Advanced Current Mirrors and Opamps

Hossein Shamsi

# Wide-Swing Current Mirrors



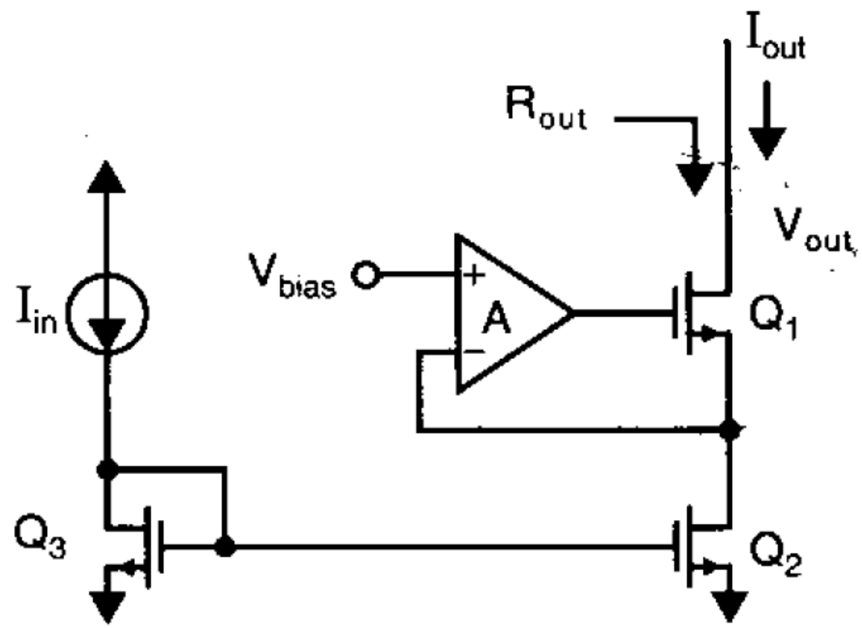

It is proven that if both of the following conditions are satisfied, then all transistors will be biased in the saturation region.

$$\begin{cases} V_{out} \geq (n+1)V_{eff} \\ V_{tn} \geq nV_{eff} \end{cases}$$

Typically n is chosen identical to 1. So the output swing will be:

$$V_{out} \geq 2V_{eff}$$

# Enhanced Output-Impedance Current Mirrors

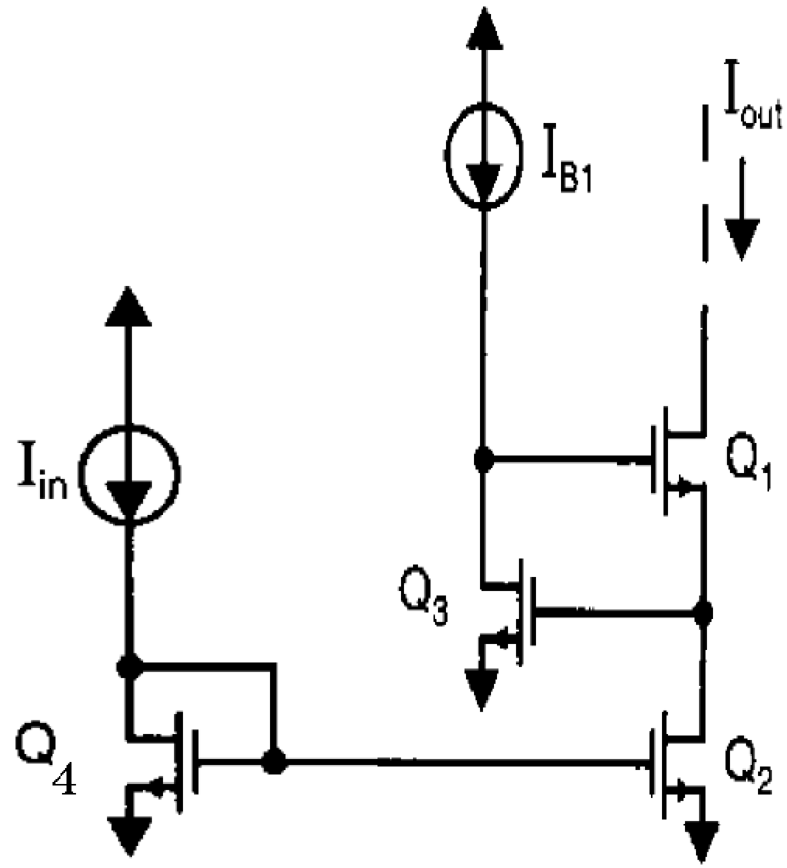



$$R_{out} \cong g_{m1} r_{ds1} r_{ds2} (1 + A)$$

# Implementation of Enhanced Output-Impedance Current Mirror

$$R_{out} \cong g_{m1} r_{ds1} r_{ds2} g_{m3} \frac{r_{ds3}}{2}$$

$$V_{out} \geq V_{tn} + V_{eff3} + V_{eff1}$$




Advantage:
- High Output-Impedance

Disadvantages:
- Low Output-Swing
- Imprecise Current Mirror

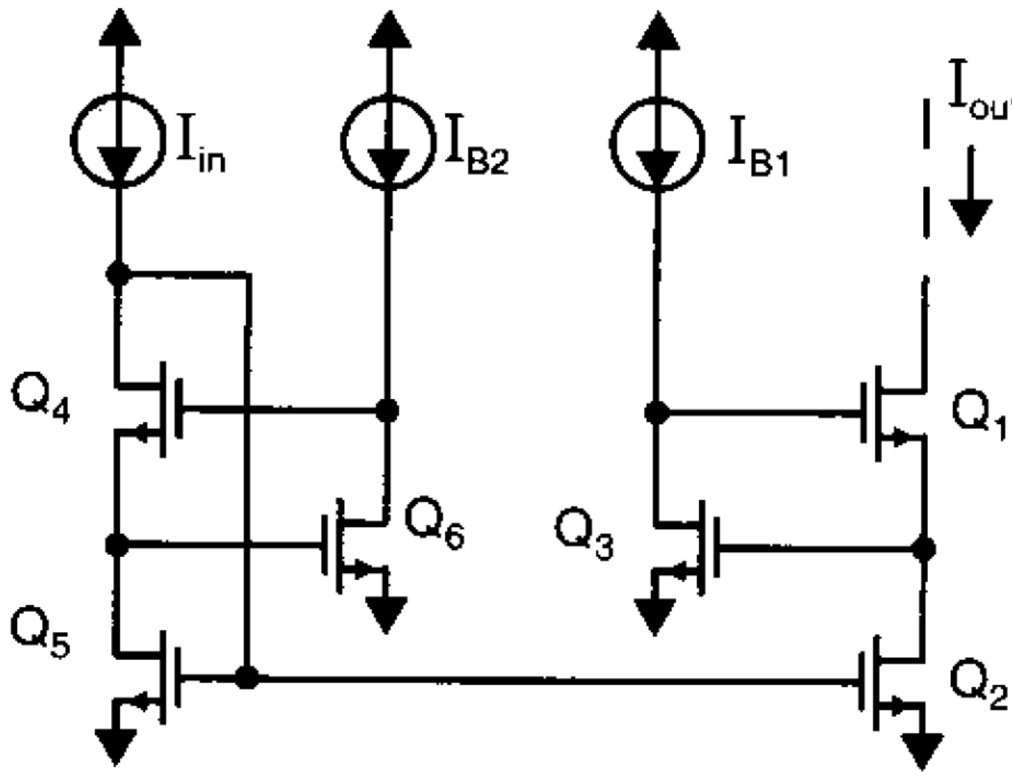
# Implementation of Enhanced Output-Impedance Current Mirror

$$R_{out} \cong g_{m1} r_{ds1} r_{ds2} g_{m3} \frac{r_{ds3}}{2}$$

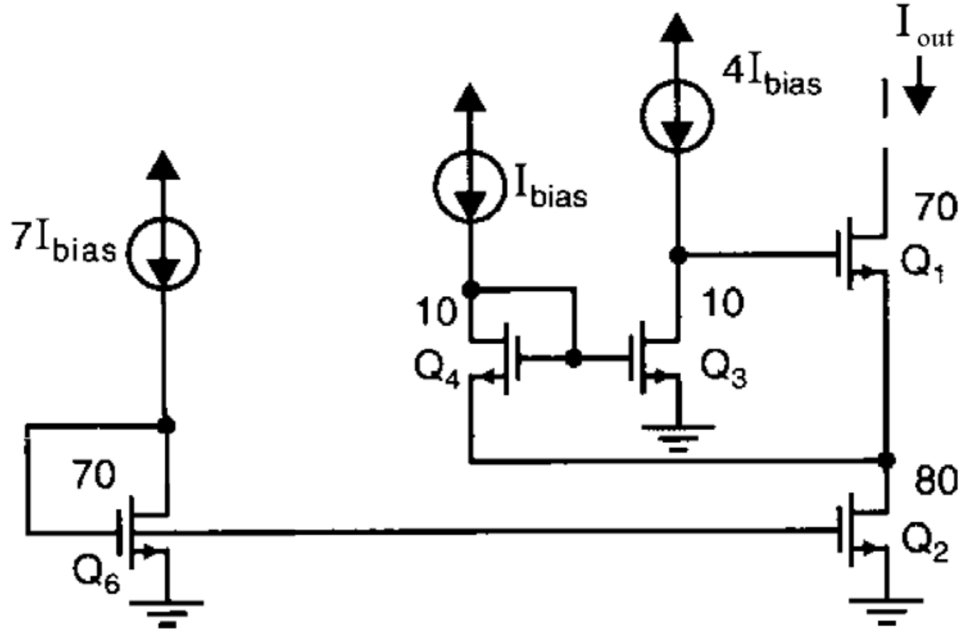
$$V_{out} \geq V_{tn} + V_{eff3} + V_{eff1}$$

Advantages:
- High Output-Impedance
- Precise Current Mirror

Disadvantage:
- Low Output-Swing



# Implementation of Enhanced Output-Impedance Current Mirror



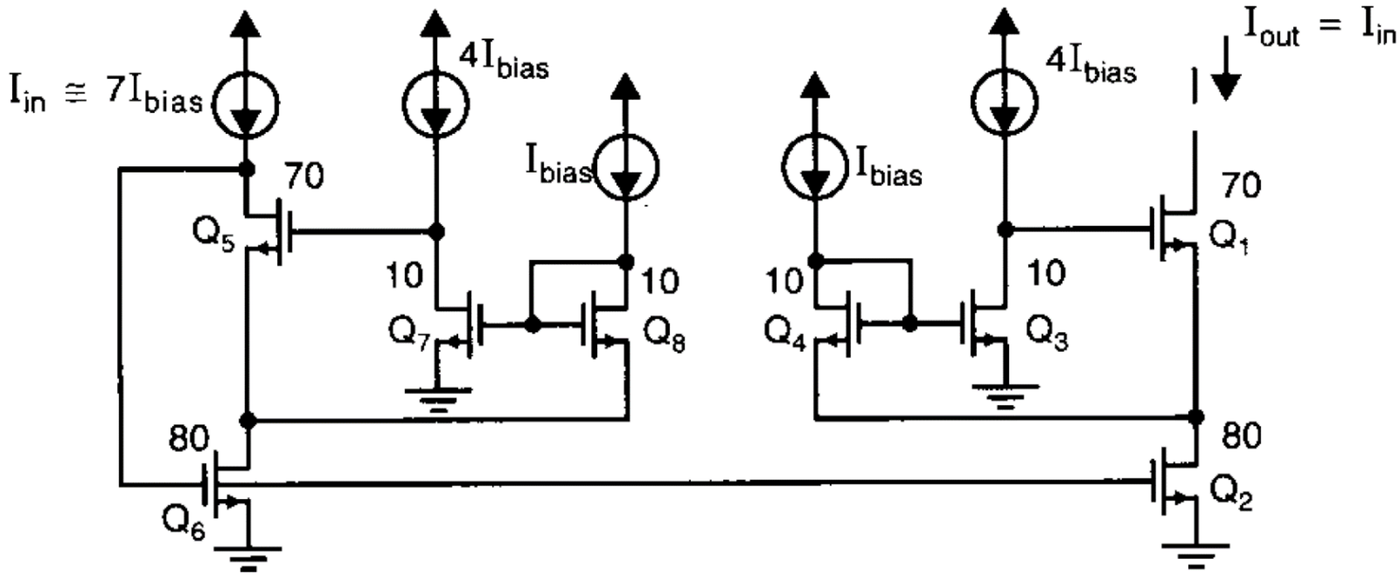

$$R_{out} \cong g_{m1} r_{ds1} r_{ds2} g_{m3} \frac{r_{ds3}}{2}$$

$$V_{out} \geq 2V_{eff1}$$

Advantages:
- High Output-Impedance
- High Output-Swing

Disadvantage:
- Imprecise Current Mirror

# Wide-Swing Current Mirror with Enhanced Output-Impedance




$$R_{out} \cong g_{m1} r_{ds1} r_{ds2} g_{m3} \frac{r_{ds3}}{2} \qquad V_{out} \geq 2V_{eff1}$$

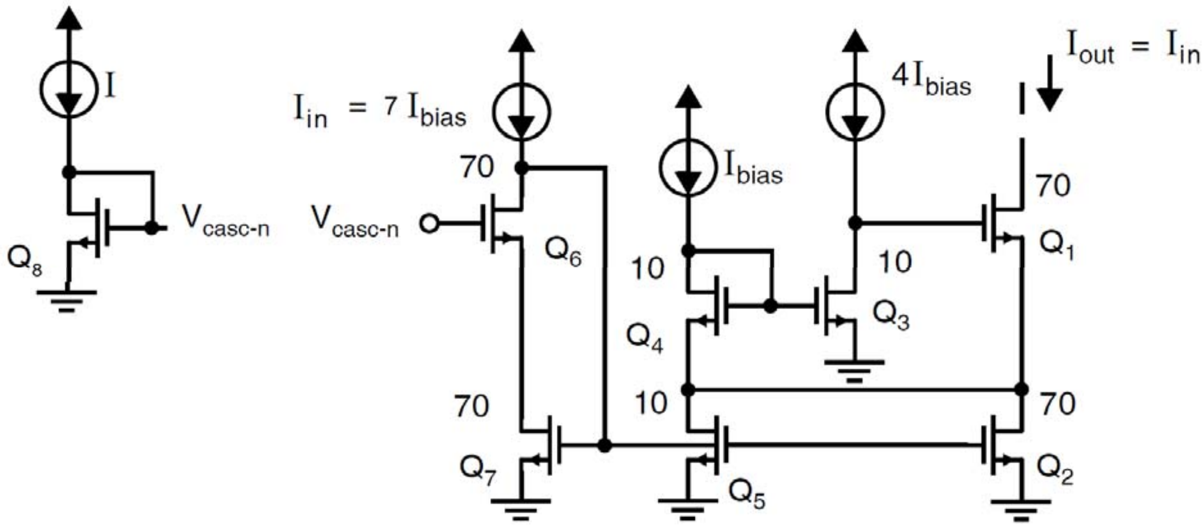
Advantages:

- High Output-Impedance
- Precise Current Mirror
- High Output-Swing

Disadvantage:

- High Power Consumption

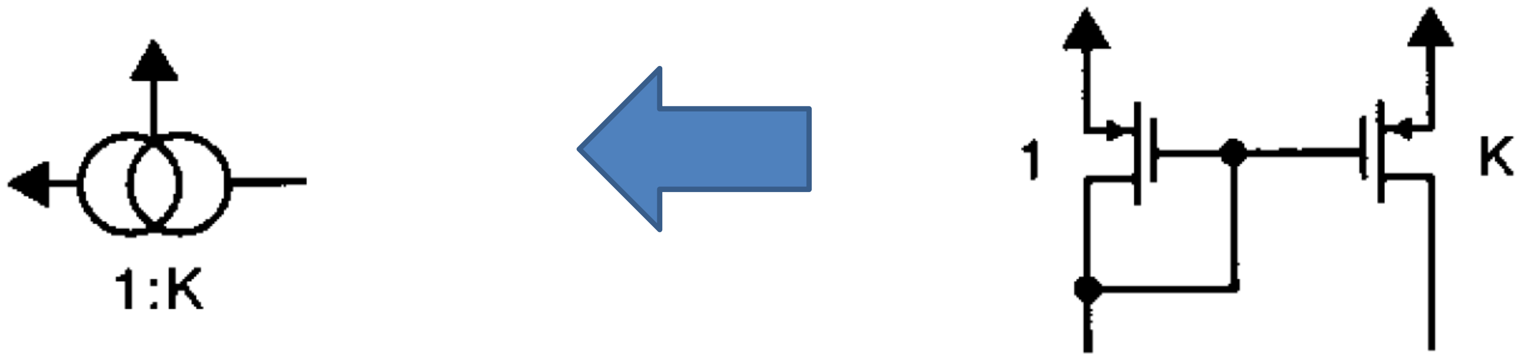
## Modified Wide-Swing Current Mirror with Enhanced Output-Impedance

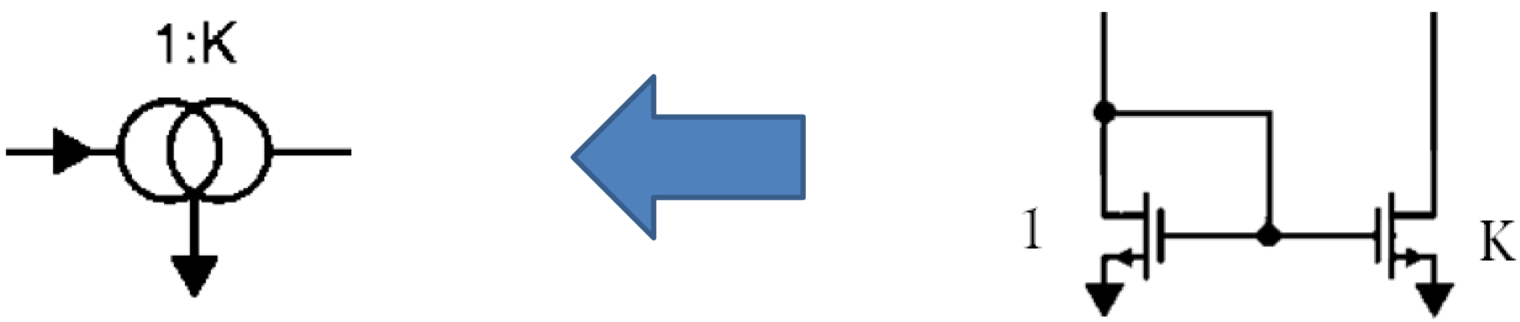



$$R_{out} \cong g_{m1} r_{ds1} r_{ds2} g_{m3} \frac{r_{ds3}}{2} \qquad V_{out} \geq 2V_{eff1}$$

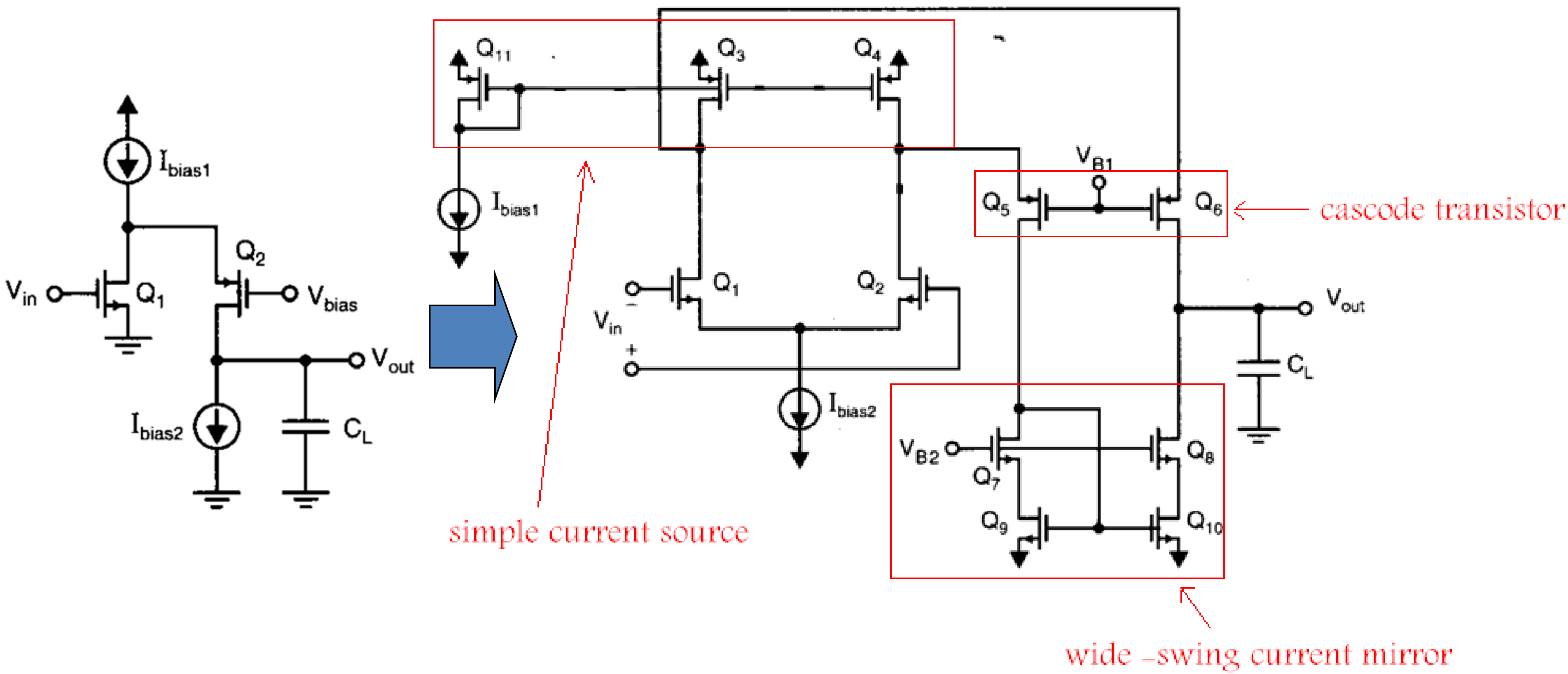
Advantages:
- High Output-Impedance
- Precise Current Mirror
- High Output-Swing

# Current Mirror Symbol



# Folded-Cascode Opamp

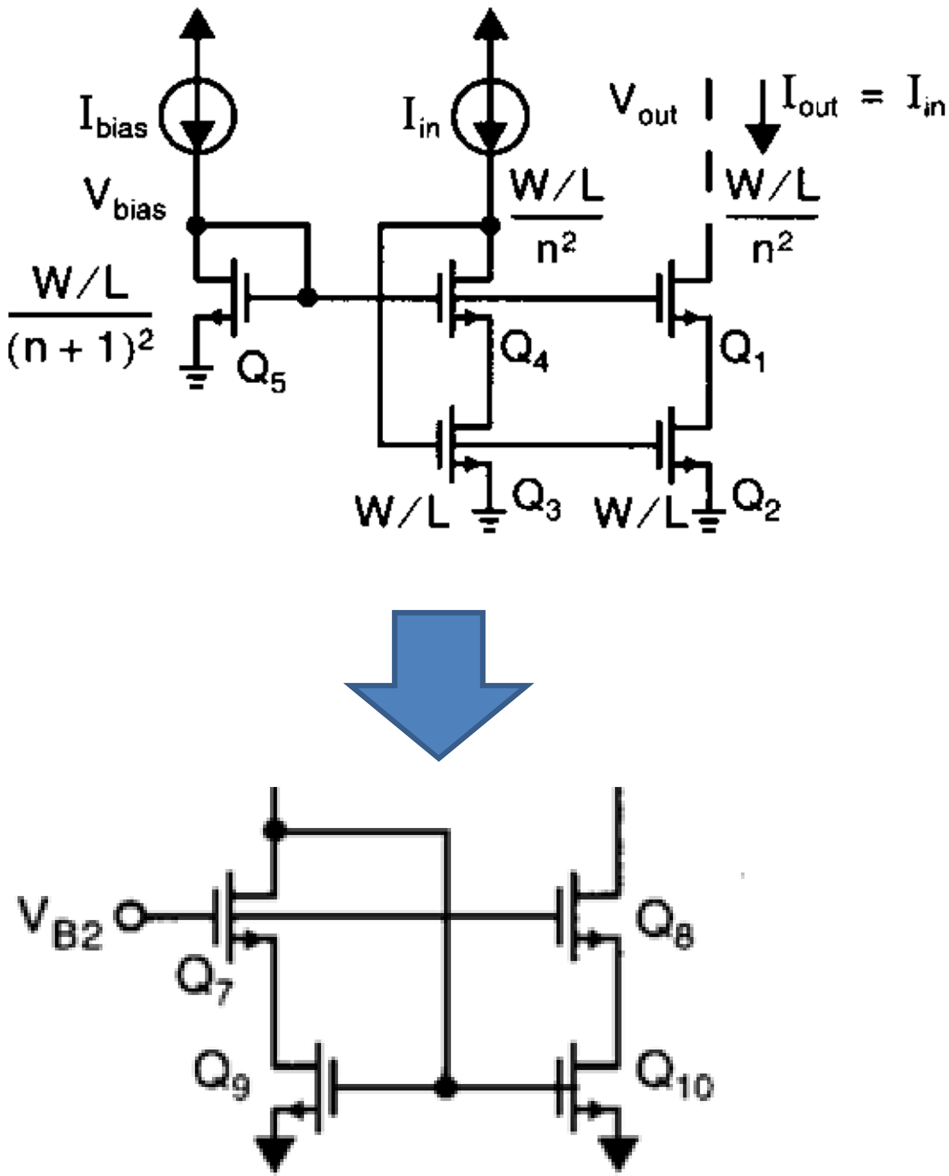



•This opamp is useful when we want to drive capacitive loads.

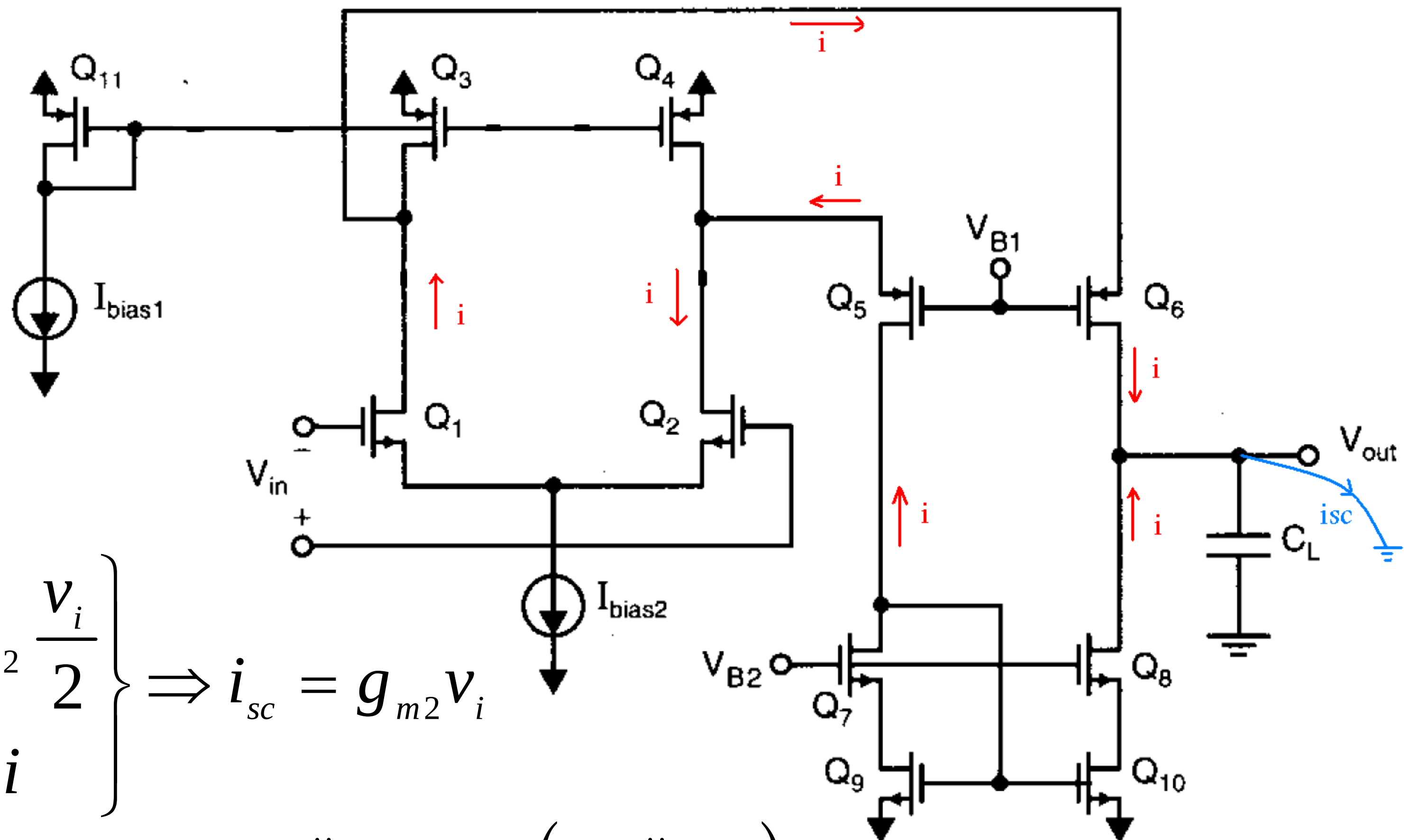
•One of the most important parameters of this modern opamp is its transconductance value.

•Therefore, some designers refer to this modern opamp as <u>Operational Transconductance Amplifier</u> (OTA).

# Remember the wide-swing current mirror



# Opamp Gain




$$\left.\begin{array}{l} i = g_{m2}\dfrac{v_i}{2} \\ i_{sc} = 2i \end{array}\right\} \Rightarrow i_{sc} = g_{m2} v_i$$

$$r_{out} \cong g_{m8} r_{ds8} r_{ds10} \| g_{m6} r_{ds6} \left( r_{ds3} \| r_{ds1} \right)$$

$$v_o = r_{out} i_{sc} \Rightarrow A_V = g_{m1} r_{out}$$

# Competition between Two Current Sources

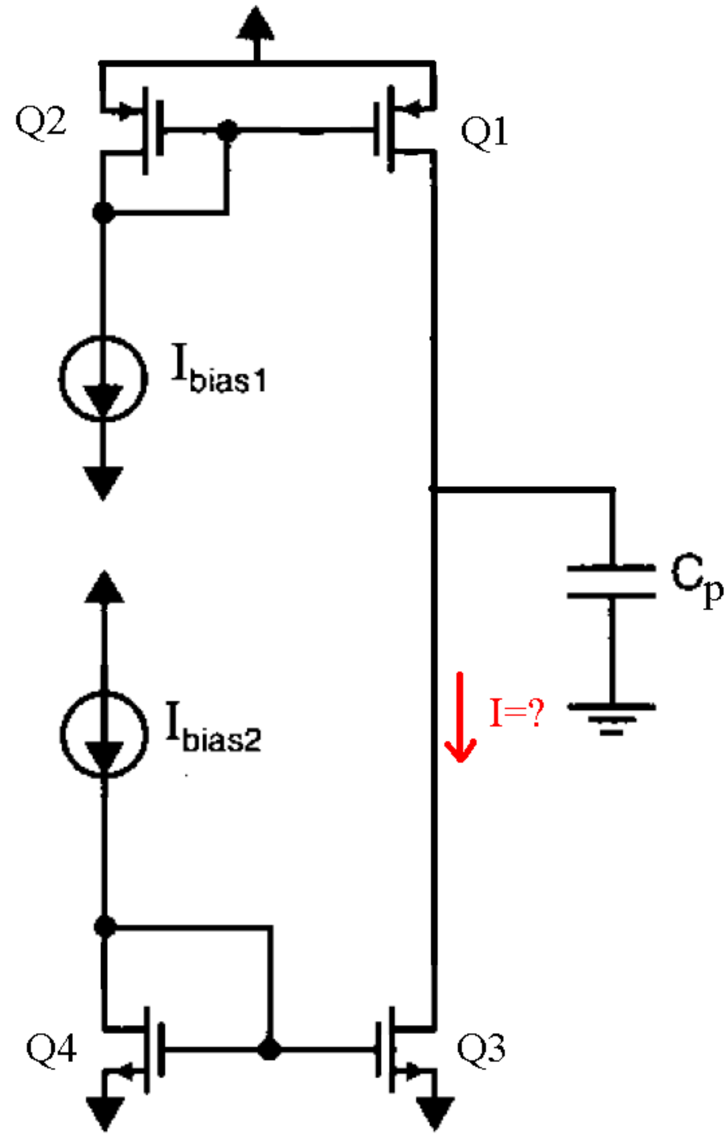
Assume that:

$$\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2$$

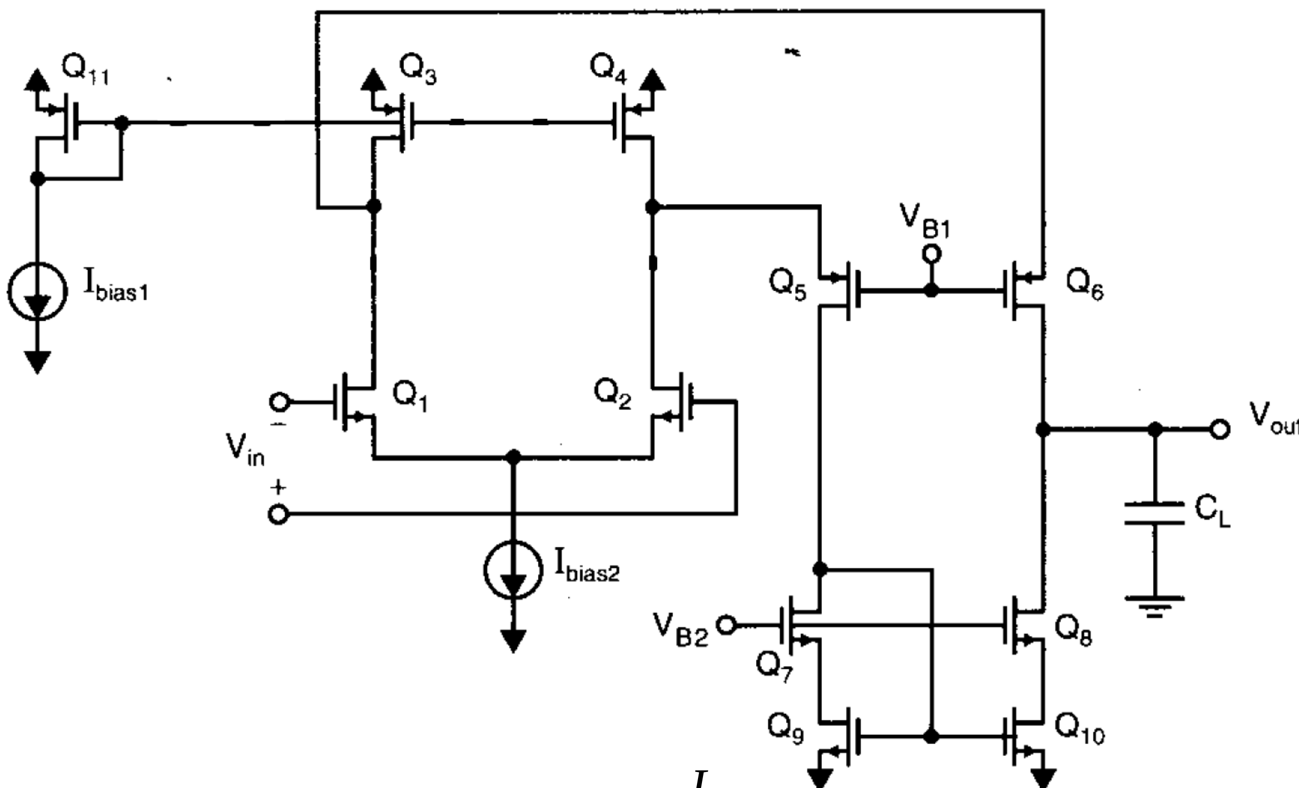
$$\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4$$

If Ibias1>Ibias2 ➔ Q1:Triode Q3:Active   I=Ibias2

If Ibias2>Ibias1 ➔ Q1:Active Q3:Triode   I=Ibias1



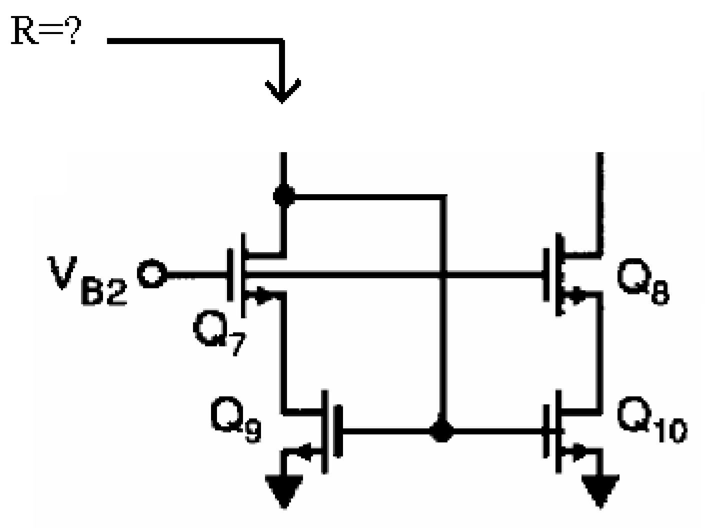
# Slew Rate




Assuming $I_{bias2} > I_{D4}$ and $V_{in+} >> V_{in-}$ ➔ $SR^{+} = \frac{I_{D4}}{C_L}$

Assuming $I_{bias2} > I_{D4}$ and $V_{in-} >> V_{in-}$ ➔ $SR^{-} = \frac{I_{D4}}{C_L}$

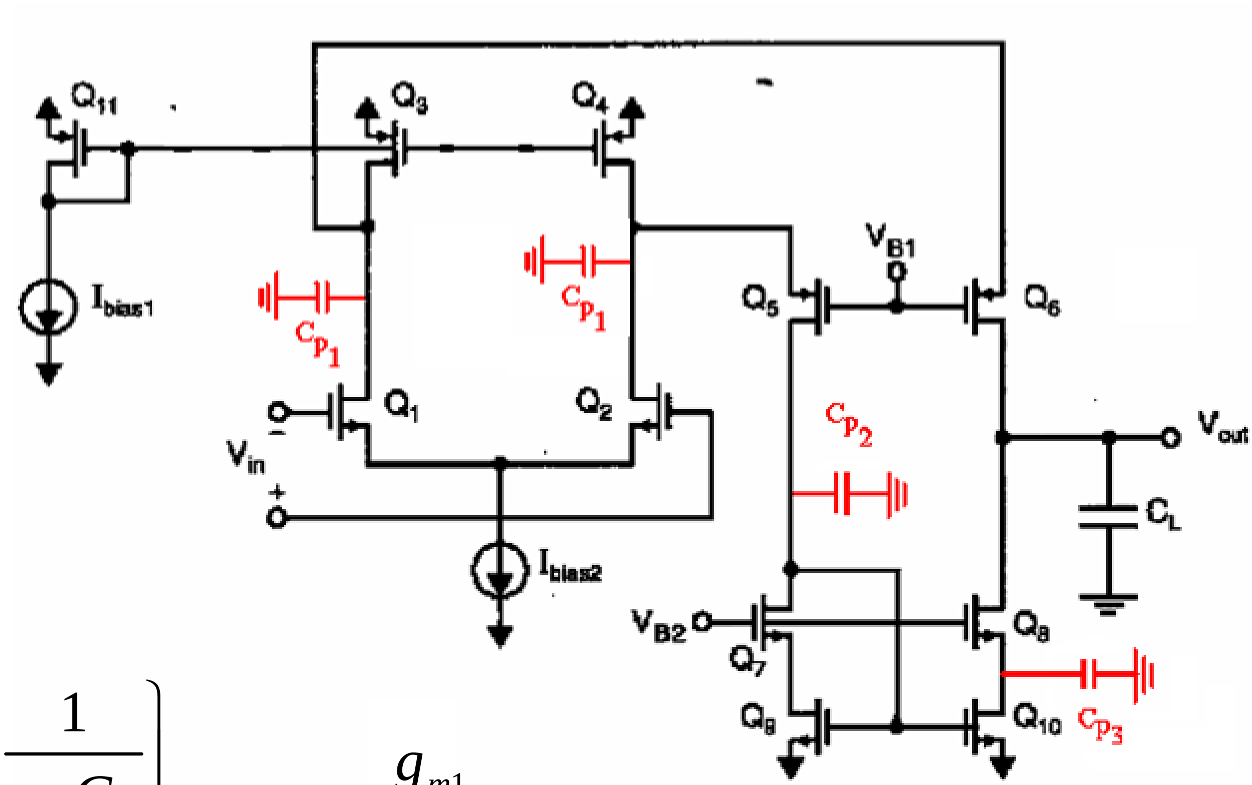
# Lemma




Wide-swing current mirror

$$R \cong \frac{1}{g_{m9}}$$

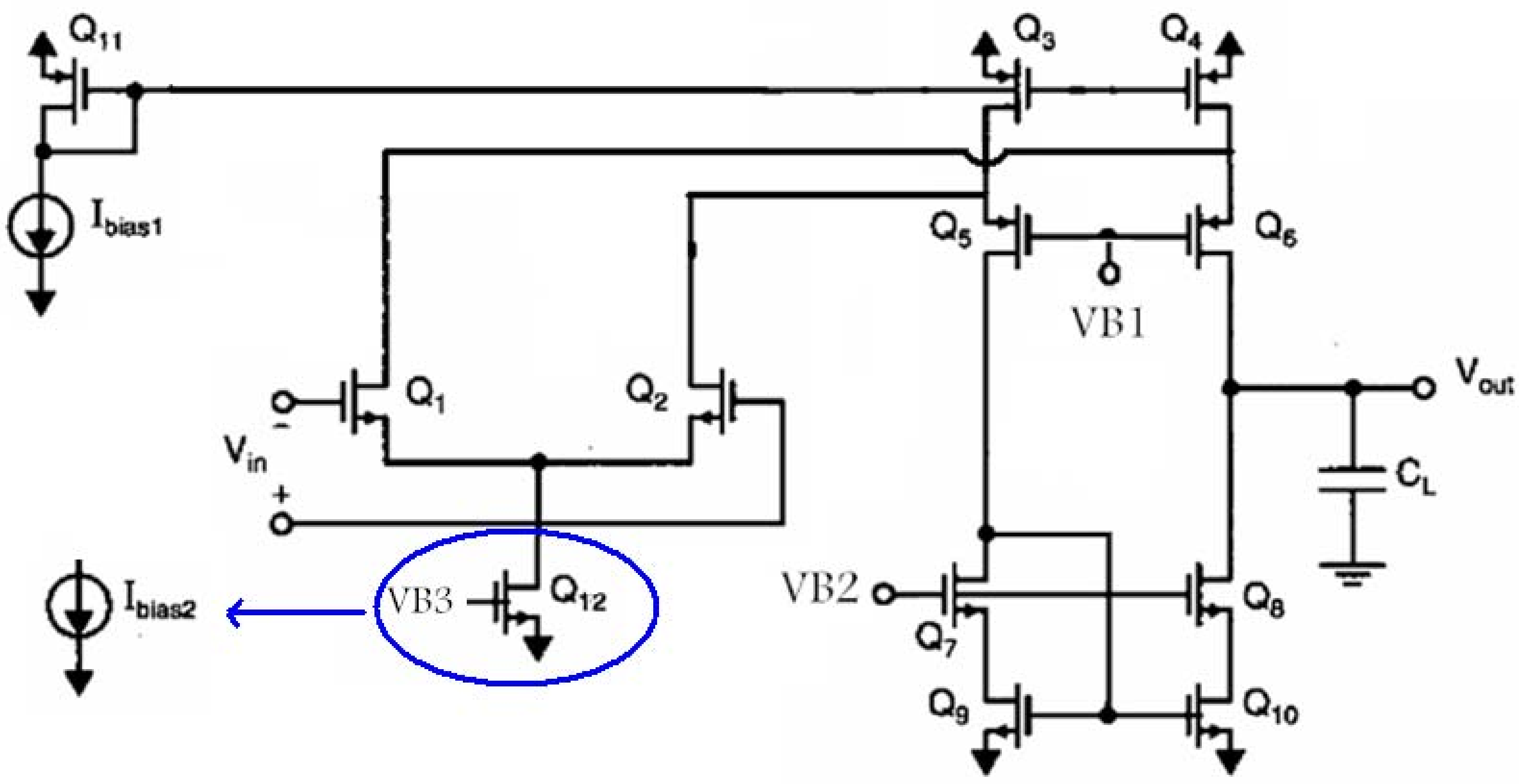
# Frequency Response




$$\left.\begin{array}{l}\omega_{p1} \cong \dfrac{1}{r_{out} C_L} \\ A_0 = g_{m1} r_{out}\end{array}\right\} \Rightarrow \omega_{ta} = \frac{g_{m1}}{C_L}$$

$$\omega_{p2} \cong \frac{1}{\frac{1}{g_{m5}} C_{p1} + \frac{1}{g_{m9}} C_{p2} + \frac{1}{g_{m8}} C_{p3}}$$

# Another Schematic for Folded-Cascode Opamp



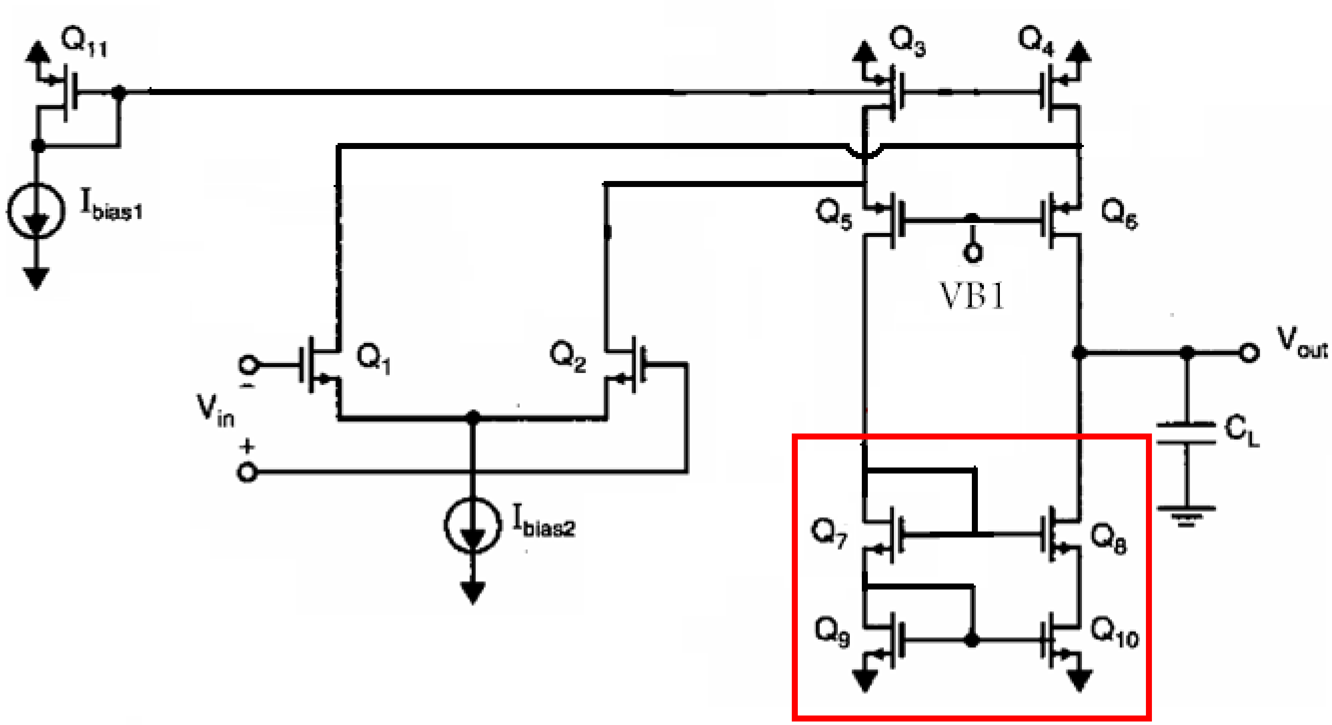

Output swing:

$$V_{B2} - V_{tn} \le V_{out} \le V_{B1} + \left|V_{tp}\right|$$

Input common-mode range:

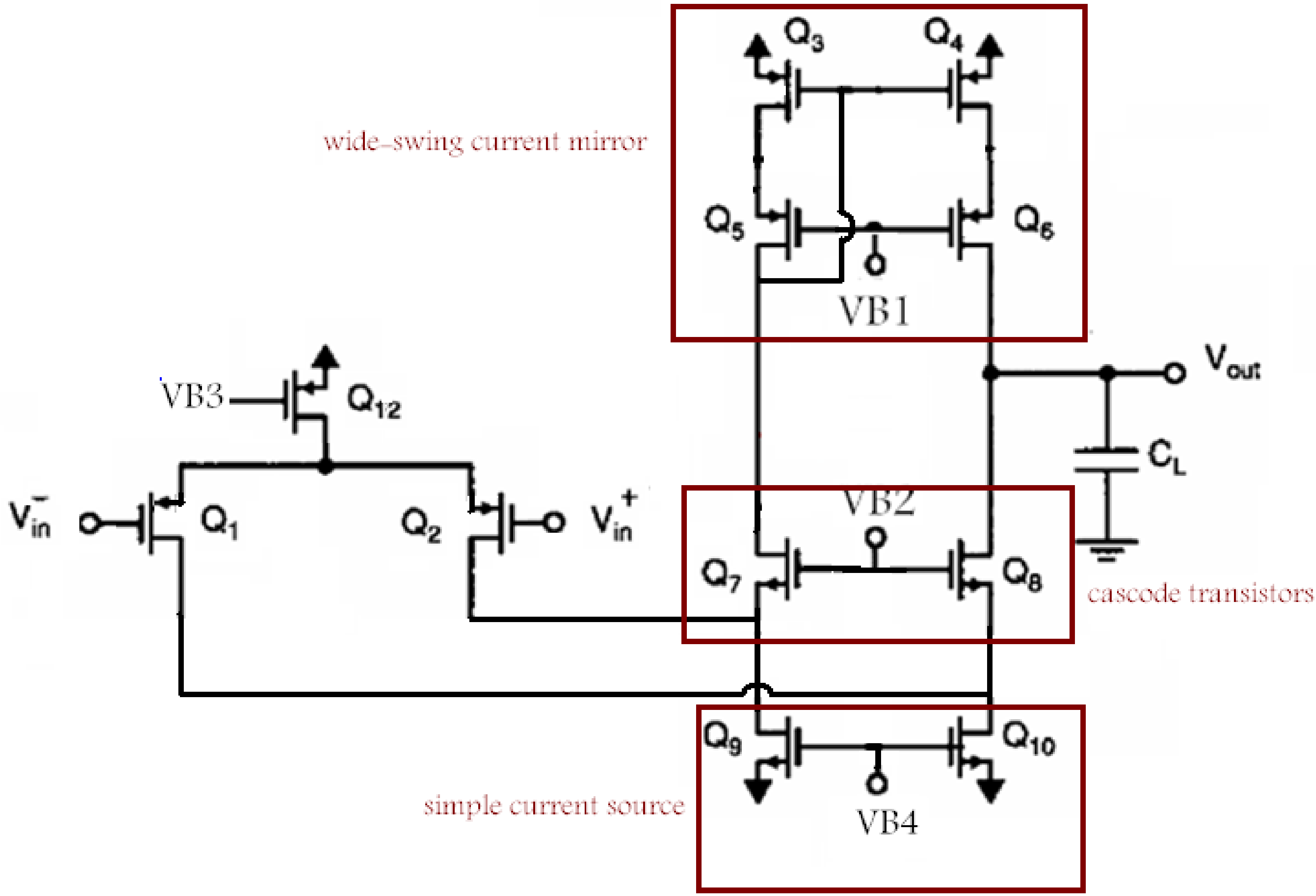
$$V_{tn} + V_{eff1} + V_{eff12} \le V_{cmi} \le V_{B1} + \left|V_{tp}\right| + \left|V_{eff6}\right| + V_{tn}$$

# Folded-Cascode Opamp without wide-swing current source

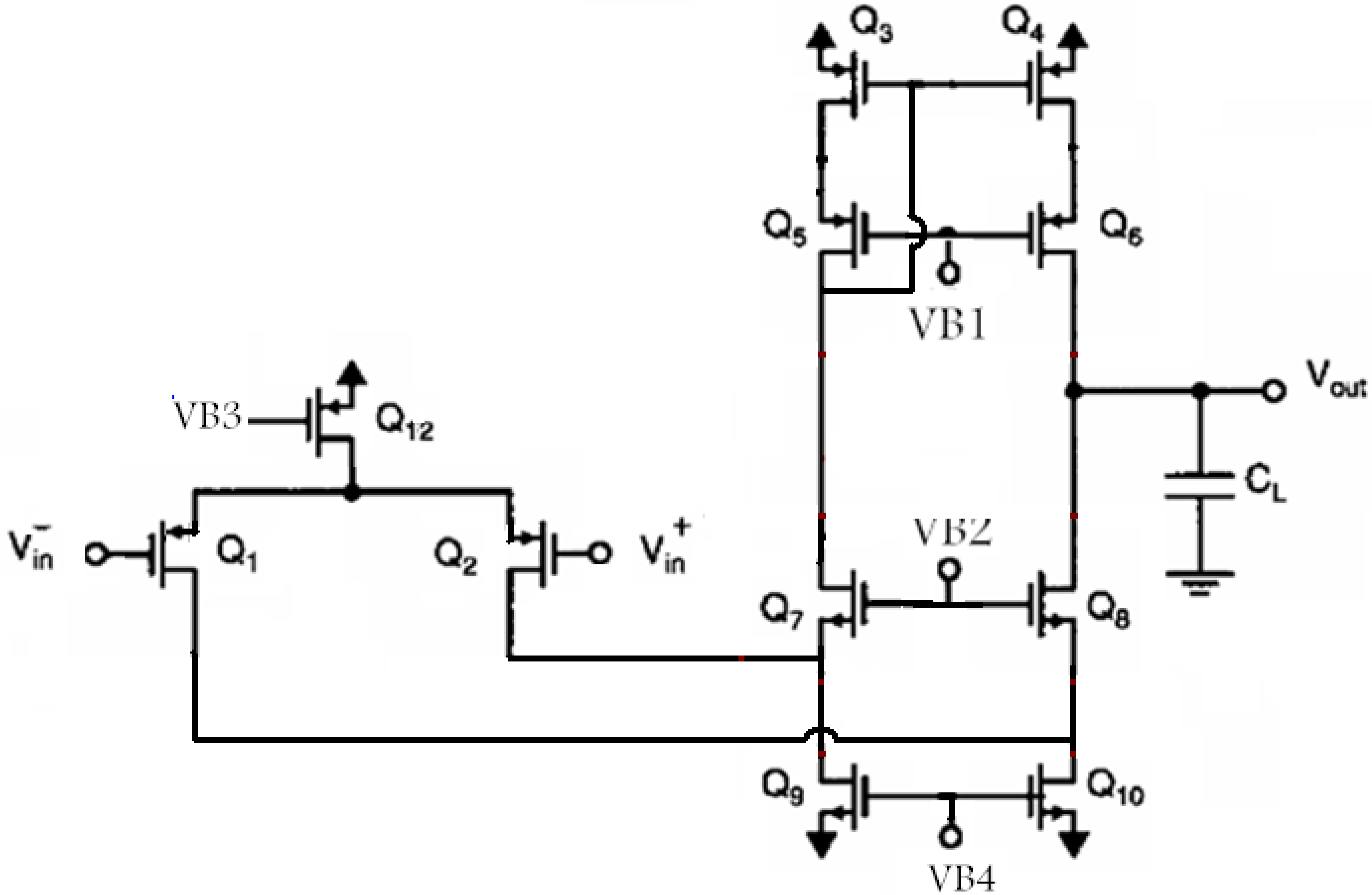



conventional cascode current mirror

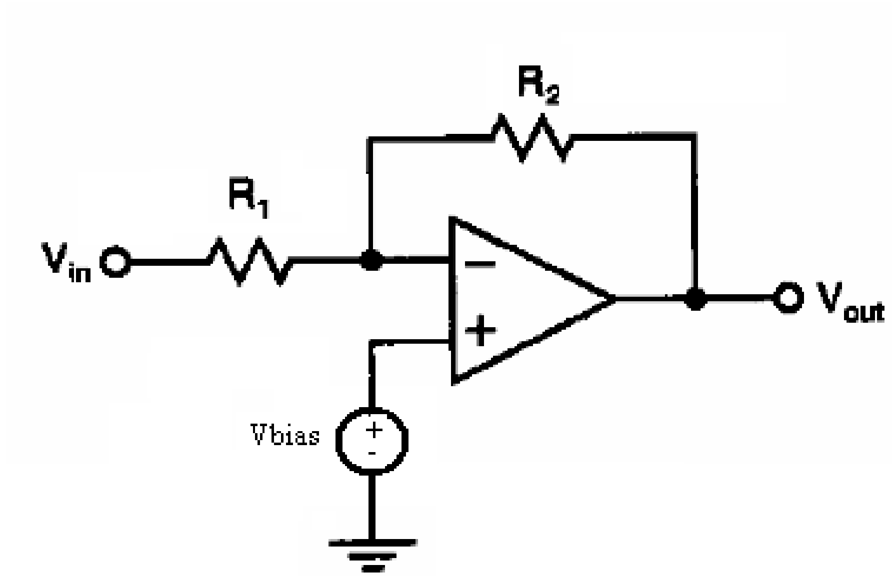
# Folded-Cascode Opamp
# (pmos-input)



# Folded-Cascode Opamp
# (pmos-input)



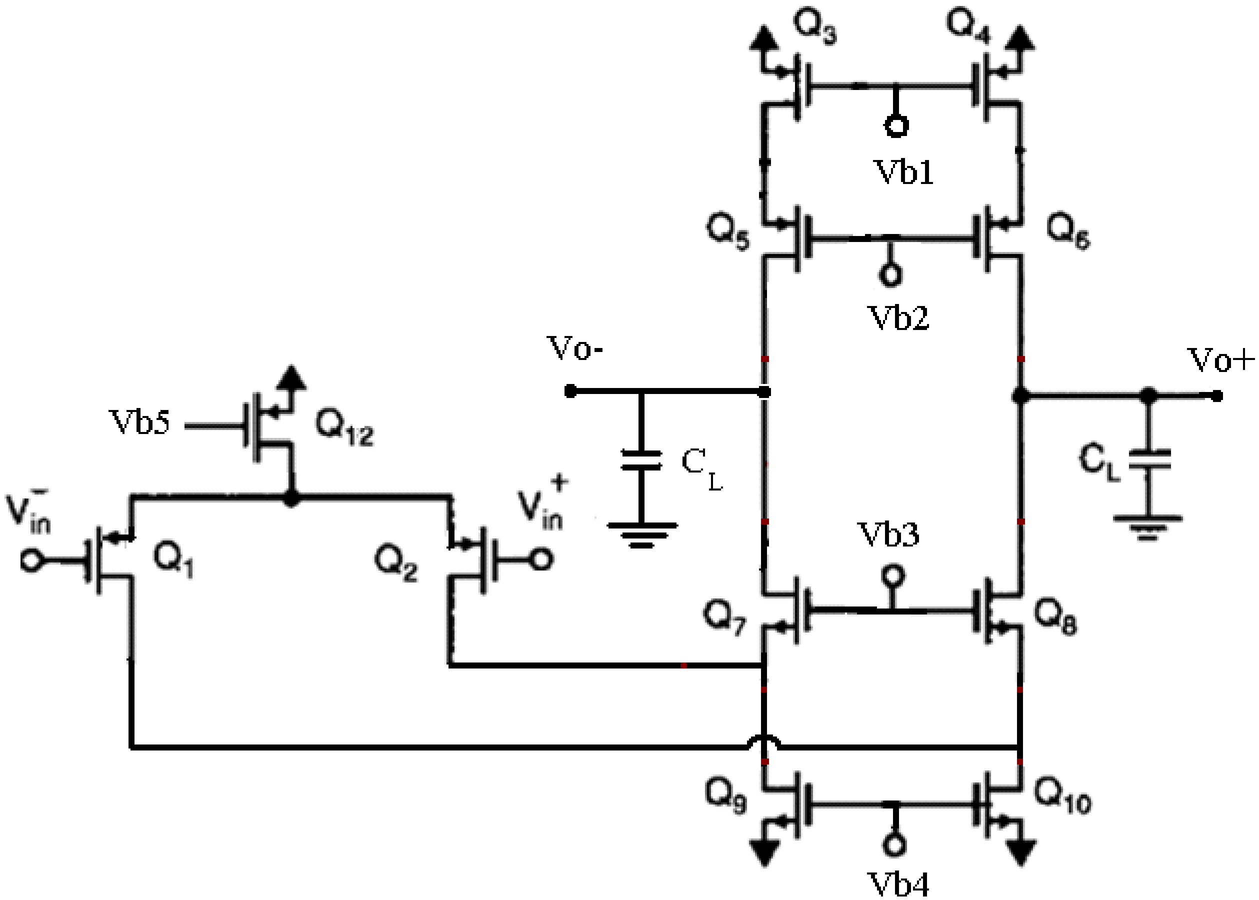
# What is the DC voltage of the output node?




In a single-ended opamp, the DC voltage of the output node is determined by the feedback circuit around the opamp.

$$V_{out} = V_{bias} + \frac{R_2}{R_1}\left(V_{bias} - V_{in}\right)$$

# Fully Differential Folded-Cascode Opamp




The bias voltages Vb1, Vb4, and Vb5 must be chosen so that the following relation is satisfied!!!

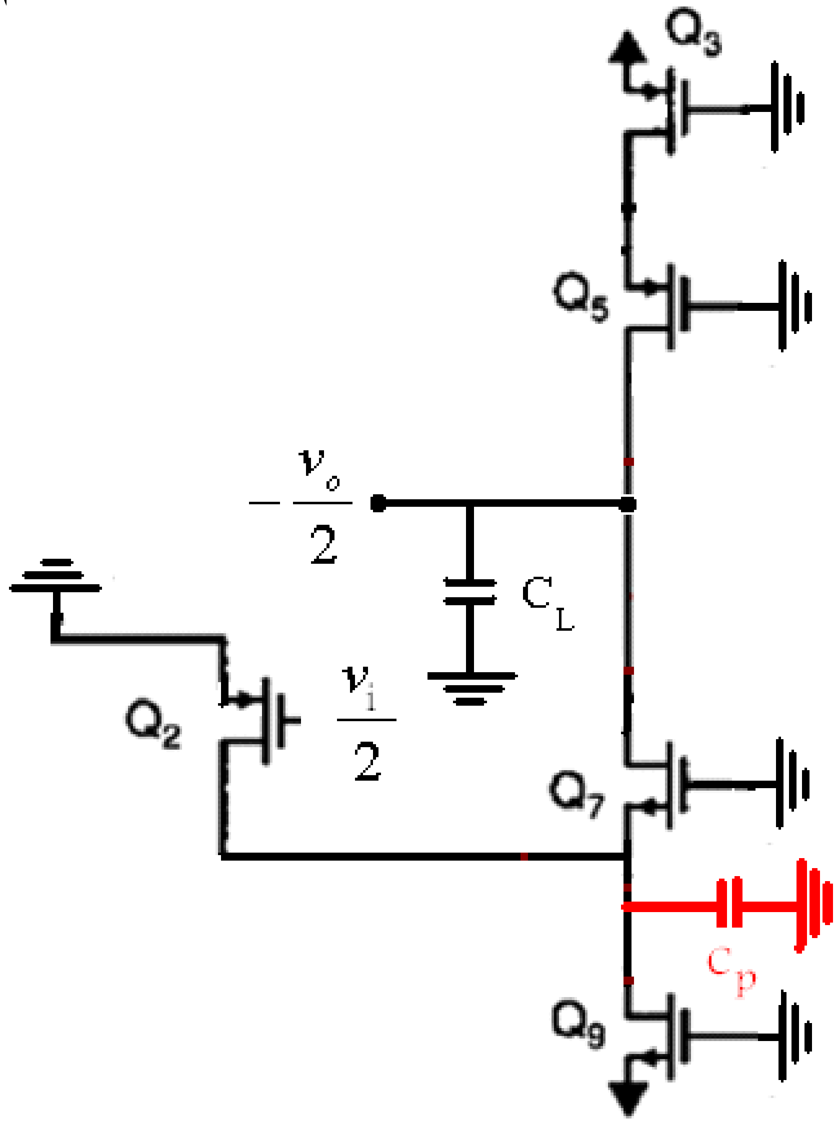
$I_{D9}=0.5I_{D12}+I_{D3}$

The opamp is completely symmetric. So we can use the half-circuit of the opamp for AC analysis.

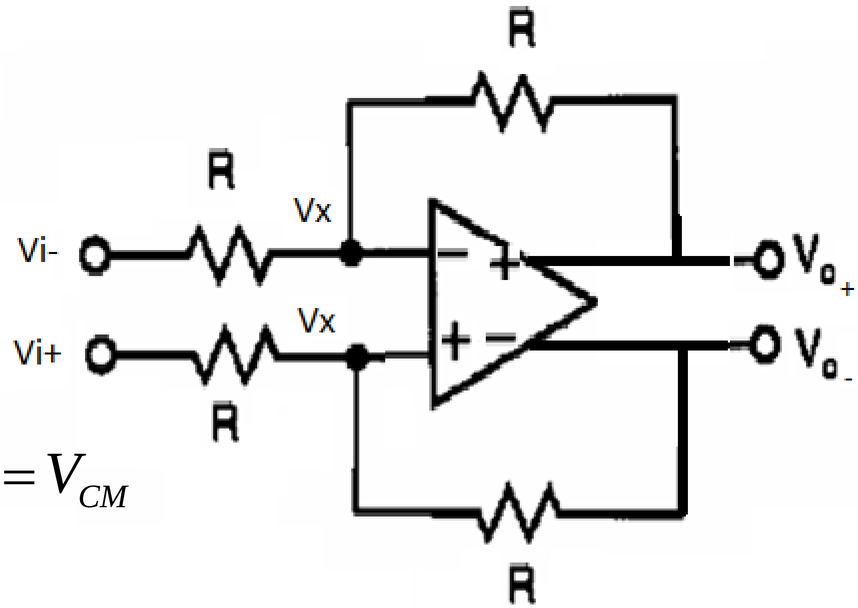
# Fully Differential Folded-Cascode Opamp
# (half-circuit)

$$\left.\begin{array}{l}\omega_{p1} \cong \dfrac{1}{r_{out} C_L} \\ A_0 = g_{m_i} r_{out}\end{array}\right\} \Rightarrow \omega_{ta} = \frac{g_{m_i}}{C_L}$$

$$\omega_{p2} \cong \frac{1}{\frac{1}{g_{m_7}} C_p}$$



# What is the DC voltage of the output nodes?




$$V_{i+} = V_{i-} = V_{CM}$$

In a single-ended opamp, the DC voltage of the output node is determined by the feedback circuit around the opamp.

$$\left.\begin{aligned} I &= \frac{V_{CM} - V_x}{R} \\ V_{CM} - V_o &= 2RI \end{aligned}\right\} \Rightarrow V_{CM} - V_o = 2\left(V_{CM} - V_x\right) \Rightarrow V_{o+} = V_{o-} = V_o = 2V_x - V_{CM}$$

The DC voltage of the output nodes can not be determined!!!

# Common-Mode Feedback Circuit (CMFB Circuit)

In a fully differential opamp, the CMFB circuit is employed inside the opamp to adjust the common-mode voltage of the output nodes identical to a predetermined voltage, Vref.

$$CMFB\ Circuit \Rightarrow \frac{V_{o+} + V_{o-}}{2} = V_{ref}$$

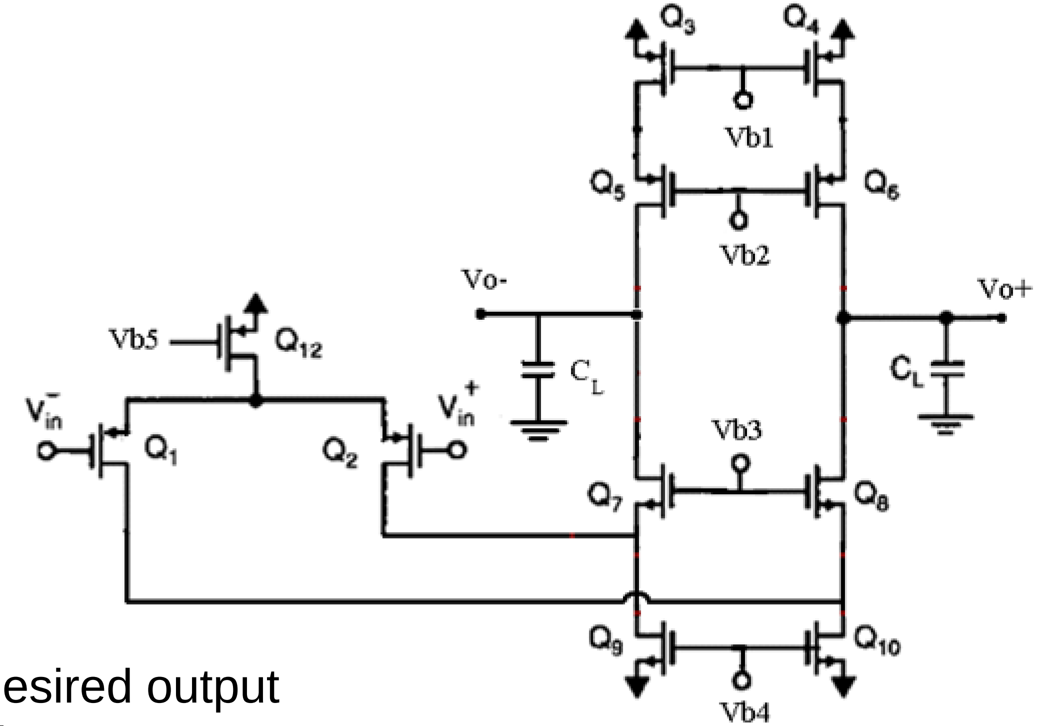
$$KVL\ and\ KCL \Rightarrow V_o = 2V_x - V_{CM}$$

$$\Rightarrow$$

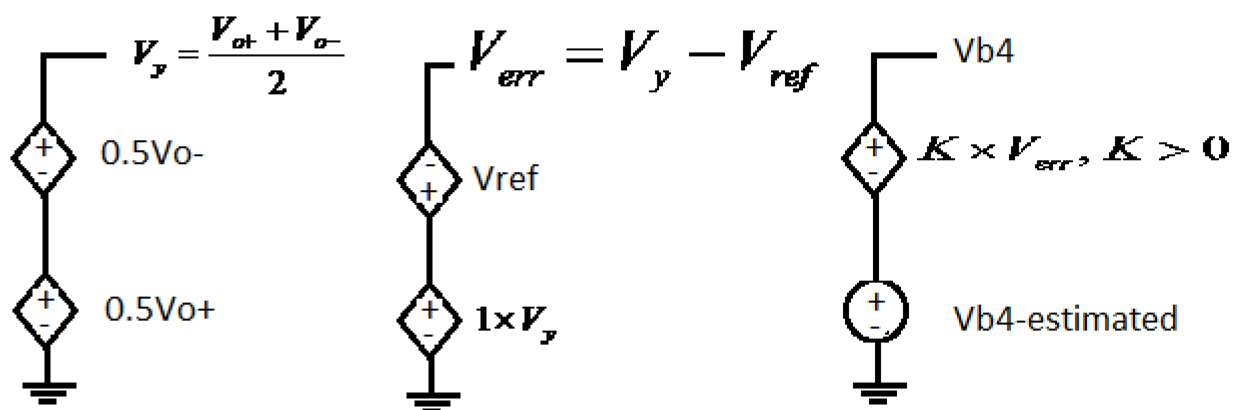
$$V_{o+} = V_{o-} = V_{ref}$$

$$V_x = \frac{V_{ref} + V_{CM}}{2}$$

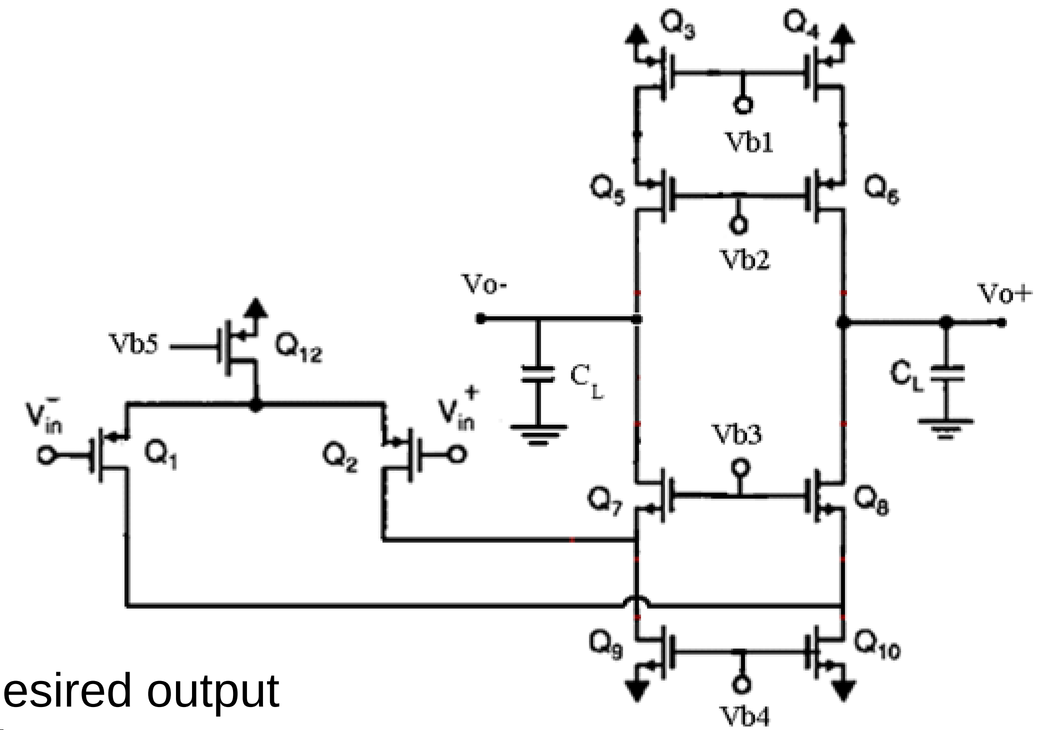
# Ideal CMFB Circuit (1)



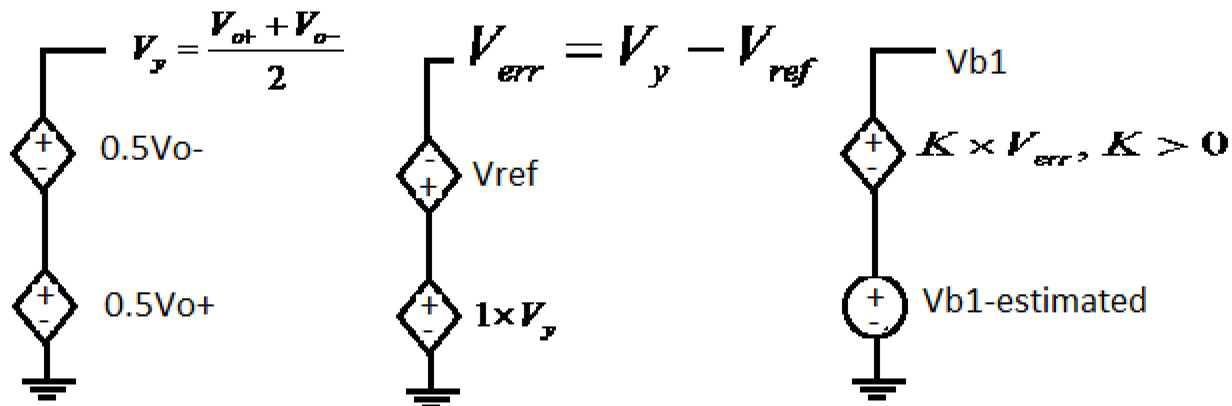

Vref denotes the desired output common-mode voltage.



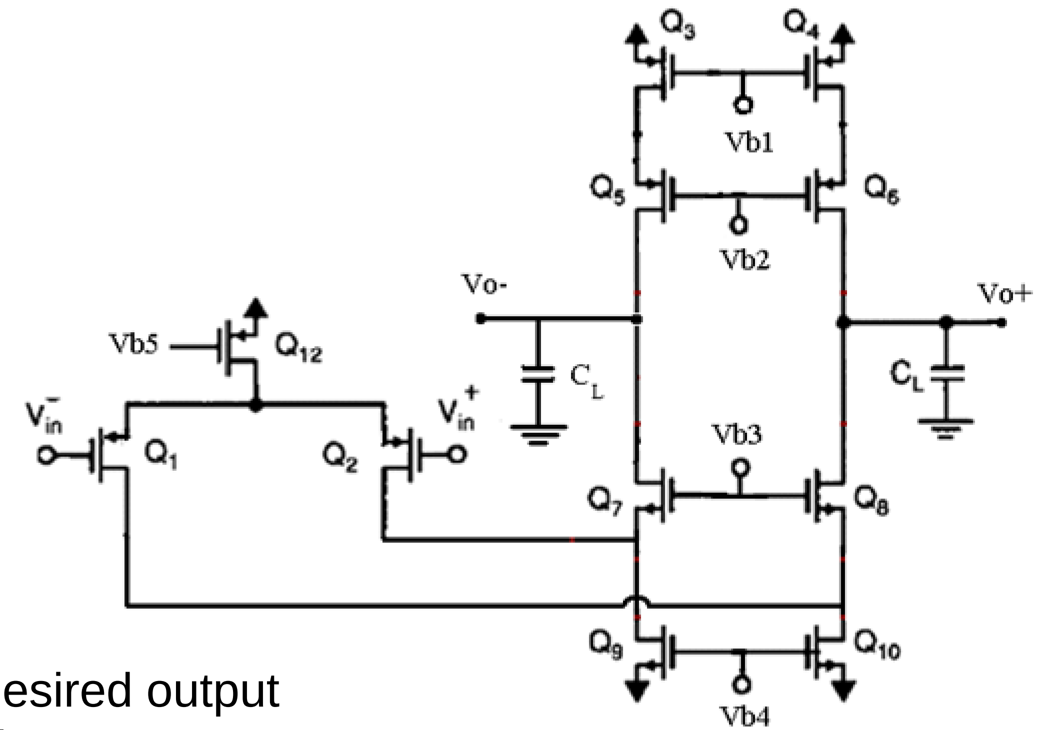
# Ideal CMFB Circuit (2)



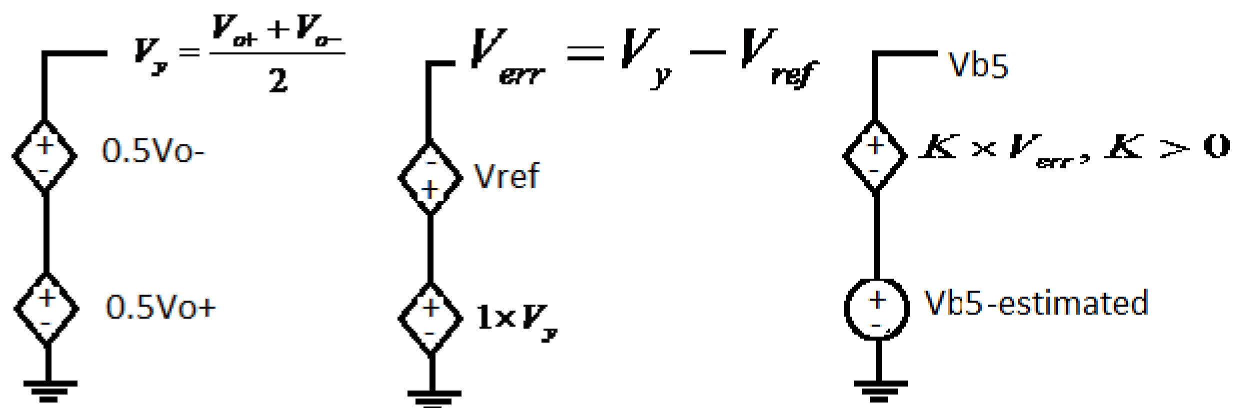

Vref denotes the desired output common-mode voltage.



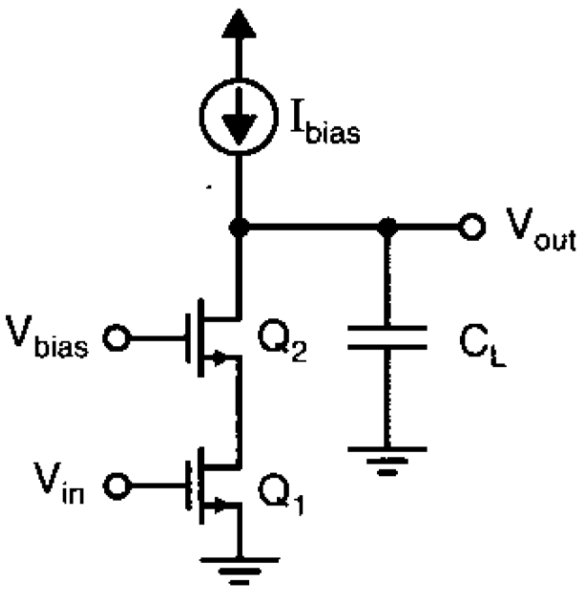
# Ideal CMFB Circuit (3)

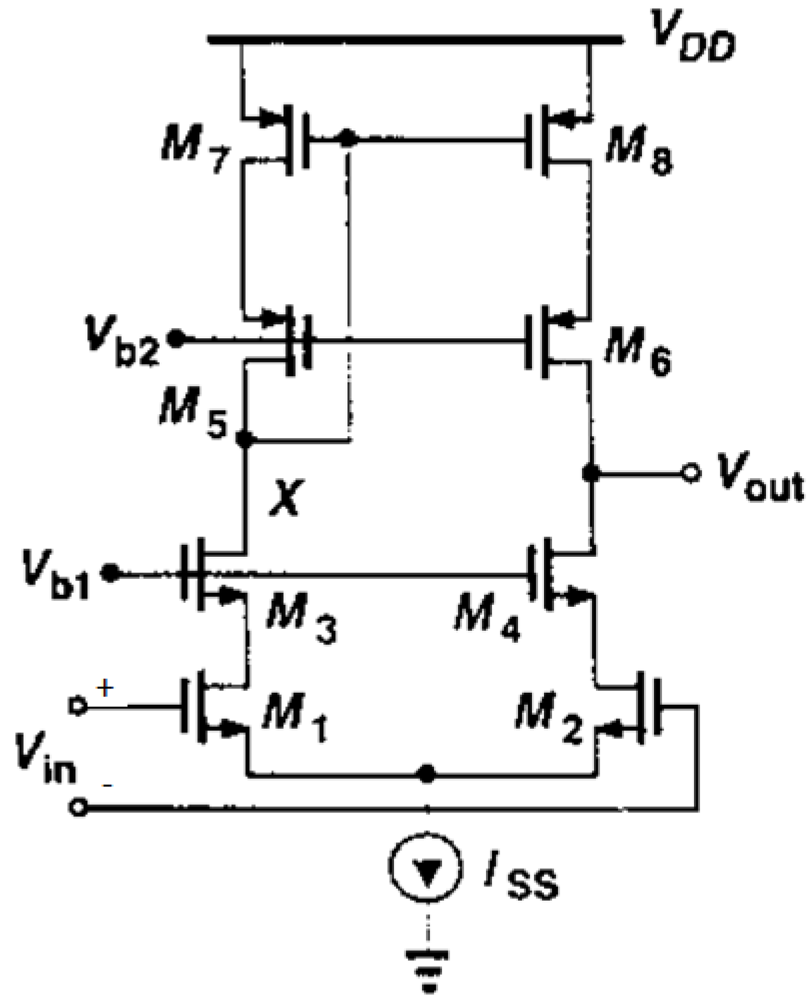



Vref denotes the desired output common-mode voltage.



# Single-ended Telescopic Opamp



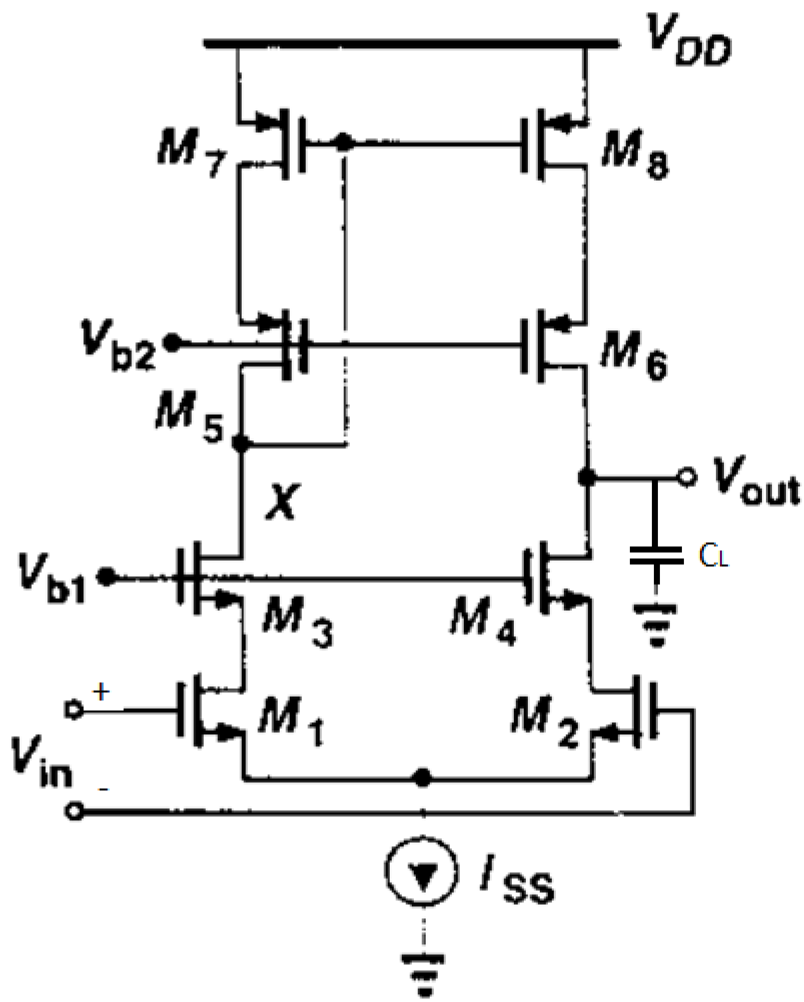




$$i_{sc} = g_{m1} v_i$$

$$r_{out} \cong g_{m4} r_{ds4} r_{ds2} \| g_{m6} r_{ds6} r_{ds8}$$

$$v_o = r_{out} i_{sc} \Rightarrow A_V = g_{m1} r_{out}$$

# Slew Rate

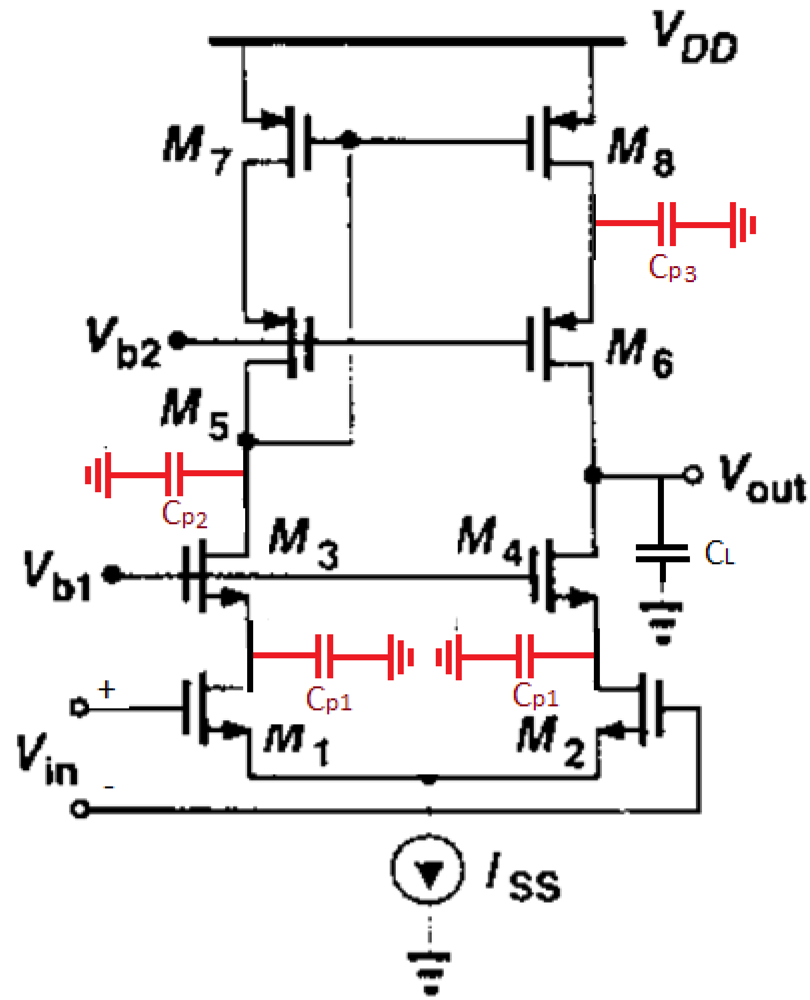



$$SR^+ = SR^- = \frac{I_{SS}}{C_L}$$

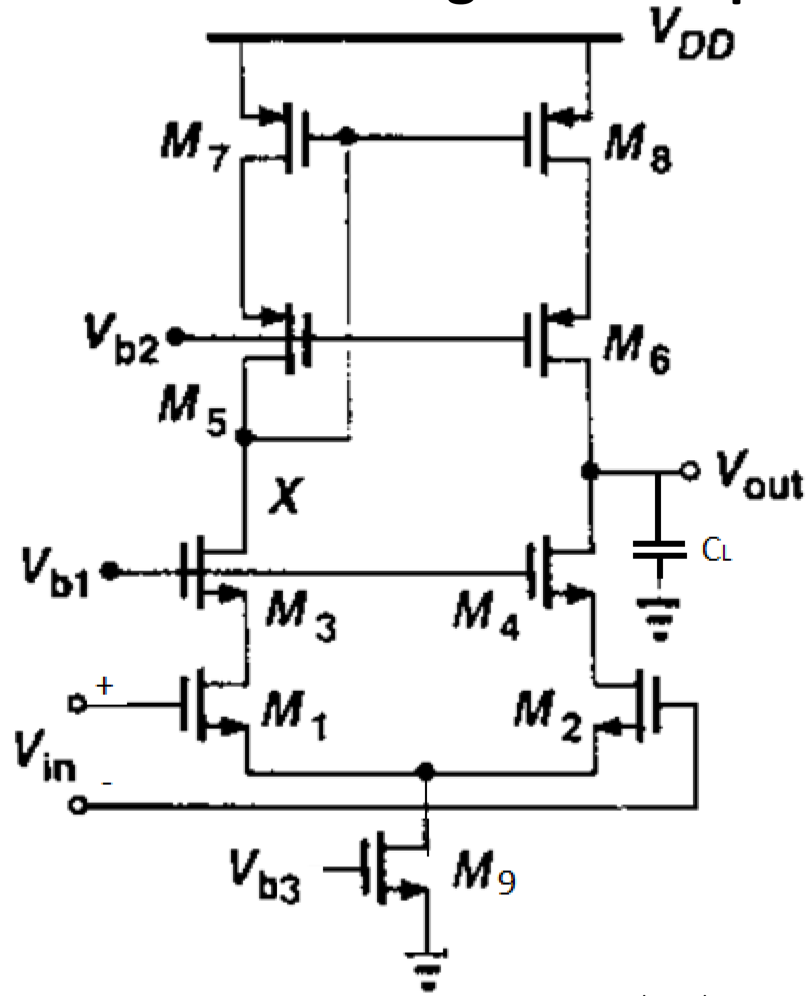
# Frequency Response

$$\left.\begin{array}{l}\omega_{p1} \cong \dfrac{1}{r_{out} C_L} \\ A_0 = g_{m_i} r_{out}\end{array}\right\} \Rightarrow \omega_{ta} = \frac{g_{m_i}}{C_L}$$

$$\omega_{p2} \cong \frac{1}{\dfrac{1}{g_{m3}} C_{p1} + \dfrac{1}{g_{m7}} C_{p2} + \dfrac{1}{g_{m6}} C_{p3}}$$



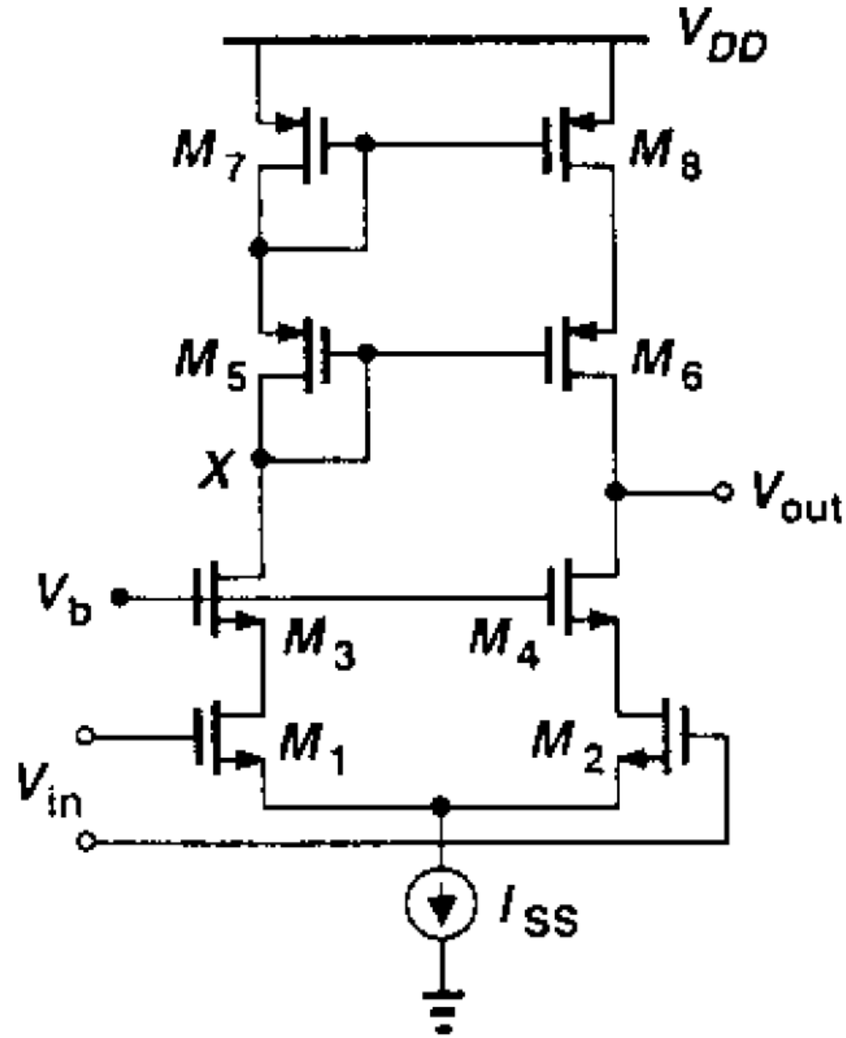
**Input common-mode range and output swing**



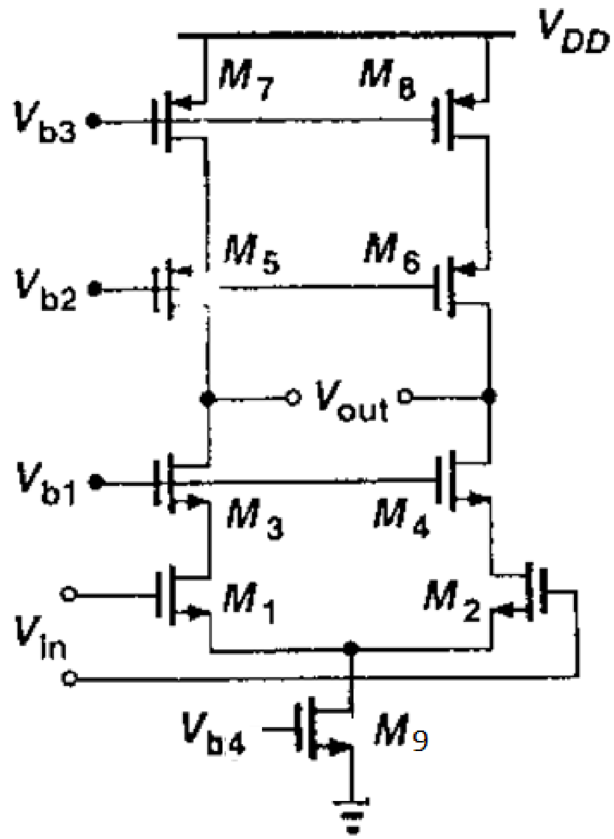

Output swing: $V_{B1} - V_{tn} \le V_{out} \le V_{B2} + |V_{tp}|$

Input common-mode range: $V_{tn} + V_{eff1} + V_{eff9} \le V_{cmi} \le V_{B1} - V_{eff3}$

## Telescopic Opamp without wide-swing current source



# Fully Differential Telescopic Opamp




The bias voltages Vb3 and Vb4 must be chosen so that the following relation is satisfied!!!

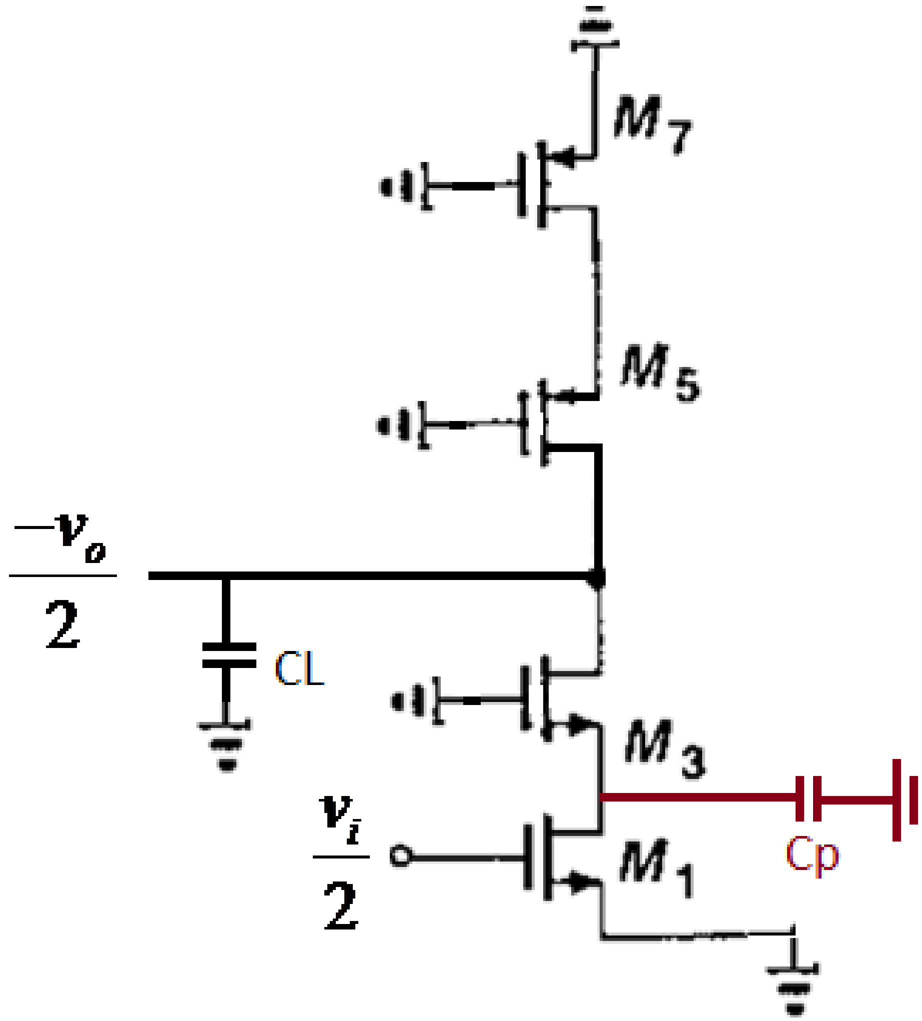
$I_{D7}=0.5I_{D9}$

The opamp is completely symmetric. So we can use the half-circuit of the opamp for AC analysis.

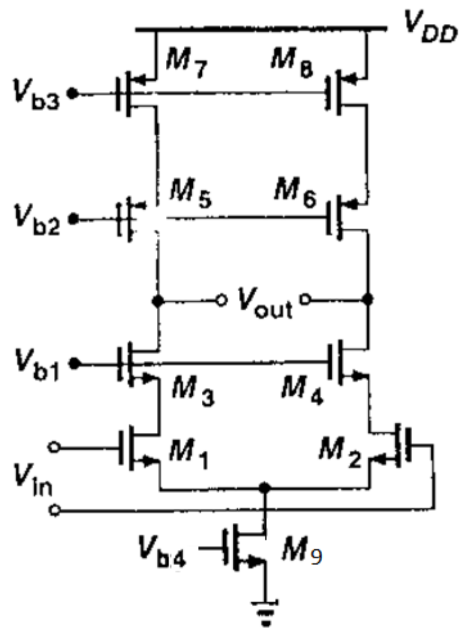
# Fully Differential Telescopic Opamp
# (half-circuit)

$$\left.\begin{aligned}\omega_{p1} &\cong \frac{1}{r_{out}C_L} \\ A_0 &= g_{m1}r_{out}\end{aligned}\right\} \Rightarrow \omega_{ta} = \frac{g_{m1}}{C_L}$$

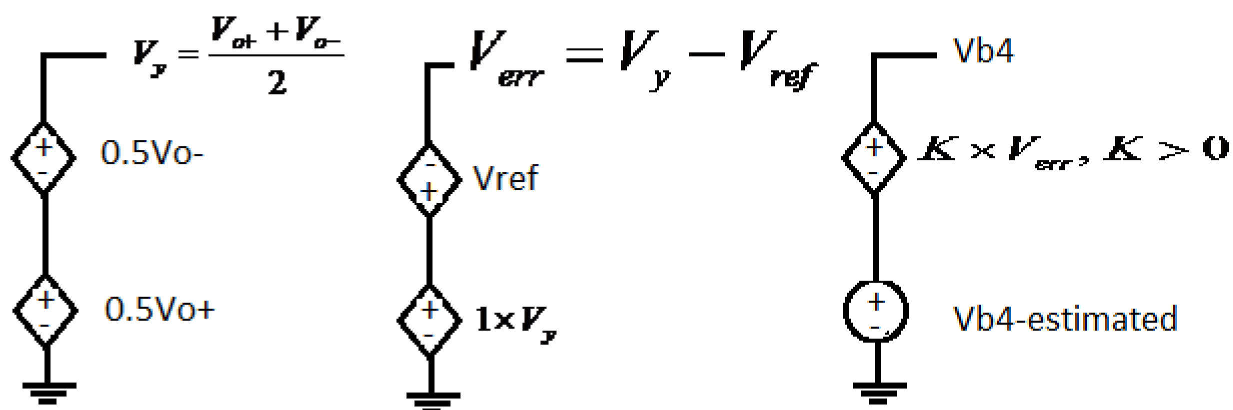
$$\omega_{p2} \cong \frac{1}{\frac{1}{g_{m3}}C_p}$$



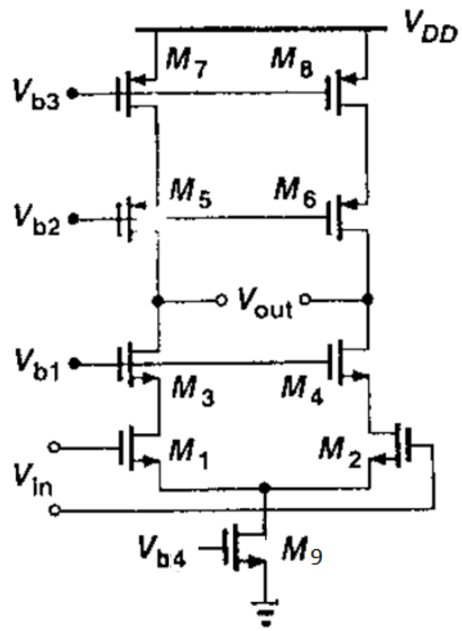
# Ideal CMFB Circuit (1)



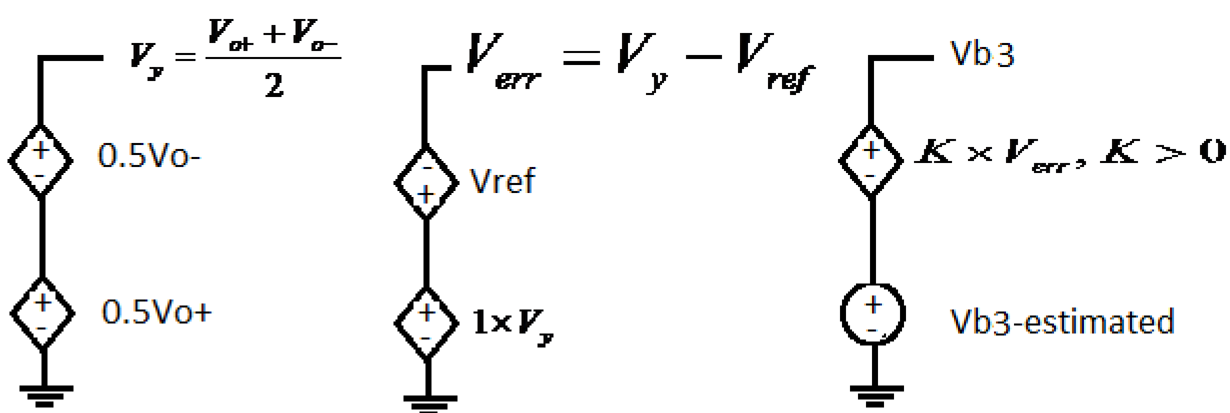

Vref denotes the desired output common-mode voltage.



# Ideal CMFB Circuit (2)




Vref denotes the desired output common-mode voltage.

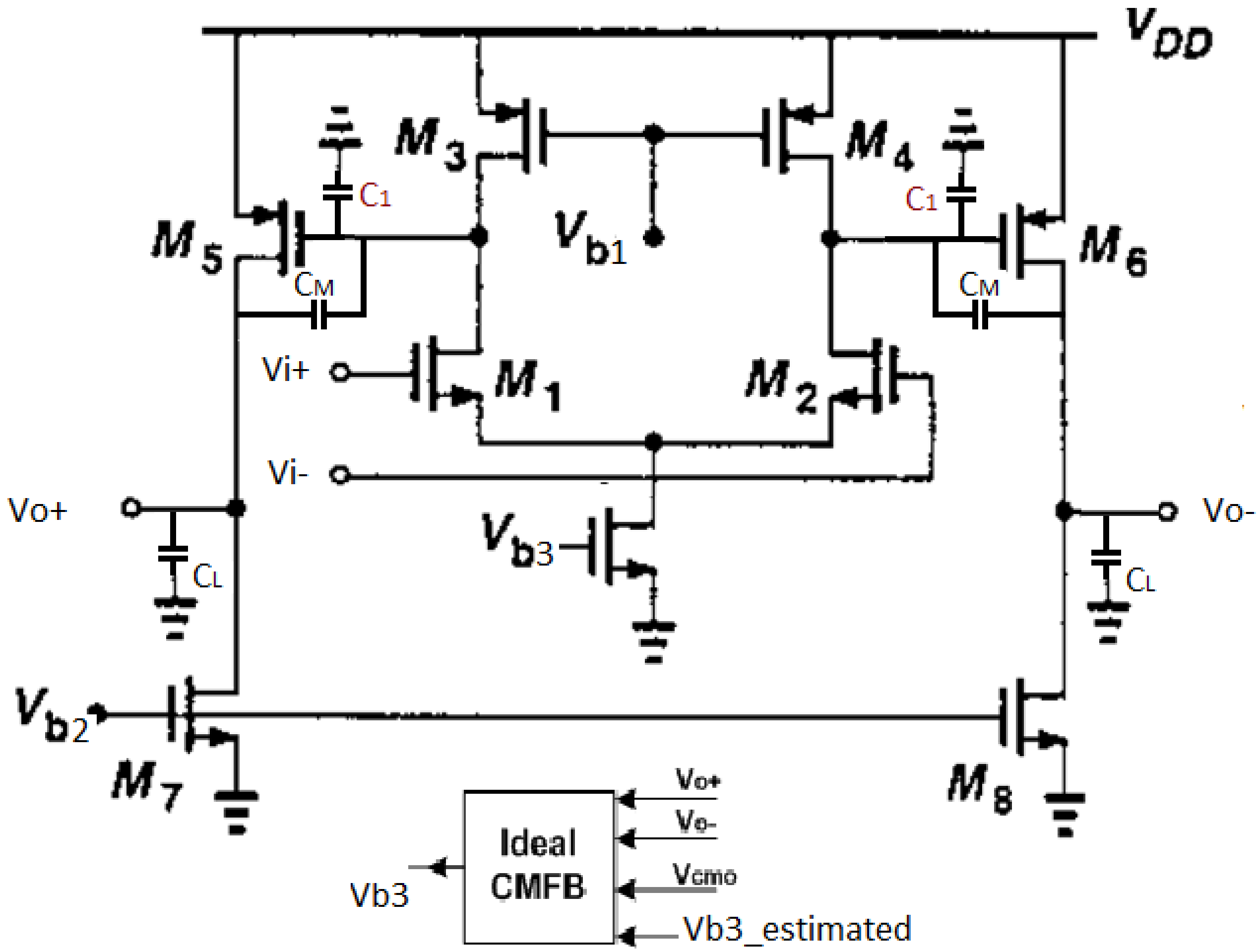


# Fully Differential Two-Stage Opamp (nmos input)

$$A_0 = g_{m1} R_1 g_{m5} R_2$$

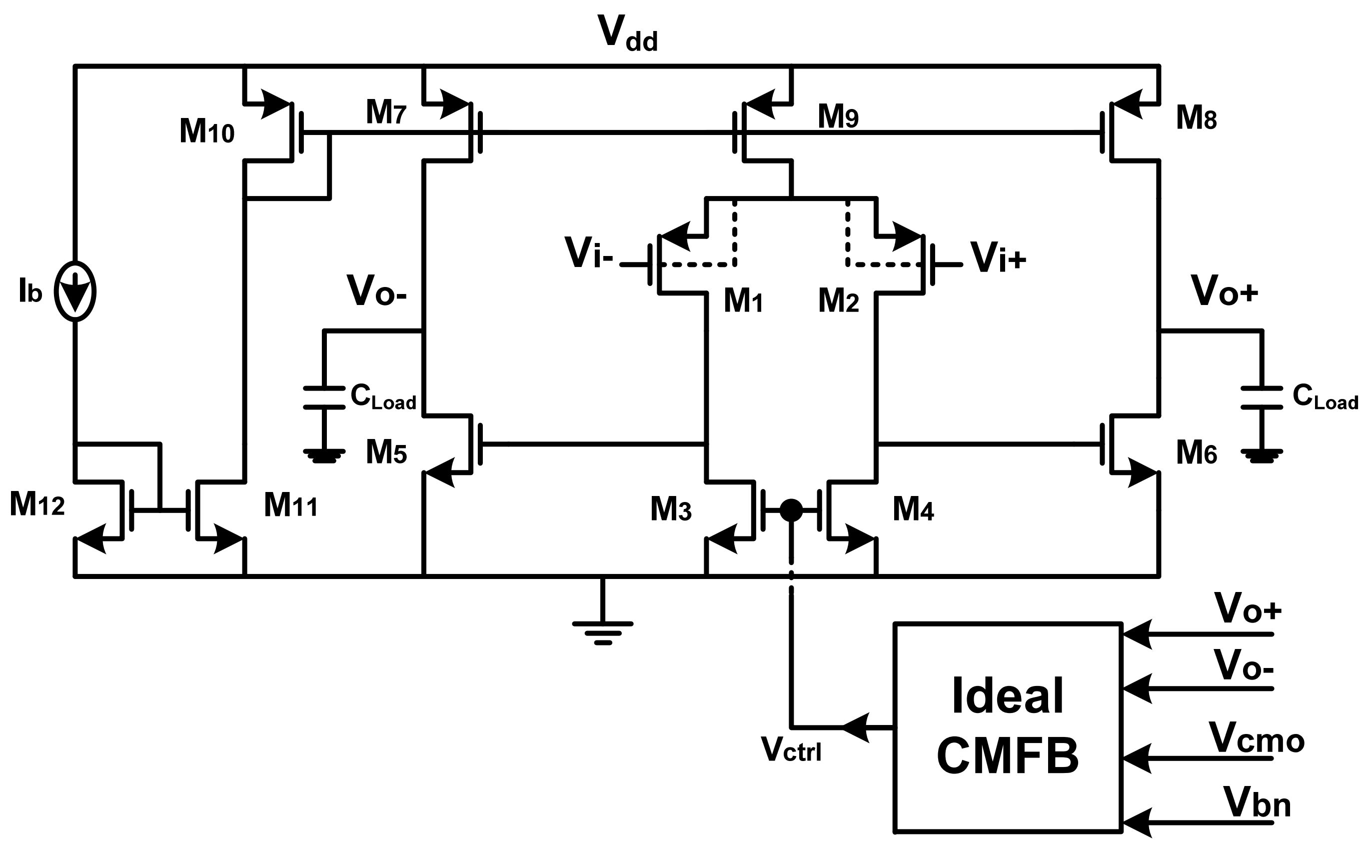
$$\omega_{ta} = \frac{g_{m1}}{C_M}$$

$$\omega_{p2} \cong \frac{g_{m5}}{C_1 + C_L}$$




C1 denotes the parasitic capacitance.

# Fully Differential Two-Stage Opamp (pmos input)

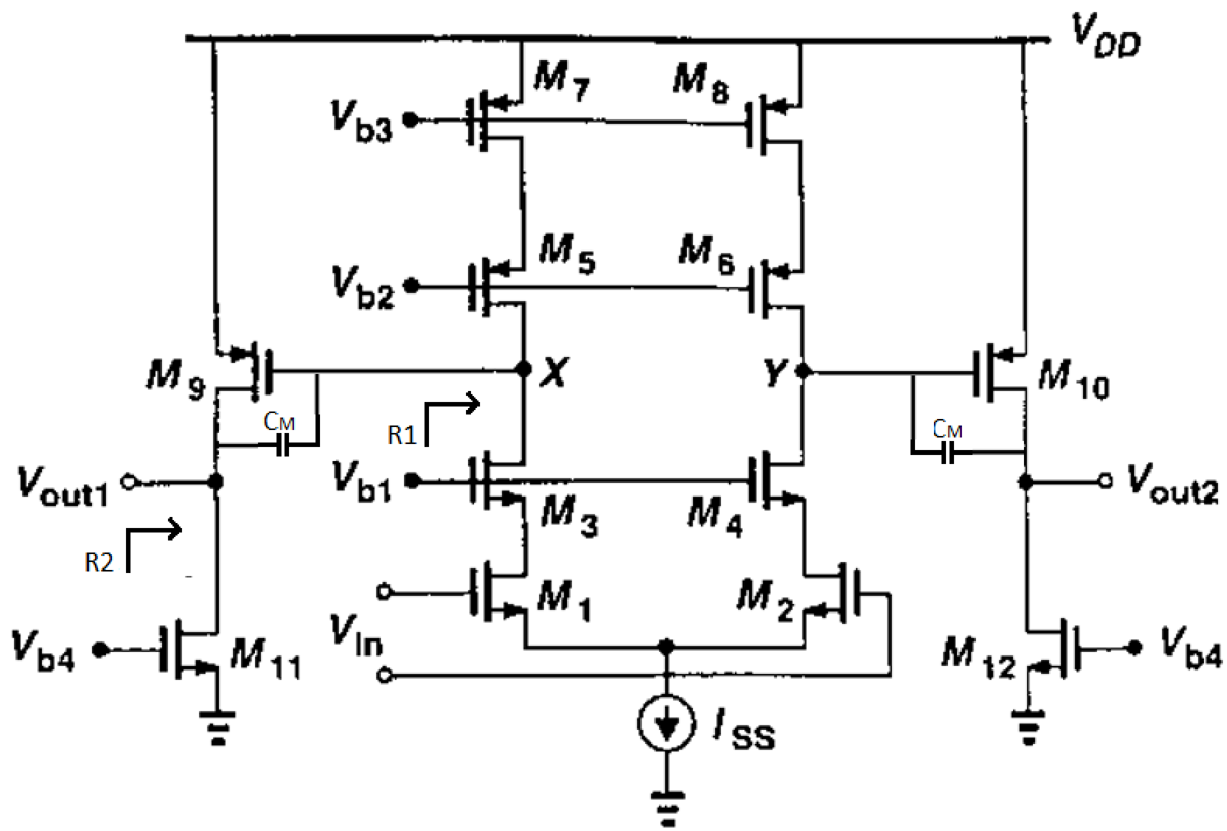


# Fully Differential Two-Stage Opamp
# (First Stage: Telescopic Cascode)

$$A_0 = g_{m1} R_1 g_{m9} R_2$$

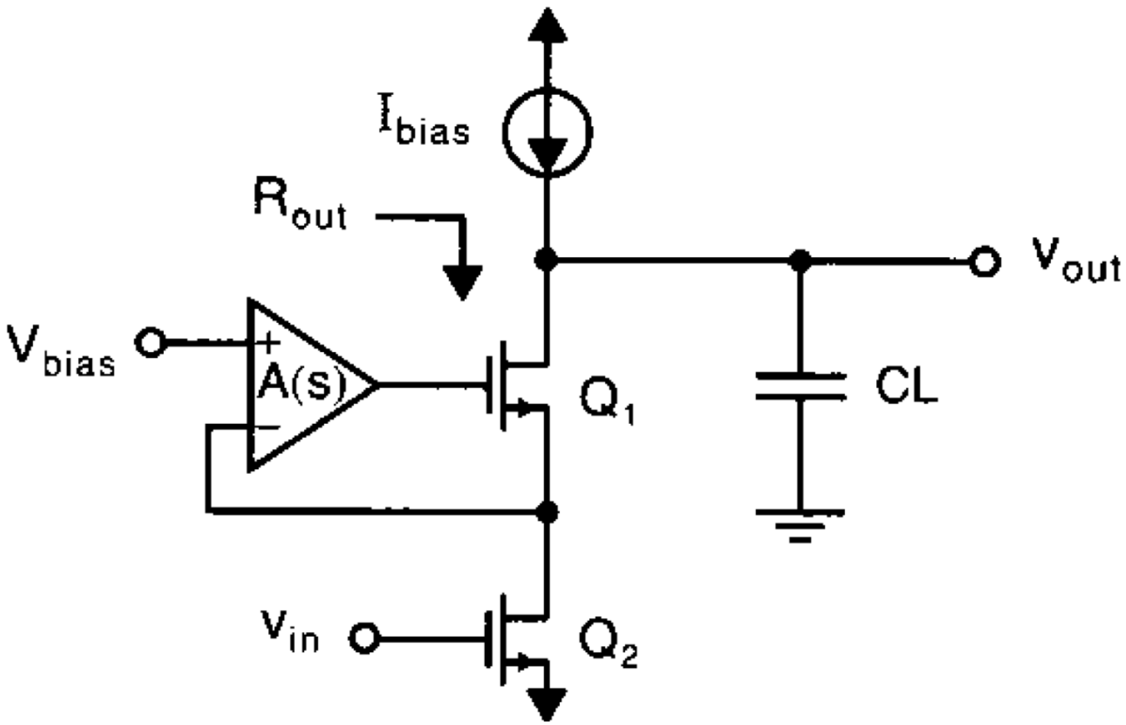
$$\omega_{ta} = \frac{g_{m1}}{C_M}$$

$$\omega_{p2} \cong \frac{g_{m9}}{C_1 + C_L}$$




C1 denotes the parasitic capacitance at node X.
Miller compensation method is utilized.

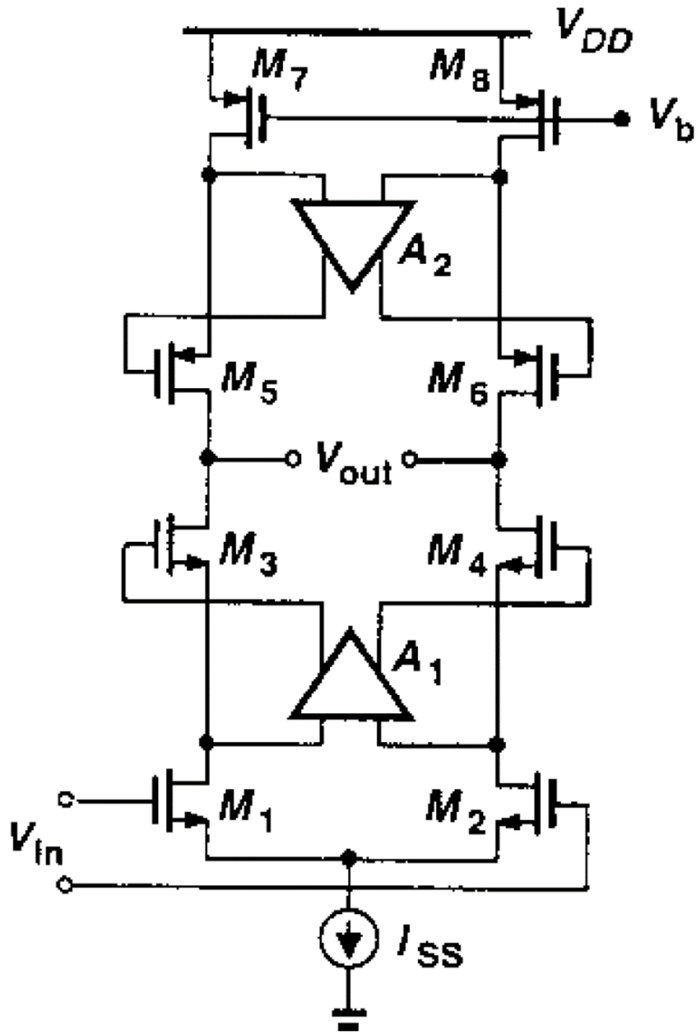
# Gain-Boosting Opamp

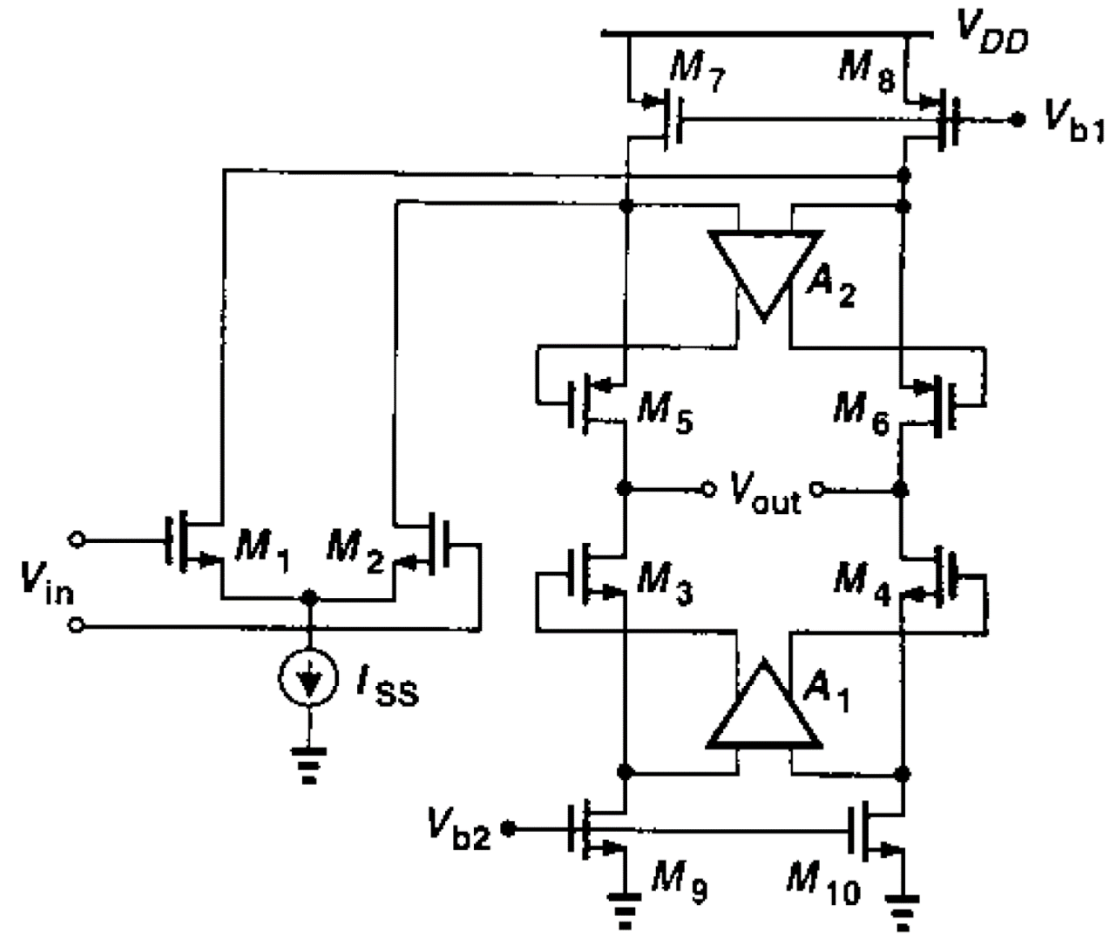



It is proven that the auxiliary amplifier will not affect the performance of the main amplifier if the following relation is satisfied.

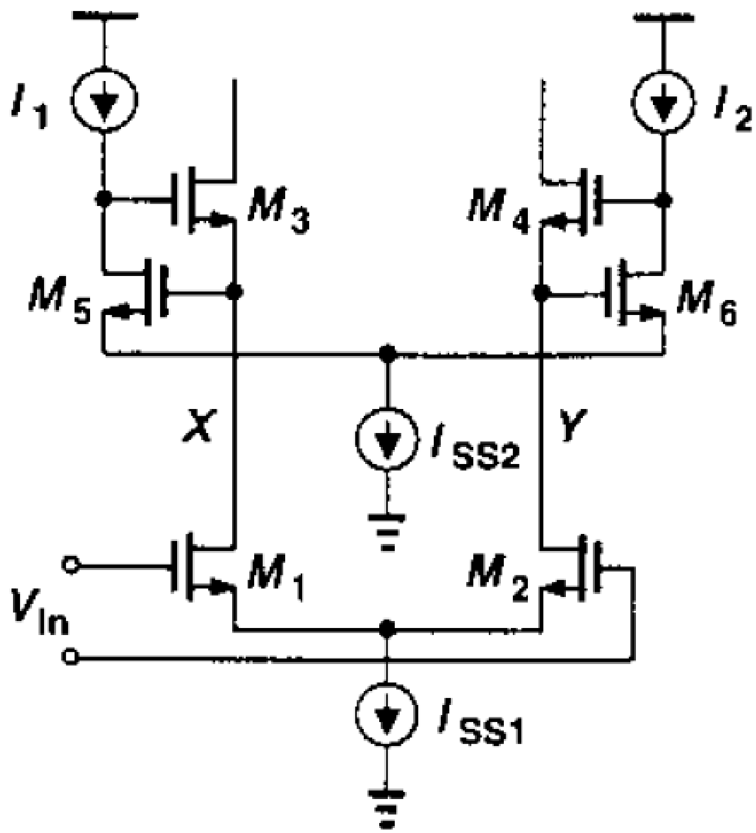
$$UGBW_{Auxiliary\ Amplifier} > UGBW_{Main\ Amplifier}$$

# Gain-Boosting Opamp

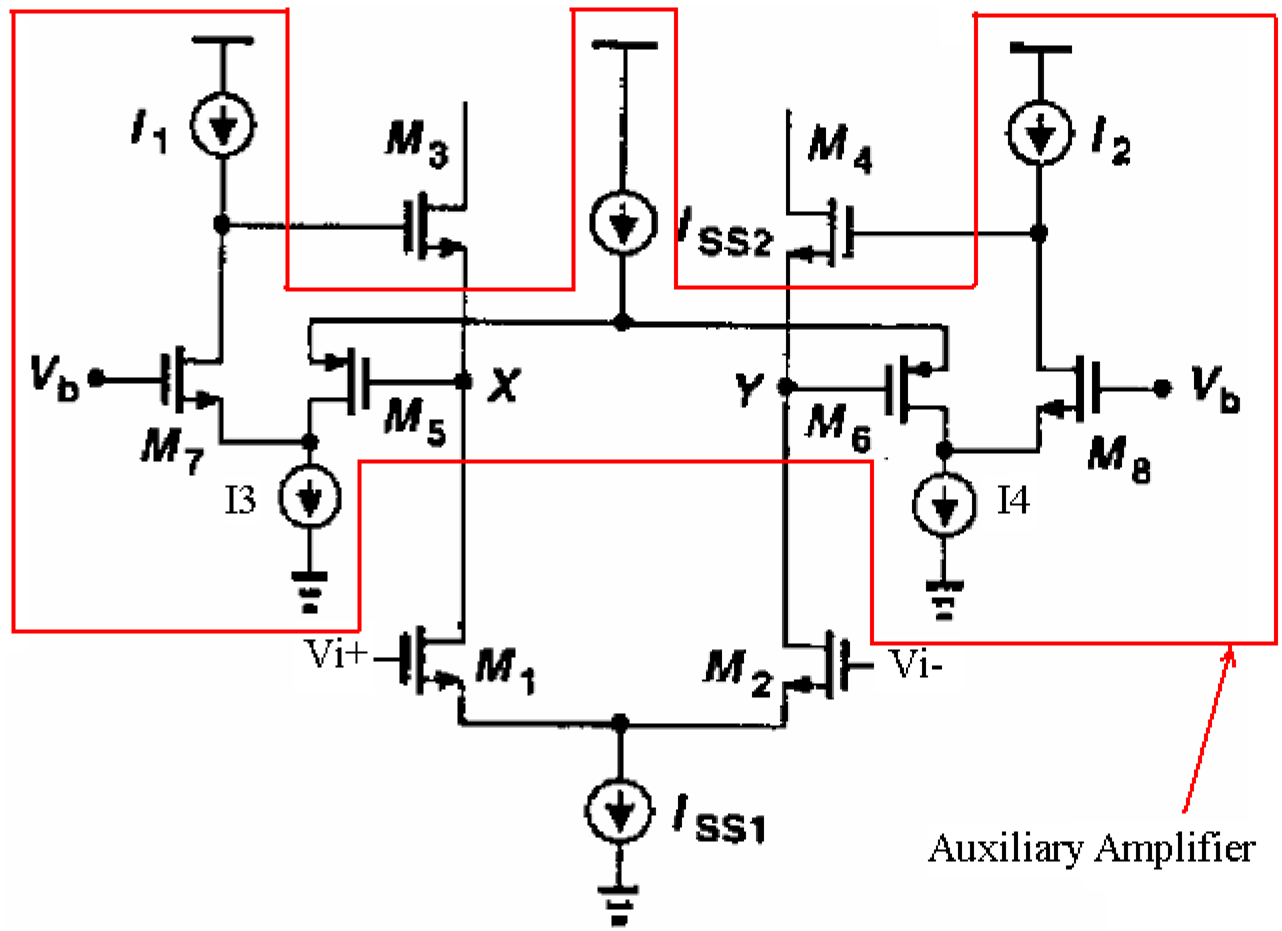


# Differential Pair as an Auxiliary Opamp



# Folded-Cascode Circuit as an Auxiliary Opamp



## Comparison of Performance of Various Opamp Topologies

| | Gain | Output Swing | Speed | Power Dissipation | Noise |
|---|---|---|---|---|---|
| Telescopic | Medium | Low | Highest | Low | Low |
| Folded-Cascode | Medium | Medium | High | Medium | Medium |
| Two-Stage | High | Highest | Low | Medium | Low |
| Gain-Boosted | High | Medium | Medium | High | Medium |