



CHAPTER 8

Operational Amplifiers

Syllabus

- Basic physics of MOS transistors and their equivalent circuit models (ch. 6)
- Elementary gain stages (ch. 7, ch. 9, and ch. 10)
- Operational amplifier basics (ch. 8)
- Frequency responses (ch. 11)
- Noise (ch.7, Design of analog CMOS ICs)
- Feedback, stability and compensation (ch. 12)
- **Operational amplifiers (ch.9, Design of analog CMOS ICs)**

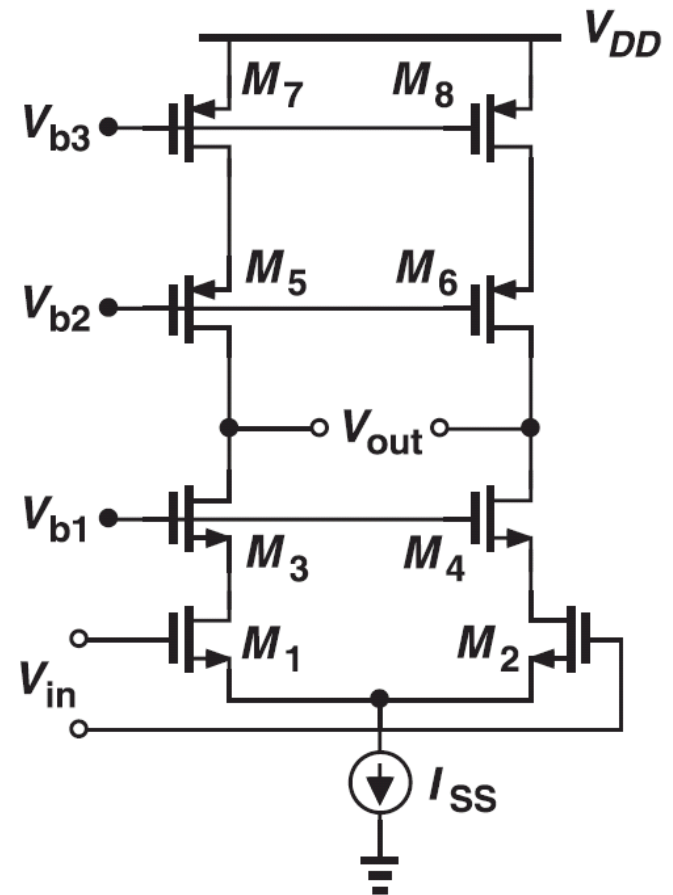
Outline

1. General Consideration

- 2. One-Stage Op Amps / Two-Stage Op Amps
- 3. Gain Boosting
- 4. Common-Mode Feedback
- 5. Input Range / Slew Rate
- 6. Power Supply Rejection / Noise in Op Amps

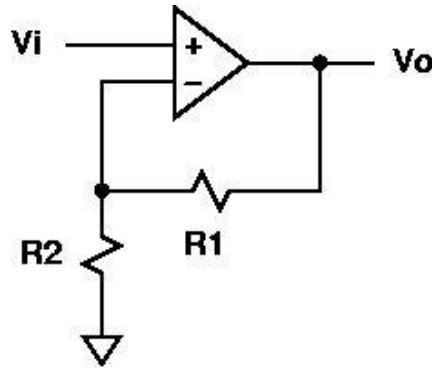
General Consideration

- Operational amplifiers (OP amps) are in general part of many analog and mixed-signal systems – ranging from DC bias generation to high speed amplification or filtering.
- Ideal characteristics
 - Very high voltage gain (several hundred thousand).
 - A high open-loop gain is necessary to suppress nonlinearity.
 - High input impedance.
 - Low output impedance.
 - Other considerations
 - Speed.
 - Output voltage swings.
 - Power dissipation.



Closed-Loop Application

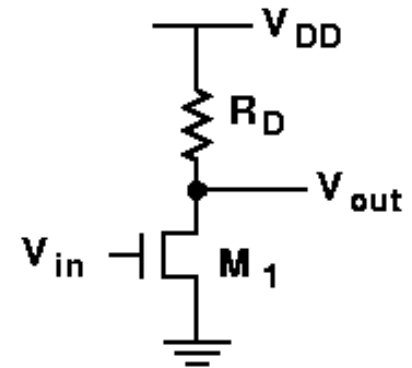
- The open loop gain of an op amp determines the precision of the feedback system employing the op amp.



$$\frac{V_{out}}{V_{in}} = \frac{A_1}{1 + \frac{R_2}{R_1 + R_2} A_1} = \frac{R_1 + R_2}{R_2} \frac{A_1}{\frac{R_1 + R_2}{R_2} + A_1}$$

to get $(1 + R_1 / R_2) = 10$ If $A_1 \gg 10$

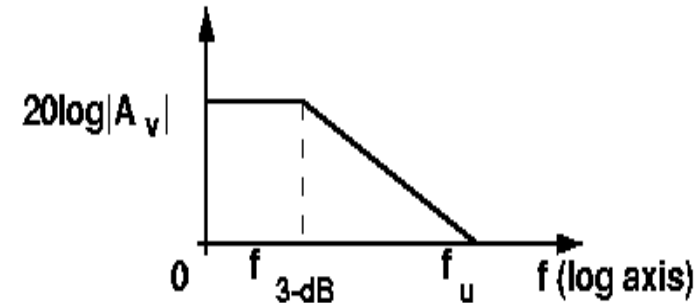
$$\frac{V_{out}}{V_{in}} \approx \left(1 + \frac{R_1}{R_2}\right) \left(1 - \frac{R_1 + R_2}{R_2} \frac{1}{A_1}\right)$$



- Relative gain error is represented as $\frac{R_1 + R_2}{R_2 A_1} = \frac{1 + R_1 / R_2}{A_1}$
- To achieve a gain error less than 1%, we must have $A_1 > 1000$.
- With open-loop implementation using common source gain stage.
 - It is extremely difficult to guarantee an error less than 1%.
 - The variations in the $\mu_{n,p}$ and t_{ox} of the transistor and the value of the resistor typically yield an error greater than 20%.

OP Properties

- The small signal bandwidth is usually defined as the “unity-gain” frequency, f_u .
- Large signal bandwidth
 - OP amps must operate with large transient signals.
 - Nonlinear phenomena make it difficult to characterize the speed by merely small-signal properties such as the open-loop response.
- Output swings
 - Most systems employing op amps require large voltage swings to accommodate a wide range of signal amplitudes.
 - The need for large output swings has made fully differential op amps quite popular – roughly doubling the swing.
 - The maximum voltage swing trades with device size and bias currents and hence speed.



OP Properties

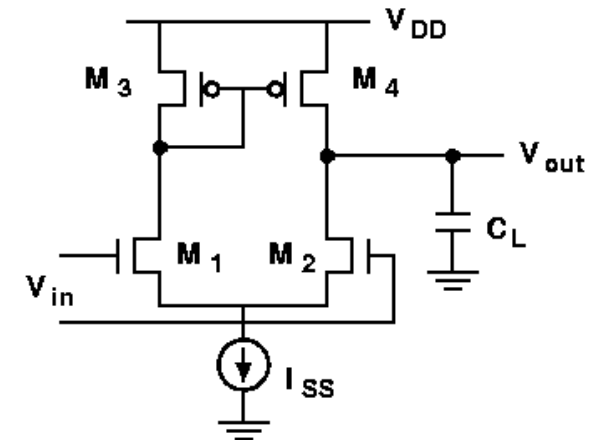
- Linearity
 - Open loop op amps suffer from substantial nonlinearity.
 - The issue of nonlinearity is tackled by two approaches
 - Using fully differential implementations to suppress even-order harmonics.
 - Allowing sufficient open-loop gain such that the closed-loop feedback system achieves adequate linearity.
- Noise and offset
 - The input noise and offset of op amps determine the minimum signal level that can be processed with reasonable quality.
- Supply rejection
 - Fully differential topologies are preferred.

Outline

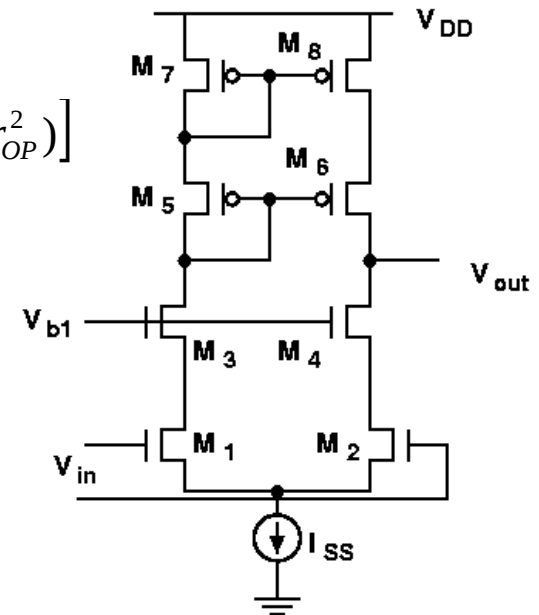
1. General Consideration
- 2. One-Stage Op Amps / Two-Stage Op Amps**
3. Gain Boosting
4. Common-Mode Feedback
5. Input Range / Slew Rate
6. Power Supply Rejection / Noise in Op Amps

One Stage Op Amps

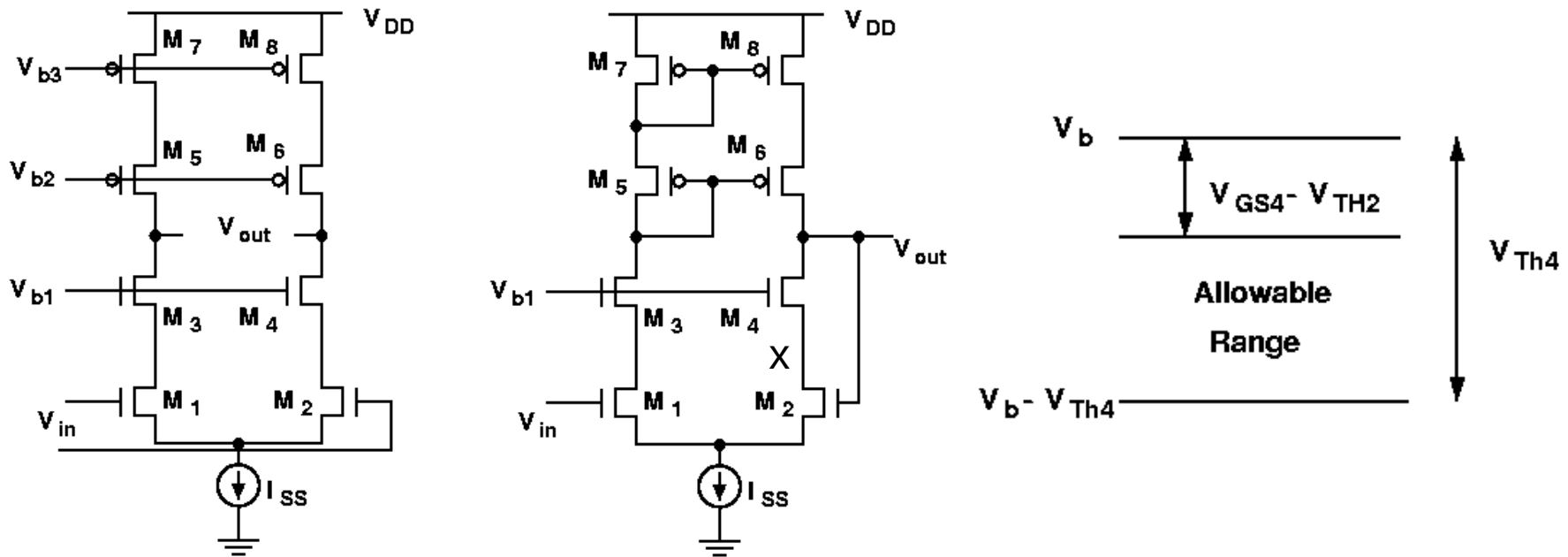
- The small-signal, low frequency gain is $g_{mN}(r_{ON} \parallel r_{OP})$
- The bandwidth is usually determined by the load capacitance C_L .
- The circuit suffers from noise contributions of M_1 - M_4 , 2 input devices + 2 load devices.



- Differential cascode op amps
- The small-signal, low frequency gain is $g_{mN}[(g_{mN}r_{ON}^2 \parallel g_{mP}r_{OP}^2)]$
- High gain at the cost of output swing and additional poles.
- These configurations are also called “telescopic” cascode op amps.



Telescopic Op Amplifiers



- The output swing = $2[V_{DD} - (V_{OD1} + V_{OD3} + V_{CSS} + |V_{OD5}| + |V_{OD7}|)]$, $V_{ODj} = V_{ov}$ of M_j .
- Difficulty in shorting their inputs and outputs, e.g., to be as a unity-gain buffer.
- For

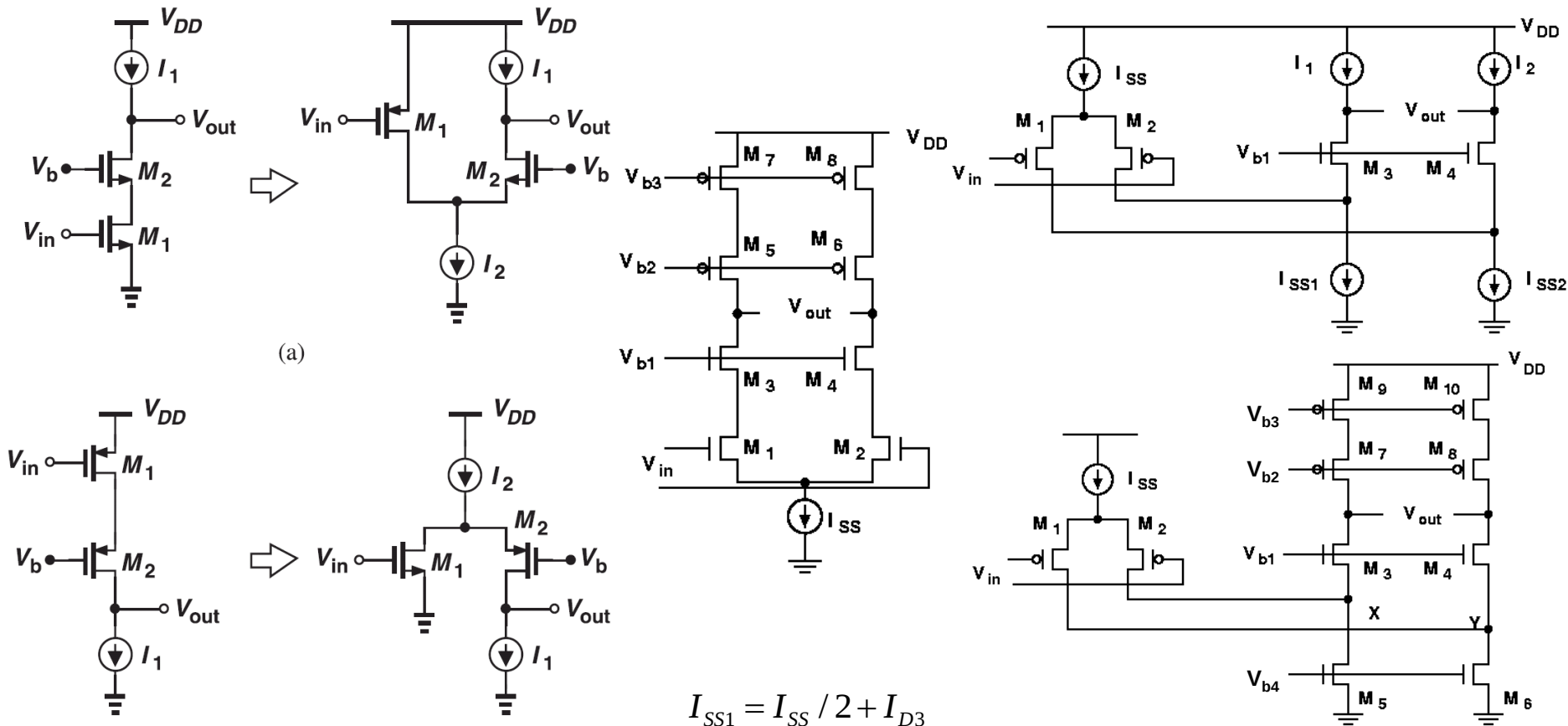
$$V_X = V_{b1} - V_{GS4} \quad V_{out} \leq V_X + V_{Th2} \quad V_{out} \geq V_{b1} - V_{Th4}$$

$$V_b - V_{Th4} \leq V_{out} \leq V_b - V_{GS4} + V_{Th2}$$

$$V_{max} - V_{min} = V_{Th4} - (V_{GS4} - V_{Th2}) = V_{Th2} - V_{OV4} \leq V_{Th2}$$
- Maximize the output swing by minimizing the V_{ov} of M_4 but always less than V_{Th2} .

Folded Cascode Circuits

- To alleviate the drawbacks of telescopic cascode op amps. $A_v = g_{m1} R_{out}$



- The maximum output voltage swing (each side)

$$V_{OD3} + V_{OD5} < V_{swing} < V_{DD} - (|V_{OD7}| + |V_{OD9}|) \quad V_{p-p} = 2[V_{DD} - (V_{OD3} + V_{OD5} + |V_{OD7}| + |V_{OD9}|)]$$

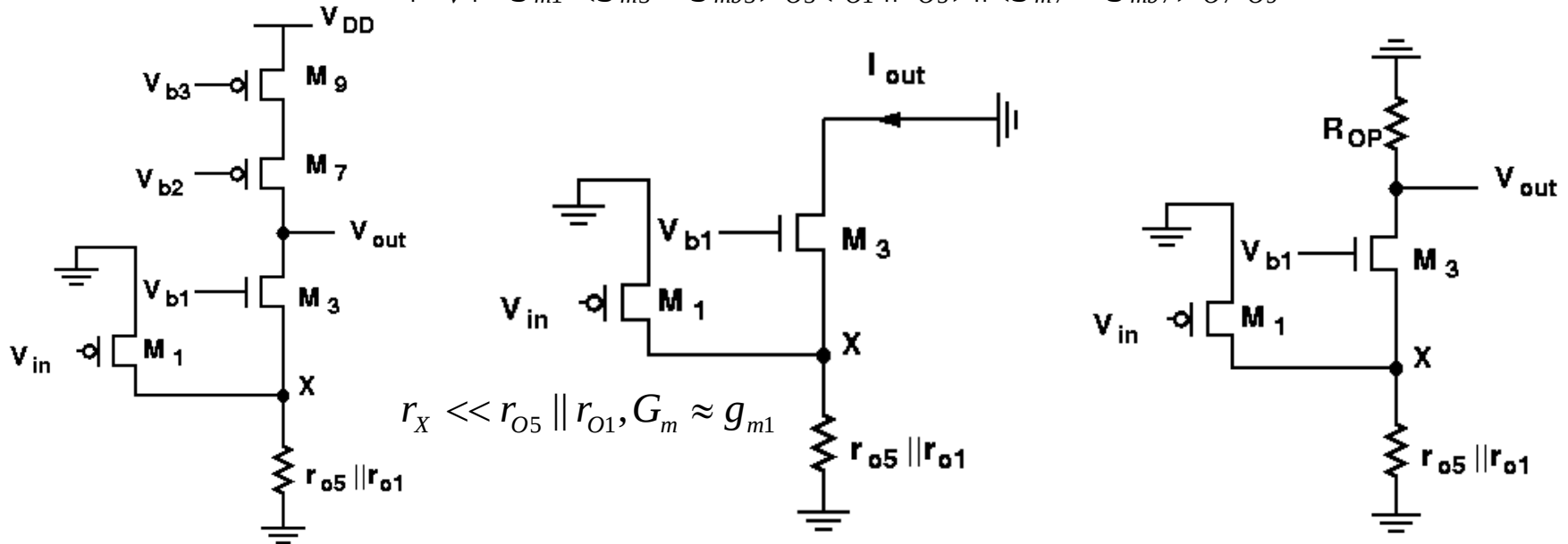
Folded Cascode Op Amp - Half Circuit

- Conversion gain –lower than that of telescopic OP
 - PMOS input differential pair exhibits a lower transconductance.
 - Lower resistance at node X.
 - The conversion gain in general lower than that of telescopic architecture.

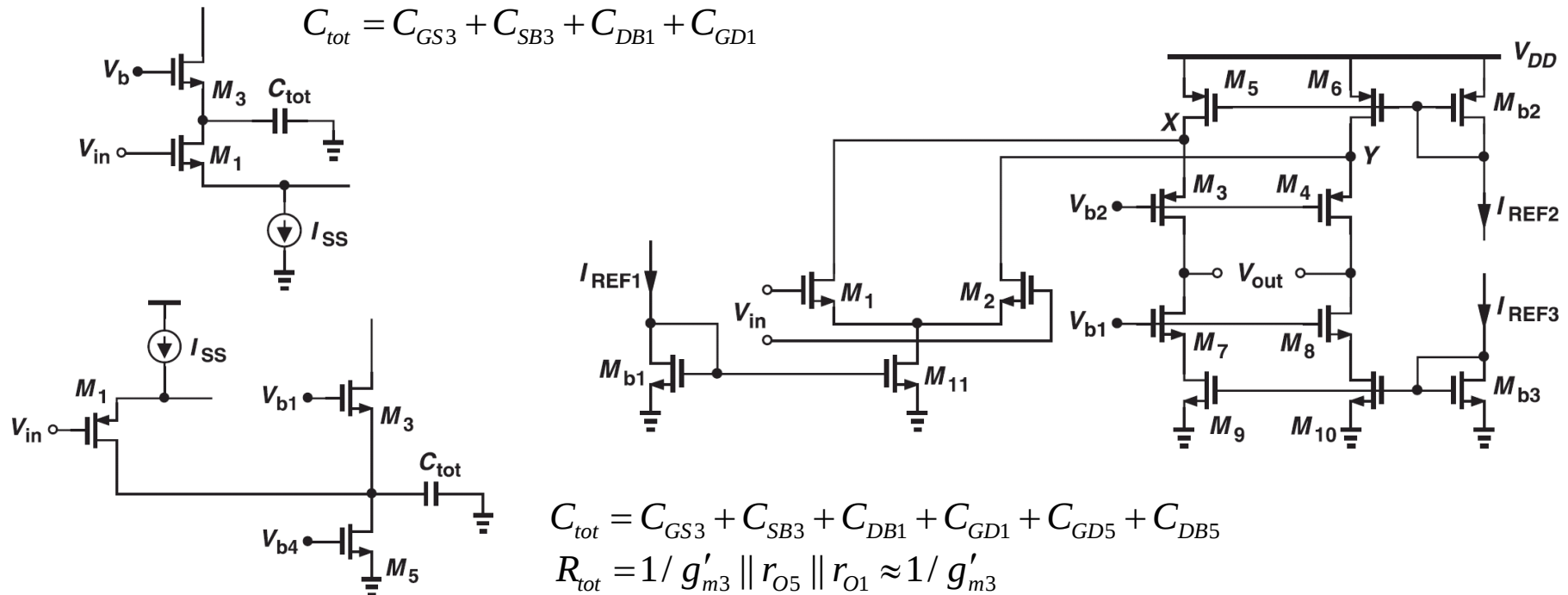
$$R_{OP} \approx (g_{m7} + g_{mb7})r_{O7}r_{O9}, \quad R_{ON} \approx (g_{m3} + g_{mb3})r_{O3}(r_{O1} \parallel r_{O5})$$

$$R_{out} = R_{OP} || R_{ON}, \quad |A_v| = G_m R_{out}$$

$$|A_v| \approx g_{m1} \{ (g_{m3} + g_{mb3}) r_{O3} (r_{O1} \parallel r_{O5}) \parallel (g_{m7} + g_{mb7}) r_{O7} r_{O9} \}$$



N-input Folded Cascode Op Amps



- Non-dominant pole frequency is determined by $C_{tot} = C_{GS3} + C_{SB3} + C_{DB1} + C_{GD1} + C_{GD5} + C_{DB5}$
- A folded-cascode op amp may use NMOS input and PMOS cascode transistors
 - Higher gain.
 - At the cost of lowering the pole at the folding point.
 - M3 suffers from a lower g_m and M5 contributes substantial capacitance.

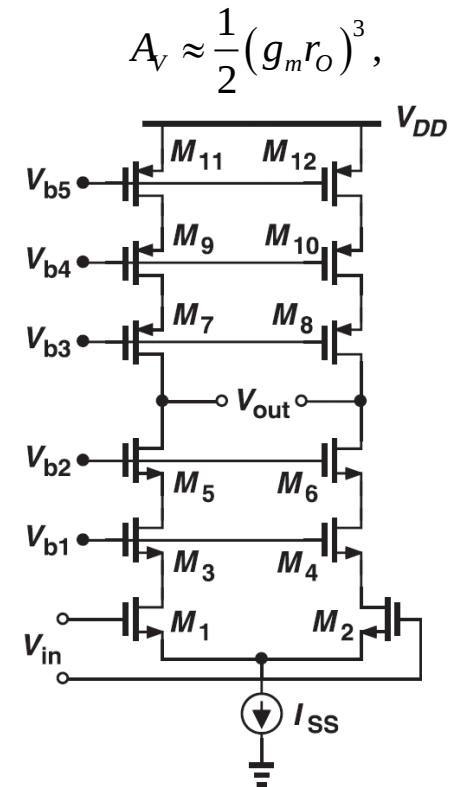
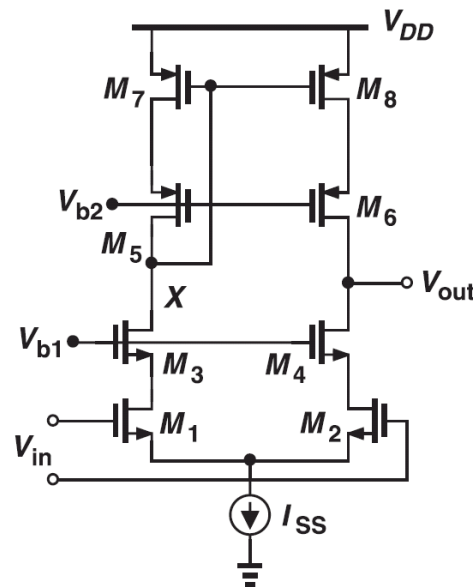
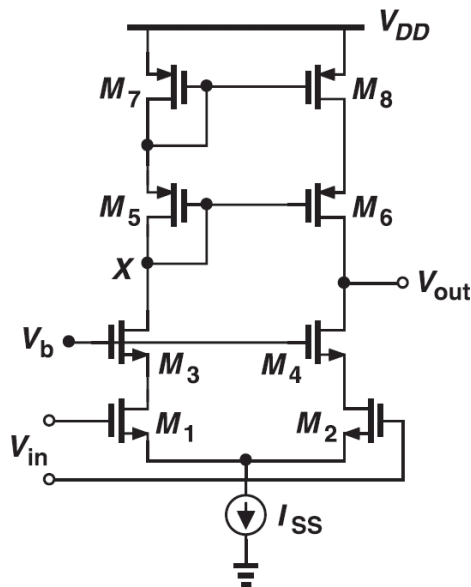
Comparison to Telescopic

- Summary for “folded cascode” OP in comparison to “telescopic” OP
 - Advantage : wider swing, the input and output can be shorted together, the choice of the input common-mode level is easier.
 - Disadvantage : Higher power, lower voltage gain, lower pole frequency.

Cascode OP Amps / Single-Ended

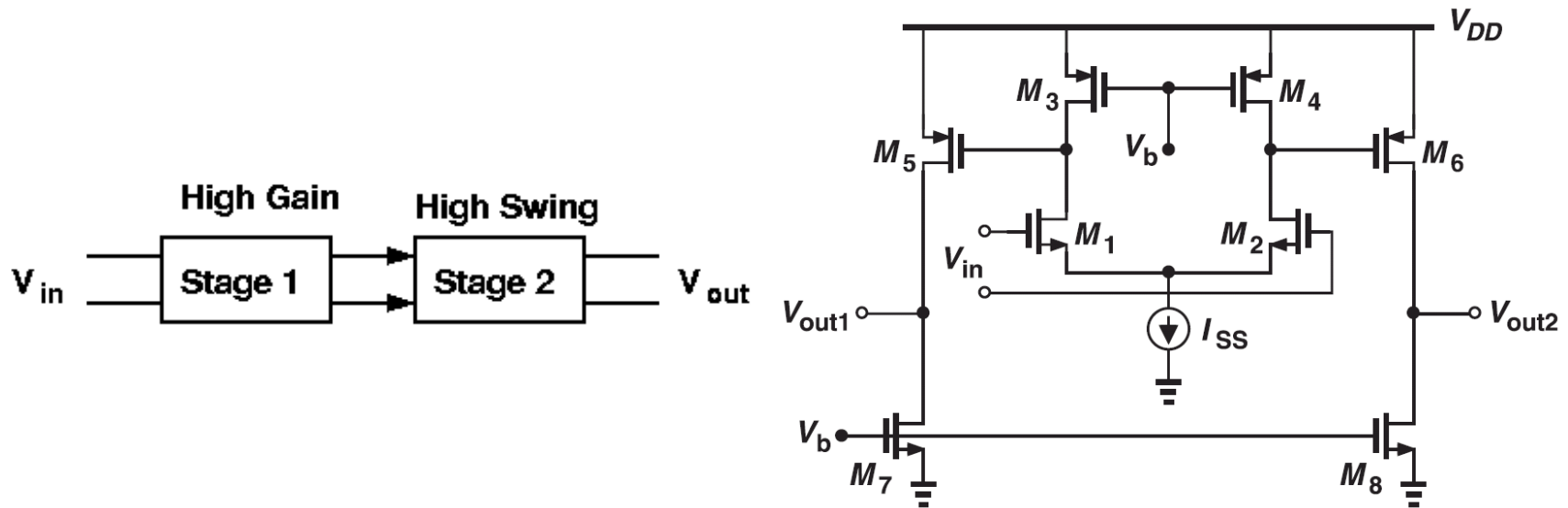
- Cascode OP using wide swing current mirror.
- For single-ended OP
 - It provides only half the output voltage swing.
 - It contains a mirror pole at node X, thus limiting the speed of feedback systems employing such an amplifier.
- Triple Cascode

$$V_X = V_{DD} - |V_{GS5}| - |V_{GS7}|, \quad V_{out(max)} = V_{DD} - |V_{GS5}| - |V_{GS7}| + |V_{TH6}|$$



$$A_v \approx \frac{1}{2} (g_m r_o)^3,$$

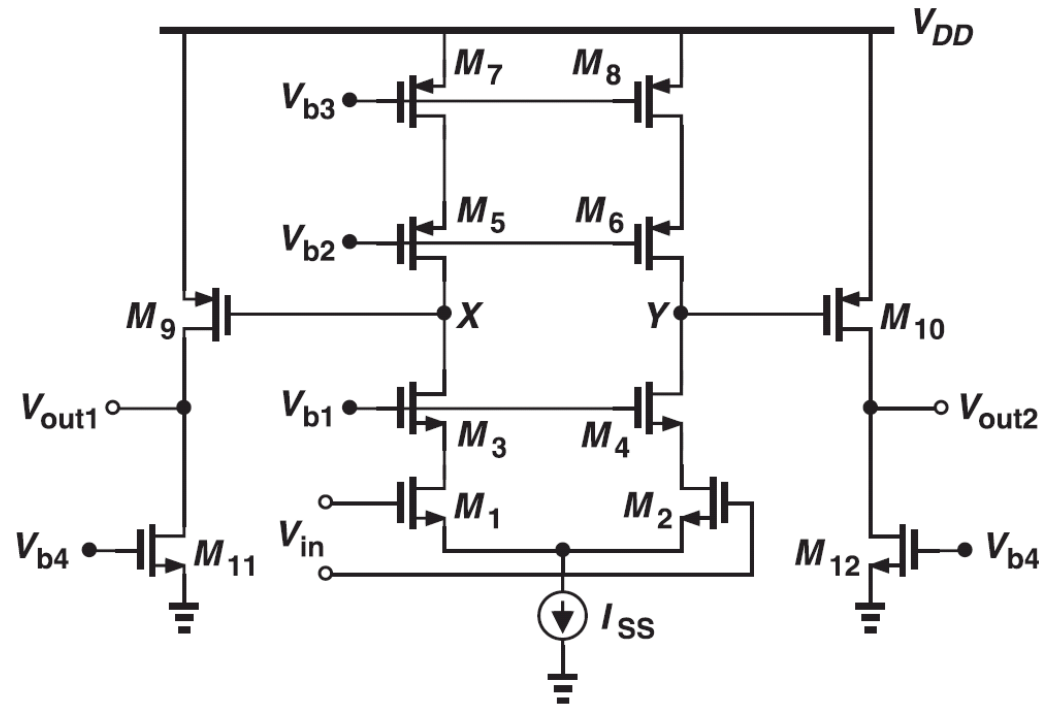
Two-Stage OP Amps



- A two-stage configuration isolates the gain and swing requirement.
- The first stage provides a high gain. $A_{v1} \approx g_{m1,2}(r_{O1,2} \parallel r_{O3,4})$
- The second stage provides large swing. $A_{v2} \approx g_{m5,6}(r_{O5,6} \parallel r_{O7,8})$
- The overall gain is comparable to that of a cascode op amp, but the swing is equal to $V_{DD} - |V_{OD5,6}| - V_{OD7,8}$

Two-Stage OP Amps + Cascode

- Two stage op amp employing cascode



$$A_V \approx \left\{ g_{m1,2} \left[(g_{m3,4} + g_{mb3,4}) r_{O3,4} r_{O1,2} \right] \parallel \left[(g_{m5,6} + g_{mb5,6}) r_{O5,6} r_{O7,8} \right] \right\} \\ \times \left[g_{m9,10} (r_{O9,10} \parallel r_{O11,12}) \right]$$

Outline

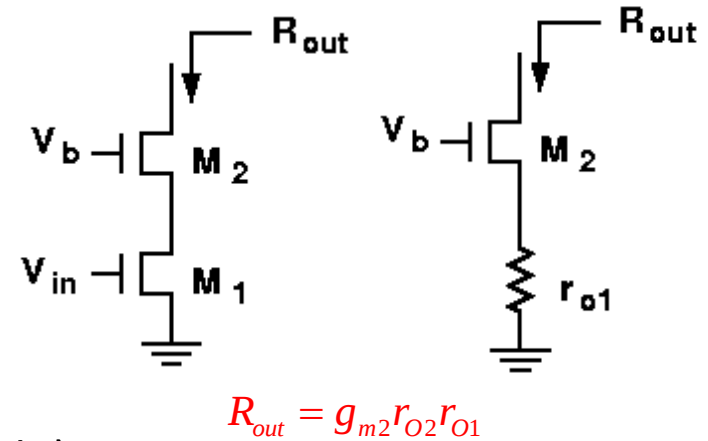
1. General Consideration
2. One-Stage Op Amps / Two-Stage Op Amps
- 3. Gain Boosting**
4. Common-Mode Feedback
5. Input Range / Slew Rate
6. Power Supply Rejection / Noise in Op Amps

Gain Boosting

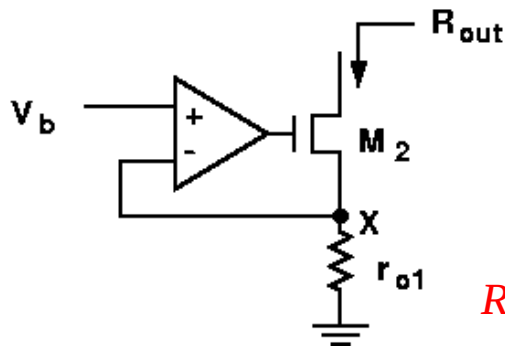
- Increasing the output impedance by feedback.

$$R_{out} = g_{m2}r_{O2}r_{O1}$$

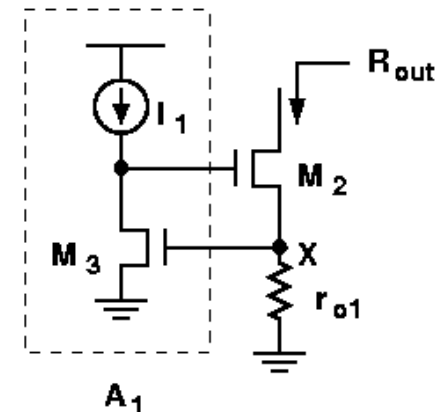
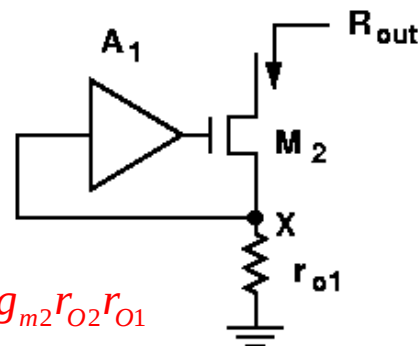
- The small signal voltage produced across r_{O1} is proportional to the output current.
- $V_{gs2} = V_b - V_{ro1}$.
- M_2 in current voltage feedback.



- Gain boosting in cascode stage (Regulated Cascode)
 - Forces V_x to be equal to V_b , such that voltage variations at the drain of M_2 affect V_x to a lesser extent.
 - For small signal operation, V_b is set to zero.



$$R_{out} \approx A_1 g_{m2} r_{O2} r_{O1}$$

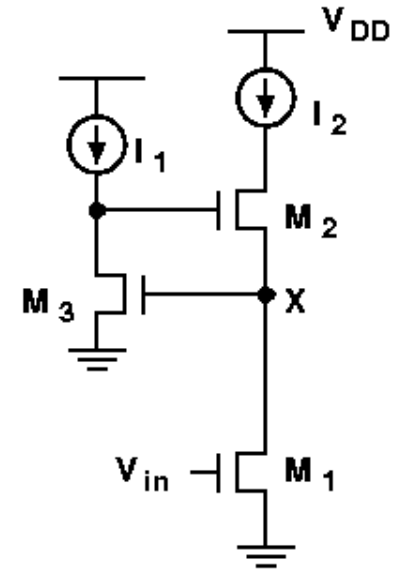


Gain Boosting in Cascode Stage

- The overall voltage gain is equal to

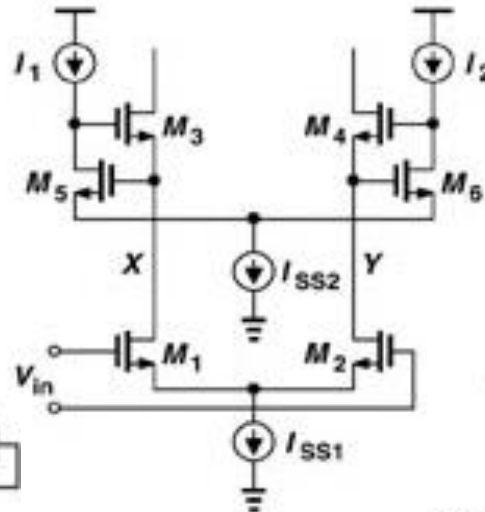
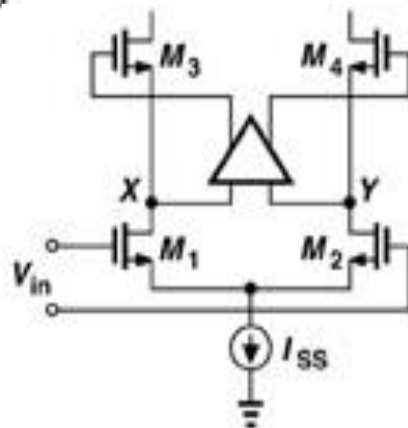
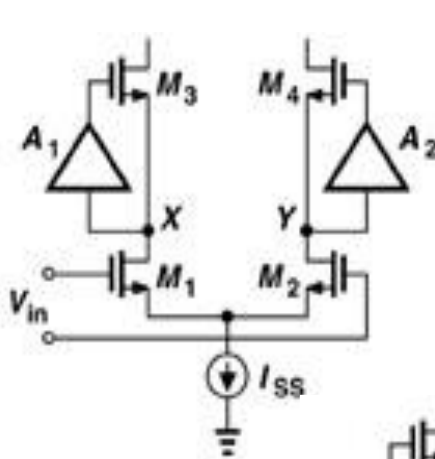
$$|A_v| \approx g_{m1}(g_{m2}r_{O2}r_{O1})(g_{m3}r_{O3})$$

- The gain is similar to that of a triple cascode.
- Consider the output swing
 - $V_x = V_{GS3}$ $V_{out(min)} = V_{OD2} + V_{GS3}$
- For simple cascode, $V_{out(min)} = V_{OD2} + V_{OD1}$
- The auxiliary amplifier limits the output swing.

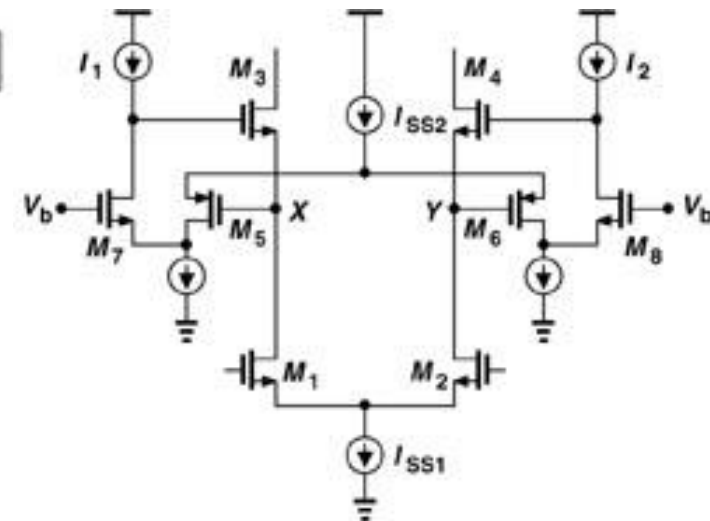


Gain Boosting in Cascode Stage

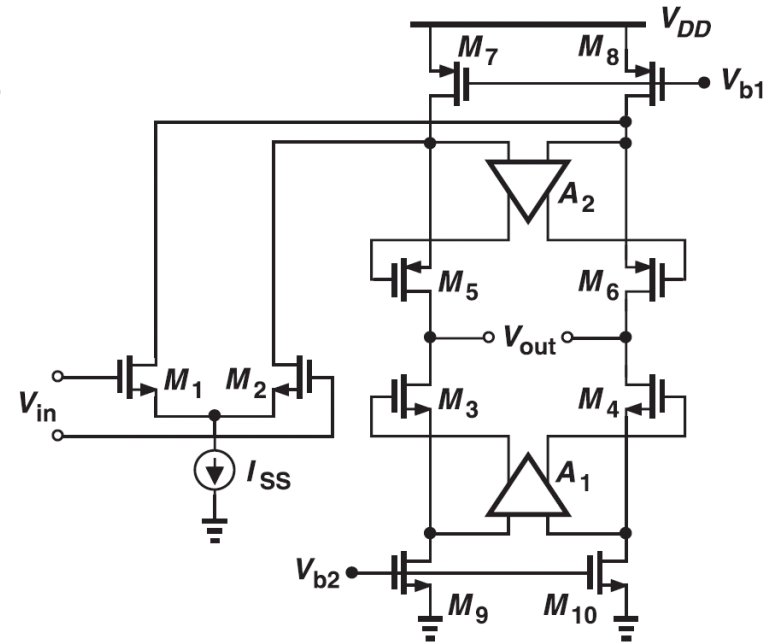
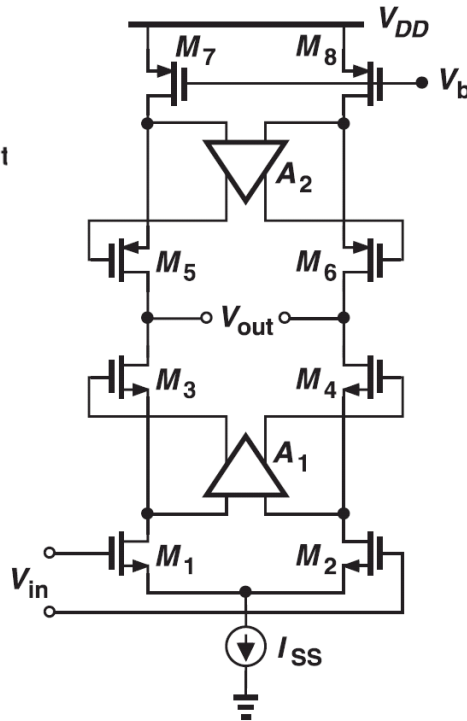
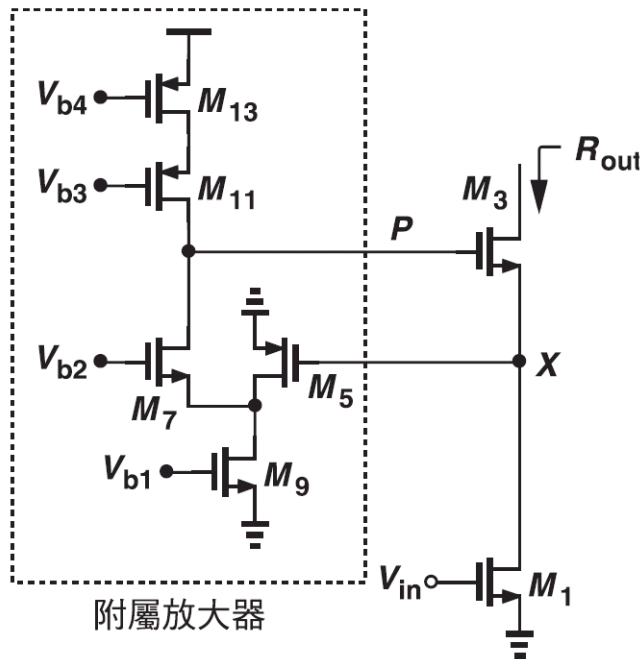
- The minimum level at the drain of M3 is equal to $V_{out(min)} = V_{OD3} + V_{GS5} + V_{ISS2}$
- If nodes X and Y are sensed by a PMOS pair, the minimum value of V_X and V_Y is not dictated by the gain-boosting amplifier.
 - In this case, $V_{out(min)} = V_{OD1,2} + V_{OD3,4} + V_{ISS1}$



Folded-cascode as
aux amplifier



Gain Boosting / Signal Path & Load



- For maximum output swings, A_2 must employ an NMOS input differential pair.
- A_1 can employ a PMOS input differential pair.
- The gain boosting amplifier introduces its own poles.
- In a g-b op amp, most of the signal directly flows through the cascode devices to the output. Only a small “error” component is processed by the g-b amplifier.

Performance Comparison

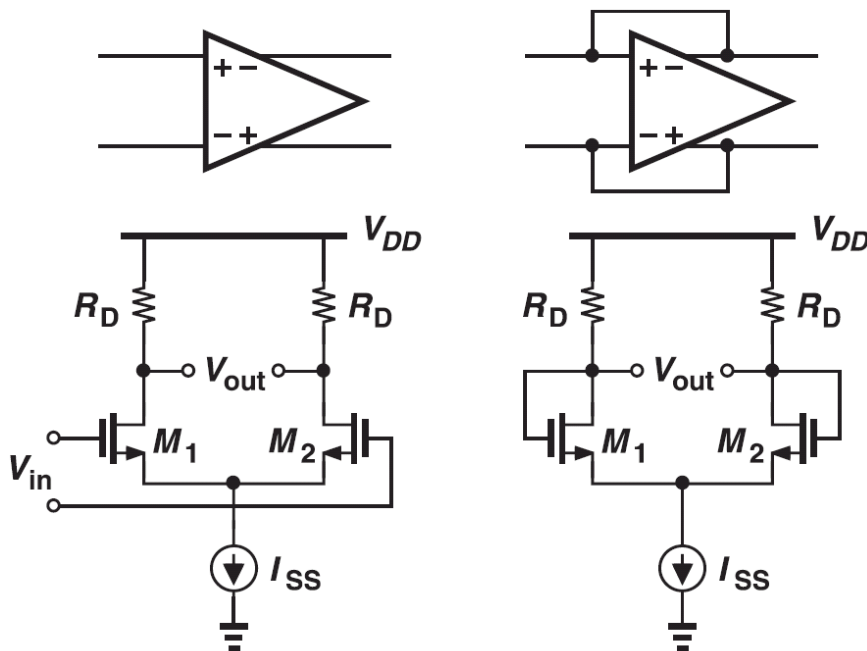
	Gain	Output Swing	Speed	Power Dissipation	Noise
Telescopic	Medium	Medium	Highest	Low	Low
Folded-Cascode	Medium	Medium	High	Medium	Medium
Two-Stage	High	Highest	Low	Medium	Low
Gain-Boosted	High	Medium	Medium	High	Medium

Outline

1. General Consideration
2. One-Stage Op Amps / Two-Stage Op Amps
3. Gain Boosting
- 4. Common-Mode Feedback**
5. Input Range / Slew Rate
6. Power Supply Rejection / Noise in Op Amps

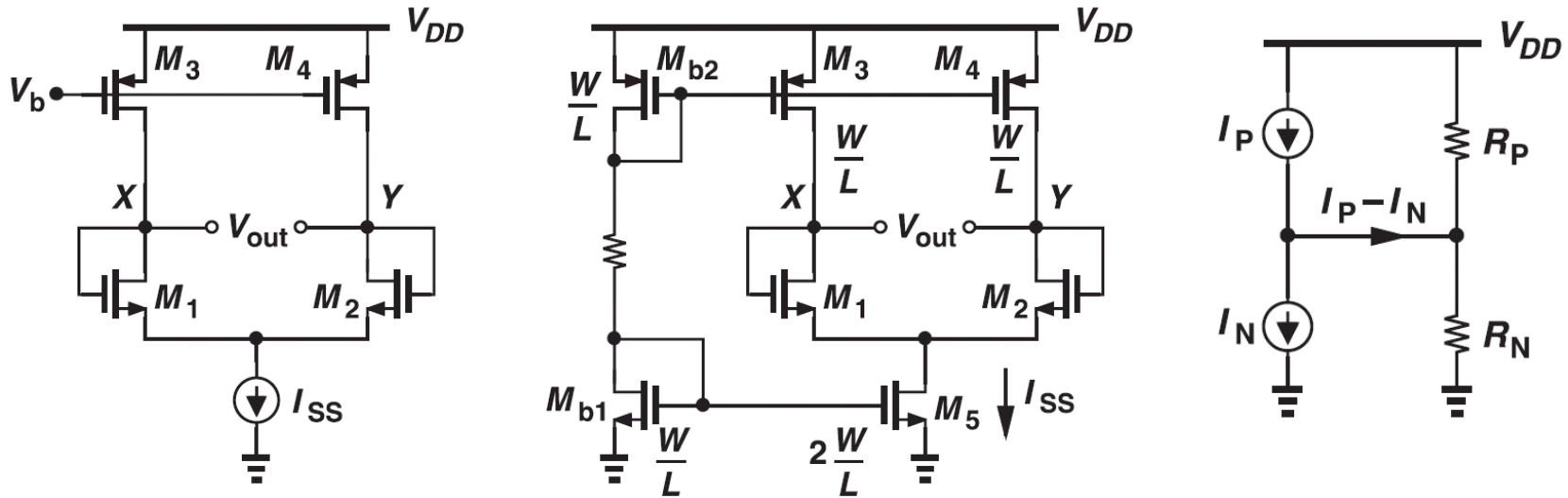
Common Mode Feedback

- Advantages of differential architecture
 - Higher noise immunity.
 - Higher output swing.
 - No mirror poles, thus achieving a higher closed-loop speed.
 - High-gain differential circuits require “common-mode feedback” (CMFB).



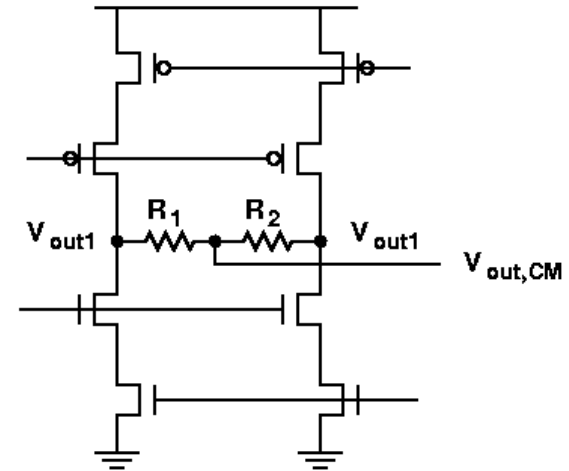
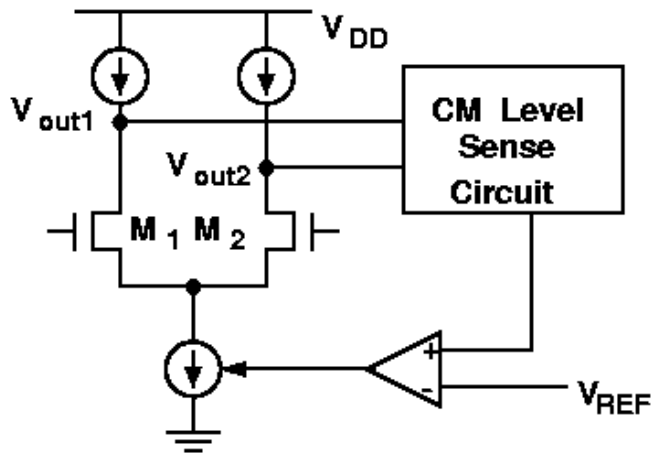
- For differential negative feedback, we short the inputs and outputs.
- In this case,
 - $V_{o,cm} = V_{DD} - I_{SS} R_D/2$

High-Gain DP with I/O Shorted



- For high gain DP with active load, assume $I_{D1} = I_{D2} = I_{SS}/2$ with I/O shorted.
- The output CM levels depends on how close I_{D3} and I_{D4} are to $I_{SS}/2$.
- If the drain currents of M_3 and M_4 in the saturation region are slightly greater than $I_{SS}/2$, both M_3 and M_4 must enter the triode region, $I_D(M_3, M_4)$ fall to $I_{SS}/2$.
- if $I_{D3,4} < I_{SS} / 2$, then both V_X and V_Y must drop, M_5 enters the triode region.
- In high gain amplifiers, the ΔI of I_P and I_N must flow through the intrinsic r_o of the amplifier, creating an output voltage change of $(I_P - I_N)(R_P \parallel R_N)$.
- The voltage error may be large, thus driving the p-type or n-type current source into the triode region.

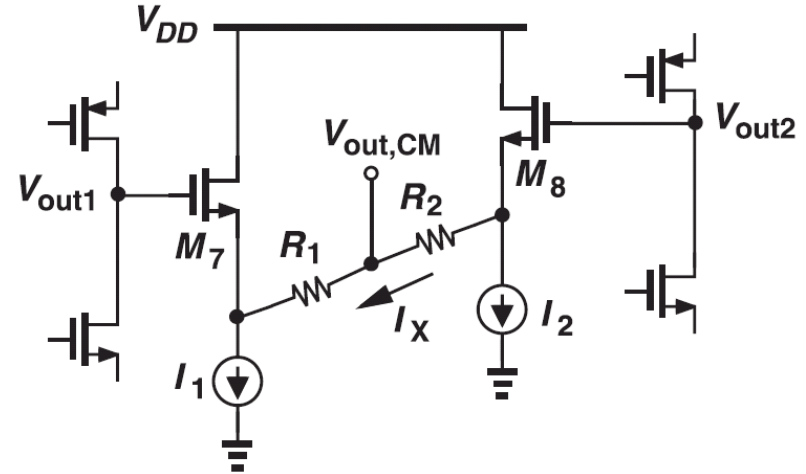
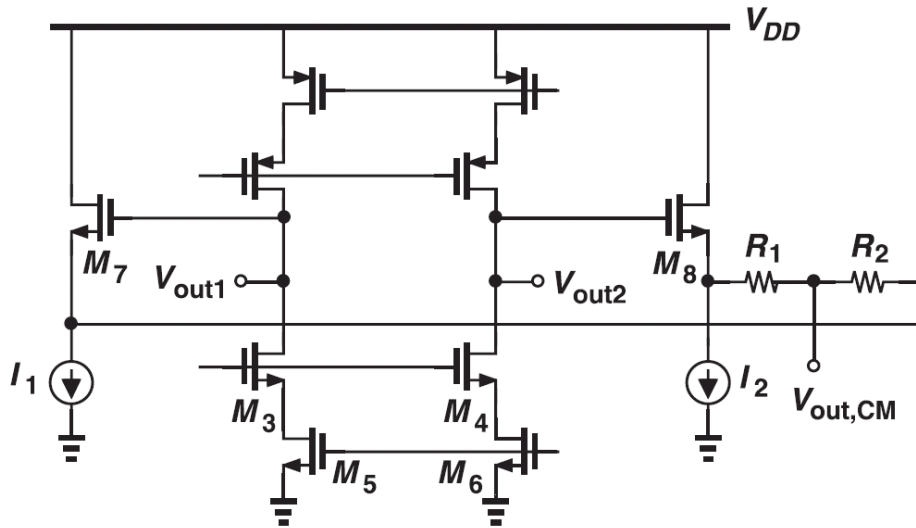
Conceptual Topology of CM Feedback



- The output common mode level is quite sensitive to device properties and mismatches and it can not be stabilized by means of *differential* feedback.
- The *task of common mode feedback*
 - Sensing the output CM level, *comparison with a reference*, and *returning the error to the amplifier's bias network*.
- Sense the output common mode level by a voltage divider

$$V_{out,CM} = (R_1 V_{out2} + R_2 V_{out1}) / (R_1 + R_2) = (V_{out1} + V_{out2}) / 2 \quad \dots \quad \text{if } R_1 = R_2$$
- R_1 and R_2 must be much greater than the output impedance of the op amp so as to avoid lowering the open loop gain – large area and capacitance.

Common Mode Feedback Topology



- To eliminate the resistive loading, we can interpose source followers between each output and its corresponding resistor.
- R_1 and R_2 or I_1 and I_2 must be large enough to ensure that M_7 or M_8 is not “starved” when a large differential swing appears at the output, i.e.,

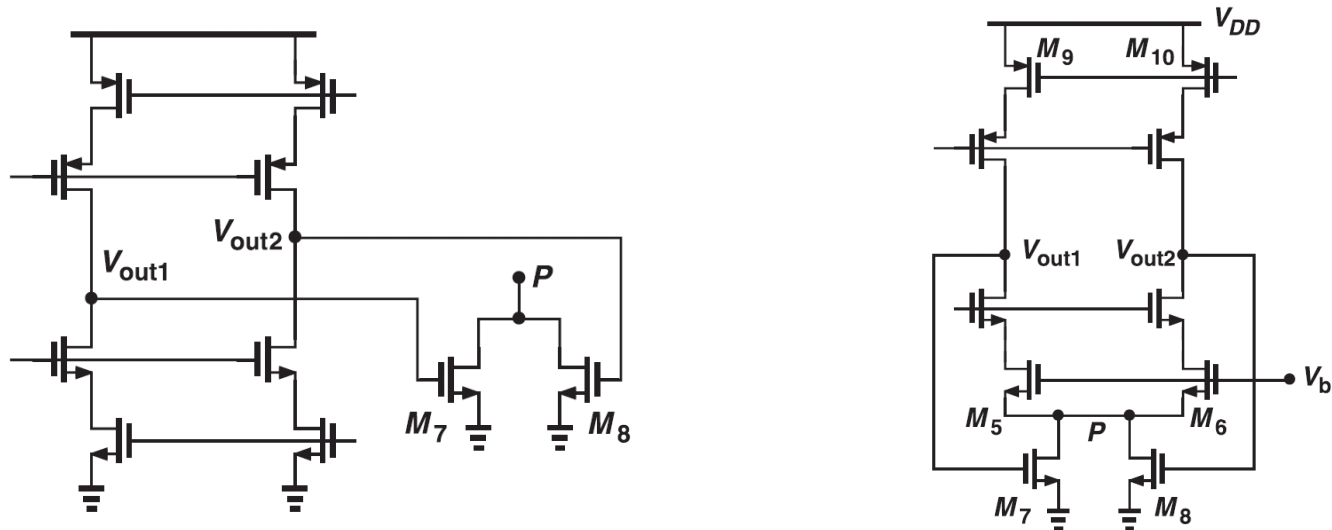
$$I_X \approx (V_{out2} - V_{out1}) / (R_1 + R_2), \quad I_1 = I_X + I_{D7}, \quad I_{D7} = I_1 - I_X > 0$$

- Otherwise, I_{D7} drops to ‘0’ and $V_{out,CM}$ no longer be the true output CM level.
- The differential output swing is limited.

$$V_{out1,min} = V_{GS7} + V_{I1} \quad \text{with CMFB}$$

$$V_{out1,min} = V_{OD3} + V_{OD5} \quad \text{without CMFB}$$

CM Sensing with Triode MOSFET

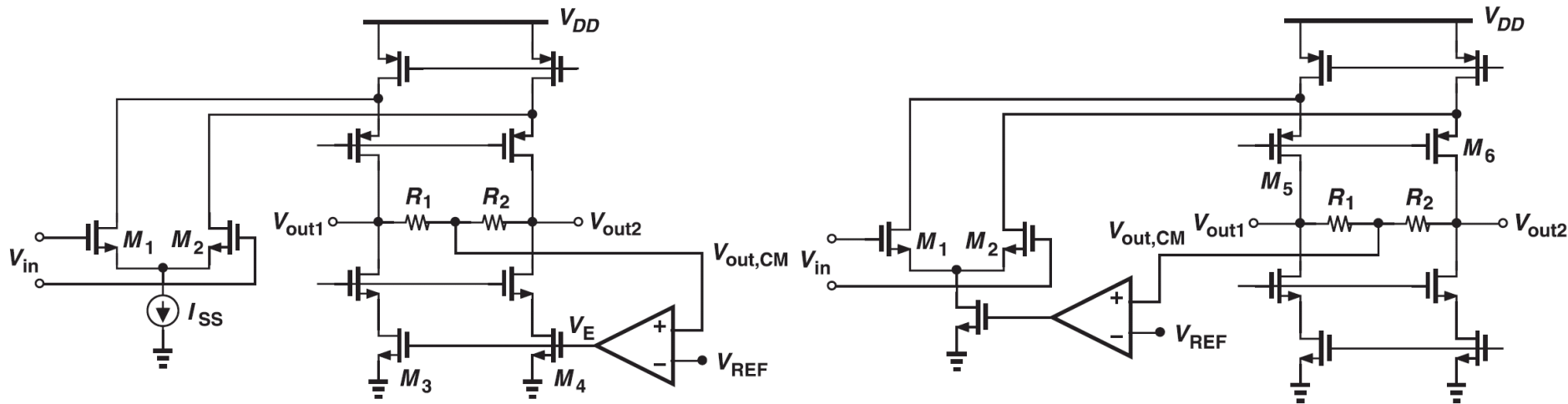


- Identical transistors M7 and M8 operate in deep triode region, introducing a total resistance between P and ground equal to

$$R_{tot} = R_{on7} \parallel R_{on8} = \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{out1} - V_{TH})} \parallel \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{out2} - V_{TH})} = \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{out1} + V_{out2} - 2V_{TH})}$$

- R_{tot} is a function of $V_{out1} + V_{out2}$ but independent of $V_{out2} - V_{out1}$.
- If the outputs rise together, then R_{tot} drops.
- The use of M₇ and M₈ limits the output voltage swings. $V_{out,min} = V_{TH7,8}$
- Need to make sure M₇ & M₈ all operated in linear region.

Sensing / Controlling Output CM Level



- We employ a simple amplifier to detect the ΔV of $V_{out,CM}$ and V_{REF} , applying the result to the NMOS current sources with negative feedback.
 If $V_{out,CM} \uparrow \Rightarrow V_E \uparrow \Rightarrow I_{D3}, I_{D4} \uparrow \Rightarrow V_{out,CM} \downarrow$
- The feedback can be applied to the PMOS current sources as well.
- The feedback may control only a fraction of the I_{source} to allow optimization of the settling behavior, i.e., the I_{source} can be decomposed into two parallel devices, one biased at a constant I and the other driven by the error amplifier.
- In a folded-cascode op amp, the CM feedback may control the tail current of the input differential pair.
 If $V_{out,CM} \uparrow \Rightarrow I_{D1}, I_{D2} \uparrow \Rightarrow V_{out,CM} \downarrow$

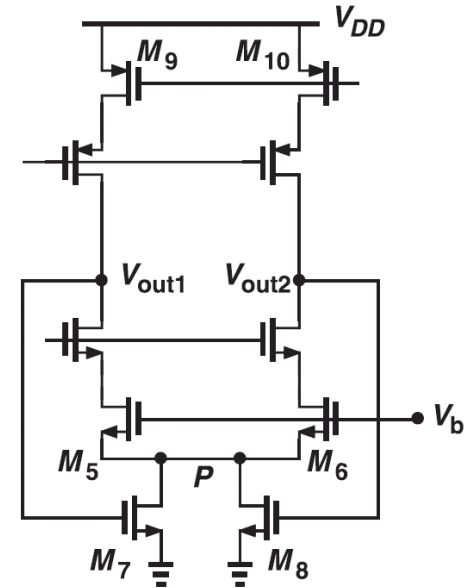
CMFB Using Triode Devices

- The output CM voltage is directly converted to a resistance or a current, prohibiting comparison with a reference voltage.
- $R_{on7} \parallel R_{on8}$ adjusts the bias current of M_5 and M_6 .
- The output CM level sets $R_{on7} \parallel R_{on8}$ such that I_{D5} and I_{D6} exactly balance I_{D9} and I_{D10} .
- Assuming $I_{D9} = I_{D10} = I_D$, we must have

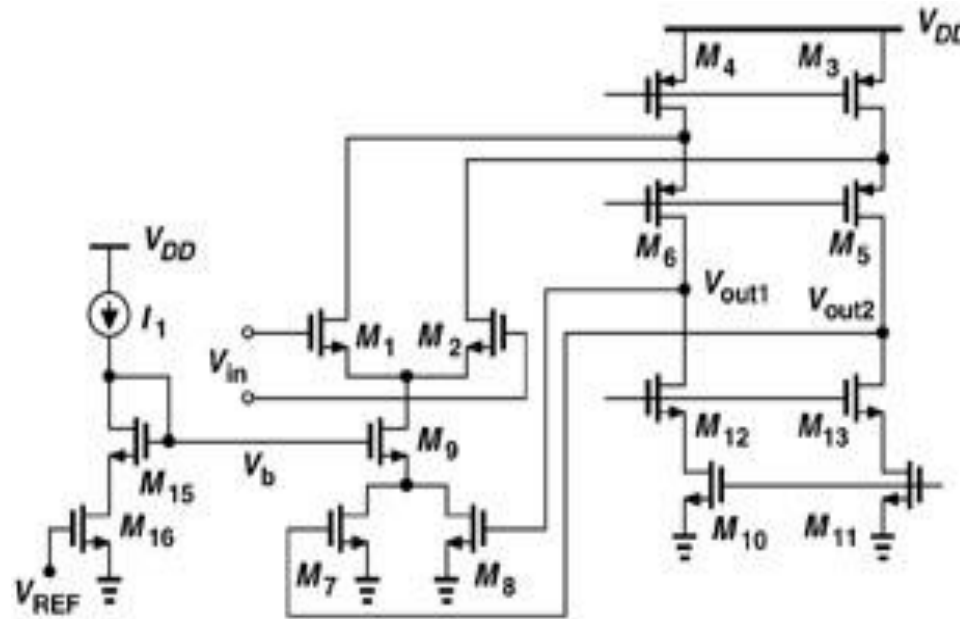
$$V_b - V_{GS5} = 2I_D (R_{on7} \parallel R_{on8}), \quad R_{on7} \parallel R_{on8} = \frac{V_b - V_{GS5}}{2I_D}$$

$$\frac{1}{\mu_n C_{ox} \left(\frac{W}{L} \right)_{7,8} (V_{out1} + V_{out2} - 2V_{TH})} = \frac{V_b - V_{GS5}}{2I_D}, \quad V_{out1} + V_{out2} = \frac{2I_D}{\mu_n C_{ox} \left(\frac{W}{L} \right)_{7,8}} \frac{1}{V_b - V_{GS5}} + 2V_{TH}$$

- Disadvantages
 - The value of the output CM level is a function of device parameters.
 - The voltage drops across $R_{on7} \parallel R_{on8}$ limits the output voltage swings.
 - M_7 and M_8 are usually quite wide devices $\rightarrow$ large capacitance at the output.
 - $V_{out,CM}$ is somewhat sensitive to the value of V_b .



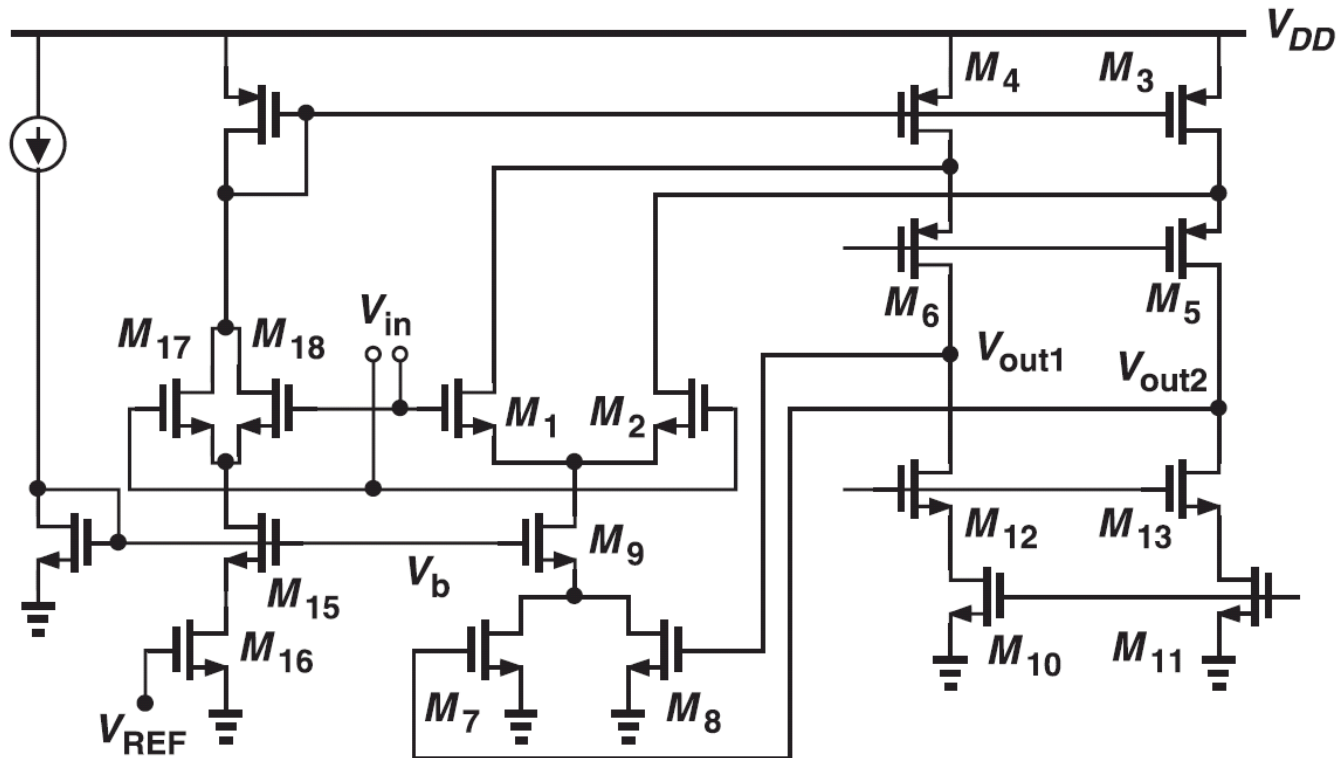
Modification of CMFB



- Define V_b by a current mirror arrangement such that I_{D9} tracks I_1 and V_{REF} .
- Suppose

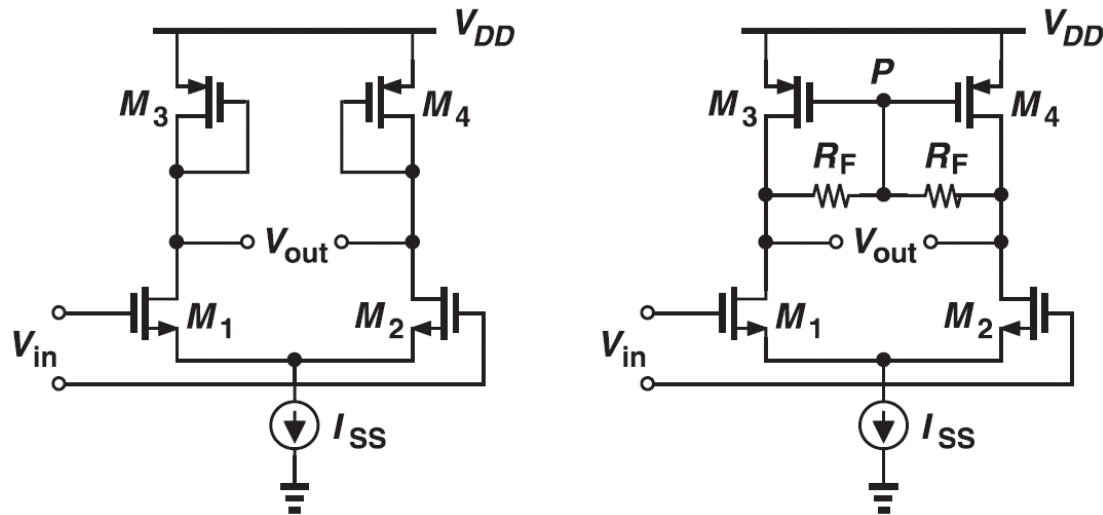
$$(W/L)_{15} = (W/L)_9 \qquad (W/L)_{16} = (W/L)_7 + (W/L)_8$$
- Thus $I_{D9} = I_1$ **only if** $V_{out,CM} = V_{REF}$.
- The circuit produces an output CM level equal to a reference but it requires no resistors in sensing $V_{out,CM}$.
- In practice, since $V_{DS15} \neq V_{DS9}$, channel length modulation results in a finite error.

Suppress Error Due to r_o



- Transistors M_{17} and M_{18} reproduce at the drain of M_{15} a voltage equal to the source voltage of M_1 and M_2 .
- $V_{DS15} = V_{DS9}$

DP using Diode-Connected Loads



- Differential pair with diode connected load
 - The output CM level, $V_{DD} - V_{GS3,4}$ is relatively well-defined, but the voltage gain is quite low.
- For differential changes at V_{out1} and V_{out2} , node P is virtual ground and the gain can be expressed as

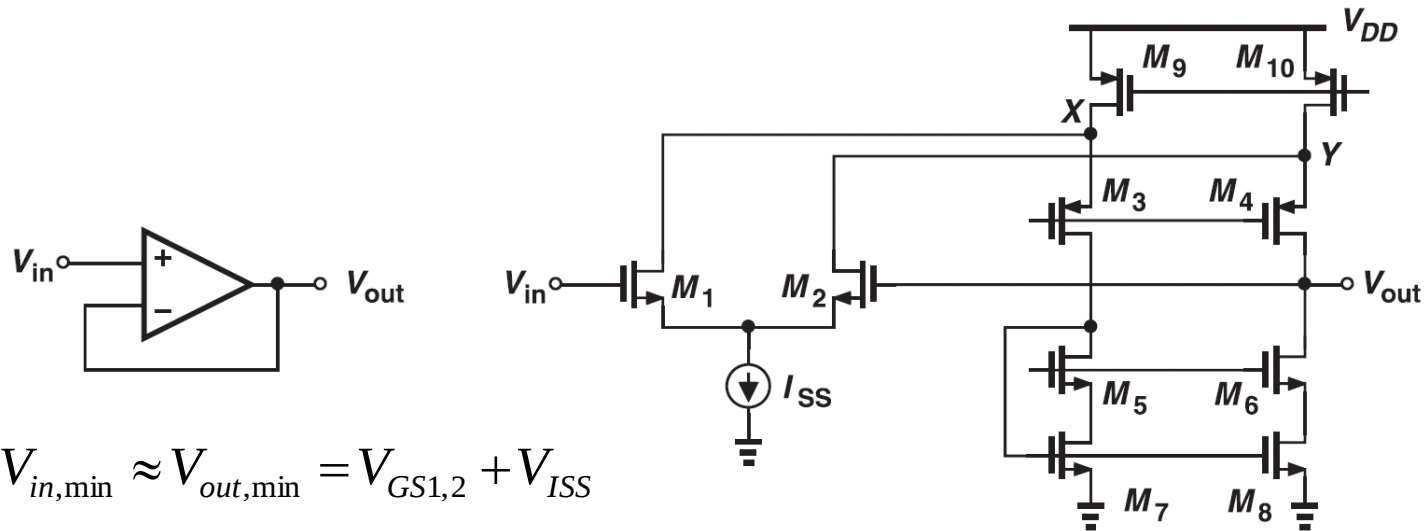
$$A_v = g_{m1,2} (r_{O1,2} \parallel r_{O3,4} \parallel R_F)$$

- For common mode levels, M_3 and M_4 operate as diode-connected devices.
- Fully differential two stage op amps require two CMFB networks.

Outline

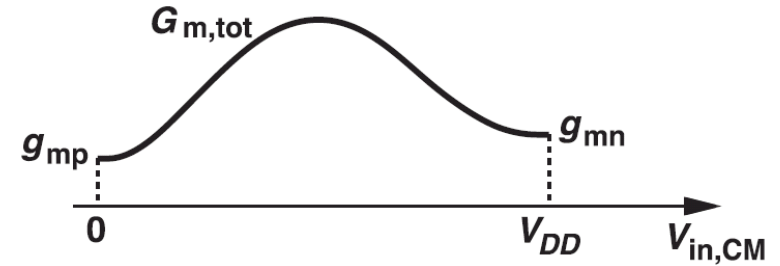
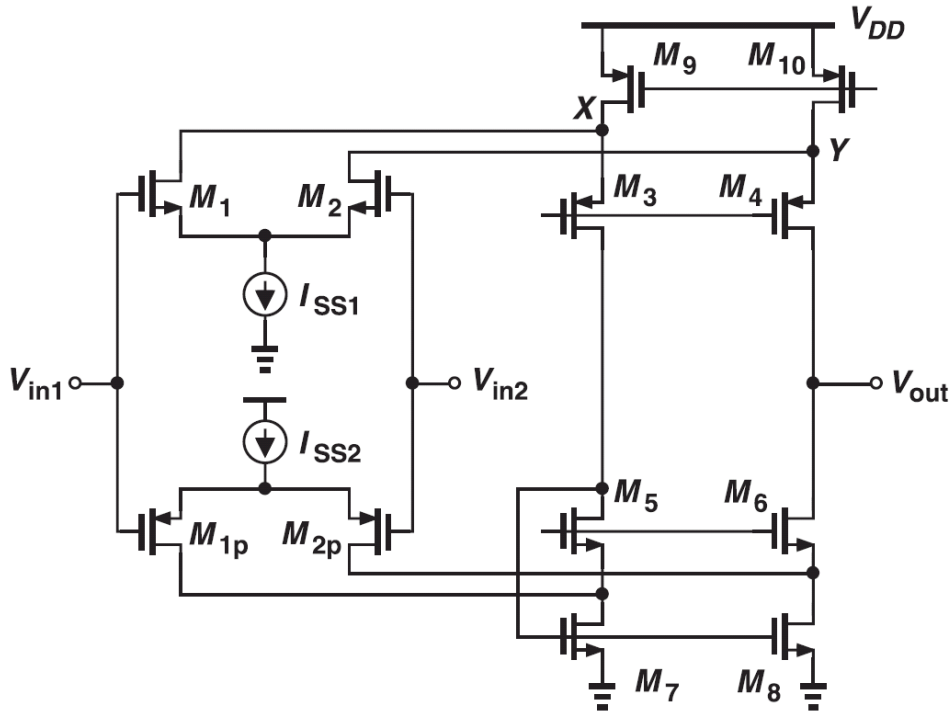
1. General Consideration
2. One-Stage Op Amps / Two-Stage Op Amps
3. Gain Boosting
4. Common-Mode Feedback
- 5. Input Range / Slew Rate**
6. Power Supply Rejection / Noise in Op Amps

Input Range Limitations



- The input CM level may need to vary over a wide range in some applications.
- The voltage swings may be limited by the input differential pair rather than the output cascode branch.
- If $V_{out} < V_{in,min}$, I_{SS} enters the triode region and the transconductance of the differential pair decreases.
- The limitation can be overcome if the transconductance can somewhat be restored.

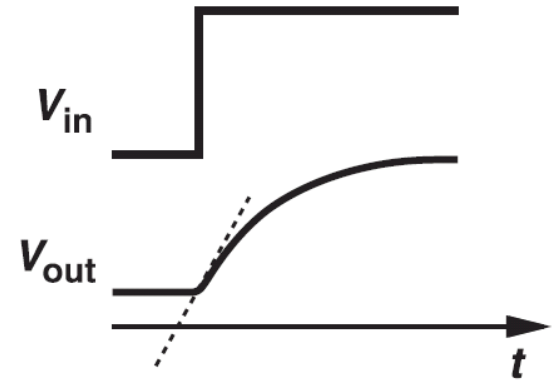
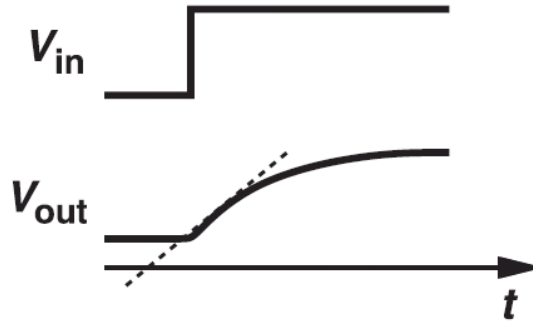
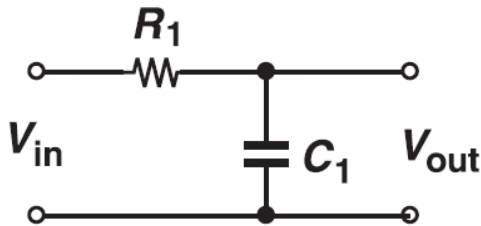
Extension of Input CM Range



➤ Incorporate both NMOS and PMOS DPs such that when one is “dead”, the other is “alive”.

- The variation of the overall g_m of the two pairs as the input CM level changes.
- Many properties of the circuit, including gain, speed, and noise vary.
- For minimizing input transconductance variation
 - Ref R. Hogervost et al, “A Compact Power Efficient 3-V CMOS Rail-to-Rail Input/Output Operational Amplifier for VLSI Cell Libraries”, JSSC, pp.1505-1513, Dec 1994

Slew Rate



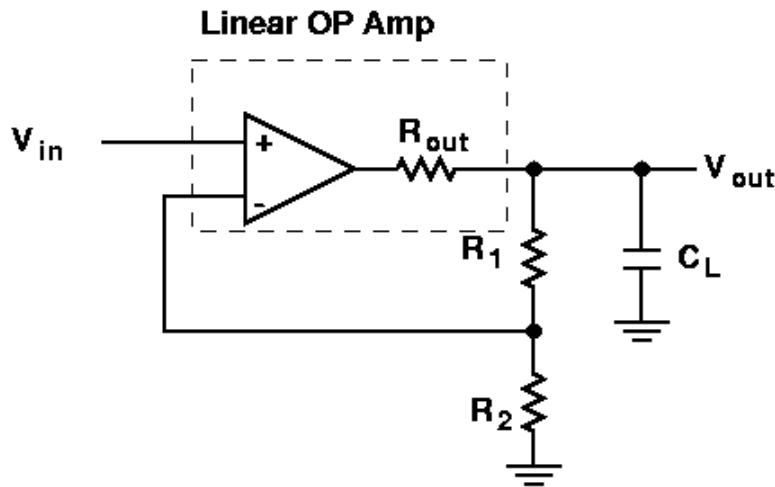
- Op amps used in feedback circuits exhibit a large-signal behavior called “slewing”.
- Linear system vanishes during slewing.
- Consider a simple RC network (http://en.wikipedia.org/wiki/RC_circuit)

$$V_{out} = V_0 [1 - \exp(-t / \tau)] \quad \tau = RC \quad \frac{dV_{out}}{dt} = \frac{V_0}{\tau} \exp \frac{-t}{\tau}$$

- The slope of the step response is proportional to the final value of the output.
- **Linear System** : If we double the input amplitude, the output signal level must double at every point.

Step Response of Linear OP Amp

- Assume the op amp is linear



$$\left[\left(V_{in} - V_{out} \frac{R_2}{R_1 + R_2} \right) A - V_{out} \right] \frac{1}{R_{out}} = \frac{V_{out}}{R_1 + R_2} + V_{out} C_L s$$

If $R_1 + R_2 \gg R_{out}$

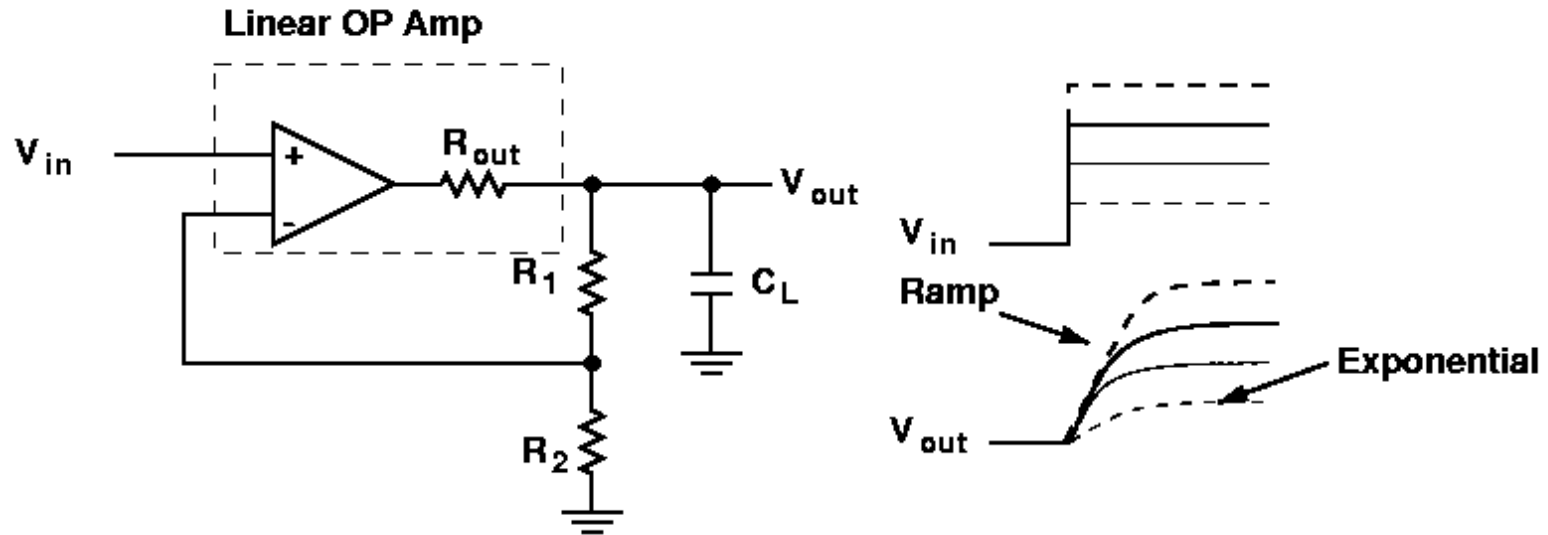
$$\frac{V_{out}}{V_{in}}(s) \approx \frac{A}{\left(1 + \frac{AR_2}{R_1 + R_2} \right) \left[1 + \frac{R_{out} C_L}{1 + AR_2 / (R_1 + R_2)} s \right]}$$

- Both the low-frequency gain and the time constant are divided by $1 + AR_2 / (R_1 + R_2)$
- The step response is given by

$$V_{out}(t) = V_0 \frac{A}{1 + \frac{AR_2}{R_1 + R_2}} \left[1 - \exp \frac{-t}{\frac{R_{out} C_L}{1 + AR_2 / (R_1 + R_2)}} \right] u(t)$$

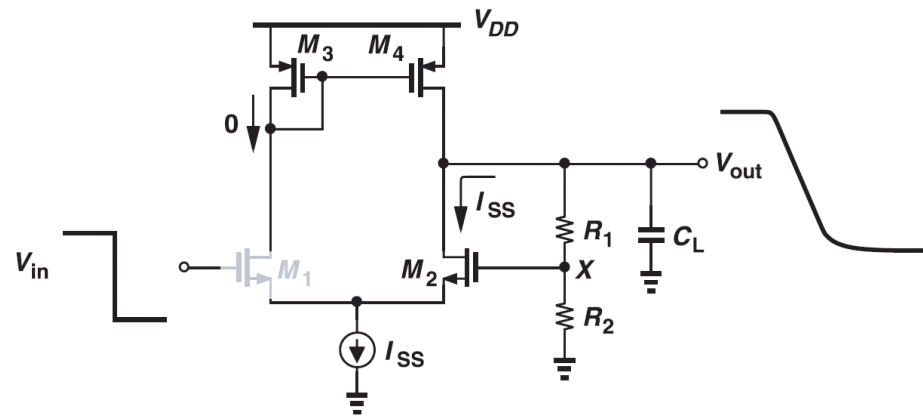
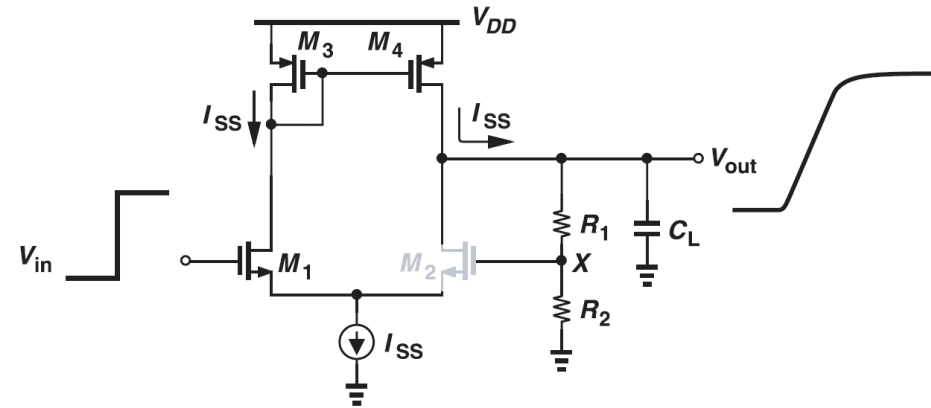
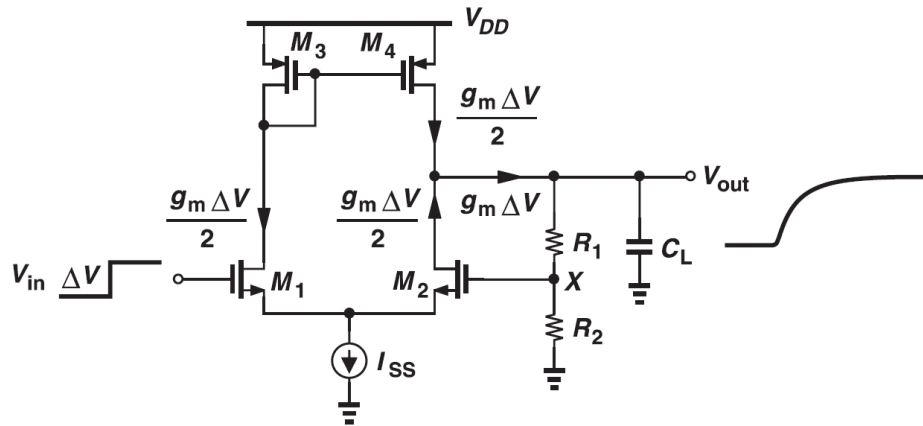
- Linear Settling : the slope is proportional to the final value (**exponential response**).

Slewing in an OP Amp Circuit



- The step response of the circuit begins to deviate from linear response as the input amplitude increases.
- The response to sufficiently small inputs follows the exponential curve, but with large input steps, the output displays a linear ramp having a constant slope.
- Under this condition, the op amp experiences slewing and call the slope of the ramp the “slew rate”.

Slewing During Transition

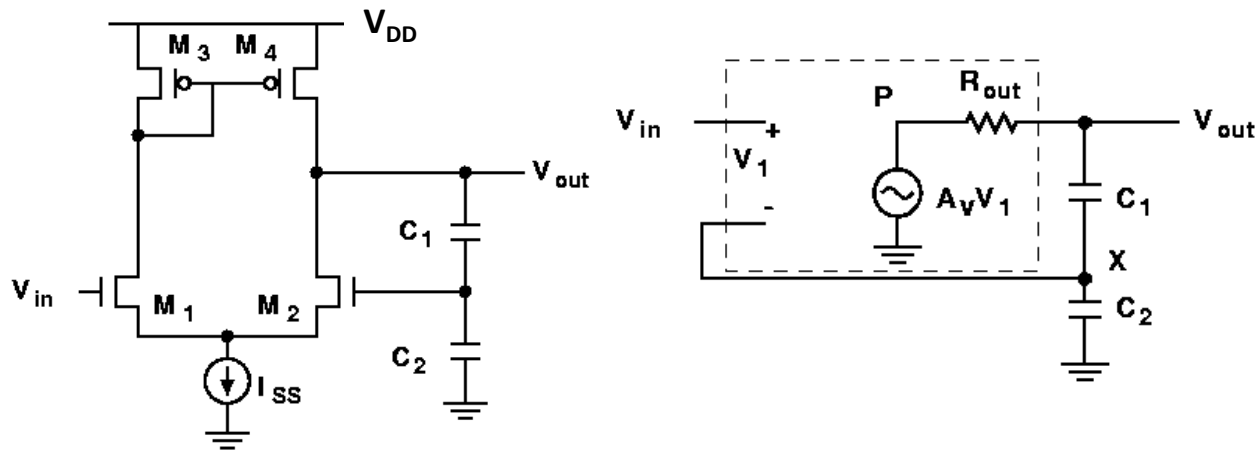


- Assume that $R_1 + R_2$ is quite large.
- If V_{in} experiences a change of ΔV , I_{D1} increases by $g_m\Delta V/2$.
- The total small-signal $I_{out} = g_m\Delta V$.
- I_{out} will charge C_L , but as V_{out} rises, so does V_X , ΔV of V_{G1} and $V_{G2} \downarrow$, hence $I_{out} \downarrow$.
- If ΔV is so large that M_1 absorbs all of I_{SS} , M_2 is turned off, generating a ramp output with a slope equal to I_{SS}/C_L (feedback is broken). (neglect I of R_1, R_2)
- $V_X \rightarrow V_{in}$, M_2 turns on, and the circuit returns to linear operation.

Slewing During Transition

- Large signal speed is limited by the slew rate because the current available to charge and discharge the dominant capacitor in the circuit is small.
- The input-output relationship during slewing is nonlinear.
- To amplify a sinusoid $V_o \sin \omega_o t$, its slew rate must exceed $V_o \omega_o$.

Feedback Amplifier Example



$$A_v = g_{m1,2} (r_{O2} \parallel r_{O4}),$$

$$R_{out} = r_{O2} \parallel r_{O4},$$

$$V_X = \frac{C_1 V_{out}}{C_1 + C_2},$$

$$V_P = \left(V_{in} - \frac{C_1}{C_1 + C_2} V_{out} \right) A_v$$

$$\left[\left(V_{in} - \frac{C_1}{C_1 + C_2} V_{out} \right) A_v - V_{out} \right] \frac{1}{R_{out}} = V_{out} \frac{C_1 C_2}{C_1 + C_2} s$$

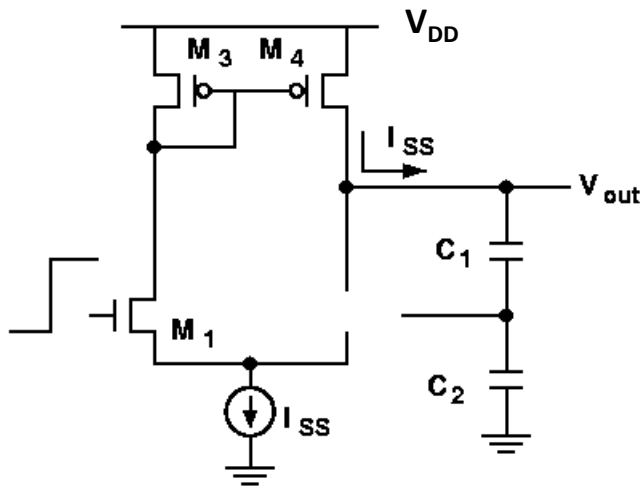
$$\frac{V_{out}}{V_{in}}(s) = \frac{A_v}{1 + A_v \frac{C_1}{C_1 + C_2} + \frac{C_1 C_2}{C_1 + C_2} R_{out} s} = \frac{A_v / [1 + A_v C_1 / (C_1 + C_2)]}{1 + \frac{C_1 C_2}{C_1 + C_2} R_{out} s / \left(1 + A_v \frac{C_1}{C_1 + C_2} \right)}$$

- Both the low-frequency gain and the time constant of the circuit have decreased by a factor of $1 + A_v C_1 / (C_1 + C_2)$

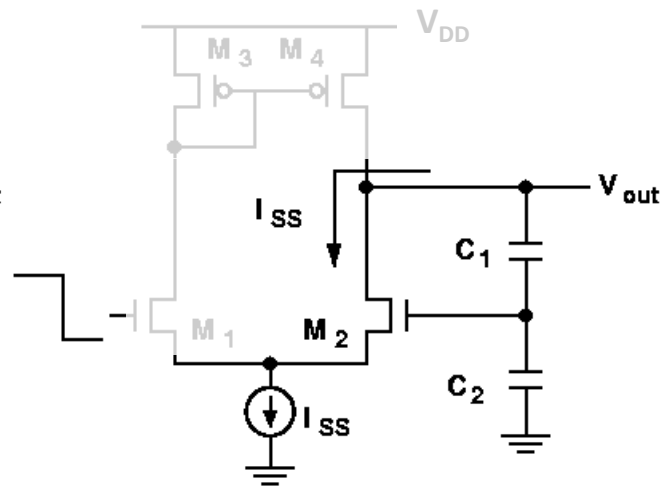
- Unity step response $V_{out}(t) = \frac{A_v}{1 + A_v \frac{C_1}{C_1 + C_2}} V_0 \left(1 - \exp \frac{-t}{\tau} \right) u(t), \quad \tau = \frac{C_1 C_2}{C_1 + C_2} \frac{R_{out}}{1 + A_v \frac{C_1}{C_1 + C_2}}$

Feedback Amplifier Slewing

- Positive & Negative Slewing

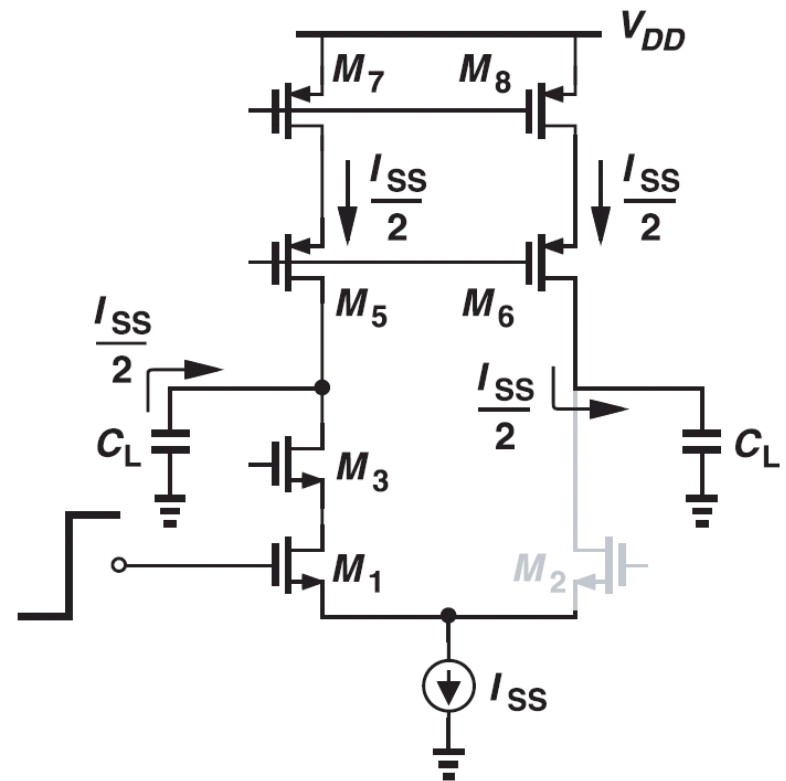
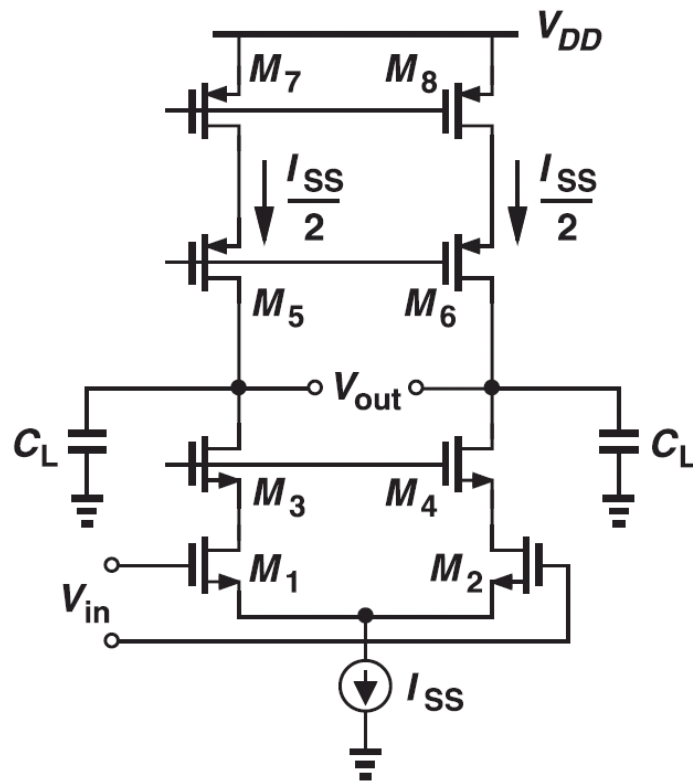


$$V_{out}(t) = \frac{I_{ss}t}{\left[\frac{C_1 C_2}{C_1 + C_2} \right]} \quad \text{positive step,}$$



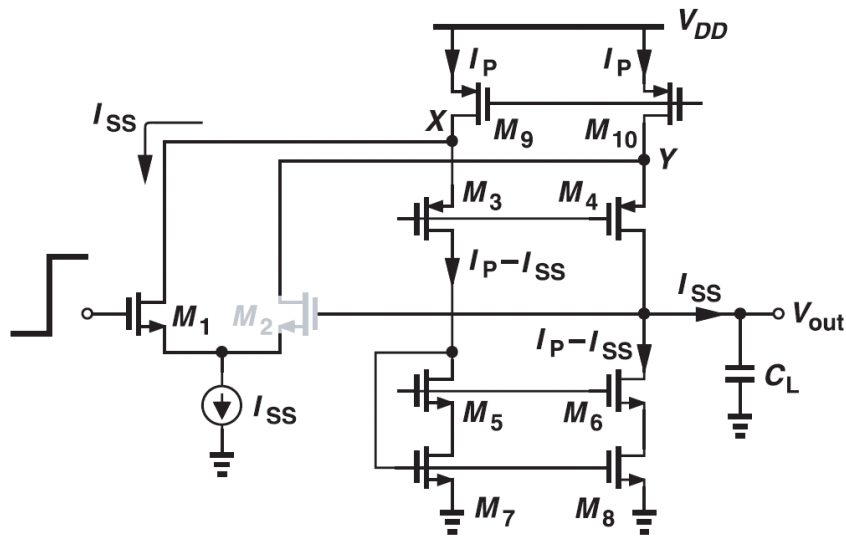
$$V_{out}(t) = \frac{-I_{ss}t}{\left[\frac{C_1 C_2}{C_1 + C_2} \right]} \quad \text{negative step}$$

Slewing in Telescopic Op Amp

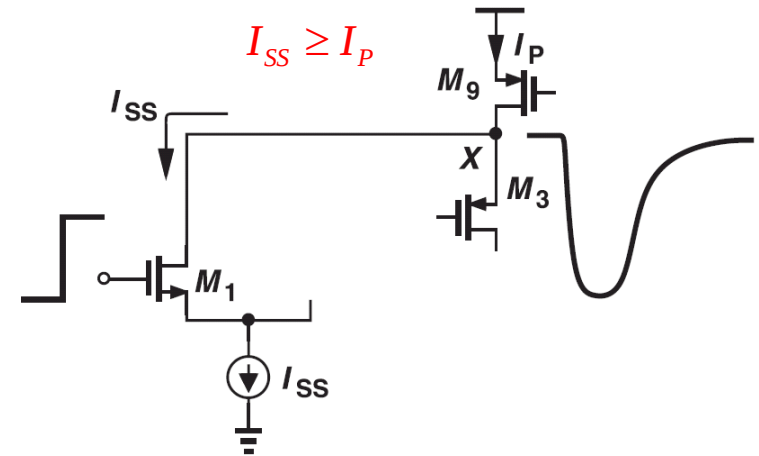
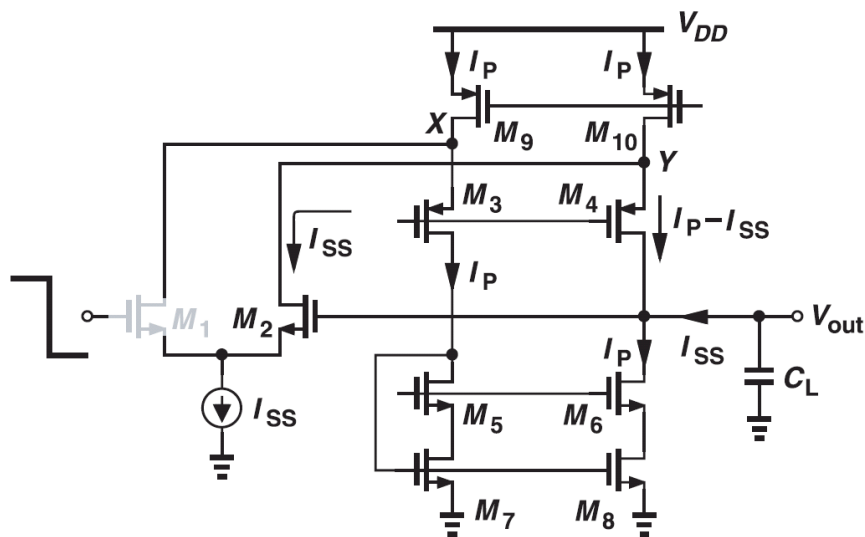


- When a large differential input is applied, M_1 or M_2 turns off.
- V_{out1} and V_{out2} appear as ramps with slopes equal to $\pm I_{SS} / 2C_L$
- $V_{out1} - V_{out2}$ exhibits a slew rate equal to I_{SS}/C_L .

Slewing in Folded Cascode Op Amp



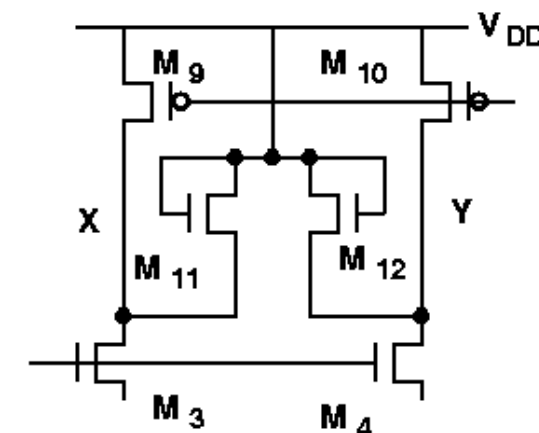
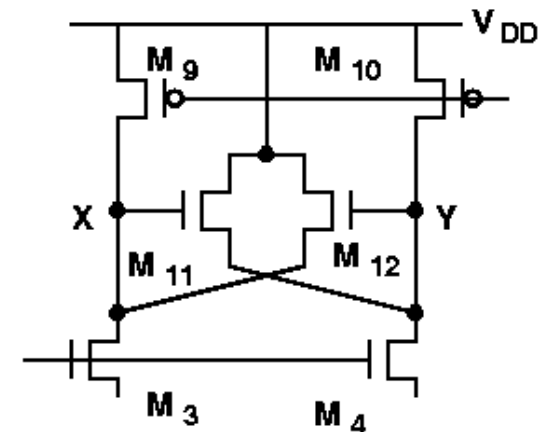
(a)



- PMOS current sources I_P .
- The current that charges / discharges C_L is equal to I_{SS} .
- Slew rate $\sim I_{SS} / C_L$.
- The SR is independent of I_P if $I_P \geq I_{SS}$.
- If $I_{SS} \geq I_P$, then during slewing M_3 turns off, and V_X falls to a low level such that M_1 and the tail current source enter the triode region.

Clamp Circuit to Limit Swings

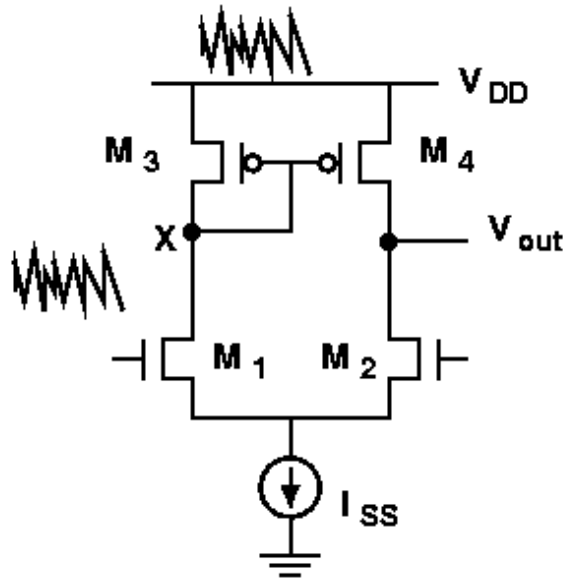
- The difference between I_{SS} and I_p now flows through M_{11} or M_{12} , requiring only enough drop in V_x or V_y to turn on one of these transistors.
- M_{11} and M_{12} clamp the two diodes directly to V_{DD} .
- The equilibrium value of V_x and V_y is usually higher than $V_{DD} - V_{THN}$, M_{11} and M_{12} are off during small-signal operation.
- Trade-offs encountered in increasing the slew rate
 - Slew rate $\uparrow \rightarrow I_{SS} \uparrow \rightarrow (W/L) \uparrow \rightarrow$ Power dissipation $\uparrow \rightarrow C_{in} \uparrow$
 - If the device currents and widths scale together, ***$g_m r_o$ of each transistor and hence the open-loop gain of the op amp remain constant.***



Outline

1. General Consideration
2. One-Stage Op Amps / Two-Stage Op Amps
3. Gain Boosting
4. Common-Mode Feedback
5. Input Range / Slew Rate
- 6. Power Supply Rejection / Noise in Op Amps**

Power Supply Rejection



$$PSRR \equiv \frac{A_{v,input-output}}{A_{v,V_{DD}-output}}$$

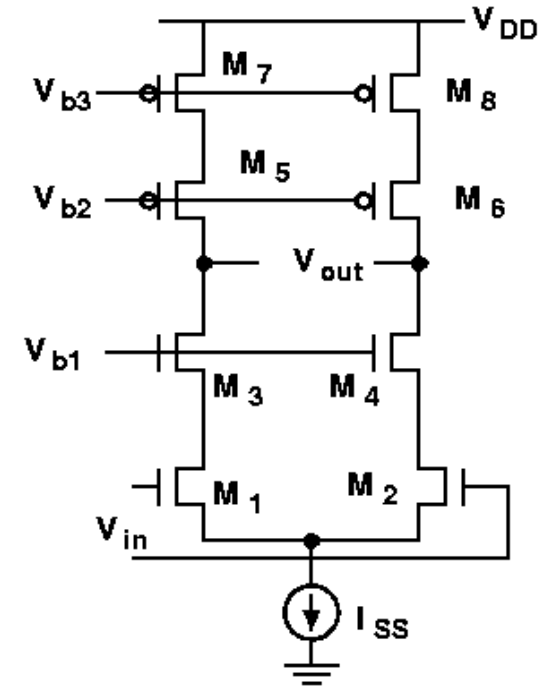
$$A_{v,input-output} = g_{mN} (r_{OP} \parallel r_{ON})$$

$$A_{v,V_{DD}-output} \approx 1$$

- OP amps are often applied from noisy lines and must therefore “reject” the noise adequately.
- If the circuit is perfectly symmetric, $V_{out} = V_X$. The diode connected device clamps node X to V_{DD} , thus $V_{out} \approx V_{DD}$.
- The gain from V_{DD} to V_{out} is close to unity.
- The power supply rejection ratio $PSRR \sim g_{mN} (r_{OP} \parallel r_{ON})$

Noise in Op Amps

- Change the gate voltage for each transistor by a small amount and predict the effect at the output.
- At relatively low frequencies, the cascode devices contribute negligible noise.
- M1-M2 and M7-M8 are the primary noises sources.
- The input-referred noise voltage per unit-bandwidth is given by (7-28, p.226, 239)
 - Similar to fully-differential amp.



$$\overline{V_n^2} = 4kT \left(2 \frac{2}{3g_{m1,2}} + 2 \frac{2g_{m7,8}}{3g_{m1,2}^2} \right) + 2 \frac{K_N}{(WL)_{1,2} C_{ox} f} + 2 \frac{K_P}{(WL)_{7,8} C_{ox} f} \frac{g_{m7,8}^2}{g_{m1,2}^2}$$

Noise in a Folded-Cascode Op Amp

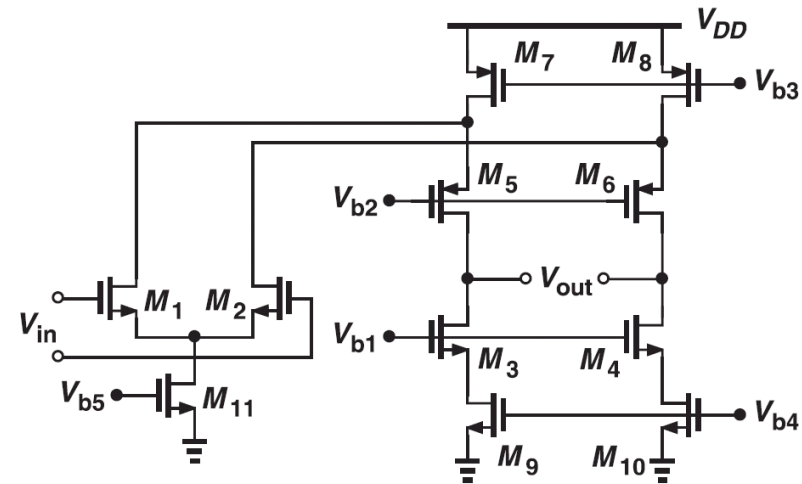
- At relatively low frequencies, the cascode devices contribute negligible noise.
- M_1 - M_2 , M_7 - M_8 , M_9 - M_{10} are potentially significant noise sources.
- Consider thermal noise only, we first refer the noise of M_7 - M_8 and M_9 - M_{10} to the output

$$\overline{V_{n,out}^2}\bigg|_{M_{7,8}} = 2 \left(4kT \frac{2}{3g_{m_{7,8}}} g_{m_{7,8}}^2 R_{out}^2 \right)$$

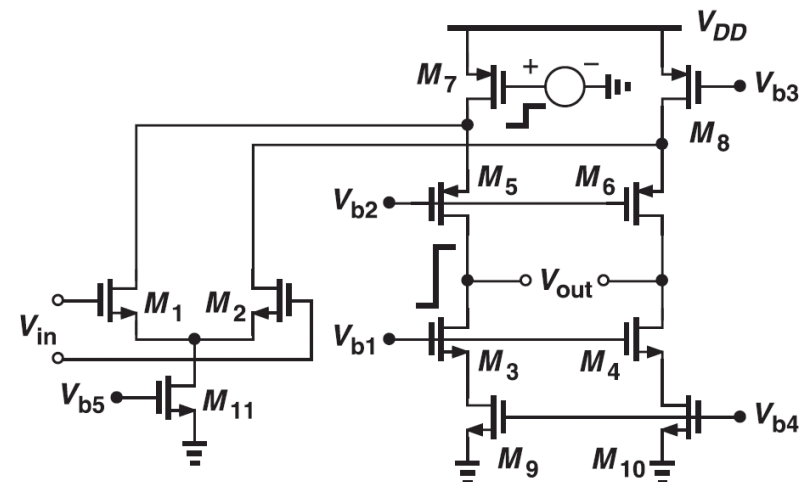
$$\overline{V_{n,out}^2}\bigg|_{M_{9,10}} = 2 \left(4kT \frac{2}{3g_{m_{9,10}}} g_{m_{9,10}}^2 R_{out}^2 \right)$$

- Adding the contribution of M_1 - M_2 , we obtain
 - Larger than telescopic amp.

$$\overline{V_{n,int}^2} = 8kT \left(\frac{2}{3g_{m_{1,2}}} + \frac{2g_{m_{7,8}}}{3g_{m_{1,2}}^2} + \frac{2g_{m_{9,10}}}{3g_{m_{1,2}}^2} \right)$$



(a)



Noise in a Two Stage OP Amp

- The noise current of M_5 and M_7 flows through $r_{O5} \parallel r_{O7}$, the input referred noise contribution of M_5 - M_8 is

$$\begin{aligned} \overline{V_n^2} \Big|_{M5-8} &= 2 \times 4kT \frac{2}{3} (g_{m5} + g_{m7}) (r_{O5} \parallel r_{O7})^2 \frac{1}{g_{m1}^2 (r_{O1} \parallel r_{O3})^2 g_{m5}^2 (r_{O5} \parallel r_{O7})^2} \\ &= \frac{16kT}{3} \frac{g_{m5} + g_{m7}}{g_{m1}^2 (r_{O1} \parallel r_{O3})^2 g_{m5}^2} \end{aligned}$$

- The noise due to M_1 - M_4 is equal to

$$\overline{V_n^2} \Big|_{M1-4} = 2 \times 4kT \frac{2}{3} \frac{g_{m1} + g_{m3}}{g_{m1}^2}$$

- It follows that

$$\overline{V_{n,tot}^2} = \frac{16kT}{3} \frac{1}{g_{m1}^2} \left[g_{m1} + g_{m3} + \frac{g_{m5} + g_{m7}}{g_{m5}^2 (r_{O1} \parallel r_{O3})^2} \right]$$

- The noise from $M_5 \sim M_8$ is negligible, it's divided by gain of first stage.

